Laminated Structures for Sports Mouthguards

Thesis Submitted for the Degree of

Doctor of Philosophy

David G Patrick

Department of Oral Health and Development

University of Sheffield

Summary

Aims and Objectives

The aims and objectives of this study are to examine the role of mouthguards and the materials that are used for their manufacture, the heating process they undergo during manufacture and how the lamination of different materials into a multi-layered system to form a composite structure may affect the impact absorbing capabilities.

The effect of heat on pEVA during the manufacturing process was investigated using an instrumented dropweight impact testing rig and a polariscope to observe internal stress as it was felt that the physical properties of the material could be adversely affected by this part of the process. Laminated structures, using several different materials, (pEVA, PMMA, silicone rubber, synthetic wax, modelling clay, soft denture lining material and a semi-solid synthetic rubber) were tested as it was felt that the lamination of different materials with a range of physical properties would exhibit less deformation and transmit less of the impact energy. To ascertain how a mouthguard may react during an impact event by simulation tests in the impact test rig.

Methods

For the heat treatment of pEVA a furnace was used to heat the test material to near its' glass transition temperature (Tg) of 84°C ± 3 °C. The material was brought up to Tg and held at that point for 10 minutes. The specimens were then removed from the furnace and allowed to cool to room temperature. Heat treated and non-heat treated

samples were placed in a polariscope to observe stress within the material. Dropweight impact tests were conducted on all samples using an instrumented impact testing rig. All samples were circularly clamped and force-time and displacement-time plots obtained. The samples were placed again in the polariscope and any changes in stress were noted. To observe the processing effects of the manufacturing procedure five mouthguards were made on the same cast and were brought to various stages of completion. Different 'lay-ups' of pEVA along with laminations and sandwiches of pEVA, PMMA, silicone rubber, synthetic wax, modelling clay, semi-solid synthetic rubber and denture soft lining were also tested using the dropweight impact tester. For the impact simulation tests samples of 50mm diameter were placed on top of a PMMA substrate, that was clamped in the impact rig, to see how the test sample would protect the substrate during impact.

Results

The Peak Impact Force (PIF) of heat treated pEVA was lower (PIF<140N) than that of untreated pEVA (PIF=160N). The displacement of the heat treated sample during impact increased by 66%, (untreated pEVA>18mm centre displacement, heat treated pEVA >30mm centre displacement). Digital photographic images from the polariscope show that the heat treatment of pEVA virtually eliminates stress and following impact the amount of stress, seen photoelastically, was also reduced. Images of material in the polariscope also indicate that the finishing techniques employed during the manufacturing process have a direct effect on the stress distribution within the mouthguard. A 5mm laminated structure of pEVA, PMMA and silicone rubber was able to absorb more impact energy (PIF = 275N) and exhibited less deformation (1.4mm) than that of a monolithic structure of 5mm heat treated pEVA (PIF <140N, displacement >30mm). Simulation tests showed that the 5mm thick pEVA protected the PMMA better (PIF = 325, displacement 6.8mm) than the 1mm pEVA (PIF = 340, displacement 7.7mm).

Conclusions

The mouthguard forming process has a direct effect on the internal stresses of pEVA and therefore its' physical response. When pEVA is laminated with PMMA and silicone rubber the impact absorbing capabilities are better than a monolithic structure of pEVA. Mouthguards for use in contact sports, therefore, should incorporate a laminated section of pEVA, PMMA and silicone rubber. Simulation tests show that 5mm thick samples protect a substrate more effectively than 1 – 4mm test samples.

Contents

Chapter 1

Introduction

Chapter 2

Review of the literature

Chapter 3

Purpose of the study

Chapter 4

Materials and methods

Chapter 5

Results

Chapter 6

Discussion

Appendix

The influence of heat treatment on the impact performance of sports mouthguard materials. D G Patrick, R van Noort and M S Found,Centre for Biomaterials and Tissue Engineering. *Proc ACUN – 4 "Composite Systems – Macrocomposites, Microcomposites, Nanocomposites", UNSW, SYDNEY, Australia, 21-25 July 2002 Eds : S. Bandyopadhyay et al, ISBN 0 7334 1862 7*

The Use of Multi-Layered Structures for Sports Mouthguards. D Patrick, R van Noort and M S Found. Centre for Biomaterials and Tissue Engineering, University of Sheffield UK. *Key Engineering Materials Vols. 221-222 (2002) pp. 133-144*

The Use of Multi-Layered Structures for Sports Mouthguards. D Patrick, R van Noort and M S Found. Centre for Biomaterials and Tissue Engineering, University of Sheffield UK. *Proc ICCM, Cagliari, Sardinia 2001.*

Acknowledgements

Help and assistance was obtained from many people who either pointed the author in the correct direction or offered their valued opinion. Special thanks to;

Professor Van Noort

Professor of Dental Materials at the University of Sheffield. Head of Department of Adult Dental Care, Head of Centre for Biomaterials and Tissue Engineering. As the supervisor of this project Professor Van Noort was a constant source of knowledge and help, his guidance and support were always forthcoming and welcomed.

Dr. M S Found

Senior Lecturer in the Department of Mechanical Engineering. Dr. Found has 30 years experience in FRP composites. His main work is on the understanding of failure mechanisms under static, impact and fatigue loading conditions. He has been instrumental in the development of models for predicting damage tolerant, crashworthy composite structures. Recent work on energy absorbing composite systems ranging from sports mouthguards to aerospace structures and rail cabs. Mike was instrumental in arranging tests using the Polariscope and the impact rig. With his help and guidance the impact rig was altered to accommodate the test samples for this study.

Mr A Paran

PhD student in the Department of Mechanical Engineering. Alex was very helpful in demonstrating and explaining the use of the impact rig and data acquisition package used in this project.

CHAPTER 1

Introduction

1.1 The History of Mouthguards

Mouthguards have been worn by sportsmen since the turn of the century, in one form or another. The English boxer Ted 'Kid' Lewis, in 1913, began using a 'mouthguard' made from a piece of natural rubber that had been trimmed and hollowed out so that it would fit over the maxillary dentition, he wore it to prevent chipped or broken teeth resulting from blows to the head. It was not adapted to the teeth and so retention was very poor, the jaw had to be clenched to hold the mouthguard in place making it difficult for the wearer to breathe (Chapman 1989; Flanders 1993). Despite its rather obvious drawbacks other professional boxers and officials in the sport tried to prevent him from wearing the mouthguard as it was thought that it gave him an unfair advantage by preventing injury so he wouldn't have to retire early from a fight. This kind of 'unfitted' or 'stock' mouthguard can still be bought today, although the materials have changed – poly ethylene vinyl acetate being substituted for rubber. Most sports shops sell them and, surprisingly, are sometimes recommended to sportsmen and women by their dentist. This type of mouthguard offers a very low level of protection to the wearer, it also has the added danger of the possibility that it may become dislodged and obstruct the oropharynx. Sportsmen should be actively discouraged from wearing such a mouthguard (Chapman 1986).

During the 1950's and 1960's in America mouthguard material research and design went through a period of rapid development. At this time many field studies were carried out and materials' testing was undertaken. From this research (Bishop, *et al*; 1985; Chapman, 1985; Craig & Godwin, 1967; Going, *et al*, 1974) it was decided that the mouthguard should be worn on the maxillary teeth (Croll, 1992) as these were the most prone to damage, the exception to this being class III arch relationships, where the mandible protrudes in front of the maxillary teeth, in this instance the mandibular teeth are recommended to be fitted with a mouthguard (Powers, *et al;* 1984). It was at this time that mouth-formed and custom-made mouthguards were developed. The early studies that were carried out could not seem to agree as to which type of mouthguard was the best. However, surveys of player opinion did report that the custom made mouthguard was the best option with regard to retention, cleanliness, ease of speech, lack of odour, taste and durability (Craig and Godwin, 1967).

The cost of the custom made mouthguard was and still can be somewhat prohibitive, which may deter many people from wearing such a mouthguard, regardless of the fact that nearly all the literature recommends that custom made mouthguards are the most effective type of protection (Oikarinen, 1993; Turner, 1977).

1.2 The need for wearing mouthguards

Sportsmen and women will spend an inordinate amount of money on the more visible items of sports equipment such as boots, shoes, clothing and the latest sports bag; but when it comes to the protection of their mouth it seems that the cheapest option will do. The implications of this attitude are far reaching. The American Association for Sports Dentistry states that the cost to replant a tooth and the follow up dental treatment is about $5000. While sportsmen and women who do not have a tooth properly preserved or replanted may face lifetime dental costs of $15,000 - $20,000 per tooth, hours in the dental chair and the possible development of other dental problems such as periodontal disease, (Sports Dentistry Facts, AASD – www.sportsdentistry.com). Thankfully dental costs aren't as high in the U.K. yet, but in terms of time off from work for a patient attending a dental surgery and the cost borne by the NHS then the hidden costs soon start to escalate. In wearing a mouthguard the athlete is wearing a protection device that will, if fitted properly, protect the teeth and other soft oral tissues from trauma due to impact. A mouthguard will limit the amount of damage sustained during wear and may also prevent the incidence of concussion from repeated blows to the mandible (Chapman 1985, 1986, 1989).

It is the purpose of the mouthguard, therefore, to protect the teeth and soft tissues of the mouth from impact causing injury and to prevent the incidence of accumulative concussion.

1.3 Investigations

This research will investigate mouthguards in relation to their ability to protect the oral tissues with regard to such criteria as;

The properties of the material from which custom mouthguards are made, polyethylene vinyl acetate (pEVA), including the heating cycle of the manufacturing process as it is felt that this part of the process may have a significant influence on the way in which pEVA reacts during an impact event.

Design features that may alter a mouthguards' protective capabilities such as the lamination of different materials with pEVA will be investigated, however, the basic shape of the mouthguard will remain the same as the mouth dictates the 'horseshoe' shape.

In an attempt to ascertain how a mouthguard may react during an impact event simulation testing of the mouthguard material in an instrumented impact testing rig will be carried out.

The purpose of the study is to examine the role of mouthguards and the materials that are used for their manufacture, the heating process they undergo during manufacture and how the lamination of different materials into a multi-layered system to form a composite structure may affect the impact absorbing capabilities.

CHAPTER 2

Review of the literature

2.1 Defining the mouthguard

A mouthguard, or gumshield as it is sometimes known, is a horseshoe shaped device that fits closely on the teeth and mucosa of the upper dental arch (athletes that with class III arch relationships may wear a mouthguard on the mandibular teeth) to protect the wearer's teeth, lips and gums from impact during contact sports such as rugby, boxing or hockey. Impacts may be from fists, elbows and other body parts or from harder objects such as hockey sticks, balls or studded boots.

In wearing a mouthguard the teeth are protected from direct impact to them and from the teeth in the lower jaw that may, in the event of an uppercut type punch in boxing, hit them with such force as to cause fracture or chipping of the enamel. Lacerations of the lips and cheeks and fractured teeth (Figure 2.1) are seen in non-mouthguard wearing athletes who participate in contact sports, while these injuries cannot always be prevented by the wearing of a mouthguard the incidence of such injuries is reduced when a mouthguard is worn (Blignaut *et al.*, 1987).

Fig. 2.1 Typical injury that may be sustained from an impact to the mouth if a mouthguard is not worn.

The mouthguard is also thought to help prevent knockouts and concussion from direct blows to the chin (Chapman, 1985; Hickey, *et al.*, 1967).

2.2 The features of mouthguards

In the prevention of intraoral trauma in sports (Johnsen and Winters, 1991) the 'characteristics of an ideal mouthguard' are said to be:

i) **Protection**

There must be the maximum amount of protection to the teeth, lips, oral mucosa and gingiva by cushioning the force of an impact to prevent any trauma.

ii) **Retention**

The mouthguard must stay firmly in place at all times.

iii) **Function**

It should not interfere with breathing or speech and should be odourless and tasteless.

iv) Fabrication

Custom made mouthguards should be easy to manufacture, needing minimal chair and lab time, while cost must not be prohibitive.

If a mouthguard meets all these criteria then the likelihood of an athlete wearing such a device is greatly improved.

A considerable amount of published research (Chapman, 1989; Clegg, 1969; DeYoung, Robinson, Godwin, 1994) regarding sports mouthguards consists mainly of comparisons of the types of mouthguard that are available, usually focusing on such areas as cost, comfort, efficacy and ease of manufacture. The types of mouthguard studied in these comparative tests are:

i) Stock mouthguards - which come in differing sizes and are ready to use, (Figure 2.2a) mostly these types are made from either polyvinyl chloride (although the use of PVC for mouthguards has now been outlawed by the E.U.), polyurethane or a co-polymer of vinyl acetate or ethylene.

Fig. 2.2a Stock mouthguard

ii) Mouth-formed - can either be a plastic rim lined with a material similar to a tissue conditioner or a 'boil and bite' type where a thermoplastic rim, often poly urethane or sometimes poly ethyl vinyl acetate (pEVA),

(Figure 2.2b)is heated in hot water then placed in the mouth and moulded by biting and sucking.

Fig. 2.2b Mouth formed mouthguard

iii) **Custom-made** - this type of mouthguard is made in a dental laboratory on a cast taken from an impression supplied by a dentist (Figure 2.2c). A thermoplastic material, such as EVA, is heated in a pressure or vacuum forming machine and when soft enough it is placed over the cast and air pressure or a vacuum is applied which closely adapts the soft material to the cast.

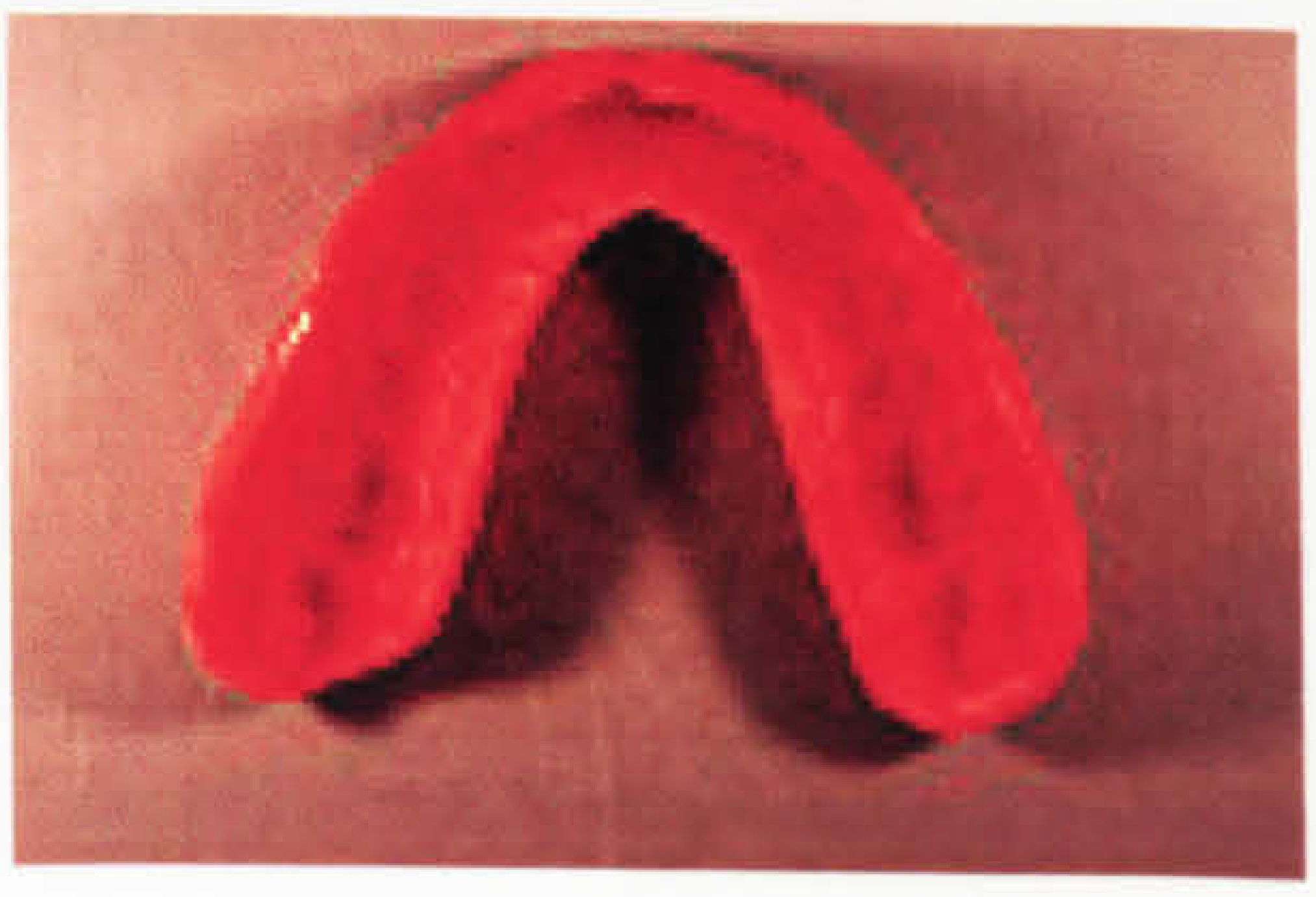


Fig. 2.2c Custom made mouthguard

Of the types listed it is generally thought that the custom-made mouthguards are the best and offer the most protection (De Young, Robinson, Godwin, 1994).

2.3 Concussion prevention and the use of mouthguards

Concussion is an alteration of consciousness, disturbance in vision and equilibrium caused by a direct blow to the head, rapid acceleration and/or deceleration of the head, or direct blow to the base of the skull from a vertical impact to the chin.

There are several levels of concussion (Cantu, 1986).

- Grade 1 (mild): No loss of consciousness (LOC) and Post traumatic amnesia (PTA) less than 30 minutes.
- Grade 2 (moderate): LOC less than 5 minutes or PTA greater the 30 minutes.
- Grade 3 (severe): LOC greater than 5 minutes or PTA greater than 24 hours.

According to E. Williams, DMD (www.sportsdentistry.com) concussive and sub-concussive blows are continually transmitted to the jaw joint during athletic competition. Symptoms include headaches, earaches, facial pain, photophobia, vertigo, and impaired speech. During a blow to the chin, in most instances, the temporal bone is violated as it houses and channels cranial nerve trunks as they exit the base of the brain, blood supply to the brain, and auditory and balance mechanisms.

In 1964 it was recognised that dental/facial injuries, concussions and head and neck injuries were dramatically reduced when mouthguards were worn by a particular American football team, (Stenger, 1964). Other researchers have also reported that properly made custom mouthguards reduce the rate of concussion as well as dental and mandibular injuries, (Heintz, 1979 and Chapman, 1985). Stenger further stated, "The use of mouthguards should be encouraged in all contact sports as the most important value of the mouthguard is the concussion saving effect following impact to the mandible. This fact alone should make the wearing of mouthguards compulsory in all contact sports". Hickey (1967), showed both intracranial pressure and bone deformation were reduced with mouth protectors.

When custom fabricated mouthguards are made, all posterior teeth can be comfortably covered with a predicted and consistent prescribed thickness to properly separate the teeth from impact to the jaw. In turn, the force of impact can be absorbed and equally distributed throughout the mouthguard. With proper thickness in the posterior segment of the mouthguard, the mandible and condyle are separated, figure 2.3a, and the force is not transmitted to the base of the brain. Insufficient thickness or when a mouthguard is not worn the condyle is in contact with the fossa and the force can be transmitted directly to the cranial base, figure 2.3b.

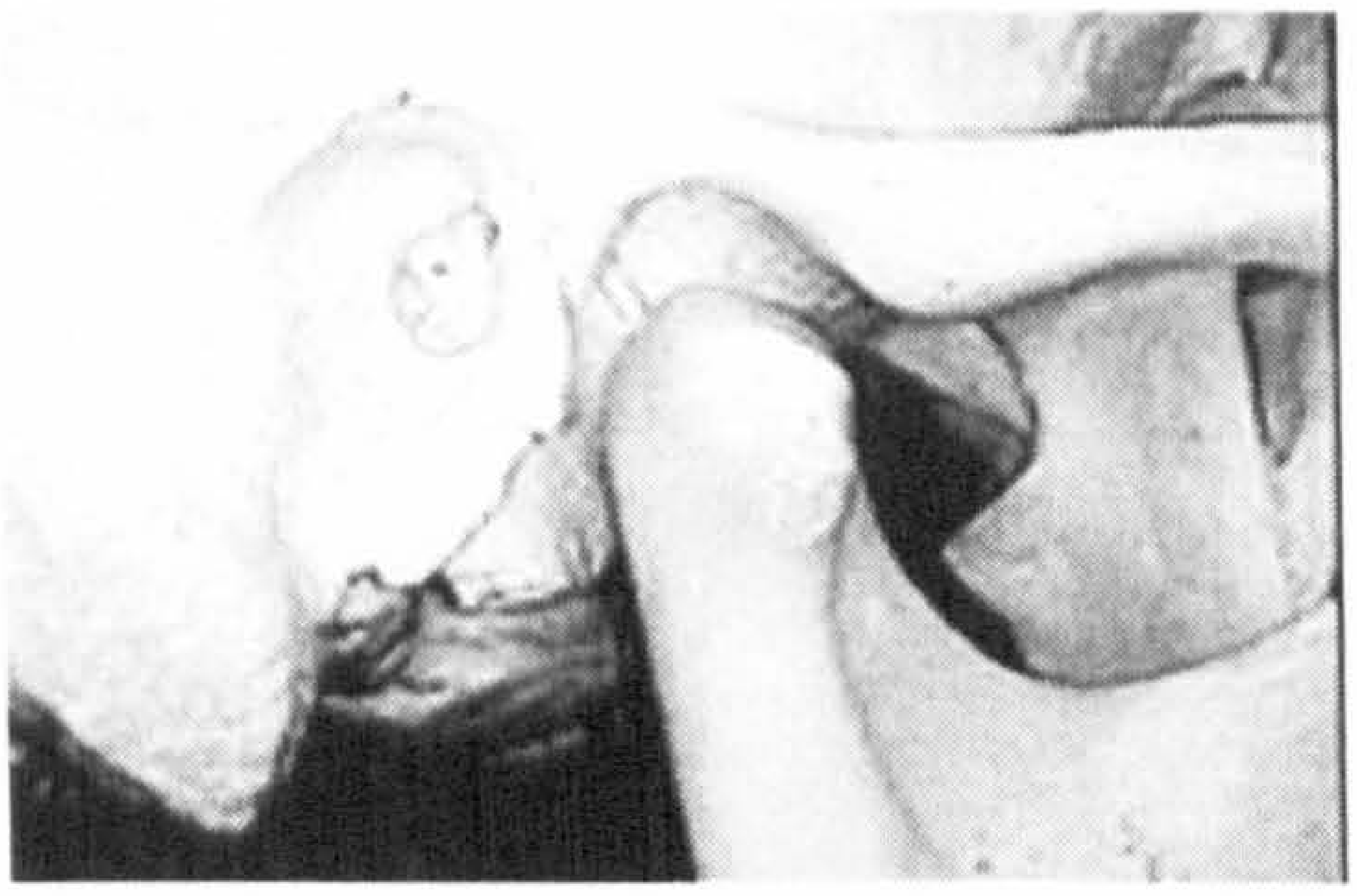


Fig. 2.3a
With a mouthguard the mandible is separated from the maxilla.

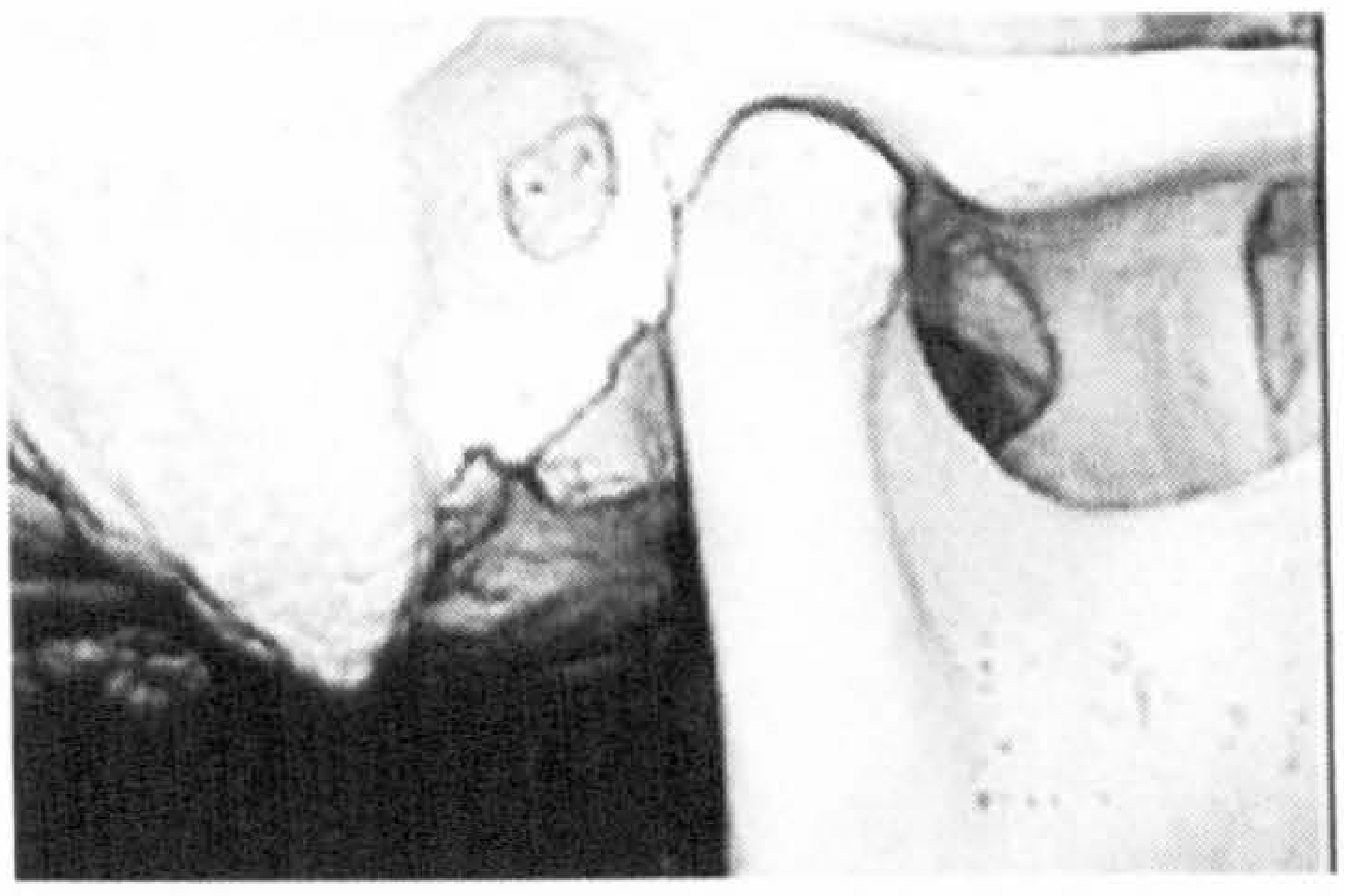


Fig. 2.3b
Without a mouthguard the mandible is in contact with the maxilla.

In all contact sports, when mouthguards are not worn, the mandible is placed in the most vulnerable position for injury and concussion, upwards and back into the fossa and base of the skull. It is no coincidence that in American football the position that least wears a mouthguard (quarterback) is the position that sustains the most concussions from blows to the chin (www.sportsdentistry.com/). The reason for the non-compliance of mouthguard wearing in this position is because it is thought, incorrectly, that speech will be affected. Mouthguards can be properly made for speech and comfort and still fulfil the important job of concussion prevention (www.sportsdentistry.com/).

It is important to seek treatment of a qualified dentist that uses a good dental laboratory for proper mouthguard design and fabrication. Over the counter mouthguards do not produce the fit and expected protection that a laminated pressure fabricated mouthguard delivers, (De Young *et al.*, 1994).

According to Ray Padilla (www.sportsdentistry.com/) in his 16 years of providing custom made athletic mouthguards for American football players, while wearing a properly fabricated custom made mouthguard there has been a significant decrease in numbers and severity of concussions.

It is felt, however, that more studies need to be done to further substantiate the relationship between mouthguards and concussion prevention. As stated by Dr E. Williams, "scientific research is difficult because we do not presently have a biofeedback articulated head-form with injury sensing capabilities to provide realistic responses, injury assessment, and force tolerance of the jaw joint", (http://www.sportsdentistry.com). However, practical experience has shown that a relationship is evident.

2.4 Relative merits of mouthguards

i) Stock mouthguards

Protection - least protective of all mouthguards. This type of mouthguard is often altered and cut by the athlete in an attempt to make it more comfortable, further reducing the protective properties of the mouthguard.

Retention – extremely poor, must be held in place by constantly biting down.

Function - They are bulky and lack any retention, and are held in place by constantly biting down. This interferes with speech and breathing, making the stock mouthguard the least acceptable and least protective, therefore functionality is greatly reduced.

Fabrication – no alteration or fabrication is required although the athlete may alter it to improve comfort.

ii) Mouth-formed/boil and bite mouthguards

Protection - Athletes often cut and alter these bulky and ill fitting boil and bite mouthguards due to their poor fit, poor retention, and gagging effects. This in turn further reduces the protective properties of these mouthguards. When the athlete cuts the posterior borders or bites through the mouthguard during forming, the athlete increases their chance of injury, especially concussion, from a blow to the chin.

Retention - Available in limited sizes, these mouthguards often lack proper extensions and repeatedly do not cover all the posterior teeth so due to these factors retention is generally poor.

Function - boil & bite mouthguards provide a false sense of protection due to the dramatic decrease in thickness occlusally during the moulding and fabrication process (Park, 1993).

Fabrication – fitted by the athlete after immersing in hot water then placing in the mouth and formed by biting and sucking. This process often leads to a mouthguard that is too thin occlusally and labially.

iii) Custom made mouthguards

Protection – as the mouthguard will be of a sufficient thickness occlusally and labially they offer the best protection to the wearer.

Retention – custom made mouthguards are made on a model of the athlete's upper dental arch and are very close fitting so retention is excellent.

Function – as they are made by dental professionals the mouthguard fulfils all the criteria for adaptation, retention, comfort, and stability of material.

They interfere the least with speaking and breathing and will protect against concussion better that the other types of mouthguard.

Fabrication – they are custom made on a model of the patient's teeth in a pressure or vacuum forming machine from a thermoplastic – usually EVA. (www.sportsdentistry.com/, DeYoung, *et al*; 1994, Flanders; 1993, Francis & Brasher; 1991, Going; 1974, Hoffmann, *et al*; 1999).

For wider acceptance and awareness of the use of mouthguards Chapman (1989) considers the role of a 'team dentist' to be a very important one. Such a person is able to provide professionally manufactured mouthguards from a dental laboratory to anyone involved in a contact sport. Also they must recognise 'injury prone dentition' so that the prevention and treatment of any orofacial injuries that may occur can be dealt with quickly and effectively. Chapman (1989) endeavoured to promote awareness amongst the dental profession and to stimulate dentists' interest in this area and to become more closely involved with sporting clubs at a consultative level. He identified central and lateral incisors as the most frequently injured teeth, involved in four fifths of all injuries, the central incisors being four times more frequently damaged than the laterals. It is reasonable to assume, therefore, that prominent incisors - class II malocclusions especially - could be defined as 'injury prone dentition'.

A number of papers relating to mouthguards, (Flanders 1993; Lee-Knight *et al,* 1991; Widmer 1992; Deyoung, Robinson and Godwin 1994; Flanders and Bhat 1995; Scott, Burke and Watts 1994; Kay *et al,* 1990; Welbury and Murray 1990) concentrate on reporting the incidences of orofacial trauma in sport and conclude that mouthguards should be worn during sport to prevent such trauma from happening. All of which would appear to be fairly obvious to the casual observer. Other papers, however, especially those from the U.S., compare the mouthguards that are available and their acceptance by athletes and sports coaches or their governing bodies (Lancaster and Ranalli 1993; Morrow *et al,* 1984; Nachman, Smith and Richardson 1965; Powers, Godwin and Heintz 1984). The one common factor that all papers have is to conclude that in order to prevent or minimise orofacial injury a mouthguard, preferably custom-made, should be worn by any athlete participating in a sport, or training session where injury to the mouth is likely to occur. Thus the evidence available points overwhelmingly to the custom made mouthguard being the preferred option.

The Academy for Sports Dentistry in the U.S., in 1991, listed forty sports in which the wearing of a mouthguard would be beneficial to the athlete. Apart from the obvious contact sports others in the list are a little bewildering as to why a mouthguard should be worn, for example - acrobatics, horse riding, surfing, gymnastics, trampolining, parachuting and weightlifting! It is in sports where there is no perceived risk to the dentition however, that dental injuries are seen possibly more frequently than organised American football or hockey in the U.S. where the wearing of mouthguards at collegiate level has been mandatory for twenty years.

A more recent development came in 1990 when the NCAA Football Rules Committee made it mandatory for "mouthguards to be yellow or any other visible colour". The reason for this is that it is within the officials' remit to enforce the mouthguard rule during games, so if the mouthguard is coloured it is easily seen whilst being worn and more easily found on the pitch if lost. As a 'spin-off' from this rule mouthguards are now being requested in specific colours and combinations of colours to reflect a teams' colours; also colour conscious teenagers are even requesting coloured mouthguards for sports that do not necessarily require the wearing of a mouthguard (Johnsen and Winters, 1991).

2.5 Summary of the ideal mouthguard

It is the purpose of a mouthguard to do, quite literally, what its name implies. It should protect the teeth from fracture by an impact. Protect the lips and cheeks from the teeth in the event of an impact, protect the teeth from each other when the mandible suffers an impact and also from bruxism, as some players tend to grind their teeth whilst participating in their chosen sport.

More recently emphasis is being placed on prevention of concussion and knock-outs by having a sufficient thickness of material occlusally to keep the condyle out of contact with the glenoid fossa. As it is the action of the condyle impacting against the glenoid fossa that directs the force of a blow directly to the brain, thereby causing unconsciousness and/or concussion. This thickening of the occlusal part of the mouthguard, to keep the condyle and glenoid fossa out of contact can also prevent fracture of the ramus and neck of the condyle (Johnsen and Winters 1991). Recently the influence that mouthguards may have on the prevention of concussion has been called in to question, and it has been said that "the ability of mouthguards to protect against head and spinal injuries in sport falls into the realm of 'neuromythology' rather than hard science" (McCrory, 1999). Whether the mouthguard does prevent concussion or not the fact that mouthguards protect the mouth still remains. It is felt that further investigation is needed to determine the effects of how impacts to the mandible may transfer an impact to the brain and whether the wearing of a mouthguard has any significant bearing on the transfer of impact energy to the brain.

A sportsman or woman, who wears a mouthguard, is a more confident participant in their sport as they are less concerned about receiving a traumatic blow that could affect consciousness or result in a disfiguring injury; they concentrate more of their efforts on the execution of their sport (Johnsen and Winters, 1991; Jakush, 1982; Nachman and Richardson, 1965). It could, therefore, be surmised that athletes who wear mouthguards and other such protective devices play their sport harder and faster than they might if they weren't wearing a mouthguard, thus making it more important for the non-mouthguard wearing players to wear a mouthguard and any other necessary protective equipment. Generally stock mouthguards are thought to be the least favourable as they offer the least protection and may even be thought of as dangerous as they may give a rugby player, for example, a false sense of security (Widmer, 1992).

Very little of the literature available is concerned with the improvement of mouthguards and their ability to protect the teeth, tongue and lips. Some of the more relevant studies (Holt, *et al*, 1991; Kawano, *et al*, 1993; Kawano, et al, 1991) seem to be in the field of soft lining materials for full and partial dentures. The studies carried out examine the way in which a soft or resilient lining can evenly distribute a pressure applied to it and thereby effectively reducing the amount of load that is transferred to the underlying structures.

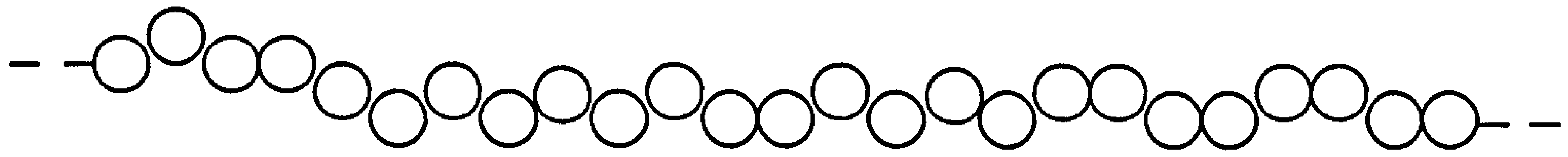
However, the loading conditions for soft liners are quite different to those experienced by a mouthguard. In the case of a soft liner its function is to provide an even distribution of the load. In the case of the mouthguard it has to absorb a high energy impact. Distribution of the resultant force is one feature that the mouthguard has to perform, and a more important feature is the mouthguard's capacity to dissipate the high energy of the impact load in such a way as to cause minimal damage to the underlying structures.

From work carried out on the use of soft lining materials as a shock absorbing layer within a partial denture (Parker, 1966) the idea of laminating different materials to absorb an impact was arrived at. Parker, instead of having the soft lining material bonded to the acrylic so it was in contact with the mucosa incorporated a layer of the material between two layers of acrylic. It was found that when a load was applied it was distributed more evenly to the mucosa and was also reduced when compared to an all acrylic denture or one that had a soft lining that was incorporated in the usual manner.

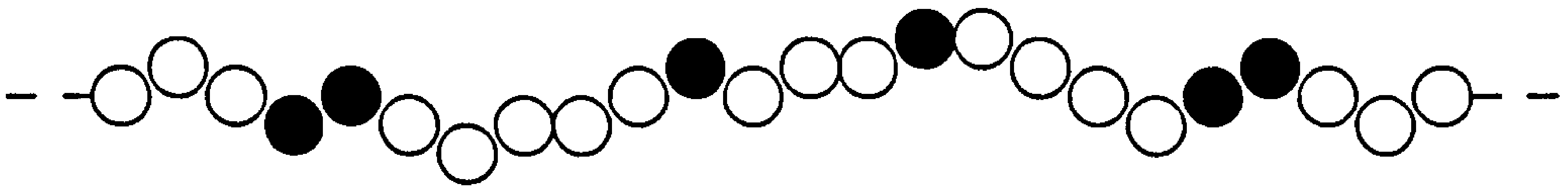
2.6 Materials for mouthguards

All mouthguards are formed from polymers. The word polymer can be literally translated from the Greek to mean *many parts,* (*polus*, many and *meros*, parts). The term is used to describe materials that are made up of many units, these units either being single atoms or a small group of atoms in a state of chemical combination, (Treloar, 1970). When determining the properties of a polymer the spatial structure is important as well as the chemical composition and molecular weight. There are three basic types of structures (Figures 2.4 – 2.4.4): linear, branched and cross-linked, (Craig, 1993).

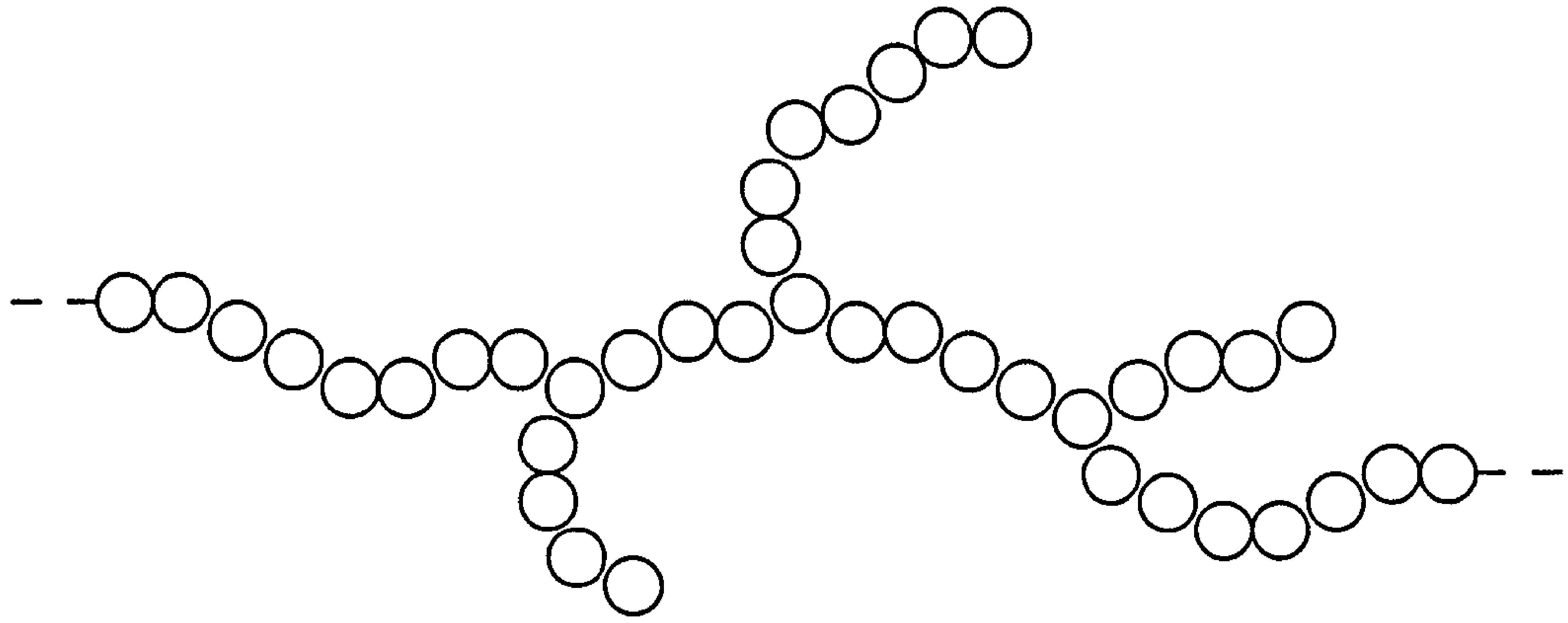
Linear homopolymer Figure 2.4



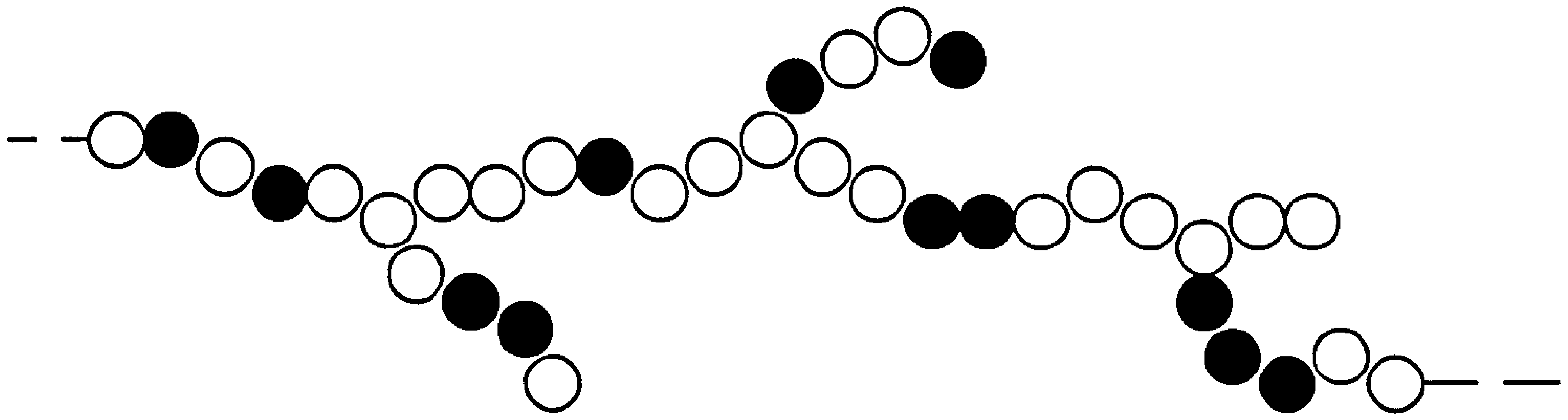
Linear copolymer, (random) Figure 2.4a



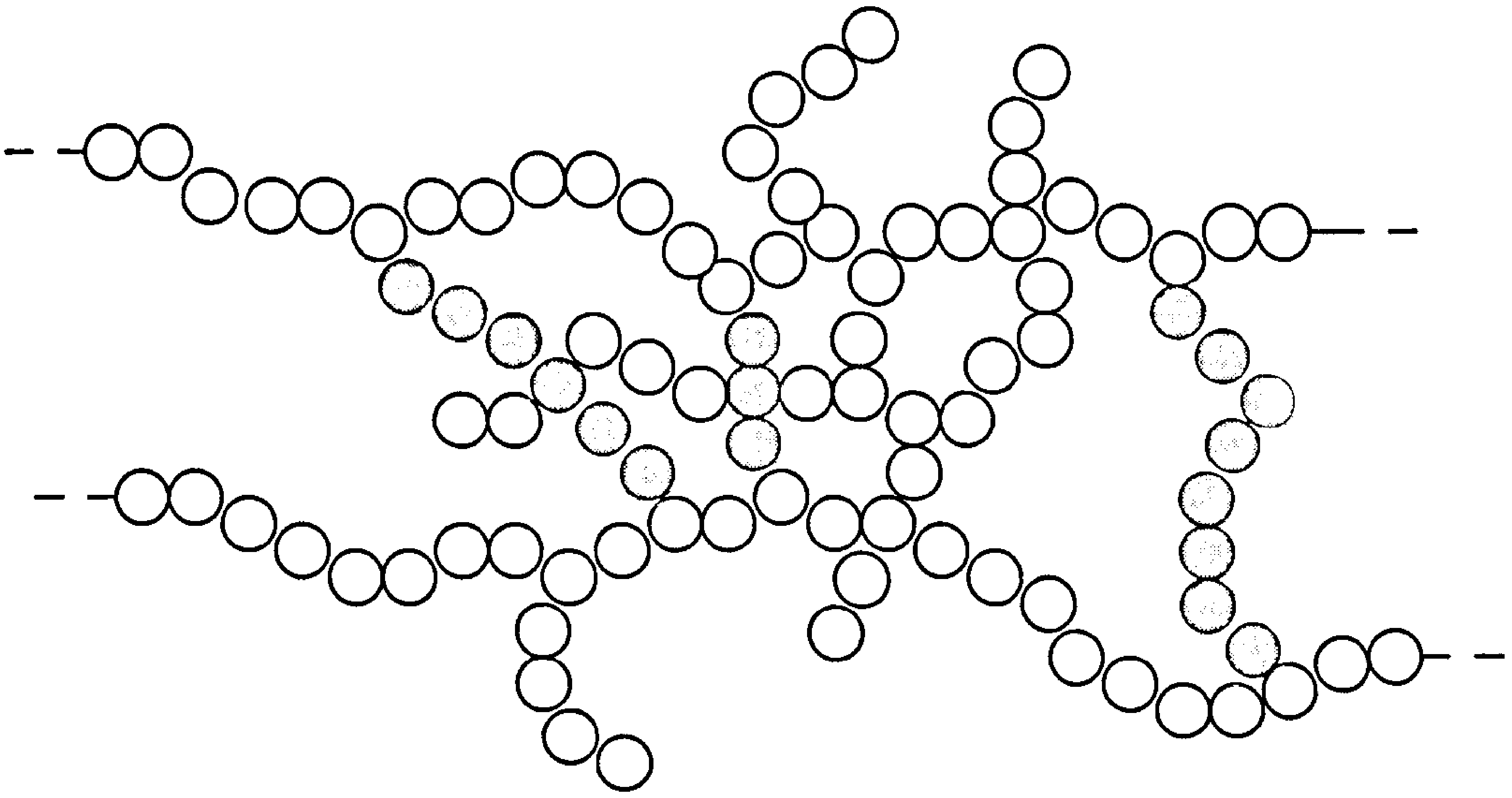
Branched homoploymer Figure 2.4b



Branched copolymer, (random) Figure 2.4c



Cross-linked polymer Figure 2.4d



Linear homopolymers have mer units of the same type, random linear co-polymers have two mer units randomly distributed along the chain. Branched homopolymers consist of the same units along the chain and the random branched co-polymers again consist of two mer units randomly distributed along the chain. The cross-linked polymer that is illustrated is made up of a homopolymer that is cross-linked with a single cross-linking agent (Craig, 1993). Cross-linking affects the physical properties of a polymer to lesser or greater degrees depending on the amount of cross-linking that takes place. Small amounts of cross-linking will limit the amount of movement of the polymer chains relative to each other when the material is stressed, thus deformation is elastic rather than plastic. Extensive cross-linking has the effect of making polymers harder and more brittle.

2.7 Physical state of polymers

Polymers tend to exist in one of four physical states:

i) elastomers or rubbers
ii) hard amorphous polymers (organic glasses)
iii) hard partially crystalline polymers
iv) fibres

The effect of intermolecular forces on the more rubbery polymers increases as temperature decreases below room temperature and at a reasonably well defined temperature (Tg, the *glass transition temperature*) the forces become so large as to inhibit uncoiling of the long chain molecules. Therefore, below the glass transition temperature the material will be rigid like polymers of type (ii) above.

If a polymer of type (ii) is heated it is found to lose rigidity at a well defined temperature above room temperature and become rubbery. The difference between polymers of type (i) and type (ii) is that the former have a Tg well below room temperature, whereas the Tg of the latter is above room temperature (Combe, 1986).

Another way of classifying polymers instead of by their spatial structure is according to whether they are *thermoplastic* or *thermoset.*

All polymers are formed from a monomer and during the polymerisation process they either become linear polymers that stay quite soft at room temperature such as wax and are known as thermoplastic, or they become branched or cross-linked polymers that are stiff at room temperature such as acrylics and restorative composite materials – these are known as thermoset.

Mouthguards are generally formed from EVA, a thermoplastic polymer, mainly because they are relatively cheap and are very easy to manipulate using modern dental laboratory equipment. A disc or square sheet of the thermoplastic material is heated to beyond Tg, the material is then rapidly adapted to a dental cast by either air pressure or vacuum before the material can cool to below Tg. The material is then left to cool for several minutes, still under vacuum of increased air pressure, to ensure stability of the material in its new shape.

2.7.1 Viscoelasticity

A viscoelastic material exhibits properties characteristic of both a solid and a liquid. The occurance of viscoelastic properties in a material are dependant, to a large extent, to the environmental conditions, particularly temperature. In general, most polymers exhibit viscoelastic behaviour when a load is applied over a period of time. The time dependence of a viscoelastic material is better understood by considering the material as a combination of an elastic solid and a viscous fluid as follows:

Elastic solid (recoverable) + viscous fluid (non-recoverable)

or,

$\sigma = E.\varepsilon$ + $\sigma = \eta.d\varepsilon/dt$

(Hooke's Law) (Newton's Law)

=

viscoelastic solid

$$\sigma = F[\varepsilon,t]$$

this is the expression for a general non-linear viscoelastic solid where the stress is a general function (F) of the strain and time,

(http://www.nottingham.ac.uk/~eazacl/H3CPOE/Viscoelasticity.pdf)

For amorphous polymers large changes in viscoelastic behaviour may be brought about by the prescence or absence of chemical cross-links or by changing the molecular weight which controls the degree of molecular entanglement or physical cross-linking, (Ward, 1971).

The effects of chemical or physical cross-links are two-fold. Firstly chemical cross-links prevent irreversible molecular flow at low frequencies or high temperatures and thereby produce a rubbery plateau region of modulus or compliance. Physical cross-links due to entanglements will restrict molecular flow by causing the formation of temporary networks.

Secondly, the value of the modulus in the plateau region is directly related to the number of effective cross-links per unit volume.

2.7.2 Temperature dependence of elastic modulus

To understand the temperature dependence of the mechanical properties of viscoelastic solids it is necessary to understand the molecular processes which occur during time-dependant deformation. Typical behaviour is illustrated below (Fig. 2.5) which shows the variation in stress relaxation modulus for typical amorphous and semi-crystalline polymers.

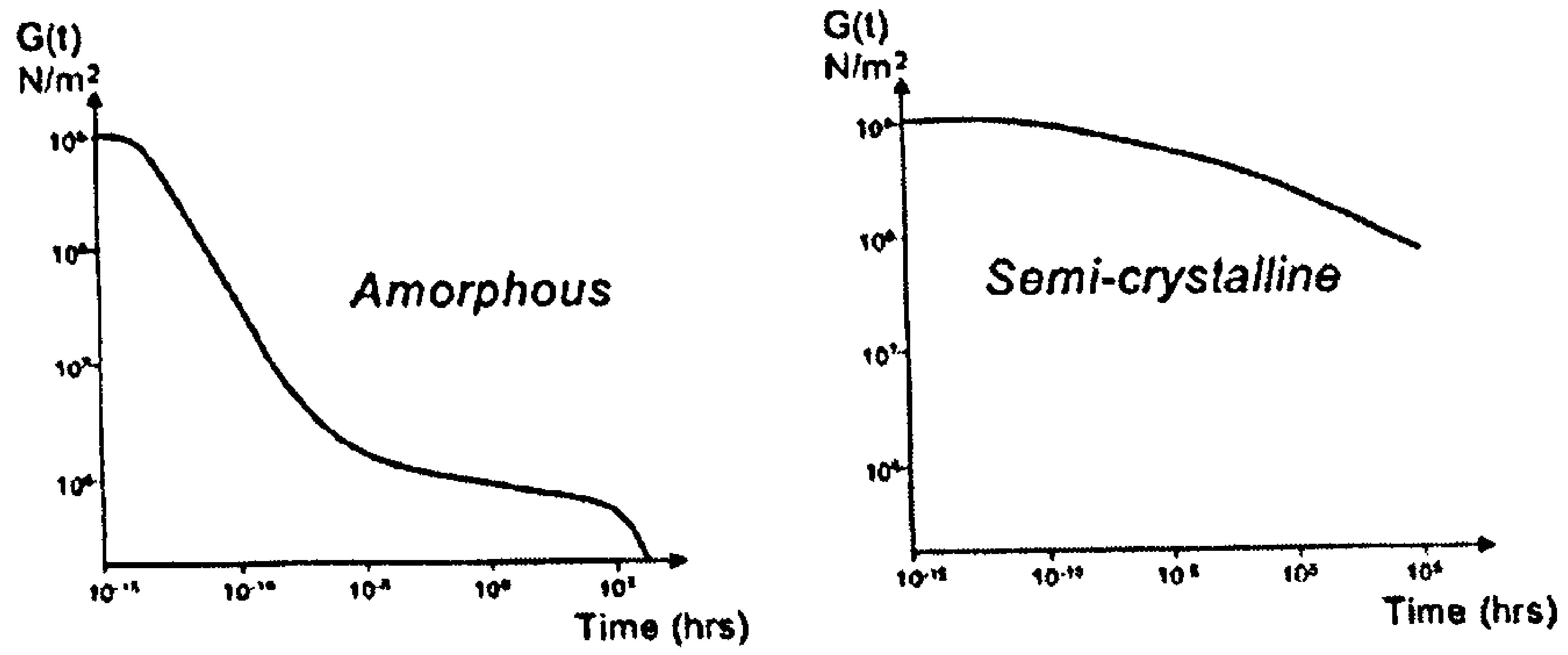


Figure 2.5 Typical creep compliance modulus versus time curves for amorphous and semi-crystalline polymers.

(http://www.nottingham.ac.uk/~eazacl/H3CPOE/Temperature_Effects.pdf)

The amorphous polymer shows the four expected regions of viscoelastic behaviour, i.e. glassy, viscoelastic, rubbery and flow regions. Although differences in time scale exist for different polymers, the general shape is the same for all. At short times the material exhibits a glassy state (G(t) ~ 10^9N/m^2), the stiffness relating to changes in the stored elastic energy on deformation associated with the rigidity of the molecular chain backbone. The motions are restricted to vibrations and large stresses are required to cause deformations. As time is increased the modulus decreases rapidly.

Additional modes of motion associated with rotation of chain segments about the main chain backbone take place. At longer times the modulus reaches a rubbery plateau where the material exhibits the characteristics of rubber elasticity (G(t) ~ 10^6N/m^2). This is associated with entanglements between and among the long chain molecules. At these long times the molecules show considerable flexibility so that in the undeformed state they adopt conformations which lead to maximum entropy (or minimum free energy) and elastic deformations are due to changes in conformation. The glassy and rubbery moduli are generally independent of time within their region of operation.

As previously stated, for amorphous polymers the viscoelastic behaviour may be changed by the presence or absence of chemical cross-links, or by changing the molecular weight which controls the degree of entanglement. The value of modulus in the plateau region is directly related to the number of effective cross-links per unit volume and hence the molecular weight (i.e. greater molecular weight → larger number of cross-links → higher relaxed modulus).

Crystalline polymers behave very differently from amorphous polymers. The presence of a crystalline fraction tends to greatly stiffen the structure and causes the relaxation to be much less distinct and broader in time scale. Moduli generally only change from ~ 10^9 to 10^8 or 10^7 N/m^2.

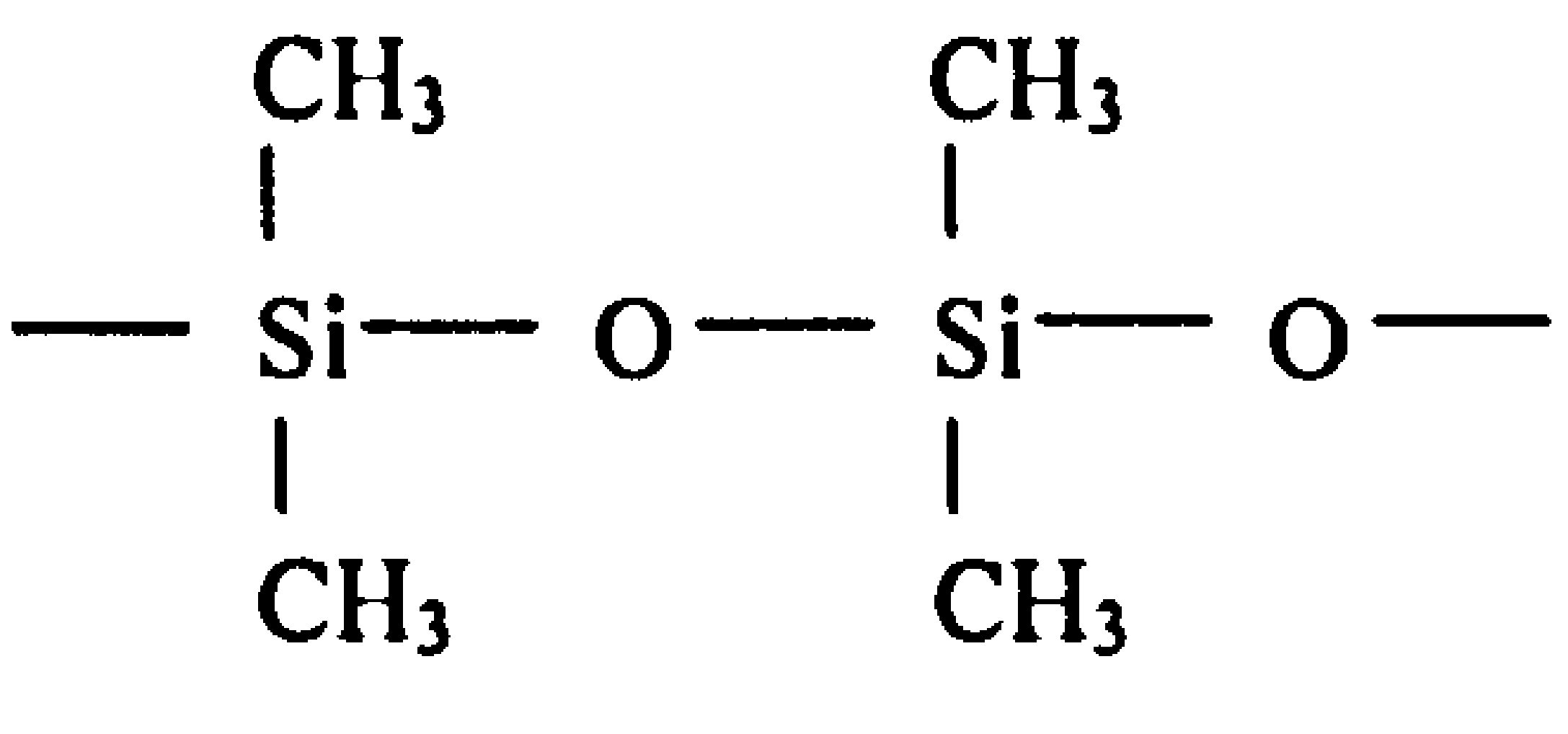
(http://www.nottingham.ac.uk/~eazacl/H3CPOE/Temperature_Effects.pdf)

2.8 Silicone

Silicones are synthetic polymers and are not found naturally. They have a linear, repeating silicon-oxygen backbone akin to silica. However, organic groups attached directly to the silicon atoms by carbon-silicon bonds prevent formation of the three-dimensional network found in silica. These types of compound are also known as polyorganosiloxanes. Certain organic groups can be used to link two or more of these silicon-oxygen backbones and the nature and extent of this cross-linking enables a wide variety of products to be manufactured.

(http://www.silicone-review.gov.uk/silicone/)

Silicone compounds can exhibit unusual behaviour in that a silicone can be a liquid and a solid at the same time. In much the same way that bitumen will creep over time or shatter like glass if struck with a hammer some silicone polymers react in a similar way. An example of this 'elastic behaviour in liquids' is provided by the silicone polymer known as 'bouncing putty'. The backbone structure of the silicone chain consists of alternate silicon and oxygen atoms. To each of the silicon atoms is attached a pair of hydrocarbon side-groups, which in the case of the most common of the silicones are simply methyl groups, thus



$$-\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{\overset{|}{\underset{|}{Si}}}}-O-\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{\overset{|}{\underset{|}{Si}}}}-O-$$

Whereas most polymers in the molten or fluid state are extremely sticky, the silicones are remarkable for their lack of stickiness. This property makes it possible to demonstrate bouncing properties which, though inherent in other rubber-like polymers, can not be so readily observed because of the general tendency of such materials to adhere to any surface with which they come into contact.

Bouncing putty is a silicone polymer that looks and feels like a putty, it can be moulded in the hands to any form. Unlike putty, however, it does not keep its shape after moulding, and if put into a beaker it will flow until a perfectly smooth horizontal surface is attained. Over time it will flow out of a beaker in a stream or it can be moulded into a ball and bounced. The bouncing properties of this silicone are due to the presence of a network of entangled long chain molecules which have elastic properties similar in principle to those of rubber in the unvulcanised state, (Treloar, 1970).

2.9 Poly ethylene vinyl acetate

Polyethylene vinyl acetate or pEVA is a co-polymer of polyethylene (Table 2.9) and vinyl acetate (Table 2.9a).

Polyethylene	
Uses	thermoplastics, fibres
Monomer	ethylene
Polymerisation	free radical chain polymerisation, Zieglar-Natta polymerisation, metallocene catalysis polymerisation
Melting temperature	137°C
Glass transition temperature	-130 to -80°C

Table 2.9

Molecular formula of polyethylene: CH_2

Polyethylene is probably the polymer seen most in daily life; it is the most widely used plastic in the world. It is the polymer that makes grocery bags, shampoo bottles, children's toys, and even bullet proof vests. For such a versatile material, it has a very simple structure, the simplest of all commercial polymers. A molecule of polyethylene is nothing more than a long chain of carbon atoms, with two hydrogen atoms attached to each carbon atom, (Figure 2.5)

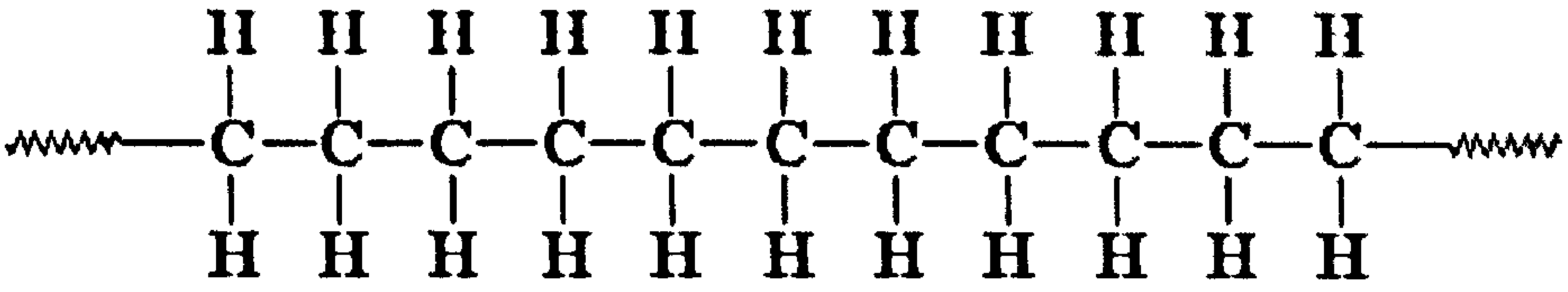


Figure 2.5 Molecular structure of polyethylene.

Vinyl acetate	
Uses	thermoplastics, adhesives, packaging, paint
Monomer	Vinyl acetate
Polymerisation	emulsion polymerisation, anionic vinyl polymerisation, free radical polymerisation
Melting temperature	100C
Glass transition temperature	-100 to -72°C

Table 2.9a

Molecular formula of vinyl acetate monomer (acetic acid vinyl ester): $C_4H_6O_2$

Many manufacturers were involved in the development of vinyl acetate co-polymers, with DuPont filing a patent in 1956 and introducing the *Elvax* range of materials in 1960. This is based on the co-polymerisation products of ethylene, with vinyl acetate and is normally produced either from bulk continuous polymerisation or solution polymerisation. The former produces low molecular weight co-polymers useful for coatings, hot melt adhesives, etc., whilst the latter yields high molecular weight products for tougher applications.

Poly ethylene vinyl acetate properties			
UL94 (1/8 inch)	No Rating	V-0	V-2
UL94 (1/16 inch)	No Rating	V-0	V-2
%Elongation	680	204	220
Tensile Strength at Yield (psi)	690	755	728
Tensile Strength at Break (psi)	935	785	810
Izod Impact (1/8 inch) (ft-lbs/in)	1.6	2.9	2.8

Table 2.9b

As the level of vinyl acetate in the copolymer increases so the level of crystallinity found in polythene alone reduces from about 60% to 10%. This yields products ranging from materials similar to low density polythene to flexible rubbers. Common grades can contain from 2% to 50% vinyl acetate. Clarity, flexibility, toughness and solvent solubility increase with increasing vinyl acetate content. Of particular note is the retention of flexibility of pEVA rubber grades down to (-70C) and because they are co-polymers, problems due to plasticiser migration are not experienced.

Good resistance to water, salt and other environments can be obtained but solvent resistance decreases with increasing vinyl acetate content. The co-polymers can accept high filler and pigment loadings. Being thermoplastic pEVA can be moulded by extrusion, injection, blow moulding (in the case of mouthguards, pressure forming), calendaring and rotational moulding. Crosslinking with peroxides can produce thermoset products.

Applications are diverse, such as flexible shrink wrap, footware soles, hot melt and heat seal adhesives, flexible toys, tubing, wire coatings, medical gloves, masks, babies' dummies and bottle teats. Crosslinked foamed tyres have been used for tough service. Many grades and modifications now exist to meet modern demands from these versatile pEVA copolymer types,

(http://www.plastiquarian.com/eva.htm).

2.10 Energy absorption & materials testing

In their discussion Craig and Godwin (1967) went on to say that caution should be exercised when interpreting the energy absorption results, "since a high energy absorption does not necessarily indicate protection of the underlying teeth." The harder urethanes may transmit more energy to the underlying teeth than some of the softer materials, such as polyvinylacetate-polyethylene which was found to have lower energy absorption than the urethanes. The latex that was tested had the lowest energy absorption and due to its exceptional softness would allow the highest penetration during impact loading, therefore transmitting a large percentage of the energy to the teeth. The polyurethanes tested exhibited high energy absorption in the static and dynamic tests, energy absorbed per cycle 0.054 – 0.07 in-lbs and 2.24 – 3.27 in-lbs respectively. However, Duraguard had a higher energy absorption in the static test (0.09 in-lbs) but this material was not tested dynamically and the material Jectron had the highest figure for the static test, 0.17 in-lbs and the second highest for the dynamic, 4.06 in-lbs; the highest being for Plastisol #1, 4.18 although this material was not static tested. As Craig and Godwin did state that high energy absorption does not necessarily indicate protection of the underlying teeth and that some of the softer materials had better energy absorption than the stronger, harder, more tough materials this could then be an indication that the lamination of several different materials with different properties could protect the teeth from trauma better than a single material mouthguard.

A visco-elastic polyurethane, Sorbothane, that has been used in orthopaedic and sports applications due to its shock absorbing properties was tested by Bulsara and Matthew, (1998) as an intermediate layer between two layers of EVA. A piezo-electric transducer was used to measure the peak force transmitted through samples with and without the Sorbothane layer from a free falling steel ram. Bulsara and Matthew concluded that using an intermediate layer of Sorbothane may dissipate significantly the force of impact from a blow to the teeth and jaws. As there is no report of how the mouthguard material is held in place or how the pressure transducers are mounted it can not be assumed that they were held rigidly when the steel ram impacted the test piece. In respect of this it could be surmised that some of the impact force may have dissipated because of the test piece not being in firm contact with the pressure transducers and therefore deformation of the material prior to the material coming into contact with the transducers is not recorded. However, in their results they compare a laminated sample of pEVA with a sample that was a laminate of pEVA and Sorbothane and the results indicate the sample with the Sorbothane transmitted approximately 30% less force than the laminate of pEVA. Results, therefore point to the use of laminated mouthguards that incorporate a material other than pEVA to act as a shock absorbing layer.

Bishop *et al.*, 1985, carried out tests on various compositions of polyvinyl acetate-polyethylene copolymers; all had varying percentages of PVA ranging from 7.5% to 33%. Tests that were carried out included, tear strength, water absorption, compression tests and static and dynamic energy absorption. To determine dynamic energy absorption a calibrated glass tube was positioned over the mouthguard material to allow a 12.7mm diameter steel ball to fall from a predetermined height then the subsequent rebound can be measured. The energy absorption was calculated from the difference in potential energy of the ball between its initial rest position (*ho*) and the height of the ball at the maximum rebound height (*hi*) using the following formula:

Absorbed energy = $mg(ho - hi)$

It was concluded that the best material was one that contained 18% PVA as the investigators deemed that it best fulfilled their pre-set criteria of what a mouthguard material should be like. The static test values were determined on 2.54cm diameter discs compressed in an Instrom Tester. Static tests don't really have a great deal of relevance when trying to assess a materials reaction to an impact and the rebound test. While it is interesting to see, it does not give a clear indication of the dissipation of the impact due to there being no instrumented data acquisition as such. Although the research highlighted the need for a material that can absorb the energy from an impact and not undergo permanent deformation, there is no mention of whether the best energy absorbing material has the steel ball bouncing the highest or lowest out of the test.

A pendulum style indentor, on testing apparatus, similar to a Charpy or Izod impact, rig was used by Westerman *et al.*, (1997) to assess the energy absorption properties of a material that contained pockets of air. In their introduction it was stated that "elasticity of the copolymer determines the effectiveness of the mouthguard material through the absorption of impact energy as it is transmitted to the underlying tissues" however, the higher the elasticity of the material then the higher the rebound energy must be with the resultant rebound affecting the underlying tissues. The head of the swing arm on the indentor was fitted with a Brüel and Kjaer accelerometer, type 4335. The acceleration of the pendulum was measured to calculate the peak transmitted force through the mouthguard material. It was reported that the inclusion of air cells within an EVA copolymer mouthguard material produced a reduction in transmitted forces when the impact was less than 10 kN. It was also reported that the sample with the biggest air cells had the best energy absorption, although other workers (Greasley *et al.*, (1998) reported that no beneficial effects are expected from the inclusion of pockets of air. The work that was carried out shows the potential for using novel shock absorbing systems in mouthguards and is working towards a material that has shock absorbing qualities without transmitting the impact energy to the underlying tissues. The use of a laminate system, incorporating a soft compliant structure rather than a hard one, for protection being indicated as opposed to a single thickness of pEVA.

Physical and mechanical tests were employed to discover the basic properties of 57 different mouthguard products, Going *et al.*, (1974). As well as carrying out tests to determine water sorption, tensile strength, elongation and tear strength tests for impact energy absorption and resistance to impact penetration were performed. Impact energy absorption and impact penetration resistance were measured with a Scott Tester by the rebound pendulum method, a similar test to that of Craig and Godwin, 1968. In this dynamic test a freely swinging pendulum is allowed to strike a test specimen that is held firmly in the apparatus. The maximum rebound of the pendulum is recorded and the difference between the release angle of the pendulum and the rebound angle is then indicative of the amount of energy absorbed by the material. A rebound of 100% indicates no energy absorbed, whereas zero rebound indicates that all the energy of the swinging pendulum has been absorbed by the material. The amount of penetration at impact was measured by adjusting the electrical contacts on the specimen holder and pendulum so that they just touched at maximum penetration. The contact completed an electrical circuit which was indicated by deflection on a voltmeter. This test tends to be rather destructive and doesn't really demonstrate how the energy is transmitted or dissipated. Energy absorption is clearly indicated as being an important factor in the properties required although how this could be translated to a mouthguard design is not clear.

In the energy absorption tests carried out by Park *et al.*, (1994) it was reported that the impact tests provided information on the peak impact forces observed and the amount of energy lost on impact. For the tests two stainless steel balls (2.54cm and 5.08cm in diameter) were used to vary the speed and amount of impact force. The small ball had a mass of 66.8g and was dropped from a height of 85.73cm while the large ball had a mass of 473.4g and was dropped from 25.4cm. A force transducer was positioned beneath the test specimen so that the force of the impact could be recorded. The impact event was digitised so that a graph that displayed the impulse could be plotted and also so that the transmitted impulse through the polymer sheet could be determined. Carbon paper was inserted between the test specimen and the transducer to estimate the area of impact; this area was used to calculate the transmitted impact stress. The information obtained from the force transducer and from the carbon paper, albeit somewhat crude, is interesting to see but doesn't say a great deal about what amount of impact, if any, was absorbed by the material.

Craig and Godwin's, (1967) study of the physical properties of materials for custom made mouth protectors comprehensively tested different materials that were available at the time for the production of sports mouthguards. The tests that they carried out were; tensile strength, hardness, water absorption and energy absorption which was determined using static and dynamic testing. The static test values were determined on one inch diameter discs compressed in an Instron Tester.

Deformation versus load curves in compression and decompression were obtained at a deformation rate of 0.5 inches per minute. The energy absorbed was determined by measuring the area between the compression and decompression curves or hysteresis loop. The energy was calculated by converting deformation to strain and load to stress: the product of these two terms divided by the volume gave the values of interest.

2.11 Summary of the literature

The literature that is available relating to the testing and efficacy of sports mouthguards, while it is worthwhile and furthers the debate about mouthguards in general, does not directly lead to any firm conclusions other than that custom mouthguards should be worn to prevent injury and that they should be of a certain thickness so that they help to prevent concussion. All in all it is fairly inconclusive. The ideas behind some of the related research in cushioning impact and preventing trauma need to be applied in some way, but keeping in mind the constraints that are put on the design of mouthguards. A great deal of the rest of the published research into mouthguards tends to focus on athletes' and coaches attitudes towards mouthguards and their comfort. Whilst other research (Blignaut J B, Carstens I L, Lombard C J, 1987; Bolhuis J H A, Leurs J M M, Flögel G E, 1987; Flanders R A, 1993) relating to mouthguard usage tend to be case studies of oral trauma, studies of general trauma from participating in sport that may result in injury to the mouth or studies relating to the compliance of mouthguard wearing.

Research into the cushioning of an impact and impact systems that are in place for personal protection use very similar basic designs, in that they use materials with different physical characteristics, in terms of stiffness and compliance, that when they are put together the overall effect is to achieve maximum protection from an impact. Motorcycle crash helmets, bullet proof vests, sports shoes, shin guards and the use of denture soft lining materials are all examples of shock absorbing systems where two or more materials are being used in a composite structure that utilise an outer layer that is stiffer than the inner more compliant material.

2.12 Methods that have been used to assess mouthguards and their materials

There are four possible ways in which mouthguards may be, and have been, evaluated.

i) Materials properties testing

Many properties have been measures but it is still not clear as to how this information translates into a good indicator of mouthguard performance.

ii) Design features

Features such as shape are relatively limited, however, mouthguard thickness and incorporation of shock absorbing layers into the mouthguard need more close examination.

iii) Simulations

Few studies have been carried out and those that have been have produces ambiguous results.

iv) In-situ

There is little evidence as to the merits of the custom made mouthguard over any other type of mouthguard. The consensus, however, is that custom made is the best.

A testing regime for mouthguards to be assessed in a more coherent manner would, in the course of the testing programme, give a better indication of the performance of a mouthguard when dealing with an impact event in a real life situation would be (Figure 2.6):

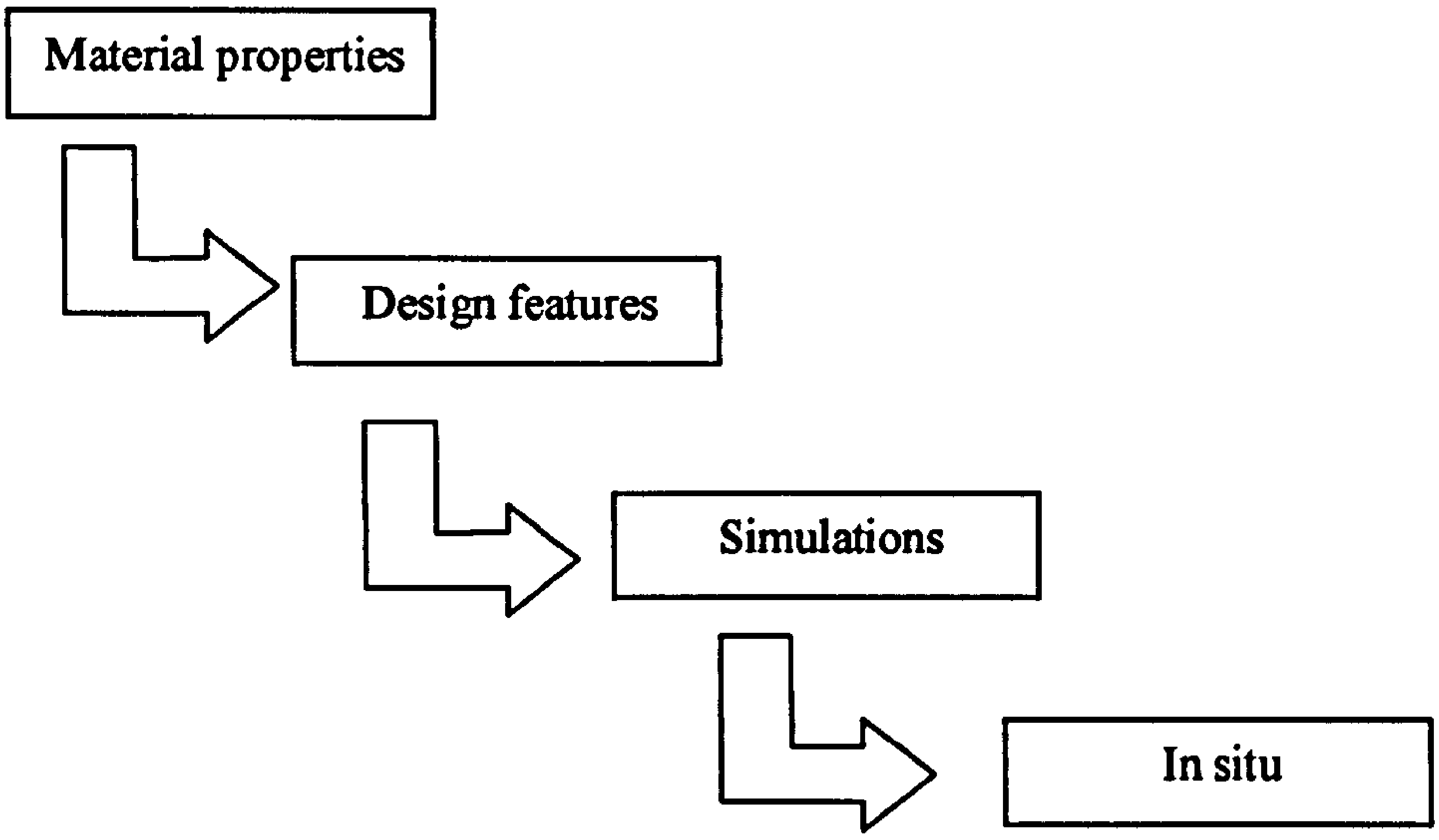


Figure 2.6 Proposed testing regime for mouthguards

The testing of mouthguards and the materials from which they have been made has been done in much the same way over the years. Many comparative studies have been made of the various types of mouthguard available and of the materials from which they are made (which may vary slightly from firm to firm).

In the tests on the material alone there have been the usual tests that may be carried out on a material, such as yield stress, compression tests, hardness tests and so on. None of these tests really reveal the ideal properties that are being looked for in a mouthguard material, the tests seem to take place only because the machine is available that can perform the test.

When considering the ideal properties of a mouthguard and the material from which it is made, some general requirements of what is expected from the mouthguard material must be carefully thought about.

If the material from which a mouthguard is made is very stiff then the harmful effects of an impact event will be transmitted directly to the underlying tissues (Figure 2.7)

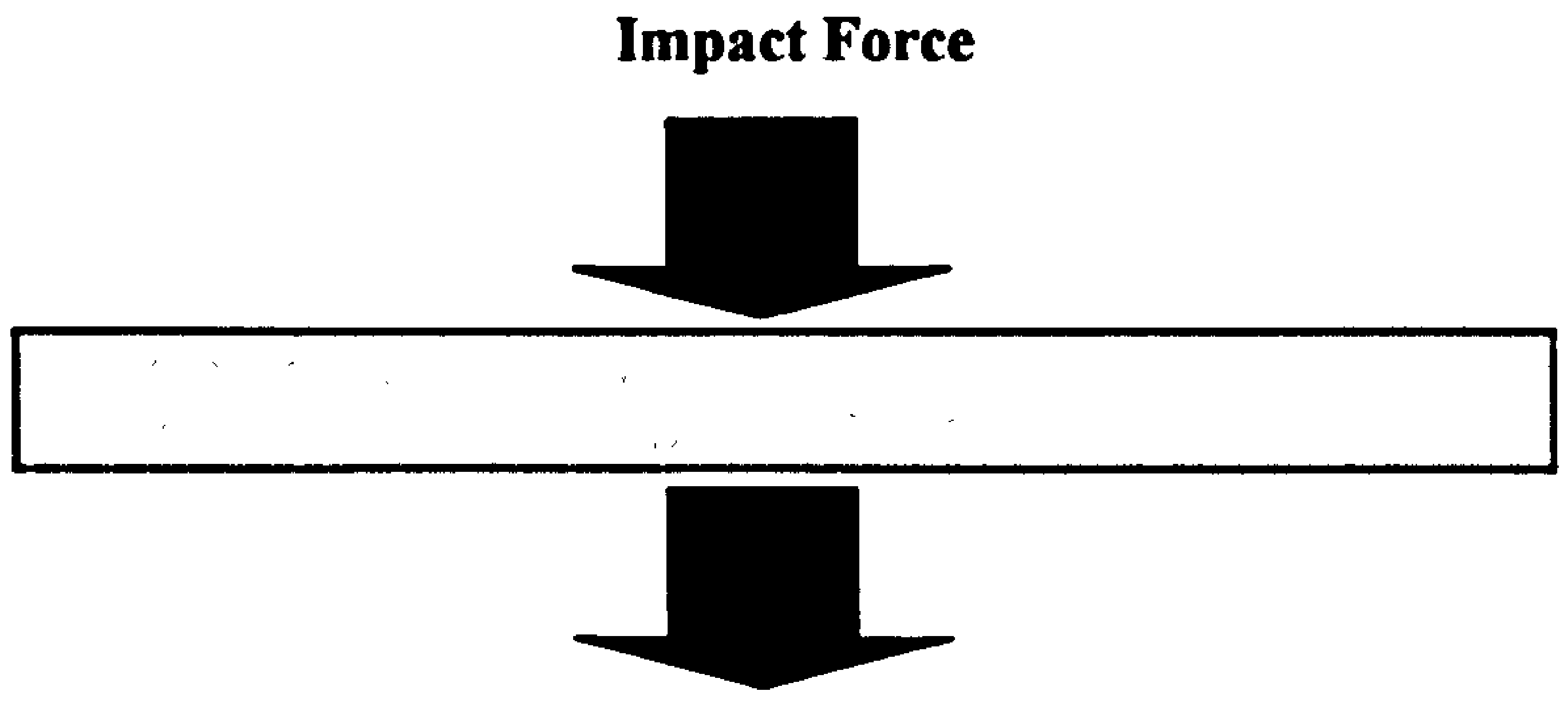


Figure 2.7 Impact force is transmitted through the material almost undiminished.

Conversely if the material from which a mouthguard is made is far too compliant then the force from an impact will travel through the mouthguard in an undiminished state to the underlying tissues that the mouthguard is supposed to be protecting. The material will be displaced and deformed so much by the impact that there will be a single high point of impact loading transmitted directly to the teeth and soft tissues (Figure 2.7a). There will be very high, localised, stresses within the material which will cause the structure to fail in its ability to protect; the mouthguard itself may be destroyed or sustain localised irreparable damage at the point of impact.

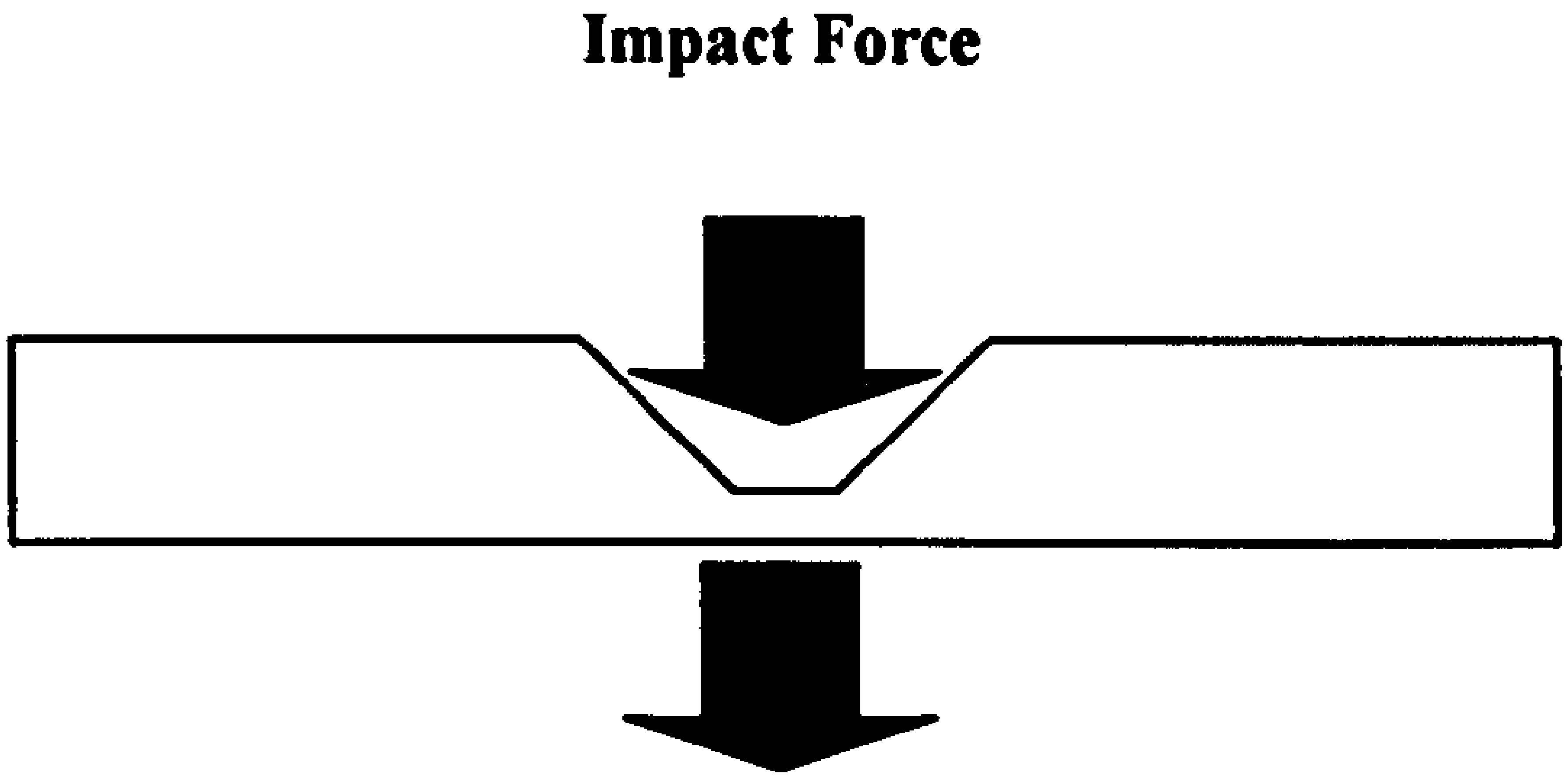


Figure 2.7a Impact force is transmitted through the too compliant material undiminished and is concentrated at the site of impact.

The mouthguard material must be able to dissipate the impact energy by either absorbing the energy into the mouthguard material or by spreading the load over a much wider area (Figure 2.7b). In either instance it would be desirable for the material to return to its original shape slower than the original impact so there is no damage sustained from the rebound energy of the material.

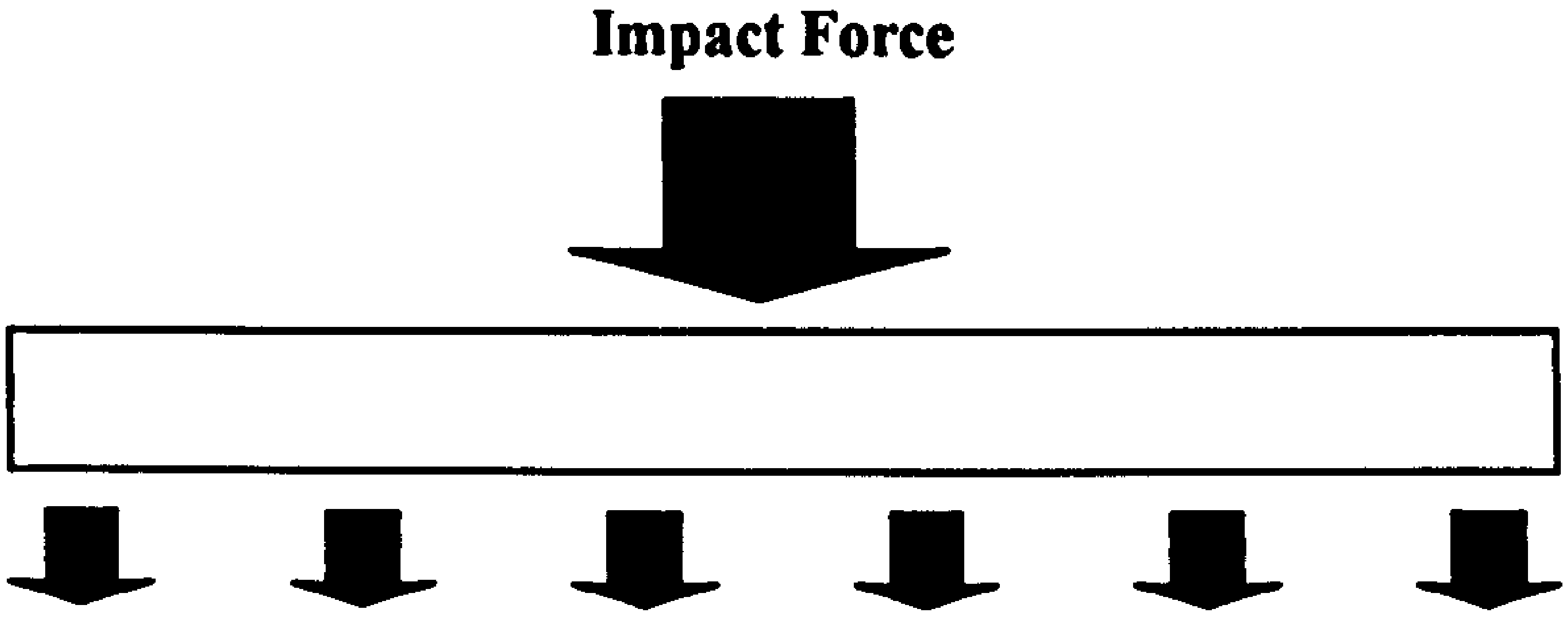


Figure 2.7b Impact force is transmitted through the material but is spread over a wider area.

The manner in which the absorbed energy is released is also an important consideration. If the material were to release the energy in a purely elastic response then it is possible that considerable damage to the soft tissues of the mouth may result. Rather like the action of a coiled spring. Thus the energy has somehow to be released in a way that does not cause damage to the structures it needs to protect. This can be done in one of three ways:

i) The energy absorbed remains stored in the mouthguard by virtue of permanent deformation.
ii) The energy is released as the material slowly regains its original shape.
iii) The material fractures.

Options i and iii are clearly not desirable as the cost of replacement each time would be prohibitive. Thus the following material properties can be identified as important:

i) Strength. The material needs to be strong so that it can withstand repeated impacts without fracture.
ii) Stiffness. If the material is too stiff then the impact will pass through and cause damage, conversely if it is very compliant the impact will, again, pass straight through causing damage to the underlying tissues.
iii) Energy absorption. Impact energy needs to be absorbed and released slowly.

iv) Permanent deformation. If a mouthguard deforms easily and retains its new shape then it will be rendered useless in a very short time.

2.12.1 Material Properties

Strength

Craig and Godwin (1967) carried out tests on thirteen different products (some commercially available, the rest experimental), used in the construction of mouthguards, three were polyurethane, six were poly vinyl acetate-polyethylene polymer, one was latex rubber, another was said to be Geon 135F1 based vinyl resin plastisol while one was simply listed as thermoplastic ! Their testing of the materials was extensive and covered such aspects as, water sorption, strength, hardness and energy absorption. In terms of strength they found that the polyurethanes had the highest strength, both tensile and tear strength, 4970 – 5630 lbs/in and 420 – 82 lbs/in respectively. This will mean that the material is tough but is in no way an indicator of good protection performance and Craig and Godwin do not comment further about what high strength may mean in terms of giving protection to a sportsman.

Stiffness

Craig and Godwin (1967), somewhat ambiguously, said that a material with intermediate hardness and energy absorption would be best for a mouthguard and that the degree of protection offered by a single material could be altered by changing the thickness of the material used. So it can be seen that quite early on with regards to mouthguard testing the properties of strength and hardness (in this case stiffness) have been highlighted as important factors in the criteria for mouthguard materials. With regard the testing of materials they did say, however, that the measurement of stress transferred to the teeth would be needed for a complete evaluation of the material.

Ranalli and Guevara (1992) describe a new method for the manufacture of mouthguards using a photo-polymerised urethane diacrylate, initially this material was introduced as a denture relining material. The only advantage this technique has over the conventional method of construction of a mouthguard is that an expensive pressure or vacuum forming machine is not necessary, the material can be cured in a relatively inexpensive light curing unit. As this paper dealt only with the manufacturing process no light was shed upon any material characteristics required of a mouthguard material. Although they do point out that an ideal characteristic of a mouthguard is that it should be 'soft', but with no clarification as to what this term means.

To find the right material for a mouthguard; Bishop, *et al*; 1985, carried out tests on nine materials that were all essentially the same but with differing mixtures of polyvinylacetate and polyethylene. The specimens contained between 7.5% and 33% polyvinylacetate (PVA), they were tested for the following properties: water absorption, tear strength, compressibility, along with static and dynamic energy absorption. Their findings were that the material used for a mouthguard should indent easily but be capable of absorbing energy under both static and dynamic loading. Polyvinylacetate-polyethylene had a far higher ability to absorb energy when higher percentages of PVA were present. Another factor that was found to be of great importance was that of the compressibility characteristics of the material, or as Bishop *et al.*, described it, the depth the material is compressed in the initial purely elastic phase; which was referred to as the elastic gradient although this is not the term that should be used as the plot was penetration on the x axis and applied force on the y, the correct term for what was being exhibited is compliance. The results that were reported demonstrated that a flat elastic gradient would indicate a material that requires too high a force to compress it, while a steep elastic gradient indicates a material that is compressed far too easily. It was concluded that the most satisfactory composition of a polyvinylacetate-polyethylene mixture for a mouth protector was one that had between 18 -24% PVA, and in the overall summing up the material with 18% PVA appeared to be the best for a sports mouthguard.

Westerman *et al.* (1995) used and impact testing rig similar to that of a Charpy or Izod impact machine that was fitted with a blunt striker on the pendulum. Acceleration of the pendulum was measured to calculate the peak force transmitted through the mouthguard material using Newton's second law of motion. Tests showed that the force transmitted through the mouthguard materials was inversely related to the thickness of the material and that a small reduction in thickness of 1 mm resulted in an increase in transmitted force of 34%. A very simple experiment was carried out that produced quite obvious results, although the amount the transmitted force increased in relation to the change in thickness was interesting. The results from this experiment indicate what might be expected, a thicker material protects better than the same material but in a thinner section.

Permanent deformation

In terms of energy absorption and permanent deformation Bishop *et al.*, made overall conclusions that are important when considering materials for mouthguard manufacture. They recognised the need for the material to absorb the energy but not to transmit it to the underlying tissue also that the material should not deform permanently.

The percentage of vinyl-acetate can be altered in a mouthguard material thereby changing the properties of EVA (Bishop *et al.*, 1985). It has been shown that an 18% content of vinyl-acetate in the EVA is the most suitable composition for mouthguard materials as it exhibited greater energy absorptive qualities over materials with a lower vinyl-acetate content (Bishop *et al.*, 1985). Conversely, a high vinyl-acetate content diminishes the energy absorption capabilities of the resultant polymer compound. Park *et al.*, (1994) found that most commercially available mouthguards had a vinyl-acetate content of 28%.

Measurement of energy absorption

Low velocity impact energy absorption is measured experimentally using such test methods as charpy impact tests (figure 2.8) and instrumented impact testing rigs that use piezoelectronic load cells to measure the energy absorbed by the material.

Figure 2.8 Charpy impact test machine.

The charpy impact test measures the energy absorbed by the high strain rate fracture of a standard notched specimen. The specimen is broken by the impact of a heavy pendulum hammer, falling through a fixed distance (constant potential energy) to strike the specimen at a fixed velocity (constant kinetic energy). Tough materials absorb a lot of energy when fractured, and brittle materials absorb very little energy.

The impact energy measured by the Charpy test is the work done to fracture the specimen.

On impact, the specimen deforms elastically until yielding takes place (plastic deformation), and a plastic zone develops at the notch. As the test specimen continues to be deformed by the impact, the plastic zone work hardens. This increases the stress and strain in the plastic zone until the specimen fractures.

The Charpy impact energy therefore includes the elastic strain energy, the plastic work done during yielding and the work done to create the fracture surface. The elastic energy is usually not a significant fraction of the total energy, which is dominated by the plastic work. The total impact energy depends on the size of the test specimen, and a standard specimen size is used to allow comparison between different materials.

In many applications polymers are required to maintain integrity under impact conditions, a condition particularly relevant in automotive applications. The aim of most mechanical testing is to produce data which represent properties of the material tested, not influenced by specimen size and shape. This then helps the designer to select the material and geometry best suited to the job in hand.

Impact tests measure the energy absorbed by the specimen before it breaks, a quantity composed of several energy contributions, including energy absorbed by the impact machine through vibrations after initial contact with the specimen and loss in pendulum energy (in pendulum impact tests) when the hammer strikes the specimen as well as the total energy consumed by specimen deformation and fracture. Although it is very difficult to measure many of the individual energy contributions, impact tests are a valuable comparative test method. It should be recognised, however, that changes of specimen geometry, temperature and test method can result in a different ranking of specimens.

The primary measurement in most impact tests is the energy U lost by the striker. In the simplest analysis it is assumed that all of the energy lost by the striker is absorbed by the specimen and that this is proportional to the fracture surface area. On this scheme different materials are compared in terms of the fracture energy/unit area, generally measured using only one standard notch depth. It has often been demonstrated that this analysis does not lead to material parameters which are independent of material geometry and so the impact test was often dismissed as being of no serious use to designers.

(http://irc.leeds.ac.uk/iaps/mod1/node60.html)

There are three main types of impact test:

1. Charpy impact testing

This is a good example of a relatively simple test to perform but which is difficult to analyse to produce genuine material property data. As a comparative technique, however, it is very useful. In the Charpy test the specimen is held horizontally but not clamped whereas in the Izod test the specimen is held vertically and clamped. Clamping force is a variable which can affect the energy absorption and for this reason the Charpy test is often preferred.

2. Izod

A bar of polymer is held vertically by a clamp at its lower end. The pendulum of known mass falls through a measured distance and strikes horizontally the free upper end of the specimen. The height to which the pendulum rises after impact is recorded in order to calculate the energy absorbed in the impact. The specimen is usually notched close to the clamp in the face struck by the pendulum. A correction, which may be significant, is required to account for the energy required to throw the broken section of polymer away from the test area.

3. Falling Weight

In this test a dart with a hemispherical tip falls vertically onto the test specimen. The specimen is usually a thin disk resting on a hollow cylinder. The falling weight has excess energy; fracture occurs at constant velocity - a known weight dropped from a standard height - and a force-time curve can be constructed. The force is measured by a transducer from the instant of impact through the fracture process. From this a force-displacement curve can be made and the energy absorbed and characteristic parameters calculated.

Non-mechanical issues affecting impact absorption

While mouthguards are not worn for particularly long lengths of time they may be worn by an athlete for several years if their dentition does not change and the mouthguard maintains its' precise fit. During this time it will be in contact with saliva and water when it is cleaned. Water sorption can lead to a hardening of certain polymers (poly vinyl chloride, PVC) and would therefore alter the mouthguards' response to an impact event. Also the leaching of plasticiser from a polymer can lead to hardening of the material which would affect the way in which the mouthguard reacts to an impact event. This was a problem with PVC and so was banned for use as a mouthguard material by the EU because of fears over the toxicity of the leachant.

2.12.2 Design features and considerations

In conclusion to their impact tests Park *et al.,* (1994) found that a thicker mouthguard is more effective in withstanding a blow to the mouth and in some cases the thinner sheets of material used were destroyed. Overall a 4mm thick sheet was deemed to be the best choice for constructing a mouthguard. One of the materials tested, Proform, had a harder material laminated into the sheet which is intended to reinforce the mouthguard after fabrication from behind the anterior teeth, but this harder material did not seem to have any positive effects - the EVA without it performed better in all the impact tests. Park *et al.,* (1994) went on to say that more interesting results may be gained by sandwiching harder materials, such as 99% acetate in the middle with 28% acetate on the outside so giving maximum protection and comfort, a sandwich panel for use as a mouthguard where a stiffer material is encapsulated by a softer one.

A more recent test by Greasley *et al.*, (1998), found that "the incorporation of the stiff and hard styrene butadiene material into the guard had no observable beneficial effects. It made the mouthguards difficult to fit and susceptible to crack damage in the impact zone." Godwin and Craig (1968) investigated the effectiveness of different mouthguards that were commercially available in 1968 with some interesting results. It was found that the thickness of the protector does have a direct influence on the effectiveness of a single material, but it is not true to say that all thick materials are as effective as each other. In tests, the material 'Featherbrite' (Featherlax Corp.) that was 5.3mm thick provided a very similar amount of protection to the material 'Shield Protector' at a thickness of only 2.7mm. However, it is not clear what these materials are made from but it can be deduced that the former is polyurethane and the latter is either latex or polyethylene-polyvinylacetate.

Park *et al.,* (1994), after testing five different types of material that are used in the construction of mouthguards reported that "the thicker the material is, the greater the resulting energy absorption." The materials tested were polyvinylacetate-polyethylene (EVA), polyvinylchloride (PVC), natural rubber, soft acrylic resin and polyurethane (PU). In the tests that were carried out the mouthguards that were made from EVA, PVC and PU were grouped together as there were no significant differences in the parameters measured of these materials.

In some recent work the worthiness of hard inserts, or a harder layer of material in lamination with EVA has been evaluated, (Westerman *et al.*, 2000). The tests were performed using apparatus similar to an IZOD impact rig, the impact being produced by a striker that had a flat circular face of 12.75mm and a pendulum impact energy of 1.05 joules, impact velocity was 3 metres per second. Interestingly, the results from the force transducer that was used showed that the further away from the site of impact that the hard insert was the better the material was at absorbing the impact. The best results were obtained from the control material that was made from only EVA with no hard layer. The researchers concluded that the use of a hard insert in a mouthguard decreases the energy absorption of the mouthguard and increases the risk of injury to the mouthguard wearer. The use of hard inserts into the overall make-up of a mouthguard is also thought to be of no advantage by other researchers Greasley *et al.*, (1998).

At the Department of Mechanical Engineering, University of Newcastle in New South Wales, Australia, Kim and Mathieu (1998) studied the lamination of mouthguards using finite element analysis. A flat-ended indentor and a disc representing a colliding object was made so that stress distribution within mouthguard materials could be recorded. The laminates that were tested consisted of a hard and soft material, a bi-laminated structure, rather than a sandwich panel or a multi-layered structure. When the soft layer was uppermost (in contact with the indentor) no significant difference from a monolithic test piece was recorded. However, when the test specimen was inverted so that the hard layer was uppermost, similar to the tests carried out by Oikarinen *et al.* (1993), there was found to be a significant effect on stress distribution and the effect could be increased by controlling 'ratios of modulus and volume fractions of the top and bottom layers'. It was also found that the magnitude of the impact force increases with the increasing effect of stress distribution, but this competition can be reduced to some degree by decreasing the volume fraction ratio of top to bottom layers. In other words, the results could be altered by adjusting the thickness of the hard or soft layers. This research gives an insight into the functioning of a mouthguard under impact loading conditions and the use of finite element analysis will be considered further by this researcher as a means of providing a better understanding of the protection capabilities of a mouthguard structure.

2.12.3 Simulation testing

Tests that have utilised mouthguards on some form of model or on the maxilla of a cadaver (Hickey *et al.*, 1967) may give a clearer indication of the protection against concussion that is offered by the various mouthguards and materials tested.

In tests carried out Hoffmann *et al.*, (1999) several commercially available mouthguards were studied to determine their effectiveness. The mouthguards were fitted onto a specially made study model so that tooth deflection caused by an impact from a pendulum ram could be recorded. Data from the teeth protected with a mouthguard were compared to unprotected teeth so that the cushioning effects of the various mouthguards could be evaluated. It was surmised that the cushioning effects are directly correlated to the thickness of the mouthguard, thicker = more cushioning, and that the force distribution is governed by the rigidity of the mouthguard, greater rigidity = wider force distribution. This test method does not give any indication of force distribution within a material and whilst it may give some indication of a particular material's protective capabilities it is not ideal. If a tooth sustains an impact around the middle of its long axis the pendulum effect of the root moving (the point that is recorded) will be minimised, so in a material that is far from ideal an impact in this position would give an inaccurate assessment of its worthiness.

Oikarinen *et al.*, (1993) compared the 'guarding capacity' of several mouth protectors whilst on a standard sized maxillary plaster model, two tests on models without a mouthguard acted as a control. A dropweight impact tester was constructed for the purpose of the experiment, the falling weight was designed to simulate an ice hockey puck. The mouthguards were constructed from two layers of material with a resilient outer layer and a more compliant material next to the teeth, using stepwise regression analysis the only variable that had any statistical significance on the guarding capacity was the thickness of the more compliant layer. One conclusion drawn from the tests was the researchers indicated that the types of mouthguard with hard outer layers would be best suited to sports where impact only from soft objects would be encountered! It was also concluded that the thickness of the hard material had little effect on the protective capacity of the mouthguard.

To determine the effect of mouthguards on pressure changes and bone deformation within the skull, Hickey *et al.*, (1967) constructed an impact producing mechanism that was attached to an American football helmet. In doing so a blow of known force could be delivered to the chin of an intact male cadaver. The research that was carried out did not examine the design of the mouthguard or the material from which it was made but did give a great insight into the protection capabilities of mouthguards with regard to concussion. No reporting of the guarding abilities and protection of the teeth was incorporated.

In an attempt to develop a standard test procedure for mouthguard assessment Greasley *et al.*, (1997 and 1998) constructed an upper jaw made from a rubber arch containing replaceable ceramic teeth and a renewable composite jawbone on which mouthguards were to be tested. Different profiles of projectile, at various energies, were impacted into the model jaw by dropping them down a clear plastic tube whilst a mouthguard was in situ and the damage to the teeth and jaw was recorded. The objective of the exercise was to produce a testing regimen that could easily be applied to any mouthguard that was made to fit the standard model that they produced, there is, however, no instrumented documentation of how the mouthguard dissipates impact energy. As far as simulation of the type of impact that may be sustained by a mouthguard goes and how it would protect the underlying substructure is concerned the test was quite limited in that there was no instrumentation of the impact event. The reliance on the material from which the models of the teeth and jaws were made to react in a similar way to that in which real teeth and oral soft tissues may react has to be questioned. Comparisons can be made from mouthguard to mouthguard but the results would not translate, realistically, to the oral environment and a real impact situation. Although the 'archform' to which the mouthguard was fitted was mounted on springs this would not sufficiently represent the movement of the head and neck during a real impact event during the course of wear during, for example a boxing match.

Further to their previous work Craig and Godwin, 1968 examined the stress transmitted through mouth protectors. Brittle lacquer coatings on maxillary models that were then fitted with mouthguards demonstrated quite graphically the effectiveness of the individual mouthguards. By studying the cracks in the lacquer on the models the amount of protection that the individual mouthguards gave could be recorded. It was reported that the results obtained illustrated that energy absorption tests or rebound tests are not adequate indicators of the most effective mouthguards and that the brittle lacquer coating method provided better information.

2.12.4 In-situ testing

In-situ testing of mouthguards is an area that is largely untouched, however the use of cadavers (Hickey *et al.*, 1967) to study the effect of pressure within the cranium during an impact event was used almost forty years ago. Results did show that the wearing of a mouthguard did reduce the inter cranial pressure and therefore the incidence of concussion could be reduced.

2.14 Related research

There are many situations in which impact absorption is desirable such as car manufacture, crash helmet design, body armour for the armed forces and police, train carriage design; the list could be almost endless. In studying the related research and other fields which use a system of impact energy absorption a rationale for how to absorb impact energy will be seen. Although many instances of impact energy absorption will not be applicable to a mouthguard, crumple zones in cars for example, a wider understanding of the mechanics of an impact is needed.

Related research & its' relevance to mouthguards

In mouthguard construction there is little scope for making the mouthguard very thick in the area most prone to damage – the anterior teeth. However, from the related research that has been looked at, the idea that a material with shock or impact absorbing qualities should be incorporated within the mouthguard. This material needs to be recoverable and should not be destroyed by one impact, for compliance amongst athletes the mouthguard needs to have a life of at least one or two seasons' of use otherwise cost becomes an issue. Crash helmets are very effective at protecting the head within but in doing so this may destroy the helmet or at least compromise its' effectiveness in the event of further impacts.

2.14.1 Denture soft lining

A resilient layer incorporated into a partial denture to act as a 'shock absorber' or 'stress distributor' has been discussed (Parker, 1966). The trauma caused by impact forces during mastication would be distributed more evenly over the edentulous ridge by a resilient layer being 'sandwiched' in between layers of the denture base, so that the make-up of the denture was; hard-soft-hard. The principle idea of this 'shock absorber' is to recreate the type of shock absorption that is naturally present in some structures of the body such as the periodontal membrane. When a load is applied to the denture that load is then directly transmitted to the underlying tissues. If a layer of material that possesses a certain amount of elasticity is incorporated between two layers of the hard denture base then some of the energy of an impact force can be absorbed and so reducing trauma to the oral tissues.

Parker (1966) found that there is a much better stress distribution in dentures that contain a soft or resilient liner than that of a hard denture base alone, and decided that the softer layer acts in a similar manner to the way in which a fluid may act by transferring the pressure in a much more even manner instead of in localised points of intense pressure. The soft lining then transmits the stress to the underlying structures in a much more even way than that of a denture without a soft or resilient lining, therefore reducing the resorption of the underlying bone due to the pressure of the denture acting upon it.

Kawano *et al* (1991) found that when pressure was applied to a testing plate with pressure sensors underneath to measure the amount, and distribution of force the absence of a soft lining material meant that there was a large discrepancy in the amount of pressure measured by the pressure sensors, indicating uneven loading and, therefore, giving rise to areas of localised high pressure which have proven to be painful and very damaging to the residual ridge (Parker 1966; Basker, Davenport and Tomlin 1976). When pressure was applied to the plate in the presence of a soft liner the variation in recorded pressures at the four sensors was much less, no matter what thickness of soft liner was used, showing that the soft lining material evenly distributes any pressure that is applied to it.

The use of soft linings in dentures does seem to be useful in the improvement of stress distribution in the supporting structures under a denture (Kawano *et al* 1993), this greater distribution also means a reduction in the impact stress during function and therefore the residual ridge will show less resorption (Davidson and Boere 1990). However, the soft lining must be of a sufficient thickness to absorb the pressures put upon it otherwise they are of little use to the patient whose main concern is that of comfort. A thickness of 3mm has been suggested (Kawano *et al* 1991), although this is not always possible. Due to the overall thickness of the dentures a soft lining of 3mm would make the dentures very weak and prone to frequent breakage. The methods of testing the soft lining materials, however, do not concern themselves with the force of an impact but with the materials' ability to withstand pressure over a longer period and the time in which the material takes to return to normal after loading. This applies for the newly processed material and after the denture has been worn for pre-determined lengths of time.

Holt, Zylinski and Duncanson (1991) tested several different kinds of soft lining material in an attempt to find the material that felt the most comfortable to the patients who were wearing the soft lined dentures. Their research was based on the theory that the time-dependent shape-recovery behaviour of a resilient liner will indicate its potential for clinical success. To relate this theory to mouthguards it is necessary to look at the type of experiment carried out in their research. The first experiment consisted of a programmed indentation test, in situ, whereby a parameter was obtained to enable the various resilient liners to be compared. The materials tested were either modified acrylic resins or silicone based and following the experiments it transpired that the silicone based materials had the better rates of recovery after loading and performed much better, overall, than the modified acrylic resins. This was also corroborated by the patients' preference for these materials, saying they were the most comfortable and needed fewer adjustments due to soreness.

2.14.2 Crash helmets

In the production of crash helmets, Arai address the issue of impact distribution and shock absorption by having a hard outer shell to a helmet with a softer, foam structure that consists of tiny beads as a liner. The strong shell can transfer impact energy to the liner over a broader area, also the time of the impact is extended as the beads in the liner are compressed and destroyed piece by piece, acting in much the same way as a crumple zone in a car (www.araiamericas.com/tec/shock.htm). Some helmets have an outer shell that is not as hard so light impacts are dealt with in the same way as if the shell was hard, but heavy impacts will tend to destroy the outer shell leaving the inner liner to deal with the impact. If the impact is excessive there will then be damage to the soft inner liner and consequently to the cranium. Crash helmets of this type should be replaced after any kind of impact, no matter how light, as the integrity of the outer shell may be compromised. An impact that would normally be absorbed by the helmet may pass straight through to the liner and/or cranium. This kind of system (the less hard helmet) would not be ideal for a mouthguard as cost for the athlete would become prohibitive if the mouthguard had to be replaced after every knock sustained, which could conceivably be after every time it was worn. However, the incorporation of an impact absorbing zone that can sustain repeated impacts with no immediate or long-term effects is ideal. The use of synthetic rubber to absorb the impact energy would be ideal as it would be able to sustain repeated impacts with little or no long term damage to its properties.

2.14.3 Sports shoes

Another area of research that has strong similarities with the problems addressed in this project is that of sports shoe design. It has been evident for some time now that repeated impact to the foot when running or jogging can have serious implications or the athlete. Sports scientists refer to the action of the foot hitting the ground as 'heel strike'. It is a very apt description as the impact can be excessive and very damaging, not only to the foot but also to the ankle, knee, hip and so on eventually, if the damage is not rectified, resulting in mobility problems in later life.

Sports shoe manufacturers have tried to combat the problems associated with heel strike in a variety of ways, some of which may be pertinent to this study. One method that has been used is the incorporation of pockets of air or gas into the sole, as with Dr Martens 'Air-Wear' footwear and more recently the Nike 'Air' range of athletic shoes.

According to the Nike website Nike Air is a gas that's pressurised inside a tough yet flexible urethane bag. The large molecular structure of this gas prevents it from escaping through the urethane membrane. These Air-Sole units are encapsulated in the mid-sole beneath the heel, forefoot or in both locations, depending upon the specific needs of the athlete for whom a particular shoe is designed. These needs are determined by the sport played, athlete's size, terrain, distance covered, speed and direction of movement. Whatever the circumstances, the Air-Sole unit compresses to reduce the force of impact and then immediately recovers to its original shape and volume, ready for the next blow. During the 26.2 miles of a marathon, a runner's foot endures more than 25,000 heel strikes,
(http://info.nike.com/story/pr_tech2.shtml).

The action of the pockets of air, as mentioned before, returning to their original position very rapidly could be harmful in the oral environment. However tests carried out on a mouthguard material that included pockets of air did show a reduction in the transmitted force through the material when compared to a standard mouthguard material, (Westerman et al, (1997).

2.14.4 Packaging

Also of interest is the use of different kinds of foam in the packaging industry for the protection of goods during transportation, although the foams that are used tend to be in much thicker sections than could be feasibly tolerated in the mouth. The thinking behind the use of foams in packaging though is similar to the technology used in the production of motorcycle crash helmets. So if the protective material or cushion is permanently damaged after an impact then it doesn't matter so long as the cargo is still in it's original condition and totally undamaged.

2.14.5 Body armour

Body armour of some sort has been worn for protection for thousands of years. Ancient tribes fastened animal hide and plant material around their bodies when they went hunting, and the warriors of ancient Rome and medieval Europe covered their torsos in metal plates before battle. By the 1400's, armour in Europe had become highly sophisticated and with the right armour knights were almost invincible. However, the development of the long bow and later the canon and gun changed the way in which armour was made and worn. The development of these weapons meant that thin plates of armour could be penetrated, thickening the armour helped to some extent but meant that the armour was cumbersome. With the development of weapons that could kill or maim from a distance the whole battle scenario changed as did the armour that was needed. Thick felt wadding was worn under a metal breastplate to take the impact out of a penetrating arrow or piece of shot – a two layered or composite protection system. It wasn't until the 1960's that a reliable bullet resistant armour was developed. Unlike traditional armour, the 'soft' body armour is not made from metal but from advanced woven fibres, (http://www.howstuffworks.com).

Modern body armour is divided into two main categories: hard and soft. Hard body armour, made out of thick ceramic or metal plates, functions in the same basic way as the suits of armour worn by medieval knights. It is hard enough so that a bullet or other weapon is deflected. That is, the armour material pushes out on the bullet with the same force (or nearly the same force) with which the bullet pushes in, the armour, therefore, is not penetrated.

Typically, hard body armour offers more protection than soft body armour, but it is much more cumbersome. Police officers and the armed forces may wear this sort of protection when there is a high risk of attack, but for everyday use they generally wear soft body armour, flexible protection that can be worn more comfortably. Soft body armour is a mystifying concept, how can it stop bullets? The principle at work within the armour is a very strong net.

The woven fibres of the bullet proof vest work in much the same way as a football goal. The back of the goal consists of a net formed by many long lengths of tether, interlaced with each other and fastened to the frame of the goal. When a ball is kicked into the goal, the ball has a certain amount of energy, in the form of forward inertia. When the ball hits the net, it pushes back on the tether lines at that particular point. Each tether extends from one side of the frame to the other, dispersing the energy from the point over a wide area.

The energy is further dispersed because the tethers are interlaced. When the ball pushes on a horizontal length of tether, the tether pulls on every interlaced vertical tether. These tethers in turn pull on all the connected horizontal tethers. In this way, the whole net works to absorb the ball's inertial energy, no matter where the ball hits. If a piece of bullet-proof material was placed under a microscope, it would be seen that a similar structure exists, (http://www.howstuffworks.com). Long strands of fibre are interlaced to form a dense net. A bullet is travelling much faster than a football, of course, so the net needs to be made from stronger material. The most well known material used in body armour is Kevlar fibre. Kevlar is lightweight, like a traditional clothing fibre, but it is five times stronger than a section of steel of the same weight. When interwoven into a dense net, this material can absorb a great amount of energy.

In addition to stopping the bullet from reaching the body, a piece of body armour also has to protect against blunt trauma caused by the force of the bullet. Like a football net, it has to deform by a certain amount to absorb the energy of a projectile. When a ball is kicked into a net, the net is pushed back a long way slowing the ball down gradually. For a football goal this is a very efficient design as it keeps the ball from being lost or travelling too far. Bullet-proof vest material can not deform by large amounts otherwise the vest would push too far into the body at the point of impact; focussing the blunt trauma of the impact in a small area and thereby causing severe internal injuries.

Bullet-proof vests have to spread the blunt trauma out over the whole vest so that the force is not felt too intensely in one spot. To do this, the bullet-proof material must have a very tight weave. Typically, the individual fibres are twisted, increasing their density and their thickness at each point. To make it even more rigid, the material is coated with a resin substance and sandwiched between two layers of plastic film.

A person wearing body armour will still feel the energy of a bullet's impact but over the whole torso rather than a specific area. Since no one layer can be permitted to deform to a vast extent, the vest has to slow the bullet down using many different layers. Each 'net' slows the bullet a little bit more than the previous layer until the bullet finally stops. The material also causes the bullet to deform at the point of impact. This process, which further reduces the energy of the bullet is called 'mushrooming'.

No bullet-proof vest is totally impenetrable, and there is no piece of body armour that will make anyone invulnerable to attack. There is a wide range of body armour available today, and the types vary considerably in effectiveness. In much the same way that some dental labs offer different designs of mouthguards for different sports, all supposedly with different levels of protection.

Generally speaking, armour with more layers of bullet-proof material offers greater protection. With some bullet-proof vests, layers can be added. One common design is to fashion pockets on the outside of the vest so that when extra protection is needed metal or ceramic plates can be inserted.

To determine how effective a particular armour design is, researchers shoot it with all sorts of bullets, at all angles and distances. For a piece of armour to be considered effective against a particular weapon at a particular range, it has to stop a bullet without causing dangerous blunt trauma. The researchers determine the amount of blunt trauma by moulding a layer of clay on to the inside of the armour. If the clay is deformed more than a certain amount at the point of impact, the armour is considered ineffective against that weaponry, (http://www.howstuffworks.com).

2.15 Defining the design and properties of a mouthguard

To function correctly, thereby protecting the oral, facial and cranial structures previously mentioned the mouthguard should be able to absorb the energy of an impact and then release that energy in a slow and controlled manner. The mouthguard should not be so resilient that it releases impact energy immediately, as this release of energy could, potentially, be as damaging as the initial impact. The mouthguard should be capable of withstanding many blows without any permanent deformation and without the mouthguard failing totally for reasons of cost, as previously stated, ideally the mouthguard should last for at least one or two seasons without the loss of any physical properties.

In the anterior and occlusal regions of a mouthguard there needs to be some sort of 'shock-absorbing' material that can take up large amounts of impact stress and then release it slowly to reduce the spring-like recoil effect of the more resilient materials used in mouthguard manufacture. This material must then return to its original shape and be able to do this time and time again. These areas that have the shock-absorbing material laminated into them would act rather like the 'crumple zones' that are present in cars. Therefore the impact would deform the material and in doing so the energy of the impact is taken up by the material rather than the impact energy being transferred to the underlying structures in the mouth. The mouthguard 'crumple-zones' would differ in that both light and heavy impact blows will be taken up by the material which then returns to its original size and shape; unlike cars which will withstand light impacts without any serious effect but heavy impacts render them useless. The impact force would also be distributed over a wider area of the dental arch and in doing so be diminished.

No matter what type of mouthguard is fitted they must all fit the same criteria that is required to ensure maximum protection. Briefly, the mouthguard must:

i) Absorb the impact into the mouthguard.

ii) Redistribute the impact energy applied to it.

The impact, or kinetic energy, is then converted into elastic energy due to the deformation of the material from which the mouthguard is made, it is this elastic energy which must be slowly recoverable so as not to cause damage with a recoil type of action.

The mouthguard should be made in such a way as to have a soft layer next to the teeth and other oral tissues to even out the contacts with the surface and eliminate any high spots that may be present. It is these areas that would be the most prone to trauma in the event of an impact. Any teeth outstanding from the line of the arch, especially in the anterior region, must have sufficient coverage of the soft material to prevent damage from an impact. It is all too easy to let the material thin out in these prominent areas. Due to the process by which the vast majority of mouthguards are produced this is almost unavoidable. So producing a smooth, even mouthguard that is both thin and thick in all the wrong places is all too easy. Although it is the anterior region which is most at risk in contact sports it is probably this area that frequently ends up as the thinnest part of the mouthguard.

As someone who has worn a mouthguard for many years it is this researchers' opinion that more could be done to make the mouthguard more comfortable to wear. The anterior region is the one main area where the mouthguard can be built up excessively as it will not impede air-flow or affect comfort to any great effect. Palatally and disto-bucally is where the mouthguard can be thinner to a somewhat greater degree than the anterior and occlusal areas. Disto-buccally because teeth from the first premolars to the molars have much larger roots and therefore more anchorage in the alveolus, protection is needed mainly from chipping of the cusps if the lower teeth are smashed against them and from bruxism. In the palatal region there is no real need of protection from an impact, the mouthguard extends here to serve as retention only. This area is generally left as thick as the rest of the mouthguard because most dental technicians, when making mouthguards, use a thermoforming blank that has a uniform thickness and only the periphery is trimmed and smoothed for the comfort of the wearer. However, palatally is the one area where bulk may be reduced without any loss of protection; in fact it is more comfortable to wear and far more easy to speak coherently with the reduced thickness in the palatal region. Occlusally there should be some build up of material so it is not bitten through quite so easily, this area can be thickened to a much greater extent when producing mouthguards for boxers to prevent knock-outs and severe concussion from blows to the mandible. The mouthguard can be made to incorporate indentations of the lower teeth on the occlusal surface to give a positive key for the lower teeth to bite into; doing so should reduce wear and tear of the mouthguard in this region which is prone to wear thin due to bruxism, however, care must be taken when doing this to ensure that the occlusal thickness is not reduced. If the lowers have a positive bite on the mouthguard there will be a reduced tendency for grinding the teeth on the surface of the mouthguard. The occlusal surface of the mouthguard has to be heated to soften slightly so the lower teeth can be pressed into the material - care must be taken not to over-heat the mouthguard, as this could compromise the fit. Although in the general course of a practice session or a full game of rugby, for example, the athletes' mouth will generally be open as the nature of the modern game dictates that it is played faster and harder and therefore the players will be breathing hard through their mouths.

A design of mouthguard that has been recommended for use in contact sports incorporates the following criteria (Scott *et al*,1994).

i) It should enclose the maxillary teeth to the distal surface of the second molars.

ii) Thickness should be 3mm on the labial aspects, 2mm on the occlusal aspect and 1mm on the palatal aspect.

iii) The labial flange should extend to within 2mm of the vestibular reflection.

iv) The palatal flange should extend about 10mm above the gingival margin.

v) The edge of the labial flange should be rounded in cross section whereas the palatal edge is tapered.

vi) Even when a maxillary guard is constructed it should be articulated against the matching mandibular model to give optimum comfort.

2.16 Statement of the problem

Custom-made mouthguards, made to a dentists' prescription in a dental laboratory protect the wearers' teeth and oral soft tissues from trauma; they may also protect against concussion. The material that mouthguards are routinely made from, pEVA, has a relatively high hysteresis which means that after deformation it returns to its original shape rapidly, a material or combination of materials that exhibited a low hysteresis would be more beneficial as the mouthguard, after deformation from an impact, would return to its' original shape more slowly.

It is felt however, that mouthguards could offer far greater protection from injury with the incorporation of a 'shock absorbing' material. A softer, more compliant material would dissipate the harmful effects of impact and spread a reduced force over a wider area of the dental arch thereby minimising the effect of a direct blow to the teeth.

The manufacture of a mouthguard from pEVA material means that the material undergoes several processes the main one being the heating cycle to ensure mouldability of the pEVA to the cast of the dentition. As this heating process is felt to be having a significant effect on the ability of pEVA to withstand an impact due to internal stresses being removed this must be accounted for in the design and manufacture of a mouthguard; i.e. thickness must not be compromised and the lamination of pEVA with other materials becomes more important.

If the mouthguard had been made solely from a material that is softer than the pEVA that is used at present the protection capabilities of such a mouthguard would be reduced due to the space limitations and the need for comfort and 'wearability' of a mouthguard. A very soft mouthguard would have to be made prohibitively thick in order to produce a mouthguard that could protect against the kind of impacts received in such sports as boxing, rugby and hockey. The need for comfort is of great importance in the design characteristics of a mouthguard because if a mouthguard is not comfortable then the athlete will not wear the device. So a compromise will have to be made between maximum protection and the 'wearability' of a mouthguard. As previously stated the maximum thickness possible for a mouthguard is 5mm, limited mainly to the anterior region which is most prone to the trauma seen from impacts to the mouth. So it is within the thickness of 5mm that the optimum protection must be obtained from the use of pEVA and the incorporation of softer materials that can absorb the impact.

CHAPTER 3

Purpose of the study

The processing of mouthguard material may have a significant effect on the physical responses demonstrated in an impact on that material. The heating during the manufacture of a mouthguard to beyond Tg needs to be investigated for a more detailed examination of the properties of mouthguards and to help design future test procedures that may need to be carried out on mouthguards in a working model of the head and neck.

It is hypothesised that the lamination of different materials, with softer more compliant materials being used within the mouthguard, would have the effect of absorbing more of the impact energy while dissipating the force over a wider area. The outer layer, if stiffer than the inner layer, would distribute the force to a wider area of the more compliant material. The outer more stiff material would be prevented from returning too rapidly to its original shape because of the compliant layer sandwiched between the two stiffer layers. It would, instead, have a more controlled return phase so that any harmful rebound energy is minimised.

In general the custom mouthguards that are available to the athlete at the present time do offer protection from an impact that is directed at the mouth, but the amount of protection and the method by which the mouthguard deals with the impact is not fully understood. By using an instrumented dropweight impact testing machine the materials that are under scrutiny can be observed in a much more analytical way, by examining the way the energy at impact is absorbed and distributed.

3.1 The effects of heat treatment

To produce a more accurate model of a finished mouthguards' behaviour under impact conditions by heat-treating the mouthguard material in a similar way to which the material would be heated in the manufacturing process.

3.2 Effect of lamination on impact measurements

To examine the standard mouthguard material (pEVA) and its ability to protect an underlying substructure from impact trauma. To determine the effects of laminating pEVA with non-standard mouthguard materials such as PMMA, silicone rubber and synthetic wax.

CHAPTER 4

Materials and methods

4.1 Materials

Most of the materials being used in the study (Table 4.1) are materials that are routinely used in the manufacture of mouthguards, splints and other thermoforming procedures and are readily available from dental laboratory supply companies.

Table 4.1 Materials and manufacturer of thermoformable discs.

Name	Description of Material	Thickness (mm)	Manufacturer
Erkoflex	Poly ethylene vinyl acetate, pEVA	1 - 5	Erkodent
Erkocryl	Polymethyl methacrylate, PMMA	1 - 2	Erkodent

Erkodent Erich Kopp GmbH, Siemensstrasse.3, Postfach 11 40, Pfalzgrafenweiler, Germany. Sole agents in U.K. – E M Natt Ltd., 45-47 Friern Barnet Road, London, N11 3EG.

Erkoflex is pEVA, it has a Shore A hardness of 82 and is used mainly for making mouthguards but is also used for bracket transfer trays, tooth positioners, fluoride splints and also for duplicating models.

Erkocryl is PMMA and is used for interim dentures, dressing or compression plates and orthodontic plates.

Also materials of a non-standard mouthguard nature will be tested to assess their protection capabilities (Table 4.2), in their own right and as part of composite, multi-layered systems. The different types of material to be tested will fall into three categories.

i) Soft compliant materials such as synthetic rubber that deforms easily, so absorbing an impact, but then return to their original shape more slowly than a rigid material would.

ii) Hard/stiff materials such as PMMA that have a high impact resistance but exhibit high rebound characteristics.

iii) The third group of materials shall be referred to as intermediate. These materials shall fall between the two extremes of the other two groups of materials.

iv)

Table 4.2 Non – standard materials.

Name	Description of Material	Thickness (mm)	Manufacturer
Blu-Tack	Semi-solid synthetic rubber	3, 5	Bostik (1)
Plasticene	Modelling clay	3, 5	Newclay Ltd (2)
Plasticene	Modelling clay	5	Newclay Ltd(2)
Elite Double	Addition cured silicone	1, 3, 5	Zhermack (3)
Erkogum	Synthetic wax	2	Erkodent (4)
Flexibase	Denture soft lining	1, 3	Flexico (5)

(1)Bostik Findley Ltd., Common Road, Stafford, ST16 3EH
(2) Newclay Products Ltd., 1 Battle Road, Heathfield, Newton Abbot, TQ12 6RY
(3)Zhermack, GmbH 49448 Lemförde, Germany
(4)Erkodent, Erich Kopp GmbH, Siemensstrasse.3, Postfach 11 40, Pfalzgrafenweiler, Germany. Sole agents in U.K. – E M Natt Ltd., 45-47 Friern Barnet Road, London, N11 3EG.
(5)Flexico, Flexico Developments, J & S Davis, Summit House, Summit Road, Potters Bar, Herts, EN6 3EE

Blu-Tack is manufactured by Bostik and is used for fixing posters and such like to walls, although it has a very wide range of uses in the office e.g. as a pencil eraser. Plasticene is a modelling clay used by children and also by professional model makers, it also has a variety of uses in the dental laboratory, as an aid in articulating models and as a medium for blocking out undercuts when thermoforming – although a separator needs to be applied.

Elite Double is an addition cured silicone rubber that is used for the duplication of casts and dies in the dental laboratory and is available in different Shore a hardness ratings, for this particular test silicone with a Shore A hardness of 22 was used.
Erkogum is a pliable, synthetic gum/wax that is used as a blocking out medium when thermoforming blanks using the pressure forming technique.
Flexibase is a cold cure denture soft lining material that is a plasticised acrylic.

The thickness of the test specimen has to be limited to approximately 5mm, this is because the thickest mouthguard that will be tolerated by an athlete is around this thickness. Clearly the thicker the material the more beneficial it is to the wearer. However an upper limit has to be set and, as stated earlier, a mouthguard should comply to a certain set of fixed dimensions to offer best protection in the areas of the mouth that need it most and also to be comfortable to the wearer.

As the limit for overall thickness is going to be 5mm if a laminated structure is produced the thickness of each ply will be a great deal thinner if a multi-layer system is adopted. This will then allow for many layers of differing materials to be built up within the composite each contributing to the efficacy of the mouthguard. Because each ply may have different properties from that of the next ply, the amount of impact energy transferred through the composite will be affected.

4.2 Methods

4.2.1 Polariscope study

A polariscope is an optical instrument that utilises the properties of polarised light to analyse the stress distribution within a photoelastic specimen. Two types of polariscope are commonly employed in stress analysis work, the *plane polariscope*, and the circular polariscope.

The Plane polariscope is the simplest optical system used in photoelasticity; it consists of two linear polarisers (which transmit light only along their axis of polarisation) and a light source. The linear polariser nearest the light source is called the *polariser*, while the second linear polariser is known as the analyser. In the plane polariscope, the two axes of polarization are always crossed; hence no light is transmitted through the analyser.

Circular polariscope: This polariscope employs circularly polarised light (light which sweeps a circular helical trace through time as it passes through a wave plate, which basically has two perpendicular axes of polarisation). The photoelastic apparatus contains four optical elements and a light source (Figure 4.1). Various configurations of the polariser, 1st and 2nd wave plates, and analyser produce light and dark bands beyond the analyser.

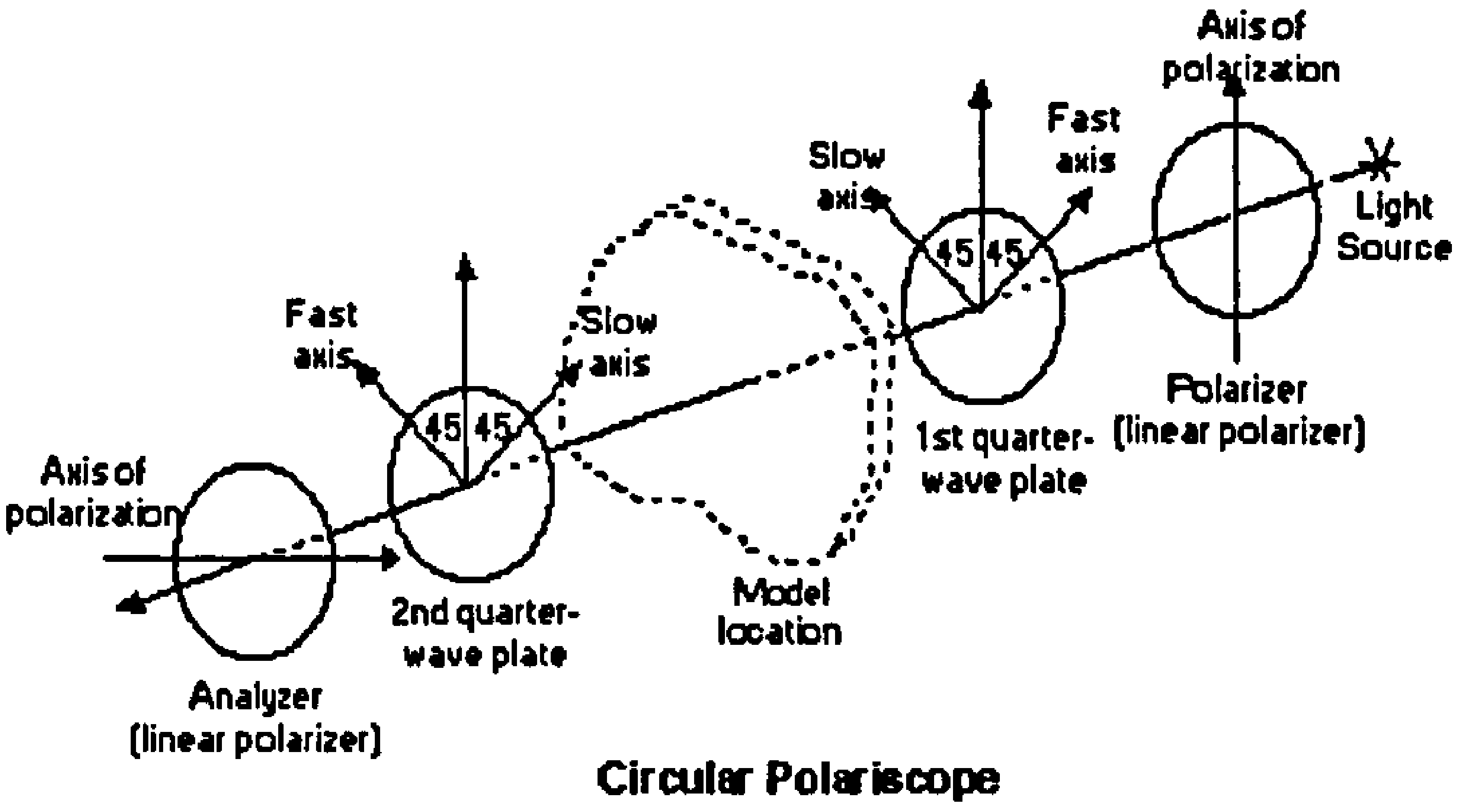


Figure 4.1 The circular polariscope.

http://www.mie.utoronto.ca/labs/emdl/people/kanth/photo2.htm

In definition; photoelasticity is a method of examining transparent polymer models of structures etc. to isolate stress concentrations and other weak zones. The test sample is placed between crossed circular polarising filters (e.g. Polaroid sheets) and either a force is applied to show stress patterns or the residual stress that is present will be indicated by the different colour banding seen within the test sample, the amount of different colour indicates the amount of stress that is present. (http://www-ec.open.ac.uk/materials/mem/mem-photo.html).

4.2.2 Test procedure

During the preparation of the test specimens it was considered likely that the heat treatment of the specimens would have an effect on the performance of the material that was to be tested in the impact rig. To test this theory heat-treated samples and non-heat treated samples were placed within a circular polariscope to observe any strain that may be present within the material.

4.2.3 Analysis of polariscope images

As polarised light passes through strained or stressed glass/plastic, it experiences retardation that is proportional to the amount of residual stress present in the material.

A polariscope enables the observer to view relative stress gradients in a brilliant spectrum within the sample that is placed in the polariscope. The usual method for observing strain within a test sample, that is not transparent, under either static or dynamic testing requires a special, strain-sensitive plastic coating to be bonded to the test part. Then, as test or service loads are applied to the part, the coating is illuminated by polarised light from a polariscope. When viewed through the polariscope, the coating displays the strains in a colourful, informative pattern which immediately reveals the overall strain distribution and pinpoints highly strained areas.

Due to the transparent nature of the pEVA being tested it is quite easy to see the patterns of strain within the material when viewed in a circular polariscope, (figure 4.2).

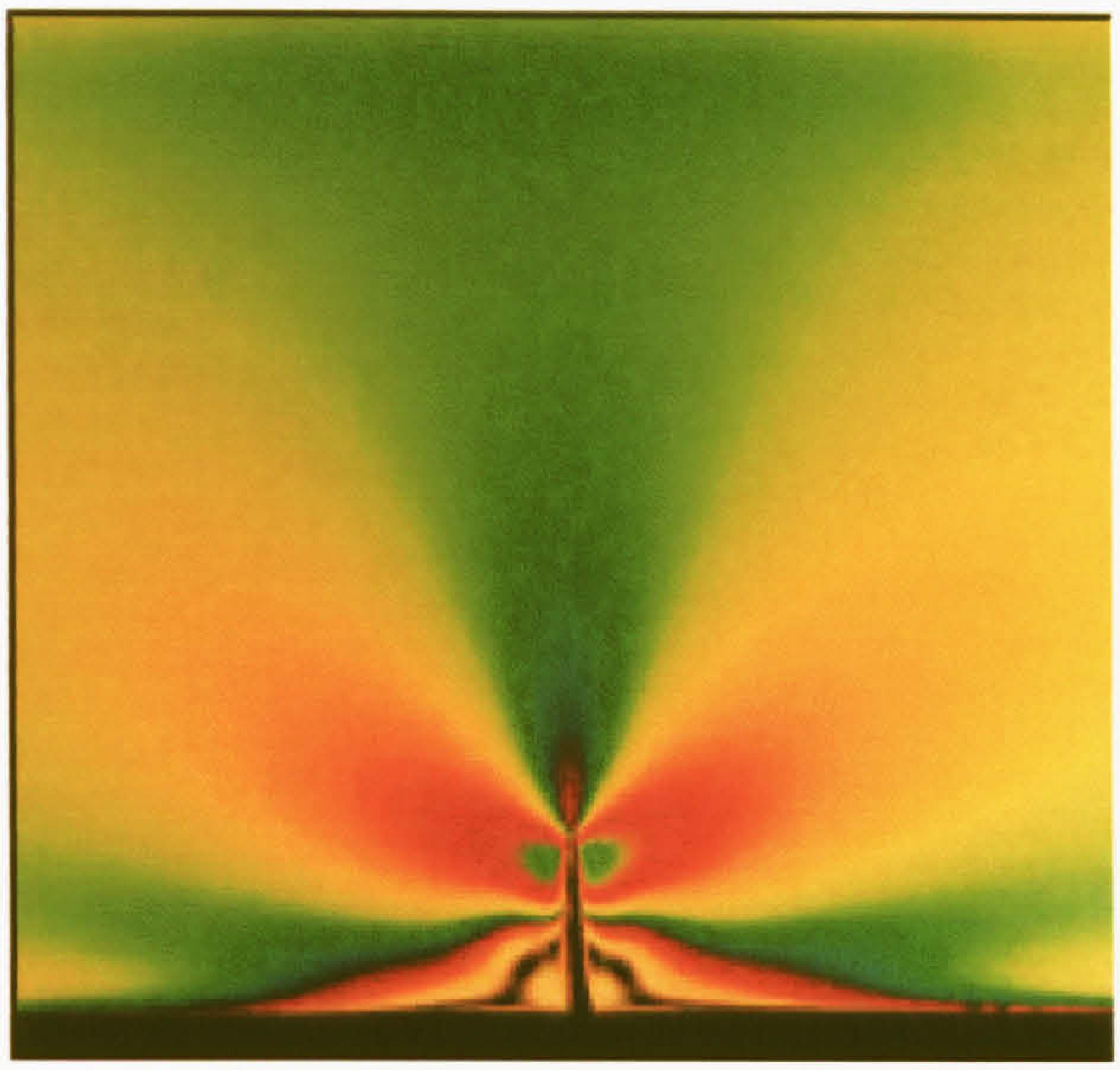


Figure 4.2 Photoelastic stress fringe pattern of a 3D corner crack in tension – for illustrative purposes,

Stress can be measured by making use of certain optical effects:

1. Ordinary light is transmitted by wave motion in which the vibrations are normal to the direction of propagation. A polariser will only transmit components of light rays which are vibrating in a particular plane – so producing polarised light.

2. On entering a stressed transparent model, in this instance the EVA mouthguard material, the polarised light is split into two components which vibrate

in the two perpendicular planes of principal stress. The velocity of propagation of each component light ray differs from that in unstressed material by an amount which depends on the magnitude of the stresses. Therefore, the two rays emerge from the observed stressed material out of phase, the difference in phase is dependant on the difference between the two principal stresses, the wavelength of the light, the thickness of the model and the stress-optical sensitivity of the material.

3. The two rays emerging from the material are received by a second polariser – the analyser, this only transmits components of the two rays in its plane of polarisation. The two emerging components can be added together and cause extinction with monochromatic light if one components is half a wavelength (or 1.5, 2.5. etc., wavelengths) behind the other and maximum light intensity if one component is an integral number of wavelengths behind the other. Therefore, a variation in magnitude of the principal stress differences at points within a model will cause varying degrees of optical interference, so that the whole surface of the model appears to be covered with fringes. From an observation of fringe orders the maximum shear stress, or the difference in principal stresses acting in a plane normal to the direction of propagation of the light can be obtained mathematically.

With monochromatic light the surface of a stressed model, when observed through the analyser of a crossed polariscope, appears to be covered with a number of black and monochromatic fringes. If white light is used, however, the model will appear to be covered with a series of brightly coloured bands, called isochromatics, having the same colour sequence that is observed with a film of oil on water, or with Newton's interference rings between a spherical and flat surface. This appearance is due to the varying relative retardations at different points of the model which cause each colour to be extinguished in turn according to its wavelength.

With zero relative retardation all light is extinguished in the crossed polariscope. As the retardation is increased the colours are restored to produce, first a grey tone and then a white light. Thereafter the two components of the violet become out of phase to give a residual colour of white minus violet which produces a complimentary yellow hue. Blue is the next colour extinguished, to produce an orange colour and so on through the various colours of the spectrum, the complementary colour to the extinguished one thus appears in the model. The colours that will be produced in a crossed polariscope by gradual increase of retardation are shown in Table 4.3, Table 4.4, Table 4.5 and Table 4.6

Table 4.3 Colours produced in a crossed polariscope by gradual increase of retardation.

Composition	Resulting first order colour	Relative retardation Å (10^{-8}cm)	Equivalent fringe order for monochromatic light	
			5461 Å	5891 Å
Black	Black	0	0	0
White	Grey	1400	0.29	0.27
White	White	2600	0.48	0.44
White-violet	Pale yellow	3300	0.64	0.59
White-blue	Orange	4600	0.84	0.78
White-green	Dull red	5200	0.95	0.88
White-yellow	Purple (tint of passage)	5800	1.06	0.98
White-orange	Deep blue	6200	1.14	1.05
White-red	Blue-green	7000	1.28	1.19

A second interference of colours of the spectrum arises when the retardation corresponds to two cycles out of phase thereby giving second order colours. These colours are not quite the same as colours of the first order, it may be that the extinction of more than one colour occurs at a time.

Table 4.4 Colours produced in a crossed polariscope by gradual increase of retardation.

Composition	Resulting second order colour	Relative retardation Å (10^{-8}cm)	Equivalent fringe order for monochromatic light	
			5461 Å	5891 Å
White-1st deep red, 2nd violet	Green-yellow	8300	1.46	1.36
White-2nd blue	Orange	9600	1.72	1.59
White-2nd green	Rose red	10500	1.9	1.78
White-2nd yellow	Purple	11500	2.1	1.95
White-2nd red, 3rd violet	Green	13500	2.5	2.3

Third order colours consist predominantly of pink and green, becoming more and more washed out in appearance with the higher orders owing to the complex nature of the interference. It is difficult to distinguish the two colours above the eighth order when white light predominates.

Table 4.5 Colours produced in a crossed polariscope by gradual increase of retardation.

Composition	Resulting third order colour	Relative retardation Å (10^{-8}cm)	Equivalent fringe order for monochromatic light	
			5461 Å	5891 Å
White-2nd deep red, 3rd blue	Green-yellow	14500	2.65	2.45
White-3rd green	Pink	15500	2.85	2.6
White-3rd yellow, 4th violet	Green	18000	3.3	3.05

Table 4.6 Colours produced in a crossed polariscope by gradual increase of retardation.

Composition	Resulting fourth order colour	Relative retardation Å (10^{-8}cm)	Equivalent fringe order for monochromatic light	
			5461 Å	5891 Å
White-3rd deep red, 4th green, 5th violet	Pink	21000	3.85	3.55
White-4th yellow, 5th blue, 6th violet	green	24000	4.4	4.05

The stress field at any point in a photoelastic specimen can be related to its index of refraction through Maxwell's stress optic laws. The light emerging from the analyser is subject to prior conditioning from the polariser and specimen, and can be described as follows: The intensity I diminishes when either sin term goes to zero, and therefore we have two possible fringe patterns of points where the light is extinguished, i.e.,

Isochromatics - and indicate areas of constant stress magnitudes.
Isoclinics - and indicate principal stress directions.

4.2.4 Impact testing

An instrumented dropweight rig has been developed, within the department of Mechanical Engineering at the University of Sheffield, enabling impact tests and static indentation tests to be conducted on circularly clamped panels. The test rig has recently been modified to permit clamping of smaller panels, i.e. mouthguard blanks. The clamping rings that were made specifically for the testing of mouthguard blanks have a slightly smaller internal diameter than the clamping rings that were used as standard for the testing of materials in the Department of Mechanical Engineering. The rings for the purposes of these tests have an internal diameter of 80mm and an external diameter of 125mm. This is so that the material that is to be tested can be clamped with the optimum force in the impact rig, existing rings could not have been used as they were all too large for the size of test specimen used in these tests. The impact rig is equipped with four transducers namely, an accelerometer, a strain-gauged load cell, a displacement transducer and opto-electronic triggering and timing sensors. For the purposes of this study the strain gauge readings will not be required and are not measured.

The accelerometer is a miniature piezoelectronic transducer, supplied by Endevco, which is connected via signal conditioner model 4416B to the data acquisition system. An infrared LED/phototransmitter reflective transducer, comprising a spectrally matched GaAs infrared emitter (type SE 3455) and a silicon phototransistor (type SD 5443) supplied by Honeywell Optoelectronics is used to determine the displacement of the test specimen during impact. The transducer is located beneath the test specimen at a position 25mm offset from the point of load application in order to prevent the signal being affected by any damage produced on the backface. The transducer is calibrated from static load tests performed under identical clamping conditions using an LVDT to measure the deflection at the centre of the test specimen.

The instrumented indentor is released from a predetermined height by an electromagnetic switch. For the purposes of this study the indentor is dropped from a height of 0.5m. This height was chosen as it was thought to be best not to totally destroy each sample. Data was required that showed how the samples reacted to an impact event not at what impact energy they were destroyed. The data acquisition system is triggered when an aluminium flag, attached to the indentor assembly, passes the first opto-interrupter, an infrared emitting LED and phototransistor (type 307-913) supplied by RS Components. The indentor velocity immediately before the impact event is determined by measuring the time taken for the flag, of 15.5mm depth, to cross the line of sight of the second opto-interrupter. The sensors are also used to determine the rebound velocity when energy is returned to the indentor after the impact event

The transducers are connected to a Keithley Instruments DAS 1401 data acquisition board which is installed in an IBM PC/AT compatible desktop computer as shown schematically, below (Figure 4.5).

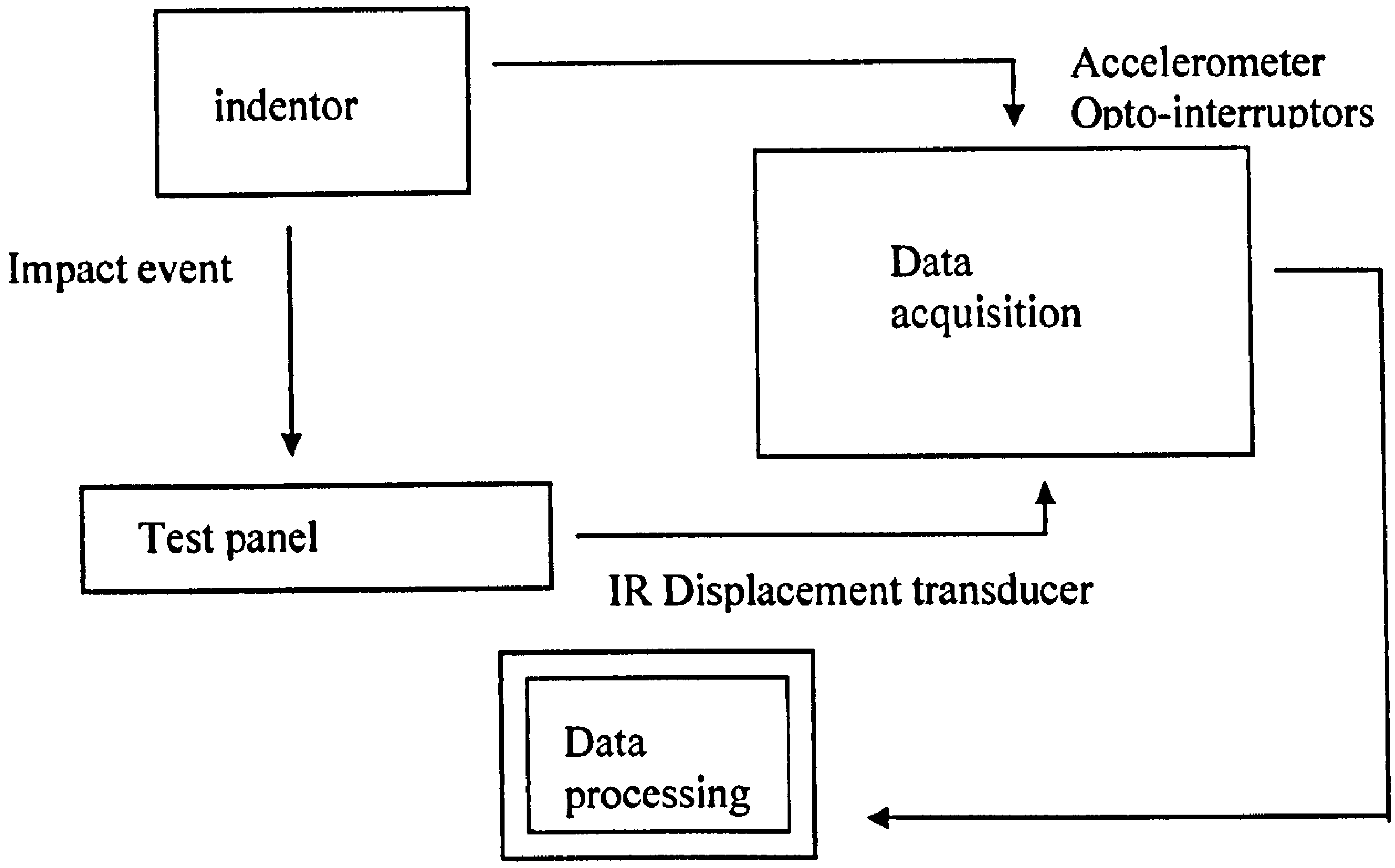


Figure 4.5 Schematic of data acquisition.

The board is a multi-layer construction with integral ground plane to minimise noise and crosstalk. The system has a maximum sampling rate of 100kHz and allows the monitoring of up to eight channels of bipolar data. For monitoring of the transducers three channels are employed and the data sampled at a rate of 25kHz. With more advanced, and expensive, equipment it is possible to sample all channels at a higher single rate. The system is triggered via the reference or zero channel whilst the accelerometer, load cell and displacement transducer are connected to channels 1 – 3 respectively and the timer operates via channel 4. The data acquisition system is completed with the Easyest LX software from Keithley Asyst enabling storage, manipulation and filtering of the data. Three types of digital filter are available, low pass, high pass and band pass. In addition, a transition width must be specified to determine the region where the filter's passband response drops from one to zero. This varies from a maximum of 0.5 times to a minimum of 0.05 times the acquisition rate with the cut-off frequency used at the centre point for the transition. Invalid results are obtained for a transition width too large for the specified cut-off frequency. The set up of the indentor (Figure 4.6) is shown below, schematically, and photographically (Figure 4.7).

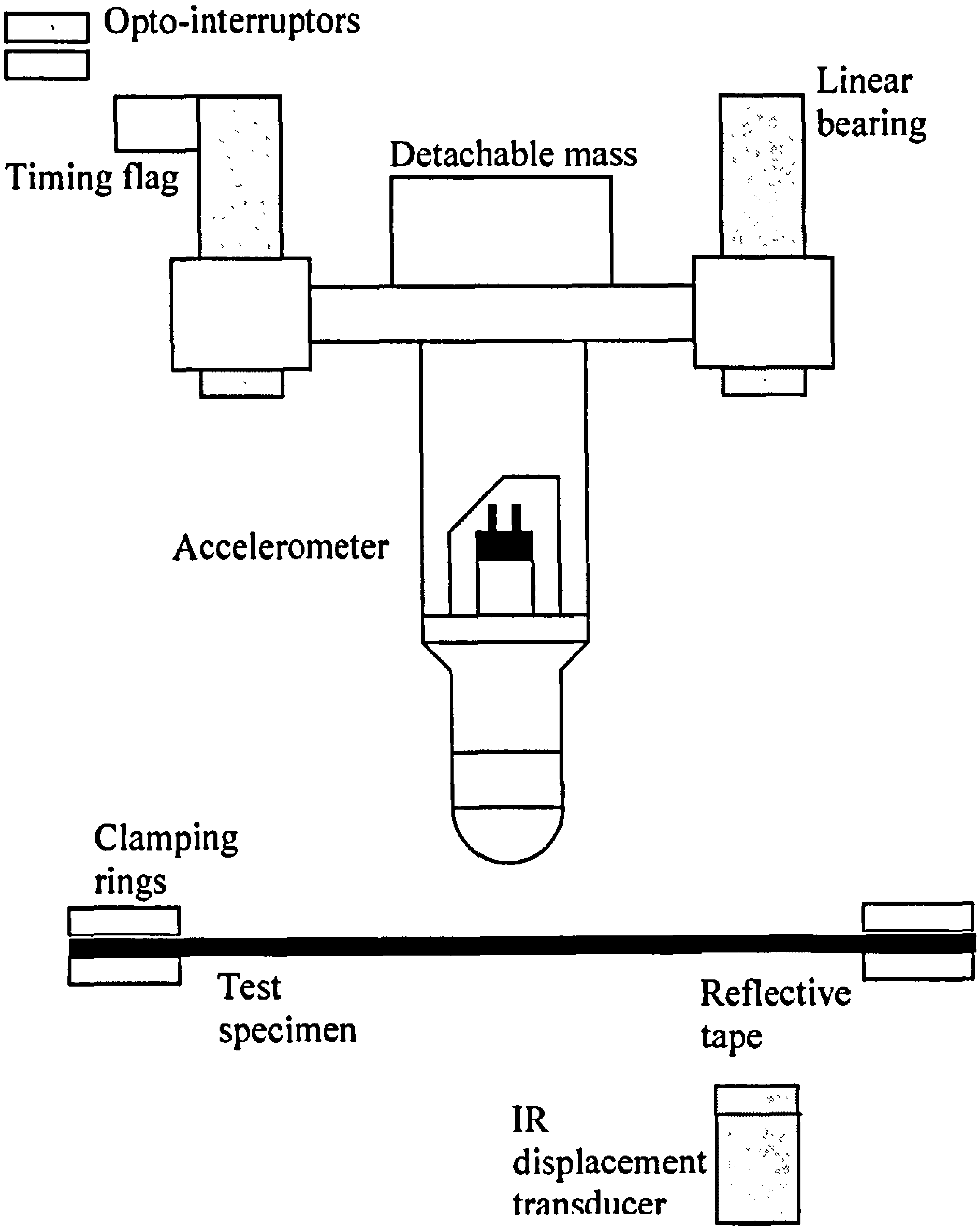
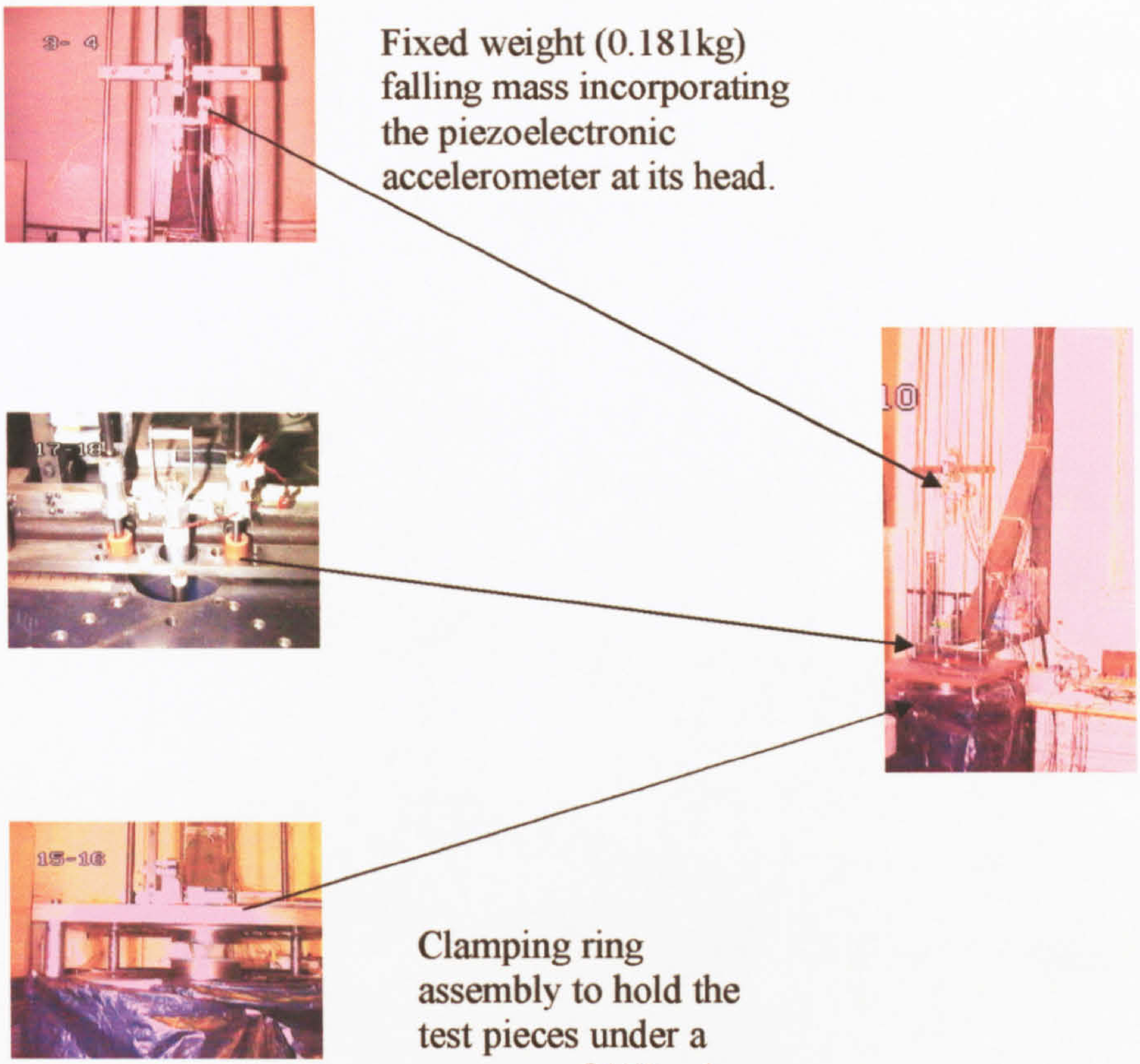


Figure 4.6 Arrangement of indentor assembly



Fixed weight (0.181kg) falling mass incorporating the piezoelectronic accelerometer at its head.

Clamping ring assembly to hold the test pieces under a pressure of 150 psi.

Figure 4.7 The impact rig and its component parts.

4.2.5 Specimen preparation and test procedure

Materials have been tested in their own right in the 'as received from the supplier' condition, as heat treated monoliths to relieve stress, in composite laminate systems or as layered structures. For impact testing all materials were clamped into the impact test rig using the annular rings to hold the test specimens rigidly. Also, to try and emulate intra-oral conditions, a much smaller specimen has been tested (50-60mm ∅). The smaller specimen was placed on top of a 3mm thick panel of PMMA that was clamped into the test rig so the amount of protection offered by the smaller specimen could be more accurately assessed. To keep the smaller test piece in contact with the 3 mm panel of PMMA a light film of petroleum jelly was smeared onto the surface of the PMMA in an attempt to replicate the cohesion that would exist between saliva and a mouthguard.

In many applications polymers are required to maintain integrity under impact conditions. The aim of most mechanical testing is to produce data which represent properties of the material tested, not influenced by specimen size and shape. This then helps the designer to select the material and geometry best suited to the job in hand. In this instance design and shape of the finished product (mouthguard) is determined entirely by the dimensions and anatomy of the mouth, which to all intents and purposes is always going to be the same shape.

Impact tests tend to measure the energy absorbed by a specimen before it breaks, a quantity composed of several energy contributions, including energy absorbed by the impact machine through vibrations after initial contact with the specimen and loss in pendulum energy (in pendulum impact tests) when the hammer strikes the specimen as well as the total energy consumed by specimen deformation and sometimes fracture. Although it is very difficult to measure many of the individual energy contributions, impact tests are a valuable comparative test method. It should be recognised, however, that changes of specimen geometry, temperature and test method can result in a different ranking of specimens.

The primary measurement in most impact tests is the energy *U* lost by the striker. In the simplest analysis it is assumed that all of the energy lost by the striker is absorbed by the specimen and that this is proportional to the fracture surface area. In this study it is not a pre-requisite to destroy any of the test specimens in the course of the tests, but to perform such tests that will indicate the way in which the material is reacting to the impact load so the information obtained can be incorporated into the material design features of future test regimes.

Advantages of impact testing:

- Finite control of test parameters – energy, speed, drop height
- Ability to test suitability and adjust as required (retrospectively)
- Gives a picture of the impact event over a small timescale

4.2.6 Repeatability of the tests

To ensure the test system was accurate for each impact event the first tests to be carried out were repeatability tests to ensure validity of the data and to make sure that the tests were reproducible in each case. In this instance five separate sheets of 5mm pEVA were impact tested under exactly the same test conditions as each other. All the material was from the same batch received from the supplier, the clamping conditions of the material and the drop height (0.5m) of the indentor was the same for each impact event. This initial test of pEVA (any material could have been used) is done so that each test does not have to be repeated several times with a mean of results being obtained, each individual test on the material represents the material as closely as possible therefore negating repeated tests on each set of samples.

4.2.7 Effect of annealing

For the initial investigations of the mouthguard material using a polariscope a mould was taken of a round disc 125mm in diameter and 6mm thick to contain the test samples when they are placed in an oven (Vecstar Furnaces, model N° LF2, range 0°C - 1200°C) and heated. This was for ease of removal from the oven and to keep the test sample clean and to prevent distortion. The test specimens that were produced fitted in the clamping rings on the impact testing rig. The glass transition temperature (Tg) of pEVA is 83°C ± 3° so the oven was set to 80°C to achieve a stress relieving heat treatment, the sample was held at this temperature for three different lengths of time – 3 minutes, 6 minutes and 10 minutes to ascertain the optimum time for a stress relieving heat treatment.

4.2.8 Effect of pEVA thickness

To test the effect that thickness of the test specimen had on the impact event different thickness sheets of pEVA (1 – 5mm) were subjected to impact tests under the same clamping conditions and with the indentor being release from the same drop height (0.5m) as for all other tests in this study.

4.2.9 Effect of homogenous pEVA against bonded and non-bonded laminates

Test specimens of 125mm diameter were constructed to fit the clamping mechanism of an instrumented impact testing rig, using a piezo-electric accelerometer to determine the peak impact force (PIF) and an infra-red sensor to measure the amount of deflection (Δ) respectively. Single thickness specimens of ethylene vinyl acetate (pEVA), 5mm thick, were compared with laminated and layered structures of pEVA, using various various thicknesses of each ply (Figure 4.3). Design e is described as being bonded with stiction, this refers to the natural affinity the pEVA has to stick to other samples when received from the supplier. Design f was bonded thermally using the heat from the flame of a microtorch – standard eqipment for smoothing the edges of a finished mouthguard. Only the surface of the pEVA was heated to ensure that the layers of pEVA would be bonded to reach other.

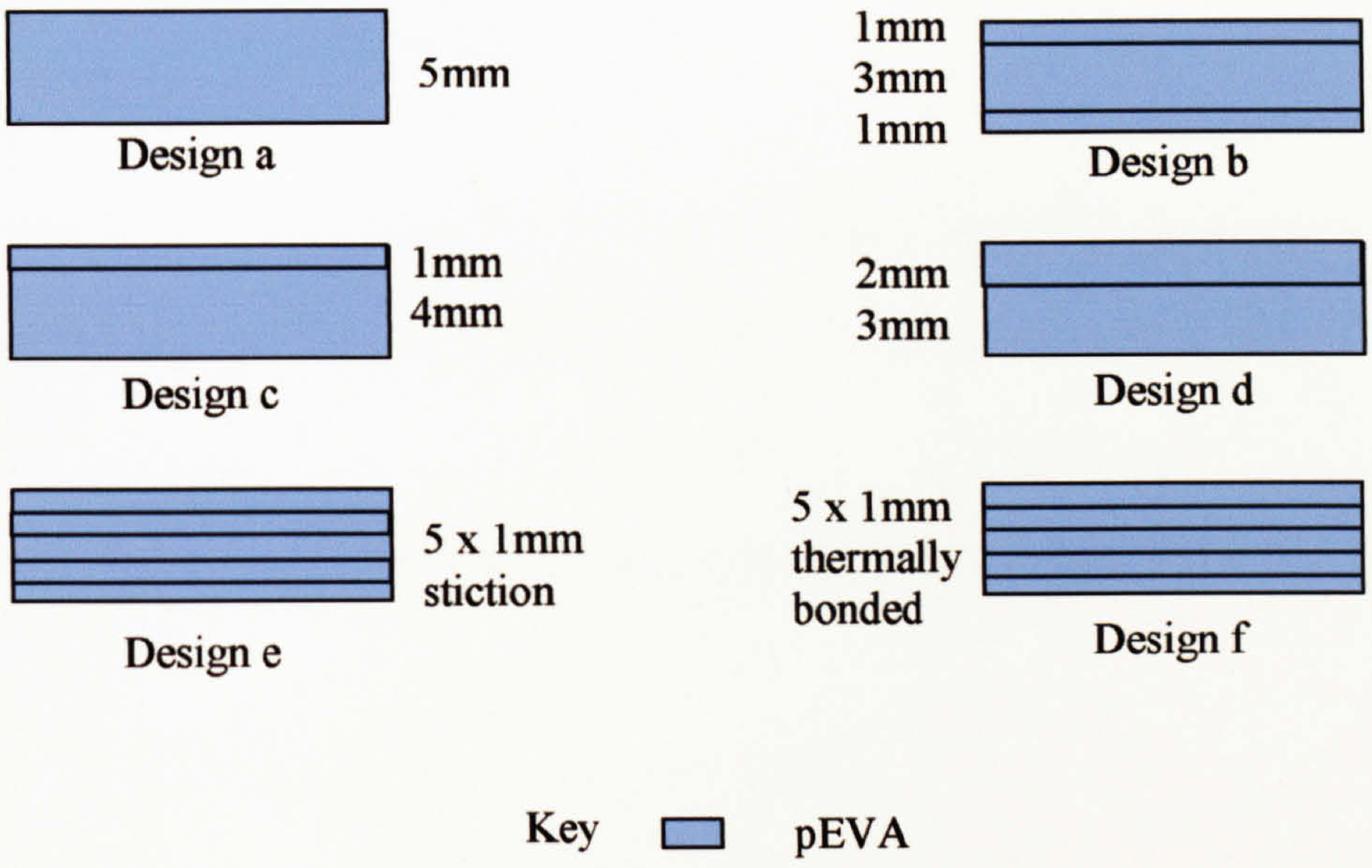


Figure 4.4 Example of samples to compare different laminates of EVA and whether bonding of the laminates had an effect.

4.2.10 Effect of introducing multiple material laminate designs

In a further test (Figure 4.4) four different types of laminate of pEVA together with PMMA and silicone rubber were compared with a 5mm monolith of pEVA.

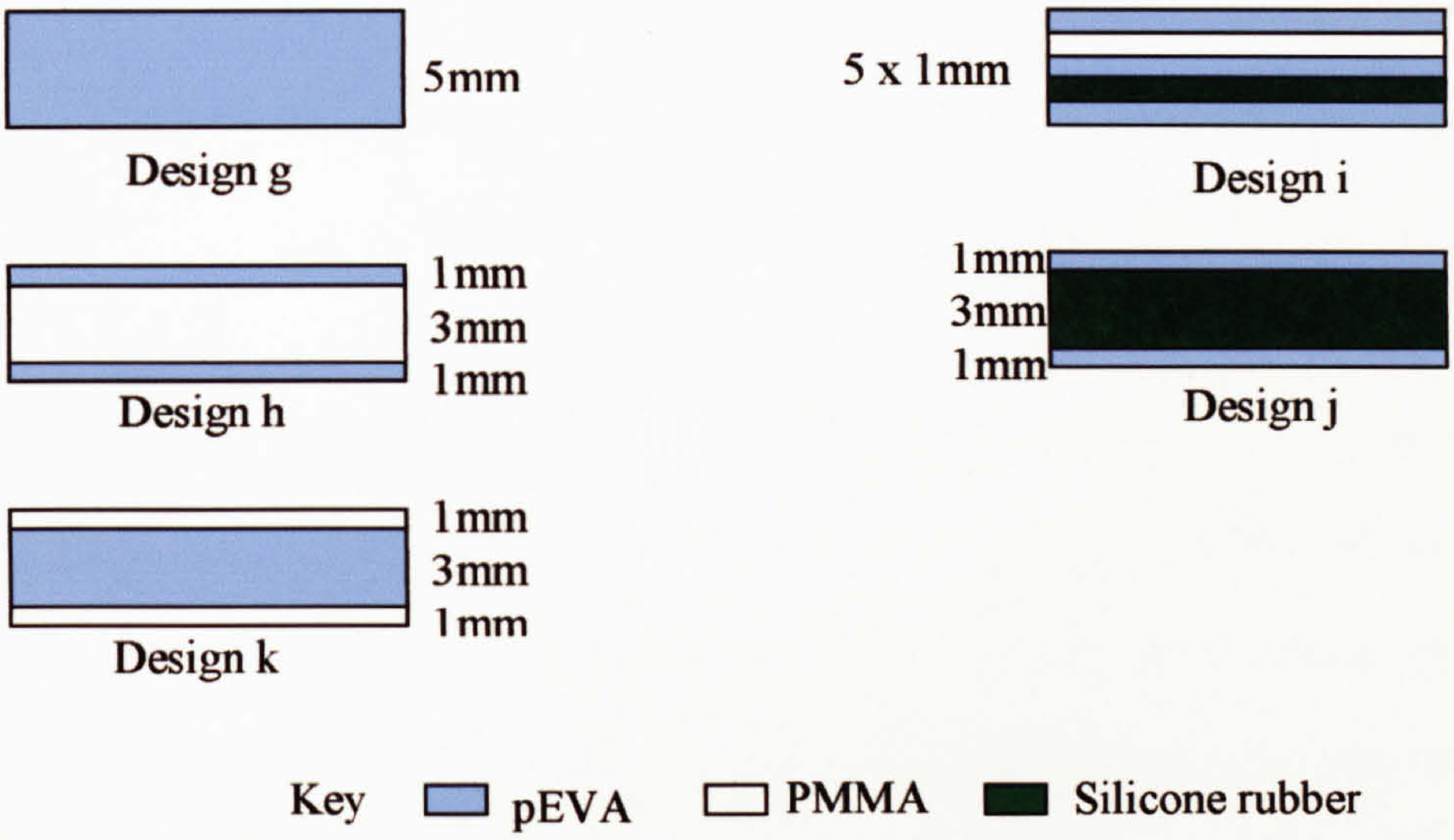


Figure 4.4 Example of samples to compare laminates of pEVA and different materials.

All tests were carried out under the same test conditions as before.

4.3 Data analysis

During the impact event the peak impact force, in Newtons, will be measured along with the displacement, in millimetres, of the various test samples. The impact event will be recorded over a 10 millisecond period, the start of the recording begins when the timing flag on the indentor assembly passes the first of the opto-interrupters, an infrared emitting LED and phototransistor, that are attached to the static frame of the impact rig. Even though the indentor assembly is dropped from a relatively low height, 0.5m, and there is no additional weights added to the indentor assembly there is a lot of electro-static noise inherent in the system that is from the indentor assembly travelling down the guide rods of the impact rig. Although the extent of the noise is low and efforts are made to keep this to a minimum it has to be taken out of the data that is acquired during an impact event. Results that have not had this noise removed can be difficult to read or there may be a lot of extraneous data that can mask the real impact event and the plots made from the raw data could be misleading.

For the best results to be obtained from the impact rig it was felt that the data should be filtered (Found, Howard and Paran, 1998) to minimise the effects of noise, or ringing. To minimise these effects, firstly, careful design of the impact rig was considered, especially how the impactor carriage slides down the guide rods. Next, it was found that the amplitude of ringing may be reduced by lowering the impact velocity since the amplitude is proportional to velocity. It is essential to save the original unfiltered data so that the effects of filtering can be readily compared. Therefore, digital filtering methods are preferred to analogue methods since the latter increase the risk of masking or losing data. Whilst it is usual to filter data recorded from impact tests, extreme care is required in order to ensure that significant events are not removed by the filtering process and thus preventing erroneous interpretation of the impact event. The use of models enables interpretation of the signals prior to filtering and to assess the separate responses of the indentor, rig constraint and test panel during and after the impact event. A linear mechanical model (Figure 4.9) was constructed of a dynamic system comprising the dropweight and the test panel using masses, springs and dampers.

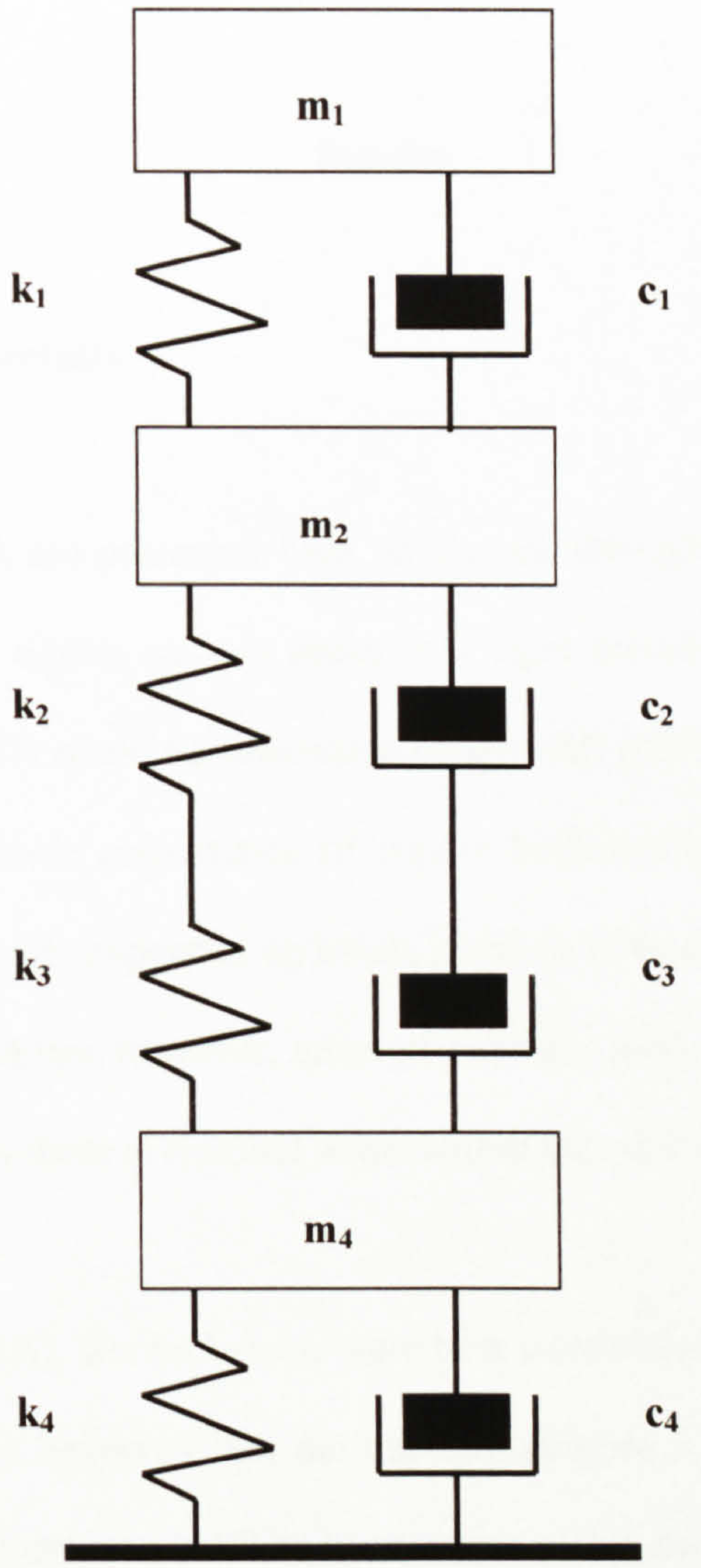


Figure 4.9 Model of impact event.

The elements m_1, m_2, k_1 and c_1 represent the dropweight and the elements k_2 and c_2 represent the stiffness of the indentor nose. The surface indentation stiffness of the panel is represented by the elements k_3 and c_3 and the test specimen is represented by its equivalent mass m_4 and the stiffness elements k_4 and c_4.

Chapter 5

Results

5.1 Polariscope results

Images of the pEVA are presented here, as viewed through the polariscope. These were taken using a digital camera under low light conditions so that the colours observed in the pEVA could be seen more easily. All pEVA was obtained from the same supplier to ensure consistency of results both in the polariscope and in the impact tests. Areas that appear to be black, grey, or without colour, are areas where there is little or no stress; however, areas of colour – more colours generally means more stress, is where there is residual stress within the pEVA.

Samples (5mm pEVA), shown below, were heat treated then impacted in the impact test rig. It was also observed that the material (Figure 5.1, 5.2, 5.3, 5.4) that had undergone the heat treatment exhibited less stress within the material after the impact event.

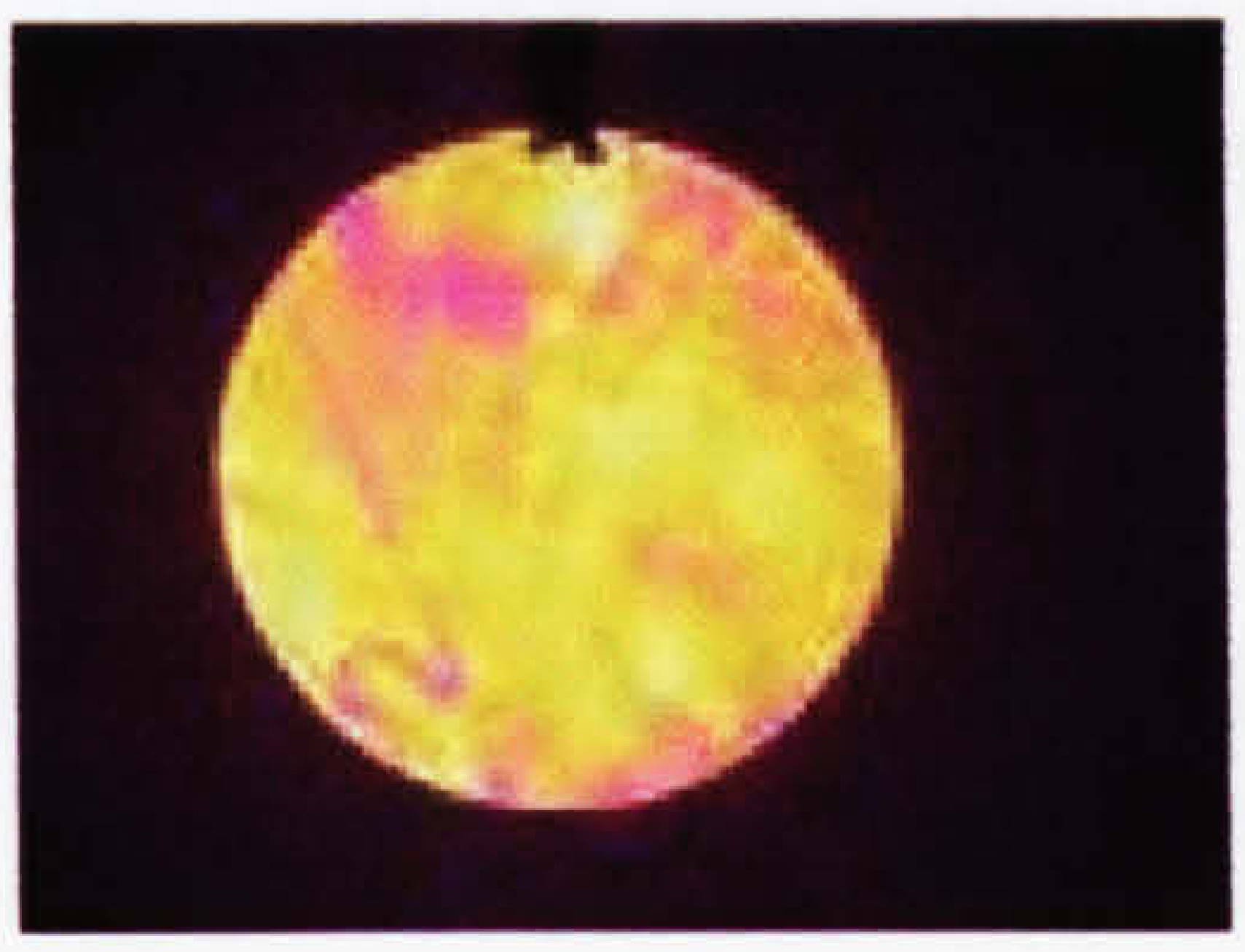


Figure 5.1

Sample 1 before heat treatment

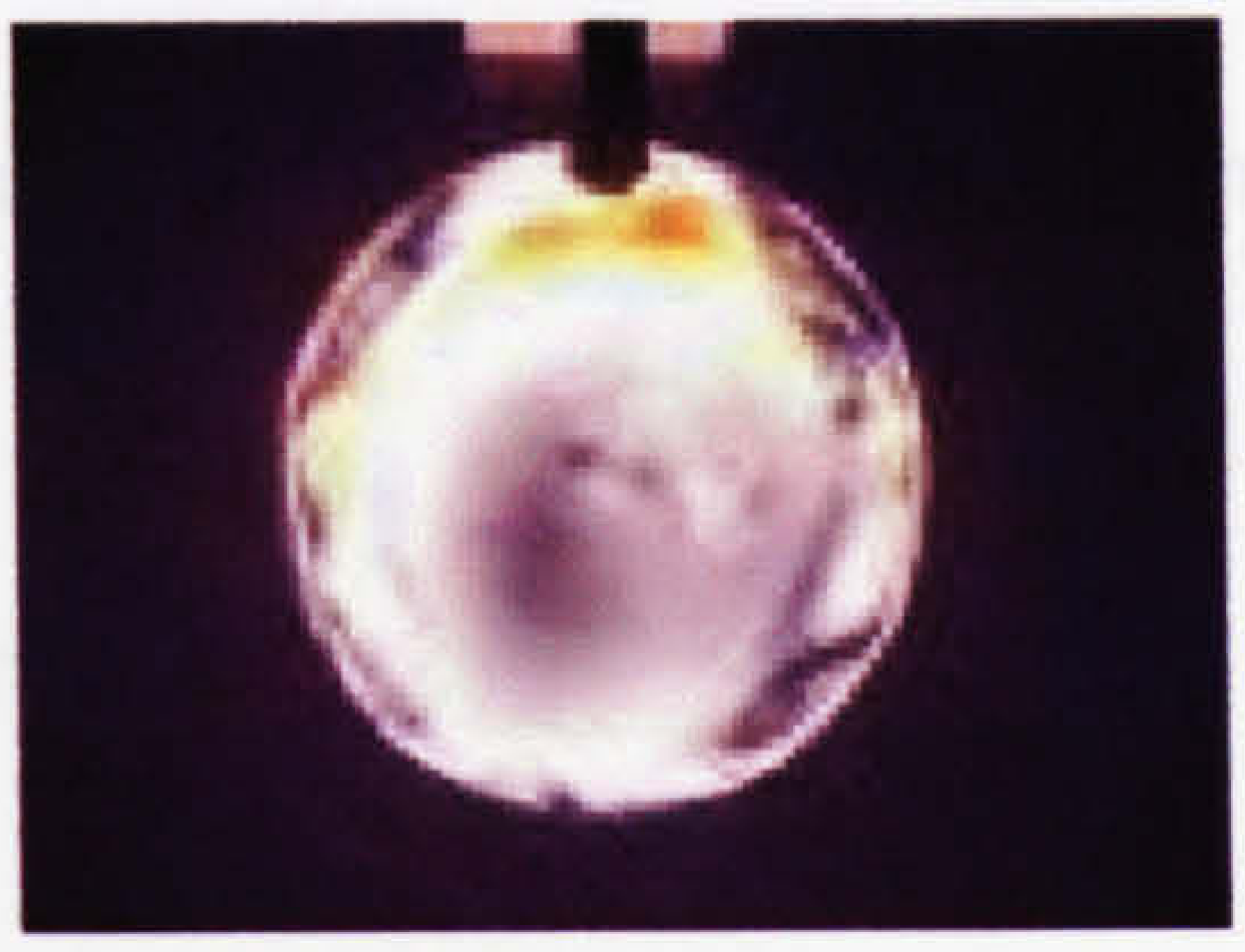


Figure 5.2

Sample 1after heat treatment

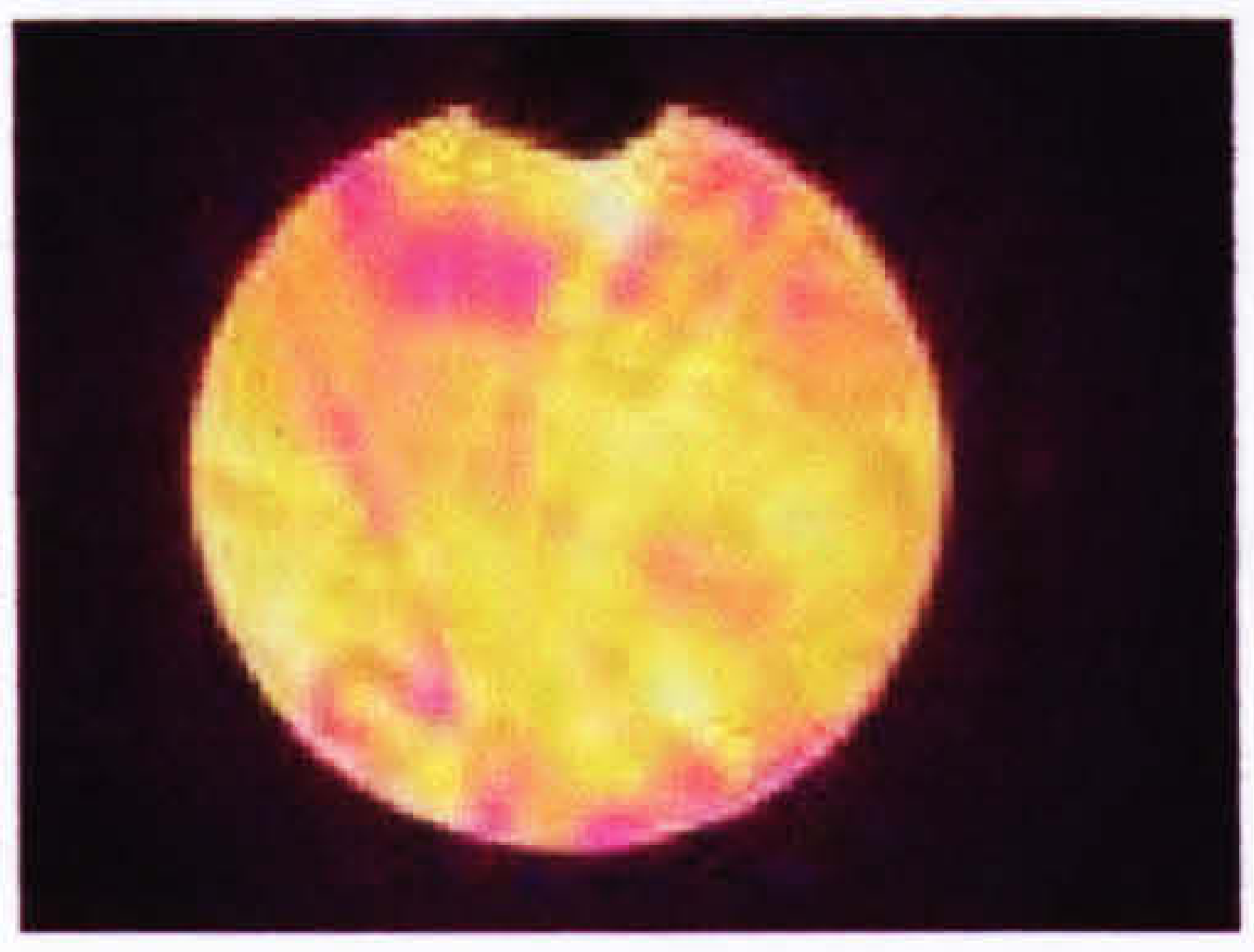


Figure 5.3

Untreated after impact

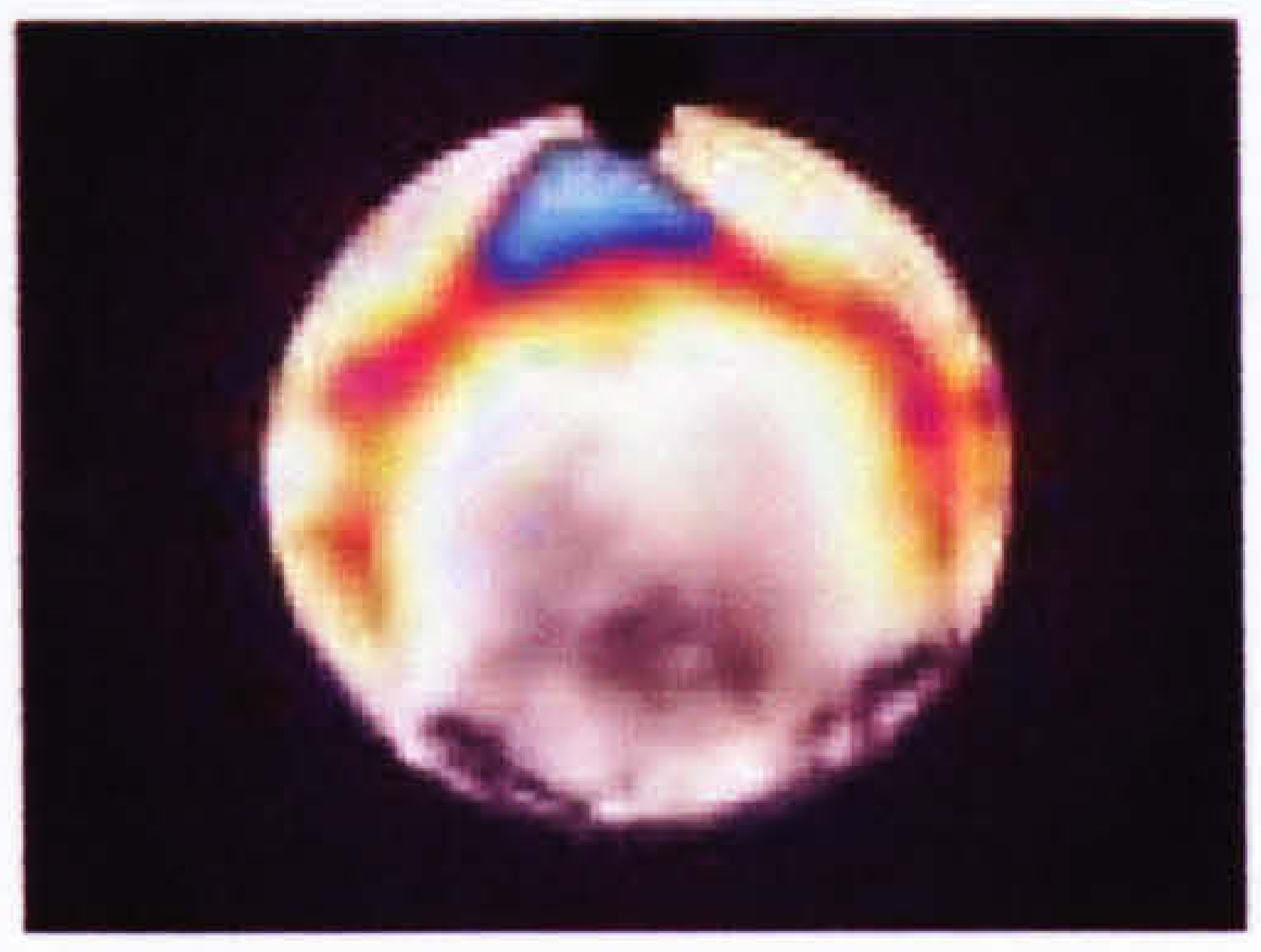


Figure 5.4

Heat treated after impact

Even after the impact event the heat treated pEVA exhibits less stress than the 'as received from the supplier' sample which is highly coloured (colouration is more intense after impact) and therefore full of residual stress, presumably from the manufacturing process.

The brightly coloured fringes (first order fringes) that can be seen around the periphery of the heat treated sample are thought to be caused by removal of the test sample from the plaster mould it was held in while it was in the oven during the heat treatment process. They do not impinge on the test area that is in the exact centre of the test sample and can therefore be dismissed. These stress patterns (fringes) do, however, indicate how easy it is to incorporate stress within the material during a manufacturing process but also, at the same time, it is quite apparent how easy it is to remove the residual stress with a simple stress relieving anneal of the pEVA sample.

5.1.1 Non heat treated pEVA polariscope images

Images were taken under different lighting conditions within the polariscope to emphasise the stress patterns observed within three different thickness samples of pEVA (Figure 5.5 – 5.10a). There is no 'fringing' present – which indicate lines of stress, but there is an overall colouration of the samples that relates to stress levels being distributed fairly uniformly throughout the whole sample.

Samples of pEVA 'as received from the supplier' – residual stress is visible within the pEVA, the samples of all thicknesses viewed have high levels of stress. Images were taken in the dark field of the polariscope (on the left) and light field (right) of the polariscope. This is to demonstrate the stress that is present, apart from the colour there is no difference between the two images, i.e., one does not have more stress than the other. The stress that is present in all samples is consistent across all thicknesses that were tested, one thickness does not seem to display more stress than any other.

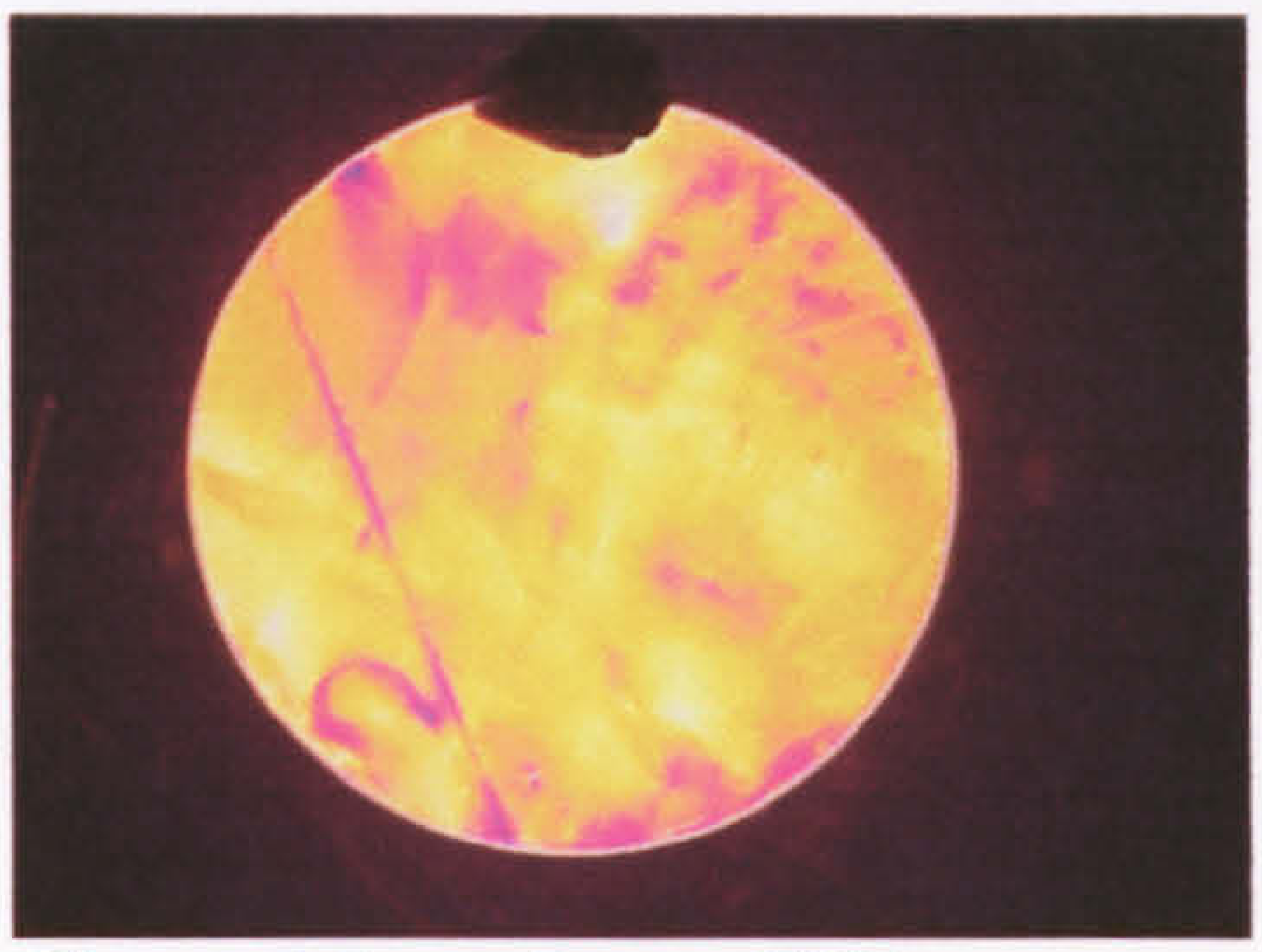


Figure 5.5 5mm pEVA

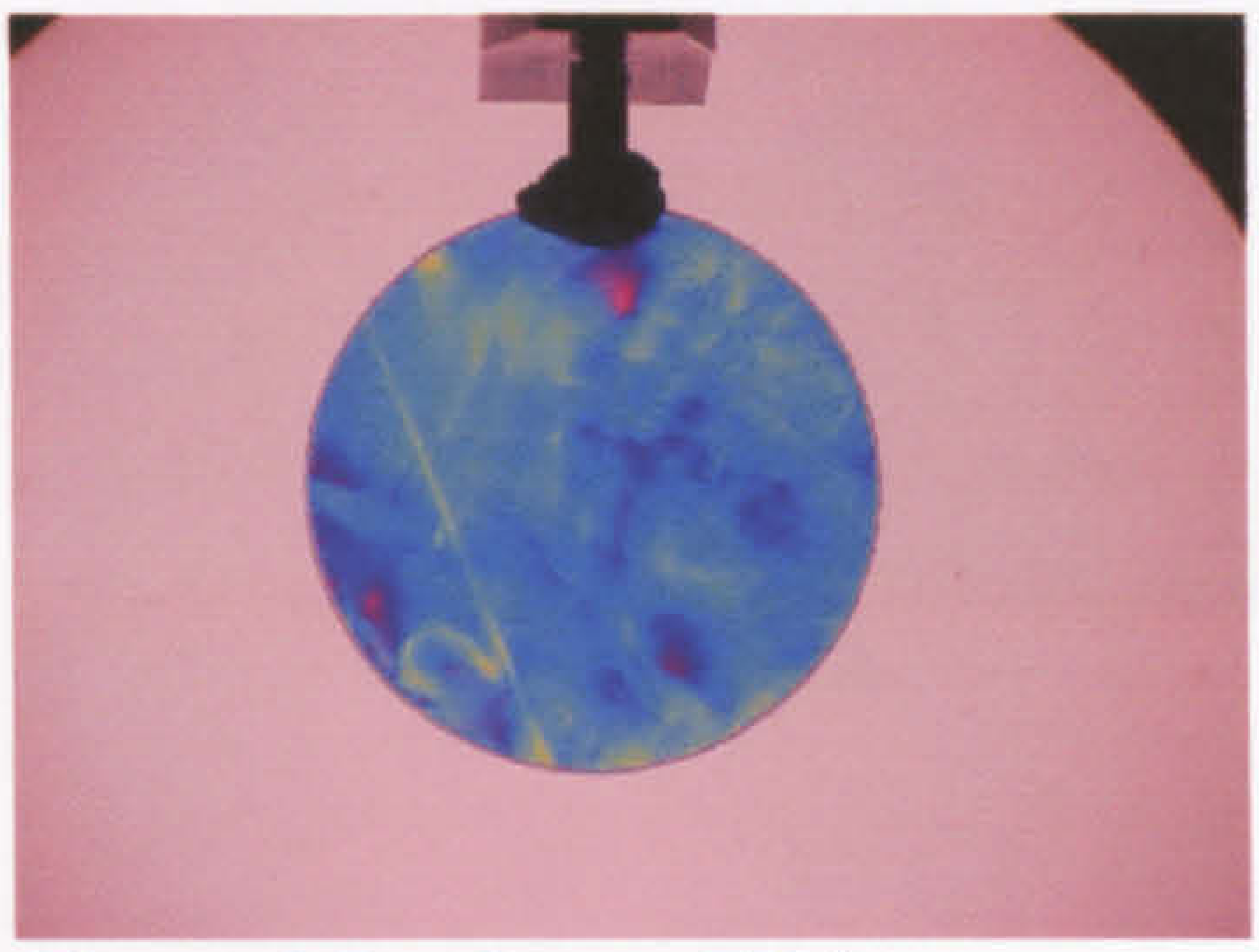


Figure 5.5a 5mm pEVA

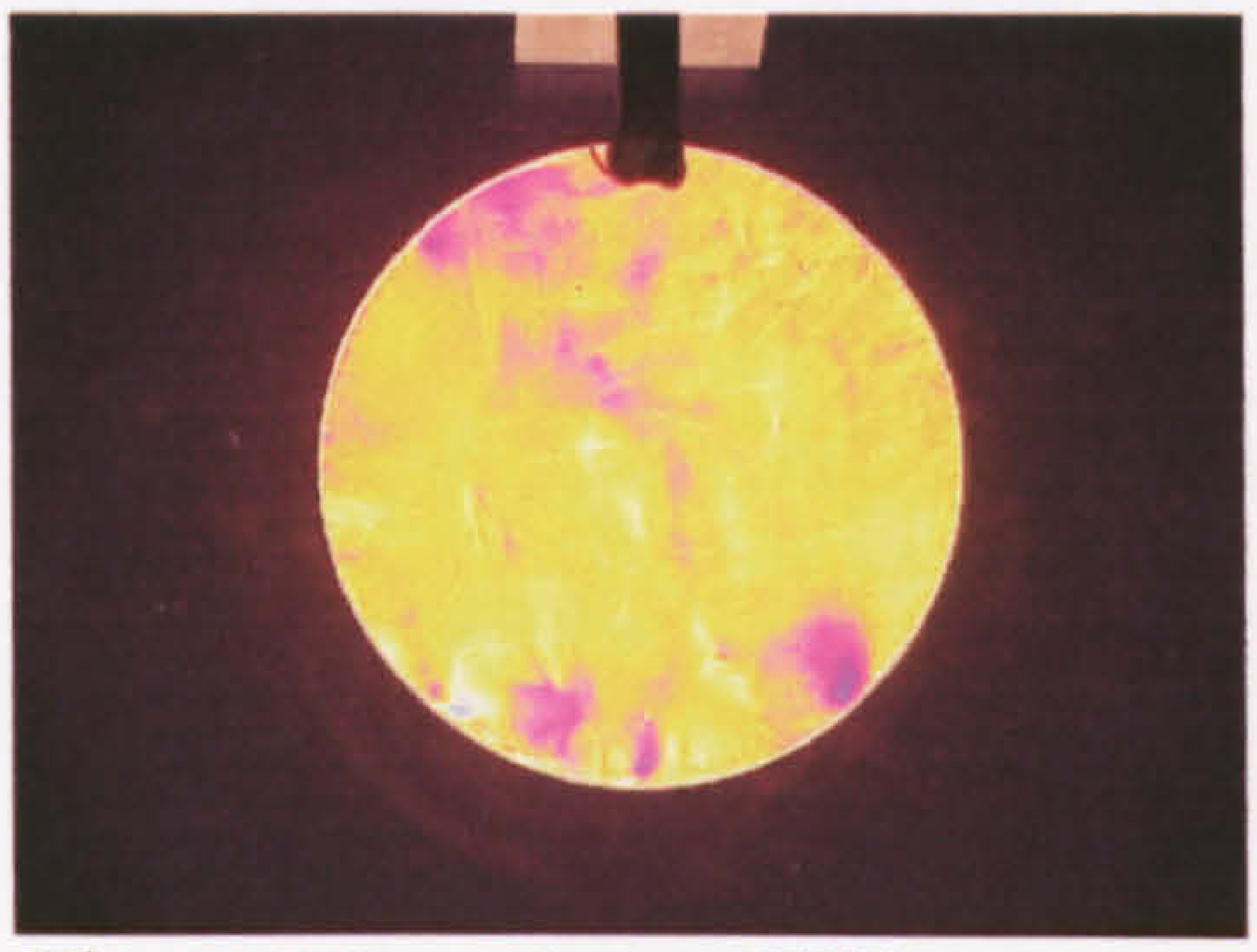


Figure 5.6 4mm pEVA

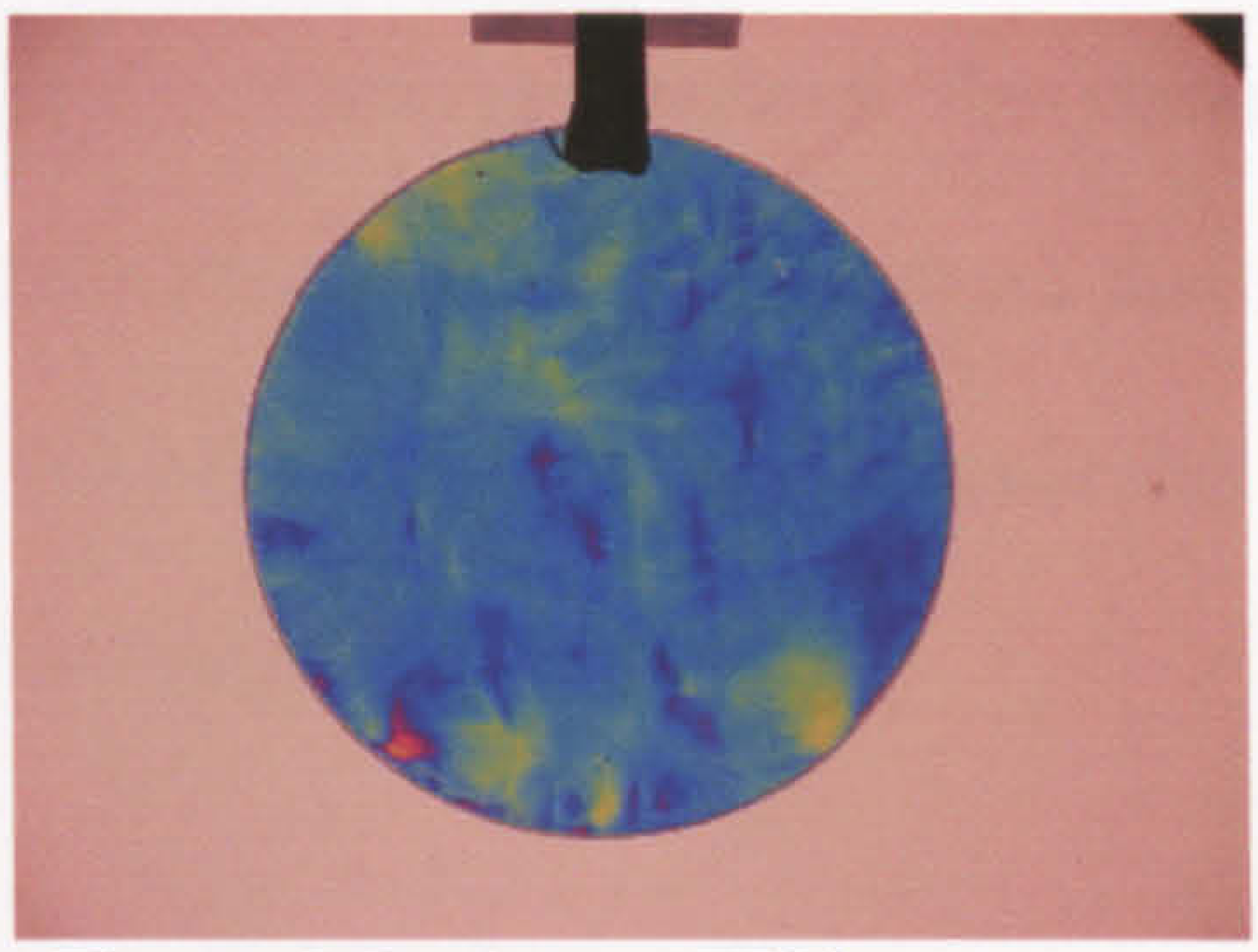


Figure 5.6a 4mm pEVA

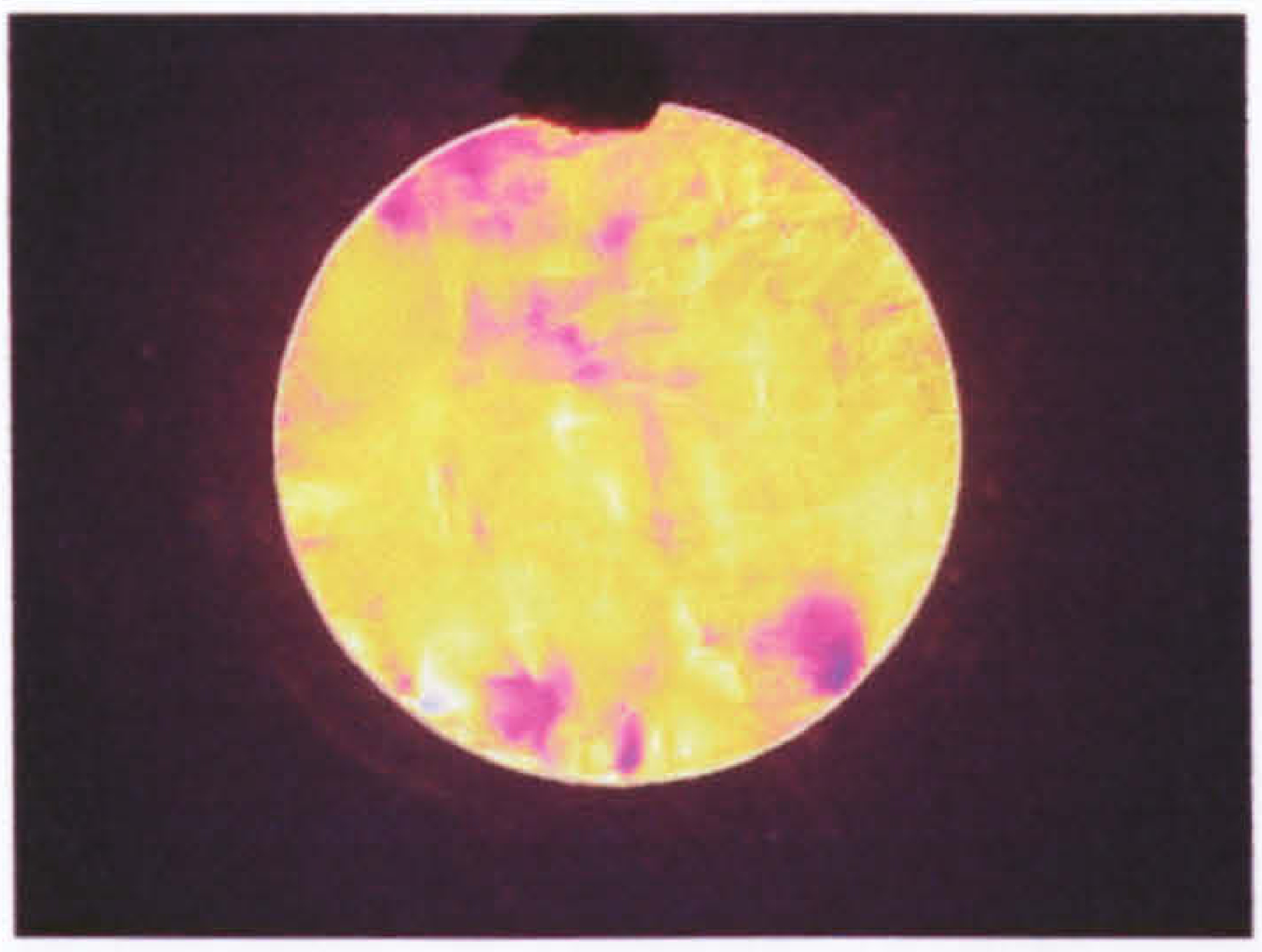


Figure 5.7 3mm pEVA

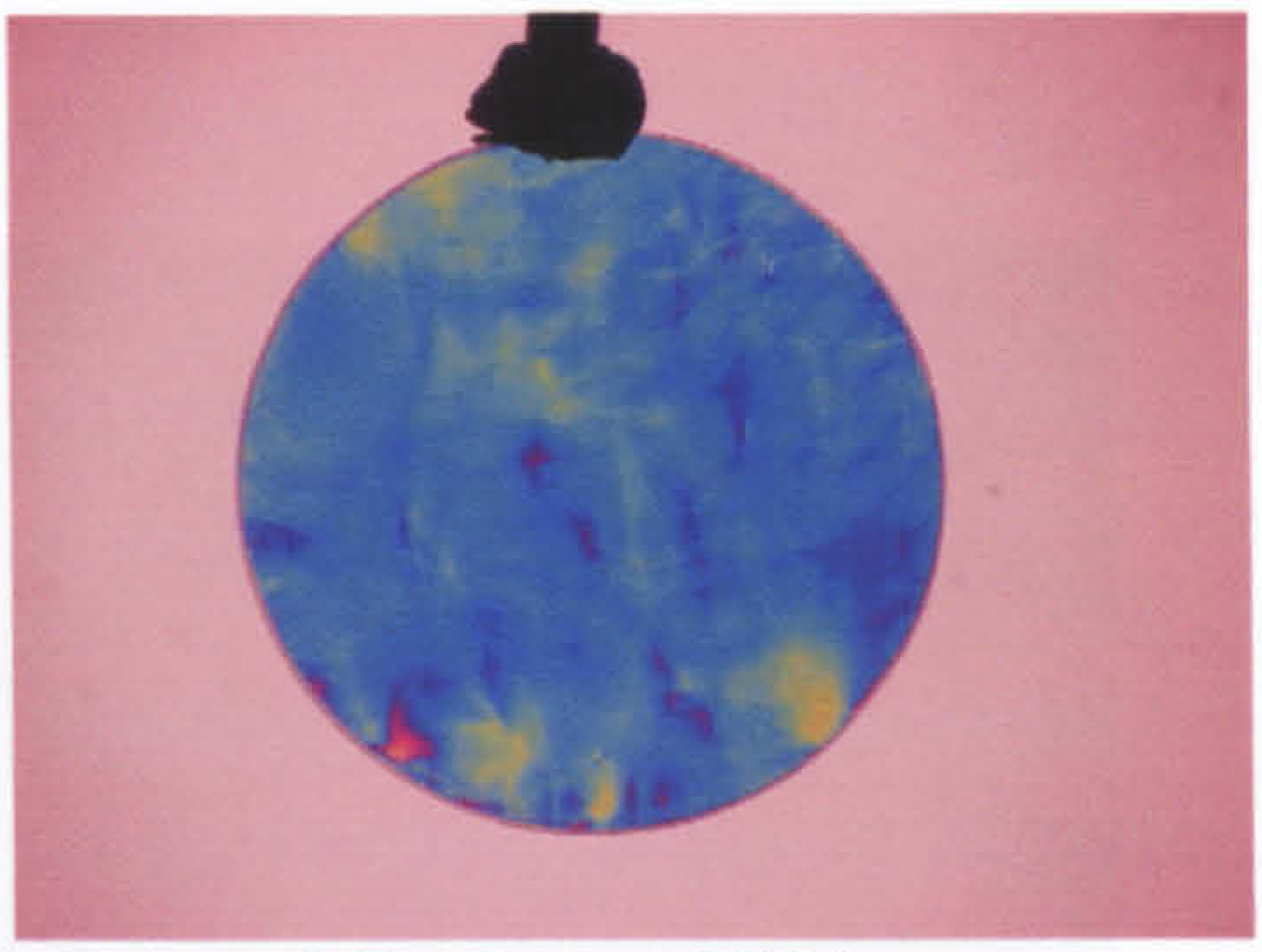


Figure 5.7a 3mm pEVA

Samples of pEVA after heat treatment

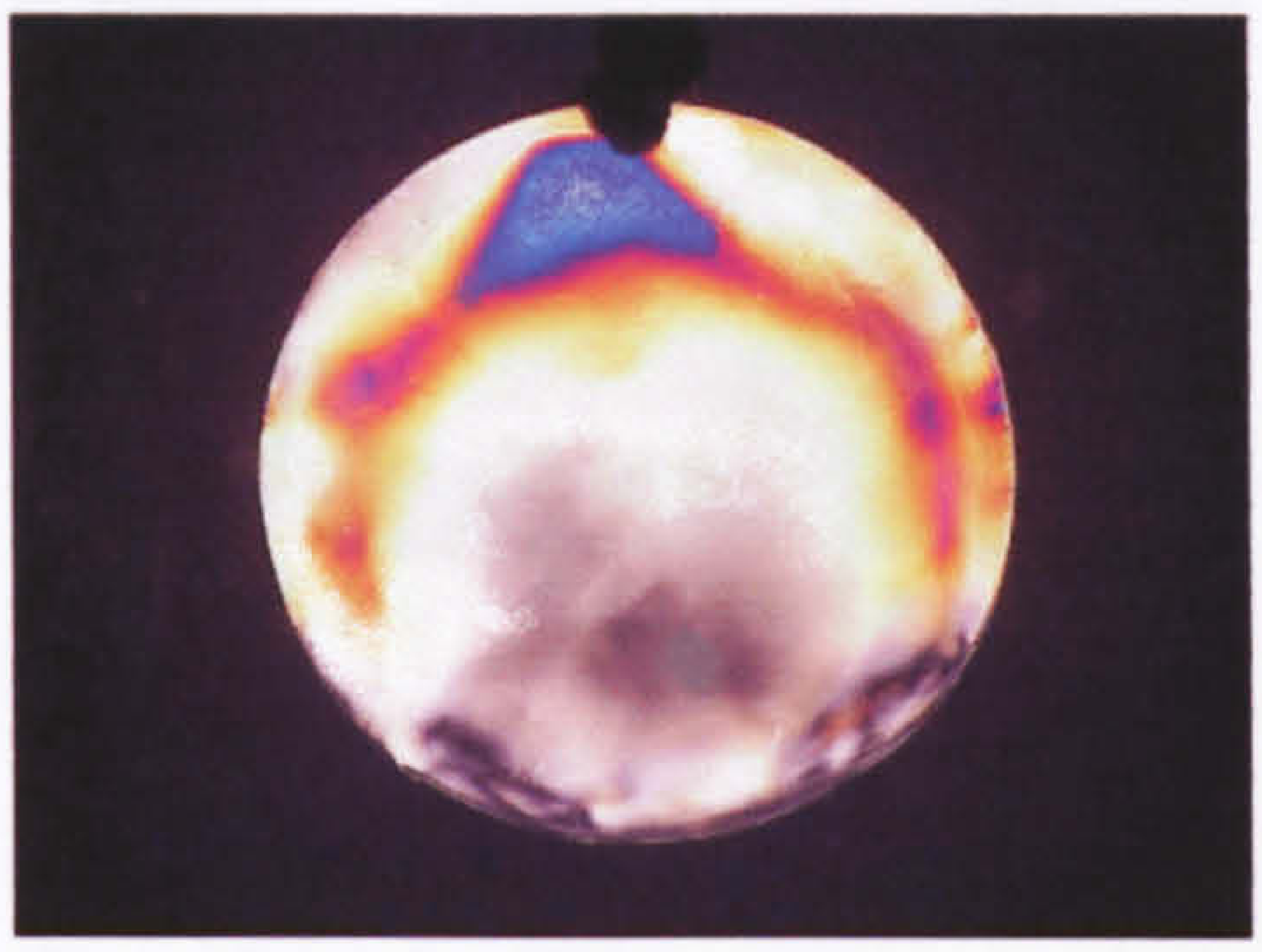


Figure 5.8 5mm pEVA

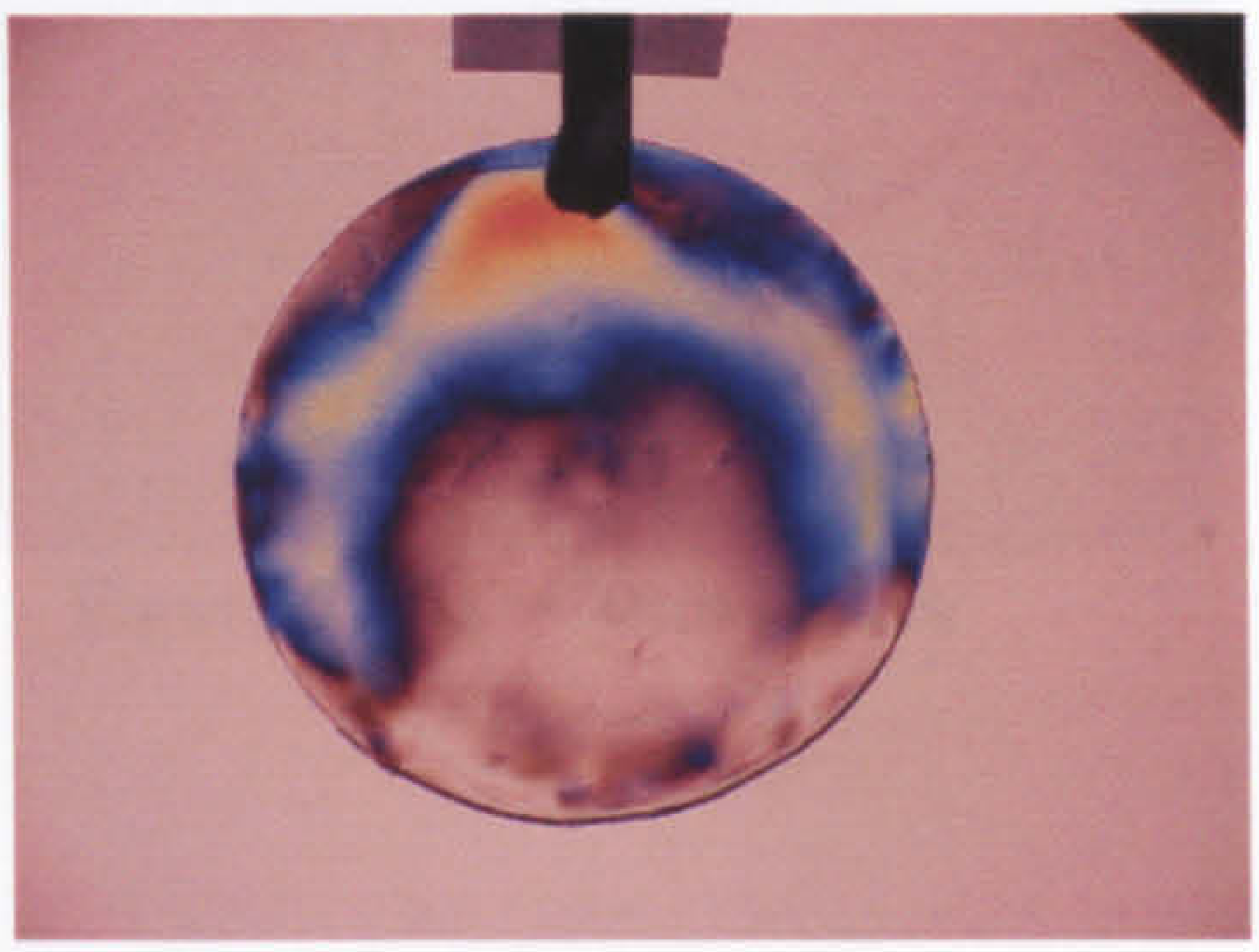


Figure 5.8a 5mm pEVA

There is little or no stress present. Although there are some areas that are brightly coloured and are therefore indicative of stress within the material the overall condition of the samples is one of being relatively stress free. The stress that is present can be largely attributed to the removal of the sample from the mould that it was held in whilst in the oven undergoing the heat treatment process.

Figure 5.9 4mm pEVA

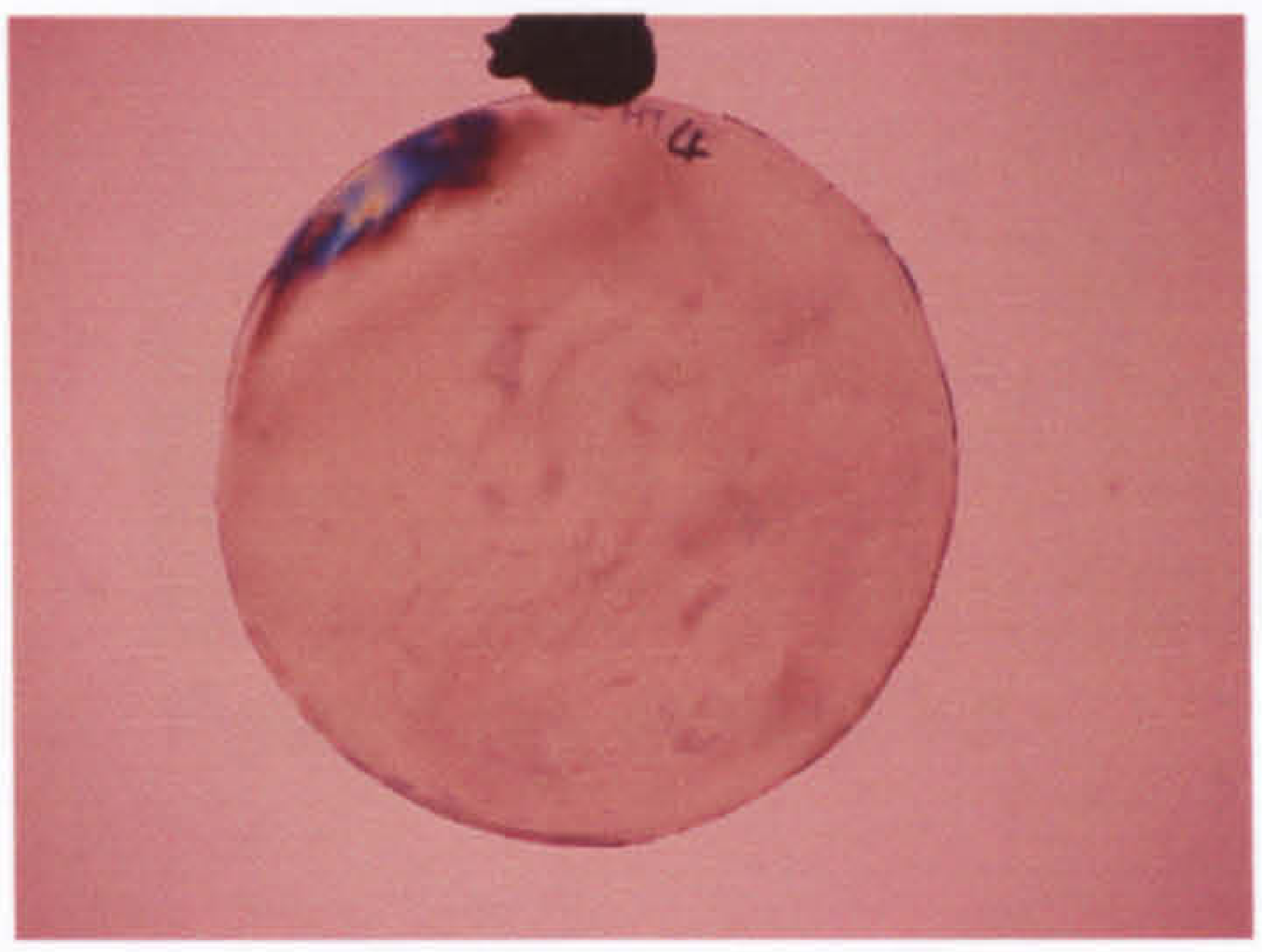


Figure 5.9a 4mm pEVA

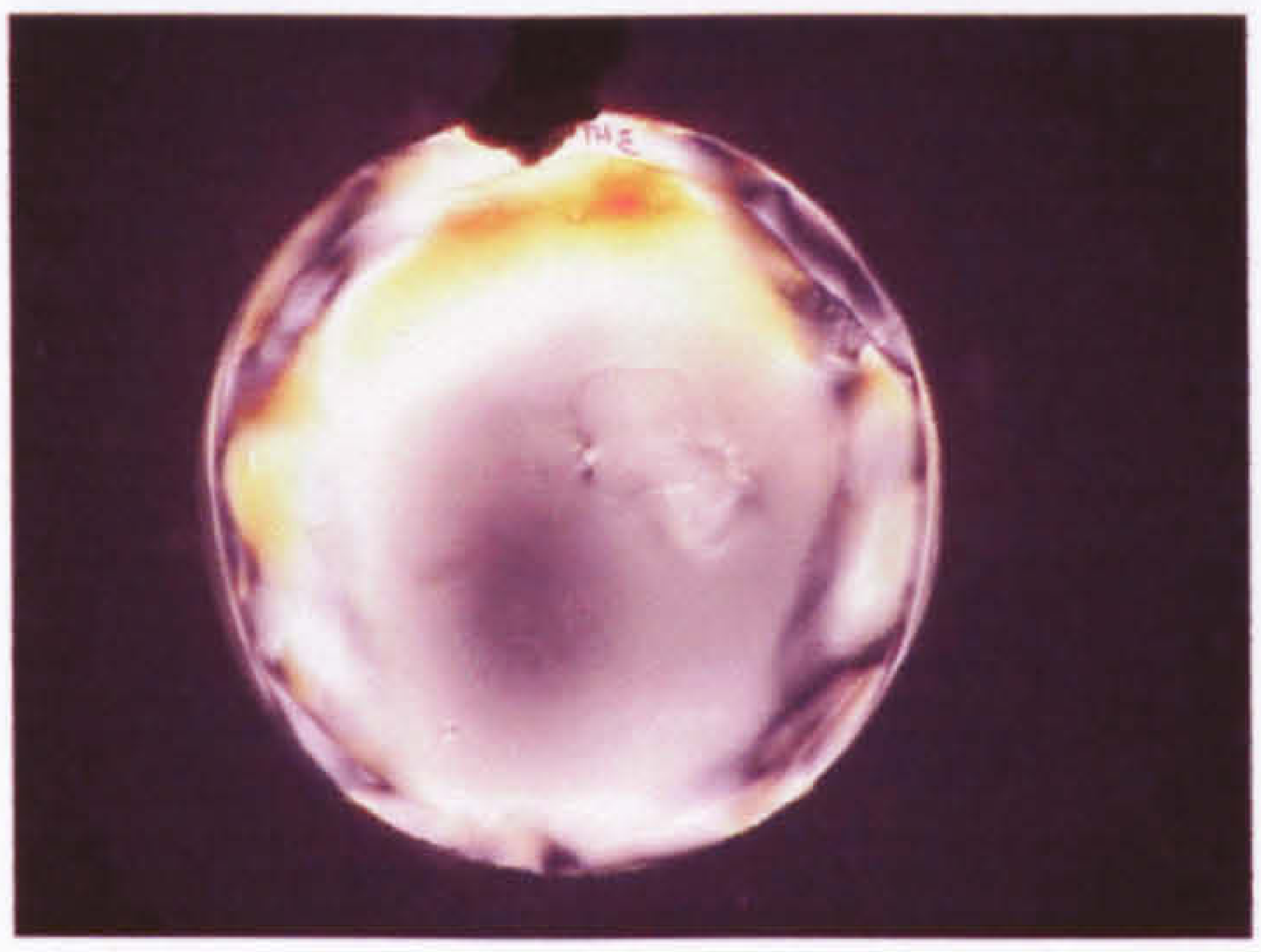


Figure 5.10 3mm pEVA

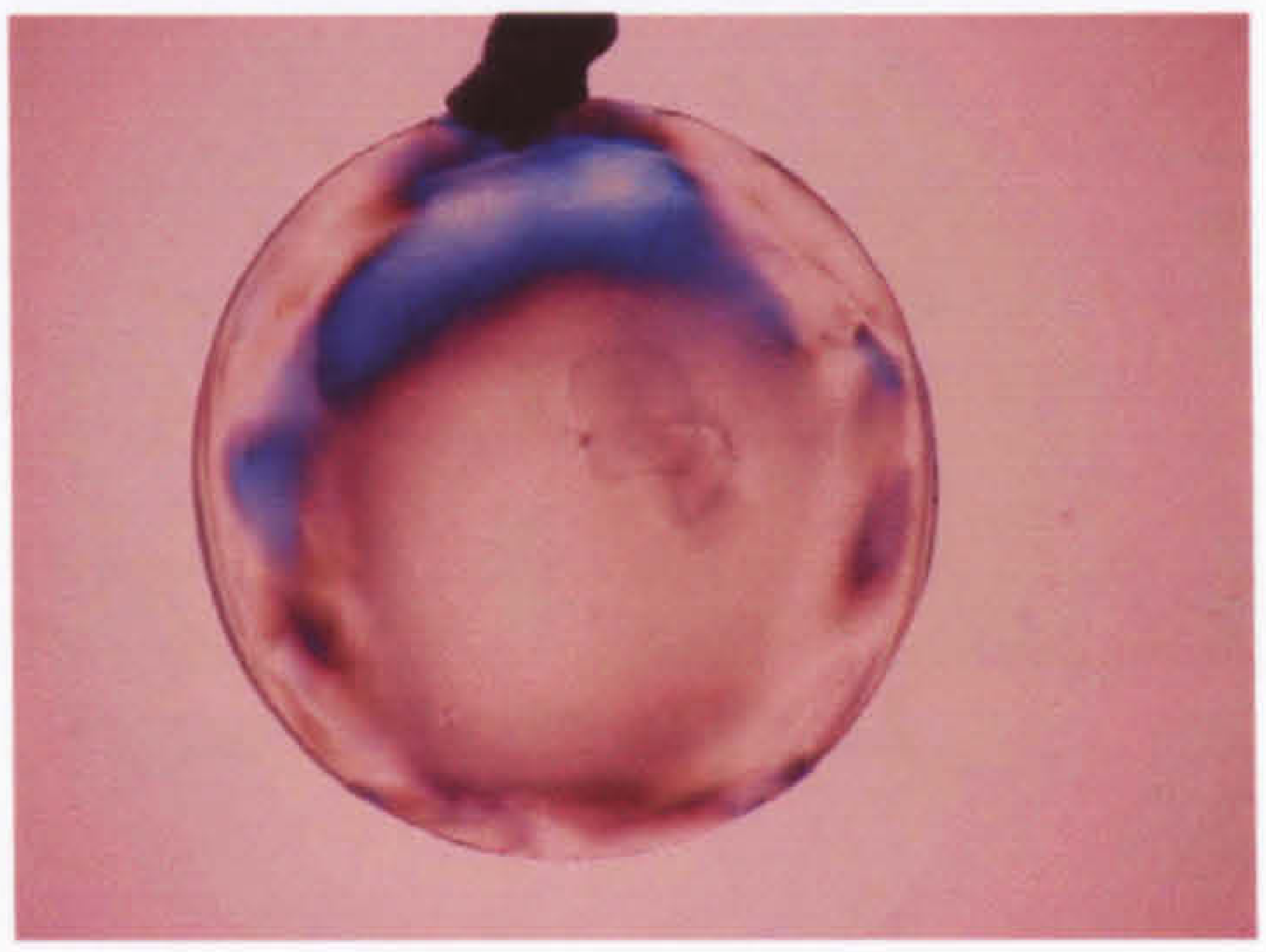


Figure 5.10a 3mm pEVA

Samples of pEVA, as received from the supplier, after impact (Figure 5.11 – 5.13a). Stress is present throughout the material but the colour is now more intense after impact, the level of stress has increased.

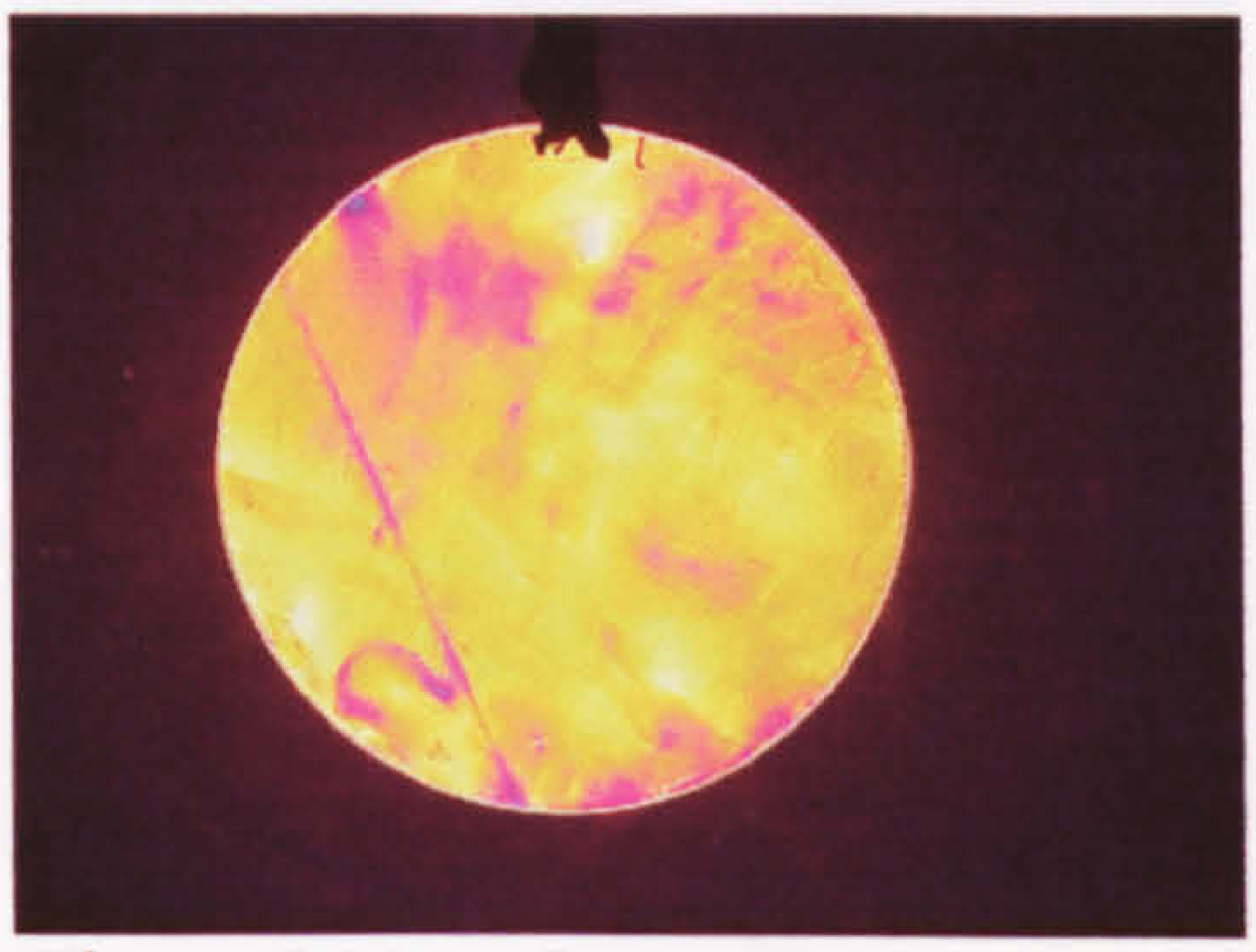


Figure 5.11 5mm pEVA

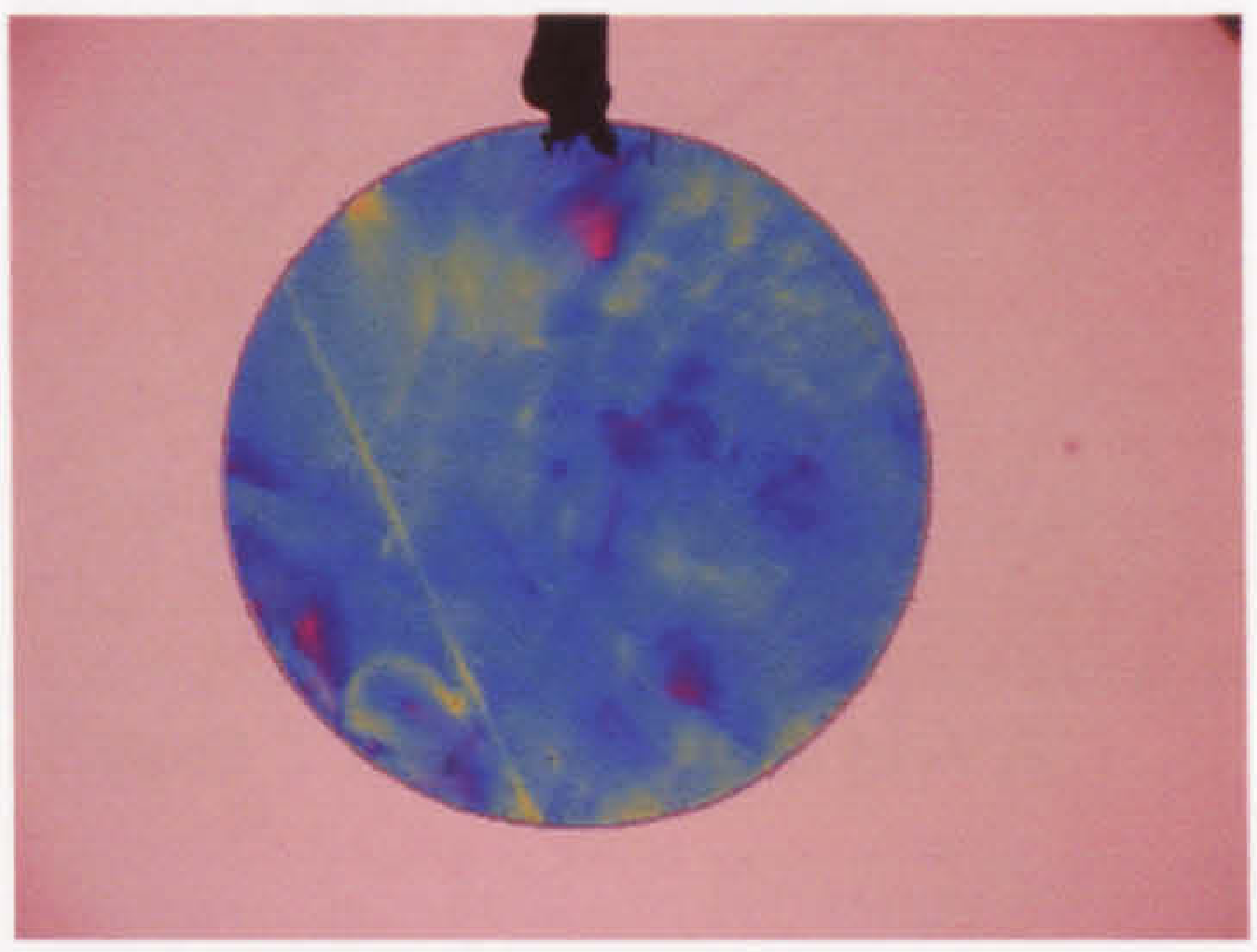


Figure 5.11a 5mm pEVA

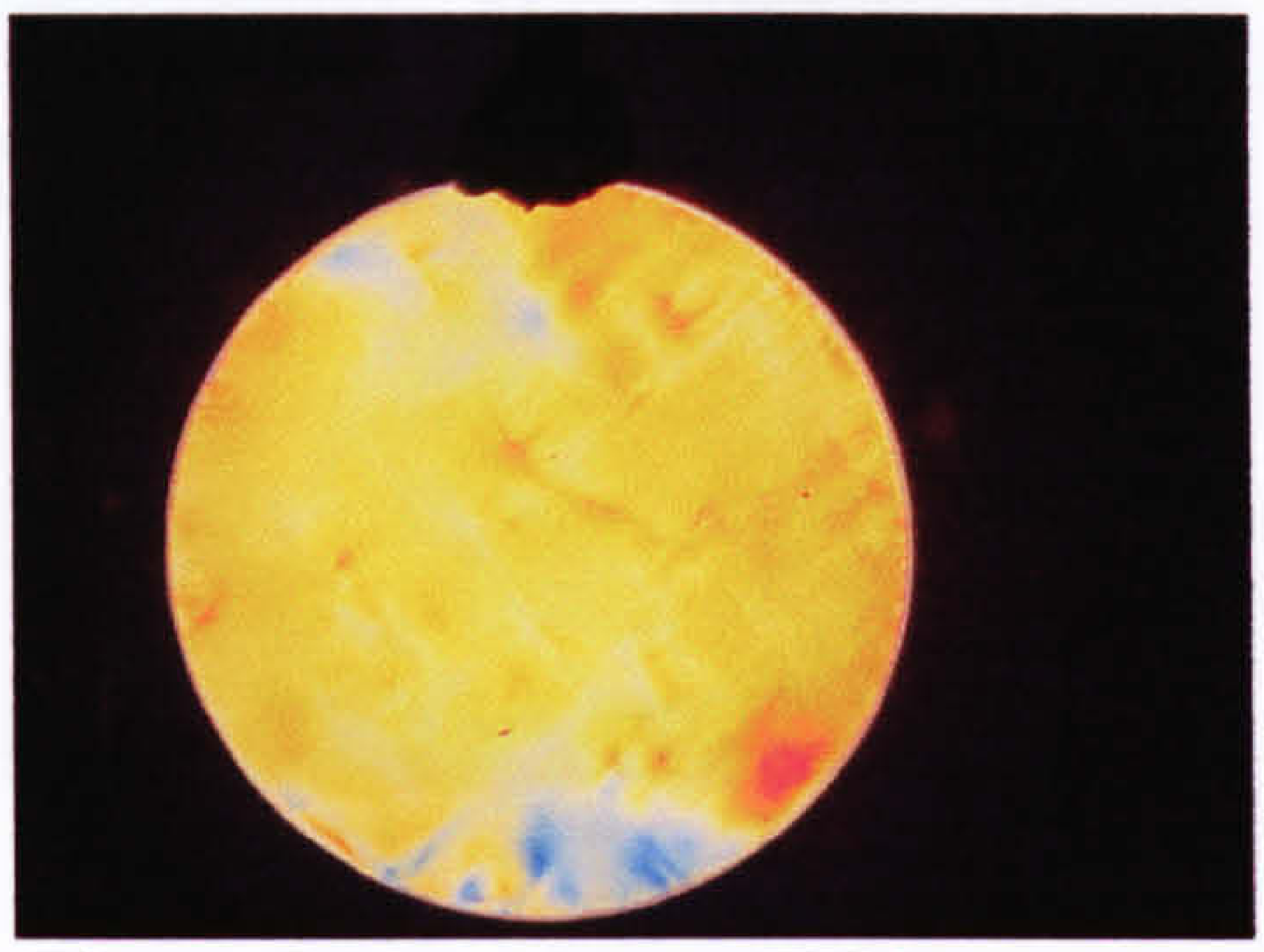


Figure 5.12 4mm pEVA

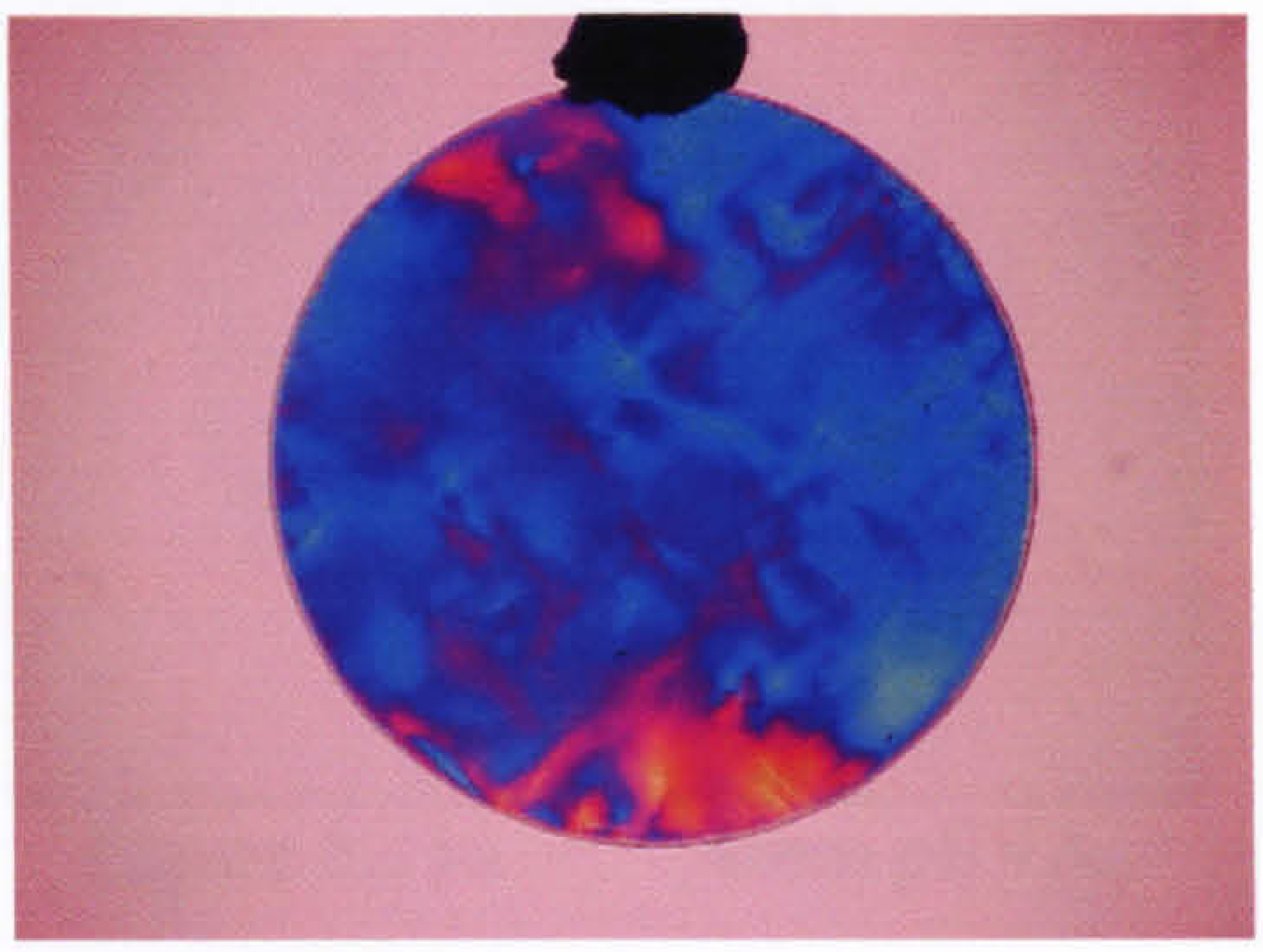


Figure 5.12a 4mm pEVA

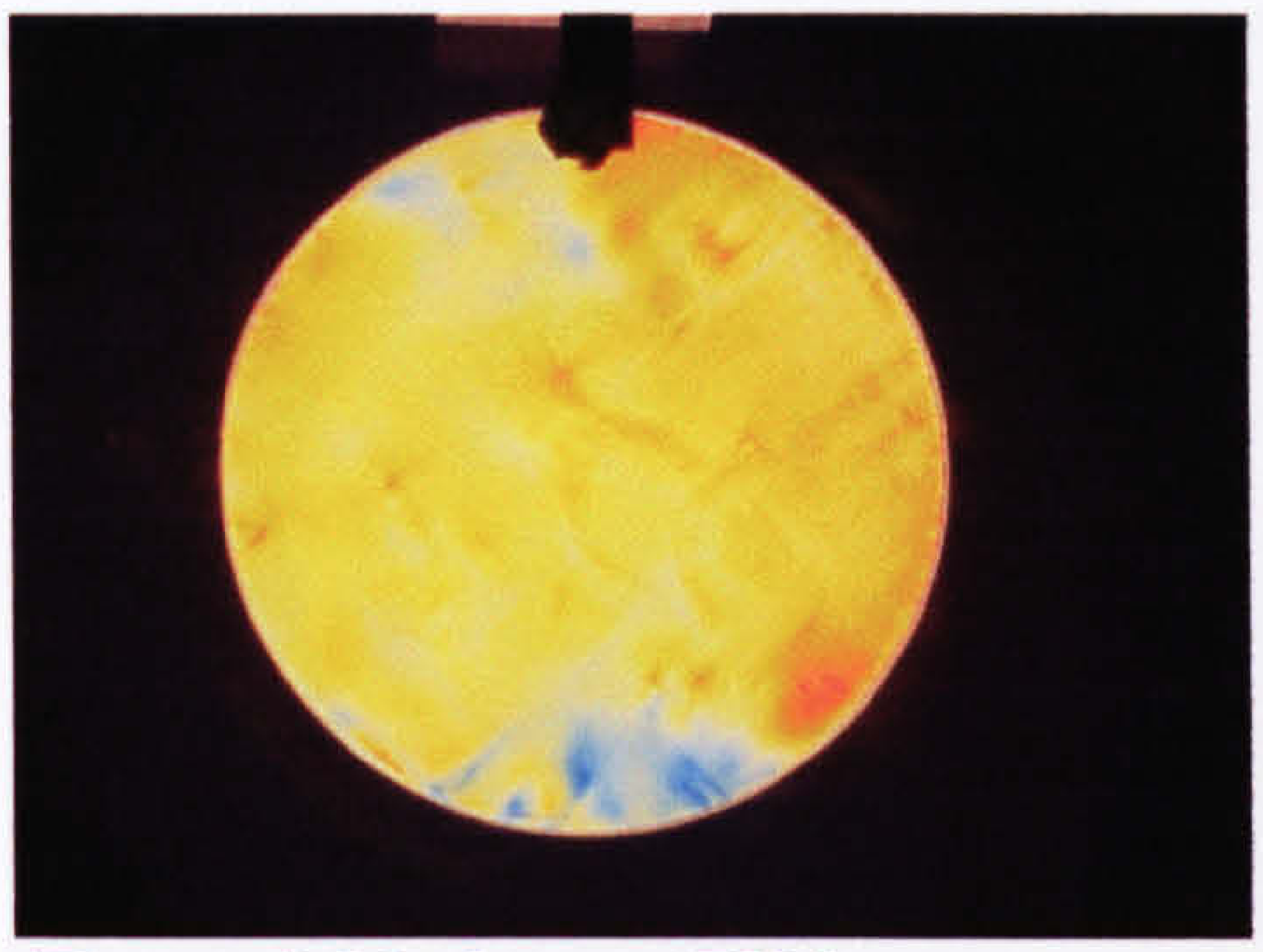


Figure 5.13 3mm pEVA

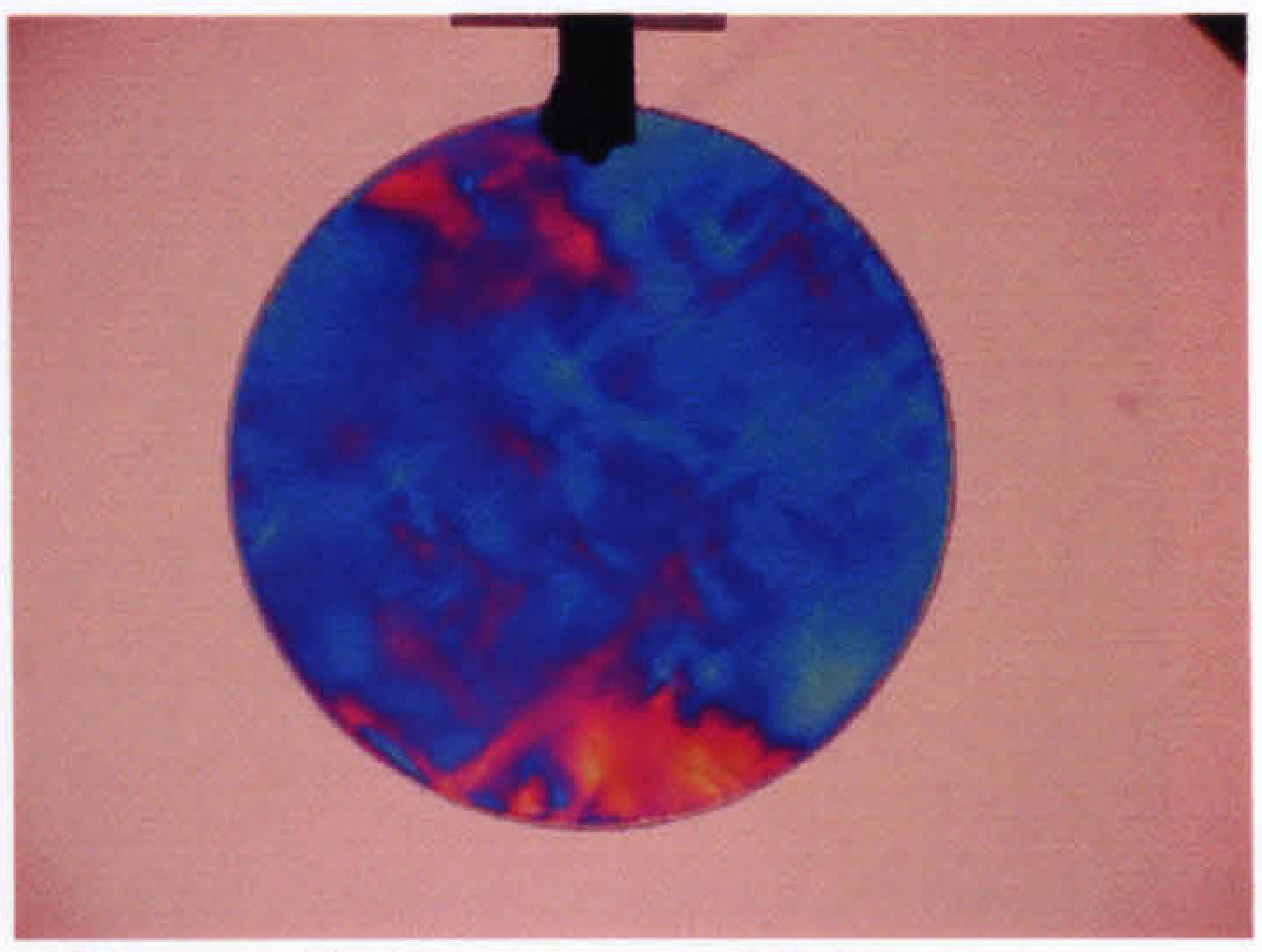


Figure 5.13a 3mm pEVA

5.1.2 Heat treated pEVA polariscope images

After impact – stress is present although not as prevalent when compared to the non-heat treated samples (Figure 5.14 – 5.16a).

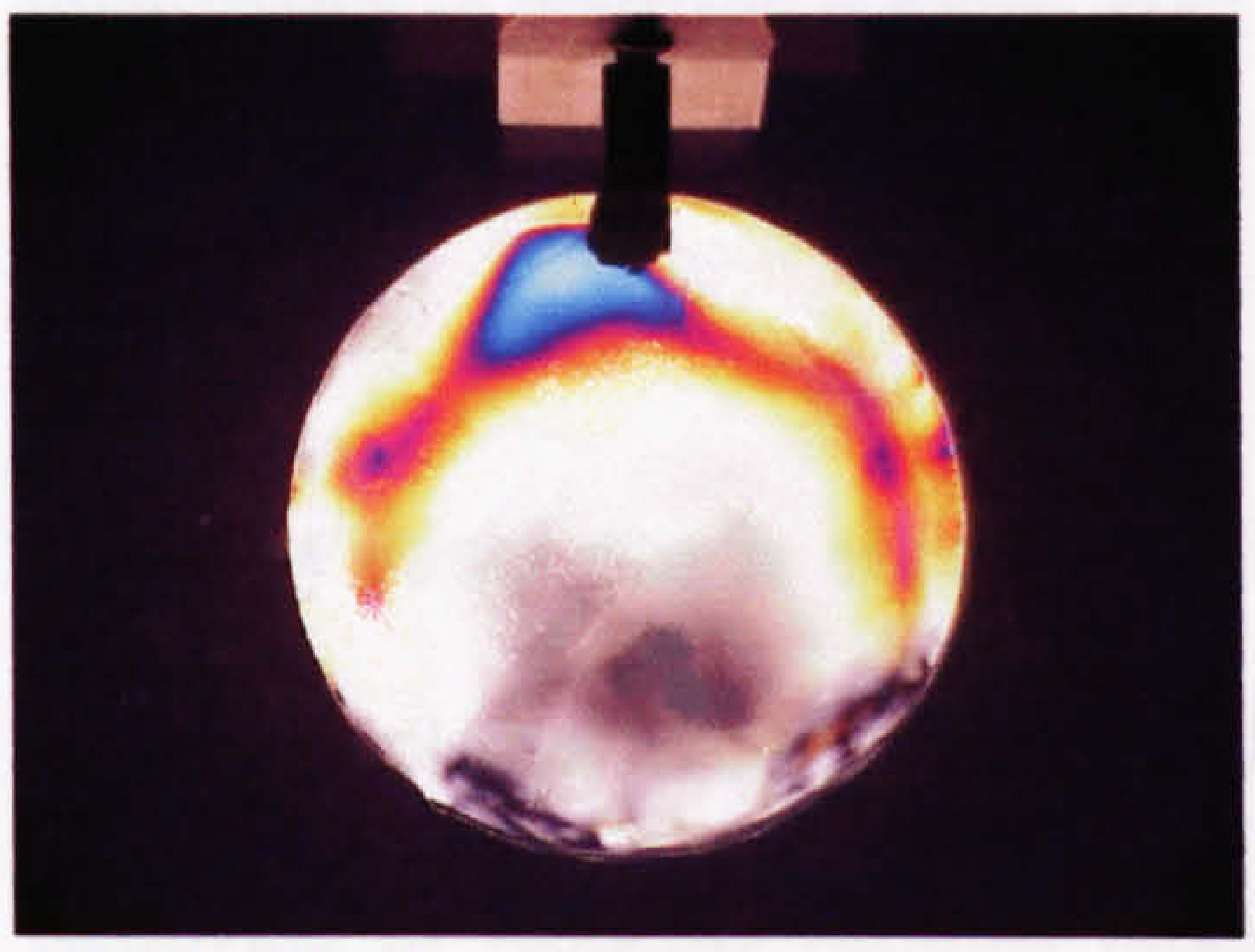


Figure 5.14 5mm pEVA

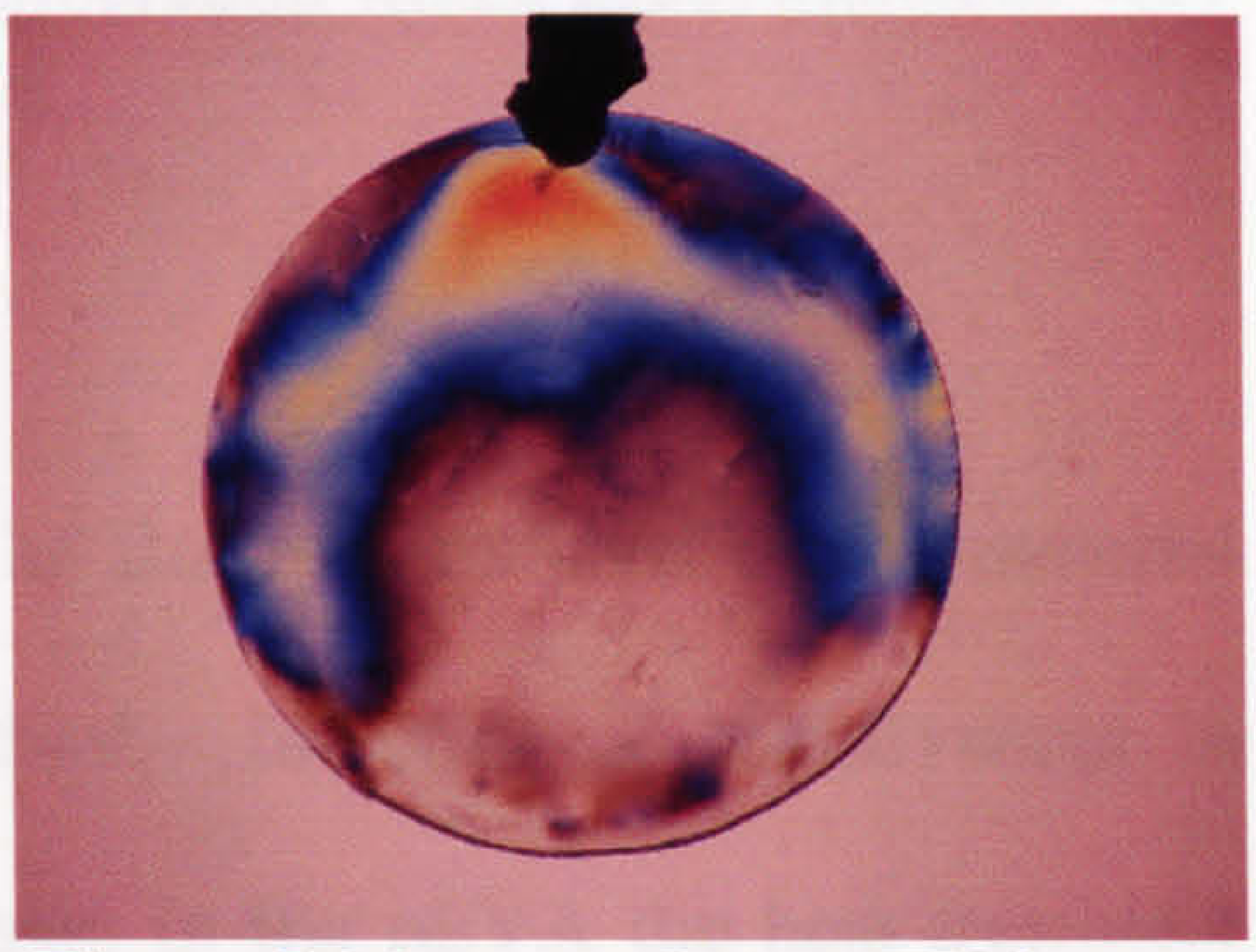


Figure 5.14a 5mm pEVA

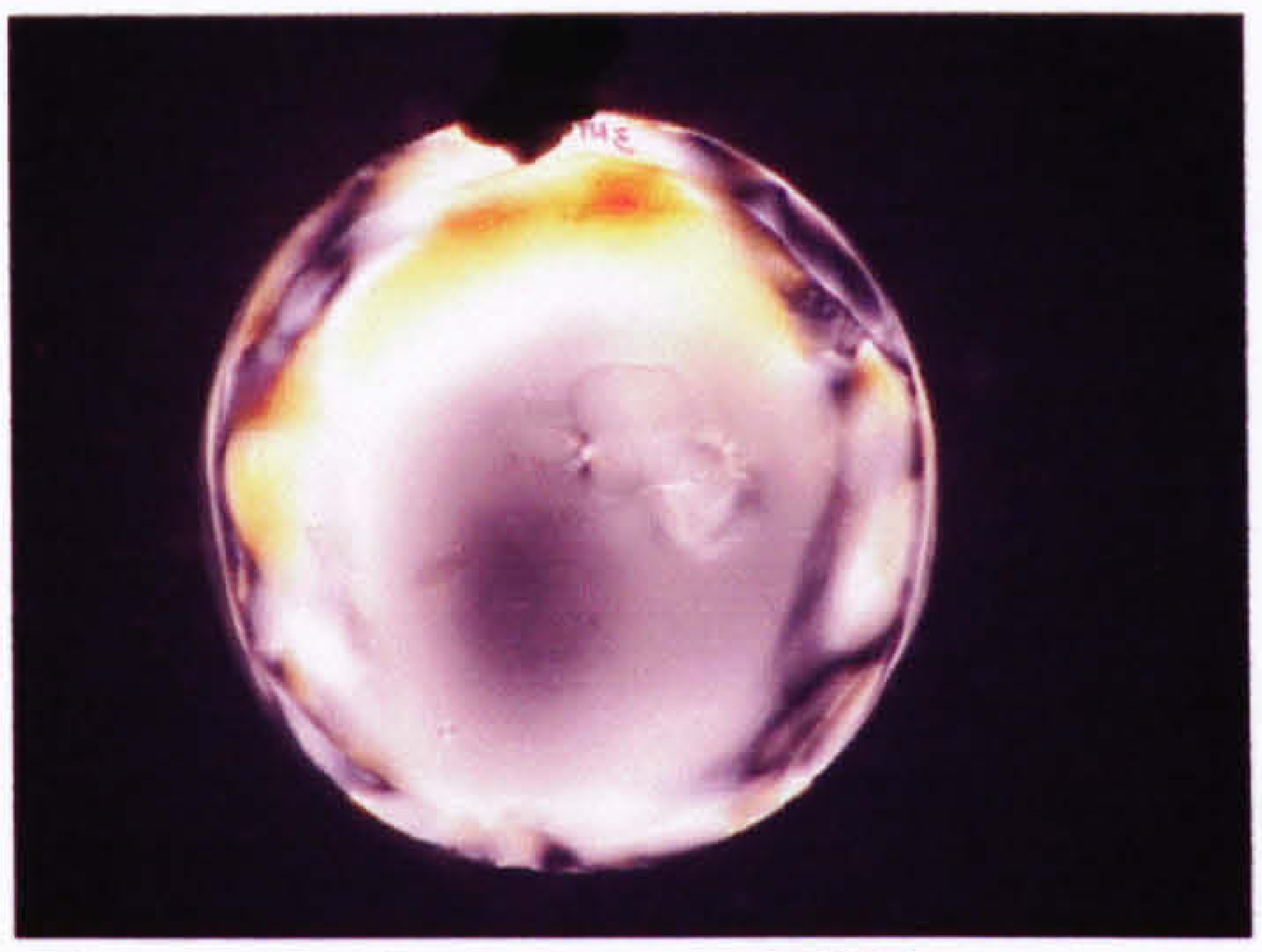


Figure 5.15 4mm pEVA

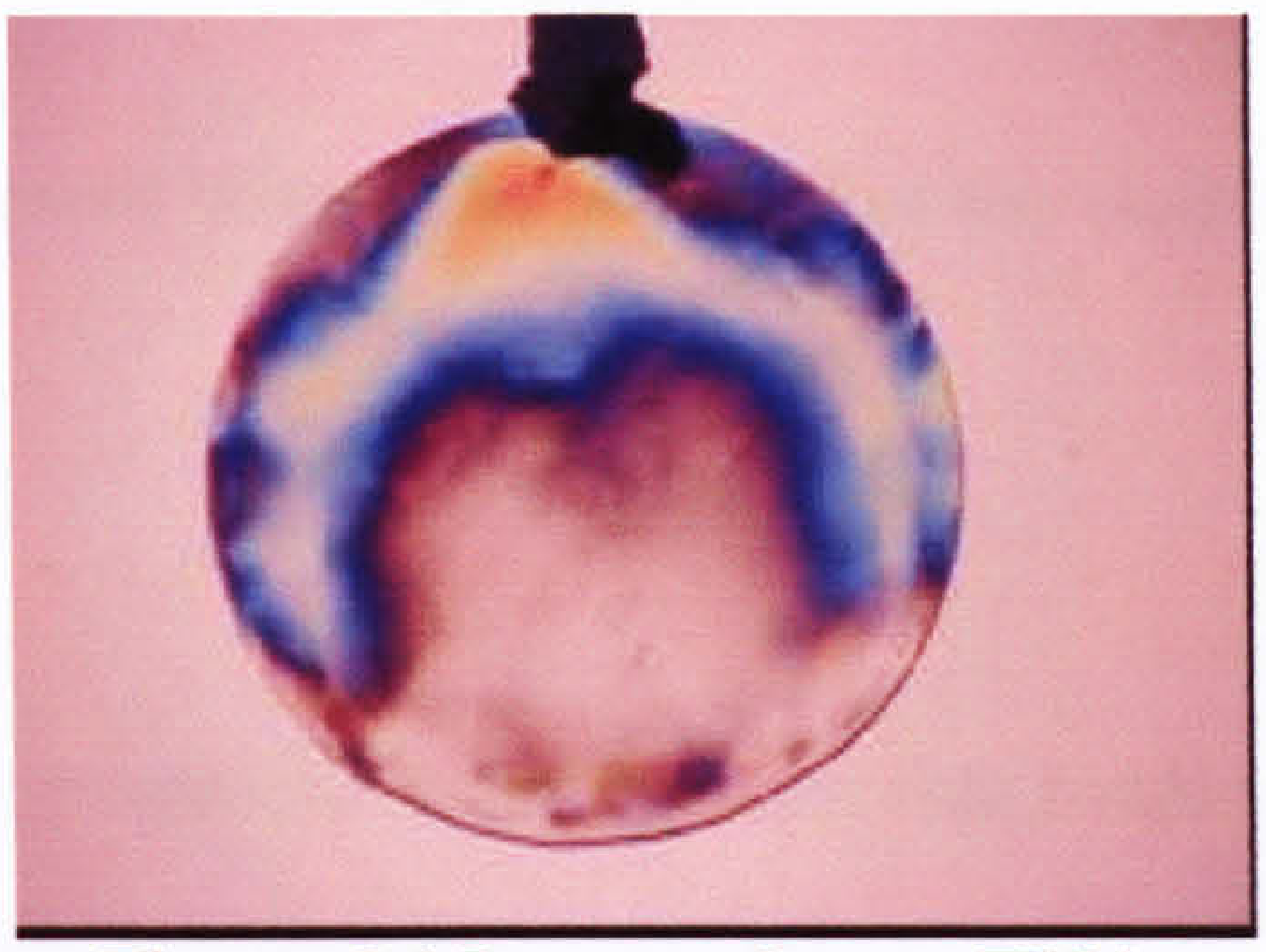


Figure 5.15a 4mm pEVA

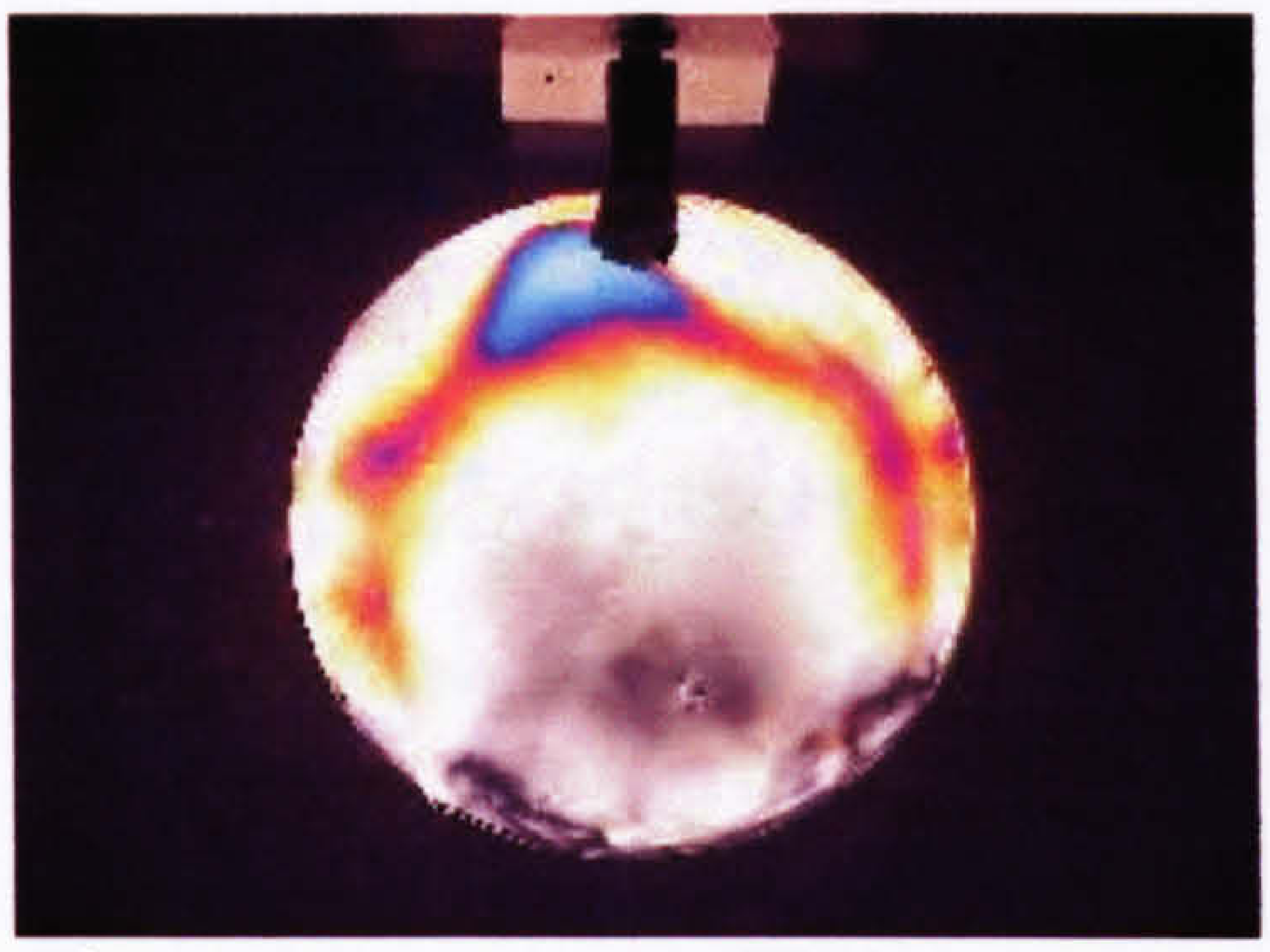


Figure 5.16 3mm pEVA

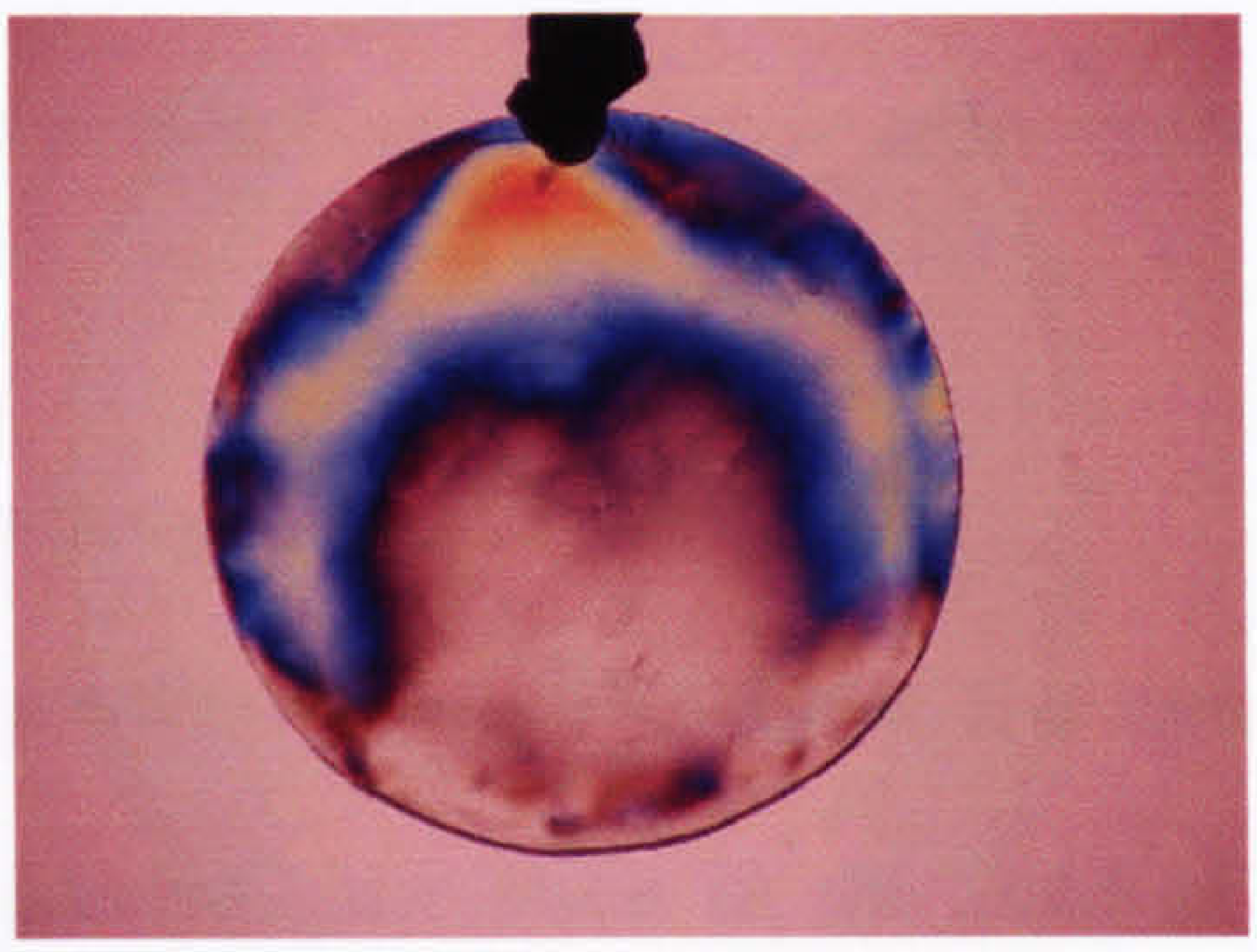


Figure 5.16a 3mm pEVA

When comparing the heat treated with the non-heat treated samples of pEVA it can be seen that the residual stress that was present within the pEVA is eliminated leaving the pEVA, in some cases, with a clear appearance when viewed in the polariscope or showing a white, grey or black colouration which again indicates very low stress.

The only stress that is apparent is thought to be from the removal of the material from the plaster mould after the heat treatment. In terms of effectiveness in removing or reducing residual processing stresses in the pEVA the heat treatment seems to be excellent.

After impact there is still little or no stress present within the material at the point of impact.

From the colours that are present prior to heat treatment it can be seen that there is a uniformity of stress within the material, although there is variation in the colour observed there are no fringes present. After the heat treatment there are fringes that can be observed, due to removal of the pEVA from the mould. The stress is not great in magnitude and the colours that are present only indicate first fringe order stress.

5.1.3 Mouthguards observed in the polariscope.

To observe the effects of the manufacturing process on the pEVA sheets five samples were put through various stages of the process then place in the field of the polariscope.

Sample 1

The pEVA was formed onto the model and then the model removed, no further processes were used.

Sample 2

The pEVA was formed onto the model and then the model removed. A heated scalpel was then used to cut the basic mouthguard shape from the blank.

Sample 3

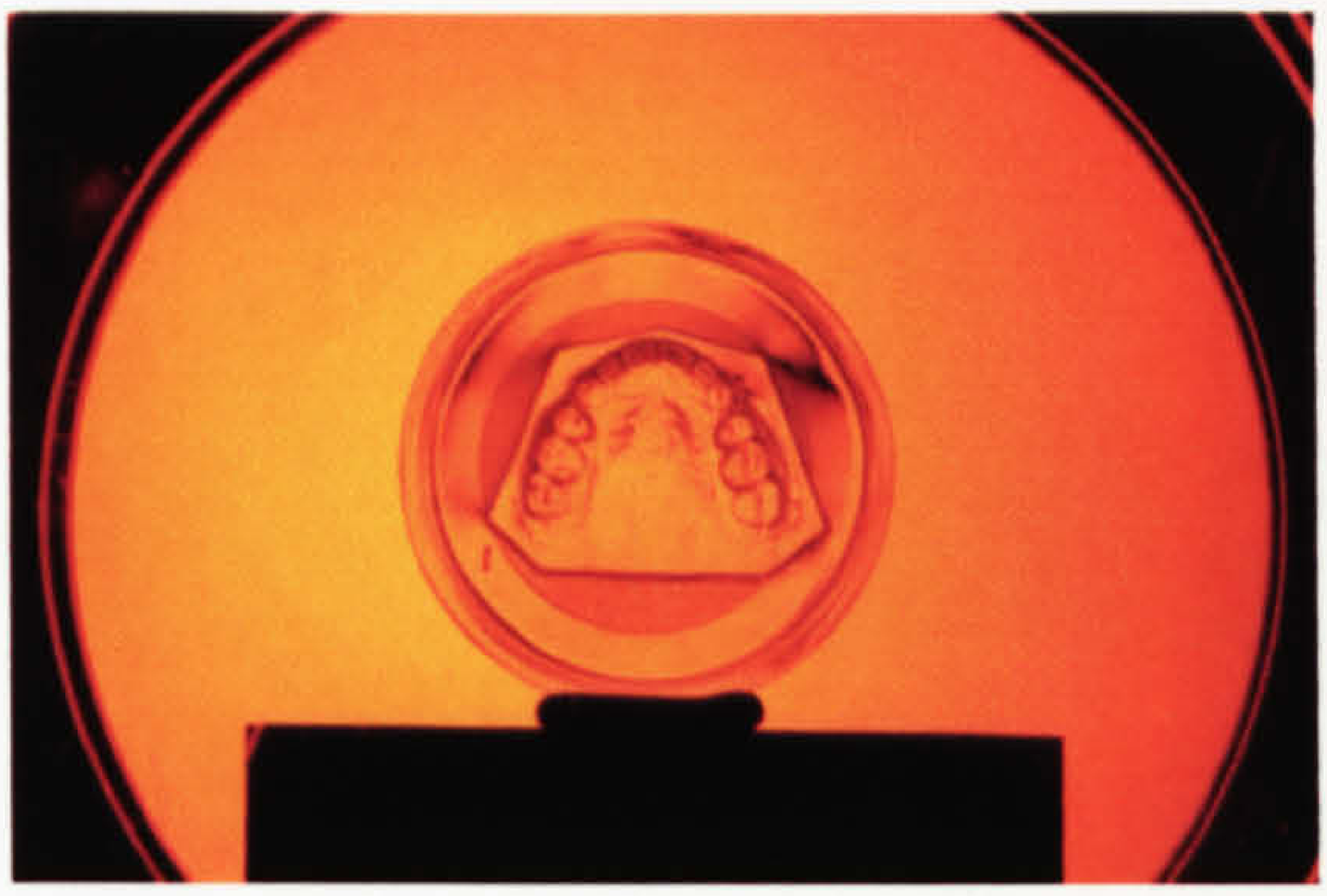
The pEVA was formed onto the model, the model removed, a heated scalpel was then used to cut the basic mouthguard shape from the blank and the mouthguard was trimmed with a tungsten carbide bur followed by a smooth stone to eliminate the roughness left by the tungsten carbide bur.

Sample 4

All the aforementioned stages were completed and then the mouthguard's edges were smoothed using chloroform.

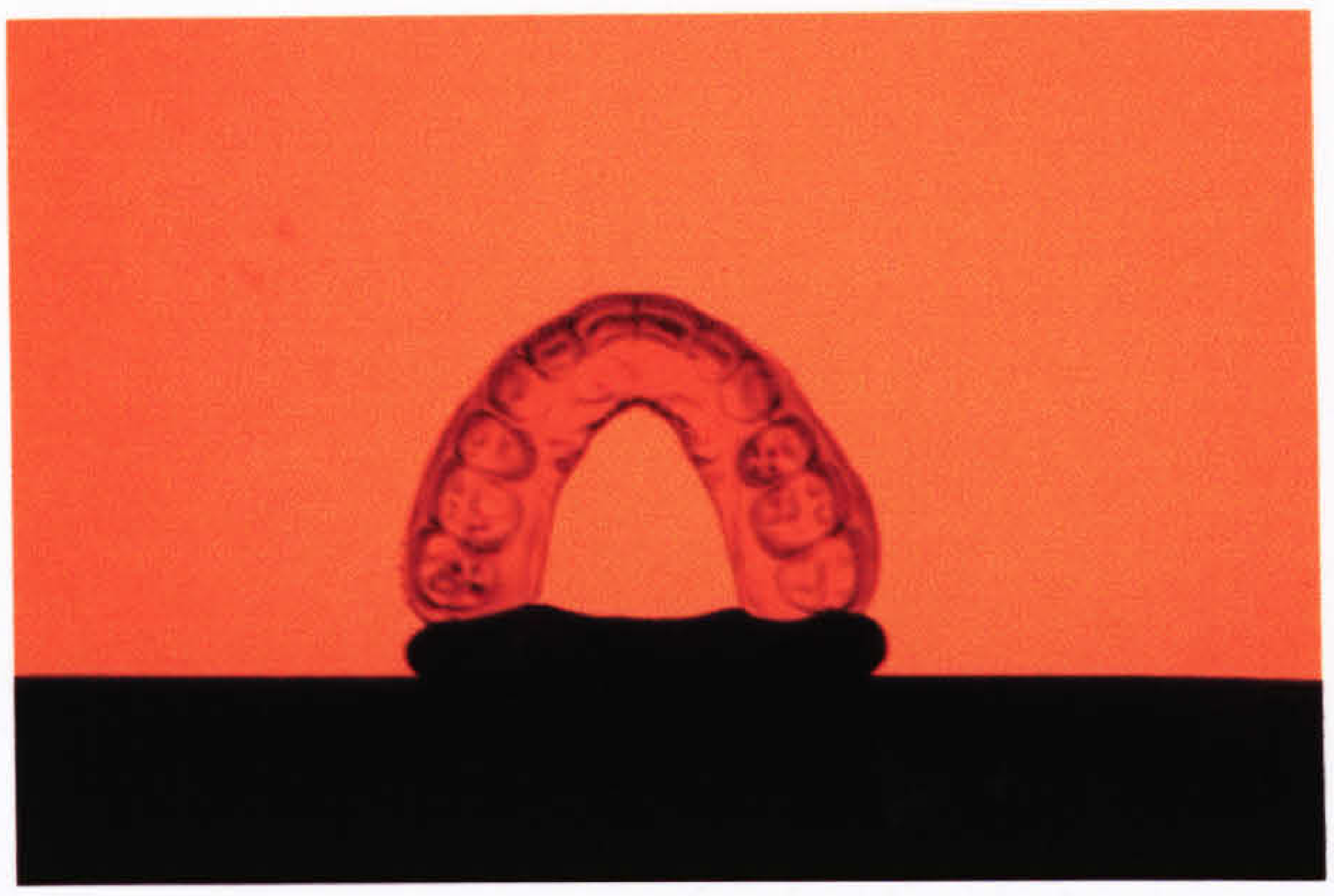
Sample 5

All the aforementioned stages were completed and then the mouthguard's edges were carefully smoothed using an open flame of a soldering torch to mely away the roughness.



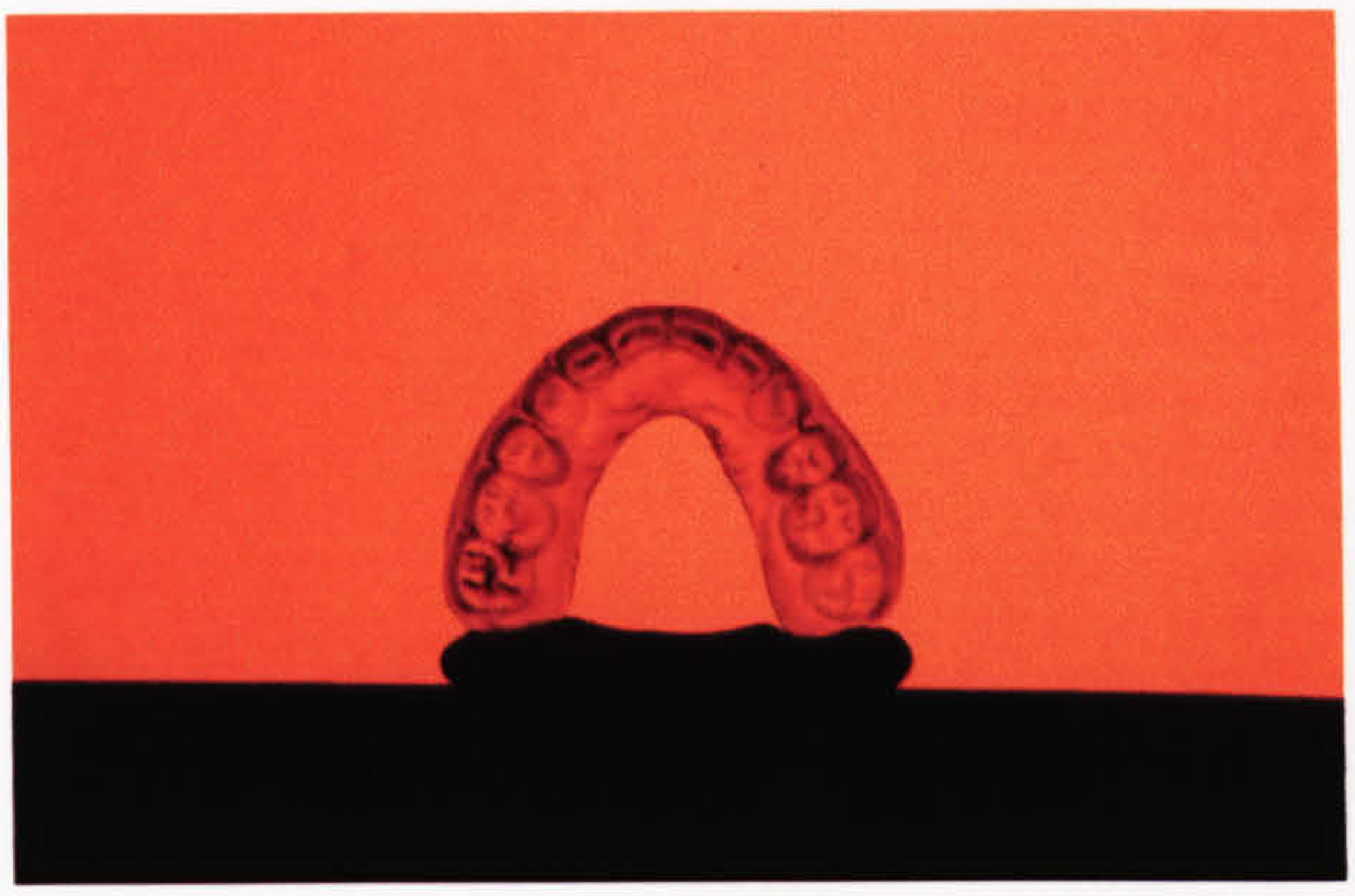
Sample 1

Stress can be seen at the edge of the base of the model, along the incisor tips and on the buccal cusps of the posterior teeth.



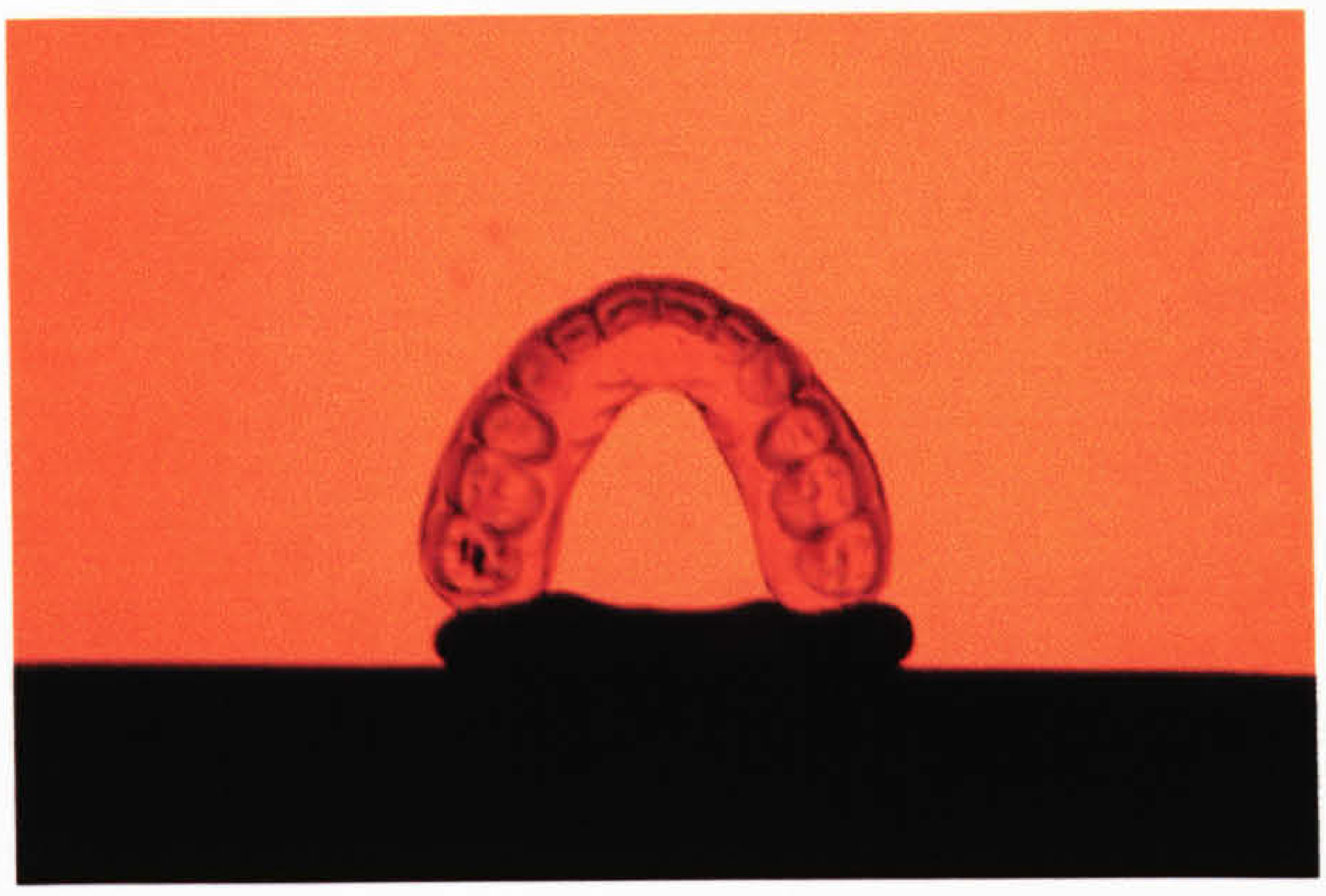
Sample 2

Stress can be seen at the periphery of the mouthguard, along the incisor tips and on the buccal cusps of the posterior teeth.



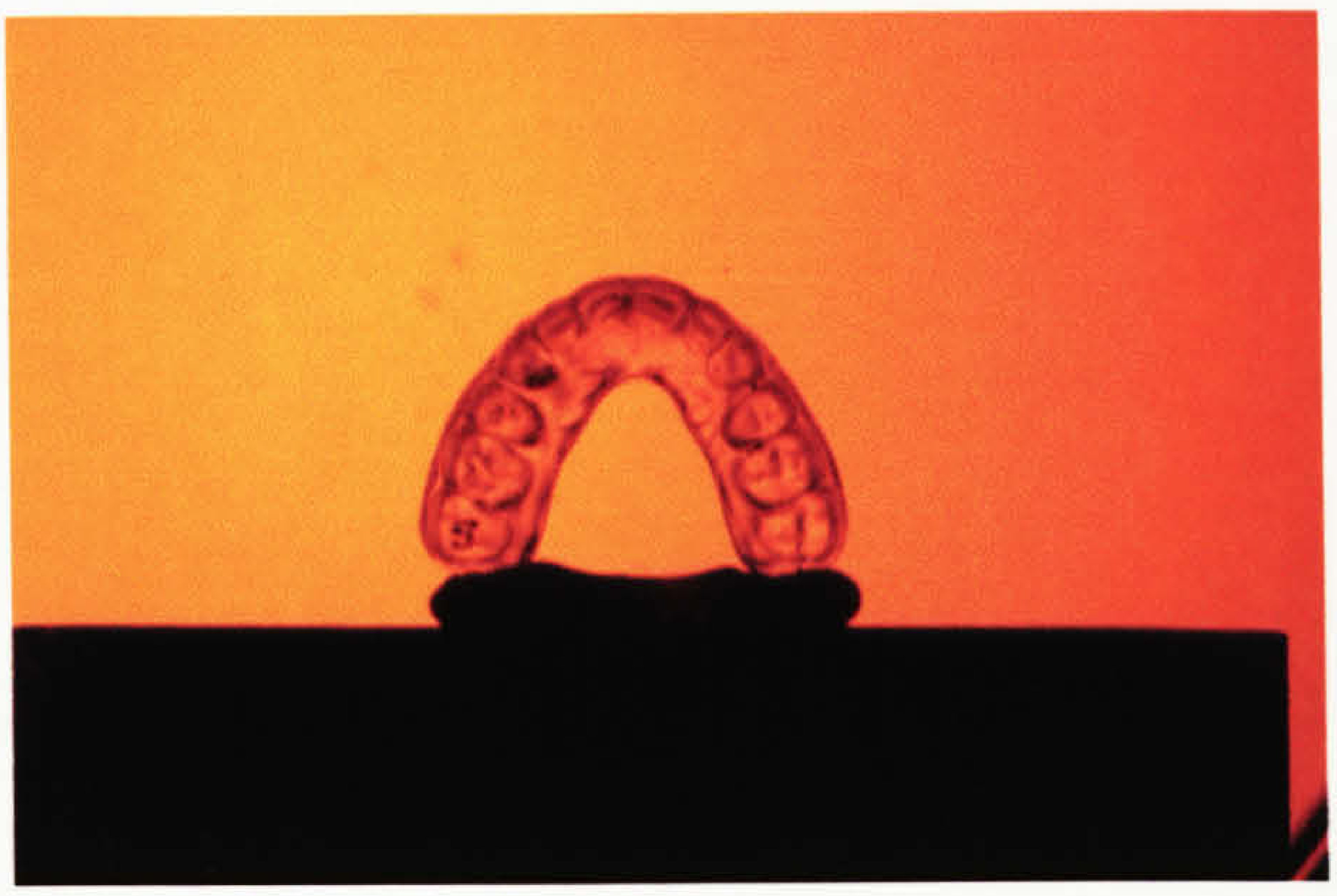
Sample 3

Stress can be seen at the periphery of the mouthguard, along the incisor tips and on the buccal cusps of the posterior teeth.



Sample 4

Stress can be seen at the periphery of the mouthguard, along the incisor tips and on the buccal cusps of the posterior teeth.



Sample 5

Stress can be seen at the periphery of the mouthguard, along the incisor tips, on the palatal and buccal cusps of the posterior teeth. In this case there is more stress at the periphery and throughout the whole of the mouthguard, this can be judged by the extent of the appearance of blackness throughout the image.

5.2 Impact test results

The results from the instrumented impact test rig were converted into force/time and displacement /time plots that could easily be compared using Microsoft Excel. The histories of each indicate, visually, the extent and duration of the impact event and the tabulated results are also presented.

5.2.1 Reproducibility of impact test

To ensure that the impact tests that were being carried out on all test samples were accurate a simple reproducibility test was carried out. However, prior to any discussion on error measurement two terms used in statistical analysis need to be defined: validity and reproducibility. Validity is the extent to which, in the absence of measurement error, the value obtained represents the impact. The term accuracy may also be used in this way. Reproducibility, or precision, is the closeness of successive measurements of the same impact on the same material. The term reliability is sometimes used as a synonym for reproducibility, but it may also be used in a broader sense to encompass both validity and reproducibility.

In this instance five separate sheets of non-heat treated 5mm pEVA were impact tested under exactly the same test conditions as each other (Table 5.1). All the material was from the same batch received from the supplier, the clamping conditions of the material and the drop height (0.5m) of the indentor was the same for each impact event. From the results tabled below it can be seen that both the repeated impact force and the repeated displacement of each 5mm sheet of pEVA are within acceptable limits – standard deviation of the impact force = 4N, and standard deviation of the displacement = 1mm. This is to say that the test has proved to be easily reproducible and that each individual test on the material represents the materials genuine response therefore negating repeated tests on each set of samples and each set of different materials. Typical impact/time and displacement/time histories for 5mm pEVA can be seen in Figure 5.17.

Table 5.1 Repeatability test on non-heat treated 5mm pEVA

Material	Peak Force, N	Peak Displacement, mm
5mm pEVA	164	18
5mm pEVA	163	20
5mm pEVA	161	19
5mm pEVA	155	17
5mm pEVA	155	19
Mean	160	19
Standard deviation	4	1

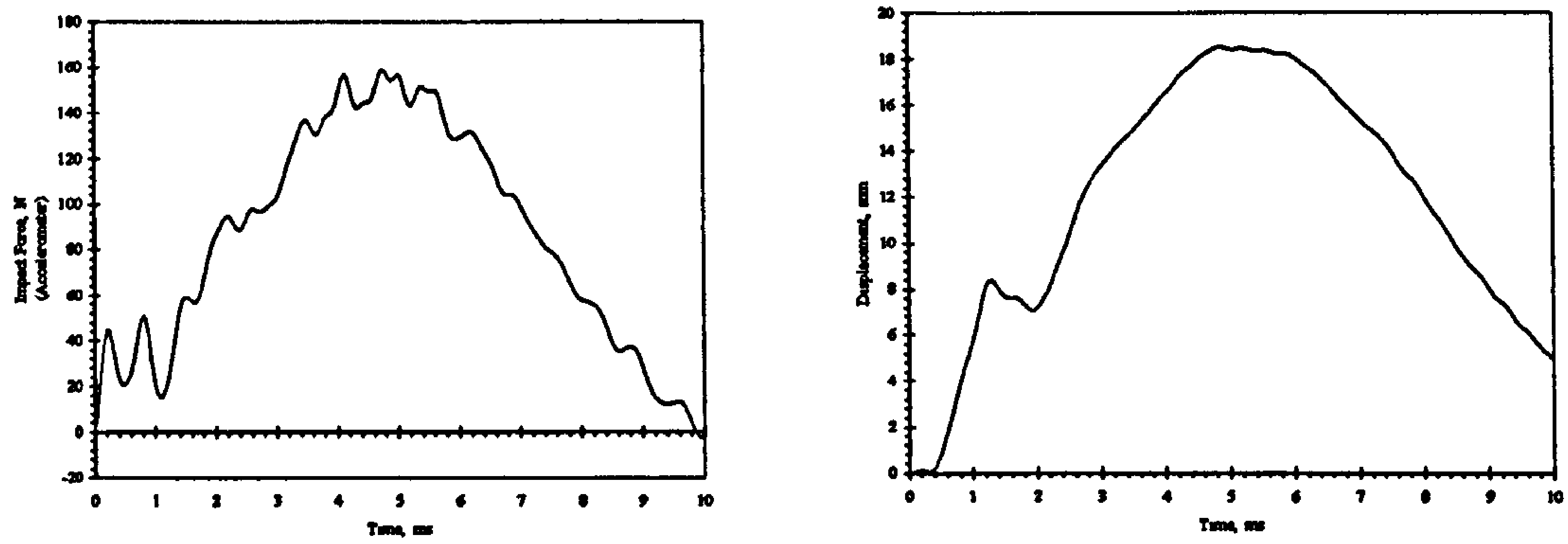


Figure 5.17 Typical impact/time and displacement/time histories for 5mm pEVA

It can be seen from Figure 5.17 that the impact event for the 5mm pEVA takes place over a relatively long period of time, in excess of 10ms, but the material is distorting by a very large amount.

5.2.2 Effects of heat treatment on pEVA

While the force transmitted through the pEVA has remained about the same for the heat treated sample the amount of deformation has increased dramatically, the heating process producing a softening anneal on the pEVA (Table 5.2).

Table 5.2 Effects of heat treatment on peak force and displacement.

Heat treated and non heat treated pEVA		
Material	**Force, N**	**Displacement, mm**
Heat treated 5mm pEVA	135	30
Untreated 5mm pEVA	160	18.5

The heating of the pEVA during the manufacturing process associated with producing mouthguards has a direct influence on the way in which the mouthguard material (pEVA) reacts to an impact force. This can be seen in the displacement and transmitted impact force associated with an impact event (Figure 5.18 – 5.18a).

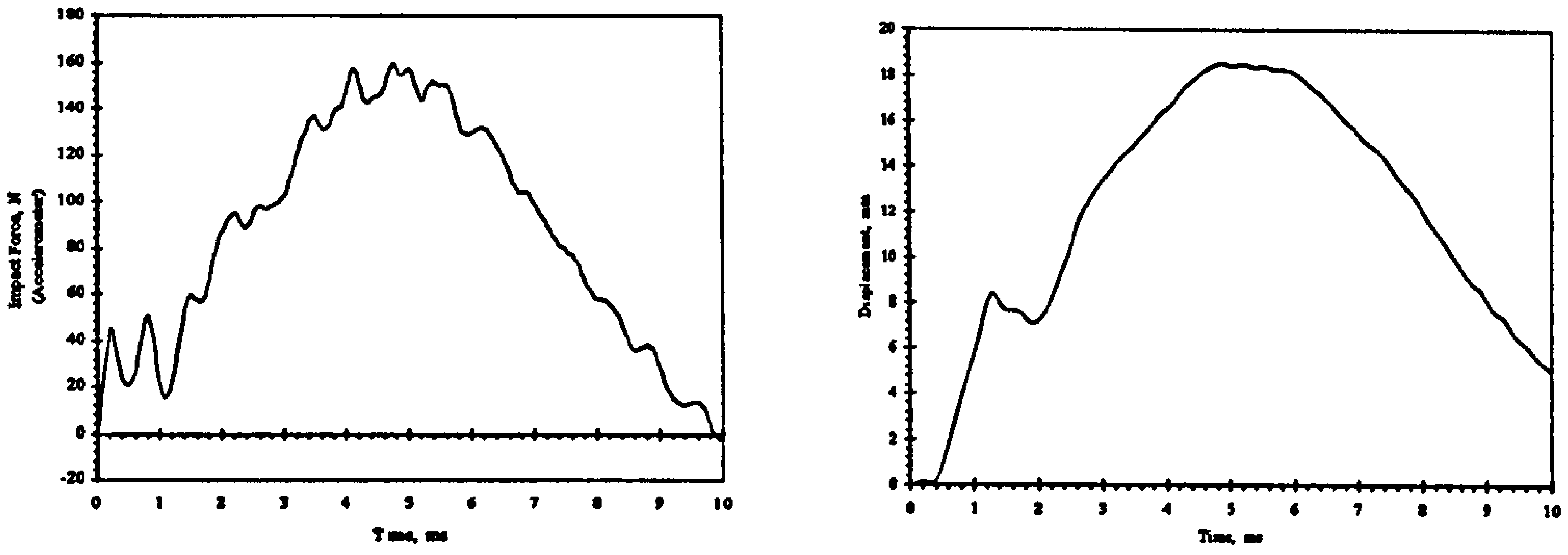


Figure 5.18 Non- heat treated pEVA

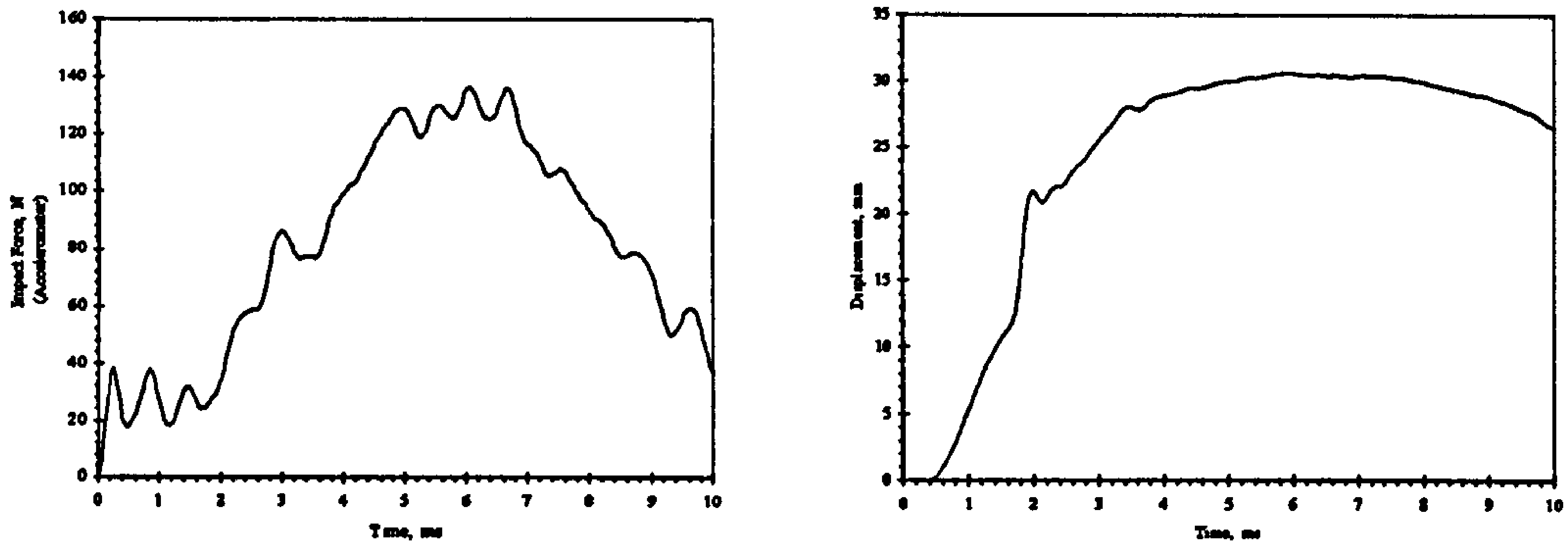


Figure 5.18a Heat treated pEVA

The force/time and displacement/time plots demonstrate the extent of the physical change that has taken place within the EVA. The calculated displacement has increased significantly, >66%, (untreated EVA>18mm centre displacement, heat treated EVA >30mm centre displacement). Peak Impact Force (PIF) was also reduced in the heat treated sample (PIF<140N) compared to that of untreated EVA (PIF=160N).

5.2.3 Effect of thickness

From tests carried out on varying thickness pEVA sheets it can be seen that as the thickness increases so does the amount of absorbed impact force and that the displacement decreases (Table 5.3). This is exactly what would be expected of any material. As Figure 5.19 illustrates as pEVA thickness increases the trend for peak force increases and displacement decreases.

Table 5.3 Effect of thickness of non-heat treated pEVA on peak force and displacement.

Material	Force, N	Displacement, mm
1mm pEVA	112	38
2mm pEVA	124	28
3mm pEVA	135	25
4mm pEVA	128	19
5mm pEVA	165	19

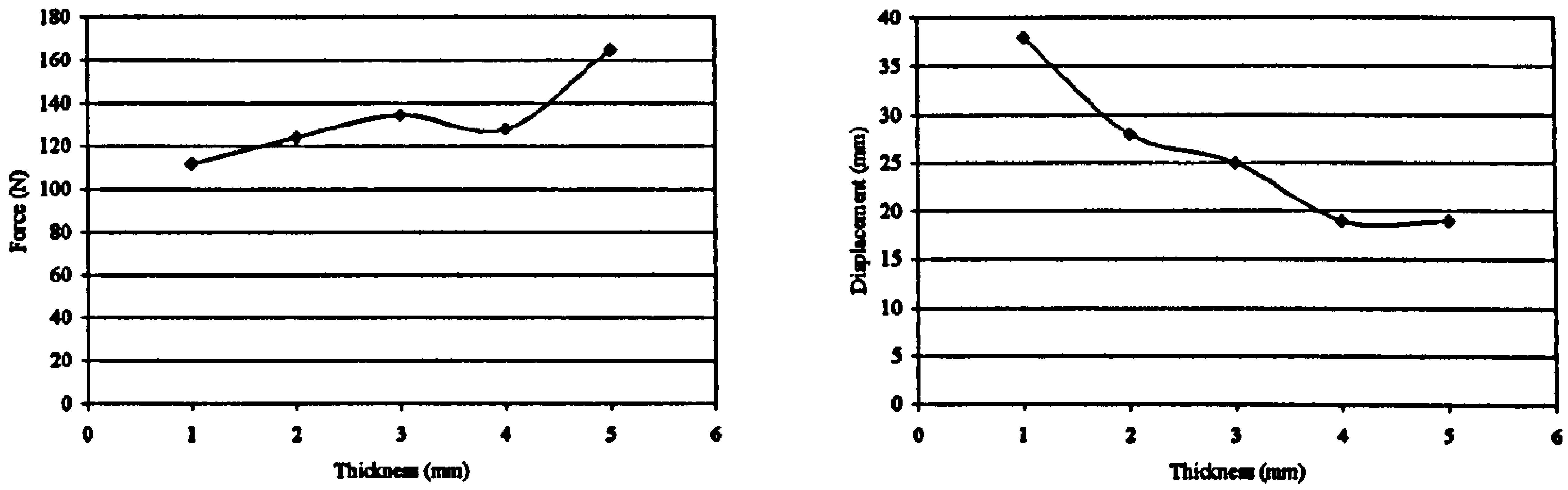


Figure 5.19 Force/thickness and displacement/thickness plots.

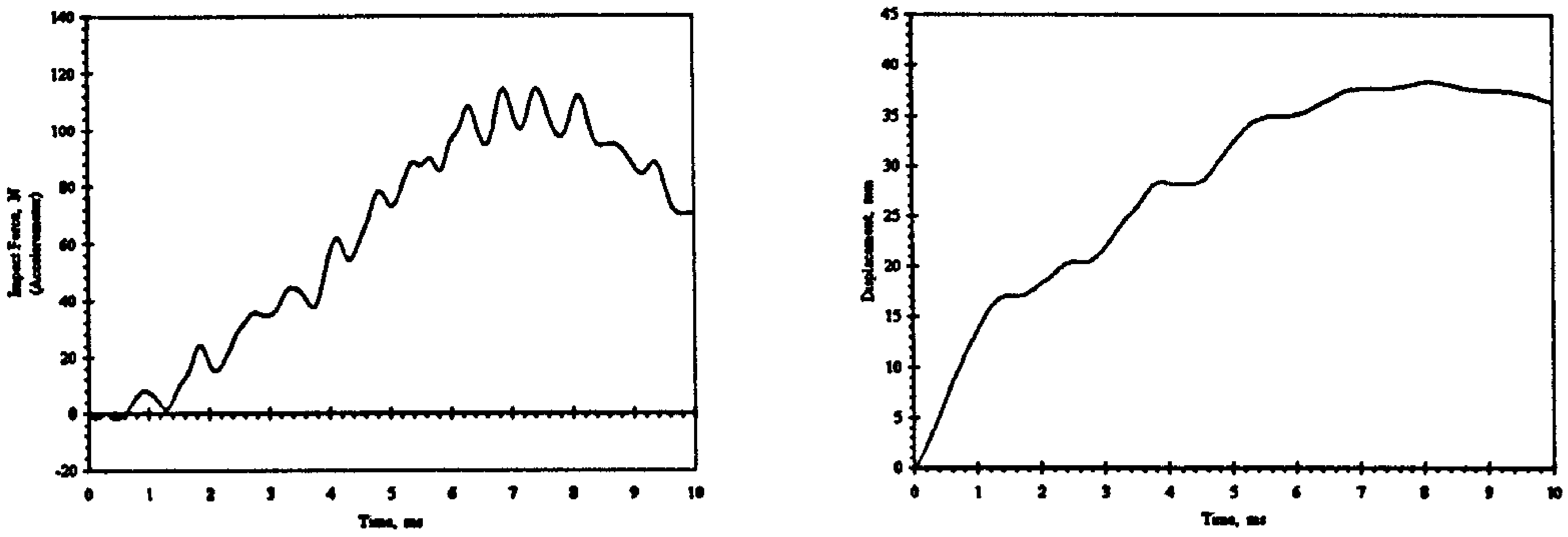


Figure 5.20 Peak force and displacement for 1mm pEVA.

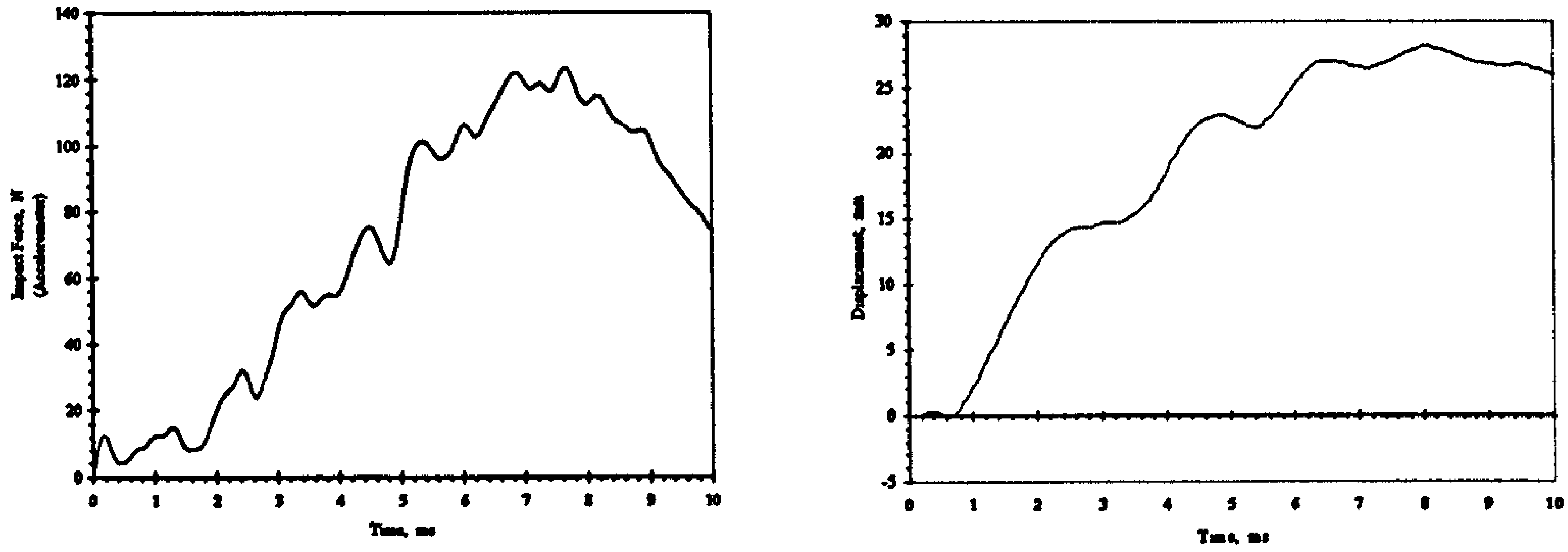


Figure 5.20a Peak force and displacement for 2mm pEVA.

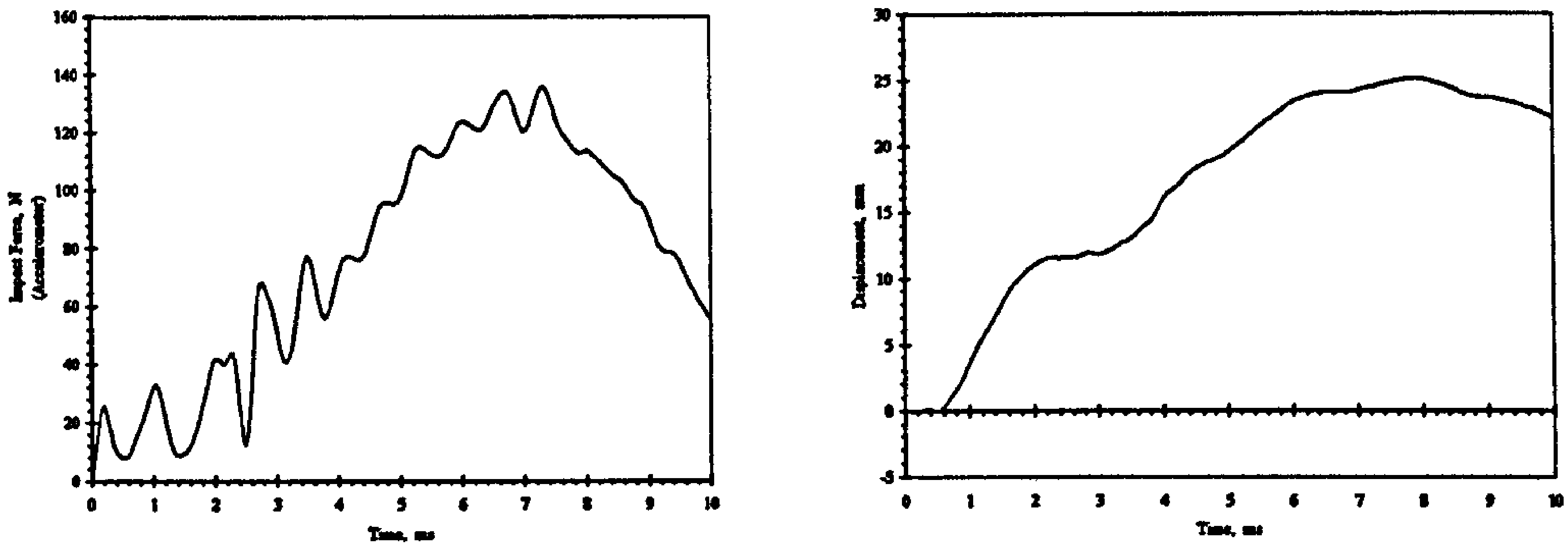


Figure 5.20b Peak force and displacement for 3mm pEVA.

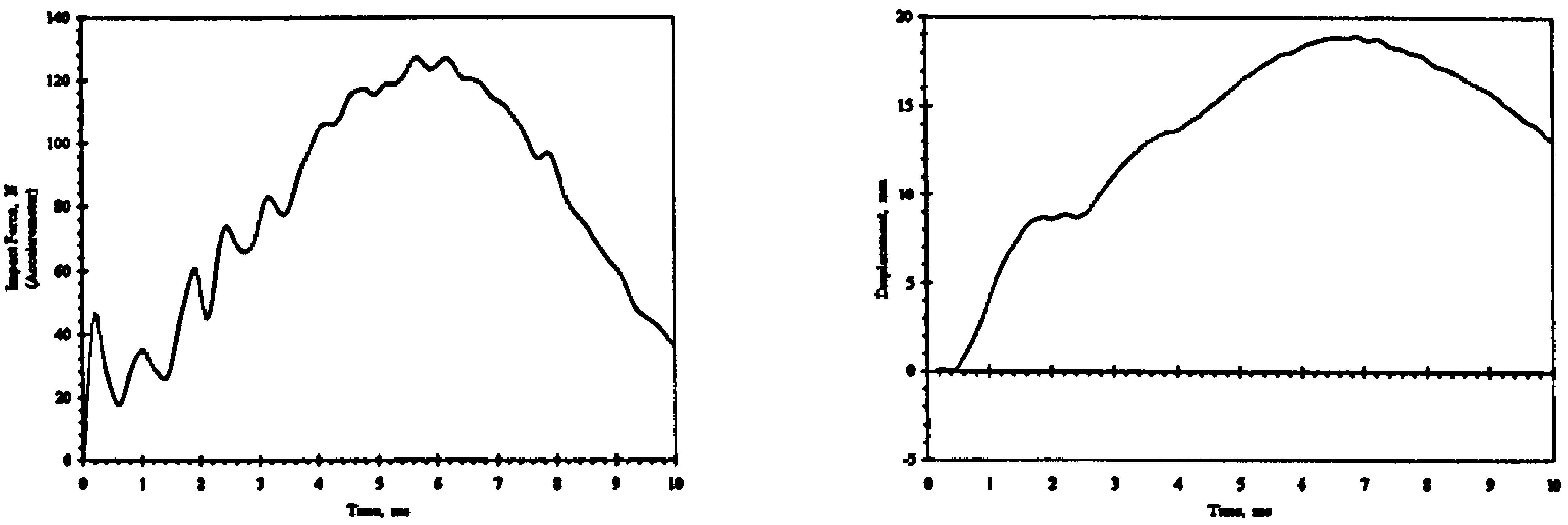


Figure 5.20c Peak force and displacement for 4mm pEVA.

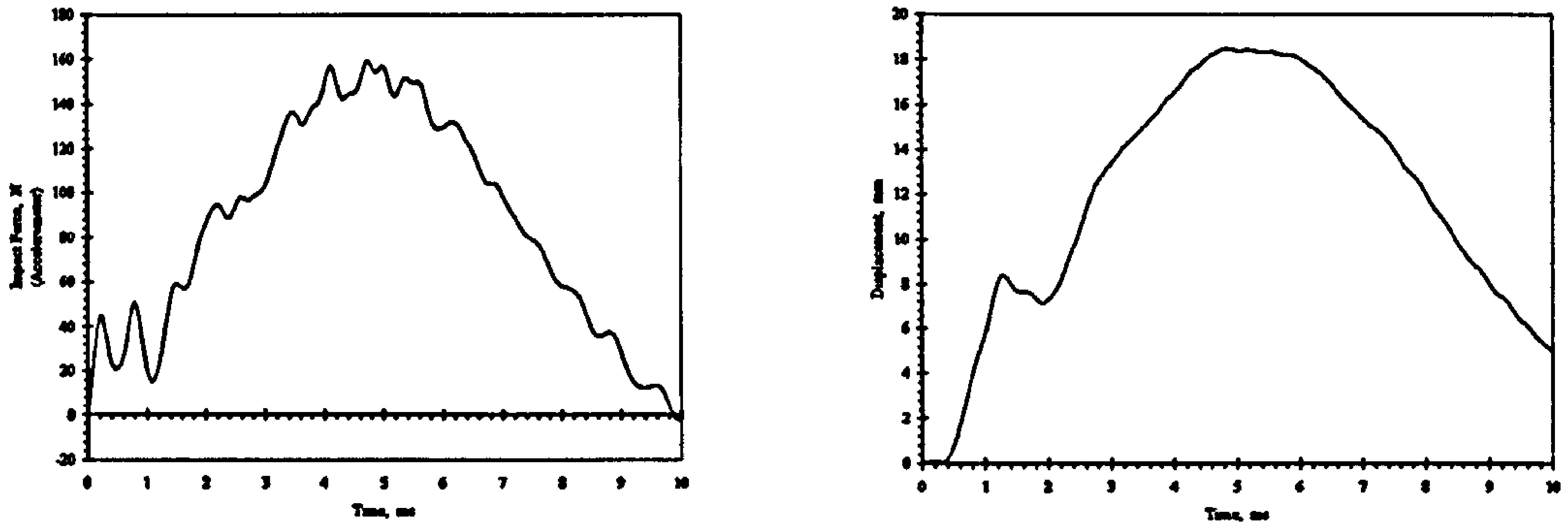


Figure 5.20d Peak force and displacement for 5mm pEVA.

Results show that as the thickness of the pEVA increases the deformation decreases and the impact force increases, demonstrating that the thicker material is absorbing more of the impact energy (Figure 5.20 – 5.20d). As the material increases in thickness its relative stiffness also increases, hence the rise in impact force – if a very stiff material, e.g., PMMA was impacted the impact energy would be far higher than for pEVA but the orce/time history shows a sharp spike of the impact event rather than a smoother, flatter curve of a more compliant material.

5.2.4 Effect of material stiffness

To illustrate the effect that stiffness has on the impact response of the test specimen PMMA is compared to pEVA (Figure 5.21 & 5.22). Although PMMA would not be solely used for a mouthguard it was tested so that the effects of a material stiffer than pEVA could be gauged. As expected, the force/time and displacement/time histories are more 'spikey' in appearance to that of the pEVA – the impact event is much shorter, 4.5ms instead of over 10 ms for the pEVA. Although the displacement of the PMMA is far less, at around 1.5mm compared with nearly 30mm for the pEVA.

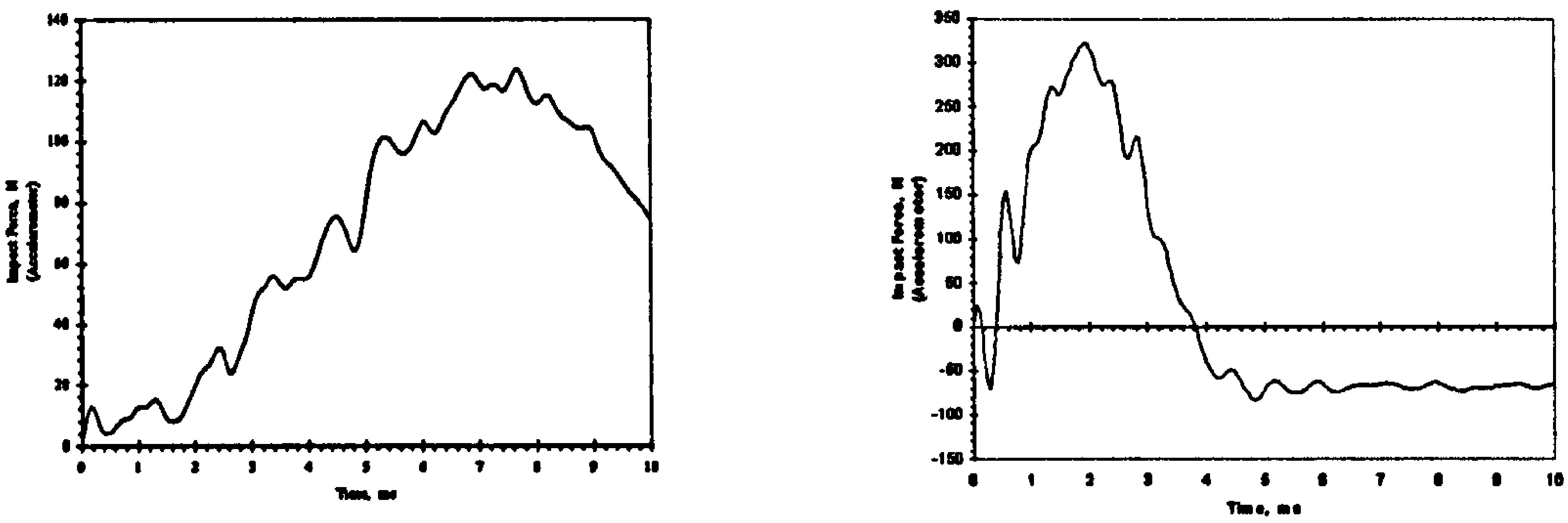


Figure 5.21 Force/time history for 2mm pEVA compared with 2mm PMMA.

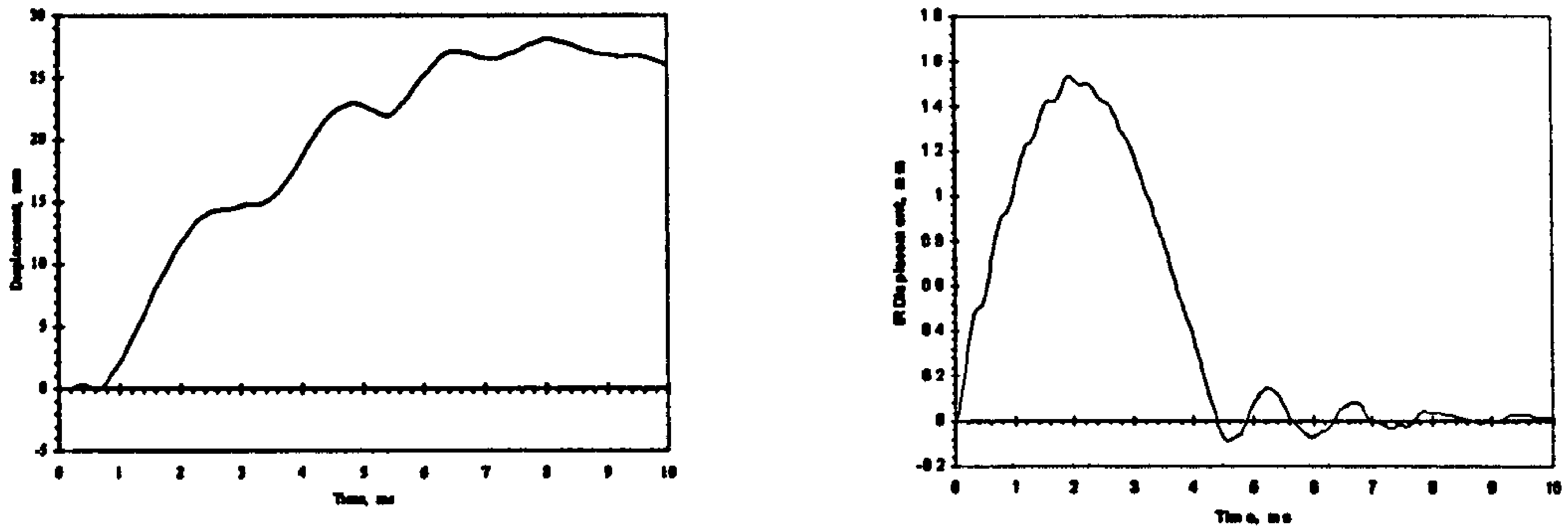


Figure 5.22 Displacement/time history for 2mm pEVA compared with 2mm PMMA.

There is also a high rebound characteristic associated with a stiffer material such as PMMA, the material is returning energy to the indentor, indicating that transmitted force through the material is high. A very compliant material with no elastic properties such as Plasticene exhibits no rebound of the indentor and absorbs all of the impact energy through either deformation or permanent destruction of the shape and form of the Plasticene.

5.2.5 Effect of Composite

In tests where pEVA sheets of 1mm thick were clamped together to give an overall thickness of 5mm where one sample was thermally bonded, one was separated by talcum powder and one was not bonded or separated but natural stiction of the pEVA sheets was relied upon; the thermally bonded structure exhibited a displacement that was lower than the other structures (displacement = 12.5mm); lower than the monolithic structure of 5mm pEVA (displacement = 19mm) although the impact force was quite similar (Table 5.4).

Table 5.4

Various 5mm structures of pEVA		
Material	**Force, N**	**Displacement, mm**
5mm pEVA	165	19
5x1mm EVA, natural stiction	185	23
5x1mm pEVA, separated with talc	205	15
5x1mm pEVA, thermally bonded	150	12.5

5.2.6 Effect of Design

Composite structures that were formed in either a laminate or as a layered test sample made from materials that are not normally associated with the manufacture of mouthguards exhibited results that indicate the use of compliant materials in the 'lay up' absorb a greater amount of impact energy than laminates with stiff/rigid materials. The laminated samples were clamped in the impact under the same conditions as for all previous tests to ascertain the protective capability of each of the different laminates. The results show that the laminate with the 3mm PMMA transmits more impact force but the displacement is within the limits of the other laminates with the exception of the laminate with the synthetic wax – in this sample the 2mm substructure fractured (Table 5.5).

Table 5.5 Effects of lamination on peak force and displacement.

Laminated and layered test samples using non-mouthguard material		
Materials (in order of 'lay up')	**Force, N**	**Displacement, mm**
pEVA, PMMA, Silicone rubber, PMMA, pEVA (all 1mm)	275	1.4
pEVA, PMMA, Synthetic wax (2 mm), pEVA	255	2.1
pEVA, PMMA (3 mm), pEVA	330	1.4
PMMA, pEVA (3 mm), PMMA	270	1.5

5.2.7 Substrate Behaviour

When the pEVA is used to protect an underlying substructure of 2mm PMMA the increase in pEVA thickness does not seem to have much of an effect on either the impact force or the displacement of the structure as a whole. Although the transmitted force through the material and the amount of displacement seen in the PMMA substructure does reduce (Table 5.6). The effects can be seen graphically (Figure 5.23 – 5.23d).

Table 5.6 Effect of substrate on peak force and displacement.

50mm discs of pEVA on a 2mm PMMA substrate		
Material	**Force, N**	**Displacement, mm**
1mm pEVA	340	7.7
2mm pEVA	370	8.3
3mm pEVA	300	8.2
4mm pEVA	320	7.9
5mm pEVA	325	6.8

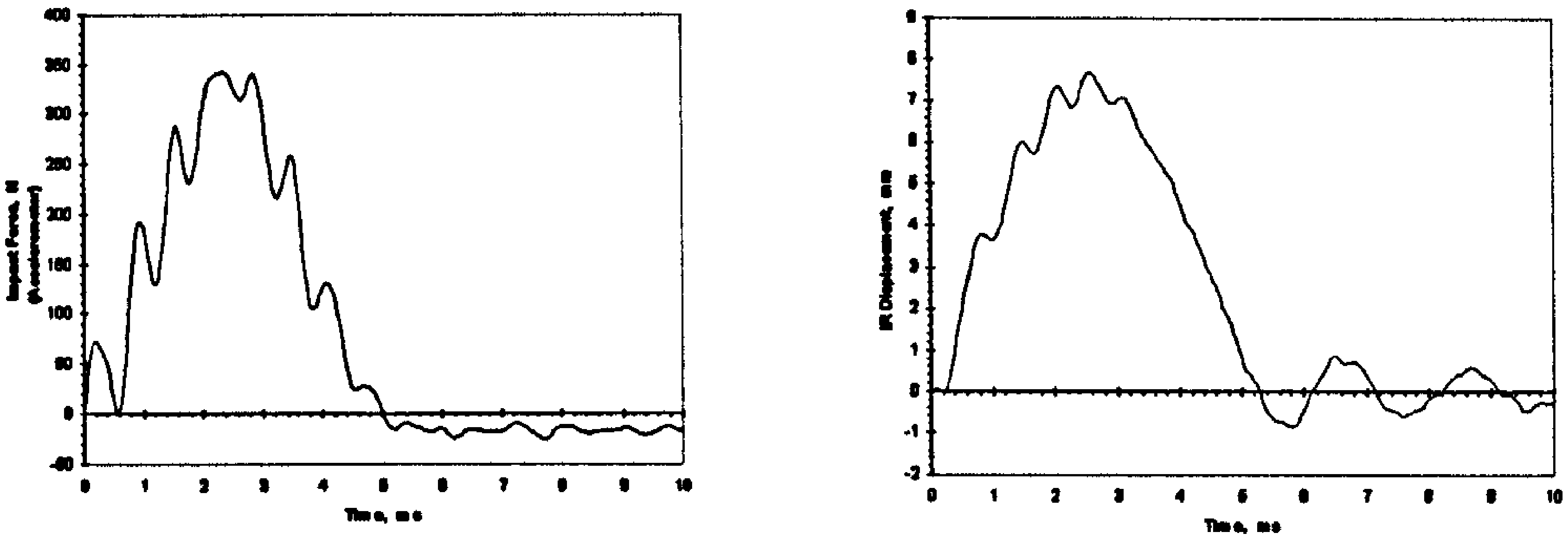


Figure 5.23 Effect of substrate on peak force and displacement of 50mm Ø 1mm pEVA on 2mm PMMA substrate.

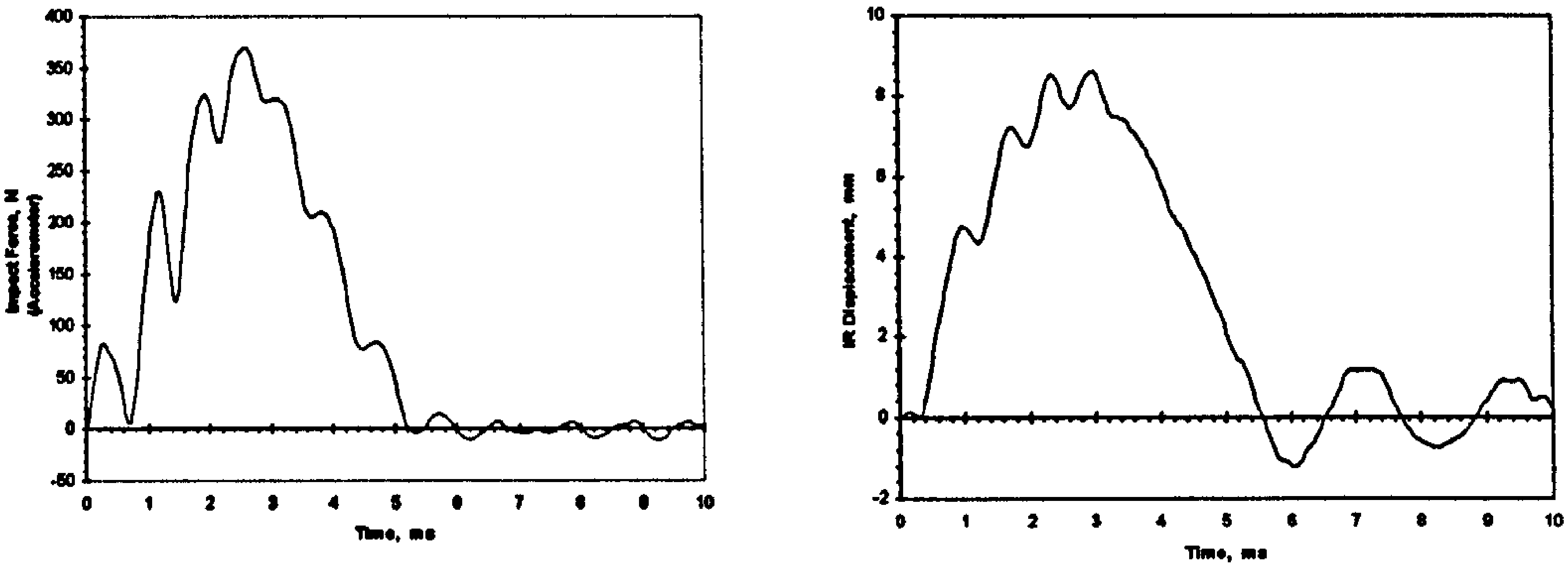


Figure 5.23a Effect of substrate on peak force and displacement of 50mm Ø 2mm pEVA on 2mm PMMA substrate.

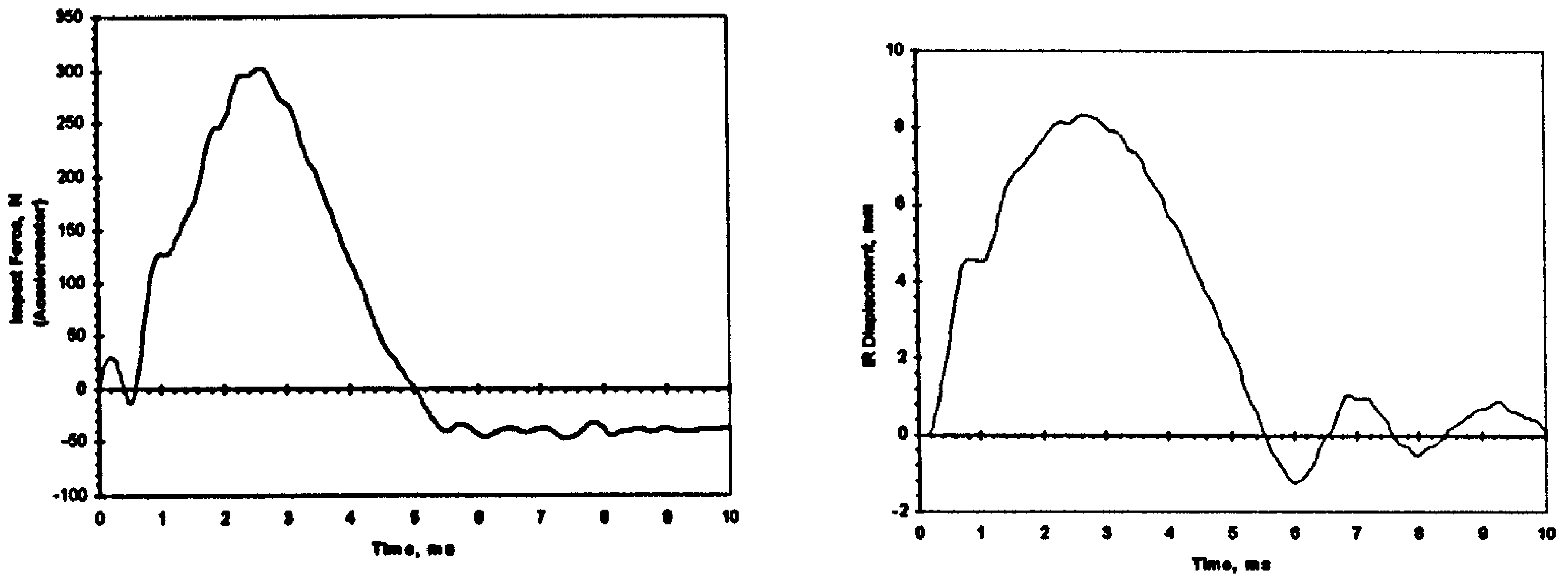


Figure 5.23b Effect of substrate on peak force and displacement of 50mm Ø 3mm pEVA on 2mm PMMA substrate.

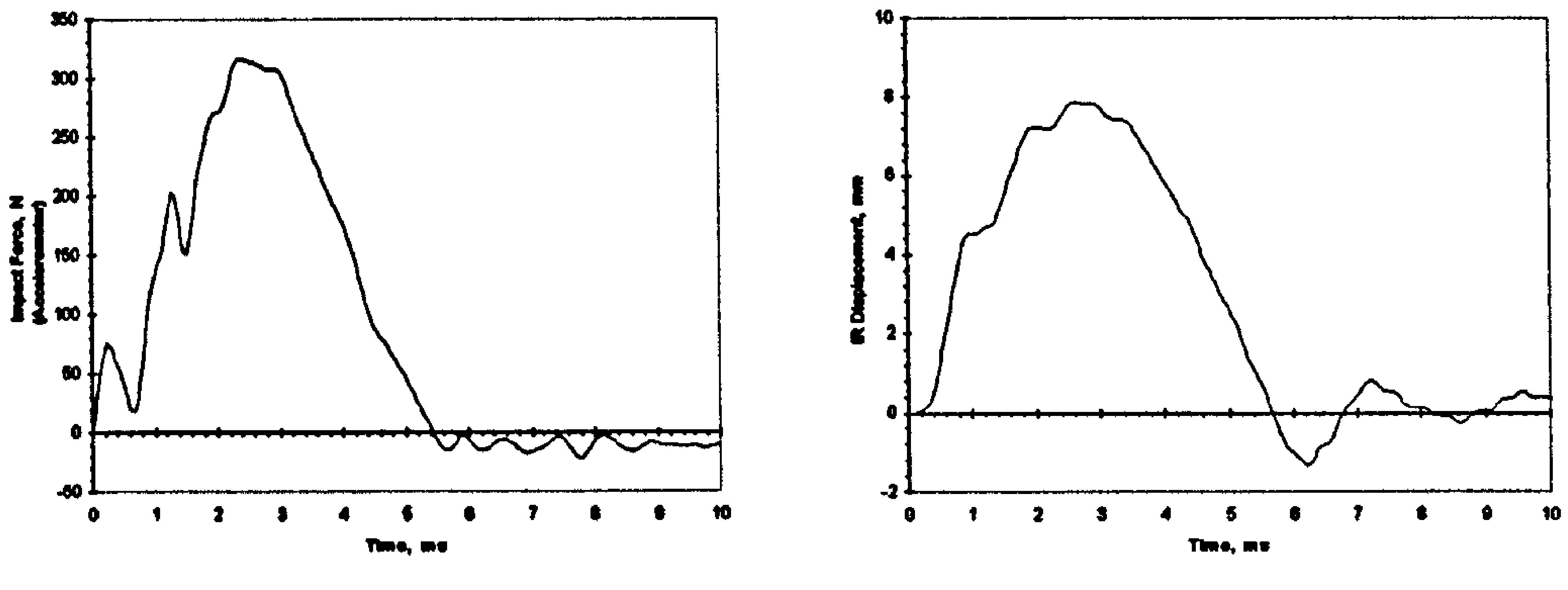


Figure 5.23c Effect of substrate on peak force and displacement of 50mm Ø 4mm pEVA on 2mm PMMA substrate.

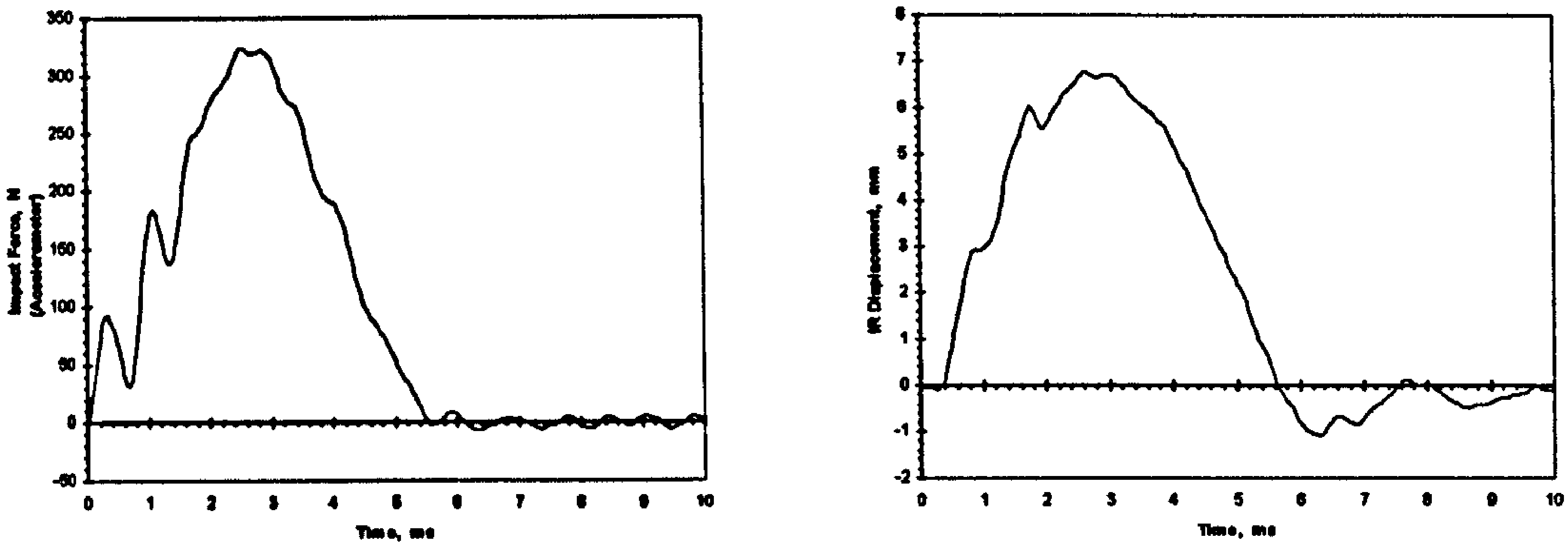


Figure 5.23d Effect of substrate on peak force and displacement of 50mm Ø 5mm pEVA on 2mm PMMA substrate.

Chapter 6

Discussion

6.1 Impact tests

The instrumented impact tester was chosen as it was thought that this would give a much clearer indication of how the materials that were tested would react during an impact event. The use of the data acquisition package that was linked to the impact rig gave very accurate force/time and displacement/time histories that show a ten millisecond 'snapshot' of the impact event. In some cases this very small window into the impact event was a little too short as the whole of the impact event was not acquired. This is due to the nature of the material – it being very compliant and easily displaced with a relatively slow recovery time when compared to more stiff materials such as PMMA. However, there was enough detail in the resulting data to ensure that very meaningful graphs could still be obtained for the thinner test samples, as these were the samples that exhibited the longest impact events.

6.1.1 Experimental impact test design

In designing the experiment it was felt that the amount of protection a material, or composite material demonstrated, the more valid the experiment would be. Previous studies have tended to show the amount of resilience present in a material by using a 'rebound test' or testing its modulus of elasticity. These kinds of tests were felt to be inappropriate as not enough information about the way in which a material reacts under impact loading conditions could be obtained from such simple tests. In testing for a materials' suitability for a particular purpose it has to be clear as to what parameters and characteristics of the material are ideal. In the case of a material for a mouthguard the ideal would be:

- Ability to absorb impact
- No transference of impact to underlying structure
- Integrity after impact

In the first instance a material would need to be tested to ascertain its material properties. The pEVA and other materials used such as PMMA were clamped into the impact test rig so that their response to an impact event could be recorded. Once these materials had been tested the design features on lamination of the same material and with different materials were tested to see which design may have properties more suitable for use as a mouthguard.

For simulation testing, smaller test samples were used. These were not clamped using the annular rings but were placed on top of a 2mm sample of PMMA that had been clamped and held in place using petroleum jelly. The protective capabilities of each sample that was tested could be demonstrated.

In-situ testing does not exist at present for mouthguards. For there to be a complete view of how well a mouthguard of any given design or material reacts during an impact event the ability to carry out in-situ testing must be realised. Materials testing and simulation tests can only be used as indicators of actual performance of a mouthguard in an impact event. Many factors will affect the way in which the mouthguard responds whilst being worn such as movement of the head, neck and mandible, type of impacting object and direction of movement of the athlete being hit. It is this kind of impact event modelling that needs to be carried out so that the mouthguards' protective qualities against trauma and concussion can be assessed.

6.1.2 Previous impact test research

In tests on mouthguards and the materials from which they are made, many investigators have focussed on the physical properties of the materials; Going *et al*, 1974; Craig and Godwin; 1967, it was felt that these tests could not demonstrate, in enough detail, exactly how the material, when made in to a mouthguard, would react under impact conditions.

In the testing of mouthguard materials under impact conditions, the use of an instrumented impact test rig, to give a quantifiable value of a materials' reaction to an impact event is an area that has been explored but not in as detailed a manner.

Some related studies (Holt, *et al*, 1991; Kawano, *et al*, 1993; Kawano, et al, 1991) are in the field of soft lining materials for full and partial dentures. The studies carried out examine the way in which a soft or resilient lining can evenly distribute a pressure applied to it and thereby effectively reducing the amount of load that is transferred to the underlying structures.

Other studies have concerned themselves with the material properties of the mouthguard material, such as water sorption, strength and hardness, (Craig and Godwin, 1967; Bishop, *et al* 1985; Going *et al* 1974.) While these tests are important and give an insight into the material properties the issue of protection is not addressed.

Westerman *et al.* (1997) used a pendulum style indentor, on testing apparatus, similar to a Charpy or Izod impact rig to assess the energy absorption properties of a mouthguard material that contained pockets of air. Although the head of the indentor used was fitted with an accelerometer, subsequent researchers, Greasley *et al,* (1998) reported that no beneficial effects are expected from the inclusion of pockets of air, Westerman *et al.* (1997) compared novel samples with air included to a 4mm thick mouthguard material (Stay-Guard, Worldwide Dental Inc., Clearwater, Florida, USA). It was found that the incorporation of air into the mouthguard reduced transmitted forces but only when the impact force was less than 10kN. The sample that exhibited the best results had large air pockets, 3mm x 3mm x 2mm with 1mm walls separating them. This would make a mouthguard very thick or if the outer wall was made much thinner to compensate then it may compromise the lifespan of the mouthguard.

The research and testing procedures carried out by Westerman *et al.* (1997) is of a similar nature to that carried out in this study, however, results that were produced are not as detailed as in this study. It is felt that the instrumented impact rig used in this research is a progression from the work carried out by Westerman *et al.* (1997) as the impact event is recorded in such detail that a more comprehensive view of the impact event can be obtained. In energy absorption tests carried out by Park *et al.* (1994) it was reported that the tests provided information on the peak impact forces and the amount of energy lost on impact. In the tests stainless steel balls were dropped from a predetermined height to produce the impact. A force transducer was positioned beneath the test specimen so that the force of the impact could be recorded. The impact event was digitised so that a graph that displayed the impulse could be plotted and also so that the transmitted impulse through the polymer sheet could be determined.

As previous work in this field has used quite different data acquisition methods and different testing regimes from this work it is difficult to relate experimental findings from this research to any previous impact data. There is also the problem of previous work testing materials that are in a non-heat treated state and therefore will have residual stress present. In their work, Bishop *et al.* (1985) tested for static energy absorption and dynamic energy absorption. Their findings were that a (pEVA) mouthguard material (no indication of thickness was given although the thickest sample used was 4mm and the thinnest was 1mm) with a PVA content of 18% was best and had a value for dynamic energy absorption of 31.18 mJ

6.1.3 Significance of the instrumented impact test results

To validate the instrumented impact tests a repeatability study of the impact response of 5mm pEVA was carried out. From this study it was found that the repeatability of the impact test was good so that future tests could be carried out and the data from each test could be relied upon as being a true representation of the impact event.

6.1.4 Limitations of impact testing method

At present the impact test rig that was used is not capable of carrying out impact tests on mouthguards that are mounted on a simulation of a jaw. This would be ideal so that greater insight into the effect of heat treating the pEVA, laminations of various materials and different designs could be observed.

6.2 Stress relief

In the results the effect of heat treatment of pEVA is clearly shown. Although the material that has been heat treated has a much higher displacement there is no residual stress present that over time may reduce the lifespan of a mouthguard. The PIF is roughly the same in both samples (heat treated =155N, non-heat treated =160N). The ability to absorb more energy in the heat treated sample is indicated by its greater displacement (30mm instead of 18.5mm) although the way in which the material reacts to the impact is changed. The built in stress may have the effect of raising the stiffness of the material if its behaviour is non-linear. When considering the design of mouthguards it would be possible to incorporate a layer within the mouthguard of heat treated pEVA that would act as a shock absorbing layer in the anterior region.

From the results it can be seen that the heat treated (non-stressed) samples of pEVA exhibit greater displacement for the same peak impact force (PIF) when compared to non heat treated (pre-stressed). The heat treated sample acts like a softer material absorbing more energy. In comparison the non heat-treated pEVA displays a shorter time for the impact event, although the force/time history is not as 'spikey' as for a hard material such as PMMA the difference between pre-stressed and non-stressed force/time histories is quite marked. The heat treatment of the pEVA clearly affects the material in such a way as to relax the rigidity of the molecular chain backbone.

6.3 Thickness

The testing of heat treated pEVA falls under two categories,

i) Materials properties testing and
ii) Design features.

The properties of the material have changed after the heat treatment and this change could have design implications for the mouthguard. Under identical impact loading conditions heat treated pEVA exhibits a greater displacement than non-heat treated pEVA. This means that the minimum thickness of material in the anterior region of the mouthguard is ever more critical. It may mean that in sports where there is the possibility of impact from a very hard object, travelling at speed, such as a hockey ball or puck the mouthguard may have to have an increased thickness to provide an appropriate level of protection.

In the tests that were carried out it was quite clear that the thickness of the mouthguard material had an influence on the characteristics the material displayed as it underwent an impact event. As one might expect, thicker material protects better than thinner material. The 5mm pEVA had a peak impact force (PIF) of 165N and a displacement of 19mm, while the 1mm pEVA had a PIF of 112N and a displacement of 38mm. The thinner pEVA exhibits significantly more displacement and in terms of mouthguard protection a mouthguard this thin would not offer the required protection that an athlete would expect. Besides protection from concussion a mouthguard of 1mm thickness would be wholly inadequate as there needs to be at least 3mm of material on the highest point of the occlusal surface to keep the condyles out of contact with the glenoid fossa.

6.4 Laminate

The results from the tests that were carried out on pEVA monoliths compared with samples that were made up of layers of pEVA of differing thickness and were either bonded or kept entirely separate indicated that it is better to use a multi-layered system of many sheets of pEVA. This system of bonding two layers of pEVA was arrived at in many laboratories that were using machines that could not cope with material thicker than 3mm or where the incorporation of the athlete's name within the mouthguard was required. Without realising it these laboratories were producing mouthguards that were superior to a one-thickness system of manufacture.

6.5 Multiple material Laminates

In tests on composite structures, addressing design issues, the results showed that a multi-layered structure made up of differing materials, pEVA, PMMA and silicone rubber had a very significant effect on the PIF and displacement for a 5mm structure. PIF was 275N and displacement was 1.4mm. Although the 5mm layered composite structure made up of pEVA and PMMA, where there was a sandwich of 3mm PMMA between two layers of pEVA, exhibited better results (PIF = 330N and displacement the same at 1.4mm). The 3mm PMMA displayed cracking therefore would need to be replaced each time and so could not be of use as a mouthguard. As reported by Greasley and Karet (1998) the use of a hard insert had no effect on the protective capabilities of a mouthguard, their hard insert was of thinner dimensions, 1.5mm and 2mm and it also exhibited cracking at the impact site. Significantly, the multi-layered structure was displaced by less than a tenth of that of the 5mm pEVA monolith, exhibited a PIF over 100N higher than 5mm pEVA and exhibited no damage to the PMMA layer.

When the mouth is subject to an impact of sufficient force there will be trauma if no protection is worn over the teeth and gums. If the force of impact is of a magnitude such that it that makes the head jerk backwards, especially from blows to the chin, then the brain will move within the skull due to inertia and is flung to the inside front of the skull with considerable potential for damage. This may cause concussion and over time if this scenario is repeated often; then the cumulative effects can be extremely debilitating with Parkinson's disease type symptoms manifesting themselves. A mouthguard of 5mm thickness in the occlusal region, in this researchers' opinion, will minimise the effects from impacts to the chin due to the condyle being sufficiently out of contact with the glenoid fossa and thereby not transmitting as much of the impact force up through the mandible and into the base of the skull.

6.6 Outcomes – design pointers

Results from the impact testing regime indicate that, thicker pEVA material deforms less than thinner pEVA also that the impact event is a much shorter event. Multiple material laminated structures offer better protection to the wearer of such a mouthguard in terms of deformation and absorbed energy than a single material system of the same thickness.

Should the mouth be protected by a mouthguard of sufficient thickness that incorporates a cushioning or shock absorbing layer, impact energy will be absorbed and velocity reduced - the oral tissues and brain will suffer less damage.

The outer layer of the mouthguard needs to be strong enough and stiff enough (when compared to the inner shock absorbing layer) to withstand repeated blows, the force of the impact will then be spread across a wider area of the softer more compliant inner layer and the risk of traumatic injury being sustained is substantially decreased.

A stiff outer layer (in relation to the inner layer) transferring impact energy to a larger underlying more compliant material, will result in impact energy being absorbed more easily over a large area. A less stiff outer layer will absorb an impact but will exhibit partial destruction, and if the impact energy is more than it can handle the compliant shock absorbing layer may not be able to absorb all remaining impact energy, with trauma to the underlying tissues occurring.

A thinner internal compliant material with a harder outer has a smaller area to absorb impact energy, therefore, the final transmitted energy is higher as the time period of the impact is shorter giving rise to trauma to the underlying teeth and mucosa.

Larger, softer materials on the inside of a less compliant outer shell can provide large amounts of material to absorb the destructive impact energy, destruction time is longer, and as a result transmitted force is smaller.

6.7 Simulations

In simulation tests where a PMMA substrate was used to simulate the underlying structures of the mouth it could be seen from the results (Chapter 5, table 5.6) that the transmitted force through the material and the amount of displacement seen in the PMMA substructure reduces with an increase in the thickness of the mouthguard being modelled. In other tests designed to simulate the mouthguard as it would act in the oral environment, 50mm Ø pEVA discs were held in position with petroleum jelly on a 2mm thick substrate of PMMA. The results give an indication of how the mouthguard material would react to an impact event with a substructure that models the teeth and mucosa. Although the results seem to show that the PIF has increased for all samples this will be due to the effect of the PMMA substrate. Overall the displacement is reduced with the smallest displacement being observed for the 5mm test sample. However the results for all samples (1mm – 5mm) are all within close proximity to each other with regards both PIF and displacement indicating that the substrate must have a dominant role in the impact event such that the differences could be quite small.

6.8 Polariscope

The use of a polariscope to assess the levels of stress within the pEVA, in a raw state 'as received from the supplier' and after it has undergone the heat treatment process is a testing regime that has not been carried out before and has highlighted the effect that the manufacturing process has on the pEVA material. This has indicated that tests on mouthguards will have very different results to tests on just the material itself due to marked changes in the residual stress in the material after processing. It could be seen from the images that not only the forming of the pEVA into a mouthguard has an effect but also the subsequent finishing techniques also alter the stress levels present in the pEVA.

The results that were obtained from the polariscope tests show that there is uniform distribution of stress throughout the pEVA material 'as received from the supplier'. This stress can be eliminated when the pEVA is heat treated. The finishing procedures that are routinely employed by dental technicians when making a mouthguard also have an effect on the levels of stress present within the mouthguard.

In terms of a comparison with research previously carried out by other researchers the use of a polariscope is an area that has not been utilised. The incidence of inherent stress within the mouthguard material and the effect that this has on the impact characteristics of the pEVA can, therefore, not be compared to previous work.

6.8.1 Significance of the polariscope results

In examining the pEVA test samples photoelastically the amount of stress within the pEVA has been highlighted. The pEVA, as received from the supplier, has stress present throughout the material. Heat treatment of the pEVA results in stress relaxation and gives rise to impact test data that is significantly different to that of pEVA that has not been subjected to the heat treatment process.

All medical plastics manufacturing processes— including injection moulding, extrusion, vacuum/pressure-forming, and machining—inherently introduce residual stresses. These stresses sometimes have an intentional and highly desirable purpose, as in the case of bi-axially oriented films, whose carefully designed orientation enhances mechanical properties. In other products, residual (or 'frozen-in') stresses can be a problem, reducing end-use performance and resulting in increased scrap and rejects. When high levels of stress are present in a part, impact strength is lowered, high-temperature performance is diminished, and environmental stress cracking becomes more prevalent, (http://www.devicelink.com/mddi/archive/99/03/008.html). In terms of mouthguard testing and production the residual stress that can be seen in the polariscope plays an important role in the efficacy of a mouthguard. Heat treated pEVA reacts very differently to non-heat treated pEVA, therefore, as a predictor of performance under impact loading conditions. The residual stress must be removed or acknowledged as being a factor in the resultant impact test data.

6.9 General Discussion

When considering materials for impact protection systems certain criteria have to be observed and in designing a mouthguard that protects the wearer in a more effective manner the same criteria as for any number of other applications have to be adhered to. Materials absorb kinetic energy, or impact energy by plastic deformation, elastic deformation, brittle fracture, or by the fluid dynamics of gases or liquids within the material. Materials used for absorbing impacts are commonly organic foams, such as expanded polystyrene, polyurethanes, polyethers, or polyethylene. These typically show elastomeric or plastic behaviour. In a system such as that used for mouthguards the absorption of impact energy needs to be one that can withstand repeated impacts without seriously compromising the protection capabilities of the mouthguard, therefore the use of foams in mouthguards can largely be discounted as an inappropriate material.

An effective material for use in safety devices will serve to minimise the force felt by the object (or person) to be protected. This is done by spreading the deceleration of the impacting object over a longer period of time.
(http://eande.lbl.gov/ECS/aerogels/sakinegy.htm)

There are two possible modes of operation for an impact protector:

- Load spreading - the force from a small impact area is spread over a large area, thus minimising the pressure (force/unit area) and reducing the risk of trauma.
- Energy absorption - or the 'crumple zone effect' - the material used deforms and absorbs the energy of impact (converting it into heat), so less pressure is applied to the underlying structure.

Soft materials such as silicone rubber operate predominantly as energy absorbers, whilst hard plastics are predominantly load spreaders. Therefore it is this composite model that could benefit and protect an athlete more effectively if a mouthguard were to be made from these kinds of materials rather than a single material system. However, it must be remembered that the materials need careful selection and that the composite mouthguard should have enough flexibility and compliance to be comfortable for the wearer. The stiffer outer material must not be so stiff as to be difficult to be placed in the mouth where it may have to flex around undercut areas or be brittle in anyway, this is especially important as any piece that may break off due to an impact could cause serious trauma or asphyxiation. Any material used for making a mouthguard must be able to retain its physical properties for a long period of time – a material that will become brittle or hard due to leaching of chemicals must be avoided to retain the mouthguards' integrity and also so as not to introduce any toxins into the oral environment.

Kinetic energy, such as the energy found in a facial impact from participating in a contact sport, cannot be destroyed or stopped easily so it must be converted into a form of energy that will not cause trauma. The kind of kinetic energy in an impact event is, by its own nature, the kind of event that happens very fast with little or no time for the athlete to react or for the protective system of a mouthguard to deal with the impact and protect the wearer from sustaining trauma. Energy that is dissipated in the deformation of a shock absorbing layer is the ideal kind of energy conversion that is needed to prevent harm to the teeth and soft oral tissues from the impact.

Future work in developing mouthguards that protect the wearer from trauma need to focus on the use of a shock absorbing layer that can absorb and dissipate the impact energy from a traumatic blow to the mouth. Laminated mouthguards, as indicated by this research, or mouthguards that contain a laminated insert that is built into the mouthguard need further investigation. From the results it can be seen that this type of mouthguard has better energy absorbing capabilities than that of a monolith of pEVA.

Air bags inflate extremely quickly and then deflate relatively much slower than the initial inflation. The bag is porous to the gas that inflates it. If the bag was filled to capacity with no escape for the gas then the person hitting the air bag would rebound from it causing trauma or it would be so hard because of being filled with gas that the bag itself would cause injury. A mouthguard must act in a similar manner to dissipate and absorb the impact, although gas cannot be used easily and the inclusion of air pockets has been dismissed (Westerman *et al.* 1997) as being ineffective, a compliant material, however, in the body of the mouthguard can have a similar effect, in terms of impact force dissipation, on the impact energy of a blow to the mouthguard.

In the manufacturing process mouthguard materials, specifically the vacuum and pressure formed thermoplastics that are routinely used for making custom mouthguards; undergo a heating/softening stage that alters the way in which the material reacts to an impact force. As the results show, the heating of the pEVA acts as a stress relieving anneal on the material thereby giving rise to quite different results from that of untreated pEVA. Future work on the efficacy of a mouthguard will have to incorporate this stress relieving anneal on the test samples or finished mouthguards will have to be tested on a model of the dental arch with instrumented strain gauges to assess the mouthguards' response to the impact of the indentor. In situ tests for mouthguards do not exist. The importance of materials properties can be tested thoroughly in simulations and specific materials tests can be used as a good predictor of performance but as far as design is concerned the need for in situ tests is crucial so that the optimum mouthguard can be made in accordance with materials and design features.

Some laboratories make mouthguards by laminating two or more layers of pEVA together, often this is because the equipment being used will not accommodate material that is thick enough to produce a satisfactory mouthguard. It also facilitates the incorporation of the athlete's name within the two layers. In the course of the experiments that have been carried out this procedure has been found to have no effect upon the efficacy of the mouthguard; only that it ensures the mouthguard is made to the correct thickness. A single 5mm blank of pEVA can thin out quite severely when the forming process takes place – generally in the most crucial areas, i.e. anterior and occlusal regions. Therefore, building up a multi-layer mouthguard from the same material can minimise the thinning effect, the use of heat and pressure to join the laminates ensures that a homogenous structure is formed from the pEVA. Although this type of mouthguard is essentially a monolithic structure it is more desirable than one made from a single sheet because the mouthguard can have layers added only where the mouthguard needs to be thick, e.g. on the labial and occlusal areas. The buccal and particularly the palatal areas can be left thinner so that the mouthguard is more easily tolerated and speech is made easier.

In the manufacture of mouthguards for contact sports the use of the polariscope has highlighted the fact that the manufacturing process affects the way in which the pEVA reacts to an impact event. It has shown that pEVA that has undergone a heating process is more easily deformed than pEVA which has not, as this is an integral part of the manufacturing process the finished product may not be as protective as at first was thought. Clinically speaking the mouthguard may have to be made thicker in prominent areas to offer the kind of protection that may be expected from a mouthguard.

The use of a multi-laminated or multi-layered structure for incorporation into a mouthguard will protect the underlying teeth better than a single material system of protection. The mouthguard that incorporates such a laminate design would minimise the effect of direct impacts to the mouth, also in the thickening of the occlusal areas of the mouthguard the possibility of repeated or cumulative concussion will be reduced.

From the results obtained from the impact testing rig it can be seen that the use of compliant materials in a layered or laminated structure aids in the protection of the oral structures in the event of an impact directed at the mouth. Also with the correct thickness in the occlusal region the incidence of concussion can be reduced.

Future tests on mouthguards need to be carried out 'in situ' to enable a better assessment of the mouthguard that is being tested.

6.10 Clinical considerations

From the work that has been carried out the main factor that will affect the clinical aspect of providing patients/athletes with mouthguards is that the mouthguards must be made in the correct way and be of sufficient thickness in the most critical areas (labial and occlusal) to minimise trauma. Clinicians need to be made aware of the design features and limitations of the mouthguards that are fitted.

Chapter 7

Conclusion

Results observed in the polariscope have shown that the heating process in the manufacture of mouthguards is an important factor that alters the way in which the EVA reacts to an impact force. Future testing of materials for mouthguards must take account of the heating process involved in the production of sports mouthguards.

For a better mouthguard, more suitable for the rigours of modern contact sports, a laminated mouthguard incorporating a compliant anterior section to distribute and dissipate the force of an impact is recommended.

Mouthguard testing and assessment needs to be carried out in the four stages of; materials properties testing, design features, simulation testing and finally but most importantly tests and assessments made in-situ.

Chapter 8

Further Work

The use of pEVA for a mouthguard material has been well established for some years now because of its ease of manufacture for mouthguards and because it fulfils the basic accepted criteria for a sports mouthguard. There is some debate, however, as to how thick the mouthguard should be, despite that the general thought is, the thicker the mouthguard is the better it will protect.

In the pursuit of the most effective mouthguard, one that will withstand repeated impacts, not transfer impact energy to the teeth or to the cranial base, a testing regime, as previously described, should be adhered to.

The methods that have been used in this project to test mouthguard materials have tried to identify what it is that makes a mouthguard an effective protective device, that reduces the incidence of oral trauma and the effects of repeated concussion. Tests carried out examined,

1. The material properties of mouthguard materials,
2. The design features of various laminated designs and
3. In simulation tests the efficacy of a material or design was examined.

8.1 Material properties

Any material that is to be considered for use as a mouthguard must be tested to ascertain its material properties. In this way unsuitable materials, such as a material that can not be repeatedly impacted and return to its original shape or that will be destroyed easily with an impact, can be discounted early on without any unnecessary further studies taking place.

8.1.2 Design features

The desired design features need to be considered of any material or combination of materials. Whether to laminate in one configuration or another, then the different 'lay-ups' tested so feasible composite structures can be obtained.

8.1.3 Simulations

In testing a mouthguard material simulation of the type of impacts that will be received and how well the structure will cope in protecting an underlying substructure will give clearer indications as to the best mouthguard design. To ensure that the tests are accurate there needs to be consideration given to the model used and also to the materials from which the model is made, the design of the rig must simulate the movement of the head, neck and jaw as closely as possible.

8.1.4 Applying the force in a simulation test

If a dropweight test rig was used the problem of the orientation must be overcome in the case of the upper cut and frontal impacts. The head is normally in the vertical position and gravity acts downward (Figure 9.1a). However if a dropweight rig is used to provide the frontal impact the head will be orientated so that it is in the horizontal plane and gravity acts through the back of the head (Figure 9.1b) hence the head has a natural tendency to tilt backwards.

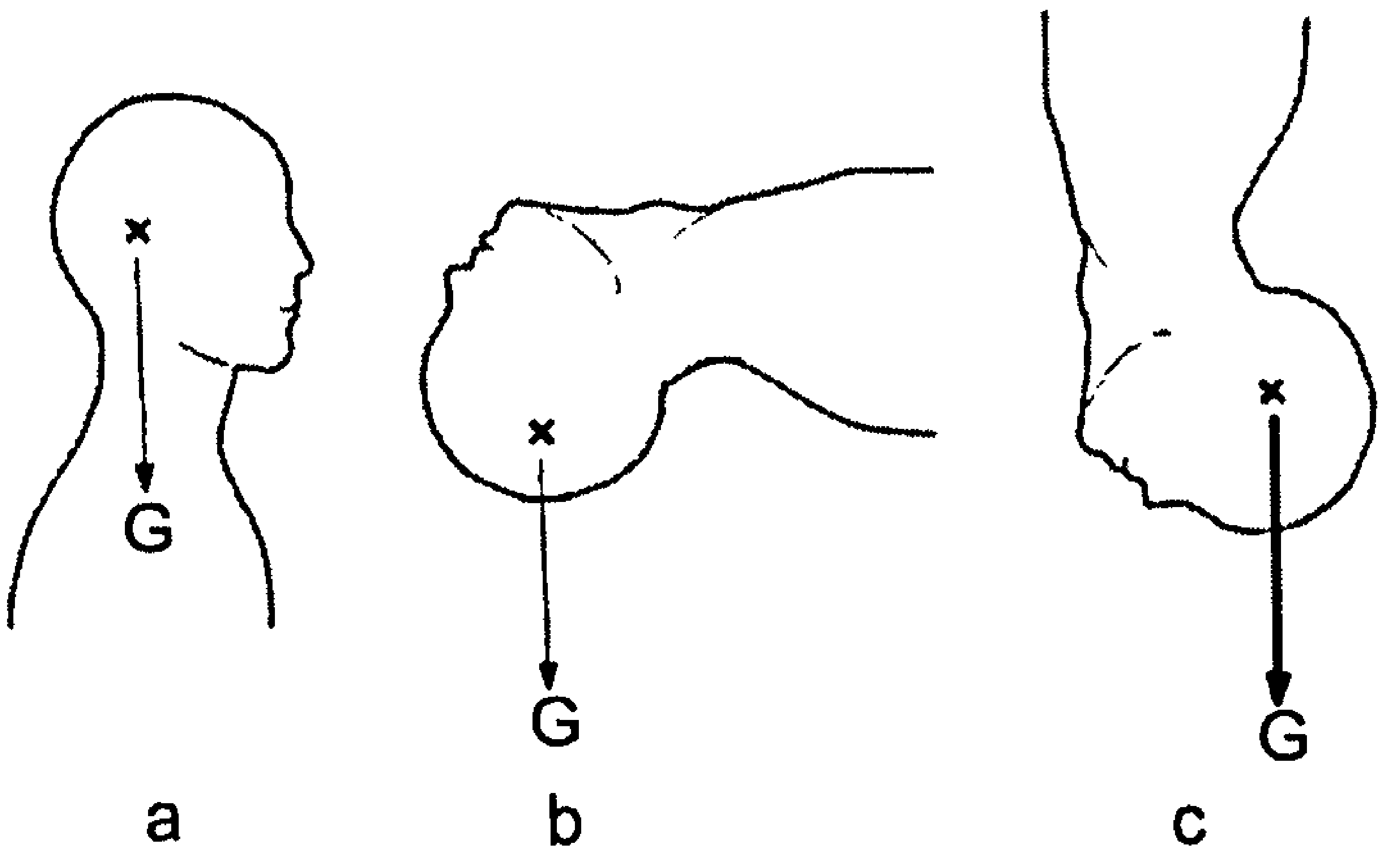


Figure 0.1, Problems with Orientation

To overcome this problem springs or a similar mechanism will have to be used to keep the head horizontal while still allowing displacement in the downwards direction.

A similar problem occurs when the upper cut is investigated using the dropweight rig, the head in this case will be upside-down and because the centre of mass is not in the centre of the head it will tilt towards the ground (Figure 9.1c)

If a Charpy type impact rig was used the frontal impact will occur horizontally (as it is in most real life incidents) with the head in the vertical position, but for the drop weight test the head will be in the horizontal position and will tilt backwards (Figure 9.1b).

8.1.5 Hydraulic/Pneumatic

Another method of creating the impact force would be to use a hydraulic or pneumatic cylinder. This could then be orientated in whichever direction required allowing for both the upper cut and frontal type impacts to be produced without the need for additional mechanisms to counteract gravity. Because this system is not reliant on gravity to cause the weight to swing or drop the test mouth can be orientated however desired.

8.1.6 Simplifications

The main area of interest is the mouth, for this study the rest of the head just adds mass to the system. To simplify the model while still keeping it physically accurate in the area of interest a jaw with the correct mass and centre of gravity can be built to replace the rest of the head (Figure 9.2).

The lower jaw should be as close to reality as possible and must have independent movement from the upper jaw.

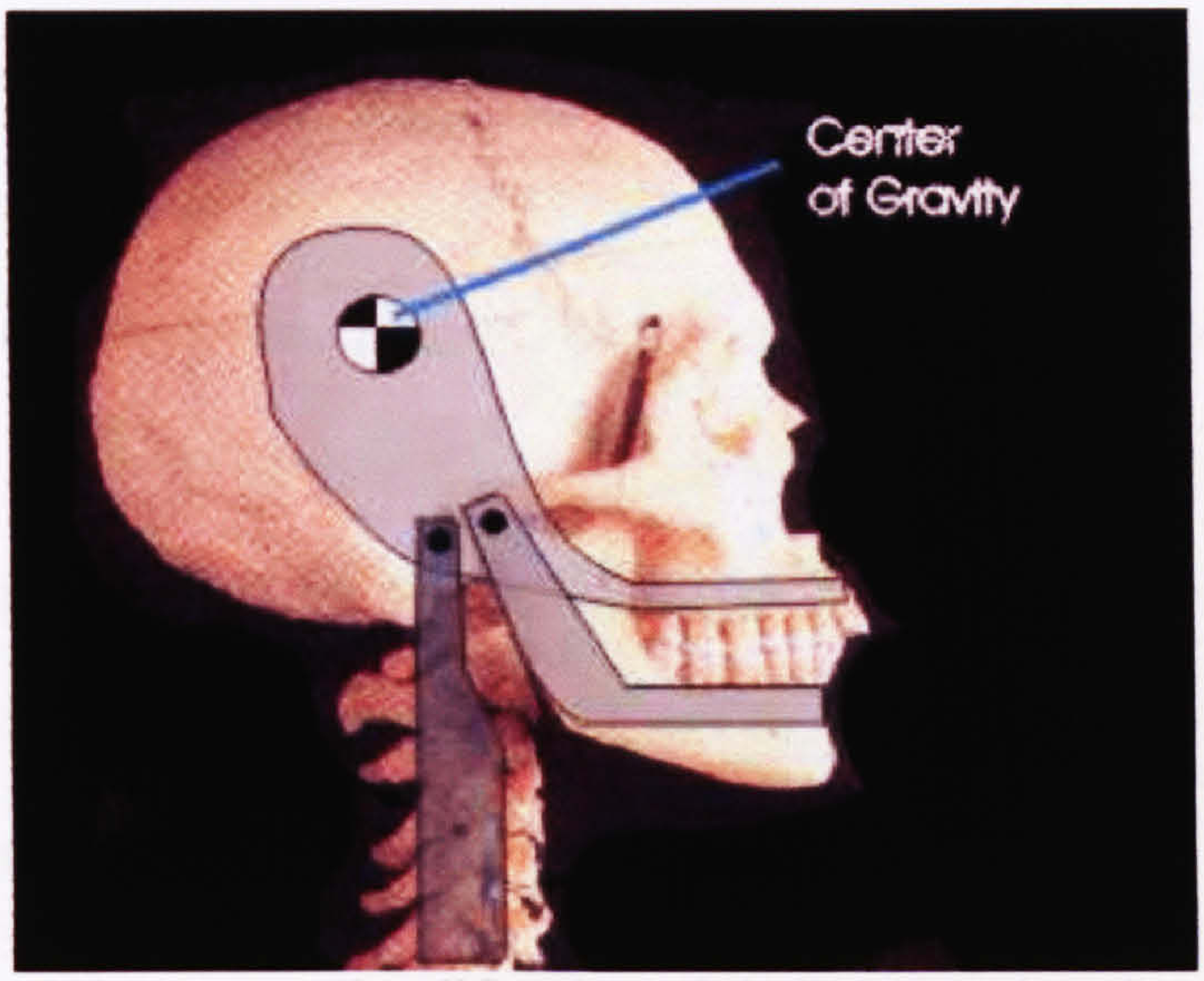


Figure 0.2, Simplification of skull, jaw and neck

8.1.7 Recommendations

From the Literature survey it can be said that no definitive findings have been made as to the best materials or design for a mouthguard. For the performance of the material as a mouthguard to be investigated a test rig needs to be built. The following recommendations are made so that a rig can be designed and tested.

8.1.8 Materials

The choice of material for the jaw is dependant upon how the tests will be carried out and what the maximum force is going to be. If the forces are high and the budget / time are tight then the jaw must not break during testing. If this is the case a metal jaw that held ceramic or dental stone teeth would be the best option. If the teeth break they can be replaced relatively cheaply and easily. The choice of adhesive that bonds the teeth to the jaw must be carefully chosen so that it does not interfere with the mechanical properties of the teeth or jaw. The shape of the hole in the jaw to hold the teeth must not cause undue strain at the interface (i.e. stress concentrators)

8.1.9 Anatomical Considerations

The human head and skull can be simplified as an upper and lower jaw. The upper jaw would have a mass equal to that of the head, and the lower law a mass as close to clinically recorded as possible. Because the side impact has been discounted from investigation, this leaves only the upper cut and frontal impacts, the movement from these is going to be predominately forward and backward if the force is applied to the centre of the jaw. If the force is applied to one side, rotation about the vertical axis will occur. If only centralised impacts are being studied then this rotation can be ignored making the model simpler to design, make and use.

The shape of the jaw can be simplified without making a difference to the performance of the rig (Figure 9.2)

Summary of Physical Dimensions (Average values)

A (Width lower jaw)	B (Horizontal length lower jaw)	C (Vertical height lower jaw)	D (Horizontal length upper jaw)	E (Width upper jaw)
98	**89**	**62**	**59**	**62**

The weight of the head of a 50 percentile man if 4.9Kg.

8.2 Forces

The force applied to the model is dependant upon which impact type is being investigated. For frontal impacts such as hockey pucks and cricket balls the force applied should be between 320N and 800N. Further work is required to investigate the force occurring during upper cut type impacts. The best method of finding the force associated with the upper cut is to use a system such as the hydraulic cylinder and pressure transducer which can measure the pressure and hence the force directly without the need for a punch bag or similar equipment.

8.2.1 Method of applying the force

All three methods of applying the force (dropweight, Charpy or hydraulic/pneumatic) could be used to apply the force. The hydraulic/pneumatic system would be the easiest and most adaptable system to design a test mouth for, but the cost and complexity of the liquid or gas circuitry may be prohibitive.

8.2.2 Methods of measuring force/displacement

The method employed to measure the force must affect the measurements little as possible. The best solution is to lacquer the teeth and use the results from this to accurately position strain gauges. The strain gauges will have to be connected to a data logger so that the strains occurring during the impact can be recorded. To get a basic idea of what is happening plasticine teeth could be used to determine

8.2.3 Additional Findings

The research into the best method of measuring the forces acting on a punch bag highlighted the use of a prescale film produced by Fuji. This film was not suitable for the purpose but another use has been found.

Two issues that affect the performance of the guard over time are the wear rate of the guard and the material thickness over the molars. These are important issues that need investigating. The use of the prescale film will allow the bite pattern of the wearer to be obtained. This information will allow the technician producing the guard to add extra material to problem areas where it is required. The prescale film would have to be encased in a plastic bag or some other protective coating because the film must by dry to work.

Thorogood M, MSc project, Department of Mechanical Engineering, University of Sheffield. Supervised by Dr M S Found.

8.3 In situ

To give the best possible indications of mouthguard efficacy an 'in-situ' test needs to be developed, as yet there is no method available for this type of test.

In the research that was carried out the results have indicated the properties of mouthguard design and material that are desirable when considering the impact conditions that are present in a contact sport, for example:

---

1. Sufficient occlusal thickness to reduce the effects of cumulative concussion and lessen the incidence of total loss of consciousness.
2. The material must return to its original shape, even after repeated impacts, but in a controlled manner that will not be harmful to the oral tissues. The material must not return to its original shape too quickly.
3. The research has shown that in-situ tests are vital to assess the efficacy of any type of mouthguard.
4. The polariscope has shown that the manufacturing process has a very real and significant effect on the way pEVA mouthguard material reacts during an impact event.

References

Barankovich, G. (1975). "Mouth protector for an edentulous patient." Journal of Prosthetic Dentistry. **34**(5): 588-90.

Bishop, B. M., E. H. Davies, et al. (1985). "Materials for mouth protectors." Journal of Prosthetic Dentistry. **53**(2): 256-61.

Blignaut, J. B., I. L. Carstens, et al. (1987). "Injuries sustained in rugby by wearers and non-wearers of mouthguards." British Journal of Sports Medicine. **21**(2): 5-7.

Bolhuis, J. H., J. M. Leurs, et al. (1987). "Dental and facial injuries in international field hockey." British Journal of Sports Medicine. **21**(4): 174-7.

Braden, M., P. S. Wright, et al. (1995). "Soft lining materials--a review." European Journal of Prosthodontics & Restorative Dentistry. **3**(4): 163-74.

Bulsara, Y. R. and I. R. Matthew (1998). "Forces transmitted through a laminated mouthguard material with a Sorbothane insert." Endodontics & Dental Traumatology. **14**(1): 45-7.

Chalmers, D. J. (1998). "Mouthguards. Protection for the mouth in rugby union." Sports Medicine. **25**(5): 339-49.

Chandler, N. P., N. H. Wilson, et al. (1987). "A modified maxillary mouthguard." British Journal of Sports Medicine. **21**(2): 27-8.

Chapman, P. J. (1985). "Improved mouthguard design for the edentulous sportsman." Australian Dental Journal. **30**(2): 86-8.

Chapman, P. J. (1986). "The bimaxillary mouthguard: a preliminary report of use in contact sports." Australian Dental Journal. **31**(3): 200-6.

Chapman, P. J. (1989). "Players' attitudes to mouthguards and prevalence of orofacial injuries in the 1987 U.S. Rugby Football Team." American Journal of Sports Medicine. **17**(5): 690-1.

Chapman, P. J. (1989). "Mouthguards and the role of sporting team dentists. [see comment]." Australian Dental Journal. **34**(1): 36-43.

Chapman, P. J. (1995). "Mouthguard protection in sports injury.[comment]." Australian Dental Journal. **40**(2): 136.

Chapman, P. J. (1996). "Mouthguard protection in sports.[comment]." Australian Dental Journal. **41**(3): 212.

Clegg, J. H. (1969). "Mouth protection for the rugby football player." British Dental Journal. **127**(7): 341-3.

Craig, R. (1993). Restorative Dental Materials. ISBN 0-8016-6872-7

Craig, R. G. and W. C. Godwin (1967). "Physical properties of materials for custom-made mouth protectors." Journal of the Michigan State Dental Association. **49**(2): 34-40.

Croll, T. P. and C. R. Castaldi (1989). "The custom-fitted athletic mouthguard for the orthodontic patient and for the child with a mixed dentition." Quintessence International. **20**(8): 571-5.

Davidson, C. L. and G. Boere (1990). "Liquid-supported dentures. Part I: Theoretical and technical considerations." Journal of Prosthetic Dentistry. **63**(3): 303-6.

DeYoung, A. K., E. Robinson, et al. (1994). "Comparing comfort and wearability: custom-made vs. self-adapted mouthguards." Journal of the American Dental Association. **125**(8): 1112-8.

Dorney, B. (1996). "Mouthguard protection in sports injury. Author's reply.[see comment][comment]." Australian Dental Journal. **41**(1): 63.

Flanders, R. A. (1993). "Mouthguards and sports injuries." Illinois Dental Journal. **62**(1): 13-6.

Flanders, R. A. (1995). "Project Mouthguard." Illinois Dental Journal. **64**(2): 67-9.

Found M S, Howard I C, Paran A P. (1998). "Interpretation of signals from dropweight impact tests." Composite Structures. **42**: 353-363.

Francis, K. T. and J. Brasher (1991). "Physiological effects of wearing mouthguards." British Journal of Sports Medicine. **25**(4): 227-31.

Gerke, D. C. (1980). "Mouthguards for edentulous patients." Australian Dental Journal. **25**(1): 25-7.

Godwin, W. C. (1991). "The role of the sports team dentist." Dental Clinics of North America. **35**(4): 701-5.

Godwin, W. C. and R. G. Craig (1968). "Stess transmitted through mouth protectors." Journal of the American Dental Association. **77**(6): 1316-20.

Going, R. E., R. E. Loehman, et al. (1974). "Mouthguard materials: their physical and mechanical properties." Journal of the American Dental Association. **89**(1): 132-8.

Greasley, A., G. Imlach, et al. (1998). "Application of a standard test to the in vitro performance of mouthguards." British Journal of Sports Medicine. **32**(1): 17-9.

Greasley, A. and B. Karet (1997). "Towards the development of a standard test procedure for mouthguard assessment." British Journal of Sports Medicine. **31**(1): 31-5.

Guevara, P. A. and D. N. Ranalli (1991). "Techniques for mouthguard fabrication." Dental Clinics of North America. 35(4): 667-82.

Guevara, P. H., S. O. Hondrum, et al. (2001). "A comparison of commercially available mouthguards and a custom mouthguard." General Dentistry. 49(4): 402-6.

Hickey, J. C., A. L. Morris, et al. (1967). "The relation of mouth protectors to cranial pressure and deformation." Journal of the American Dental Association. 74(4): 735-40.

Hoffmann, J., G. Alfter, et al. (1999). "Experimental comparative study of various mouthguards." Endodontics & Dental Traumatology. 15(4): 157-63.

Holt, R. A., C. G. Zylinski, et al. (1991). "Force versus time profiles of selected heat-processed denture liners." International Journal of Prosthodontics. 4(2): 164-8.

Jagger, R., P. Milward, et al. (2000). "Properties of an experimental mouthguard material." International Journal of Prosthodontics. 13(5): 416-9.

Johnsen, D. C. and J. E. Winters (1991). "Prevention of intraoral trauma in sports." Dental Clinics of North America. 35(4): 657-66.

Johnston, T. and L. B. Messer (1996). "An in vitro study of the efficacy of mouthguard protection for dentoalveolar injuries in deciduous and mixed dentitions." Endodontics & Dental Traumatology. **12**(6): 277-85.

Kawano, F., A. Koran, 3rd, et al. (1993). "Effect of soft denture liner on stress distribution in supporting structures under a denture." International Journal of Prosthodontics. **6**(1): 43-9.

Kawano, F., N. Tada, et al. (1991). "The influence of soft lining materials on pressure distribution." Journal of Prosthetic Dentistry. **65**(4): 567-75.

Kay, E. J., P. Kakarla, et al. (1990). "Oro-facial and dental injuries in club rugby union players." British Journal of Sports Medicine. **24**(4): 271-3.

Lancaster, D. M. and D. N. Ranalli (1993). "Comparative evaluation of college football officials' attitudes toward NCAA mouthguard regulations and player compliance." Pediatric Dentistry. **15**(6): 398-402.

Lee-Knight, C. T., R. D. Bell, et al. (1991). "Protective mouthguards and sports injuries." Journal (Canadian Dental Association). **57**(1): 39-41.

Lephart, S. M. and F. H. Fu (1991). "Emergency treatment of athletic injuries." Dental Clinics of North America. **35**(4): 707-17.

Loehman, R. E., M. S. Chan, et al. (1975). "Optimization of materials for a user-formed mouthguard." Annals of Biomedical Engineering. **3**(2): 199-208.

McCrory, P. (1999). "The eighth wonder of the world: the mythology of concussion management." British Journal of Sports Medicine. **33**(2): 136-7.

McNutt, T., S. W. Shannon, Jr., et al. (1989). "Oral trauma in adolescent athletes: a study of mouth protectors." Pediatric Dentistry. **11**(3): 209-13.

Oikarinen, K. S. and M. A. Salonen (1993). "Introduction to four custom-made mouth protectors constructed of single and double layers for activists in contact sports." Endodontics & Dental Traumatology. **9**(1): 19-24.

Oikarinen, K. S., M. A. Salonen, et al. (1993). "Comparison of the guarding capacities of mouth protectors." Endodontics & Dental Traumatology. **9**(3): 115-9.

Park, J. B., K. L. Shaull, et al. (1994). "Improving mouth guards." Journal of Prosthetic Dentistry. **72**(4): 373-80.

Parker, H. M. (1966). "Impact reduction in complete and partial dentures, a pilot study." Journal of Prosthetic Dentistry. **16**(2): 227-45.

Powers, J. M., W. C. Godwin, et al. (1984). "Mouth protectors and sports team dentists. Bureau of Health Education and Audiovisual Services, Council on Dental Materials, Instruments, and Equipment." Journal of the American Dental Association. **109**(1): 84-7.

Ranalli, D. N. and P. A. Guevara (1992). "A new technique for the custom fabrication of mouthguards with photopolymerized urethane diacrylate." Quintessence International. **23**(4): 253-5.

Ranalli, D. N. and D. M. Lancaster (1993). "Attitudes of college football officials regarding NCAA mouthguard regulations and player compliance." Journal of Public Health Dentistry. **53**(2): 96-100.

Ranalli, D. N. and D. M. Lancaster (1995). "Attitudes of college football coaches regarding NCAA mouthguard regulations and player compliance." Journal of Public Health Dentistry. **55**(3): 139-42.

Rosen, M. and J. Gritzman (1996). "A mouth protector for an edentulous patient: a case report." Journal of the Dental Association of South Africa. **51**(7): 417-8.

Scott, J., F. J. Burke, et al. (1994). "A review of dental injuries and the use of mouthguards in contact team sports." British Dental Journal. **176**(8): 310-4.

Seals, R. R., Jr. and B. C. Dorrough (1984). "Custom mouth protectors: a review of their applications." Journal of Prosthetic Dentistry. **51**(2): 238-42.

Stenger, J. M. (1987). "Mouthguard report." Journal of the American Dental Association. 114(6): 766.

Treloar, L. R. G. (1970). Introduction to Polymer Science. ISBN 0 85109 100 8

Turner, C. H. (1977). "Mouth protectors." British Dental Journal. 143(3): 82-6.

Ward, I. (1971). Mechanical Properties of Solid Polymers. London, Wiley-Interscience. ISBN 0 471 91995 0

Warnet, L. and A. Greasley (2001). "Transient forces generated by projectiles on variable quality mouthguards monitored by instrumented impact testing." British Journal of Sports Medicine. 35(4): 257-62.

Welbury, R. R. and J. J. Murray (1990). "Prevention of trauma to teeth." Dental Update. 17(3): 117-21.

Westerman, B., P. M. Stringfellow, et al. (1995). "Forces transmitted through EVA mouthguard materials of different types and thickness." Australian Dental Journal. 40(6): 389-91.

Westerman, B., P. M. Stringfellow, et al. (1997). "An improved mouthguard material." Australian Dental Journal. 42(3): 189-91.

Westerman, B., P. M. Stringfellow, et al. (2000). "The effect on energy absorption of hard inserts in laminated EVA mouthguards." Australian Dental Journal. 45(1): 21-3.

Widmer, R. P. (1992). "Oro-facial trauma in children." Australian Family Physician. 21(9): 1263-5, 1268-70.

http://www.sportsdentistry.com

http://www.experimental-stress.com/ University of Sheffield

http://eande.lbl.gov/ECS/aerogels/sakinegy.htm

http://www.howstuffworks.com

http://www.plastiquarian.com/eva.htm

http://www.devicelink.com/mddi/archive/99/03/008.html

http://www-tec.open.ac.uk/materials/mem/mem-photo.html

http://info.nike.com/story/pr_tech2.shtml

http://www.nottingham.ac.uk/~eazacl/H3CPOE/Viscoelasticity.pdf

http://www.nottingham.ac.uk/~eazacl/H3CPOE/Temperature_Effects.pdf

http://www.silicone-review.gov.uk/silicone/

http://irc.leeds.ac.uk/iaps/mod1/node60.html

Proc ACUN – 4 "Composite Systems –
Macrocomposites, Microcomposites, Nanocomposites",
UNSW, SYDNEY, Australia, 21-25 July 2002
Eds : S. Bandyopadhyay et al, ISBN 0 7334 1862 7

The influence of heat treatment on the impact performance of sports mouthguard materials

D G Patrick, R van Noort and M S Found
Centre for Biomaterials and Tissue Engineering
m.s.found@sheffield.ac.uk

Abstract

During the course of this research the effect of heat processing on the physical properties of ethylene vinyl acetate (EVA) was observed. The treatment reduced the process stresses, giving reduced impact force and increased displacement. The mouthguard manufacturing process may compromise its performance as a protective device.

1 Introduction

Mouthguards have been worn by sportsmen now for about a hundred years and were initially used by boxers. Initially the mouthguard was made from a horseshoe shaped piece of natural rubber that had been hollowed out on one side so that it would fit over the upper teeth and was worn to prevent the teeth from being chipped or broken. It was not adapted to the teeth, the jaw had to be clenched to hold the mouthguard in place, making it difficult for the wearer to breathe [1,2]. Athletes can still buy this type of 'unfitted' mouthguard today, the materials have changed however – EVA being substituted for rubber. Many sports shops sell these types of mouthguard and, surprisingly, are sometimes recommended to sportsmen and women by their dentist. It has been recognised that this type of mouthguard offers a very low level of protection to the wearer and has the added danger of becoming dislodged and obstructing the air passage causing asphyxiation. Sportsmen should be actively discouraged from wearing such a mouthguard [3].

Three types of mouthguard are available today:

i) **Stock mouthguards** - come in differing sizes and are ready for immediate use with no adaptation of the device being required. These types of mouthguard are made from either polyvinyl chloride (although the use of PVC for mouthguards has now been outlawed by the E.U.), polyurethane or a co-polymer of vinyl acetate or ethylene. Stock mouthguards are thought to be the least favourable as they offer the lowest level of protection and may even be dangerous as they may give an athlete a false sense of security [4].

ii) **Mouth-formed** – also known as a 'boil and bite' type. A thermoplastic rim is heated in very hot water, placed in the mouth and then moulded by biting and sucking.

iii) **Custom-made** - this type of mouthguard is made in a dental laboratory on a cast of the mouth. EVA is heated in a pressure or vacuum forming machine and when soft enough it is placed over the cast and air pressure or a vacuum is applied which closely adapts the soft material to the cast.

Of the types listed it is generally thought that the custom-made mouthguards are best and offer the most protection to the wearer [5].

During the 1950's and 1960's, in America, mouthguard technology went through a period of rapid development. The research carried out suggested that the mouthguard should be worn on the upper (maxillary) teeth as they were the most prone to damage. Around this time mouth-formed and custom-made mouthguards were developed although the early studies did not seem to agree as to which type of mouthguard was the best. Surveys of player opinion, however, did report that the custom made mouthguard was the best option with regard to retention, cleanliness, ease of speech, lack of odour, taste and durability [6].

Cost can be a prohibiting factor when choosing a mouthguard and may deter many people from opting for a custom made mouthguard, regardless of the fact that nearly all the literature recommends that custom made mouthguards are the most effective type of protection.

It is the purpose of a mouthguard to do, quite literally, what its name implies. It should protect the teeth from fracture by an impact. Protect the lips and cheeks from the teeth in the event of an impact, protect the teeth from each other when the mandible suffers an impact and also from bruxism, as some players tend to grind their teeth whilst participating in their chosen sport. More recently emphasis is being placed on prevention of concussion and knock-outs by having a sufficient thickness of material occlusally to keep the condyle out of contact with the glenoid fossa. As it is the action of the condyle impacting against the glenoid fossa that directs the force of a blow directly to the brain, thereby causing unconsciousness and/or concussion. This thickening of the occlusal part of the mouthguard, to keep the condyle and glenoid fossa out of contact can also prevent fracture of the ramus and neck of the condyle [7].

A sportsman or woman, who wears a mouthguard, is a more confident participant in their sport as they are less concerned about receiving a traumatic blow that could affect consciousness or result in a disfiguring injury; they concentrate more of their efforts on the execution of their sport [7]. It could, therefore, be surmised that athletes who wear mouthguards and other such protective devices play their sport harder, thus making it more important for the non-mouthguard wearing players to wear a mouthguard and any other necessary protective equipment.

2 Ideal Mouthguard Properties

When considering the ideal properties of a mouthguard and the material from which it is made some general requirements of what is expected from the mouthguard material must be carefully thought about.

Craig and Godwin [6] carried out tests on thirteen different products (some commercially available, the rest experimental), used in the construction of mouthguards, three were polyurethane, six were polyvinylacetate-polyethylene polymer, one was latex rubber, another was said to be Geon 135F1 based vinyl resin plastisol while one was simply listed as thermoplastic ! Their testing of the materials was extensive and covered such aspects as, water sorption, strength, hardness and energy absorption. In the discussion that followed Craig and Godwin went on to say that caution should be exercised when interpreting the energy absorption results, "since a high energy absorption does not necessarily indicate protection of the underlying teeth." The harder urethanes may transmit more energy to the underlying teeth than some of the softer materials, such as polyvinylacetate-polyethylene which was found to have lower energy absorption than the urethanes. The latex that was tested had the lowest energy absorption and due to its exceptional softness would allow the highest penetration during impact loading, therefore transmitting a large percentage of the energy to the teeth. Somewhat ambiguously Craig and Godwin went on to decide that a material with intermediate hardness and moderate energy absorption would be best for a mouthguard and that the degree of protection offered by a single material could be altered by changing the thickness of the material used.

To find the right material for a mouthguard; Bishop, Davies and von Fraunhofer [8] carried out tests on nine materials that were all essentially the same but with differing mixtures of polyvinylacetate and polyethylene. The specimens contained between 7.5% and 33% polyvinylacetate (PVA), they were tested for the following properties: water absorption, tear strength, compressibility, along with static and dynamic energy absorption. Their findings were that the material used for a mouthguard should indent easily but be capable of absorbing energy under both static and dynamic loading. Polyvinylacetate-polyethylene (EVA) had a far higher ability to absorb energy when higher percentages of PVA were present. Another factor that was found to be of great importance was that of the compressibility characteristics of the material, or as Bishop, Davies and von Fraunhofer described it, the depth the material is compressed in the initial purely elastic phase; which was referred to as the elastic gradient. A low elastic gradient would indicate a material that requires too high a force to compress it, while a high elastic gradient indicates a material that is compressed far too easily. It was concluded that the most satisfactory composition of a polyvinylacetate-polyethylene mixture for a mouth protector was one that had between 18 - 24% PVA, and in the overall summing up the material with 18% PVA appeared to be the best for a sports mouthguard.

Godwin and Craig [9] investigated the effectiveness of different mouthguards that were commercially available in 1968 with some interesting results. It was found that the thickness of the protector does have a direct influence on the effectiveness of a single material, but it is not true to say that all thick materials are as effective as each other. In tests, the material 'Featherbrite' (Featherlax Corp.) that was 5.3mm thick provided a very similar amount of protection to the material 'Shield Protector' at a thickness of only 2.7mm. However, it is not clear what these materials are made from but it can be deduced that the former is polyurethane and the latter is either latex or polyethylene-polyvinylacetate.

Park *et al* [10], after testing five different types of material that are used in the construction of mouthguards reported that "the thicker the material is, the greater the resulting energy absorption is." The materials tested were polyvinylacetate-polyethylene (EVA), polyvinylchloride (PVC), natural rubber, soft acrylic resin and polyurethane (PU). In the tests that were carried out the mouthguards that were made from EVA, PVC and PU were grouped together as there were no significant differences in the parameters measured of these materials. It should be noted, however, that the percentage of vinyl-acetate can be altered thereby changing the properties of EVA (Bishop, Davies and von Fraunhofer, [8]). It has been shown that an 18% content of vinyl-acetate in the EVA is the most suitable composition for mouthguard materials as it exhibited greater energy absorptive qualities over materials with a lower vinyl-acetate content (Bishop, Davies and von Fraunhofer, [8]). Conversely, a high vinyl-acetate content diminishes the energy absorptive capabilities of the resultant polymeric compound. Park *et al* [10] found that most commercially available mouthguards had a vinyl-acetate content of 28%. In conclusion to their impact tests Park *et al* [10] found that a thicker mouthguard is more effective in withstanding a blow to the mouth and in some cases the thinner sheets of material used were destroyed. Overall a 4mm thick sheet was deemed to be the best choice for constructing a mouthguard. One of the materials tested, Proform, had a harder material laminated into the sheet which is intended to reinforce the mouthguard after fabrication from behind the anterior teeth, but this harder material did not seem to have any positive effects - the EVA without it performed better in all the impact tests. Park *et al* went on to say that more interesting results may be gained by sandwiching harder materials, such as 99% acetate in the middle with 28% acetate on the outside so giving maximum protection and comfort.

A more recent test [11] found that "the incorporation of the stiff and hard styrene butadiene material into the guard had no observable beneficial effects. It made the mouthguards difficult to fit and susceptible to crack damage in the impact zone."

Ranalli and Guevara [12] describe a new method for the manufacture of mouthguards using a photopolymerised urethane diacrylate, initially this material was introduced as a denture relining material. The only advantage this technique has over the conventional method of construction of a mouthguard is that an expensive pressure or vacuum forming machine is not necessary, the material can be cured in a relatively inexpensive light curing unit.

We have previously identified [13] that a mouthguard should be made of a composite laminate construction and that a typical structure would have a very compliant centre region with a more rigid outer layer. Combinations of compliant/rigid materials can be built up in a multi-layered composite system with materials and layer thickness being adapted according to the requirements for a particular sport or individual. For example, if a mouthguard is made with a softer more compliant material sandwiched between two layers of a more rigid material, such as EVA, there will be a reduced impact force transferred to the teeth due to the shock absorbing capability of the compliant material layer. Harmful rebound energy will also be reduced as the composite laminate will return to its original shape more slowly than a single material system.

The aim of this study is to identify the influence of heat treatment during the processing of the mouthguard materials observed during earlier investigations [13]. Impact tests on samples with and without heat treatment were evaluated using photoelastic methods.

3 Materials and Methods

Samples of Erkoflex EVA measuring 120mm diameter with thickness ranging from 1 – 5mm were supplied by Erkodent with a Shore A hardness of 82. Typical mechanical properties are: tensile strength 11 MPa, elongation 900% and tear strength 350N/cm. For the thermal processing of the EVA a furnace was used to heat the test material to it's glass transition temperature (Tg) of 84°C ± 3 °C. A plaster mould was taken from a 6mm thick, 125mm diameter disc and was used to hold and contain the test piece which was, in each instance, 125mm diameter and no thicker than 5mm. The material was brought up to the Tg and held at that point for 10 minutes. The specimen was then removed from the furnace and allowed to cool to room temperature.
After the heat treatment all samples were then placed in a circular polariscope to observe, photoelastically, strains within the material. Transmission photoelastic methods of stress analysis were used to provide a full field of the strain distribution within the mouthguard material. As the material used was transparent the strain present was easily observed.

Dropweight impact tests were then conducted on the moulded samples using a custom built instrumented impact testing rig [14]. The incident kinetic energy was obtained by varying the mass from a fixed drop-height of 0.5m. All samples were circularly clamped (to give a test region of 80mm diameter) and force-time and displacement-time plots obtained. After the impact event all samples were placed again in the polariscope and any changes in strain were noted.

4 Results

The force/time and displacement/time plots (Figs.1-4) demonstrate the extent of the physical change that has taken place within the EVA. The calculated displacement has increased significantly, >66%, (untreated EVA>18mm centre displacement, heat treated EVA >30mm centre displacement). Peak Impact Force (PIF) was also reduced in the heat treated sample (PIF<140N) compared to that of untreated EVA (PIF=160N).

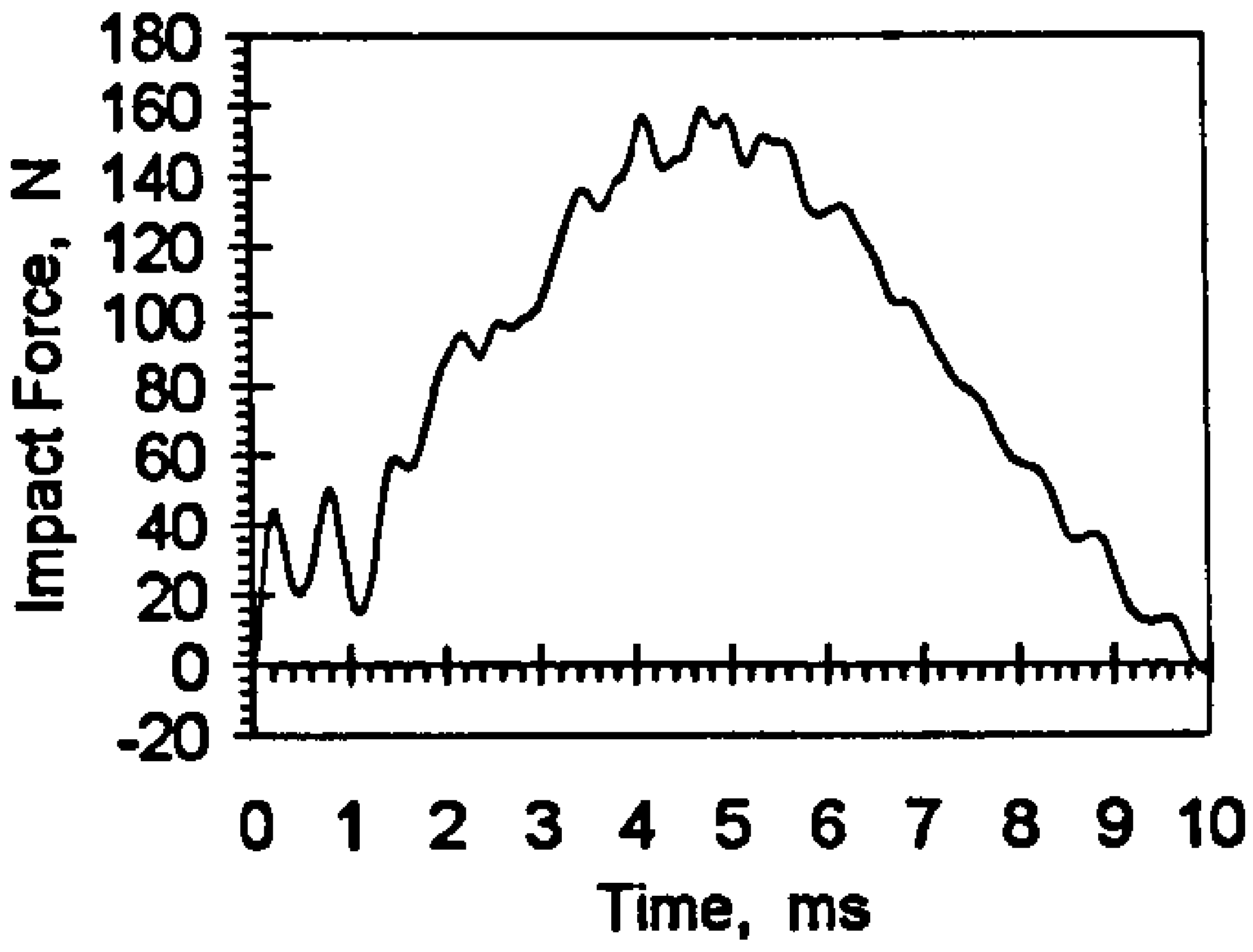


Figure 1. Force/time history for untreated EVA of 5mm thickness

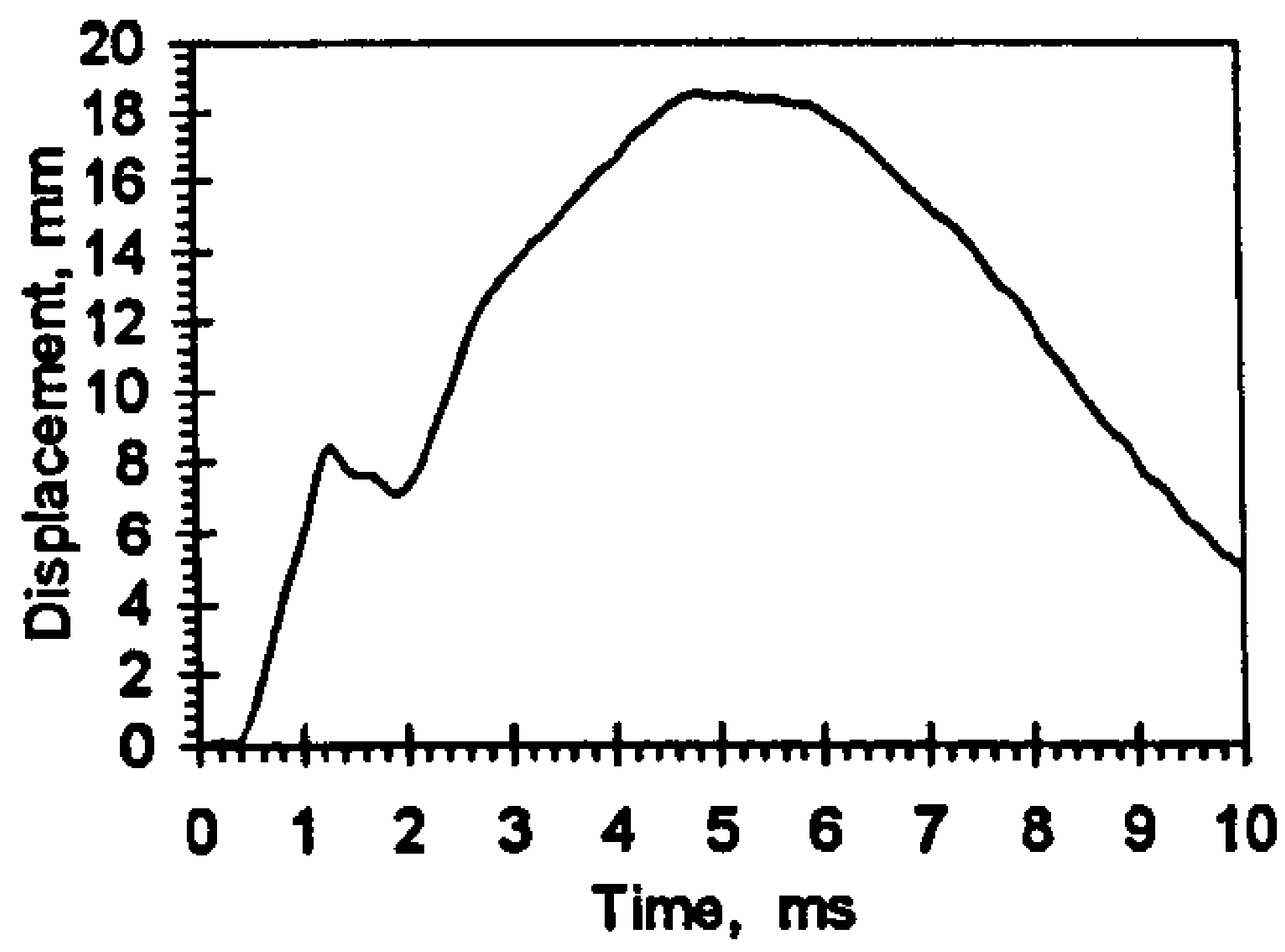


Figure 2. Displacement/time history for untreated EVA of 5mm thickness

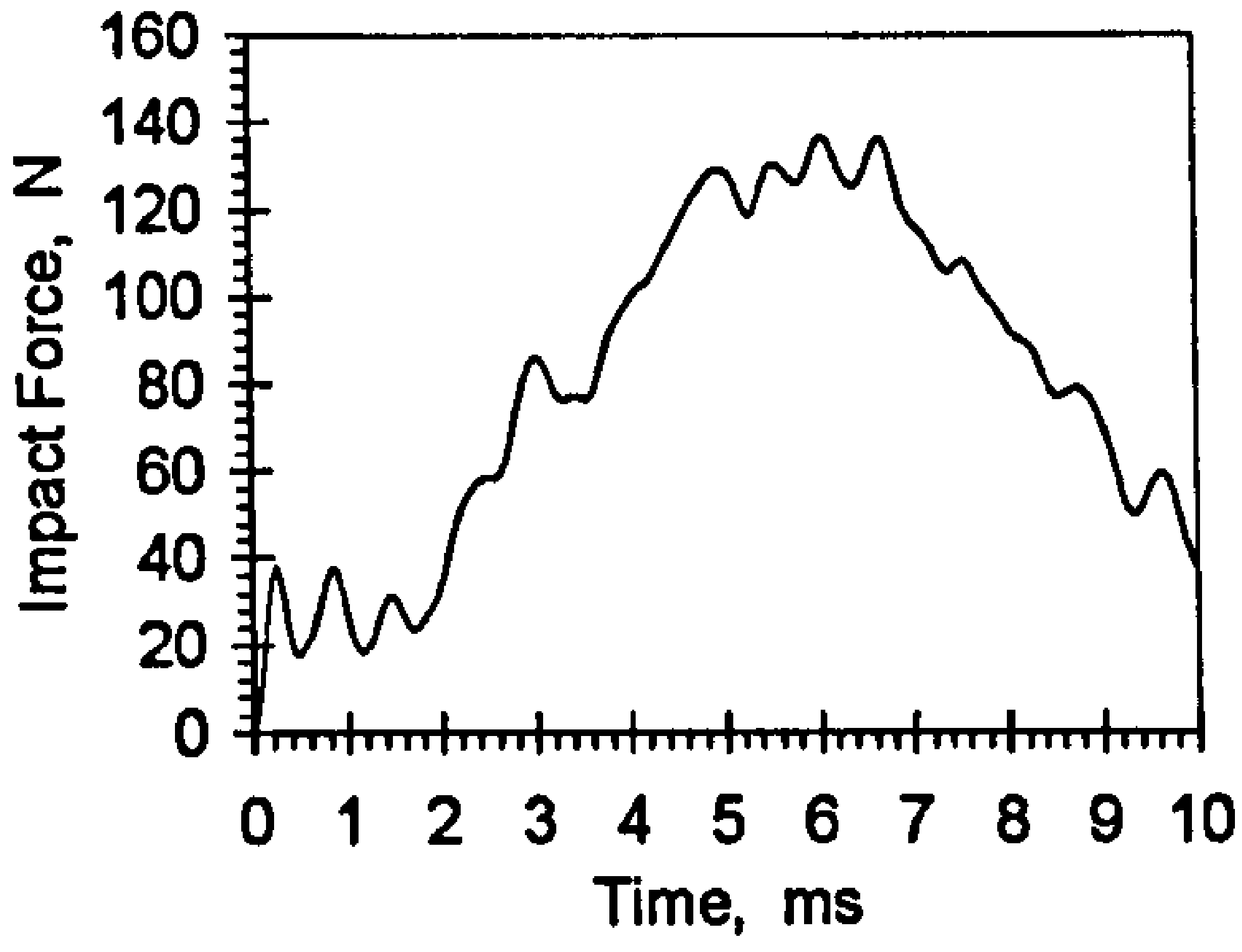


Figure 3. Force/time history for heat treated EVA of 5mm thickness.

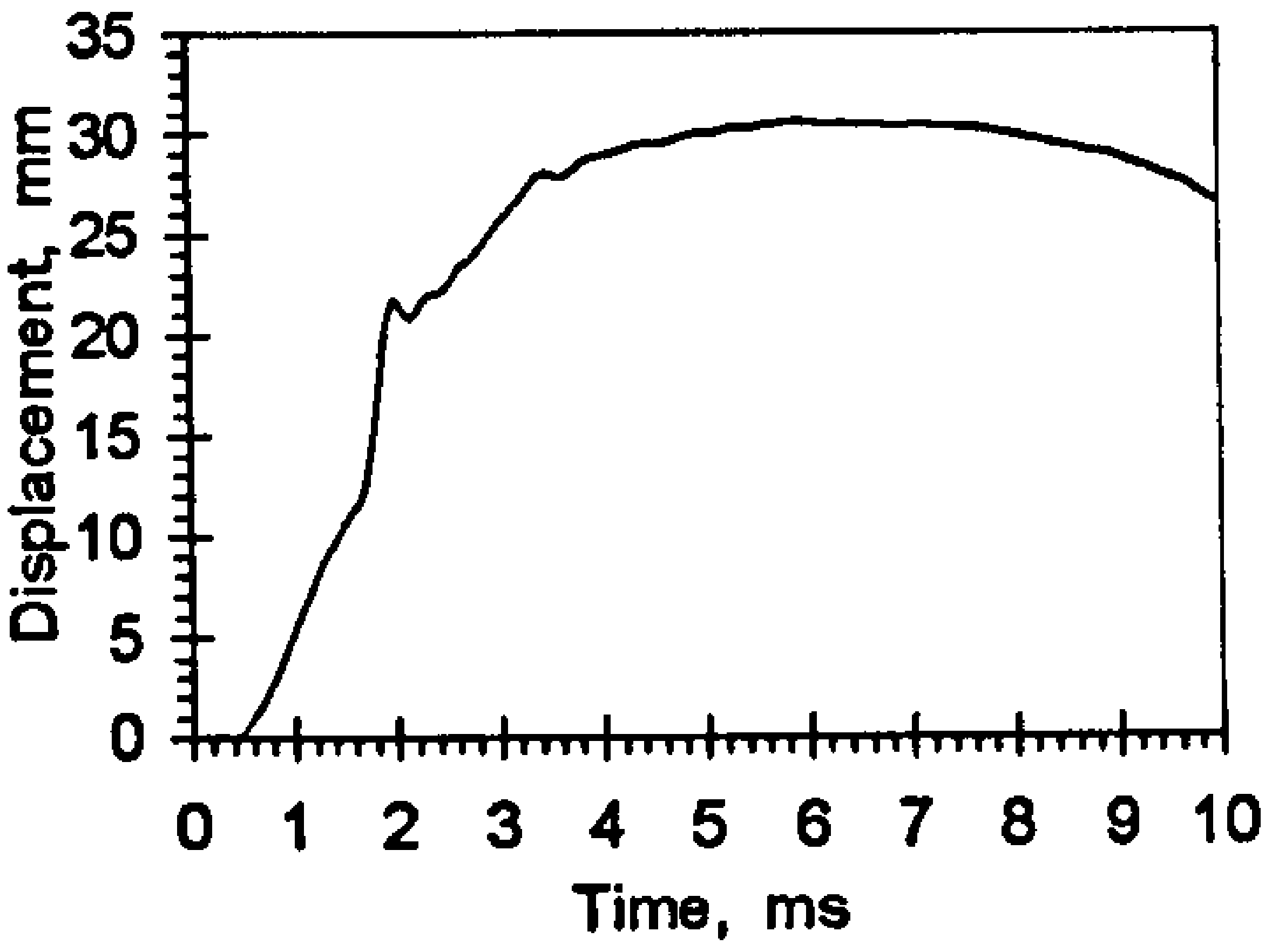


Figure 4. Displacement/time history for heat treated EVA of 5mm thickness.

Results from the polariscope showed that stress is already present in the EVA when received from the supplier, indicating the effect of processing conditions for the initial material. The results of the impact test did not noticeably change the fringe patterns observed in the polariscope. The heat treatment undertaken at the glass transition temperature of EVA virtually eliminates stress from the material. In the main test region the impact response of the heat-treated sample showed little difference to that before testing. However, the influence of the stresses induced by the circular clamping could be observed in the polariscope.

5 Discussion

The expected result of the heat treatment of the EVA was to relieve most of the residual stress from the EVA left over from the manufacturing process. The vast majority of tests and experiments that have been carried out in the past, by other researchers, has always tested the mouthguard material in an unprocessed, as received condition from the supplier, a state which may give rise to misleading information on how well a mouthguard will perform in a protective capacity. The impact results from all the various tests that have been carried out will not give a true representation of the mouthguards ability to withstand an impact. Whilst the tests reported here allow a better understanding of a mouthguard material to be evaluated, ultimately the mouthguards themselves need to be tested. We are presently designing a new impact machine in order to fully evaluate the behaviour of the mouthguards.

6 Conclusion

The processing of an EVA mouthguard material significantly affects its performance under impact.

Unprocessed EVA mouthguard materials exhibit significant differences in their impact properties compared with heat treated EVA due to the influence of moulding stresses.

It is essential that the mouthguard should be evaluated not just the material in isolation.

7 Acknowledgements

The authors wish to thank Dr S J Zhang and Mr R J Greene for their assistance with the photoelastic studies.

8 Authors resumes

David G Patrick
Main work on the development of sports mouthguards as my PhD project, working towards a more effective mouthguard using heat treatments and lamination of composite structures. Development of web based teaching for dental students. The use of image analysis for assessing dental anomalies and research mechanisms.

Richard van Noort
Professor of Dental Materials at the University of Sheffield and Head of Centre for Biomaterials and Tissue Engineering.

Michael S Found
30 years experience in FRP composites. Main work on understanding of failure mechanisms under static, impact and fatigue loading conditions. Development of models for predicting damage tolerant, crashworthy composite structures. Recent work on energy absorbing composite systems ranging from sports mouthguards to aerospace structures and rail cabs.

9 References

[1] Chapman. P J. Mouthguards and the role of the sporting team dentists Australian Dent J; 30(2)(1989):86-88

[2] Flanders. R A. Mouthguards and sports injuries. Illinois Dent J;62 (1)(1993);13-16

[3] Chapman. P J. Orofacial injuries and the use of mouthguards by the 1984 Great Britain rugby league touring team. Br J Sp Med. Vol 19, No. 1, March 1985, 34-36

[4] Widmer. R P. Oro-facial trauma in children. Australian Family Physician,vol 21, (9), September 1992

[5] DeYoung A K, Robinson E, Godwin W C. Comparing comfort and wearability: custom-made vs. self-adapted mouthguards. JADA, vol 125, August 1994, 1112-1117

[6] Craig R G, Godwin W C. Physical properties of materials for custom made mouth protectors. Journal of the Michigan State Dental Association; vol 49, February 1967, 34-40

[7] Johnsen D C, Winters J E. Prevention of intraoral trauma in sports. Dental Clinics of North America - vol 35,(4),Oct 1991

[8] Bishop B M, Davies E H, von Fraunhofer J A. Materials for mouth protectors. J Prosthet Dent;Feb 1985; vol 53 (2)

[9] Godwin W C, Craig R G. Stress transmitted through mouth protectors. J Am Dent Assoc 1968;77:1316-20

[10] Park J B, Shaull K L, Overton B, Donly K J. Improving mouthguards. J Prosthet Dent;1994;72:373-80

[11] Greasley A, Imlach G, Karet B. Application of a standard test to the in vitro performance of mouthguards. Br J Sports Med 1998; 32: 17-19

[12] Ranalli D N, Guevara P A. A new technique for the custom fabrication of mouthguards with photopolymerised urethane diacrylate. Quintessence International; vol 23,(4), 1992, 253-255

[13] Patrick D, van Noort R and Found M S. The use of multi-layered structures for sports mouthguards. 13th International Conference on Composite Materials, ICCM 13, Beijing, June 2001 ISBN 7-900075-46-I/Z,28

[14] Found M S, Howard I C and Paran A P. Interpretation of signals from dropweight impact tests. Comp Struct; vol 42, 1998, 353-363

THE USE OF MULTI-LAYERED STRUCTURES FOR SPORTS MOUTHGUARDS

D Patrick, R van Noort and M S Found
Centre for Biomaterials and Tissue Engineering
University of Sheffield UK

SUMMARY: Previous work has indicated that the incorporation of a shock absorbing layer into the sports mouthguard reduces the likelihood of injury to the head, neck and oral cavity of the wearer. The purpose of this study is to investigate the use of multi-layered structures that protect an easily deformable structure during an impact. Dropweight impact tests were conducted on a series of moulded samples which were circularly clamped and force-time and displacement-time plots obtained. Single thickness specimens of ethylene vinyl acetate (EVA), 1-5mm thick were compared with laminated structures of EVA, incorporating 1mm thick layers of polymethylmethacrylate (PMMA) and a silicone or synthetic rubber up to a thickness of 5mm. In addition different thicknesses of EVA were placed on a 2mm thick substrate of PMMA. The multi-layered structures exhibited less deformation thereby transmitting less of the harmful effects through the laminate. The increase in thickness of EVA while on a PMMA substrate had little effect. It was concluded that laminated systems for mouthguards using different materials appear to offer better protection to the wearer.

KEYWORDS: mouthguard, shock absorbing, protection, impact

INTRODUCTION

Mouthguards have been worn by sportsmen for almost a hundred years and were initially used by boxers. A 'mouthguard' made from a piece of natural rubber that had been trimmed and hollowed out so that it would fit over the maxillary dentition, was worn to prevent chipped or broken teeth resulting from blows to the head. It was not adapted to the teeth, the jaw had to be clenched to hold the mouthguard in place, making it difficult for the wearer to breathe [1,2]. This type of 'unfitted' mouthguard can still be bought today, although the materials have changed - ethylene vinyl acetate being substituted for rubber. Most sports shops sell them and, surprisingly, are sometimes recommended to sportsmen and women by their dentist. This type of mouthguard offers a very low level of protection to the wearer, it also has the added danger of the possibility that it may become dislodged and obstruct the air passage causing asphyxiation. Sportsmen should be actively discouraged from wearing such a mouthguard [3].

There are three types of mouthguard that are generally available today:

i) STOCK MOUTHGUARDS - which come in differing sizes and are ready to use, mostly these types are made from either polyvinyl chloride (although the use of PVC for mouthguards has now been outlawed by the E.U.), polyurethane or a co-polymer of vinyl acetate or ethylene. Generally stock mouthguards are thought to be the least favourable as they offer the least protection and may even be thought of as dangerous as they may give a rugby player, for example, a false sense of security [4].

ii) MOUTH-FORMED - known as a 'boil and bite' type, where a thermoplastic rim is heated in hot water then placed in the mouth and moulded by biting and sucking.

iii) CUSTOM-MADE - this type of mouthguard is made in a dental laboratory on a cast taken from an impression supplied by a dentist. A thermoplastic material is heated in a

pressure or vacuum forming machine and when soft enough it is placed over the cast and air pressure or a vacuum is applied which closely adapts the soft material to the cast.
Of the types listed it is generally thought that the custom-made mouthguards are the best and offer the most protection [5].

Mouthguard technology went through a period of rapid development during the 1950's and 1960's in America. This research suggested that the mouthguard should be worn on the upper (maxillary) teeth as they were the most prone to damage. Mouth-formed and custom-made mouthguards were developed around this time and the early studies did not seem to agree as to which type of mouthguard was the best. However, surveys of player opinion did report that the custom made mouthguard was the best option with regard to retention, cleanliness, ease of speech, lack of odour, taste and durability [6].

The cost of the custom made mouthguard was, and still can be somewhat, prohibitive which may deter many people from wearing such a mouthguard, regardless of the fact that nearly all the literature recommends that custom made mouthguards are the most effective type of protection.

EVALUATION OF MOUTHGUARD MATERIALS

Ideally a mouthguard material should be odourless, tasteless, non-toxic, have good resistance to abrasion, have low water absorbency and be tough enough to last at least one season, or maybe two, of wear during competitive sport and training. Craig and Godwin [6] carried out tests on thirteen different products used in the construction of mouthguards. Their testing of the materials was extensive and covered such aspects as, water sorption, strength, hardness and energy absorption. They suggested that caution should be exercised when interpreting the energy absorption results, "since a high energy absorption does not necessarily indicate protection of the underlying teeth." Craig and Godwin [6] went on to decide that a material with intermediate hardness and moderate energy absorption would be best for a mouthguard and that the degree of protection offered by a single material could be altered by changing the thickness of the material used.

Bishop, Davies and von Fraunhofer [7] carried out tests on nine materials that were all essentially the same but with differing mixtures of polyvinyl acetate and polyethylene. The specimens contained between 7.5% and 33% polyvinyl acetate (PVA) and were tested for the following properties: water absorption, tear strength, compressibility, along with static and dynamic energy absorption. Their findings were that the material used for a mouthguard should indent easily but be capable of absorbing energy under both static and dynamic loading. Polyvinyl polyethylene acetate (EVA) had a far higher ability to absorb energy when higher percentages of PVA were present. They also observed the importance of the compressibility characteristics of the material, or the depth the material is compressed under a known force in the initial purely elastic phase; which was referred to as the elastic gradient. A low elastic gradient (penetration vs force) would indicate a material that requires too high a force to compress it, while a high elastic gradient indicates a material that is compressed far too easily. It was concluded that the most satisfactory composition of a polyvinyl polyethylene acetate mixture for a mouth protector was one that had between 18 -24% PVA, and in the overall summing up the material with 18% PVA appeared to be the best for a sports mouthguard.

Godwin and Craig [8] investigated the effectiveness of different mouthguards that were commercially available in 1968 and found that the thickness of the protector does have a direct influence on the effectiveness of a single material. However it is not true to say that all

A visco-elastic polyurethane, Sorbothane, that has been used in orthopaedic and sports applications due to its shock absorbing properties was tested by Bulsara and Matthew [15] as an intermediate layer between two layers of EVA. A piezo-electric transducer was used to measure the peak force transmitted through samples with and without the Sorbothane layer from a free falling steel ram. Bulsara and Matthew concluded that using an intermediate layer of Sorbothane may dissipate significantly the force of impact from a blow to the teeth and jaws.

In an attempt to develop a standard test procedure for mouthguard assessment Greasley and Karet [16, 17] constructed an upper jaw made from a rubber arch containing replaceable ceramic teeth and a renewable composite jawbone on which mouthguards were to be tested. Different profiles of projectile, at various energies, were impacted into the model jaw by dropping them down a clear plastic tube whilst a mouthguard was in situ and the damage to the teeth and jaw was recorded. The objective of the exercise was to produce a testing regime that could easily be applied to any mouthguard that was made to fit the standard model that they produced.

Westerman [18] used an impact test rig similar to that of a Charpy or Izod impact machine that was fitted with a blunt striker on the pendulum. Tests showed that the force transmitted through the mouthguard materials was inversely related to the thickness of the material and that a small reduction in thickness of 1 mm resulted in an increase in transmitted force of 34%. Westerman *et al* [19] also assessed the energy absorption properties of a material that contained pockets of air. It was reported that the inclusion of air cells within an EVA copolymer mouthguard material produced a reduction in transmitted forces when the impact was less than 10 kN.

Further to their previous work Godwin and Craig [8] examined the stress transmitted through mouth protectors. Brittle lacquer coatings on maxillary models that were then fitted with mouthguards, demonstrated quite graphically the effectiveness of the individual mouthguards. Physical and mechanical tests were employed to discover the basic properties of 57 different mouthguard products by Going *et al* [20] in 1974. As well as determining material properties tests for impact energy absorption and resistance to impact penetration were performed using a rebound pendulum method. It was concluded that the interpretation of the dynamic energy data from the rebound test should be viewed cautiously and that a high energy absorption level does not necessarily mean that the material will give maximum protection, since some of the absorbed energy may be transmitted directly to the underlying tooth structure.

HYPOTHESIS

It is proposed that a mouthguard should be made of a composite laminate construction and that a typical structure would have a very compliant centre region with a more rigid outer layer. Combinations of compliant/rigid materials could be built up in a multi-layered composite system with materials and layer thicknesses being adapted according to the requirements for a particular sport or individual. For example, if a mouthguard is made with a softer more compliant material sandwiched between two layers of a more rigid material, such as EVA, (see Fig. 1) there will be a reduced impact force transferred to the teeth due to the shock absorbing capability of the compliant material layer. Harmful rebound energy will also be reduced as the composite laminate will return to its original shape more slowly than a single material system.

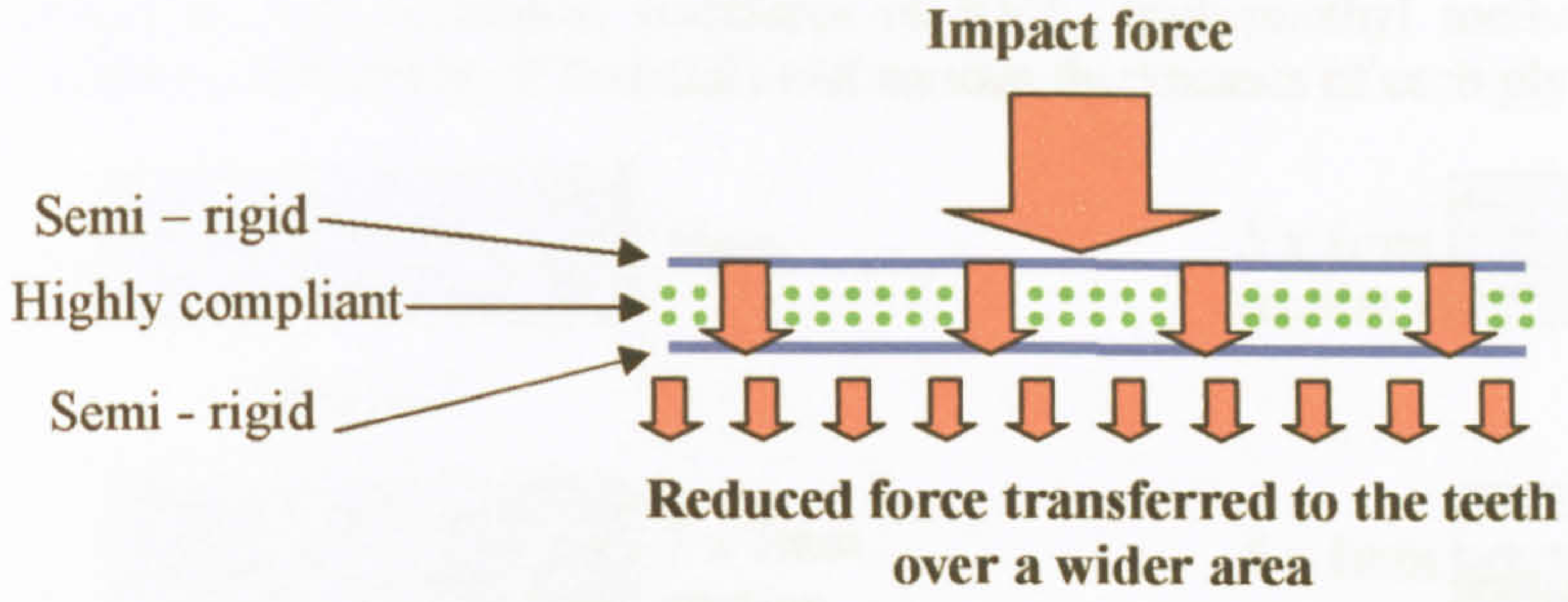


Fig. 1 Force distribution for laminate design

The aim of this study is to develop a method for the assessment of mouthguard materials and designs with the objective of improving the degree of protection provided by a mouthguard.

EXPERIMENTS

In designing the experiment it was felt that the amount of protection a material, or composite material, demonstrated the more valid the experiment would be. Previous studies have tended to show the amount of resilience present in a material by using a 'rebound test'. This kind of test was felt to be inappropriate as not enough information about the way in which a material reacts under impact loading conditions could be obtained from such a simple test.

An instrumented dropweight rig has been developed, within the Department of Mechanical Engineering at the University of Sheffield, enabling impact tests and static indentation tests to be conducted on circularly clamped panels, Found *et al* [21]. The test rig has recently been modified to permit clamping of smaller panels, i.e. mouthguard blanks. The impact rig is equipped with four transducers namely, an accelerometer, a strain-gauged load cell, a displacement transducer and opto-electronic triggering and timing sensors. The accelerometer is a miniature piezoelectronic transducer, which is connected via a signal conditioner to the data acquisition system. An infrared LED/phototransmitter reflective transducer is used to determine the displacement of the test specimen during impact. Calibration of the transducer is from static load tests performed under identical clamping conditions using an LVDT to measure the deflection at the centre of the test specimen.

The instrumented indentor is released by an electromagnetic switch from a height of 0.5m to produce an impact velocity of the impactor of about 3m/s. The data acquisition system is triggered when an aluminium flag, attached to the indentor assembly, passes the first opto-interrupter. The indentor velocity immediately before the impact event is determined by measuring the time taken for the flag, of 15.5mm depth, to cross the line of sight of the second opto-interrupter. The sensors are also used to determine the rebound velocity when energy is returned to the indentor after the impact event.

The impact forces and displacements were obtained from data that was processed through a low – pass filter at a cut – off frequency of 3.5 kHz.

Test specimens of 125mm diameter were constructed to fit the clamping mechanism of an instrumented impact testing rig, using a piezo-electric accelerometer to determine the peak impact force (PIF) and an infra-red sensor to measure the amount of deflection (Δ) respectively. Single thickness specimens of ethylene vinyl acetate (EVA), 5mm thick, were compared with laminated structures of EVA, (poly)methyl methacrylate (PMMA) using various combinations of materials and various thicknesses of each ply as shown in Fig 2

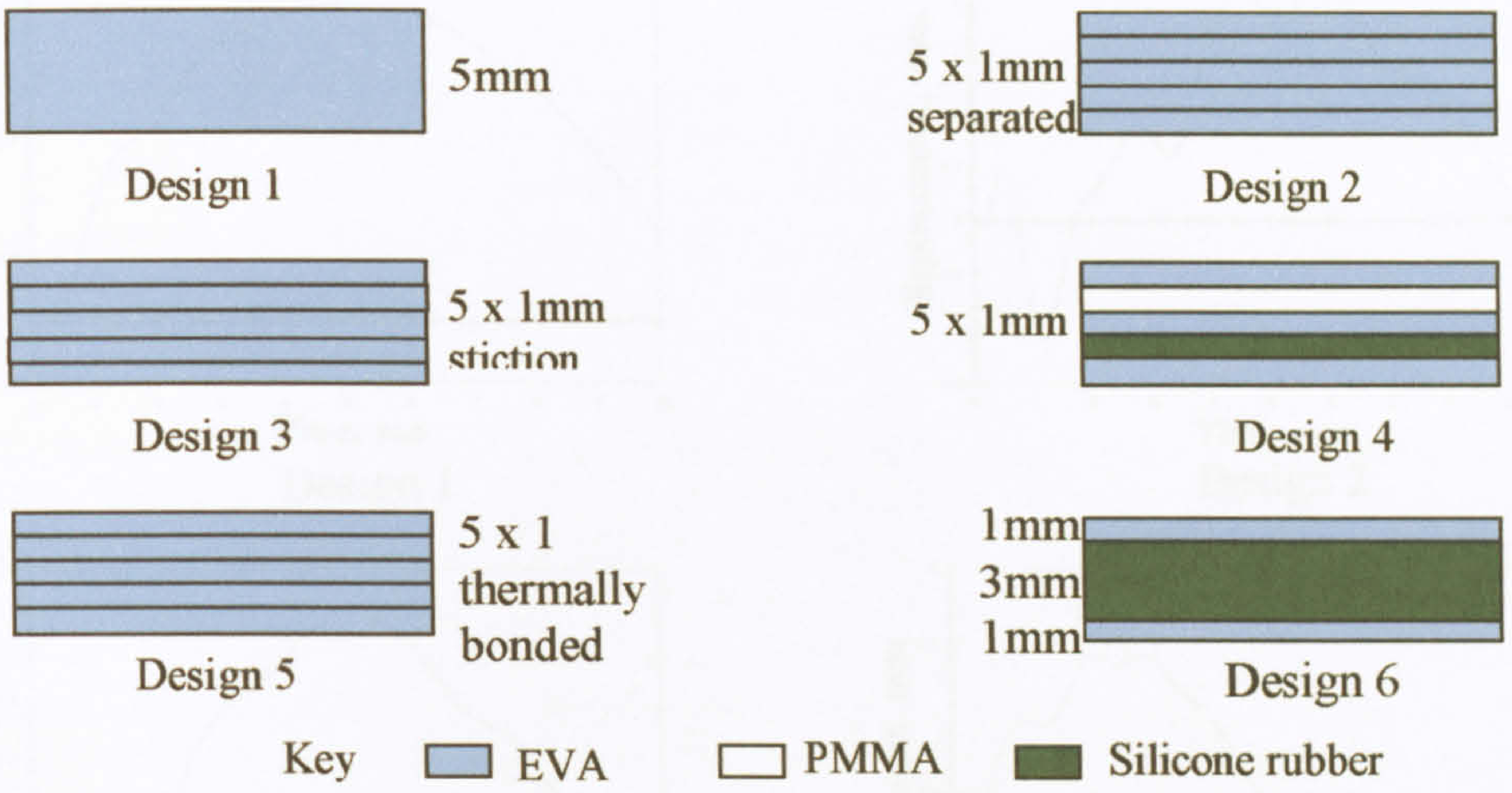


Fig 2 Mouthguard laminate designs

RESULTS

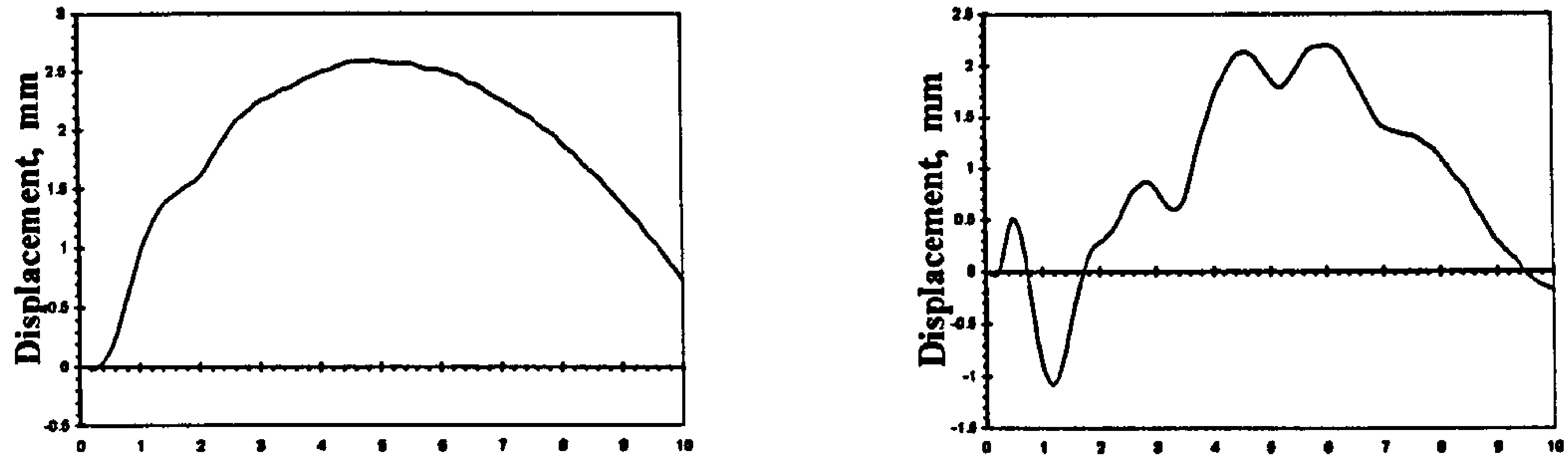
A summary of the impact performance of each laminate design is presented in Table 1 in terms of the peak impact force and maximum displacements observed during each test series.

Table 1. Peak impact force (PIF) and maximum displacement (Δ max) for each design.

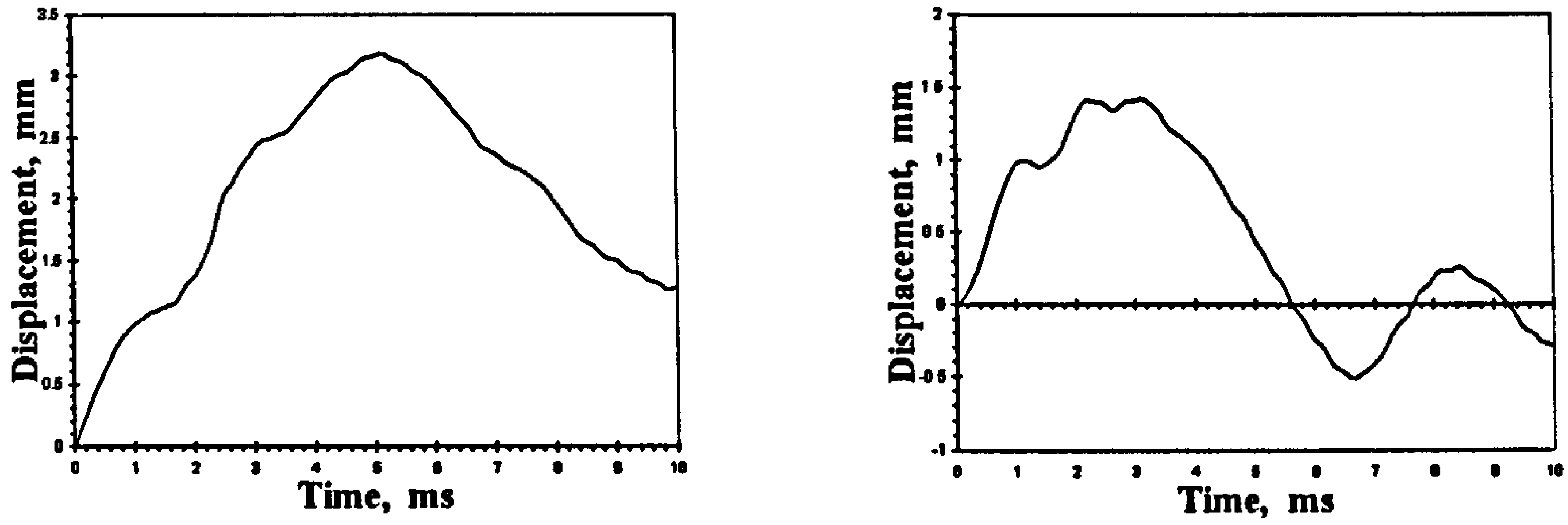
Design	PIF (N)	Δ max (mm)
1	160	2.6
2	185	2.2
3	150	3.2
4	280	1.4
5	90	1.3
6	210	1.9

From the above it was found that the laminated structures using a multi-layered system, with the exception of Design 3 which was not strictly laminated but a layered structure, exhibited less deformation (Δ max = 1.3 – 2.2 mm, Design 3 being 3.2mm) than the single system EVA (Δ max = 2.6mm). The soft compliant materials absorbed more impact and so transferred less impact energy to the substructure.

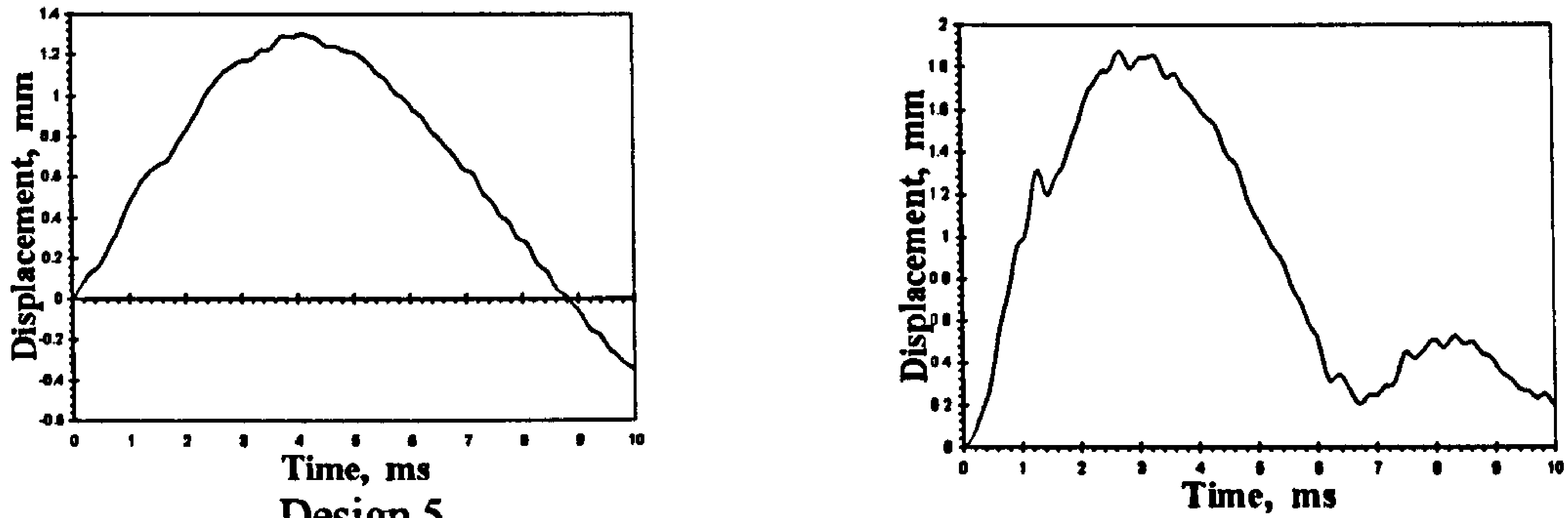
As previously reported the laminates containing synthetic rubber exhibited greater impact absorption with a peak impact force (PIF) of 300N, compared with a single material system (PIF >400N) or laminates with PMMA (PIF >500N) (Patrick *et al.* [22]). However these laminates are 2mm thicker and therefore as expected show a higher peak impact force. From Table 1 it can be observed that changing the laminate structure or even laminating thin layers of the same material can influence the peak impact force and amount of displacement that the mouthguard material exhibits.



Design 1 Design 2



Design 3 Design 4



Design 5 Design 6

Fig 3 Displacement – time histories for each laminate design

From the displacement/time curves shown in Fig 3 it can be seen that Designs 4 and 5 perform the best overall with Design 5 possibly reacting the best to the test conditions. Expectations were that Design 5 would act similarly to the monolithic structure of Design 1. A compromise, however, will have to be reached between the use of materials and thicknesses to provide the optimum laminate that could be encapsulated within a mouthguard for a particular application.

DISCUSSION

A brief review of materials and test methods for sports mouthguards shows that a wide range of thermoplastic and rubber materials have been evaluated employing different test methods. Whilst many of the tests are often only determining material properties they however suggest; that EVA appears to be an appropriate material [7, 9], the importance of section thickness [8, 9, 12], the influence of a sandwich construction [9, 10, 14, 15] and the effect of force distribution [12, 14, 15] and hence the effectiveness of the mouthguard. Furthermore, in order to fully assess the influence of an impact and the resilience of mouthguards more appropriate tests need to be carried out [11 – 13, 16, 17].

Whilst it appears that EVA is an appropriate choice of material for mouthguards it should be noted, however, that the percentage of vinyl-acetate can be altered thereby changing the properties of EVA (Bishop, Davies and von Fraunhofer, [7]). It has been shown that an 18% content of vinyl-acetate in the EVA is the most suitable composition for mouthguard materials as it exhibited greater energy absorptive qualities over materials with a lower vinyl-acetate content. Conversely, a high vinyl-acetate content diminishes the energy absorptive capabilities of the resultant polymeric compound. Park *et al* [9] found that most commercially available mouthguards had a vinyl-acetate content of 28% and observed from their impact tests that a thicker mouthguard is more effective in withstanding a blow to the mouth and in some cases the thinner sheets of material used were destroyed.

We consider that an instrumented dropweight impact rig as used in this study is more appropriate for evaluating possible material/laminate configurations for use in sports mouthguards. It enables the force-time and displacement-time characteristics of the various material/thickness combinations to be evaluated and hence to obtain a more effective measure of the energy absorbed by the mouthguard.

The multi-layered structures exhibit less deformation than the monolithic structure of pure EVA. The incorporation of a compliant material to act as a shock absorbing layer may reduce the maximum impact force transmitted to an underlying substructure (teeth). Similarly, the duration of impact may be increased by modification of the layers and hence reduces the effect of a sudden sharp shock. The lamination of thin (1mm) layers of EVA with identical layers gave surprising results and the structure in Design 5 will need further investigation to assess this laminates feasibility for use as a mouthguard design. Rebound energy, that is potentially as harmful as the original impact, is also reduced in Design 5 as well as in the composite laminated. The results for Design 5 using five 1mm layers of EVA that have been thermally stuck reacted quite dissimilarly to the monolithic 5mm EVA indicating that the lamination of the same material adds beneficially to the effectiveness of the material.

At this stage of our work it is becoming clear that a multi-laminated design would be best for a mouthguard but the need to compromise between force, displacement and duration of impact suggests that Design 5 with multiple layers of EVA and Design 4; multi-laminated with silicone rubber and PMMA warrant further investigation. However, analysis of our results indicates that the variation in laminate construction influences the response of the mouthguard to impact and hence its ability to absorb energy.

CONCLUSIONS

A review of the literature indicates that ethylene vinyl-acetate (EVA) is a suitable material for sports mouthguards. We have undertaken dropweight impact tests on five laminated structures of EVA, one incorporating polymethylmethacrylate (PMMA) and silicone rubber, one with silicone rubber and the others with further ply of EVA and compared the results with that of a similar specimen of 5mm thickness EVA only. With the exception of Design 3 the multi-layered structures exhibited less deformation than the monolithic structure of pure EVA. The multi-layered structure of EVA that had been thermally bonded gave good results which require further investigation. It is therefore suggested that multi-laminated mouthguards or mouthguards that incorporate an insert that is multi-laminated may offer better protection to the wearer since they reduce the transmission of harmful effects.

REFERENCES

[1] Chapman. P J. Mouthguards and the role of the sporting team dentists Australian Dent J; 30(2)(1989): 86-88

[2] Flanders. R A. Mouthguards and sports injuries. Illinois Dent J;62 (1)(1993);13-16

[3] Chapman. P J. Orofacial injuries and the use of mouthguards by the 1984 Great Britain rugby league touring team. Br J Sp Med. Vol 19, No. 1, March 1985, 34-36

[4] Widmer. R P. Oro-facial trauma in children. Australian Family Physician, vol 21, (9), September 1992

[5] DeYoung A K, Robinson E, Godwin W C. Comparing comfort and wearability: custom-made vs. self-adapted mouthguards. JADA, vol 125, August 1994, 1112-1117

[6] Craig R G, Godwin W C. Physical properties of materials for custom made mouth protectors. Journal of the Michigan State Dental Association; vol 49, February 1967, 34-40

[7] Bishop B M, Davies E H, von Fraunhofer J A. Materials for mouth protectors. J Prosthet Dent; Feb; vol 53 (2) (1985)

[8] Godwin W C, Craig R G. Stress transmitted through mouth protectors. J Am Dent Assoc;77 (1968):1316-20

[9] Park J B, Shaull K L, Overton B, Donly K J. Improving mouthguards. J Prosthet Dent; 72 (1994):373-80

[10] Greasley A, Imlach G, Karet B. Application of a standard test to the in vitro performance of mouthguards. Br J Sports Med; 32 (1998): 17-19

[11] Hickey J C, Morris A L, Carlson L D, Seward T E. The relation of mouth protectors to cranial pressure and deformation. JADA, (74),(1967),735

[12] Hoffmann J, Alfter G, Rudolph, G Göz. Experimental comparative study of various mouthguards. Endod Dent Traumatol. 15 (1999): 157-163

[13] Oikarinen K S, Salonen M A M, Korhonen J. Comparison of the guarding capacities of mouth protectors. Endod Dent Traumatol. 9 (1993): 115-119

[14] Kim H S, Mathieu K. Application of laminates to mouthguards: finite element analysis. J Mat Sci: Mat Med 9 (1998) 457-462

[15] Bulsara Y R, Matthew I R. Forces transmitted through a laminated mouthguard material with a Sorbothane insert. Endod Dent Traumatol (1998); 14: 45-47

[16] Greasley A, Karet B. Towards the development of a standard test procedure for mouthguard assessment. Br J Sports Med. 31(1997): 31-35

[17] Greasley A, Imlach G, Karet B. Application of a standard test to the in vitro performance of mouthguards. Br J Sports Med. 32 (1998): 17-19

[18] Westerman B, Stringfellow P M, Eccleston J A. Forces transmitted through EVA mouthguard materials of different types and thickness. Australian Dental Journal; 40 (6) (1995) 389-91

[19] Westerman B, Stringfellow P M, Eccleston J A. An improved mouthguard material. Australian Dental Journal. 42: (3) (1997) 189-91

[20] Going R E, Loehman R E, Chan M S. Mouthguard materials: their physical and mechanical properties. JADA. 89 (1974):132-8

[21] Found M S, Howard I C, Paran A P. Interpretation of signals rom dropweight impact tests. Composite Structures. 42 (1998) 353-363

[22] Patrick *et al.* Poster presentation, British Society for Dental Research; April 2000

Proc ICCM
Cagliari, Sardinia 2001

THE USE OF MULTI-LAYERED STRUCTURES FOR SPORTS MOUTHGUARDS

D Patrick, R van Noort and M S Found
Centre for Biomaterials and Tissue Engineering
University of Sheffield UK

SUMMARY: Previous work has indicated that the incorporation of a shock absorbing layer into the sports mouthguard reduces the likelihood of injury to the head, neck and oral cavity of the wearer. The purpose of this study is to investigate the use of multi-layered structures that protect an easily deformable structure during an impact. Dropweight impact tests were conducted on a series of moulded samples which were circularly clamped and force-time and displacement-time plots obtained. Single thickness specimens of ethylene vinyl acetate (EVA), 1-5mm thick were compared with laminated structures of EVA, incorporating 1mm thick layers of polymethylmethacrylate (PMMA) and a silicone or synthetic rubber up to a thickness of 5mm. In addition different thicknesses of EVA were placed on a 2mm thick substrate of PMMA. The multi-layered structures exhibited less deformation thereby transmitting less of the harmful effects through the laminate. The increase in thickness of EVA while on a PMMA substrate had little effect. It was concluded that laminated systems for mouthguards using different materials appear to offer better protection to the wearer.

KEYWORDS: mouthguard, shock absorbing, protection, impact

INTRODUCTION

Mouthguards have been worn by sportsmen for almost a hundred years and were initially used by boxers. A 'mouthguard' made from a piece of natural rubber that had been trimmed and hollowed out so that it would fit over the maxillary dentition, was worn to prevent chipped or broken teeth resulting from blows to the head. It was not adapted to the teeth, the jaw had to be clenched to hold the mouthguard in place, making it difficult for the wearer to breathe [1,2]. This type of 'unfitted' mouthguard can still be bought today, although the materials have changed - ethylene vinyl acetate being substituted for rubber. Most sports shops sell them and, surprisingly, are sometimes recommended to sportsmen and women by their dentist. This type of mouthguard offers a very low level of protection to the wearer, it also has the added danger of the possibility that it may become dislodged and obstruct the air passage causing asphyxiation. Sportsmen should be actively discouraged from wearing such a mouthguard [3].

There are three types of mouthguard that are generally available today:

i) **STOCK MOUTHGUARDS** - which come in differing sizes and are ready to use, mostly these types are made from either polyvinyl chloride (although the use of PVC for mouthguards has now been outlawed by the E.U.), polyurethane or a co-polymer of vinyl acetate or ethylene. Generally stock mouthguards are thought to be the least favourable as they offer the least protection and may even be thought of as dangerous as they may give a rugby player, for example, a false sense of security [4].

ii) **MOUTH-FORMED** – known as a 'boil and bite' type, where a thermoplastic rim is heated in hot water then placed in the mouth and moulded by biting and sucking.

iii) CUSTOM-MADE - this type of mouthguard is made in a dental laboratory on a cast taken from an impression supplied by a dentist. A thermoplastic material is heated in a pressure or vacuum forming machine and when soft enough it is placed over the cast and air pressure or a vacuum is applied which closely adapts the soft material to the cast.
Of the types listed it is generally thought that the custom-made mouthguards are the best and offer the most protection [5].

Mouthguard technology went through a period of rapid development during the 1950's and 1960's in America. This research suggested that the mouthguard should be worn on the upper (maxillary) teeth as they were the most prone to damage. Mouth-formed and custom-made mouthguards were developed around this time and the early studies did not seem to agree as to which type of mouthguard was the best. However, surveys of player opinion did report that the custom made mouthguard was the best option with regard to retention, cleanliness, ease of speech, lack of odour, taste and durability [6].

The cost of the custom made mouthguard was, and still can be somewhat, prohibitive which may deter many people from wearing such a mouthguard, regardless of the fact that nearly all the literature recommends that custom made mouthguards are the most effective type of protection.

EVALUATION OF MOUTHGUARD MATERIALS

Ideally a mouthguard material should be odourless, tasteless, non-toxic, have good resistance to abrasion, have low water absorbency and be tough enough to last at least one season, or maybe two, of wear during competitive sport and training. Craig and Godwin [6] carried out tests on thirteen different products used in the construction of mouthguards. Their testing of the materials was extensive and covered such aspects as, water sorption, strength, hardness and energy absorption. They suggested that caution should be exercised when interpreting the energy absorption results, "since a high energy absorption does not necessarily indicate protection of the underlying teeth." Craig and Godwin [6] went on to decide that a material with intermediate hardness and moderate energy absorption would be best for a mouthguard and that the degree of protection offered by a single material could be altered by changing the thickness of the material used.

Bishop, Davies and von Fraunhofer [7] carried out tests on nine materials that were all essentially the same but with differing mixtures of polyvinyl acetate and polyethylene. The specimens contained between 7.5% and 33% polyvinyl acetate (PVA) and were tested for the following properties: water absorption, tear strength, compressibility, along with static and dynamic energy absorption. Their findings were that the material used for a mouthguard should indent easily but be capable of absorbing energy under both static and dynamic loading. Polyvinyl polyethylene acetate (EVA) had a far higher ability to absorb energy when higher percentages of PVA were present. They also observed the importance of the compressibility characteristics of the material, or the depth the material is compressed under a known force in the initial purely elastic phase; which was referred to as the elastic gradient. A low elastic gradient (penetration vs force) would indicate a material that requires too high a force to compress it, while a high elastic gradient indicates a material that is compressed far too easily. It was concluded that the most satisfactory composition of a polyvinyl polyethylene acetate mixture for a mouth protector was one that had between 18 -24% PVA, and in the overall summing up the material with 18% PVA appeared to be the best for a sports mouthguard.

Godwin and Craig [8] investigated the effectiveness of different mouthguards that were commercially available in 1968 and found that the thickness of the protector does have a direct influence on the effectiveness of a single material. However it is not true to say that all thick materials are as effective as each other. Park *et al* [9], after testing five different types of material that are used in the construction of mouthguards reported that "the thicker the material is, the greater the resulting energy absorption is." Overall a 4mm thick sheet was deemed to be the best choice for constructing a mouthguard. One of the materials tested, Proform, had a harder material laminated into the sheet which is intended to reinforce the mouthguard after fabrication from behind the anterior teeth, but this harder material did not seem to have any positive effects - the EVA without it performed better in all the impact tests. Park *et al* went on to say that more interesting results may be gained by sandwiching harder materials, such as 99% acetate in the middle with 28% acetate on the outside so giving maximum protection and comfort. A more recent test by Greasley, Imlach and Karet [10] however, found that "the incorporation of the stiff and hard styrene butadiene material into the guard had no observable beneficial effects. It made the mouthguards difficult to fit and susceptible to crack damage in the impact zone."

APPRAISAL OF MOUTHGUARDS AND MATERIALS

The testing of mouthguards and the materials from which they have been made has been done in much the same way over the years. Many comparative studies have been made of the various types of mouthguard available and of the materials from which they are made. In typical tests on the material alone none of the tests really reveal the ideal properties that are being looked for in a mouthguard material. Tests that have utilised mouthguards on some form of model or on the maxilla of a cadaver (Hickey *et al* [11]) may give a clearer indication of the protection that is offered by the various mouthguards and materials tested.

In tests carried out by Hoffmann *et al* [12] several commercially available mouthguards were studied to determine their mechanical and physical properties. The mouthguards were fitted onto a specially made study model so that tooth deflection caused by an impact from a pendulum ram could be recorded. Data from the teeth protected with a mouthguard were compared to unprotected teeth and it was found that the cushioning effects of the mouthguards are directly correlated to their thickness, and that the force distribution is governed by the rigidity of the mouthguard. Oikarinen *et al* [13]compared the 'guarding capacity' of several mouth protectors whilst on a standard sized maxillary plaster model. A dropweight impact tester was constructed for the purpose of the experiment, the falling weight was designed to simulate an ice hockey puck. The mouthguards were constructed from two layers of material with a resilient layer next to the teeth, using stepwise regression analysis the only variable that had any statistical significance on the guarding capacity was the thickness of the soft layer next to the teeth.

To determine the effect of mouthguards on pressure changes and bone deformation within the skull, Hickey *et al* [11] constructed an impact producing mechanism that was attached to an American football helmet. In doing so a blow of known force could be delivered to the chin of an intact male cadaver. The research that was carried out did not examine the design of the mouthguard or the material from which it was made but did give a great insight into the protection capabilities of mouthguards with regard to concussion.

Kim and Mathieu [14] studied the lamination of mouthguards using finite element analysis. A flat-ended indentor and a disc representing a colliding object were produced so that the stress distribution within mouthguard materials could be recorded. The laminates that were tested consisted of a hard and soft material, a bi-laminated structure, rather than a sandwich panel or a multi-layered structure. When the soft layer was uppermost (in contact with the indentor) no significant difference from a monolithic test piece was recorded. However, when the test specimen was inverted so that the hard layer was uppermost there was found to be a

significant effect on stress distribution and the effect could be increased by controlling ratios of modulus and volume fractions of the top and bottom layers.
A visco-elastic polyurethane, Sorbothane, that has been used in orthopaedic and sports applications due to its shock absorbing properties was tested by Bulsara and Matthew [15] as an intermediate layer between two layers of EVA. A piezo-electric transducer was used to measure the peak force transmitted through samples with and without the Sorbothane layer from a free falling steel ram. Bulsara and Matthew concluded that using an intermediate layer of Sorbothane may dissipate significantly the force of impact from a blow to the teeth and jaws.

In an attempt to develop a standard test procedure for mouthguard assessment Greasley and Karet [16, 17] constructed an upper jaw made from a rubber arch containing replaceable ceramic teeth and a renewable composite jawbone on which mouthguards were to be tested. Different profiles of projectile, at various energies, were impacted into the model jaw by dropping them down a clear plastic tube whilst a mouthguard was in situ and the damage to the teeth and jaw was recorded. The objective of the exercise was to produce a testing regime that could easily be applied to any mouthguard that was made to fit the standard model that they produced.

Westerman [18] used an impact test rig similar to that of a Charpy or Izod impact machine that was fitted with a blunt striker on the pendulum. Tests showed that the force transmitted through the mouthguard materials was inversely related to the thickness of the material and that a small reduction in thickness of 1 mm resulted in an increase in transmitted force of 34%. Westerman *et al* [19] also assessed the energy absorption properties of a material that contained pockets of air. It was reported that the inclusion of air cells within an EVA copolymer mouthguard material produced a reduction in transmitted forces when the impact was less than 10 kN.

Further to their previous work Godwin and Craig [8] examined the stress transmitted through mouth protectors. Brittle lacquer coatings on maxillary models that were then fitted with mouthguards, demonstrated quite graphically the effectiveness of the individual mouthguards. Physical and mechanical tests were employed to discover the basic properties of 57 different mouthguard products by Going *et al* [20] in 1974. As well as determining material properties tests for impact energy absorption and resistance to impact penetration were performed using a rebound pendulum method. It was concluded that the interpretation of the dynamic energy data from the rebound test should be viewed cautiously and that a high energy absorption level does not necessarily mean that the material will give maximum protection, since some of the absorbed energy may be transmitted directly to the underlying tooth structure.

HYPOTHESIS

It is proposed that a mouthguard should be made of a composite laminate construction and that a typical structure would have a very compliant centre region with a more rigid outer layer. Combinations of compliant/rigid materials could be built up in a multi-layered composite system with materials and layer thicknesses being adapted according to the requirements for a particular sport or individual. For example, if a mouthguard is made with a softer more compliant material sandwiched between two layers of a more rigid material, such as EVA, (see Fig. 1) there will be a reduced impact force transferred to the teeth due to the shock absorbing capability of the compliant material layer. Harmful rebound energy will also be reduced as the composite laminate will return to its original shape more slowly than a single material system.

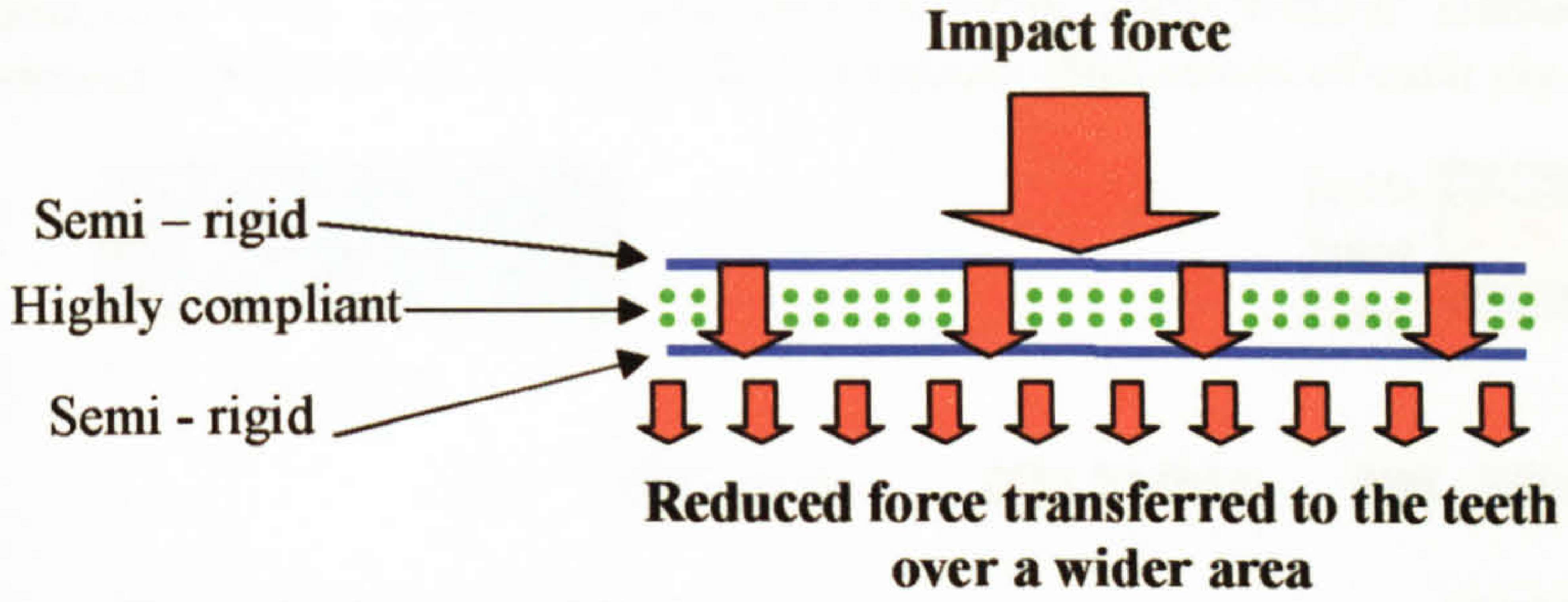


Fig. 1 Force distribution for laminate design

The aim of this study is to develop a method for the assessment of mouthguard materials and designs with the objective of improving the degree of protection provided by a mouthguard.

EXPERIMENTS

In designing the experiment it was felt that the amount of protection a material, or composite material, demonstrated the more valid the experiment would be. Previous studies have tended to show the amount of resilience present in a material by using a 'rebound test'. This kind of test was felt to be inappropriate as not enough information about the way in which a material reacts under impact loading conditions could be obtained from such a simple test.

An instrumented dropweight rig has been developed, within the Department of Mechanical Engineering at the University of Sheffield, enabling impact tests and static indentation tests to be conducted on circularly clamped panels, Found *et al* [21]. The test rig has recently been modified to permit clamping of smaller panels, i.e. mouthguard blanks. The impact rig is equipped with four transducers namely, an accelerometer, a strain-gauged load cell, a displacement transducer and opto-electronic triggering and timing sensors. The accelerometer is a miniature piezoelectronic transducer, which is connected via a signal conditioner to the data acquisition system. An infrared LED/phototransmitter reflective transducer is used to determine the displacement of the test specimen during impact. Calibration of the transducer is from static load tests performed under identical clamping conditions using an LVDT to measure the deflection at the centre of the test specimen.

The instrumented indentor is released by an electromagnetic switch from a height of 0.5m to produce an impact velocity of the impactor of about 3m/s. The data acquisition system is triggered when an aluminium flag, attached to the indentor assembly, passes the first opto-interrupter. The indentor velocity immediately before the impact event is determined by measuring the time taken for the flag, of 15.5mm depth, to cross the line of sight of the second opto-interrupter. The sensors are also used to determine the rebound velocity when energy is returned to the indentor after the impact event.

The impact forces and displacements were obtained from data that was processed through a low – pass filter at a cut – off frequency of 3.5 kHz.

Test specimens of 125mm diameter were constructed to fit the clamping mechanism of an instrumented impact testing rig, using a piezo-electric accelerometer to determine the peak impact force (PIF) and an infra-red sensor to measure the amount of deflection (Δ) respectively. Single thickness specimens of ethylene vinyl acetate (EVA), 5mm thick, were compared with laminated structures of EVA, (poly)methyl methacrylate (PMMA) using various combinations of materials and various thicknesses of each ply as shown in Fig 2

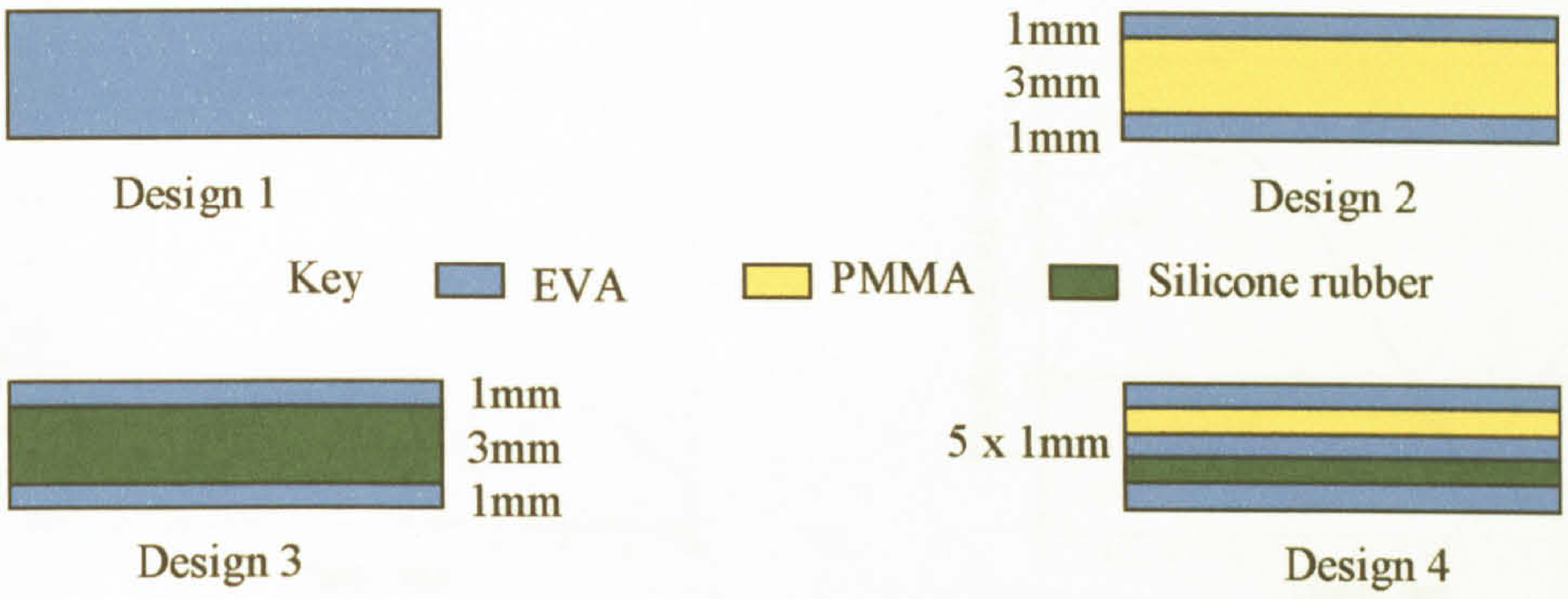


Fig 2 Mouthguard laminate designs

RESULTS

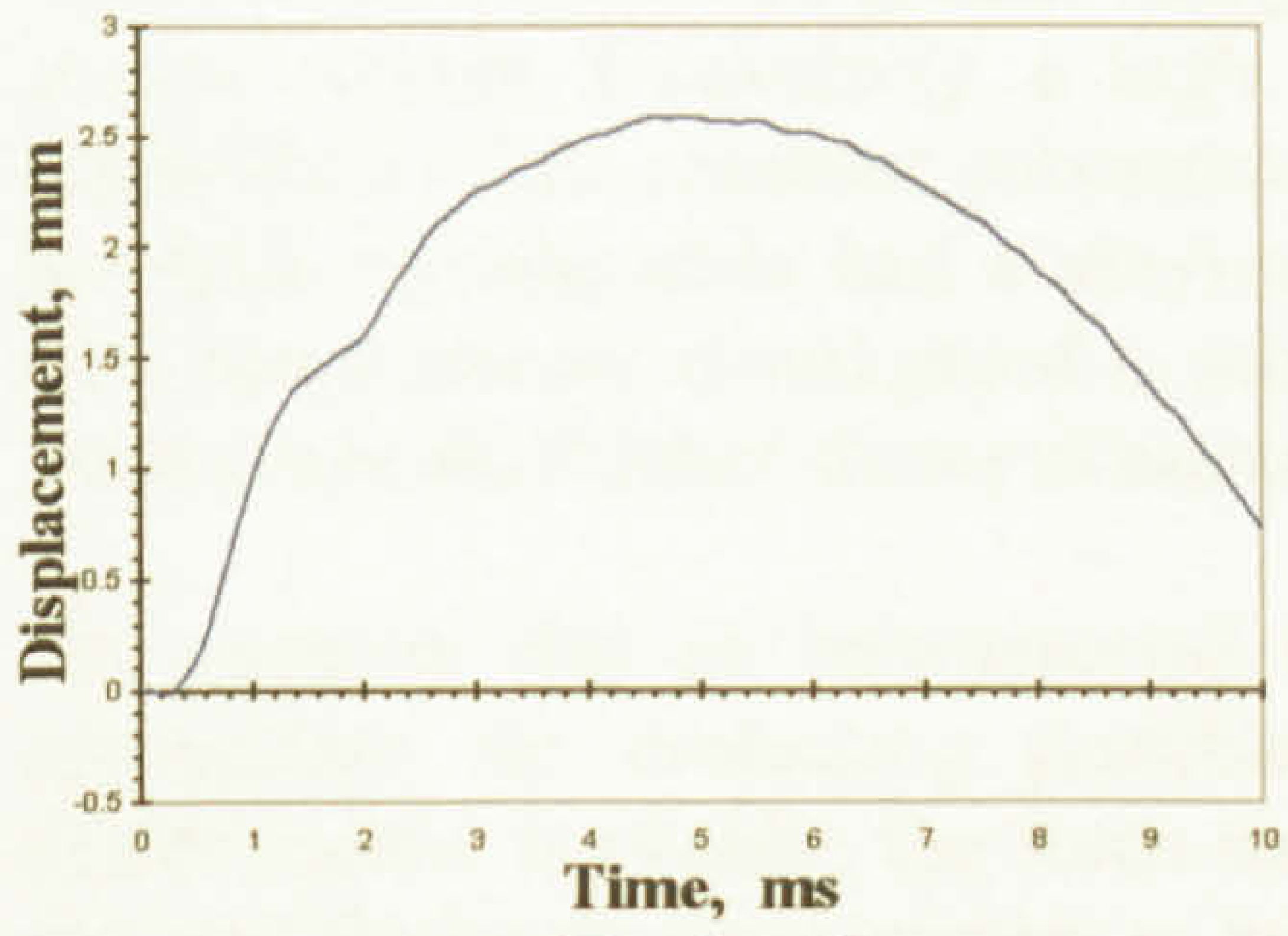
A summary of the impact performance of each laminate design is presented in Table 1 in terms of the peak impact force and maximum displacements observed during each test series.

Table 1. Peak impact force (PIF) and maximum displacement (Δ max) for each design.

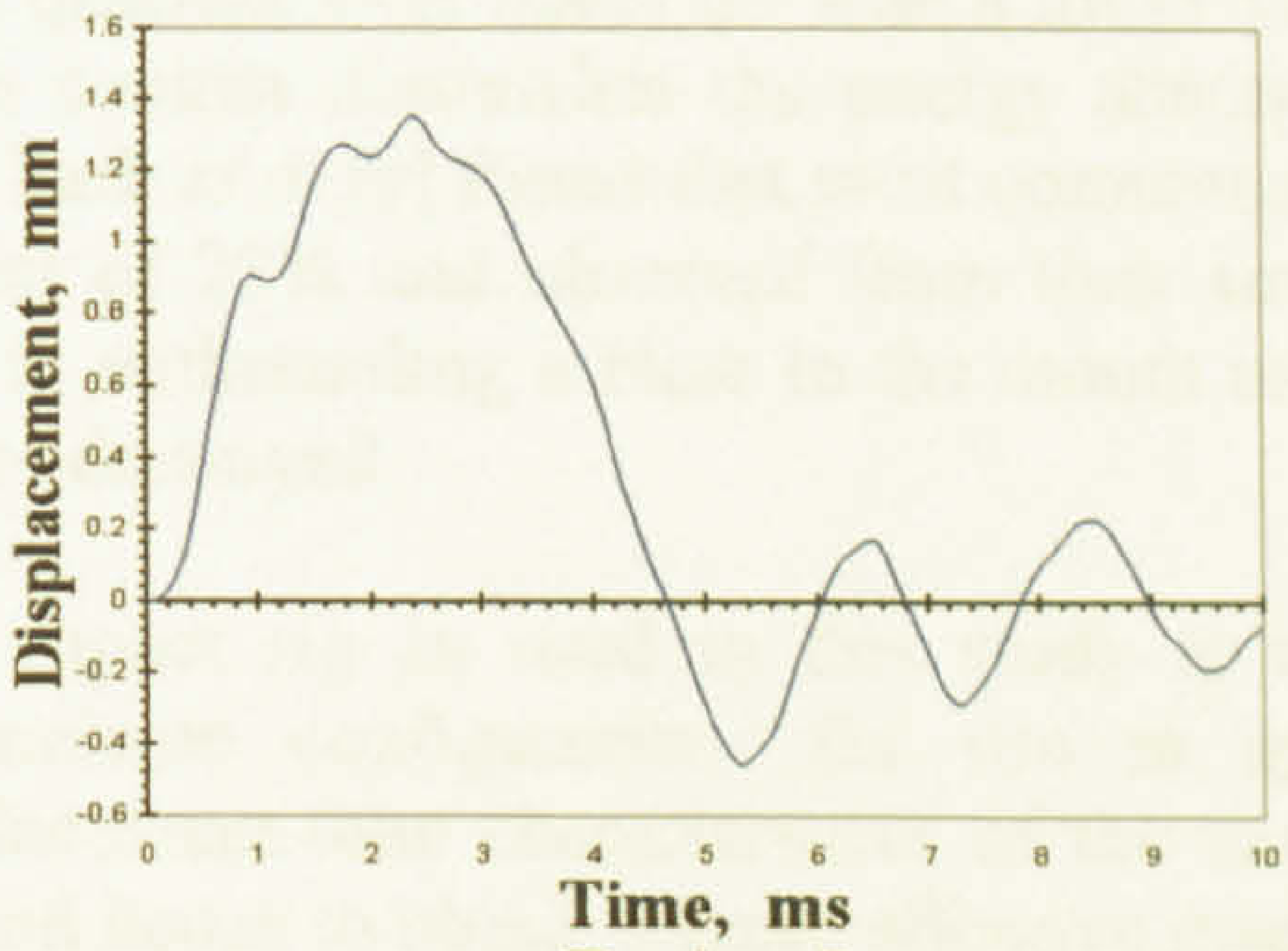
Design	PIF (N)	Δ max (mm)
1	160	2.6
2	290	1.3
3	210	2.0
4	280	1.4

From the above it was found that the laminated structures using a multi-layered system exhibited less deformation (Δ max = 1.3 – 2.0 mm) than the single system EVA (Δ max = 2.6mm). The soft compliant materials absorbed more impact and so transferred less impact energy to the substructure.

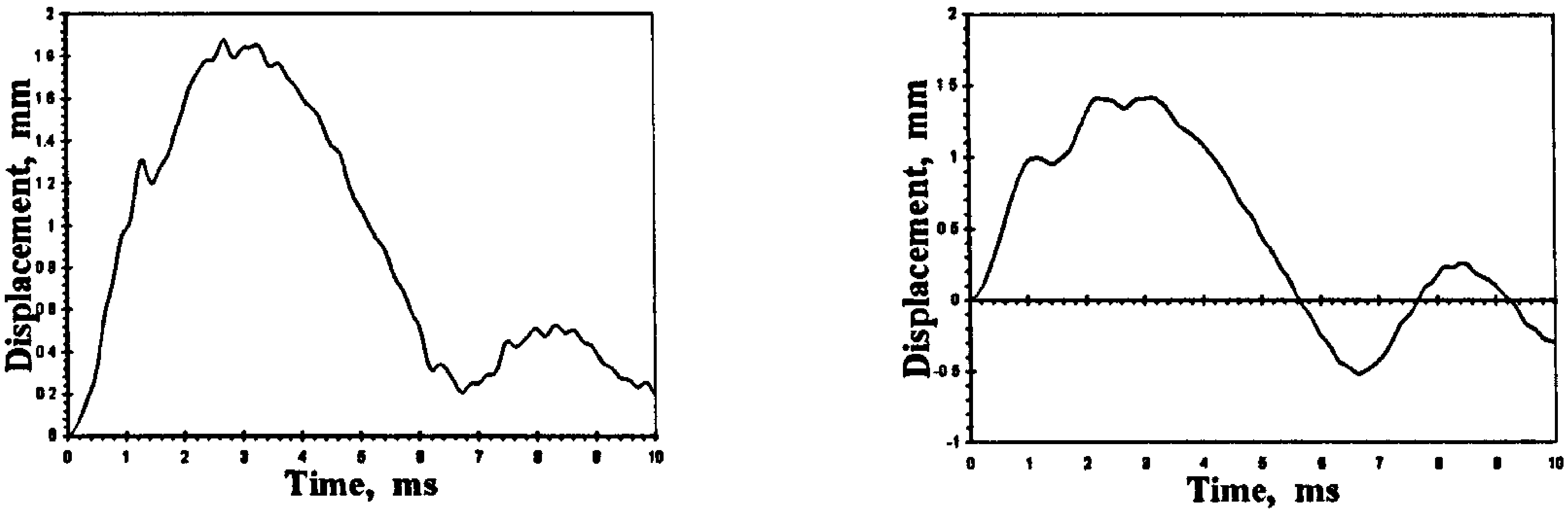
As previously reported the laminates containing synthetic rubber exhibited greater impact absorption with a peak impact force (PIF) of 300N, compared with a single material system (PIF >400N) or laminates with PMMA (PIF >500N) (Patrick *et al.* [22]). However these laminates are 2mm thicker and therefore as expected show a higher peak impact force. From Table 1 it can be observed that changing the laminate structure influences the peak impact force but is still greater than that for the monolithic EVA.



Design 1



Design 2



Design 3 Design 4

Fig 3 Displacement – time histories for each laminate design

From the displacement/time curves shown in Fig 3 it can be seen that Design 2 and 4 have similar curves although the layer of PMMA in Design 2 failed at the point of impact. The implications of this being that it would not be appropriate to use in a mouthguard as the mouthguard would be rendered useless after only one or two impacts. A compromise will have to be reached between the use of materials and thicknesses to provide the optimum laminate that could be encapsulated within a mouthguard for a particular application.

DISCUSSION

A brief review of materials and test methods for sports mouthguards shows that a wide range of thermoplastic and rubber materials have been evaluated employing different test methods. Whilst many of the tests are often only determining material properties they however suggest; that EVA appears to be an appropriate material [7, 9], the importance of section thickness [8, 9, 12], the influence of a sandwich construction [9, 10, 14, 15] and the effect of force distribution [12, 14, 15] and hence the effectiveness of the mouthguard. Furthermore, in order to fully assess the influence of an impact and the resilience of mouthguards more appropriate tests need to be carried out [11 – 13, 16, 17].

Whilst it appears that EVA is an appropriate choice of material for mouthguards it should be noted, however, that the percentage of vinyl-acetate can be altered thereby changing the properties of EVA (Bishop, Davies and von Fraunhofer, [7]). It has been shown that an 18% content of vinyl-acetate in the EVA is the most suitable composition for mouthguard materials as it exhibited greater energy absorptive qualities over materials with a lower vinyl-acetate content. Conversely, a high vinyl-acetate content diminishes the energy absorptive capabilities of the resultant polymeric compound. Park *et al* [9] found that most commercially available mouthguards had a vinyl-acetate content of 28% and observed from their impact tests that a thicker mouthguard is more effective in withstanding a blow to the mouth and in some cases the thinner sheets of material used were destroyed.

We consider that an instrumented dropweight impact rig as used in this study is more appropriate for evaluating possible material/laminate configurations for use in sports mouthguards. It enables the force-time and displacement-time characteristics of the various material/thickness combinations to be evaluated and hence to obtain a more effective measure of the energy absorbed by the mouthguard.

The multi-layered structures exhibit less deformation than the monolithic structure of pure EVA. The incorporation of a compliant material to act as a shock absorbing layer may reduce the maximum impact force transmitted to an underlying substructure (teeth), but does not reduce to that of the pure EVA of similar thickness. Similarly, the duration of impact may be increased by modification of the layers and hence reduces the effect of a sudden sharp shock. Rebound energy, that is potentially as harmful as the original impact, is reduced as the composite laminated material returns to its original shape more slowly that less compliant materials.

At this stage of our work it is not possible to state which type of design would be best for a mouthguard but the need to compromise between force, displacement and duration of impact suggests that Design 3 with silicone rubber warrants further investigation. However, analysis of our results indicates that the variation in laminate construction influences the response of the mouthguard to impact and hence its ability to absorb energy.

CONCLUSIONS

A review of the literature indicates that ethylene vinyl-acetate (EVA) is a suitable material for sports mouthguards. We have undertaken dropweight impact tests on three laminated structures of EVA incorporating polymethylmethacrylate (PMMA) and a silicone rubber and compared the results with that of a similar specimen of 5mm thickness of EVA only. The multi-layered structures exhibited less deformation than the monolithic structure of pure EVA. It is therefore suggested that laminated mouthguards may offer better protection to the wearer since they reduce the transmission of harmful effects.

REFERENCES

[1] P J. Chapman. Australian Dent J; 30(2)(1989):86-88
[2] R A. Flanders. Illinois Dent J;62 (1)(1993);13-16
[3] P J. Chapman. Br J Sp Med. Vol 19, No. 1, March 1985, 34-36
[4] R P. Widmer.Australian Family Physician,vol 21, (9), September 1992
[5] A K DeYoung, E Robinson, W C Godwin. JADA, vol 125, August 1994, 1112-1117
[6] R G Craig, W C Godwin. Journal of the Michigan State Dental Association; vol 49, February 1967, 34-40
[7] B M Bishop, E H Davies, J A von Fraunhofer. J Prosthet Dent;Feb; vol 53 (2) (1985)
[8] W C Godwin, R G Craig. J Am Dent Assoc;77 (1968):1316-20
[9] J B Park, K L Shaull, B Overton, K J Donly. J Prosthet Dent; 72 (1994):373-80
[10] A Greasley, G Imlach, B Karet. Br J Sports Med; 32 (1998): 17-19
[11] J C Hickey, A L Morris, L D Carlson, T E Seward. JADA, (74),(1967),735
[12] J Hoffmann, G Alfter, Rudolph, G Göz. Endod Dent Traumatol. 15 (1999): 157-163
[13] K S Oikarinen, M A M Salonen, J Korhonen. Endod Dent Traumatol. 9 (1993): 115-119
[14] H S Kim, K Mathieu. J Mat Sci: Mat Med 9 (1998) 457-462
[15] Y R Bulsara, I R Matthew. Endod Dent Traumatol (1998); 14: 45-47
[16] A Greasley, B Karet. Br J Sports Med. 31(1997): 31-35
[17] A Greasley, G Imlach, B Karet. Br J Sports Med. 32 (1998): 17-19
[18] B Westerman, P M Stringfellow, J A Eccleston. Australian Dental Journal; 40 (6) (1995) 389-91
[19] B Westerman, P M Stringfellow, J A Eccleston. Australian Dental Journal. 42: (3) (1997) 189-91
[20] R E Going, R E Loehman, M S Chan. J Am Dent Assoc. 89 (1974):132-8
[21] M S Found, I C Howard, A P Paran. Composite Structures. 42 (1998) 353-363
[22] Patrick *et al.* Poster presentation, British Society for Dental Research; April 2000