Design and Construction of Smart Structures for Technical Textiles

by

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The candidate confirms that the work submitted is his/her own and that appropriate credit has been given where reference has been made to the work of others.

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Dedicated to

my husband Neil

my daughter Faith

my son Miles

&

my mother Paulette Carmelita Azore-Edwards

Perplexity is the beginning of knowledge.

Kahlil Gibran

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This thesis could not have been completed without the help, love and unending support of my husband Neil, my daughter Faith and my son Miles, I thank them for their belief in me and my capabilities, as well as their infinite patience. Thank you to all of my family for their help and support, and to my friends for helping me keep my sense of humour and for promising to call me Dr Verity at all times once I have graduated.

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Abstract

The smart textiles sector is becoming increasingly significant within the technical textiles industry, contributing an increasing number of products and applications using a number of different technologies. This research is concerned primarily with electrically conductive smart textiles and, for the purposes of this project, smart structures are considered to be electrically conductive components which can be used in conjunction with technical textiles in order to enhance their performance and properties.

The term 'smart textiles' defines materials with advanced responsive properties enabling them to sense, actuate and/or control and the primary aim of this research was to characterise commercially available conductive yarns in terms of their structure, composition and physical behaviour in relation to their electrical behaviour. The secondary aim was to manufacture an electrically conductive textile material that could act as a strain sensor with the aim of integrating them into or onto existing technical textile fabrics. A range of static, dynamic and cyclic mechanical-electrical tests were carried out on a number of commercially available conductive yarns, work which informed the decision to base further experimental work on the integration of Carbon Black particles and Carbon Nanotubes into Nylon 6.10 and extrude a monofilament using a standard melt spinning technique. Although the resultant yarns manufactured did not display the properties required, analysis of the CB and CNT properties, the conductive particle dispersion within the polymer matrix, the yarn structure and the manufacturing method all informed the development of the design paradigm.

The resultant design paradigm developed highlights the most significant variables and parameters to take into consideration when designing a textile sensor, and suggests solutions that would result in successful sample production. The paradigm covers design solutions for the conductive particles, the polymer, the compounding method, yarn manufacturing parameters and the resultant yarn structure. Whilst the

information contained therein is not exhaustive, this being due to the inherent multi-level complexity of designing a textile system, it acts as a guide for sensor development and may help circumvent costly and timely sample manufacturing errors.

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Symbols and Notation

μ	Population Mean
Ω	Ohm Measurement
ρ	Resistivity
σ	Standard Deviation
Δ	Difference Operator
ε	Strain
I	Current
V	Potential Difference
R	Resistance
L	Inductance
C	Capacitance
Z	Impedance
l	Length
A	Cross-Sectional Area

Abbreviations

FICOM	Fiber Computing Group
SMA	Shape Memory Alloy
GSM	Global System for Mobile Communications
SMS	Short Message Service
OEM	Original Equipment Manufacturer
CAD	Computer Aided Design
AC	Alternating Current
CRE	Constant Rate of Extension
PES	Polyester
CB	Carbon Black
CNT	Carbon Nanotubes
CNF	Carbon Nanofibres
GF	Gauge Factor

Aims

- The experimental focus of this thesis is to characterise commercially available conductive textile yarns using a variety of mechanical and electrical test methods and equipment, as well as image analysis.
- This characterisation will inform the construction of an electrically conductive textile material, suitable for use with technical textiles to sense strain, using commercially available materials and available equipment.
- From this, a design paradigm will be developed relating to the design and construction of textile sensors.

Chapter Information

Chapter 1	Background of the Smart Textile sector.
Chapter 2	Critical review of current literature concerning strain gauges and textile strain sensors.
Chapter 3	Mechanical properties of conductive and non-conductive yarns.
Chapter 4	Mechanical-Electrical properties of conductive yarns.
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Chapter 6	Construction of strain sensor yarn.
Chapter 7	Conclusions and Further Work.

Chapter 1

Background

Chapter 1
Background

The scope of the smart/intelligent textiles industry is potentially enormous in terms of the different types of material available, usable technologies, potential applications and eventual market size. Falling under the umbrella of smart/intelligent textiles are phase change, electrically conductive, shape memory and chromic materials, and the enabling technologies include polymer development, nanotechnology and the embedding of components into fabrics. The potential sectors to which smart/intelligent textiles can be applied include commercial, retail and industrial with applications such as location monitoring devices, entertainment, communications, actuation & environmental response and sensing & biophysical monitoring. Due to the number of potential materials, technologies and applications that are available, for the purposes of this report the only material type to be considered will be electrically conductive materials and their applications.

A variety of terminologies have been used to describe electrically conductive smart textiles, some product-related and others referring to the enabling technology. This has led to such terms being used as e-textiles, electronic textiles, smart clothing, interactive wear and electro textiles. Thus for simplicity's sake, throughout this report the terminology 'smart textiles' will be used as an umbrella term in reference to the materials, technologies and applications used within the electrically conductive smart textile sector.

As such, "smart textiles" is a term used to define materials with advanced responsive properties covering a broad range of technologies and products, they are defined as;

> "Flexible fibrous structures which have multifunctional characteristics which are expected to sense, actuate and control. The integration of micro-electronics and textiles and also the new materials such as phase change, shape memory, chromic and conductive materials have all played important roles in innovation, design and production of

> intelligent textiles for variety of applications such as medical, health care and assistive technologies, protective technical textiles, multifunctional sportswear and multifunctional military clothing. [1]"

The concept of embedding or integrating a smart structure within a technical textile product or material is complex and it is simultaneously necessary to define the uses and applications of technical textiles and explain how these products can benefit from the incorporation of smart structures, whilst defining what a smart structure is and determining what forms it can take.

1.1 Use of Smart Textiles with Technical Textiles

The inclusion of smart structures (structures capable of sensing and reacting to their environment in a predictable and desired manner) into technical textiles, or the use of smart structures with technical textiles, is a means of introducing a degree of 'intelligence' into the technical textile which is not normally inherent in the material, fabric or the designed product. For example, embedding smart structures such as sensors into or onto a technical textile fabric can enhance the range of capabilities of that fabric by giving feedback on its performance whilst in use, which can then be fed back into the design and/or construction phase. In essence, high specification, high performance, multifunctional fabrics and products can be created.

In order to understand the difference between smart textiles and technical textiles, it is necessary to define them. Technical textiles are defined as;

> "Textile materials and products manufactured primarily for their technical performance and functional properties rather than their aesthetic or decorative characteristics. A non-exhaustive list of end-uses includes: aerospace, industrial, marine, medical, military, safety and transport textiles, and geotextiles." [2]

There is an extensive range of raw materials, processes, products and applications encompassed within the technical textile industry, making it an industry with a wide spread of capabilities. The defining characteristics of technical textiles are that they have very high physical and/or chemical property specifications and are typically used in applications where a high level of end-use performance is required.

The range of possible end-uses for smart textiles is significant and growing, and they can be incorporated into both the technical textile and the footwear and apparel sectors. In order to understand this industry fully the main developments in the smart textile sector will be highlighted including the application areas, products manufactured and organisations involved in research and development.

1.2 Market Analysis

The technical textile sector and the smart textile sector can currently be considered separately due to the relative maturity of the technical textile market compared to that of the smart textile market. It is important to analyse the past market performance and review predictions of future performance in terms of market value and volume for both sectors.

1.2.1 Technical Textile Market

A report by David Rigby Associates [3] estimated that in 2000 the global production of technical textiles amounted to 16.7mn tons (based on the amount of polymer and fibre used). In value terms, the market was worth an estimated US$92.9 billion (i.e. the value of finished textile products). In volume terms growth was forecast to average 3.5% a year between 1995 and 2005, and 3.8% a year between 2005 and 2010, as illustrated in Figure 1.1. However, growth was expected to be slower in terms of value rather than volume due to lower priced fibre, the increasing use of low cost nonwovens, and the slower growth of lower textile content products such as fibre-reinforced composites. Globally, Europe and the Americas were expected to experience slower growth rates than in Asia.

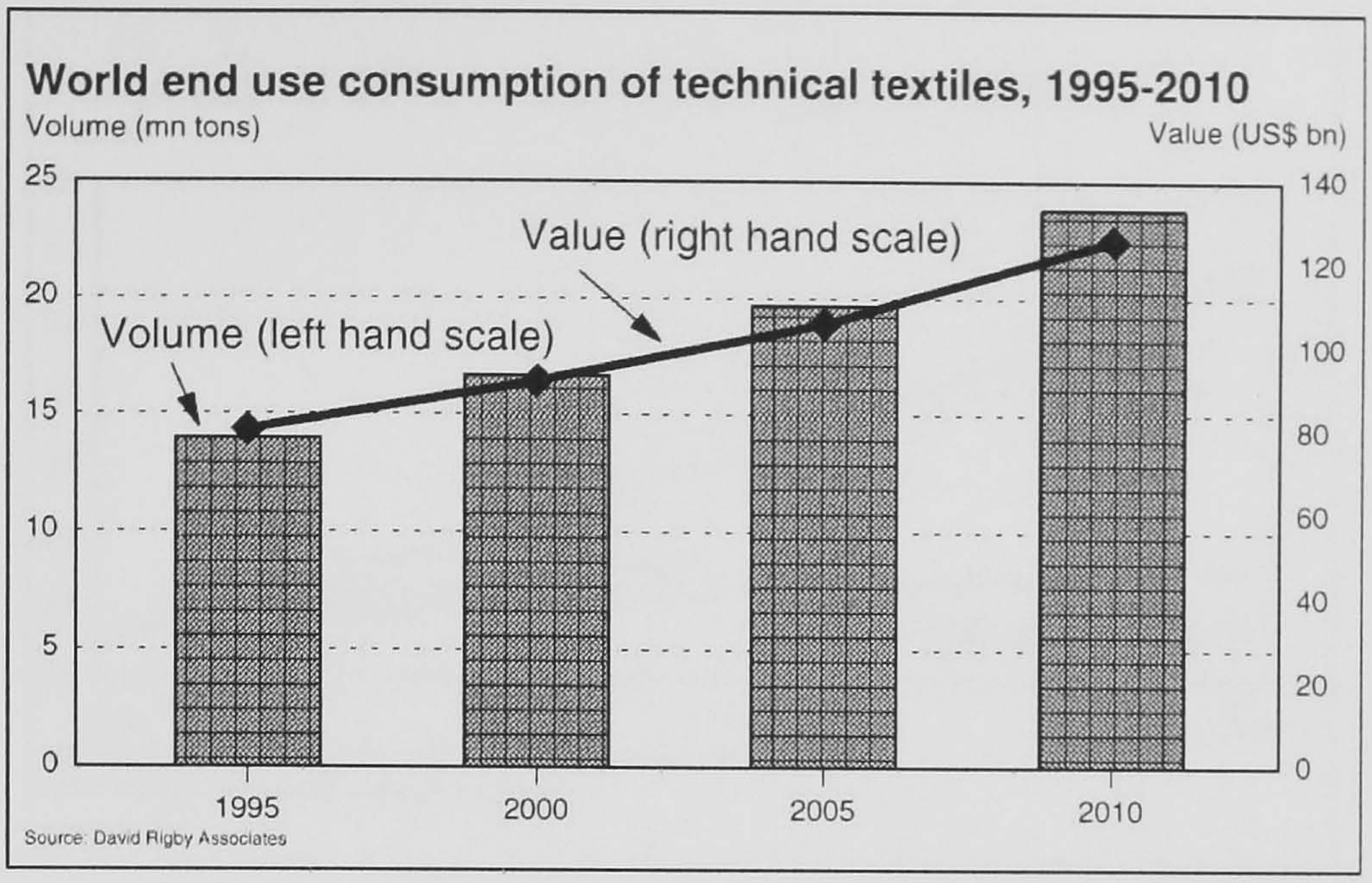

Figure 1.1 World End Use Consumption of Technical Textiles, 1995-2010 [3]

Technical textile end-uses have been quantified separately into eleven application areas and the world end used consumption in 2000 was calculated to show that the fastest growing sectors were building and construction, hygiene and medical, and personal and property protection, with environmental protection having the fastest growth rate of all with relatively slower growth rates for clothing components and sports and leisure.

1.2.2 Smart Fabric and Interactive Textile Market

According to a US report published by Venture Development Corporation (VDC) [3], the smart fabric and interactive textile (smart textile) market totalled $248 million in 2004 and $304 million in 2005, with expectations that it would grow to $642 million in 2008. The greatest growth area was in transportation with products such as carbon fibre heated seat kits, however it was expected that there would be a growth in demand for garments with integrated music and communication devices, with the overall growth in consumption shown in Figure 1.2.

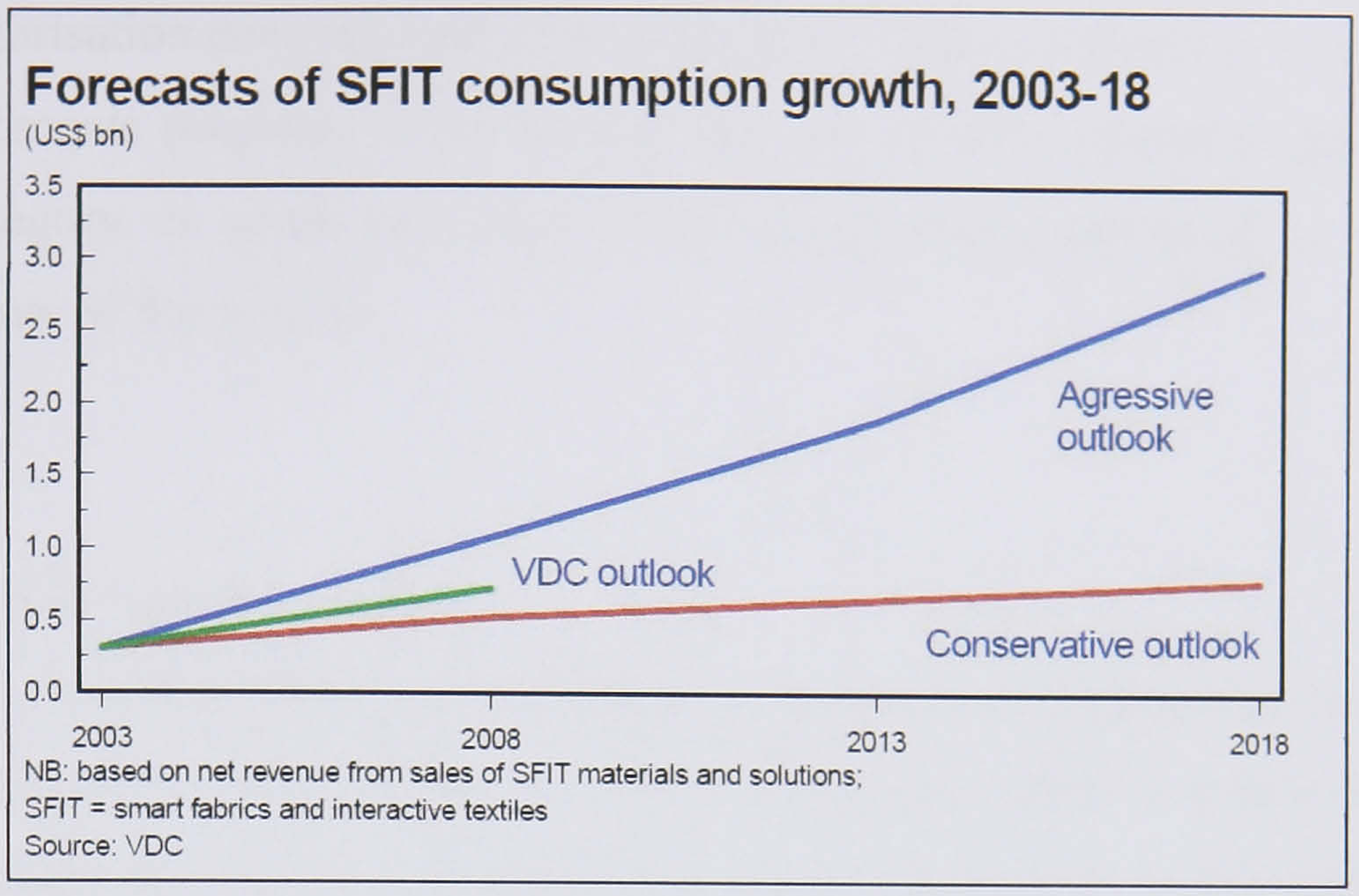

Figure 1.2 Roadmap of Smart Fabric and Interactive Textiles Consumption Growth – Overall Market [4]

The vertical markets for smart textiles are consumer (fashion and fitness clothing), government (military), medical, commercial/retail and industrial and so far the biggest investors have been the military and government bodies. Most research on electrical smart textiles by Original Equipment Manufacturers is directed towards sensing and monitoring applications, as well as actuation and response applications, whilst academic institutions are dominant participants in all areas of smart textiles research.

1.3 Classification of Smart Textiles

According to Xiang and Ming [5] smart textiles can be categorised by their reaction to external stimuli. Accordingly these classifications follow the rules that;

> "Passive smart textiles can only sense the environmental conditions or stimuli, active smart textiles will sense and react to environmental conditions or stimuli, and very smart textiles can sense, react and adapt themselves to environmental conditions or stimuli". [5]

This categorisation does not infer that one type of reaction is superior to another and, as developments progress, it can be seen that some smart textiles do not fall into a single category as multi-functional products are being produced to satisfy the requirements of the markets.

1.3.1 Passive Smart Textiles

In order for passive smart textiles to detect a change in environmental conditions or stimuli, a sensor must be present to provide a nervous system to detect signals, and some passive smart textiles can act as both sensors and actuators (an actuator being 'a device which performs a mechanical action in response to an input signal, which may either be electric or fluidic' [6]). Pressure sensing and switching technologies, as used for the keypads and touch sensitive fabric, are all classified as passive smart textiles.

1.3.2 Very Smart Textiles

Very smart textiles can sense, react and adapt themselves to changing environmental conditions or stimuli and these products have become available through combining traditional textiles and clothing technologies with material science, structural mechanics, sensor and actuator technology, advanced processing technology, communications, artificial intelligence and biology [7]. This type of smart textile includes shape memory materials, phase change materials, water resistant and vapour permeable (hydrophilic/nonporous) materials, and heat-storage & thermoregulated fabrics [8].

1.4 Global Developments in Electrically Conductive Smart Textiles

There have been a number of global developments in the smart textile industry and a selection of the major networking events, seminal innovations in each application area and the major organisations involved are overviewed.

1.4.1 Conferences, Exhibitions and Seminars

Smart textiles have been discussed both as part of computing and wearable technology conferences as well as, in recent years, smart textile specific symposia and conferences. Wearable computing was discussed at ISWC 2000 [9], embedded technology at the 2001 CASES Conference and electronic textiles for wearable computer systems at the 2002 Hightex Conference. The 2003 Textile Future Show [10] fashion show was staged in eight different German department stores to present the future of smart textiles garments and it highlighted products that were already commercially available or were soon to be available, and as part of the 2003 IEE Eurowearable Conference [11] 'intelligent garments, wearable technology and smart materials' were exhibited at the WEAR ME fashion show. The Wearable Electronics and Smart Textiles Conference (WEST) 2004 [12], held in Leeds, brought together academics, researchers and companies involved in smart textile innovation in order to exchange ideas, share knowledge and develop partnerships and networks. In 2004 a technology-specific workshop on textile sensors and actuators was held at Central Saint Martins College [13], formulating research and development proposals for various consumer products and applications.

In 2005 the Ambience conference [14] dealt exclusively with smart textiles and clothing design, whilst discussions on the technological advances of smart textiles were also held as part of a conference on technical textiles innovation hosted by the William Lee Innovation Centre (part of Manchester University) in 2006 [6]. The effect of nanotechnology on the smart textile industry was addressed at the 2006 NanoTechnologies and Smart Textiles conference [12]. The 2007 Avantex Symposium [15] (run in conjunction with Techtextil) is now a well established international event which acted as a platform for innovative developments with the aim of providing information on the opportunities and possibilities of smart textiles and improving communication between all bodies involved. It covered topics such as the future prospects of smart textiles, new fibres, yarns, finishing processes and films, smart clothing, nanotechnology and fabric developments.

1.4.2 Research Institutes and Organisations

A number of research institutes and organisations have led research into smart textiles (some of which are dedicated teams, some carry out the work through research degree work) and some have collaborated with other institutions or companies to create products and subsequent spin-off companies. A small selection of the major research institutes involved are listed in the following sections.

1.4.2.1 Europe

In 2000 at Brunel University [16] research was carried out on sensory fabric development and in 2003 at Lancaster University [17] investigation into layered wearable textile networks was carried out, whilst in 2004 at The London Institute (Central St. Martins) interactive and experiential design in smart textiles was explored. Currently in the UK, Leeds University Centre for Technical Textiles [1] is undertaking several R&D projects into smart textiles, as are researchers at Manchester University [6], and Heriot Watt University [18] who are running projects concerned with smart textiles R&D.

Further afield in Europe, in 2002 ARCES (Italy) [19] worked on textile based capacitive pressure sensors, and in the same year researchers at the Katholieke Universiteit (Netherlands), in conjunction with the University of Ghent (Belgium), developed the Intellitex suit [20]. In 2002 the University of Minho (Portugal) was involved with the with European Space Agency (ESA) workshop and in 2003 the University of Pisa (Italy) researched electroactive fabrics for interactive systems. The PLAY Interactive Institute (Sweden) was involved from 1999-2004 in R&D for textile and computational technology and the Technical University of Liberec (Czech Republic) has been involved in smart textile structure R&D through ITSAPT [21] since 2005. Two Finnish Institutions, Tampere University of Technology and the University of Lapland are involved in SmartWear Lab projects on smart wearables and intelligent garment projects respectively, and at Philipps-Universität Marburg (Germany) [22] projects are being undertaken investigating and developing nanofibres.

1.4.2.2 The Americas

The Georgia Tech Wearable Motherboard [23] was developed between 2000 and 2001 at the Georgia Institute of Technology and in 2002/03 the groundbreaking 'Electric plaid' project [24] was undertaken at Concordia University (Canada). In the same years at Carnegie Mellon University the Coatnet group [25] undertook a project on the modelling of electronic textiles and, as part of a research project, a Smart jacket (thermoregulating, light emitting) was developed at Cornell University [26]. At Virginia Polytechnic Institute and State University in 2003 their E-textiles Laboratory produced a 'STRETCH' acoustic array fabric (a project sponsored by Defense Advanced Research Projects Agency). At North Carolina State University [27] research into carbon nanotubes and nanofibres has been carried out whilst at Clemson University [28] they undertook R&D into conductive polymers for electrotextiles.

1.4.2.3 Asia

In 2003 at the Hong Kong Polytechnic University there were a number of smart textile projects being undertaken including those focusing on nanotechnology and shape memory materials, whilst at the Indian Institute of Technology (Delhi) [29] in 2005 R&D into nanofibres was undertaken. According to an Inneurotex report [30] "Japan is the second largest spender in nanotechnology research and development worldwide" and companies such as Kanebo Spinning Corp. and Toray Industries Inc. have been conducting research into developing superabsorbent polyester and nylon threads.

1.4.2.4 Australasia

The University of Wollongong (Australia) undertook projects at the Intelligent Polymer Research Institute [31] and in 2004 Charles Sturt University [32] sponsored the Higher Schools Certificate online initiative into emerging textile technologies.

1.4.3 Projects and Focus Groups

A variety of project groups have been formed, often created at the behest of governments or research institutions, in order to carry out specific projects in a particular smart textile field. Each one is made up of collaborators from a range of industries and textile sectors, and can be local, national or even international. In 2001 at the International Centre of Excellence for Wearable Electronics & Smart Products [33] they carried out R&D into smart textile applications such as health monitoring, personal protections, sports and leisure, and industry and manufacturing. In 2002 the European Fiber Computing group [34] aimed to integrate computing ability directly into fibres and in 2003 the Intelligent Textile Technological Alliance (Canada) [35] hoped to develop and promote various microelectronic technologies and applications using textile and clothing materials as carriers. The Wealthy project focussed on integrating computing, sensors and telecommunications to assist patients during rehabilitation and continuous monitoring and, as such, produced the Wealthy shirt [36] in 2005.

In the UK there are two major interest groups, namely Wearable Electronics and Smart Textiles [37], set up in 2004, which to provides opportunities for industry and academia to find out the latest developments and promote available technologies and services in the area, and the Smart Textiles Network [13] which aimed to excite development in smart textiles and systems through cross-sectoral consultation, bringing together designers, scientists and materials developers.

1.5 Product Applications

There is a wide range of potential applications for smart textile technology; a selection of the seminal developments in these areas and the companies, organisations or research institutes who have developed these products are overviewed.

1.5.1 Electromagnetic and Radio Frequency Shielding

Demand is growing for products which provide electromagnetic and radio frequency interference shielding, as well as static discharge [3], due mainly to the proliferation of computing and mobile communication equipment. Products developed are being used in novel areas such as garment pockets (for mobile phones and portable computers), and rapid growth is expected in products used in the construction of homes and buildings.

1.5.2 Military

In 2001 the US Defense Advanced Research Projects Agency released a request for proposals for projects from those in the textiles and electronics industries that would create a new class of wearable systems made of fabric, hoping to spur the development of new yarns, fabric interconnects and Computer Aided Design (CAD) tools for weaving the equivalent of a printed-circuit board into textiles. As such, in 2002 a sound detecting fabric [38] for military use was developed whereby a woven fabric had insulated stainless steel wire running through it to which tiny microphones were attached in order to pick up the sound of remote objects. The advantage of this product was that, unlike traditional radio frequency communication, the transmitting unit's location couldn't be detected and also the power requirements were reduced due to the integrated wires.

1.5.3 Healthcare Monitoring

The 'Intellitex' suit [39] was developed as a prototype health monitoring suit for long term and continuous use by children in hospital, measuring respiration rate and heart rate using a washable textile belt incorporating electroconductive stainless steel fibres and yarns. Knitted stainless steel fibre 'Textrodes' were in direct contact with the skin, thus the heart rate could be monitored without the use of the gel which often causes irritation or skin softening. Respiration rate was measured using a 'Respibelt' (also constructed from knitted stainless steel yarns), the measurement being made by noting the variation in resistance and inductance caused by breathing when the system was coiled around the abdomen or thorax.

The commercial manufacture of a Telemedicine T-shirt [40] started in 2004, this being a cotton t-shirt predominantly for use by elderly people in order to monitor their physiological status. The t-shirt measured heart rate (electrocardiogram), respiratory rhythm (by measuring the movement of the ribcage) and skin temperature using sensors integrated into the garment and transmitted via a satellite network to the specialist centre where the doctor recorded the data. The t-shirt retained its textile characteristics of moisture absorption, stretch and comfort as the technology included integrated conductive wires and miniaturized electrodes.

The Sensatex Smart Shirt [41] was manufactured as a t-shirt which functioned like a computer with optical and conductive fibres integrated into the garment. It monitored heart rate, respiration, temperature and other vital functions; as the t-shirt was threaded with conductive polymer and metallic fibres that served as data buses and power lines. It was claimed that the t-shirt was washable once any attachments were unplugged, and the sensors, processors and communication devices could be altered as required prior to manufacture.

1.5.4 Assistive Technology

Assistive technology covers a range of products created to assist those with motor-skill problems or who are weak or frail, such as the elderly. Thompson [42] has designed several products to assist those lacking manual dexterity such as a television remote control cushion with large numbers and volume controls embroidered on it underneath which is the copper-coated nylon switching mechanism, as well as a mat on which a child with cerebral palsy can sit and, by leaning forward or backward, use as a joystick for video games.

1.5.5 Space Technology Transfer

In 2002 at a European Space Agency event [43] several ideas were identified concerning the application of space technology to smart textiles and vice versa, for example, the use of shape memory alloy (SMA) fibres for signal acquisition and smart actuation, as well as superelastic fabrics allowing intimate contact between sensors and skin, was presented. The concept of smart implants, where SMA textile stents could actively monitor the blood flow and communicate to the garment possible restenosis (recurrent artery blockages after surgical treatment) or any pressure alteration, was also presented. In terms of biophysical monitoring, the same technology can play a role in thermal physiology, increasing or decreasing the insulation of a garment, which is one of the parameters to be considered during the management of a heart attack or stroke to reduce the amount of damage to the body.

1.5.6 Fashion

There have been a number of commercially available and prototype garments manufactured that use smart textile technology. The range of functions of these garments has been diverse; some enable control of integrated music players (i.e. MP3 players), some are meant to display emotion, some are purely to demonstrate the capabilities and potential uses of smart textile garments.

In 2000 Philips and Levi Strauss launched their ICD+ jacket [44] which combined a remote-controlled mobile phone and an MP3 player and, on removal of all the electronic devices, was washable. The ICD+ jacket was apparently the first wearable device to be marketed to consumers, although it was only available in Europe.

Canesis, in conjunction with Australian Wool Innovations [45] developed electrically warmed wool socks through the use of conductive yarns and wool, aimed at the hiking/walking market and expected to go on sale in late 2004 or early 2005. They were battery powered and suitable for those who worked in very cold environments or for people who suffer from poor circulation, as the amount of heat generated by the socks was to equal the rate of heat lost [46] through the foot.

Eleksen's touch-sensitive fabric was employed in the wireless keyboard introduced in 2006 by G-Tech, and in 2007 it launched an iPod control business suit [47] for sale in a major department store. Fibretronic, launched the iPod control system for the new RedWire DLX jeans, to be launched by Levi's in 2007, and Burton Snowboards has added Fibretronic's PTT (push to talk) technology to its Audex range of jackets and packs.

1.5.7 Sports

The intelligent knee sleeve [48], developed in 2001 by Intelligent Polymer Research Institute and Commonwealth Scientific & Research Organisation, was a biometric device used to teach football players how to land properly to prevent non-contact anterior cruciate ligament injuries which occur mainly when athletes land badly after jumping and twisting. The device was a lightweight fabric sleeve worn around the knee with a specially coated stretchable strip of polymer-coated fabric attached over the kneecap. The coated fabric acted as a strain gauge whereby the sensors have been subjected to a process that ensures their electrical resistance changes with the extension of the fabric [49]. The device emitted an audio tone when the knee bent beyond a pre-set angle so that if, on landing, the knee angle was insufficient, immediate feedback was provided to the player by means of an audio tone, allowing the player to adjust their landing technique accordingly until they heard the sound.

1.5.8 Outdoor Pursuits

Finnish researchers developed a machine-washable jacket, vest, trousers, and two-piece underwear set [50] for snowmobilers embedded with a Global System for Mobile chip, sensors monitoring position, motion and temperature, an electrical conductivity sensor and two accelerometers to sense impact. In the event of a crash the jacket automatically sensed the impact and a distress message was sent via Short Message Service to medical staff. The message conveyed the rider's coordinates, local environmental conditions, and data taken from a heart monitor embedded in the undershirt.

In 2003 Burton Snowboards and Apple®, with the aid of SoftSwitch technology, manufactured and sold the Amp Jacket [51] which was cited as the first and only wearable electronic jacket with an integrated iPod™ control system. It was a Gore-Tex snowboarding jacket with an integrated soft, flexible sleeve control pad for the iPod which was waterproof, seam taped and machine washable when the iPod was removed. The technology was then integrated into a backpack to create the 'Amp Pack'. There are several other products which include the same SoftSwitch technology including the North Face Met5 jacket with an integrated heating system and keypad control and the limited edition Hub jacket by O'Neill incorporating bluetooth mobile phone control and an MP3 player. Electrically conductive fabric tracks connect the chip module to a fabric keyboard and built-in speakers in the helmet of the jacket and the microphone is integrated in the collar of the jacket [52].

1.5.9 Workwear

Gorix developed an Electro-Conductive Textile (E-CT) fabric [53] which resulted from special weaving and carbon treatment procedures. The resistance of the fabric varied according to temperature variation allowing for its use as temperature sensor devices. Gorix then developed thermal clothing for hospitals, clothing for astronauts and divers, therapeutic Infra-Therm systems and workwear for people who work outdoors or in places with extreme weather conditions. The fabric could be used to detect the presence of bodies so that in a disaster situation, if an electronic control circuit is added, Gorix E-CT could detect people and alert others of this fact.

1.5.10 Home Furnishings

Malden Mills produced an electrically heated fabric [54] suitable for use as electric blankets or to make into clothing. The heating element was an insulated conductive yarn, spaced at intervals across the fabric, which comprised a core of insulating material, an electrical resistance heating element and an outer sheath. An external power source was provided for the element and the underside of the fabric comprised of a protective layer of fleece.

The Philips Sofa Q4 Plugged [55] was developed in 2001 as a modular system consisting of four square-shaped stools, as well as arm-rests, back-rests and table elements that could be re-arranged in several different ways to create different configurations. All the elements could be linked together not only physically but also electrically as one of the stools had a power lead to connect the whole to a nearby mains socket. The 'buttons' in the mattress tops were elasticated holes into which the various elements could be plugged to position them and to make the necessary electrical connections. The arm-rests were hollow and one unit is fitted with a music player, the control panel being embroidered in the side of the arm-rest using conductive fibres.

Infineon developed a smart material [56] in 2002 consisting of a self-organising network of chips woven into the fabric which enabled it to monitor temperatures, pressures or vibrations. Microelectronic modules were embedded in the textile structure in the form of a grid and each chip was connected to its four adjacent neighbours by electrically conductive threads, creating a network that enabled the flow of information to various systems via a data interface. The chips could be used as sensors in columns or walls to gather information about the condition and the loading of materials, permitting the early identification of local defects, breakage or cracks in construction materials to increase building safety and make the detection of defects easier. If a chip or conductive path failed, the network would automatically locate this fault and immediately reorganise itself, finding a new path within the overall system via the neighbouring chips in order to maintain the information flow.

1.5.11 Communications

The Reima Smart 3305 [57] was designed in 2004 to facilitate easy group communication via a wearable accessory to a GSM phone. It could be used to send group voice messages by pulling the operating band without dialling and incorporated a mobile phone, loudspeaker and microphone. A detachable belt was incorporated in the outfit into which all the functions were concentrated and the functions were controlled by the pull tags in the belt.

1.5.12 Aviation and Automotive

Merhav A.A.P Gmbh developed a 'portable airbag' system [58] in 2003 for horseriders and motorcyclists which inflated in 30 milliseconds to protect the neck and spine (the areas most vulnerable in a collision). This concept was also developed by a Japanese company (Mugen Denko) who produced the EggParka [59] in 2004 for motorcyclists, which inflated with a carbon dioxide cartridge when a pull-cord was ripped off, to protect the back, neck and waist when a rider fell from their vehicle.

The notion that airbags need to be 'smart' has been of great concern within the automotive industry in case they cause injury if, for example, a child is leaning forward at the time of a collision. The automotive unit of TRW Inc. said it would produce its first smart airbag [60] for a U.S. vehicle for the 2004 model year. A strain-gauge weight-sensing system embedded in the front seat indirectly determined the occupant's size and position before the bag deployed. The 2003 Chevy Silverado had a similar system that could automatically switch off the airbag it was detected through the seat sensor pad that the passenger was a small child.

1.6 Technologies Used to Create Electrically Conductive Smart Textile Structures

Electrically conductive smart textile structures allow electronic signals or power to flow directly through them without the use of wires or remote transmitters. Borne from the miniaturisation of computers and electronics [61] and the increasing ubiquity of these technologies, thus far there have been a wide range of technologies developed. There are a variety of suitable fibre types, yarns and materials being researched and developed in order to provide capabilities that range from simple on-off switching to pressure sensing, and currently there is ongoing research and development into gaining an understanding of the enabling technologies required to make components for myriad applications. At present the most important rudimentary requirement for developing these smart structures is to establish design paradigms for constructing textile sensors, actuators and conductive circuit pathways, such that electronic components are not merely attached to fabrics, but that they are actually integrated into fabrics.

1.6.1 Materials

In order to create electrically conductive smart structures, a degree of electrical conductivity or semi-conductivity must be imparted and this can be done during the fibre processing, yarn formation or after the fabric formation stage. A variety of methods are listed and, where possible, the advantages and limitations of each method are highlighted. The choice of material used depends on the application, the end product and the required function, and new materials are constantly being formulated.

1.6.1.1 Conductive Fibres

Fibres used for electrically conductive smart structures can be added to a nonwoven web, spun into a yarn (staple or continuous filament), used as sewing threads or knitted/woven into fabrics. The fibres can either be inherently conductive, be chemically processed to induce conductivity, or be blended with other conductive fibres to produce bi-component fibres. Conductive threads and yarns can be sewn onto fabrics to create circuits or can be embroidered onto fabrics to create switching points. There are a variety of methods of producing conductive fibres, some of which include metallic salt coating, galvanic coating, resin coating, vacuum spraying and the spinning of bicomponent fibres.

1.6.1.2 Metal Fibres

Steel, copper and aluminium are commonly used to create conductive textiles and these fibres can be blended into yarns using a variety of traditional fibre types such as cotton, polyester and nylon, using either continuous filament or staple fibres. Stainless steel fibres have already been proven in use in smart textiles [62] due to their high levels of conductivity (low electrical resistance), stability under harsh washing conditions, and their compatibility with traditional textile fibres and yarns and subsequent processing techniques. They are also used due to their high thermal resistance levels (above 600°C) and corrosion resistance properties, with a wide range of fibre and yarn configurations available from manufacturers such as Bekaert [63] and R.Stat [62].

Metal clad fibres with nickel, copper or silver coatings are available, resulting in products with the surface conductivity of a metal, and the flexibility of a fibre. Products available include Dupont Aracon yarn [64] which is made from a conductive fibre of nickel or silver clad Kevlar, and X-Static yarn [65] which is made up of silver or nickel coated monofilaments.

In metal salt coated fibres the textile characteristics of the base material are more readily maintained and products include Thunderon fibres [66] which are made from Copper Sulphide chemically bonded to Acrylic and Nylon fibres and filaments, and R.Stat/P and R.Stat/N [62] which are Copper Sulphide coated Polyester and Nylon fibres.

1.6.1.3 Carbon Fibres

Carbon fibres [67] are produced by carbonizing precursor fibres based on Polyacrylonitrile (PAN), rayon (regenerated cellulose) or pitch (coal tar or petroleum residue). These fibres are electrically and thermally conductive, and have high abrasion and wear resistance, thus making them suitable for use in conductive textile fabrics. They are available in a variety of forms, for example Hexcel carbon fibres [68] are available as both staple and continuous filaments.

Epitropic fibres [69] are a different class of carbon fibres; these synthetic fibres are produced by embedding tiny particles of electrically conductive carbon powder into the surface of a nylon or polyester fibre. Epitropic Fibres Ltd [70] manufacture epitropic polyester fibres which are used mainly for antistatic nonwoven fabrics, whilst Resistat and Sanstat fibres [71] are Nylon 6 and Nylon 6.6 monofilaments with conductive carbon absorbed into the surface.

1.6.1.4 Conducting Polymer Composite Fibres

Conducting polymers such as polyacetylene (PA), polypyrole (PPy), polythiophene (PTh) and polyaniline (Pan) offer a degree of semiconductivity. They are chemically or electrochemically doped π-conjugated polymers and they have been found to possess metallic properties [72]. The most commonly used conducting polymer is Pan and its conductivity results from a process of partial oxidation or reduction, and Pan compounds can be designed to achieve the required conductivity for a given application with the resultant blends being either highly conductive or acting as insulators. However there are still issues regarding the everyday use of these materials as the electrical conductivity could be improved further by reducing defects in the long polymer chains that carry the current. PPy exhibits good electrical conductivity, good environmental stability in ambient conditions and few toxicological problems, however the brittleness of PPy limits it practical uses. The processability and mechanical properties can be improved either by blending PPy with other polymers, then spinning into synthetic fibres, or by forming copolymers of PPy [73] and thus providing the fibres or fabrics with electrical properties.

1.6.1.5 Superconducting Fibres

Superconducting fibres [54] have been developed in order to make synthetic fibres conductive whilst reducing their tendency to become charged with static electricity, and they can conduct electricity, carry electronic signals in fabrics, and flex without cracking. If the superconductor particles are istotropic it means that the electrical current density can be improved when the particles are aligned – this can be done during spinning and increased by applying a strong magnetic field after spinning. The BASF Corporation has developed a superconducting fibre based on viscose rayon which is a core-sheath arrangement with a viscose sheath covering a multicomponent core that contains at least 10% of a superconducting liquid suspension.

1.6.1.6 Silicon-on-Insulator Fibres / Computing Fibres

Clemens et al [74] proposed the concept of fibre computing in which the goal is to embed the basic unit of computation, the transistor, into fibres that make up clothing, and then connect them to form inverters, gates and higher level circuits. The prerequisite for a fibre having computational properties is semi-conductivity or the fibre must be one that will bear a semiconductor coating and survive the microelectronics fabrication process. There are two methods to develop substrates in fibre form which are capable of carrying semiconductor circuitry. With the Silicon-On-Insulator (SOI) process transistors are formed on special SOI substrates (a 1um thick polycrystalline silicon layer deposited on oxide) and then extracted from the silcon wafer substrate in the form of very long thin membranes by using etch techniques. The Ceramic Powder Extrusion technique involves extruding a mixture of fine ceramic powder and organic additives into a fine fibre, then the organic additives are removed and the fibre is sintered to create a ceramic fibre. Thus pure polycrystalline silicon carbide fibers and pure amorphous silcon dioxide glass fibres have been produced, however if these fibres are to be integrated into traditional textile structures they must withstand the degree of twisting to which they may be subjected during fabric production.

1.6.1.7 Optical Fibres and Photonic Fibres

Glass fibres are used whereby information is encoded in light and sent through the optical glass fibre. The chemical composition and the microstructure of glass fibres must be controlled carefully during manufacture and, although they are brittle, they are extremely strong [74]. Photonic Fibres (PCF) have wavelength-scale morphological microstructure running down their length and this structure enables light to be controlled within the fibre. Photonic crystals rely on regular morphological microstructure incorporated into the material to radically alter its optical properties. To fabricate a PCF a preform is created which contains the structure required (on a macroscopic scale), this is then drawn, greatly extending its length while reducing its cross-section [75] to a fibre-like structure.

1.6.2 Yarns

As with fibres, there are a variety of methods that can be used to produce electrically conductive yarns and most of these methods can use any type of conductive fibre, depending on the required performance or application. Methods of conductive yarn construction include draw-blending, core-spinning, yarn wrapping and the creation of braided, plied or cabled yarns.

1.6.2.1 Metallised Yarn

Metallised (or metallic) yarns are those which have free metal as a component and are commonly known as Lurex yarns. There are several types including single and multi-end yarns (in which at least one yarn is metallic) in which the narrow strips of metal may be coated or laminated, or yarns may have metal deposited on the fibres either chemically, by electric arc or by adhesive [2]. The metallised yarns are typically polyester films metallised with either aluminium or pure silver [76] and the metallization process is thermal evaporation wherein the metal wire is evaporated onto a heated crucible in a vacuum chamber [77]. The yarns are then coated with either a special resin [78] or other coating materials to add the colour and to ensure resistance to physical and mechanical degradation. It is generally found, however, that these materials exhibit only low levels of conductivity which are insufficient for electrodes or sensor structures. However, they can be electrochemically modified (e.g. oxidised) to produce oxide structures with semiconducting properties [79].

1.6.3 Coating Materials

Another method of imparting conductivity is the use of conductive coatings in addition to, or instead of, conductive fibres and yarns. There are endless variations on the coating methods, numbers of layers and combinations that can be used depending on the application and materials available to use, including electroless plating, sputtering, evaporative deposition and more traditional textile coating processes.

1.6.3.1 Carbon-based Pigments

Conductive fillers such as carbon black, carbon fibres and graphite can be used in conductive pigment applications where previously metals have typically been the materials of choice. The advantages include lighter weights, resistance to corrosion, and the ability to be readily adapted to the needs of a specific application. Carbon black in particular efficiently imparts electrical conductivity with a minimum loading as the highly branched, high surface area carbon black particle structure allows it to retain contact over a large area of polymer, which results in improved electrical conductivity. It should be noted that the carbon powders will turn the coating black, however they can all be added to any suitable traditional fabric coating materials.

1.6.3.2 Metallic Conductive Pigments

Another method of imparting conductivity to a fabric coating material is to use a conductive powder. Suitable powders with high electrical conductivity include Nickel and Silver and these must be dispersed into a printing medium. Johnson Matthey produce Silver powder and Silver paste [80] for use in conductive printing pastes.

Titanium Dioxide, Tin Dioxide and Antimony Dioxide are conductive pigments which can be considered semi-conductors and coated onto materials to impart conductivity. In addition, Silver ink and Carbon inks are highly conductive and suitable for use on textiles when applied using a suitable carrier; typical products include conductive Silver and Graphite inks [78] produced by Coates.

1.6.4 Fabrics

A common approach to creating conductive fabrics is to integrate wires and plated yarns into base fabrics [81], however this approach has significant disadvantages relating to the durability of the wires or conductive plating. For example, wires that are fine enough not to significantly impair the textile's aesthetics are not durable enough to withstand elongation stresses normally encountered during textile manufacturing or use, and the same is true for metal plated yarns, where the cladding develops stress cracks leading to conductivity failure when the yarns are strained. Thus it is necessary to find a method of developing conductive fabrics in which the integrity of the fabric can be maintained whilst the conductive element remains intact during production or normal use.

1.7 Data Transfer

Once the method of imparting electrical conductivity to the fibre, yarn or fabric has been made, connections are required between the smart structure mounted onto the fabric and the electronic measurement and data gathering instruments.

1.7.1 Fabric Data Bus

A commercially available fabric data bus is typically constructed of woven fibre in a narrow strip or ribbon configuration. Parallel lines of conductive yarn, separated by non-conductive yarn (traditional textiles such as Polyester, Nylon etc) are used to conduct electricity and to provide the connection between the fabric sensor and measurement instruments. These systems are effective over long distances and available through companies such as Offray and Foster Miller [82].

1.7.2 Bluetooth Technology

Bluetooth technology enables short-range wireless connections between electronic components using a globally available frequency [83]. It can be used in the field of smart textiles to create products that incorporate mobile phone communication systems or require fast data transmission between sites. In particular it has been used with some of the biophysical monitoring products which are designed to be used at home by the patient with a link to their GP's surgery or the hospital. It is also common in outdoor performance wear or military uniforms that have GPS communication and position location systems.

1.7.3 Connectors

The connections between the smart structure and the technical textile fabric is of prime importance as this is where the two technologies meet. It is essential that firm and robust connections are made to the textile fabric and that, if necessary, they can be either removed for washing or be washable themselves and therefore remain durable and rust-proof.

1.7.3.1 Soldered Connections

This method can be used when using fabrics with integrated metallic wires and there are two possible methods for connection [84]. In the first instance, the edges of the smart structure are prepared by soldering on tiny contact plates and the electronic data transfer component is connected by electrically isolated bonding wires and lastly the wires and the contact plates are covered by a flexible and isolating layer for mechanical protection. A second approach uses a thin flexible circuit board with structured electrodes which are glued or soldered to the smart structure. In both cases the electronic data transfer component and the interconnect areas are fully encapsulated to ensure stability against mechanical and leakage problems. The benefits of soldering include the limited size, weight and effects on the comfort and aesthetics of the technical textile as the connection size itself is reduced to the size of the additional solder. Whilst in practice soldering would produce a reliable electrical connection to the fabric, the physical strength of the solder connection may be compromised on bending once the solder has hardened. In addition, soldering may not be an option for some types of wires if they are unable to withstand the heat of the soldering process.

1.7.3.2 Snap Connectors

One side of a sew-on snap connector can be connected to the fabric wire, and the other side to the electronic data transfer component [85]. Conductive or non-conductive thread helps stabilise the connection while also holding the snap in place on the fabric but there may be issues over whether sufficient contact is made between the snap and the wire, particularly if non-conductive thread is used.

Welding the snap connectors to the wire is a technique similar to soldering however the process is quicker as it is not necessary for the elements to be heated before use. This method had already been tried and the process of attachment and removal is simple, also the large surface area of the snaps provides a decent platform for an electrical connection. However, a potential disadvantage is that repeated connect/disconnect cycling could weaken the strength of the connection, thus compromising its stability. One problem common with any of these exposed-wire methods is the potential for wires to short, even insulated wires and the use of snaps provides an ever-present opportunity for two leads to touch.

1.7.3.3 Ribbon Cable

The ribbon cable connection method is called 'insulation displacement' wherein the connections are made within the housing of the connector through the use of a sharp V-shaped contact that cuts through the insulation to connect to the conductor [85]. The use of insulation displacement removes the need for mid-wire insulation stripping and the plastic housing of the connector provides insulation of the contacts. The sockets of this connector allow for easy mating with the pins of the electronic data transfer components providing a reliable connection and easy removal and when the electronic component is detached the contacts to the fabric are not exposed. Removing the ribbon cable connector, however, can lead to exposed portions of the wire or the insulation displacement could damage the conductor so much that the wire is in danger of breaking. Another significant problem with these connectors are the relatively large dimensions in the vertical direction.

1.7.3.4 Textile Interconnection System

This method is suitable for use with a fabric data bus that does not have exposed metallic wires, thus can be used easily with conductive yarns [86]. This method provides a lightweight, neat, compact connection and different sizes are available (i.e. 5-pin, 7-pin) depending on the requirement. This system is launderable and has been used successfully in commercial products where the pitch (the distance between the connection points/pins) is generally 2.54mm, meaning that the spacing of the yarns in the databus is critical to ensure connection. One disadvantage is that this method is only suitable for end of data-bus and cannot be used in the centre of a fabric, thus limiting the locations to which it can be connected.

1.7.3.5 Conductive glue

Conductive glue, as used by Sergio et al. [19] can be used to create conductive solderless connections between metal circuit elements and a fabric substrate. Most commonly these glues are silver filled epoxy adhesives and they are commercially available. Whilst these glues provide a simple method of connection, especially given that some glues cure at room temperature in less than two hours [87], and can be used on heat sensitive materials, the potential disadvantages of using glue with textile substrates relates to the strength and robustness of the bond. Given the often textured nature of a woven or knitted fabric surface, particularly if textured yarns have been used, this may present difficulties in ensuring that the bonding surface is even and subsequently that the integrity of the bonding interface is not compromised. Issues may also arise in terms of the reaction of the glue under changing environmental circumstances (temperature, moisture levels etc) and the respective reaction of the textile substrate – should there be any issues of differential shrinkage etc, this will again affect the integrity of the bond.

1.8 Power Supply

For all sensors a power supply is required in order for it to be usable and whilst industrial and home applications can use standard AC outlets (especially if they are static) there is a need to consider portable products. Batteries are commonly used to power smart textile products, for example the NorthFace MET5 jacket incorporates heat technology panels powered by lithium batteries and the Canesis heated socks [88] are powered by a 7-volt battery which give approximately three to four hours continuous warmth. However, at present there are limitations to using this standard technology such as finite battery-life, battery dimension and safety (i.e. prevention of battery leakage). For a technical textile in use in an extreme environment (manufacturing, automotive, at sea), it is not suitable to have small short life batteries, thus this is an important design consideration.

There are in development a number of alternative power sources, for example Infinite Power Solutions [89] is making lithium batteries mere micrometers thick that are essentially painted on metal foils which could potentially be incorporated into the lining of garments or on the surface of backpacks to power sensors. Researchers sought to make future batteries more slimline by incorporating them directly into textiles and creating fibre-based batteries, which layers the anode, cathode and electrolyte on top of a 100-micrometer-wide fibre that is incorporated into a textile. Postage stamp-sized bio-thermal batteries [3] generate electricity by harnessing differences in body temperature and, for example, an external surface. Fuel cells convert chemical energy into electricity by, for example, combining hydrogen and oxygen, miniature fuel cells use methanol which is cheap and readily available, and can run for several months without recharging. Large clothing manufacturers are incorporating a number of technologies into their products, for example snowboard clothing manufacturers O'Neill [90] have developed flexible solar cells, capable of charging a portable music device, which are integrated into a rucksack that also incorporates pressure sensor technology to operate the music device.

1.9 Discussion

It is clear that the smart textile industry as a whole is developing, not just in terms of materials and technologies, but also in terms of product innovations (both commercial and prototype) and market value, with further growth predicted in coming years. However, although this innovation and growth demonstrates that there are huge numbers of ideas available for exploitation, many technologies available for use, and numerous organisations, research institutes and companies keen to be part of this growing market, it does indicate that the smart textiles industry appears to be developing backwards.

As yet there is a lack of fundamental research available on the basics of designing, testing or specifying the performance of a smart textile structure or product. These design issues may be, in part, due to the complexity of the materials being considered, given the sheer number of different polymers available for use (amides, aramids, urethanes etc), their wide-ranging properties (i.e. range of tensile strengths, stretch and recovery properties, reactions to temperature and moisture), the different methods of manufacturing and processing them, and their potential final configurations and compositions as well as the materials/fabric onto which they may be integrated. These constraints, in terms of the potential number of variables that must be considered when designing a smart textile product for use with technical textiles, must be taken into consideration by the textile engineering designer. Additional problems encountered by product designers and manufacturers is the launderability of the garments once electronic components have been removed and, in particular, concerns have been raised over the robustness of these systems in the course of daily wear and tear, as well as the repeatability of performance and the issue of redundancy ("planning in an identical copy of a functional component to serve as a backup in case of failure of the primary component"). These are the issues which need to be addressed in order for solid foundation of knowledge to be built and improved upon if this industry is to survive.

The decision to investigate the construction of an electrically conductive textile-based strain sensor was based partly on the researcher's previous work experience in the smart textiles R&D industry developing pressure sensitive and keypad switch products on a laboratory scale. Whilst there was information available on the theoretical issues concerned with pressure sensing technology developments and electrically conductive metal-based yarns for use in static electricity dissipation, it was very difficult to find any information (journal articles, books/chapters, conference papers) on the theory or practical knowledge gained in order to aid the research and development into textile-based systems. The reasoning for focussing on strain sensing materials was due to the shifting focus of the products and applications being developed, from pressure sensing and switching devices, to those that were used in areas such as biophysical monitoring.

Finally, in order to address the lack of fundamental knowledge available, it has been decided to research developing a design paradigm for creating a sensor yarn. As stated in the aims of the project, the design paradigm will set out the optimal material properties, construction and manufacturing method required to construct an electrically conductive textile-based sensors capable of measuring strain exerted upon it or any material to which it is attached. This sensor will be made entirely of electrically conductive textiles such that the problems of laundering and compatibility with the technical textile will be avoided. This type of smart structure would be suitable for any number of smart textile applications, particularly those that are predicted to push the growth in smart textiles such as biophysical monitoring and military clothing.

Objectives

The objectives of this project are;

1. To critically review the current literature relating to yarn sensors in order to determine what work has already been done in this area and to determine where there are gaps in the knowledge.

2. To test and analyse the physical, mechanical and electrical properties of a number of commercially available conductive yarns such that those worthy of further characterisation can be determined.

3. To determine the relationship between the mechanical properties and the electrical properties of the yarns.

4. To construct an electrically conductive textile yarn capable of sensing strain.

5. To derive a design paradigm from the information gathered thus far for building a yarn stretch sensor. The design paradigm will set out the optimal material properties, construction and manufacturing method required to construct an electrically conductive textile-based sensors capable of measuring strain. This paradigm will contribute to the knowledge of the textile industry by enabling future researchers to more easily determine optimal materials and processing conditions for a given performance requirement.

Chapter 2

Literature Review

Chapter 2
Literature Review

As highlighted in Chapter 1 there have been a number of developments in the sector of electrically conductive smart textiles. Consequently there have been a corresponding number of raw materials and technologies used to create products, ranging from novel fibres, yarns and coatings to the methods of fabric construction and the creation of fully conductive textile systems or the integration of electronic components into traditional textile materials. This literature review will critically assess the materials and technologies used to create textile-based strain sensors.

2.1 The Need for Textile-Based Strain Sensors

Of the myriad smart textile components capable of detecting pressure, regulating temperature and transmitting electronic signals, one commonly required property is the ability to detect and measure strain, as evidenced by the increasing number of developments in biophysical monitoring applications. If the change in strain of a smart component can be related linearly to the change in the electrical conductivity, they can be attached to or integrated into technical textile materials and act as a strain gauge. Thus for a given application or product, the strain gauge can be linked to an audio/visual system such that if the outer limits of the pre-determined strain are passed the user can be alerted.

When analysing strain sensor smart components that have already been produced, it can be seen that there is a division in terms of their construction. There are smart components that have been created solely using textile raw materials and those that are fabric substrates with electronic sensor chips or components attached to them. There are many advantages of using a 100% textile-based strain sensor compared to an electronic sensor when working with technical textile materials. Issues of compatibility in terms of flexibility are less problematic when using a textile-based sensor as long as the strain sensor and technical textile material exhibit similar mechanical behaviour, and concerns about launderabilty may be lessened. Also the potential for textile-based strain sensors to corrode are lessened if non-metallic components are used, and issues of strain sensors becoming detached from the fabric substrate can be overcome if they are integrated directly into the fabric (i.e. woven or knitted).

However, there are still issues which must be considered, such as the reliability of a textile sensor which may be potentially subject to constant flexion and abrasion. If, over time, the conductive elements become damaged or frayed, the issue of redundancy and potential sensor failure becomes apparent, thus these potential problems must be taken into account at the sensor design stage.

2.2 Traditional Strain Sensors

There are many types of strain sensor available on the market, all suitable for a variety of end-uses and applications, thus a generic definition of a sensor, whether textile or electronic, is;

> "A device that responds to a physical stimulus (heat, light, sound, pressure, motion, flow, and so on), and produces a measurable corresponding electrical signal." [91].

The type of sensor being investigated is one that exhibits a change in its electrical resistance on mechanical deformation. This is similar to the behaviour of a strain gauge which can be defined as;

> "A device which experiences a change in resistance when it is stretched or strained" [92]

Each type of strain gauge is dependent on a different strain theory and those that depend on the change in electrical resistance due to strain include semiconductor or piezoresistive (i.e. resistance that changes with stress), carbon-resistive, bonded metallic wire and foil gauges. In these gauges the electrical resistance varies linearly with strain.

Strain (ε) is defined as the fractional change in length compared to the original length of the sample [93], and can either be positive (tensile) or negative (compressive) and it is a measure without dimensions. Tensile strain is illustrated in Figure 2.1.

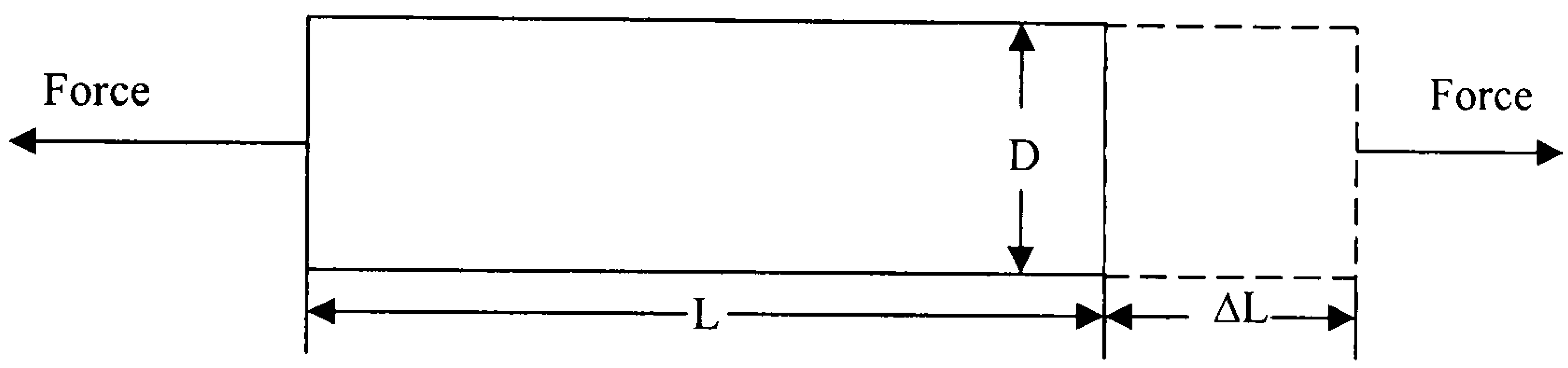

Figure 2.1 Schematic Definition of Strain

A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the gauge factor (GF). GF is defined as the ratio of fractional change in electrical resistance corresponding to the fractional change in length (strain) [93] and can be calculated according to Equation 2.1 where *R* is the resistance (ohms) and *L* is the length.

$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon} \qquad \text{-------------------- (2.1)}$$

For metals, strain measurements rarely involve quantities larger than a few millistrain ($\varepsilon \times 10^{-3}$), and are typically less than 0.005 [94]. Therefore, to calculate GF, very accurate measurement of very small changes in resistance is required and a typical GF for metal strain gauges is approximately 2.0. However, because most materials do not have the same properties in all directions, a knowledge of the axial strain alone is insufficient for a complete analysis thus Poisson's Ratio, bending and torsional strains may also need to be measured depending on the strain gauge application [94].

The ideal strain gauge [94] would change resistance due only to the deformations of the surface to which the sensor is attached. However, in real applications, temperature, material properties, the adhesive that bonds the gauge to the surface and the stability of the sensor all affect the detected resistance. Thus, when designing a strain gauge the strain characteristics of the gauge must be considered as well as its stability and temperature sensitivity. Unfortunately, the most desirable strain gauge materials are also sensitive to temperature variations and tend to change resistance as they age. For short duration usage this may not be a serious concern but, for continuous measurement, temperature and drift compensation must be taken into account.

2.2.1 Poisson's Ratio

It is necessary to consider the effect of the Poisson's ratio with textile strain sensors, whether they are yarns or fabrics, particularly if the sensor is a yarn and it is very bulky when relaxed but has a high stretch capability, which may lead to high Poisson's Ratio values. It is calculated according to equation (2.2)

$$\nu = -\varepsilon \text{ transverse} / \varepsilon \text{ longitudinal} \qquad \text{------------ (2.2) [95]}$$

Strain (ε) is defined in elementary form as the change in length divided by the original length, as shown in equation (2.3).

$$\varepsilon = \Delta L/L \qquad \text{------------------ (2.3) [95]}$$

Thus by using the pre-strain radius (R_o Original radius) and the post-strain radius (R_1), and the same measurements for the length, the individual strains can be calculated and then the Poisson's Ratio, as shown in equation 2.4.

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Radius $e_R = (R_1 - R_o)/R_o$

Length $e_L = (L_1 - L_o)/L_o$

Therefore, $\nu = e_R / e_L$ ---------------------------------- (2.4)

2.2.1 Metal Wire Strain Gauge

Figure 2.2 shows a typical metal wire strain gauge, a long thin wire folded several times along its length to form a grid and embedded in a self-adhesive tape or bonded directly to a thin layer of epoxy resin. The wire grid is approximately 0.025mm thick and the cross sectional area of the grid is minimized to reduce the effect of shear strain and Poisson's Strain. The ends of the wire are attached to terminals (solder pads) for external connections and the strain gauge is attached to the surface of the component for which the strain is to be measured . When a load is applied to the surface, the resulting change in surface length is communicated to a resistor and the corresponding strain is measured in terms of the electrical resistance of the foil wire, which varies linearly with strain. The foil diaphragm and the adhesive bonding agent must work together in transmitting the strain, while the adhesive must also serve as an electrical insulator between the foil grid and the surface [94].

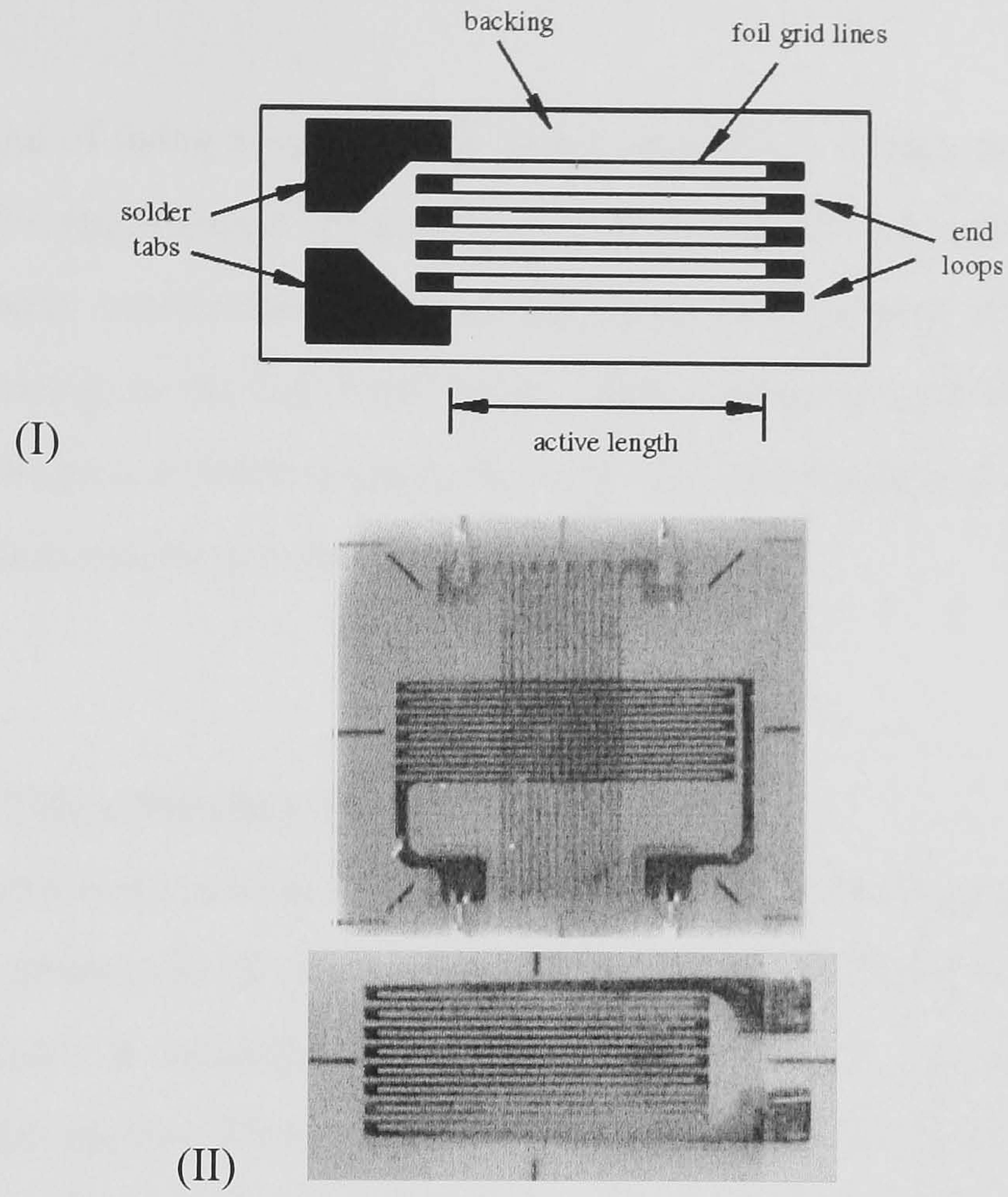


Figure 2.2 Strain Gauge (I) Construction [96] and (II) Position on Material Surface [97]

The three primary specifications when selecting strain gauges are operating temperature, the state of the strain (including gradient, magnitude, and time dependence) and the stability required by the strain gauge application [98]. Strain gauges are available commercially with nominal resistance values from 30Ω - 3000Ω, however this resistance may change only fractionally depending on the limitations imposed by the elastic limits of the strain gauge material and of the substrate material, for example the typical strain capability of a metal wire strain gauge is <5%.

Bonded resistance metal strain gauges have a good reputation as they are relatively inexpensive, can achieve overall accuracy of better than +/-0.1%, are available in a short gauge length, are only moderately affected by temperature changes, have small physical size and low mass, and are highly sensitive. Bonded resistance strain gauges can be used to measure both static and dynamic strain [94].

One disadvantage of using a metal strain gauge on a fabric substrate is that it is very important that the strain gauge is properly mounted onto the test specimen so that the strain is accurately transferred from the test specimen, through the adhesive and strain gauge backing, to the foil itself. If the fabric surface is such that it is difficult to achieve a strong connection without limiting the performance of the strain gauge or the fabric, inaccurate results will be gained.

2.2.2 Carbon Fibre Strain Gauges

Carbon fibres have been used to sense strain under tension and bending loading [73], however most carbon fibres possess a modulus of about 200GPa or more whilst textile fibres have a modulus in the magnitude of only several GPas, thus introducing rigid carbon fibres into a textile structure may alter its strain field significantly. In addition, the measurement range of carbon-fibre-based sensors is limited to small strains, while most textile fibres and some fabrics have an extensibility of over 10%.

2.2.3 Capacitance Strain Gauges

As capacitance strain gauges depend on geometric features, the capacitance can be made to vary by altering the separation between the plates or the plate area, and thus the strain can be measured. The sensitivity of a capacitance strain gauge [99] is linearly related to the plate area and inversely related to the electrode gap. The electrical properties of the materials used to form the capacitor are relatively unimportant, so capacitance strain gauge materials can be chosen to meet the mechanical requirements, however their sensitivity to vibration, their mounting requirements and circuit complexity have limited their use with textile applications [94].

2.2.4 Photoelectric Strain Gauges

In a photoelectric strain gauge a beam of light is passed through a variable slit. actuated by an extensometer, and directed to a photoelectric cell. As the gap opening changes, the amount of light reaching the cell varies, causing a varying intensity in the current generated by the cell [93]. The gauge length of these devices can be as short as 1.58mm, however they are costly to produce and delicate [94], thus limiting their use with potentially highly elastic or roughly surfaced technical textile materials.

2.2.5 Semiconductor Strain Gauges

Semiconductor (or piezoelectric) strain gauges are constructed of ferroelectric materials such as crystalline quartz, in which a change in the electronic charge across the faces of the crystal occurs when the material is mechanically stressed [94]. In the mid-1950s, researchers discovered the piezoresistive characteristics of germanium and silicon [94] and although the materials exhibited substantial nonlinearity and temperature sensitivity, they had gauge factors more than 50 times, and sensitivity more than a 100 times than that of metallic wire or foil strain gauges. The major disadvantage of these strain gauges, however, is their highly non-linear response to resistance versus strain, making prediction of their behaviour difficult.

2.2.6 Silicon Wafer Strain Gauges

Silicon wafers are more elastic than metal strain gauges and, after being strained, they return more readily to their original shapes [94]. The semiconductor bonded strain gauge is a wafer with the resistive element diffused into a substrate of silicon and the wafer element is not usually provided with a backing. They are much smaller and lower cost than metal strain gauges, however bonding them to the substrate surface requires great care as only a thin layer of epoxy can be used, which might lead to poor adhesion with a textured or hairy fabric surface.

2.2.7 Optical Strain Gauges

Optical gauges include photoelastic, moiré interferometry, and holographic interferometry strain gauges [94]. In a fibre optic strain gauge the sensor measures the strain by shifting the frequency of the light reflected down the fibre from the Bragg grating, which is embedded inside the fibre itself [93]. Optical sensors are sensitive and accurate, but are delicate and, whilst they operate well under laboratory conditions, they are not widely used in industrial applications because of this.

2.3 Methods of Measuring Strain Sensor Electrical Activity

Electrical energy in a circuit responds in three ways; if the energy is absorbed the element is a resistor, if the energy is stored in an electric field the element is a capacitor, and if the energy is stored in a magnetic field the element is an inductor [100]. As such, the electrical behaviour of textile-based strain sensors can be assessed by measuring the change in capacitance, inductance or resistance. Electrical activity occurs when a current, generated due to free electrons moving along the material, flows along a conductor when connected to a power source which has a voltage (potential difference) between its poles pushing the electrons. Current (I) is measured in Amperes, Potential Difference (V) in Volts, Electrical Resistance (R) in Ohms, Inductance (L) in Henrys and Capacitance (C) in Farads [101].

2.3.1 Capacitance

A capacitor is a device for storing charge and essentially all capacitors consist of two metal plates separated by an insulator. The insulator is called the *dielectric* and can be a substance such as air. Generally a capacitor is charged when a battery or potential difference is connected to it, and discharged when the plates of the capacitor are joined together [101]. Capacitance (C) can be calculated according to Equation 2.5 using the potential difference (V) across the plates and the charge stored in the dielectric (Q) values.

$$C = \frac{Q}{V} \qquad \text{----------- (2.5) [102]}$$

The potential difference between the terminals of a capacitor is proportional to the charge and Figure 2.3 illustrates the structure of a simple capacitor circuit.

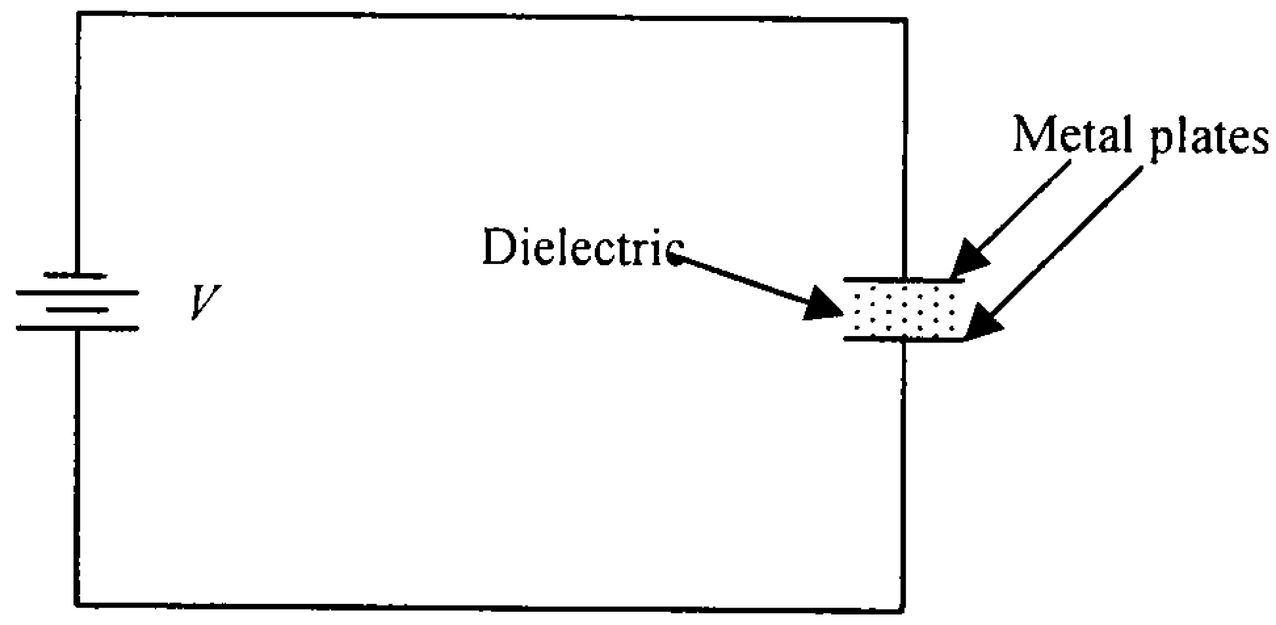


Figure 2.3 Capacitor Circuit [102]

2.3.2 Inductance

Inductance can be defined as 'the ability of a conductor to produce induced voltage when the current varies' [102], and it is an additional characteristic of the circuit besides its resistance. The effects of inductance become greater as frequencies increase as when the flux moves at a higher speed it can induce more voltage. When the current in a circuit is changing (*di/dt*), the magnetic flux linking the same circuit changes and this change in flux causes an emf (v_L) to be induced in the circuit, thus inductance (L) can be calculated using Equation 2.6.

$$L = \frac{v_L}{di/dt} \qquad \text{------------ (2.6) [102]}$$

The polarity of the induced emf (v_L) opposes the change in current (i) such that if the amount of current is increasing, v_L produces an opposing current and vice versa, as illustrated in Figure 2.4.

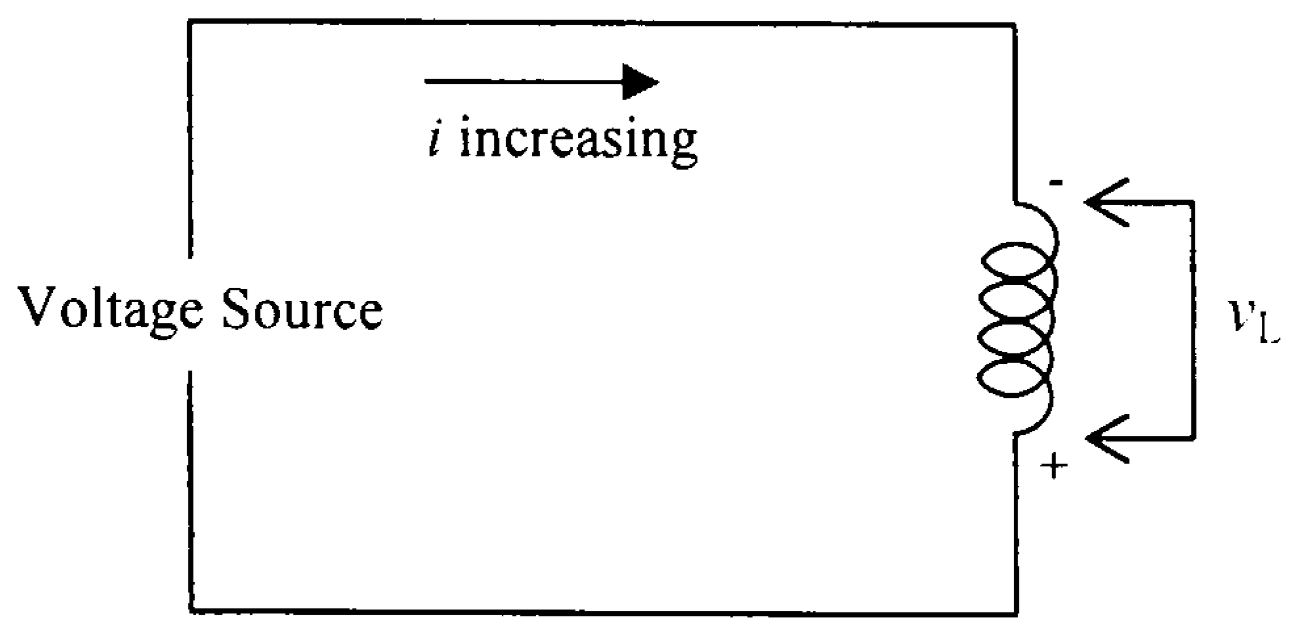


Figure 2.4 Inductor Circuit [102]

2.3.3 Impedance

Impedance (Z) is the total opposition to the flow of an AC current. It takes into account both the resistance (R) and reactance (the opposition of inductance and capacitance to AC current, X_L) and, like resistance, the lower the value the better the conductivity. The phasor triangle used to determine impedance is shown in Figure 2.5.

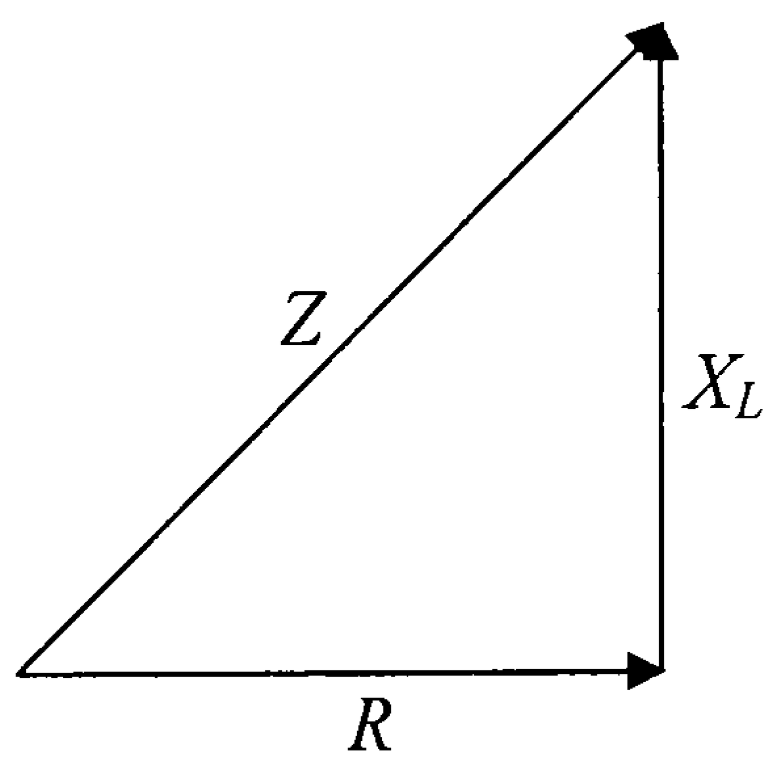


Figure 2.5 Impedance Phasor Triangle [102]

Impedance can be affected by resistance, capacitance and inductance in a circuit and is also dependent on the current frequency. It can be calculated according to Equation 2.7.

$$Z = \sqrt{R^2 + X_L^{\ 2}} \qquad \text{-------------------- (2.7) [102]}$$

2.3.4 Resistance

The ohm (Ω) indicates the resistance of a conductor through which a current of one ampere flows when a potential difference of one volt is maintained across it. The resistance (*R*) can be calculated according to Equation 2.8 using the potential difference (*V*) and the current (*I*).

$$R = \frac{V}{I} \qquad \text{------------------ (2.8) [102]}$$

Calculating the resistance is based on the principle that the potential difference (*v*) across the terminals of a pure resistor is directly proportional to the current (*i*) [100] as shown in Figure 2.6.

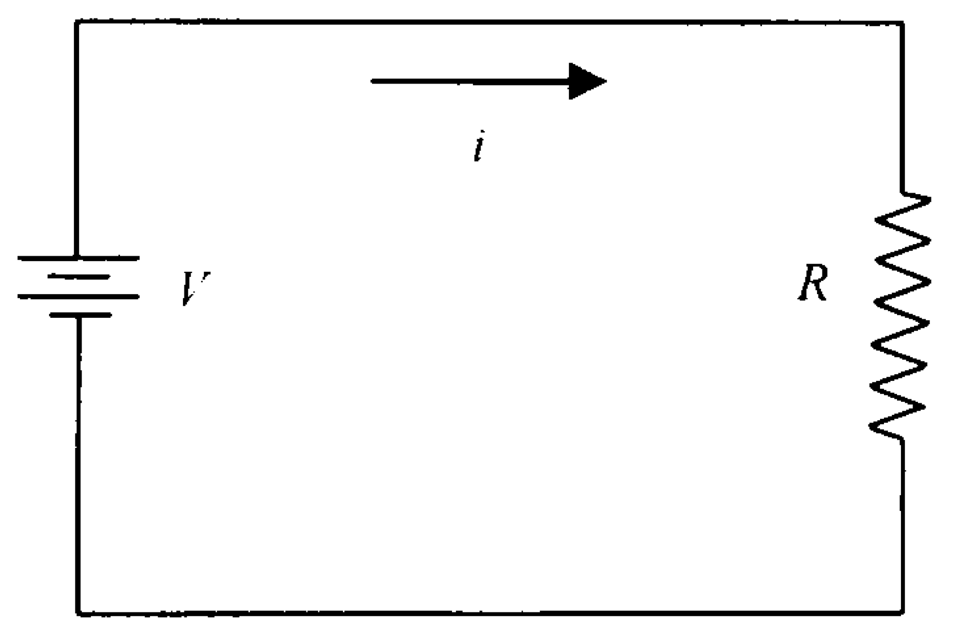


Figure 2.6 Resistor Circuit [102]

Conductivity (σ) is the inverse of resistivity. Resistivity (ρ) is the resistance (*R*) of a wire proportional to its length (*l*) and inversely proportional to its cross-sectional area (*A*) [102]. Thus the resistivity of a material can be calculated using Equation 2.9, with the resulting units being ohms per metre or Ωm.

$$\rho = R \times \frac{A}{l} \qquad \text{----------------- (2.9) [102]}$$

The resistivities of various conductive materials are shown in Table 2.1 and it is obvious that the carbon-based material have a much higher resistivity value than metals, however there is a significant difference in the resistivity of steel (an alloy) compared to the pure metals. These resistivity results, however, gives no indication of the potential strain sensitivity attainable when using one of these materials as a strain sensor.

Table 2.1 Resistivities of Conductive Materials [102]

Material	**Resitivity (ρ) in Ωm x 10^{-8}**
Silver	1.62
Copper	1.72
Aluminium	2.82
Iron	9.8
Steel	16.6
Carbon (graphite)	33 -185

2.4 Sensor Technologies under Development

There have been many developments in this area, all for different application areas and end uses. The main features of each development will be detailed along with an assessment of their effectiveness.

2.4.1 Capacitive Sensors

Sergio et al [19] developed a capacitive sensor system composed of a distributed passive array of capacitors (where each capacitor plate is separated by an elastic, dielectric material) whose capacitance varied according to the pressure exerted over a fabric surface. The fabric was employed not only as a support for the electronics, but also as a sensing element for decoding the pressure value. The sensing array resulted from the crossing of conductive threads patterned in rows and columns to form a matrix. When the dielectric layer between a given row and column of electrodes was squeezed and pressure was exerted over the corresponding fabric area, the coupling capacitance between the two plates increased and, by scanning each column and row, the image of the pressure field was obtained. However, with this system the sensor electrodes needed to be connected to a readout printed circuit board (PCB) using either a pin array or conductive glue, both of which may compromise the integrity and flexibility of the fabric.

Capacitive sensing techniques were also used by Wijesiriwardana et al [103] to create touch sensing textile products. Electrodes were knitted from conducting polymer-based fibres (R.Stat/P Copper Sulphide coated Polyester) and metallic fibres and the method of sensing required a DC power source and current detection (as opposed to an AC power source and electric field detection). In order to produce a touch and compression transducer, a 'parallel-plate arrangement', was used as shown in Figure 2.7.

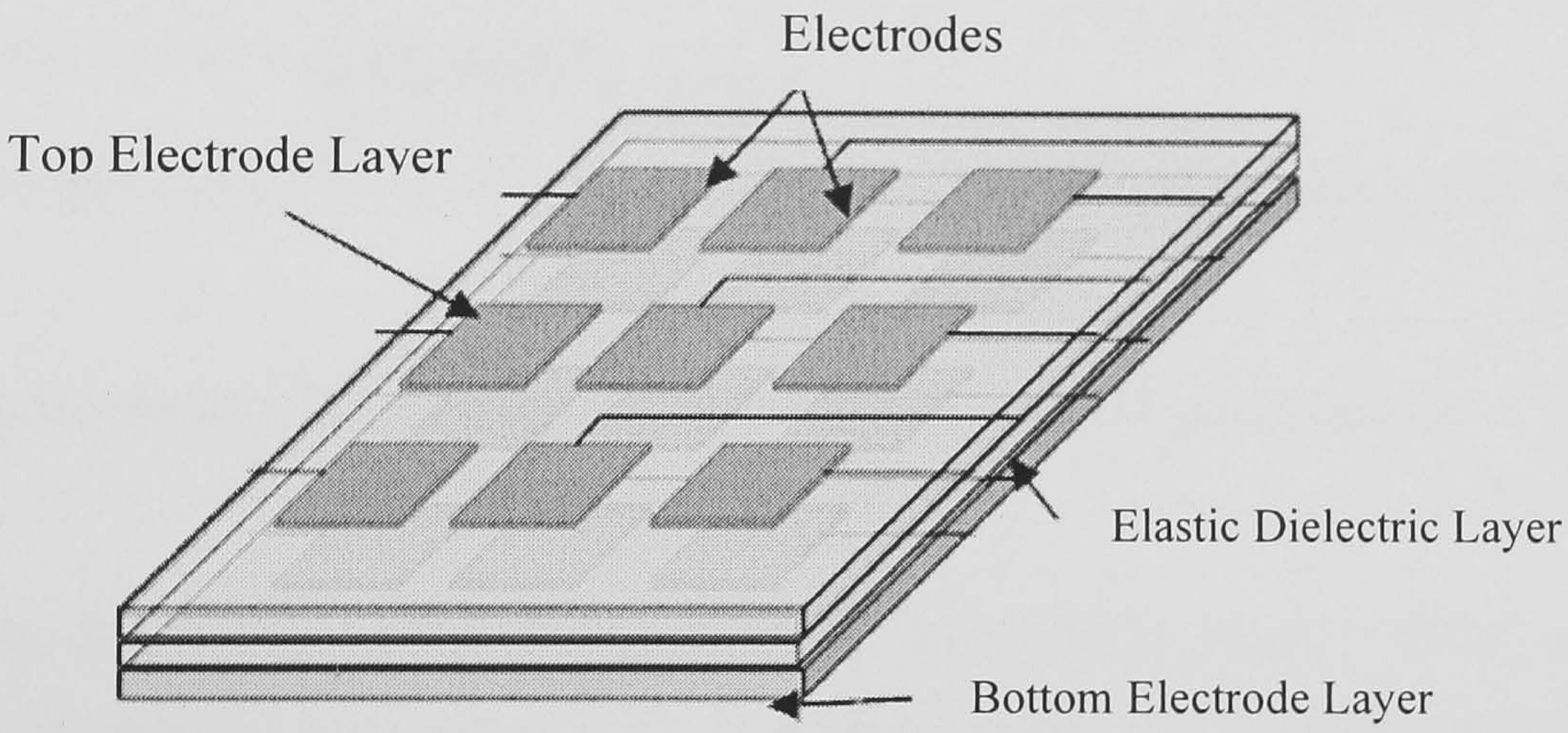


Figure 2.7 Three-Dimensional Representation of The Capacitive Sensor Double-Layer Arrangement [103]

With this system, in order for the flux to remain on one side of the sensor arrangement, an elastic non-conductive layer is required between the electrode layers before the layers were either sewn or laminated together, and each layer had to be energised individually prior to being used as a pressure pad, making this a complex arrangement to produce.

There are a number of different techniques that can be used to pattern electrodes over a textile surface, for example alternating conductive and isolating threads can be glued onto the opposite sides of a supporting layer in order to create a flexible circuit embedded in a fabric sandwich. Other methods include painting or printing conductive paint on the fabric surface or weaving patterns into the fabric using conductive threads. Kang et al [104] used conductive columns and rows drawn onto opposite sides of a piece of nonwoven insulating material using conductive ink to produce a respiration sensor. The elastic and inelastic nonwoven fabric layers were laterally attached whereby the elastic portion of the layers stretched during breathing, as illustrated in Figure 2.8.

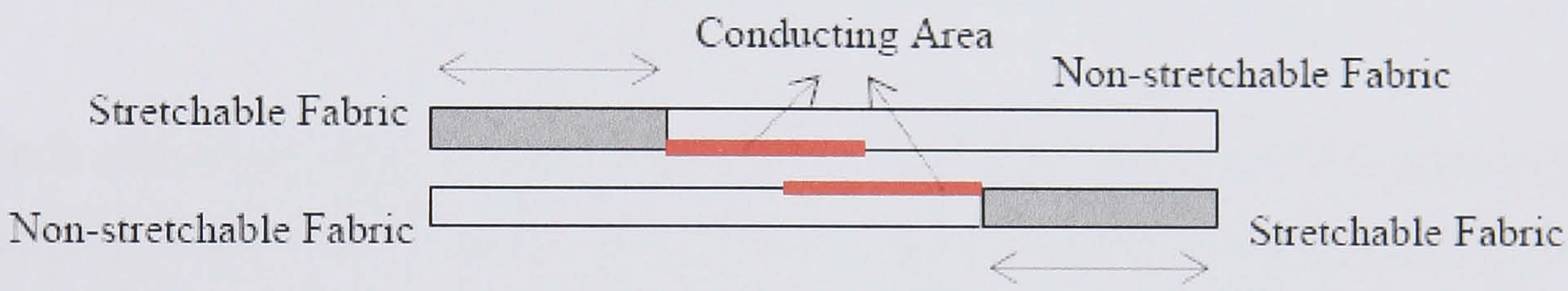


Figure 2.8 Functional Diagram of the Textile-based Displacement Sensor

The inelastic fabrics incorporated printed silver ink conductive areas which formed the capacitor’s plates and, as their positions changed relative to each other when the elastic portion stretched, the effective area and hence the capacitance value changed.

Overall, potential disadvantages of using capacitive sensors include the possibility of triggering false alarms caused by capacitance change due to fabric deformations, and potential difficulties calibrating the system where absolute readings are necessary, due to the change of capacitance following a change in humidity or temperature, ageing or washing.

2.4.2 Inductive Sensors

Many of the inductive textile sensors developed have been used in the field of biophysical monitoring and as a consequence there are a number of methods used to measure respiration including the use of magnetometers to measure the variation in chest diameter, strain gauges to measure the variation in chest circumference, and inductance plethysmography which measures the variation in cross-sectional area. Numerous studies suggested that the results gained from the use of inductance plethysmography alone are not sufficient to give accurate information on the cross-sectional area variation their findings also suggested that the results are no better than those gained with the use of strain gauges, hence alternative methods of measuring respiration have been sought. The major advantage of thes textile electrodes used with these systems remove the requirement for hydrogel, needed when using conventional electrodes to establish good contact between the electrode and the skin but which can often cause skin irritation or softening if used over long periods of time, as they can be used in direct contact with the skin.

The health monitoring Intellitex suit constructed by Catrysse et al [20] incorporated an elastic and washable textile belt, with integrated stainless steel fibres and yarns, to measure the respiration rate and the heart rate of patients. Textile electrodes were combined on a double layer belt and conductive snap fasteners used to connect the belt to the readout circuit. In order to measure the respiration rate, the belt was placed as a coil around the abdomen or thorax and the circumference or length changes caused by breathing resulted in both an inductance and resistance variation, thus both changes in perimeter and cross-sectional area are measured to give a more accurate result. Figure 2.9 shows the results of the change in inductance with elongation, with the measured inductance variation, due to stretch of the belt, calculated as 0.05μH/cm (H is the measure of inductance) based on changes in the diameter of the coil and change in coil length. Little information is given, however, on the linearity or otherwise of the change in inductance on straining outside the strain range of 0.52-0.64 and, as yet, the usable strain range for the textile-based strain sensor to be developed has not yet been determined and may not lie within these limits.

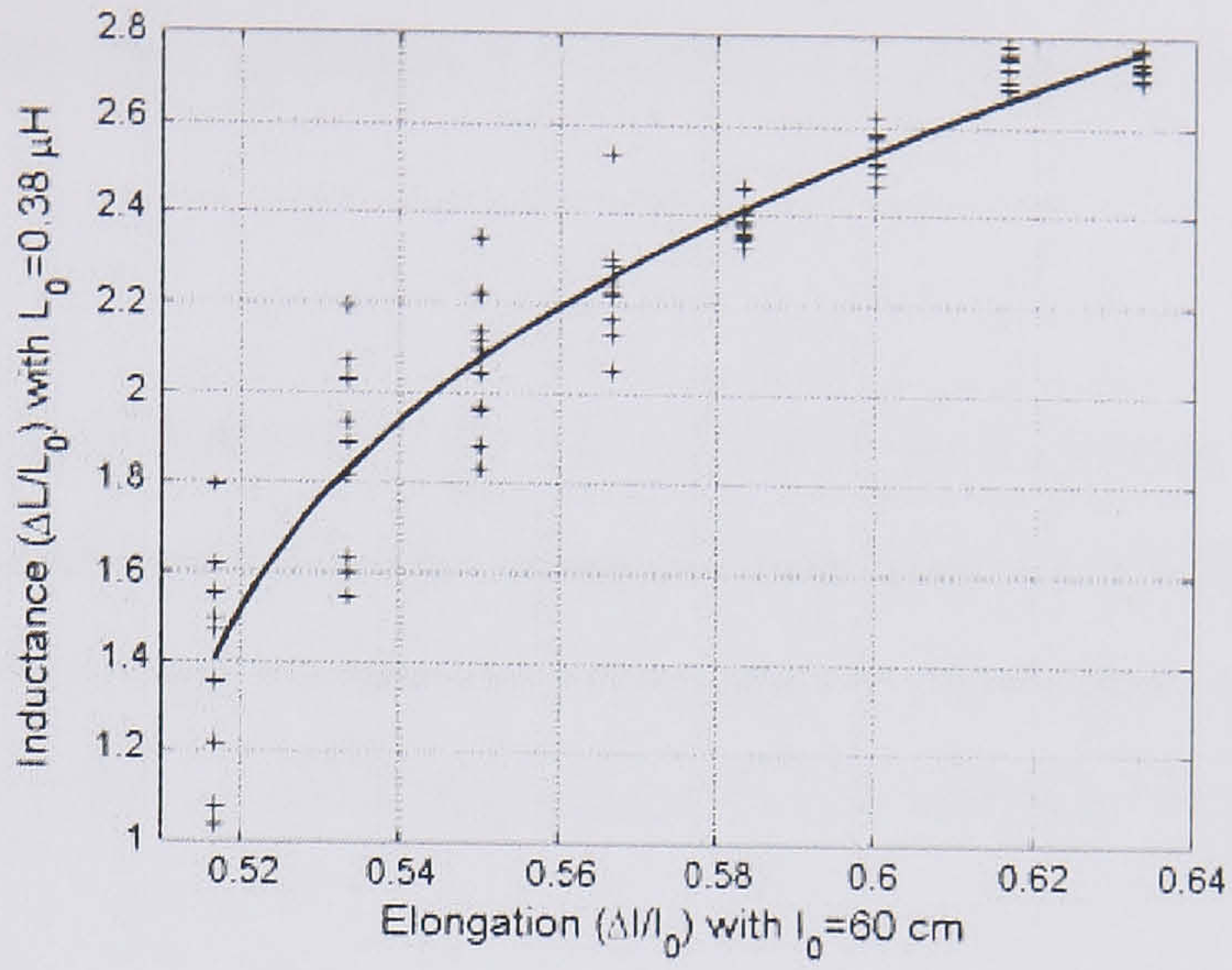


Figure 2.9 Respibelt Respiration Monitoring Belt – Change in Inductance versus Change in Elongation

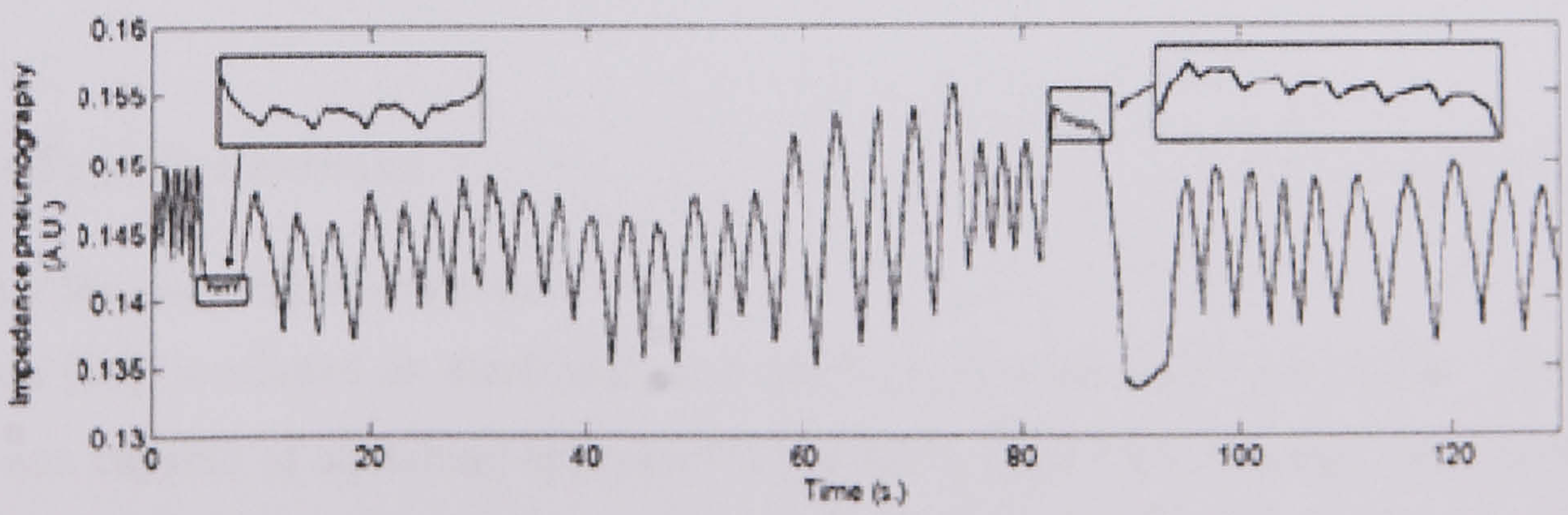
Similarly the LifeShirt, as developed by Vivometrics [105], consisted of a woven or knitted fabric band containing elastomeric yarns which included at least one conductive copper wire and was designed for physiological monitoring. As the fabric band stretched, the curvature of the conductive wire changed thus the inductance of the wire varied (this was measured and processed by an attached monitoring unit). In such a system the conductive copper wires could either be loosely connected or attached to the garment and it would be imperative to ensure that any conductive elements used in a textile-based sensor could not become caught or snagged during use, thus breaking the connection.

Wijesiriwardana et al [106] also developed an Inductive Fiber-meshed Angular Displacement Transducer using knitted coil bands to replace the resistive motion and gesture capturing systems already developed that had inherent hysteresis and thermal effects problems. The conductive coils were knitted from copper wire, cotton and elastomeric fibres, with additional stainless steel to improve the sensitivity of the sensor, and measurement of the diameter change of the coils enabled the strain to be measured. The single coil system worked on the principles of self-inductance variation, whilst for multiple coils the systems worked due to mutual or electromagnetic induction, however the comfort during wear of the double coil system was better than the single coil system where the coil position was vulnerable to movement during angular displacement. With this system, problems occurred when calibrating the system due to sleeve slippage whilst the body part (e.g. elbow) was bent, and also the developers experienced shrinkage of the fabric after laundering.

Whilst all of these developments were successful in their aims to monitor respiration and heart rate, a significant difficulty often encountered when developing and testing these products was the high sensitivity of the sensors to motion artefacts (noise) [20] [105] [106], an issue that could compromise the strain sensor performance accuracy if the GF is low.

2.4.3 Impedance Sensors

The impedance of a textile sensor system is most commonly of importance when measuring physiological signals such as heart rate or respiration with respect to impedance between the electrode and the skin, thus determining whether the use of hydrogel for adhesion and conduction is necessary. As such, studies have been carried out on the effect of textile electrode size and condition (dry, wet or covered with hydrogel membrane) on the measurement noise and skin-electrode impedance. Puurtinen et al [107] constructed electrodes of embroidered circles using conductive silver covered polyester yarns, with the results indicating that with dry electrodes the impedance was very high (>100kΩ) and that smaller 'wet' electrodes gave lower impedance readings. Loriga et al [108] showed that the breathing signals obtained when using textile electrodes covered with hydrogel, as compared to the Biopac MP30 system ("a respiratory effort transducer sensitive to changes in thoracic or abdominal circumference during respiration"), were comparable, as shown in Figure 2.10.



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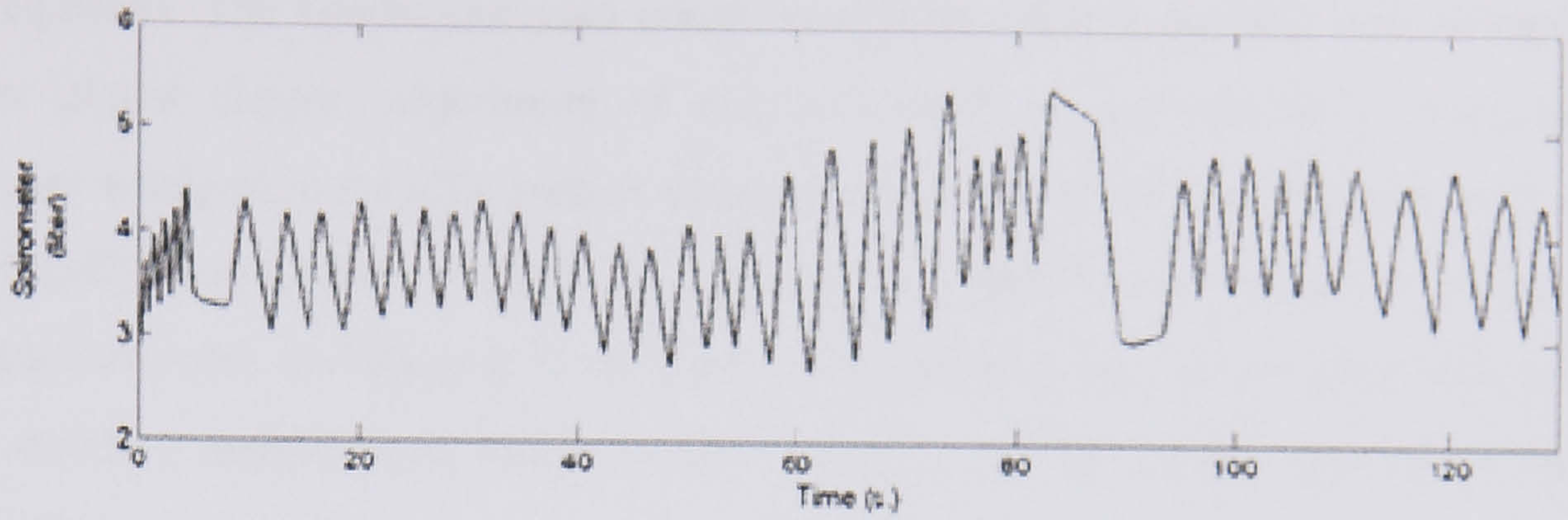

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Figure 2.10 Comparison of Signal Obtained by Impedance Pneumography (I) and Biopac (II) [108]

A garment capable of monitoring cardiopulmonary vital signs via impedance pneumography signals was developed by Loriga et al [108] wherein fabric electrodes were knitted from a stainless steel and cotton yarn and incorporated into a knitted cotton t-shirt. Four electrodes were positioned in the t-shirt and through two of them a high frequency current was sent whilst the other two measured the voltage variation signal given out due to thoracic impedance change. When the wearer breathed it changed the output signal due to changes in the body's impedance.

Catrysse et al [20] overcame the problems associated with high textile electrode to skin impedance by using a readout amplifier which converted the ECG signal into a single-ended signal with a high common mode rejection as a means of reducing the noise generated by the motion artefacts and common mode interference. However the problem of significant noise remains with this method of electrical activity measurement.

2.4.4 Resistive Sensors

2.4.4.1 Resistive Sensor Yarns

Invista [81] developed an electrically conductive composite yarn with stretch [109] that was capable of stretching between 10% to 800% whilst maintaining a high and constant conductivity. The yarn was composed of an elastomeric yarn covered with a number of conductive yarns and possibly a synthetic binder yarn to limit the stretch (if required). The conductive yarn could have been either a metallic wire (copper, silver plated copper, aluminium or stainless steel), a non-conductive synthetic polymer wrapped in metallic yarn or metal alloy yarn, or a synthetic polymer with an electrically conductive coating or additive or sheath/core structure (with a conductive core). In Figure 2.11 the curve (10) relates to the stress-strain behaviour of a standard metallic wire and curve (50) relates to the electrically conductive yarn described.

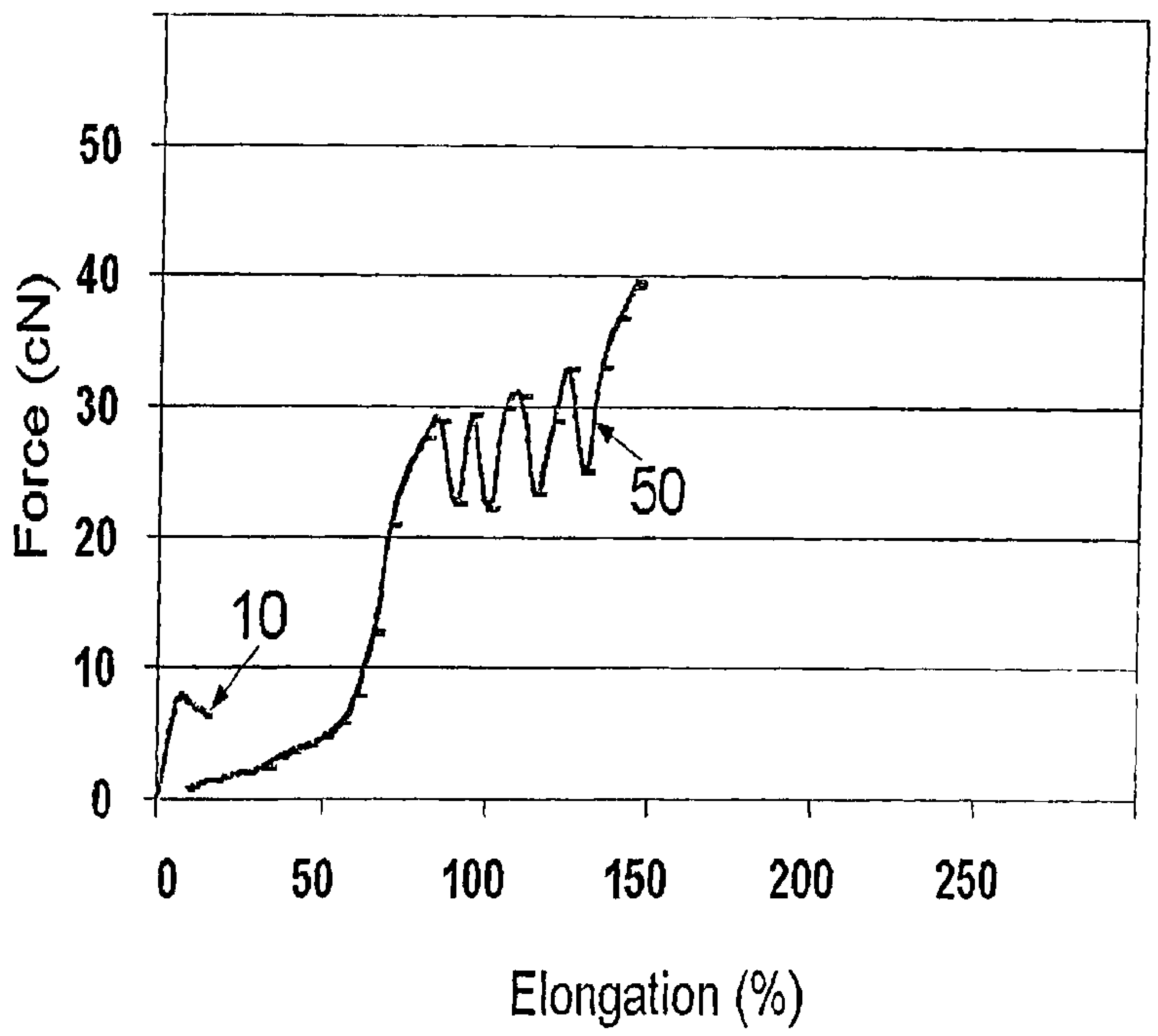


Figure 2.11 Invista Electrically Conductive Yarn Stress-Strain Curve [110]

Eleksen [111] also developed an electroconductive yarn in which a conductive carbon-based or metallic yarn (101) was wrapped around an insulating polyester yarn (102). Figure 2.12 is an illustrative diagram showing that in order to ensure that the surface of the yarn remained conductive, the count and diameter of the conductive yarn was greater than that of the insulating yarn.

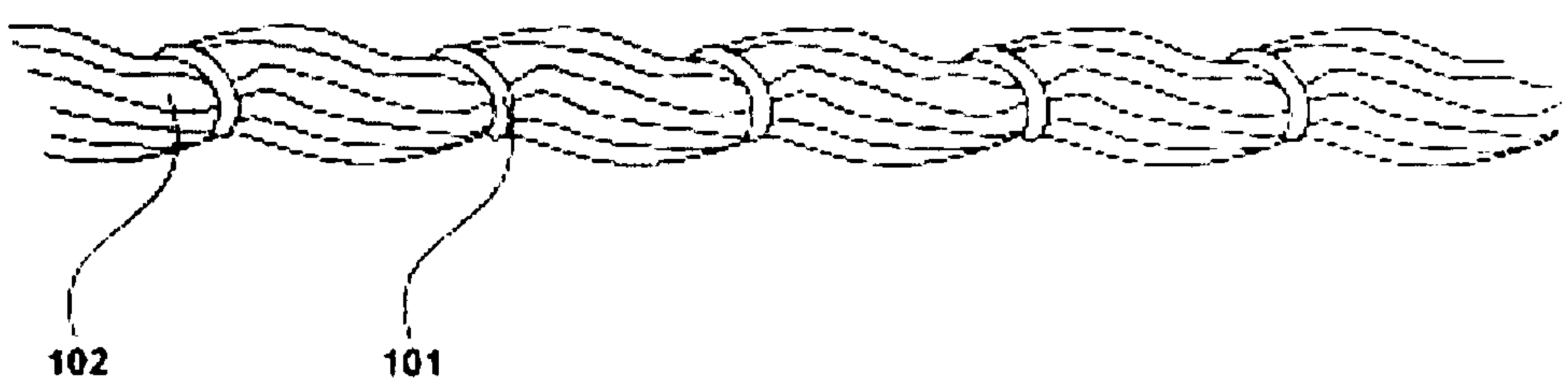


Figure 2.12 Eleksen Yarn Structure [111]

Both of these yarns have employed a wrapping method for combining the conductive and non-conductive elements of the yarn, such that a degree of elastic behaviour can be imparted to the yarn. Variations on these electrically conductive yarns include one comprising an elastomeric insulating core and conductive sheath [110] and a yarn with flexible core, conductive sheath and non-conductive wrapper yarn [112]. Potential problems associated with the use of these yarns, however, include attaining and maintaining a reliable connection between the conductive element of the yarn at any point along its length, as well as interruption of the electrical flow if the conductive filament breaks.

2.4.4.2 Resistive Sensor Fabrics

A textile strain sensor based on conducting polymers (CP) or carbon-filled rubbers (CFR) was developed by Mazzoldi et al [113] to create a wearable device able to read human posture and movements. Conventional fabrics were coated with a thin layer of Polypyrrole (PPy) or CFR. Quasistatic characterisation was carried out by applying small increments of stretch, whilst dynamic testing was performed with step-wise stretching and the resultant change in resistance measured, as illustrated in Figure 2.13. The PPy-coated fabrics had a GF of approximately -13, the GF value being calculated from a linear interpolation of the data.

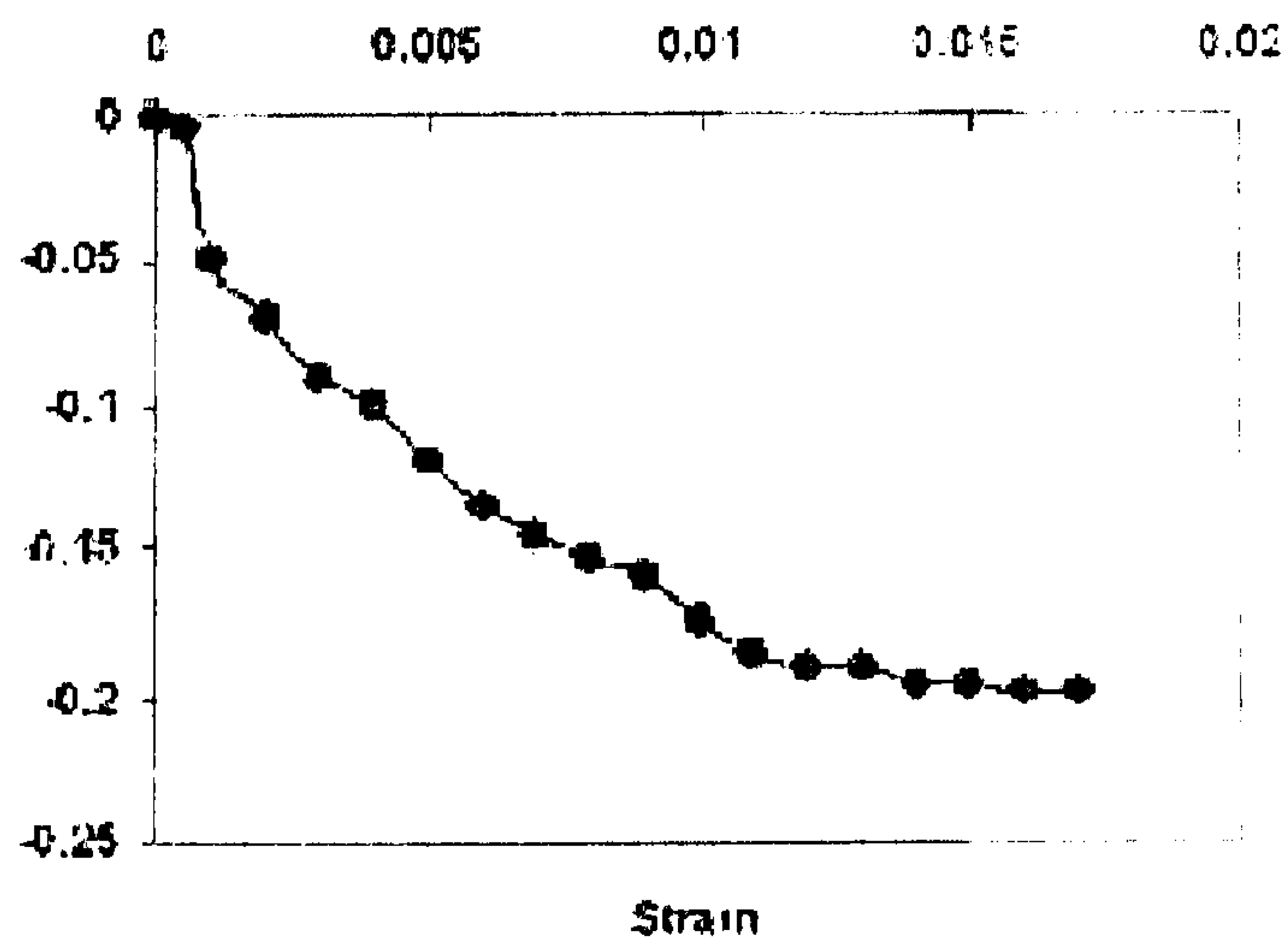


Figure 2.13 Quasistatic Response in terms of Percent Change in Electrical Resistance versus Uniaxial Strain for a Ppy Based Sensor [113]

Despite the fact that a high GF value is suitable for strain gauge implementation, two serious problems affected the PPy-coated fabric sensors [113]. The first problem was due to the drift with time of the sensor resistance, due to the slow oxidation of the polymer deposited on the textile. The second problem was the slow response time of the sensors as, after sudden application of a mechanical stretch, the resistance reached a steady state only after several minutes which would render these fabrics unusable in most applications where an instantaneous response was required.

The CFR-coated fabrics had a GF of approximately 2.5, a value quite similar to that attained by metals, and the quasistatic response is shown in Figure 2.14. Based on these results, the CFR-coated fabrics were deemed suitable for use as sensors in wearable applications, although whether they would be suitable as strain sensors attached to technical textiles is debatable as the strain levels attained are relatively low (maximum 0.14).

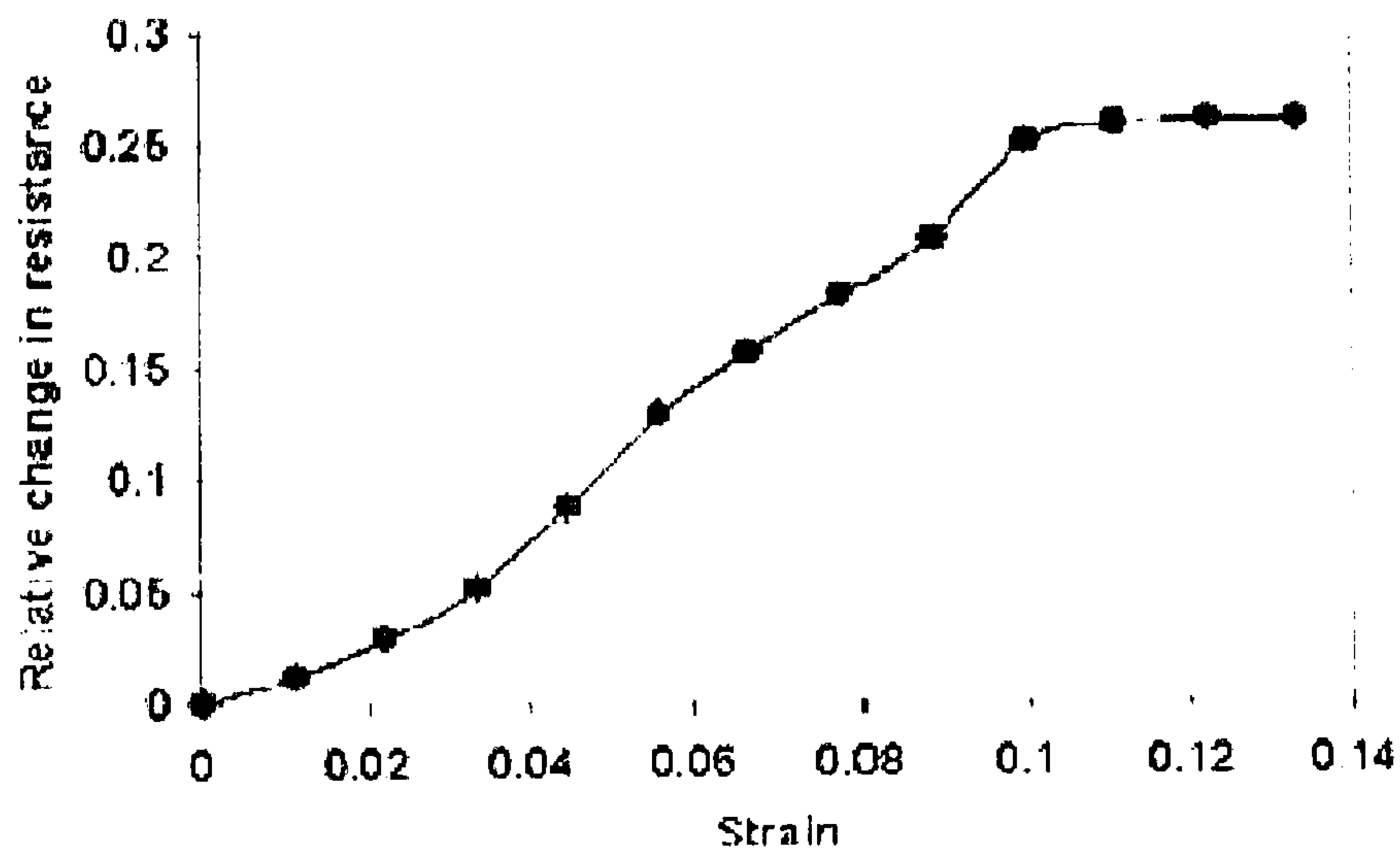
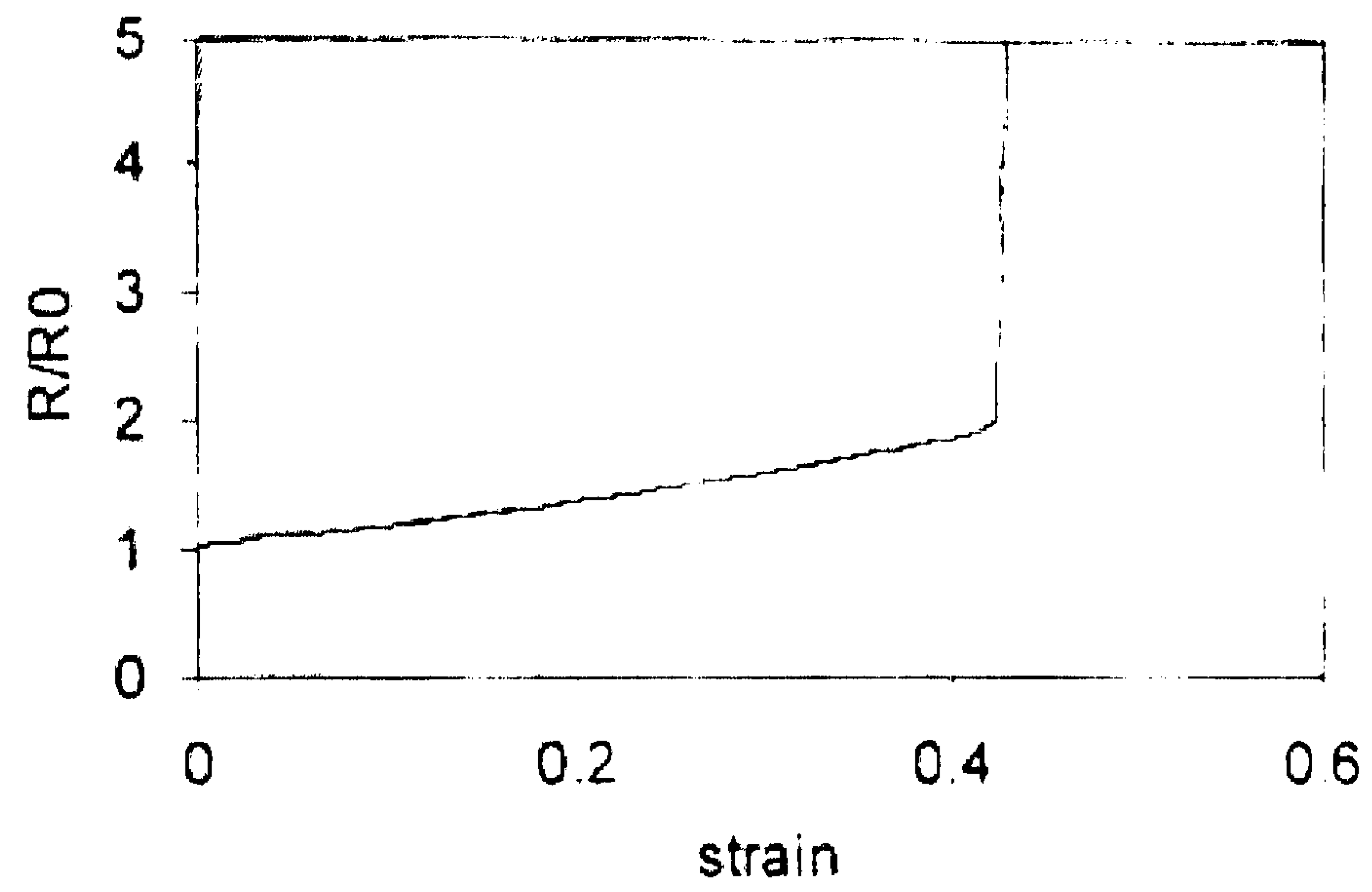


Figure 2.14 Quasistatic Response in terms of Percentage Change in Electrical Resistance versus Strain for a CFR Based Sensor [113]

Xue & Tao [72] carried out similar work to Mazzoldi et al in investigating the electromechanical response of nylon 6 and lycra fibres coated with PPy. The electrical resistance of the extended PPy coated fibres was measured by the four-probe method with a Keithley 2010 multimeter [73]. The resistance of the PPy coated nylon 6 fibres was nearly ten times higher than that of the Lycra samples with the typical resistance-strain curves is shown in Figure 2.15. For the nylon 6 fibres, the relationship between strain and resistance was almost linear until fracture, however there were two phases for the lycra fibres; a linear gradual initial phase and a non-linear rapid second phase. There was a percolation threshold value for the lycra fibres and the strain threshold for the coated fibres was much smaller than the ultimate strain of the lycra fibres. As the strain approached the percolation threshold, the resistance increased sharply.



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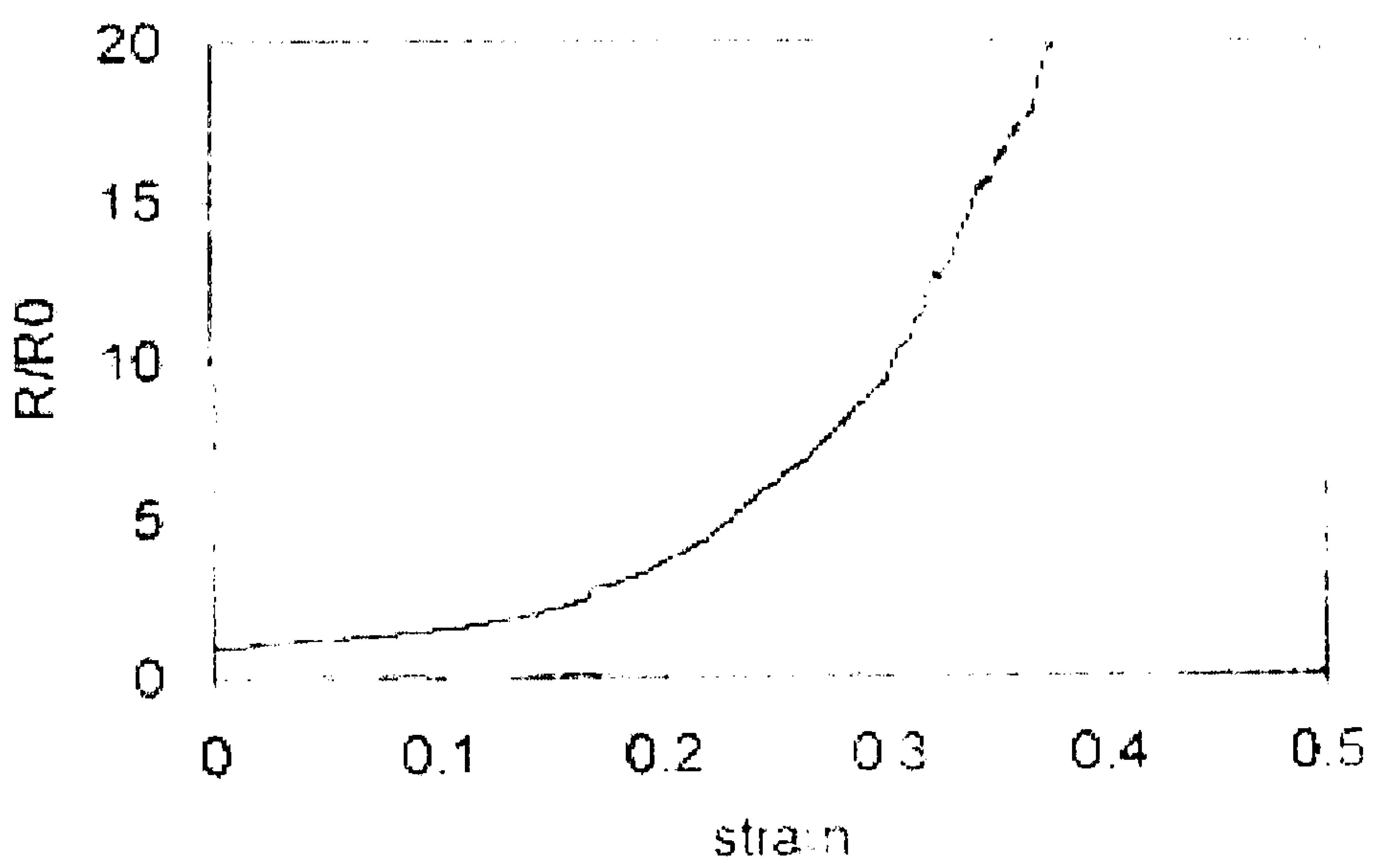


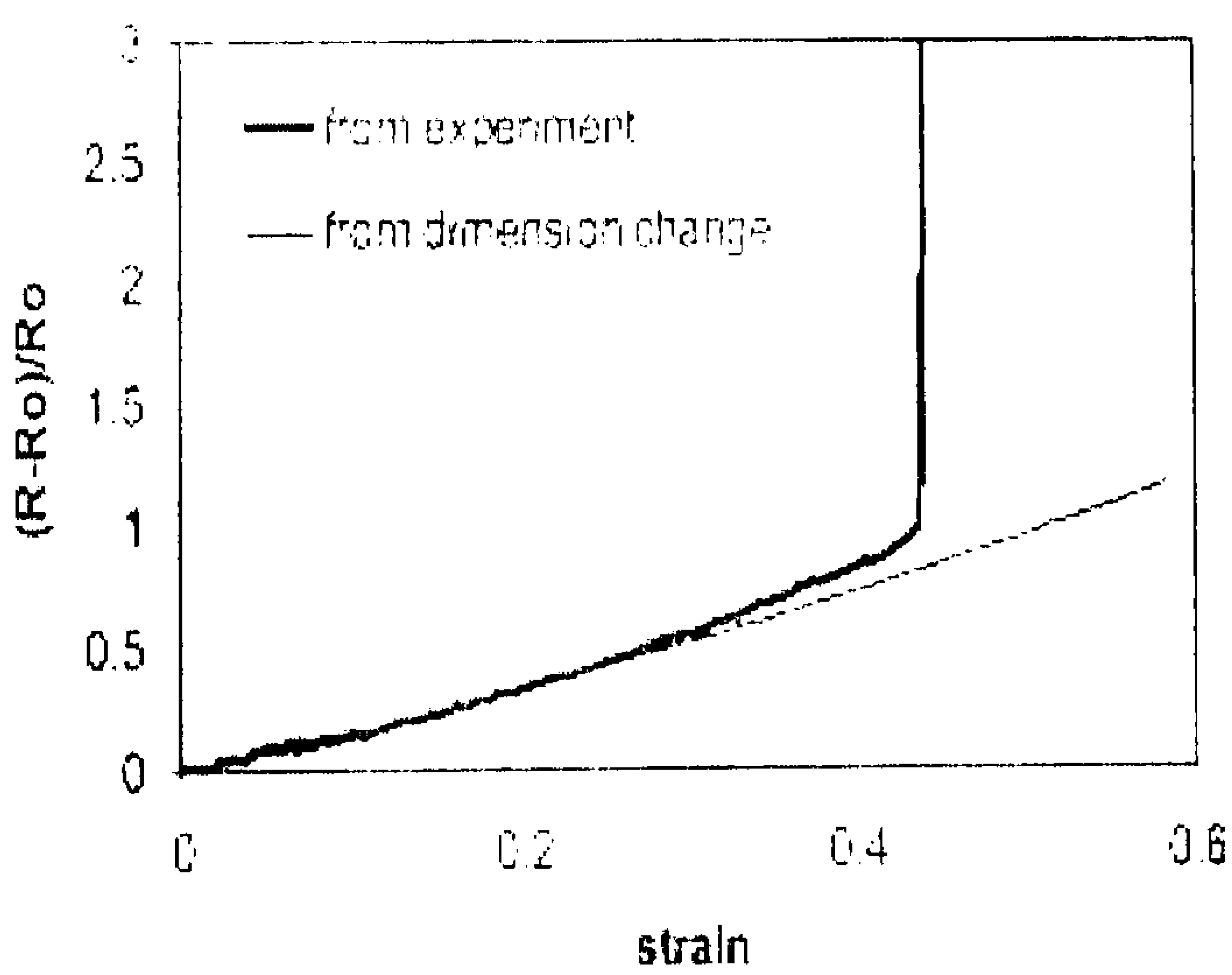
(II)

Figure 2.15 Typical Resistance-Strain Curves of PPy-coated PA6 Fibres (I), and PPy–coated Lycra Fibres (II) [73]

The GF of the PPy coated nylon 6 fibres was approximately 2 throughout the whole strain range, showing that they possessed good sensing performance. However the coated lycra fibres did not perform as well as previously thought once the Poisson's ratio was taken into account. The change in resistance ($\Delta R/R_o$) due to the change in the fibre dimensions was calculated using Equation 2.10 using the resistivity (ρ), the fibre length (L), the fibre cross-sectional area (A), the strain (ε) and the Poisson's ratio of PPy-coated fibres when longitudinally stretched (υ);

$$R = \rho \frac{L_o}{A_o} \frac{(1+\varepsilon)}{(1-\upsilon\varepsilon)^2} \quad \text{-------------------- (2.10) [73]}$$

Figure 2.16 shows a comparison of the measured and the calculated change in resistance against strain curves. The calculated change in resistance due to dimensional change does not vary significantly from the measured values for the PPy-coated nylon 6 fibres, especially at strains less than 0.3, meaning that dimensional change due to straining is the main cause of resistance change at low strains. Alternatively, for the PPy-coated lycra fibres the dimensional change only contributes a small percentage of the total change in resistance, a contribution that decreases further as the strain increases, thus for the Lycra fibres the variation in resistance is dominated by the change in conductivity during straining, most likely attributed to the coating cracking on straining.



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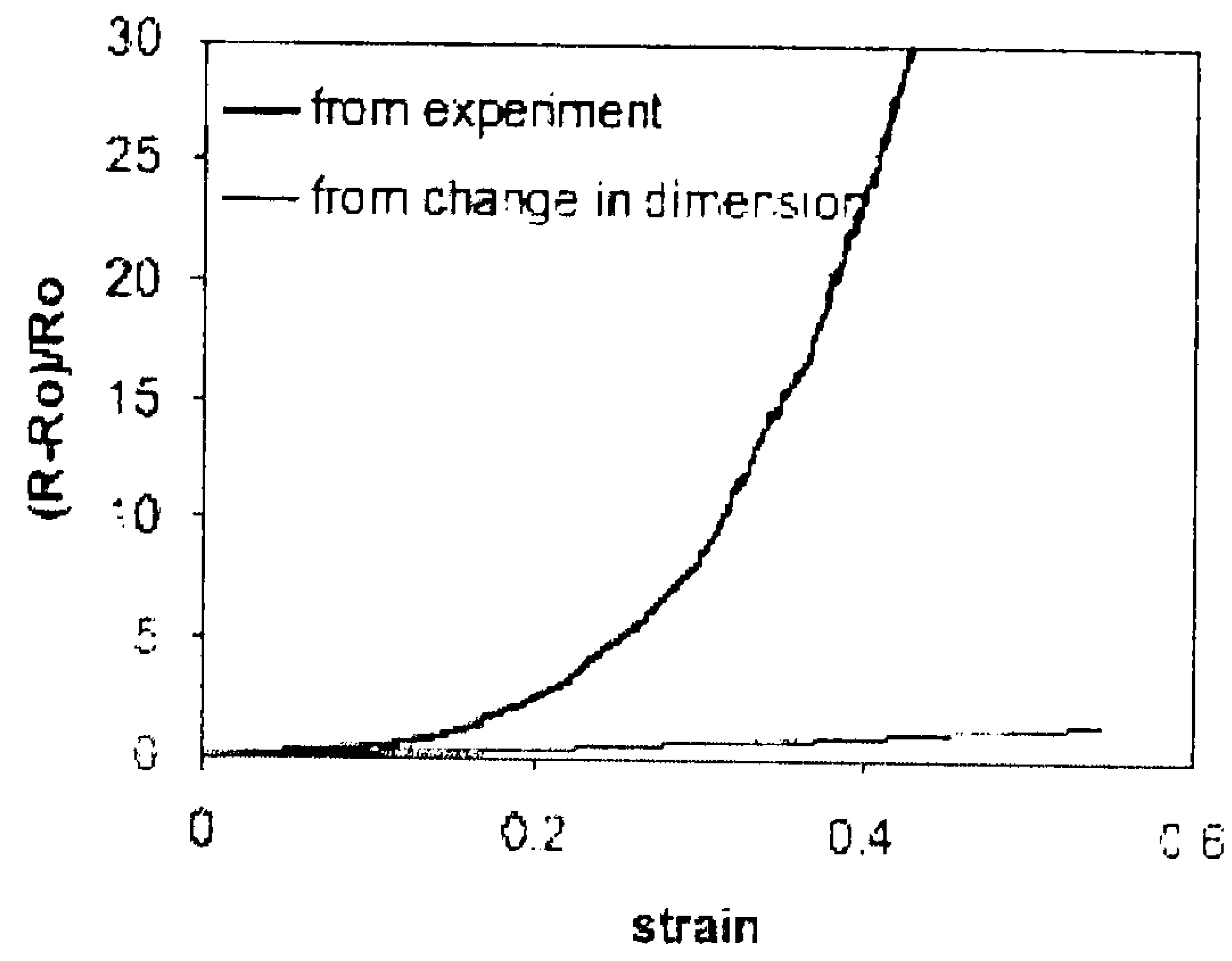

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Figure 2.16 Comparison of Calculated and Measured Results of ΔR/Ro versus Strain for (I) PPy-coated Nylon 6 Fibres and (II) PPy-coated Lycra Fibres

This research highlighted the suitability of nylon yarns for use as monofilament strain sensors (and the unsuitability of elastomeric filaments), however improvements in imparting conductivity to the filaments could be made by minimising the risk of stretching a coating such that it cracks and hence the conductivity decreasing sharply by embedding conductive particles within the polymer matrix.

As highlighted in section 2.4.2, both inductive and resistive sensing technologies are used when measuring respiration with the Respibelt [20]. The GF of the resistor is measured as -0.53 and this negative value indicates that stretching results in a decrease in resistance, caused by the tightening of the nooses of the knitted structure under stretch, thus creating a better conductive contact between them as shown in Figure 2.17.

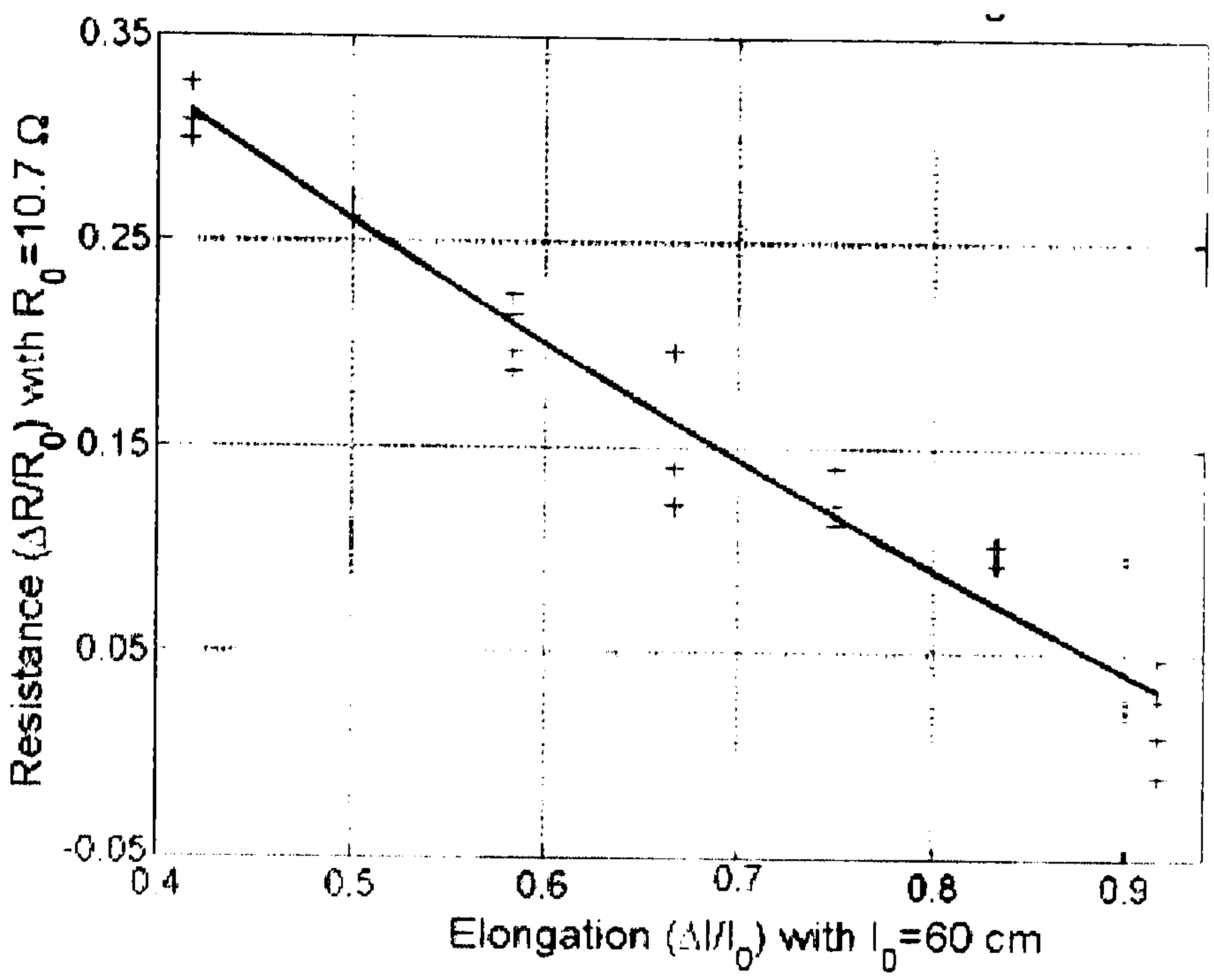


Figure 2.17 Respibelt Resistance Variation versus Elongation

This value is not as high as for the other resistive sensor fabric already reviewed which achieved GF values around 2–2.5, a value similar to that achieved using thin film metal strain gauges.

Philips [114] also created a knitted stretch sensor using a conductive carbon and elastomeric yarn. A standard basic knit structure was used where the elastomeric and conductive yarn were run together and when the fabric was stretched there was a measurable increase in longitudinal resistance up to a maximum resistance level, after which on further stretching the resistance decreases, as shown in Figure 2.18. This occured due to an increase in the length of the conduction paths in the fabric as the current in the fabric flowed perpendicular to the direction of the carbon strands, thus producing inter-fibre contact electrical conductivity.

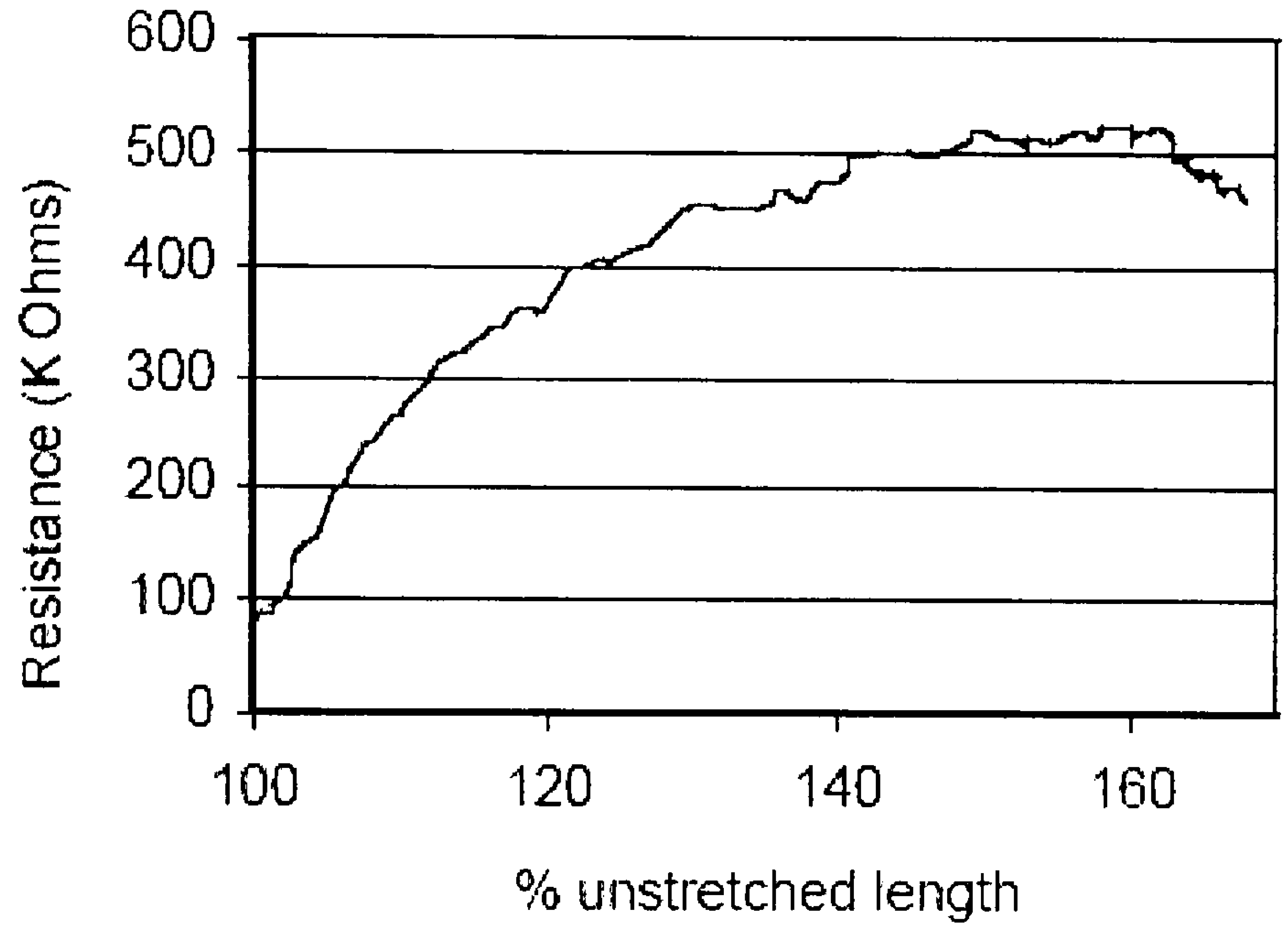


Figure 2.18 Philips Stretch Sensor; Change in Resistance on Stretching [114]

As the fabric stretched further, the carbon yarn loops were elongated, increasing the total length of carbon that the current passed along between the points of fibre contact. The other significant factor in the resistance change was the making and breaking of inter-fibre contacts, as the connections between the fibres reduced the resistance between inter-row connections. The point at which the change between increasing and decreasing resistance occurred could be altered by changing the yarn types and tensions used in the knitting process, thus yarns could be manufactured that either only increased resistance on stretching, or only decreased resistance on straining, however this phenomenon introduced complexities with respect to sensor design and applicable pre-strain levels during use.

Gibbs and Asada [69] developed a wearable sensor for measuring joint movements using conductive fibres. Using the resistive properties of the fibre, when the fibre exhibited a change in length the change in resistance could be directly correlated to the changes in the orientation of the joint. Silver plated nylon was used which had resistivity values of <10Ω/cm for a 100 denier fibre. The resistance of the length of fibre at any given time was measured across the top attachment point and the contact point through the use of a voltage divider or bridge circuit. In order to overcome the problems inherent with stretching a fibre beyond its recovery limits, thus permanently altering its conductivity, the fibre was attached above the joint but not sewn into the fabric as it needed to slide smoothly across the joint, and the other end of the conductive fibre was coupled to an elastic cord which was permanently attached below the joint, which took the strain of stretching. A significant disadvantage of the free moving non-secured conductive yarn, however, was the increased potential of yarn breakage due to snagging or abrasion.

Eleksen [111] developed a bend sensor which was woven from a conductive elastomeric yarn which measured the degree to which it was bent and/or extended. The material could be placed over a resilient deformable component and voltage applied to the conductive fabric strip terminals as well as to an interface device between the conductive fabric and the resilient component. The carbonised or metallised electrically conductive yarn was wrapped around an insulating yarn such as polyester. The sensor was weft knitted and, as the fabric stretched, the resistance of the sensor increased as the adjacent yarns were pulled apart and there were fewer paths for the current to flow down, as shown in Figure 2.19. If the material was to be constructed as a warp knit, the resistance would have decreased as the fabric is stretched.

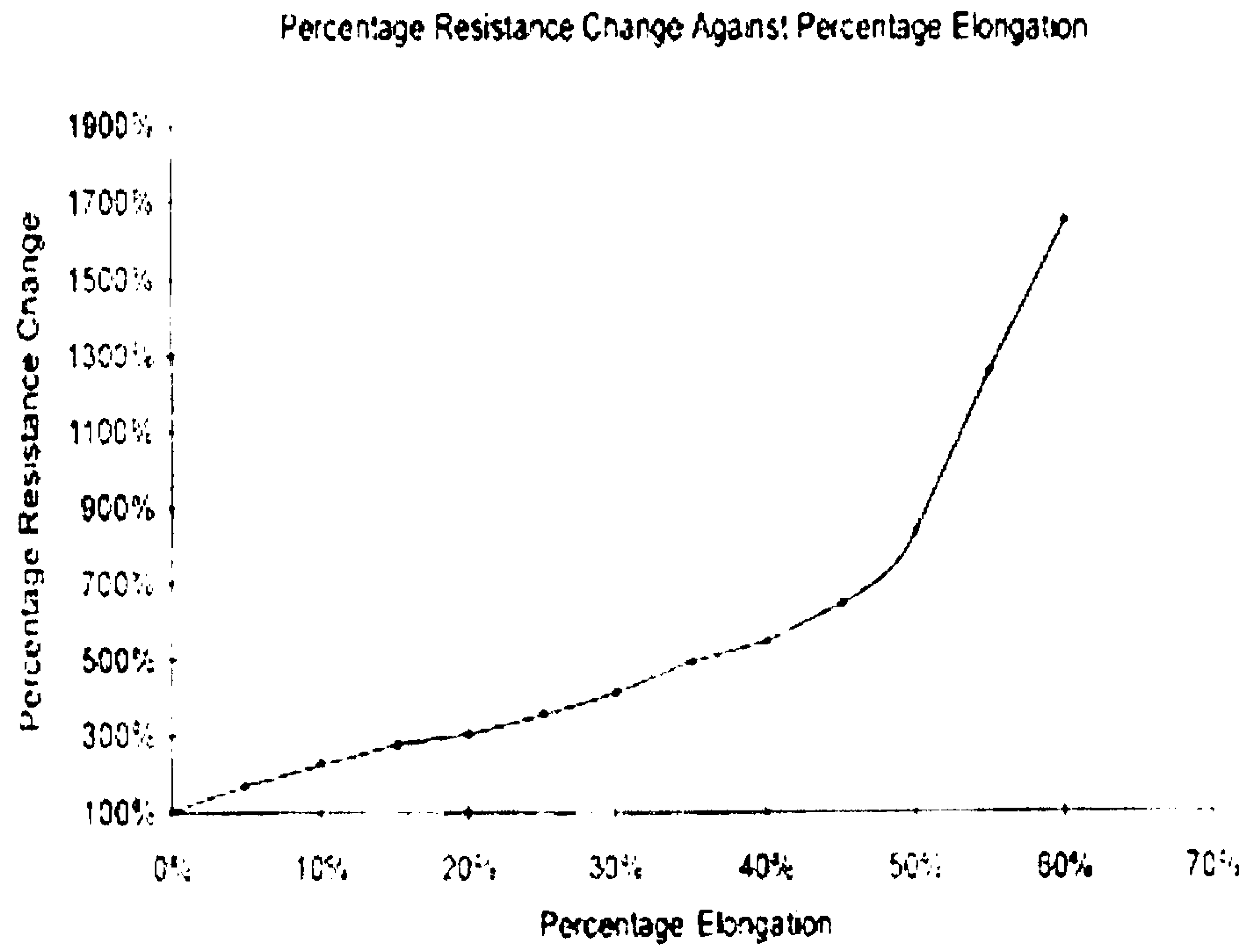


Figure 2.19 Eleksen Bend Sensor Change in Resistance versus Change in Elongation [111]

Based on the information reviewed, it is clear that these resistive sensors worked well in terms of measuring strain, both when in yarn form and when in fabric form, however the challenge was to determine the optimum strain sensor structure that would provide linear resistance versus strain behaviour and still have a high GF.

2.5 Discussion

A number of conductive materials, yarn configurations and fabric structures have been researched and developed in order to produce textile components capable of behaving similarly to traditional metal-based strain gauges, although with greater levels of elasticity. Reviewing the strain sensor technologies under development greatly informed the direction of the research and helped determine some of the materials to use and issues to take into consideration.

The use of capacitive sensing to detect changes in electrical conductivity for textile-based sensors is useful in the field of pressure sensing, however not necessarily the best method for sensing change in electrical activity on strain. The complexities of using a capacitor include deciding what material the dielectric should be, what to make plates from, what size of plates to use and how to keep them the same distance apart at all times is a potentially significant difficulty if the textile-based strain sensor were to be attached to a free moving, flexible technical textile substrate.

Although inductive, and indeed impedance sensing techniques, were suitable for use when measuring biophysical changes such as respiration and heart rate, a significant level of noise was evident in these systems which had not yet been designed out or required sophisticated equipment to filter out .

Thus the measuring technique that had provided very successful results in strain sensing and was the most suitable for further investigation were the resistive sensor techniques. It is apparent that systems could be designed either to be very simple or highly complex depending on the application or product, and there are a variety of methods for analysing the results. It is important to realise, however, that there may be a difference in the performance of different smart structures in that the resistance might either increase or decrease with changing strain, and it is imperative to determine the sensitivity (GF) of the sensor as well as the response time as this might govern potential applications. Temperature and moisture effects are also very significant factors in strain sensor performance which must also be investigated, particularly if the sensors are intended for use with technical textiles used in extreme or exposed conditions.

Chapter 3

Physical and Mechanical Characterisation of Strain Sensor Yarns

Chapter 3
Physical and Mechanical Characterisation of Conductive Yarns

As deduced from the available literature it is apparent that there are a number of applications, and thus performance requirements, for electrically conductive textile strain sensors and, as such, a number of technologies are being developed and products are becoming available commercially. These technologies and products utilise a range of conductive yarns (commercial and development), thus in order to begin to understand the fundamentals of strain sensor design, a preliminary examination of commercially available conductive yarns was carried out to determine whether their physical and mechanical properties were comparable with those of standard technical textile yarns.

3.1 Required Properties of the Conductive Yarn

A conductive textile yarn should possess the physical and mechanical characteristics of standard technical textile yarns such as flexibility, durability, abrasion resistance and predictable behaviour changes under fluctuating environmental conditions. In terms of their use as strain sensors, the change in electrical signal on stretching should be linear and repeatable, with the strain sensor preferably having a high GF [73]. The end use application of the sensor will determine the most important mechanical performance characteristics and some deficiencies in the raw materials can be compensated for, for example an inelastic material can be combined with an elastomeric material to provide the flexibility required, or materials very sensitive to changes in temperature or moisture can be sheathed or coated to minimise the impact of these changes.

3.2 Conductive and Elastomeric Yarns Tested

A variety of commercially available conductive yarns which are mainly used for dissipation of static electricity or for industrial use were tested. In addition a number of elastomeric yarns were tested as they were potentially usable in conjunction with very stiff or inelastic conductive yarns to ensure that the finished strain sensor might be more compatible with the mechanical performance of traditional technical textile fabrics.

3.2.1 Conductive Materials

The yarns tested were sourced from local and international suppliers and, although the range of yarns tested is not exhaustive, a broad range of materials and configurations was included. The conductive material-bases include metal, metal-oxides and carbon, and the configurations tested include staple, monofilament and crimped or straight multifilament yarns. There is also a very wide range of conductivity levels tested with resistivities ranging from 60Ω.cm to 80MΩ.cm, as shown in Table 3.1

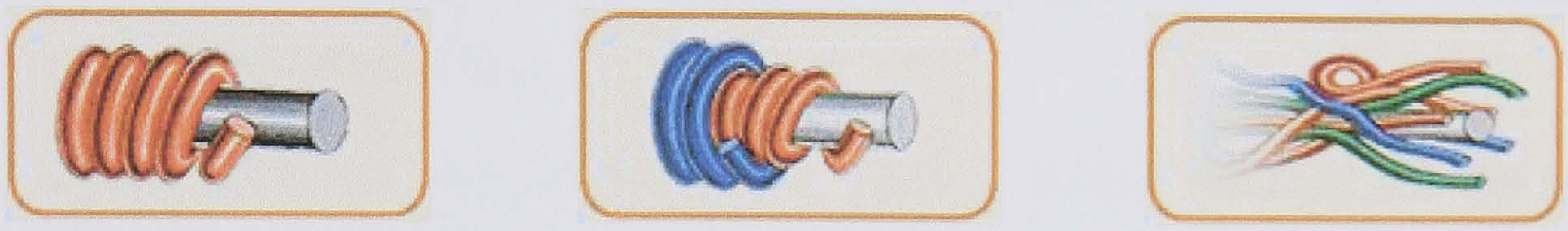
Table 3.1 Conductive Yarns Tested

Name	Material	Configuration	Count (Tex)	Resistivity
Bekinox VN	100% stainless steel	14 μm diameter 90F continuous filament	110	71 Ω/m
BK 50/1	Bekinox stainless steel fibres blended with polyester	20% Bekinox + 80% PES, staple yarn	20	100 Ω/cm
BK 50/2	Bekinox stainless steel fibres blended with polyester	20% Bekinox + 80% PES, staple yarn	40	50 Ω/cm

Epitropic OE Rotor Spun	Polyester fibre with embedded conductive carbon	30% Epitropic fibres, 70% HT PES, staple yarn	29.5	10-80 MΩ/cm
Epitropic Plied	Polyester fibre with embedded conductive carbon	50% OE Rotor spun blend yarn, 50% HT PES	220	10-100 MΩ/cm
Resistat F902	Nylon 6 with conductive carbon sheath	Monofilament	2.4	400 kΩ/cm
Resistat F9301	Nylon 6 with 1μm conductive carbon sheath (F901)	1 end F901 + 1 end 2.2 Tex nylon 6, continuous yarn	4.6	300 kΩ/cm
Resistat F9306	Nylon 6 with ~1μm conductive carbon coating on surface (F901)	1 end F901 + 1 end 2.2 Tex nylon 6 + 1 end 8.6 Tex nylon 6.6, continuous yarn	12.7	300 kΩ/cm
R.Stat/N	Nylon 6.6 with 0.2μm copper sulphide coating	10 filament continuous crimped yarn	22	10^5 Ω/cm
R.Stat/P	Polyester with 0.2μm copper sulphide coating	200 filament, continuous crimped yarn	167	10^4 Ω/cm
R.Stat/S	100% stainless steel fibres	12 μm diameter spun yarn	182	60-80 Ω/cm
Stainless Steel Wire	100% stainless steel	Monofilament	22.7	170 Ω/cm

3.2.2 Elastomeric Materials

There is a wide range of elastomeric yarns available based on different base materials (rubber or polyurethane) and the products can vary according to whether they are bare or covered, the covering methods used, recovery strengths, twist levels and count. Both bare and covered yarns were used in these experiments and examples of some covering configurations available are shown in Figure 3.1.



A – Single covering B – Double covering C – Air intermingling

Figure 3.1 Wykes' Elastomeric Yarn Covering Methods [115]

The full product details including yarn composition are shown in Table 3.2.

Table 3.2 Elastomeric Yarns Tested

Name	Material	Configuration	Count (tex)	Twist (turns/m)
Linel	100% Polyurethane	Bare continuous monofilament	15.6	N/A
Lycra	100% Polyester [116]	Bare continuous monofilament	7.8	N/A
Lycra 2569	Core: 200dtex Lycra T902c, covers: 78/34 crimp nylon T66	Double covered (hollow spindle)	20.7	600 / 1000
Lycra 276B	Core: 200dtex Lycra T902c, cover: 78/34 crimp nylon T66	Single covered (hollow spindle)	12.3	800

3.3 Determination of the Physical and Mechanical Properties of the Yarns

Tests were carried out to determine the following properties of the yarns according to the prescribed methods;

1. Count; this was measured following the test methodology as stated in British Standard BS 947:1970 [117] using an automatic wrap reel and laboratory grade weighing scales.
2. Twist level; this was measured according to British Standard BS EN ISO 2061:1996 [118] using a manual twist tester.
3. Stress-strain behaviour; this was measured using an Instron Constant Rate of Extension (CRE) tensile tester according to British Standard BS EN ISO 2062 [119] with one slight amendment to the test method whereby the yarns were mounted into cardboard frames with a 20mm gauge length such that they could fit the Instron clamps available for use with the 10kg load cell. The Coefficient of Variation (CV) of the specific stress and strain of the samples was calculated according to Equation 3.1 using the standard deviation (σ) and the mean (μ).

$$CV = \frac{\sigma}{\mu} x100\% \text{ -------------} \quad (3.1)\ [120]$$

The Regression values for the specific stress and strain were calculated, using Origin software, to determine the equation for the line of best fit.

3.3.1.4 Yarn Structure Analysis

Nikon Microscope images were taken, where possible, of the yarns in order to show the fine detail, otherwise Nikon Coolpix 4500 digital images were taken if a combination of the yarn structure and microscope depth of field limitations caused ruled out microscope imaging.

3.3.2 Physical and Mechanical Property Results

3.3.2.1 Count

Most measured values of the yarn counts were similar to the manufacturers` supplied information showing less than ±7.5% difference. The R.Stat/N yarn showed a difference of ±19.5%, due mainly to the crimped nature of the yarn making it difficult to replicate the tension under which the yarn was measured by the manufacturer.

3.3.2.2 Conductive Yarn Specific Stress-Strain

The specific stress and strain at break values, as shown in Table 3.3, give an indication of the effect of yarn structure on the conductive yarn tensile behaviour. Due to the variety of yarn counts, structures and materials used, it is difficult to make a direct comparison of the conductive yarn structure-property relationships, however the individual CV values give information on the repeatability of the yarn behaviour. For example, it can be seen that the metal-based multifilament and monofilament yarns (Bekinox VN, R.Stat/S and SSW) exhibit good tensile behaviour repeatability, whilst the staple yarns (Bekitex 50/1 and 50/2, Epitropic plied and rotor spun) tensile behaviour results are less repeatable.

Table 3.3 Conductive Yarn Specific Stress and Strain at Break Results

Material	Specific Stress at Break (mN/tex)	Specific Stress CV	Strain at Break	Strain CV
Bekinox VN	76.78	4.86	0.05	0
BK 50/1	343.96	15.10	0.2	22.22

BK 50/2	340.28	8.39	0.2	23.52
Epitropic OE Rotor Spun	170.37	8.41	0.15	34.64
Epitropic Plied	643.22	11.55	0.2	22.22
Resistat F902	584.51	35.82	0.4	31.18
Resistat F9301	379.72	14.01	0.35	35.05
Resistat F9306	433.66	7.72	0.55	30.93
R.Stat/N	520.82	6.71	0.55	26.72
R.Stat/P	543.95	17.88	0.35	23.16
R.Stat/S	131.44	11.11	0.05	0
Stainless Steel Wire	49.26	1.75	0.35	0

Due to the complexity of comparing the performance of all the yarns, they were separated into their core conductive material-base groups of metals, carbons and metal oxides in order to analyse their stress-strain behaviour fully.

3.3.2.2.1 Metal-based yarns

The metal-based yarn curves, shown in Figure 3.2, indicate that the staple BK50/1 and BK50/2 exhibit high stress and low strain at break performance (the high strength could be attributed to the 80% PES in the yarn) whilst the monofilament Stainless Steel wire exhibits the opposite behaviour of low stress and high strain at break. Both 100% Stainless Steel yarns (Bekinox VN and R.Stat/S) display behaviour typified by low strain and relatively low stress at break compared to the staple yarns, regardless of the differences in their structure.

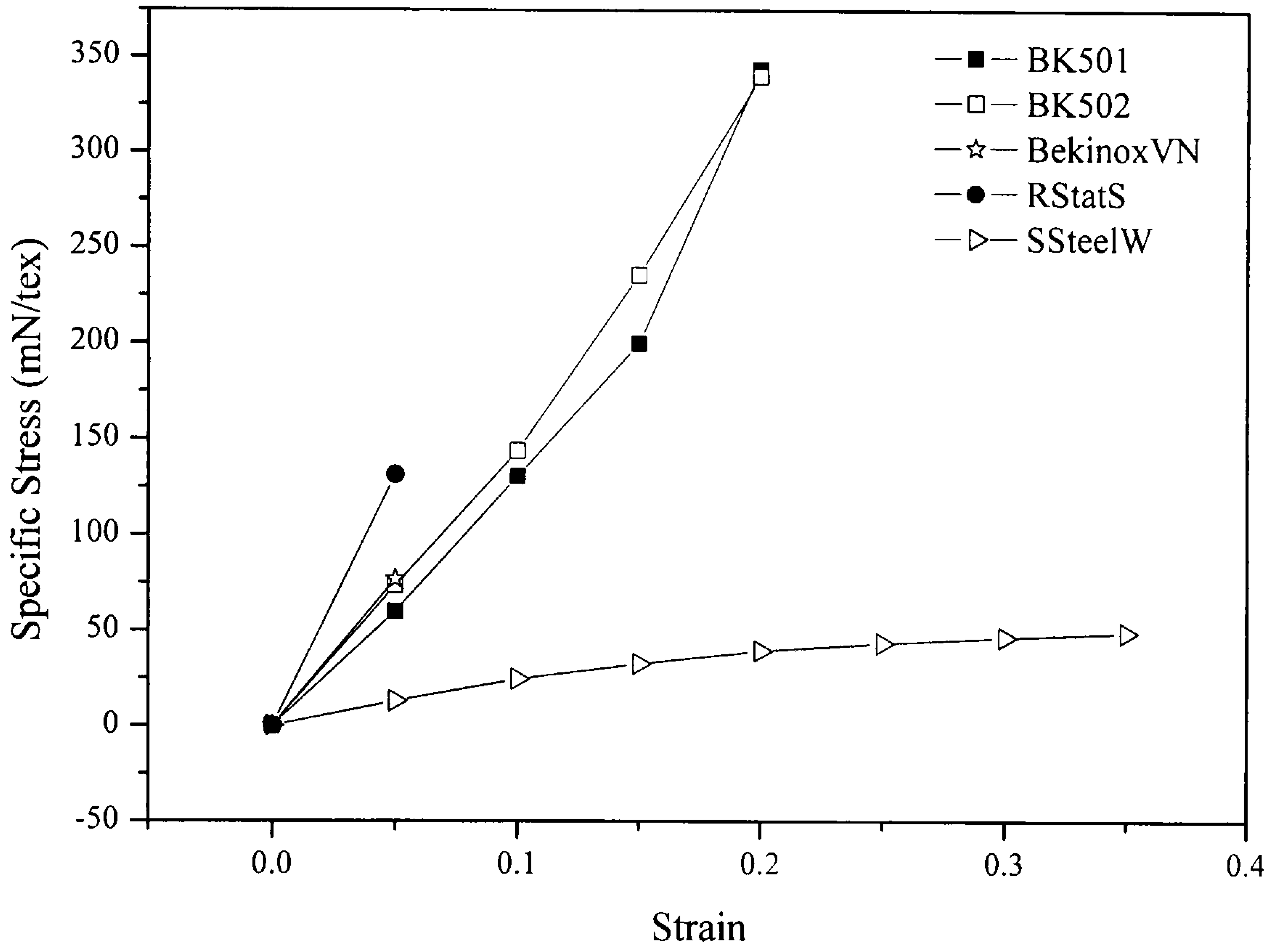


Figure 3.2 Metal-based Yarns Stress-Strain Curves

3.3.2.2.2 Carbon-based yarns

Figure 3.3 shows the differences in strain at break performance of the carbon-based yarns due to structure, such that the continuous monofilament Resistat yarns (F902, F9301 and F9306) exhibit relatively high strain behaviour compared to that of the staple Epitropic yarns. The high stress at break value of the Epitropic Plied yarn can be attributed to both the tight plied nature of the yarn and the inclusion of 50% HT PES continuous filaments, and conversely the low stress at break value of the Epitropic OE Rotor spun yarn may be due to the staple structure of the yarn.

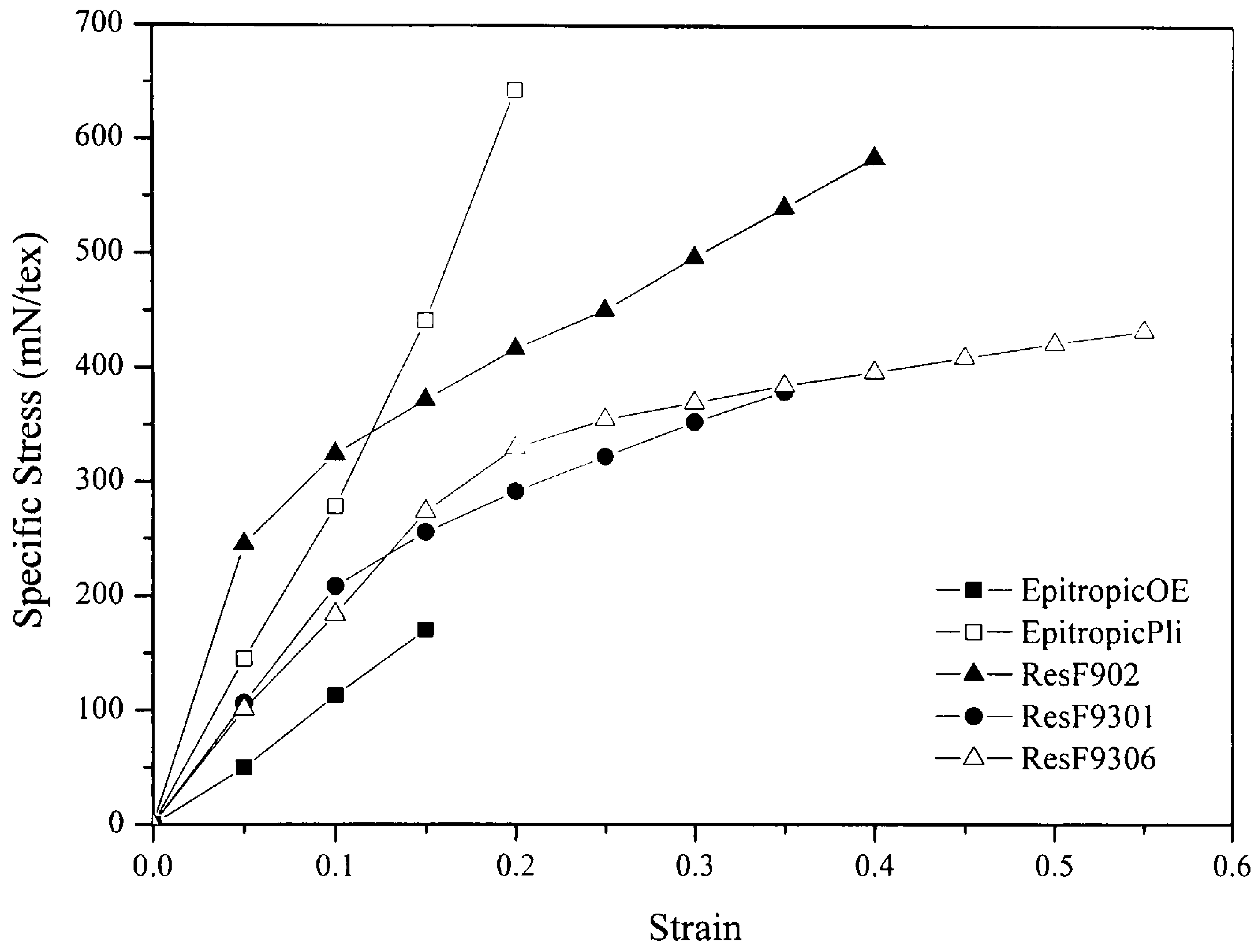


Figure 3.3 Carbon-based Yarns Stress-Strain Curves

The continuous filament Resistat yarns are Nylon 6 based and, as such, closely mimic the stress-strain behaviour of a nylon monofilament as measured by Ahumada et al [121] and illustrated in Figure 3.4.

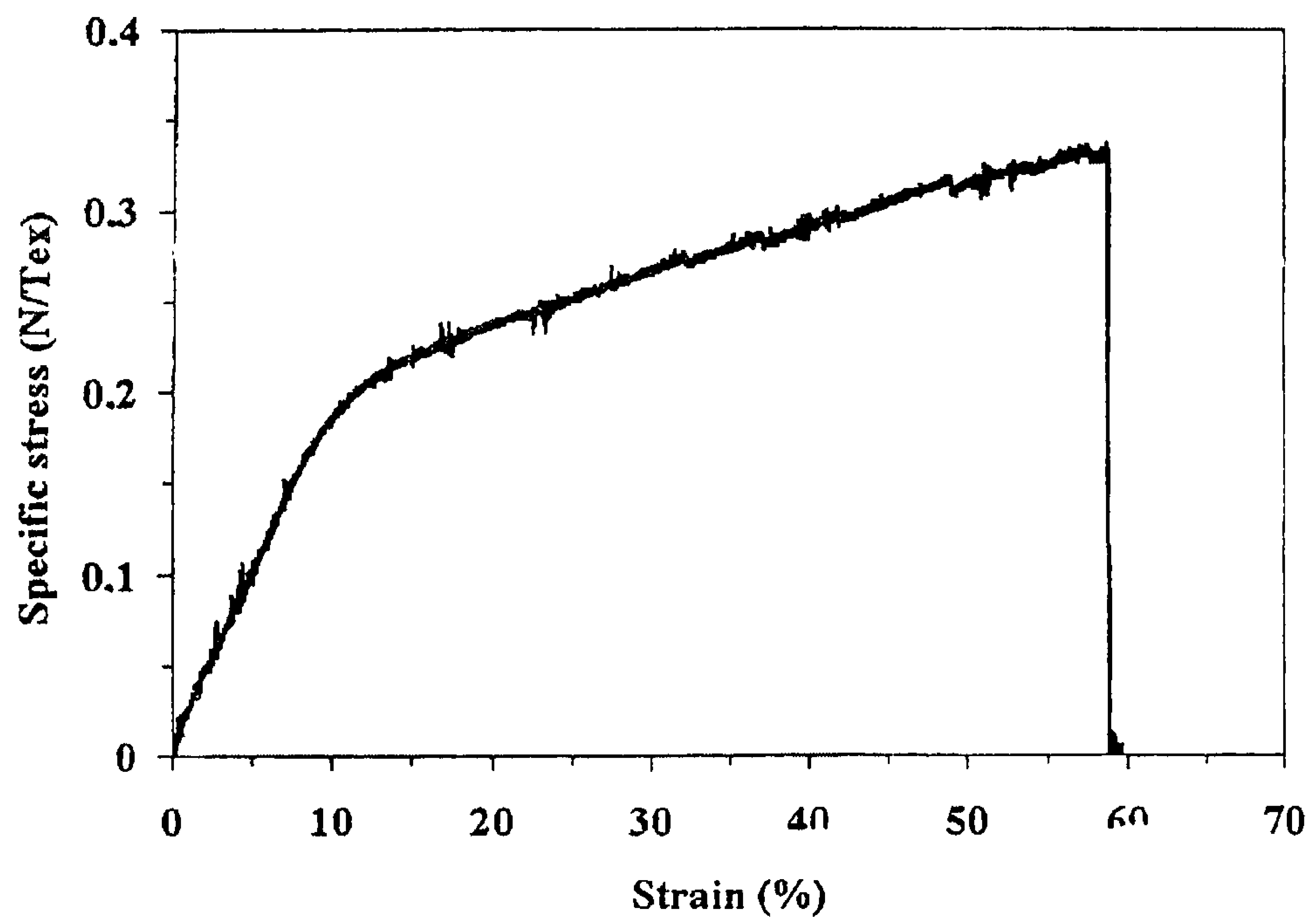


Figure 3.4 Typical Stress-Strain Curve of Model Nylon 6.6 Monofilament Yarn [121]

3.3.2.2.3 Metal-Oxide Yarns

Both R.Stat metal oxide yarns have high specific stress at break values, however the strain at break values differ markedly, with the Nylon based yarn (R.Stat/N) being 20% more elastic than the polyester based yarn (R.Stat/P) as illustrated in Figure 3.5.

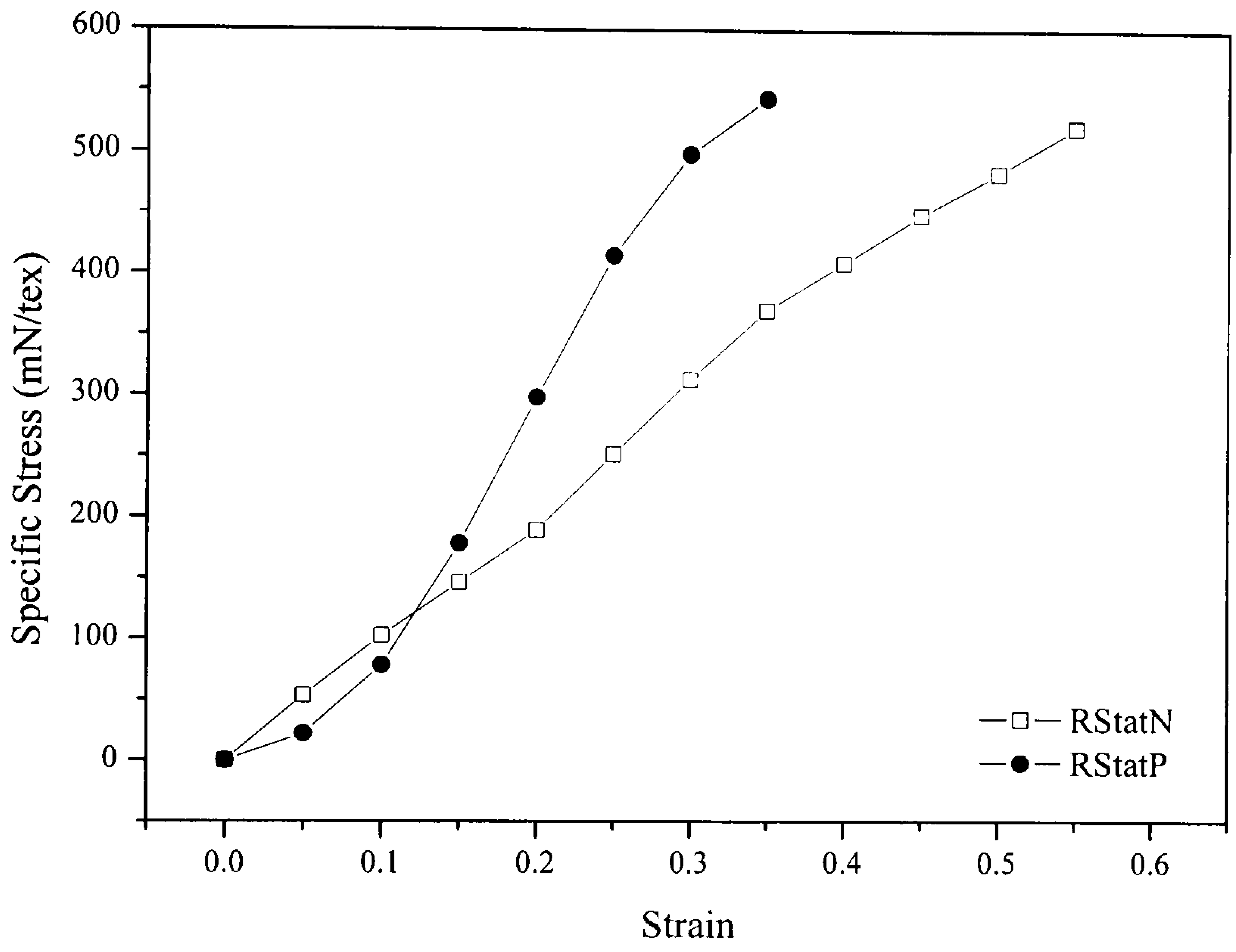


Figure 3.5 Metal Oxide Yarns Stress-Strain Curves

This is due mainly to the inherent extensibility of the base yarn, as shown in Figure 3.4 (nylon monofilament) and Figure 3.6 (polyester monofilament) as it can be seen that the yarn structure does not differ enough to contribute to this result. The crimp levels of each yarn has little influence on the difference in strain at break values as the R.Stat/N has a percentage crimp of 10-12% and the R.Stat/P yarn has a percentage crimp of 13%, and whilst the R.Stat/N yarn is untwisted the R.Stat/P yarn has only a very low twist level of 0.6 twists/cm.

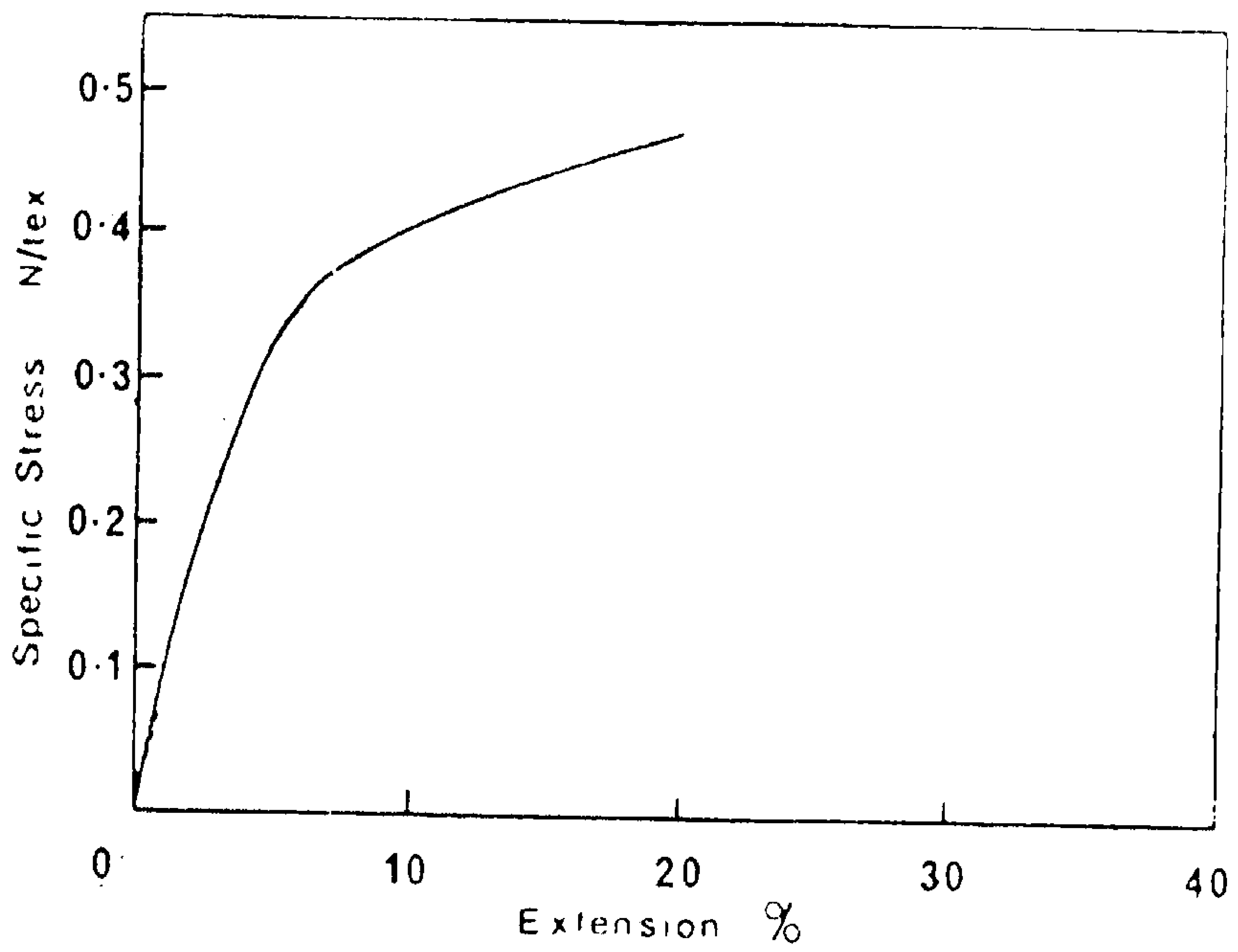


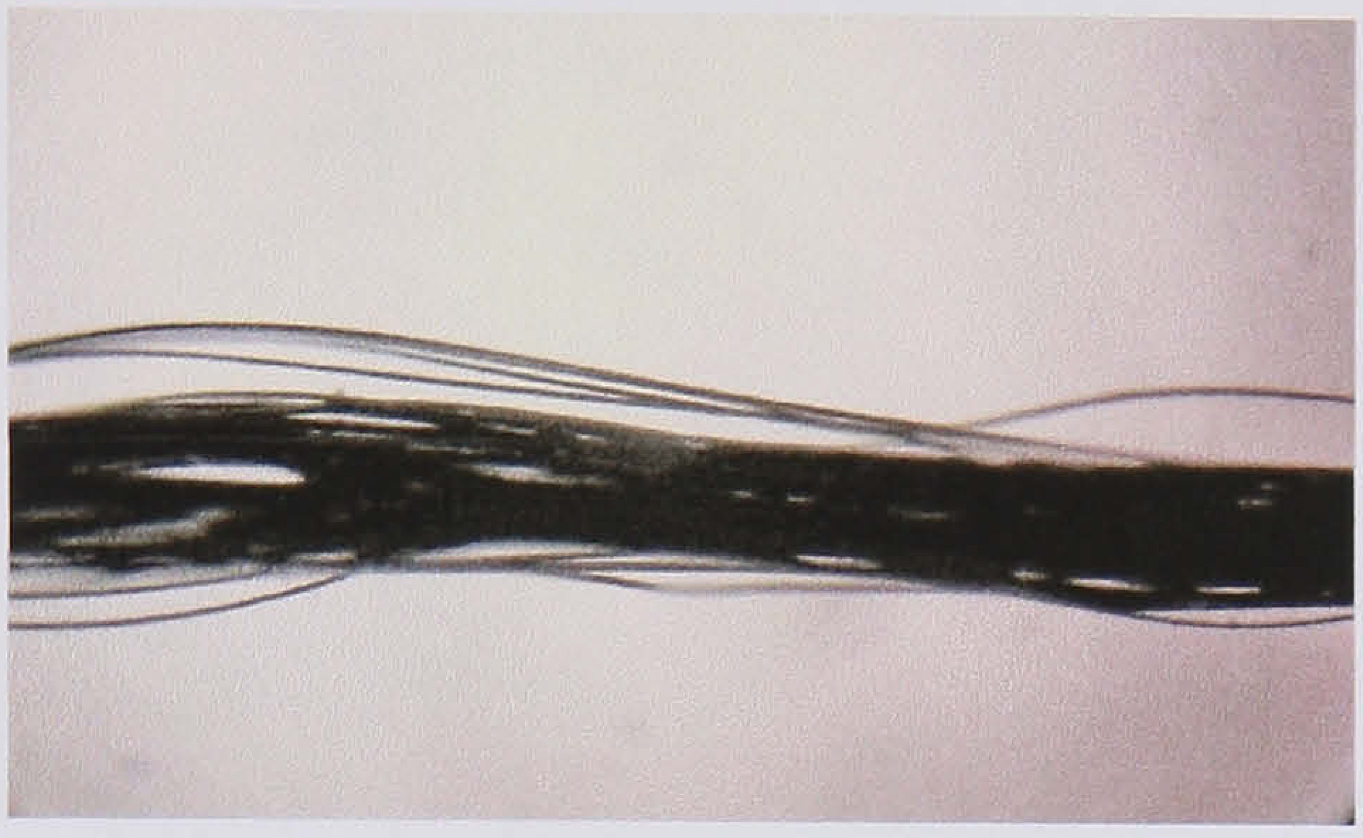
Figure 3.6 Stress-Strain Curve of Polyester Fibre under Standard Conditions [122]

3.3.2.4 Conductive Yarn Structure Analysis

The variety of conductive yarn structures can be seen in Figure 3.7 with the structure of continuous monofilament yarns (Resistat F902 and Stainless Steel Wire) lying in sharp contrast all others (which consist of staple and twisted/crimped continuous multifilament yarns). It is important to note the positioning of the conductive element within the blended yarns with regard to attaining maximum electricity flow or ensuring optimal connection between the conductive yarn and the measuring equipment connector. For example, the stainless steel filament is only sometimes at the surface of the Bekitex and Epitropic yarns, a factor which could potentially lead to electrical connection difficulties should these yarns to be woven or knitted into a fabric, or even if attached directly to electrical connectors. With the continuous multifilament Resistat yarns, the conductive carbon filament is more pronounced at the yarn surface, thus reducing the potential for this type of electrical misconnection.

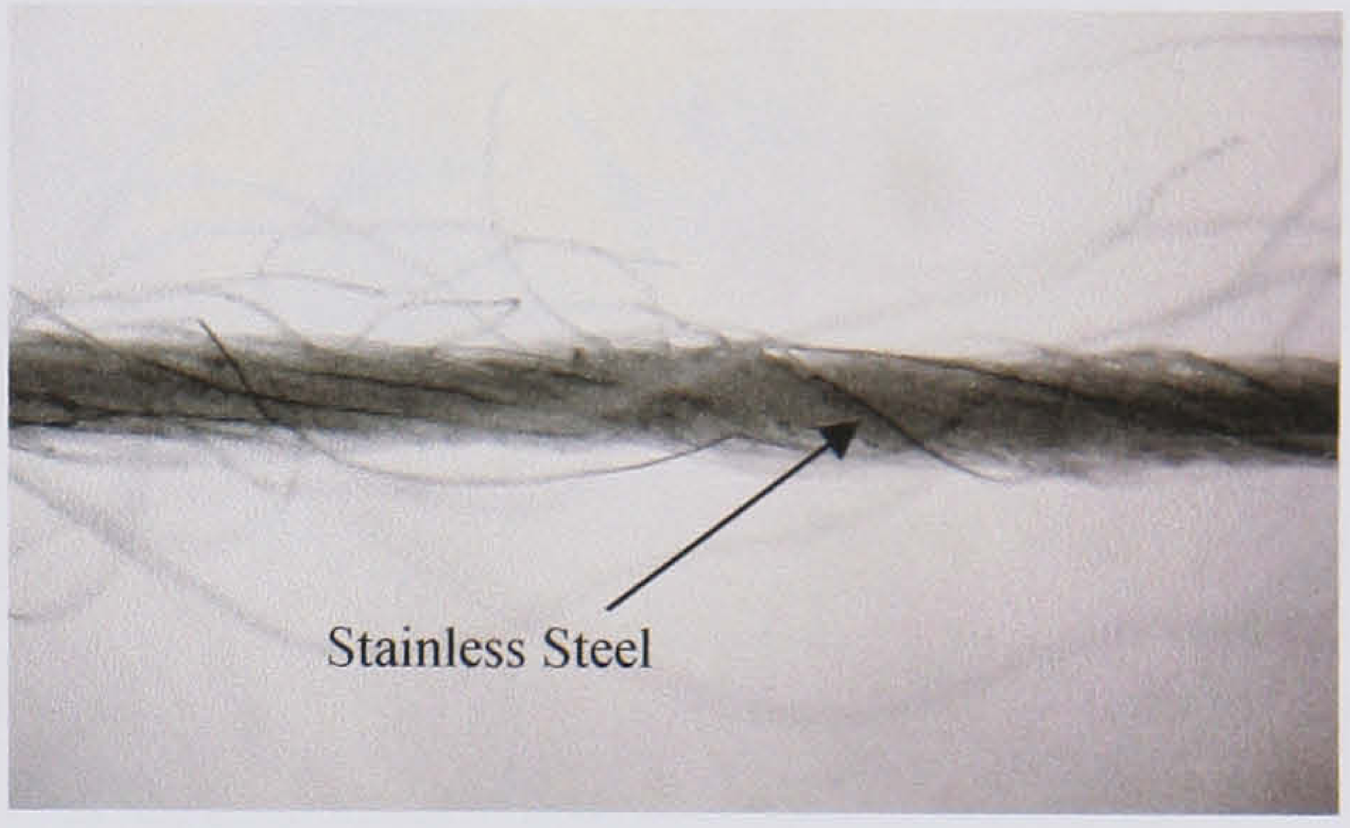
Bekinox VN (5x magnification)

Yarn diameter 0.27mm



BK 50/1 (5x magnification)

Yarn diameter 0.24mm



BK 50/2 (5x magnification)

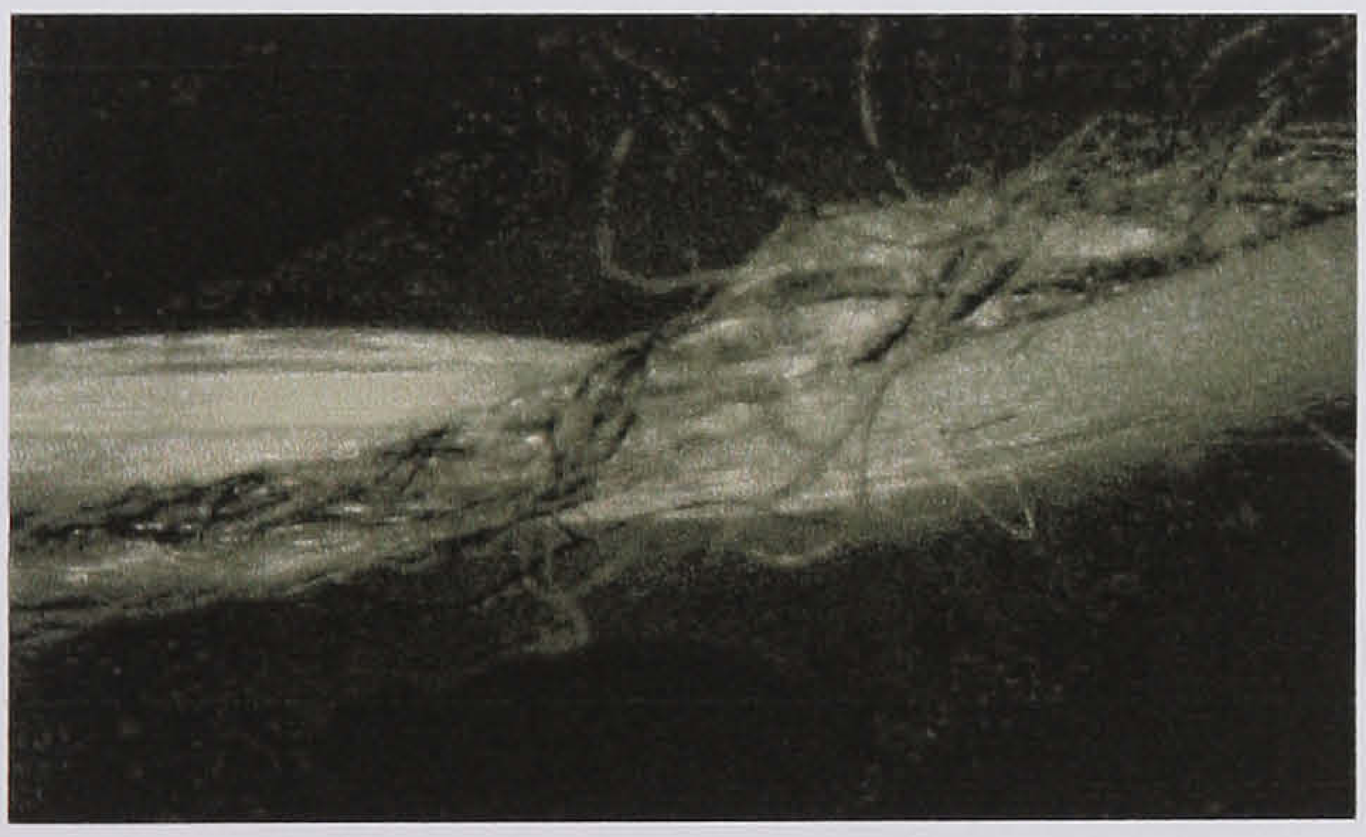
Yarn diameter 0.24mm

Epitropic OE Rotor Spun (10x mag.)

Yarn diameter 0.31mm

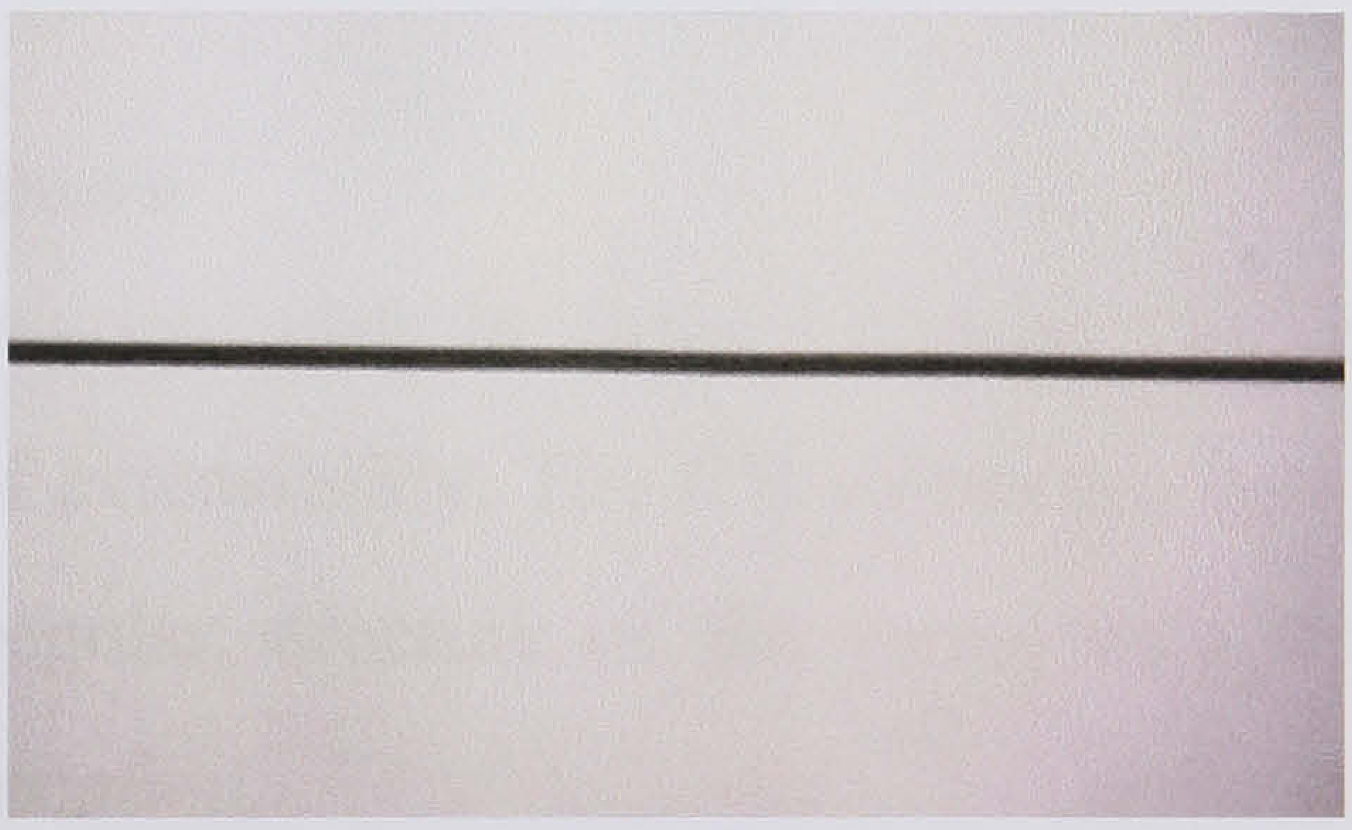
Epitropic Plied (10x magnification)

Yarn diameter 0.5mm



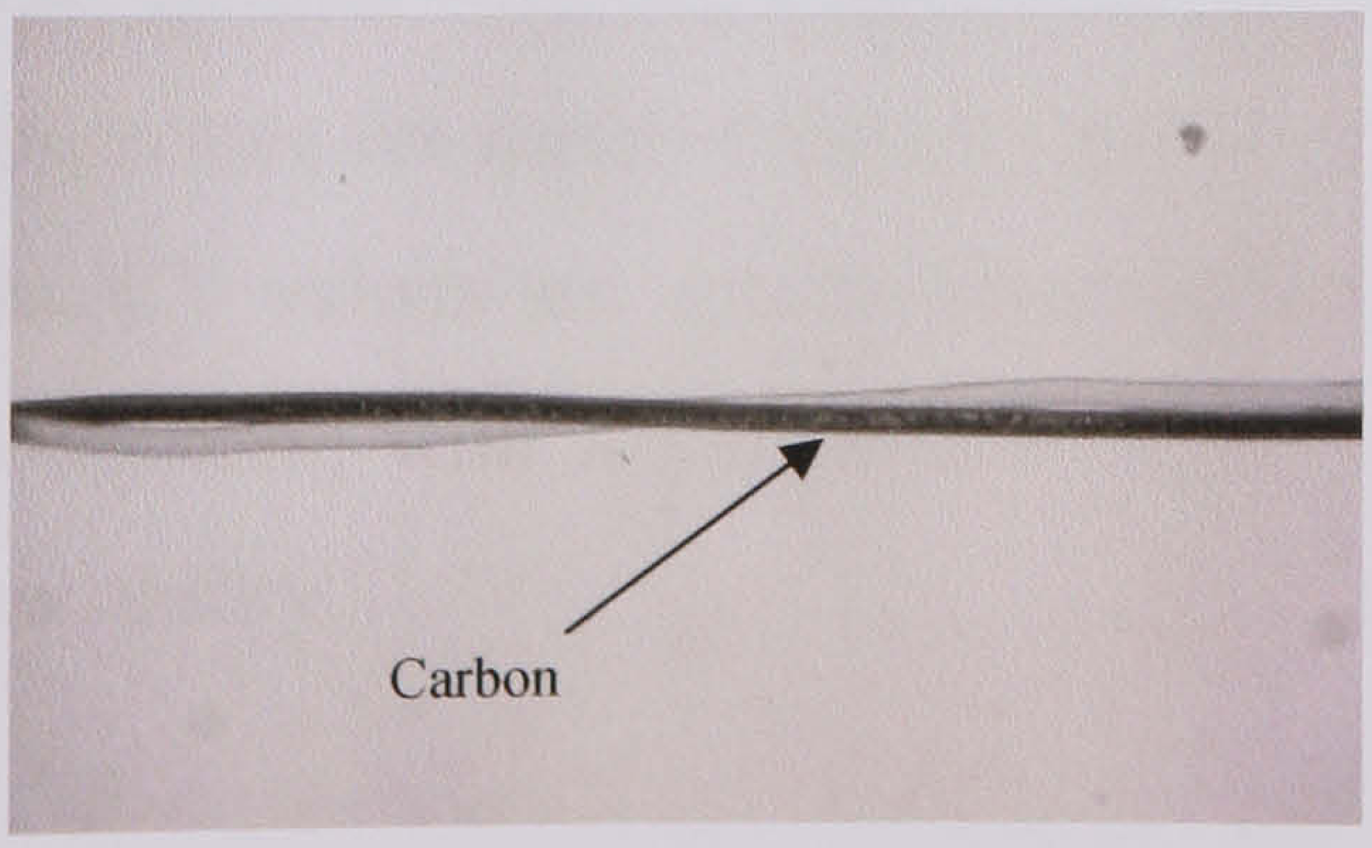
Resistat F902 (5x magnification)

Yarn diameter 0.06mm



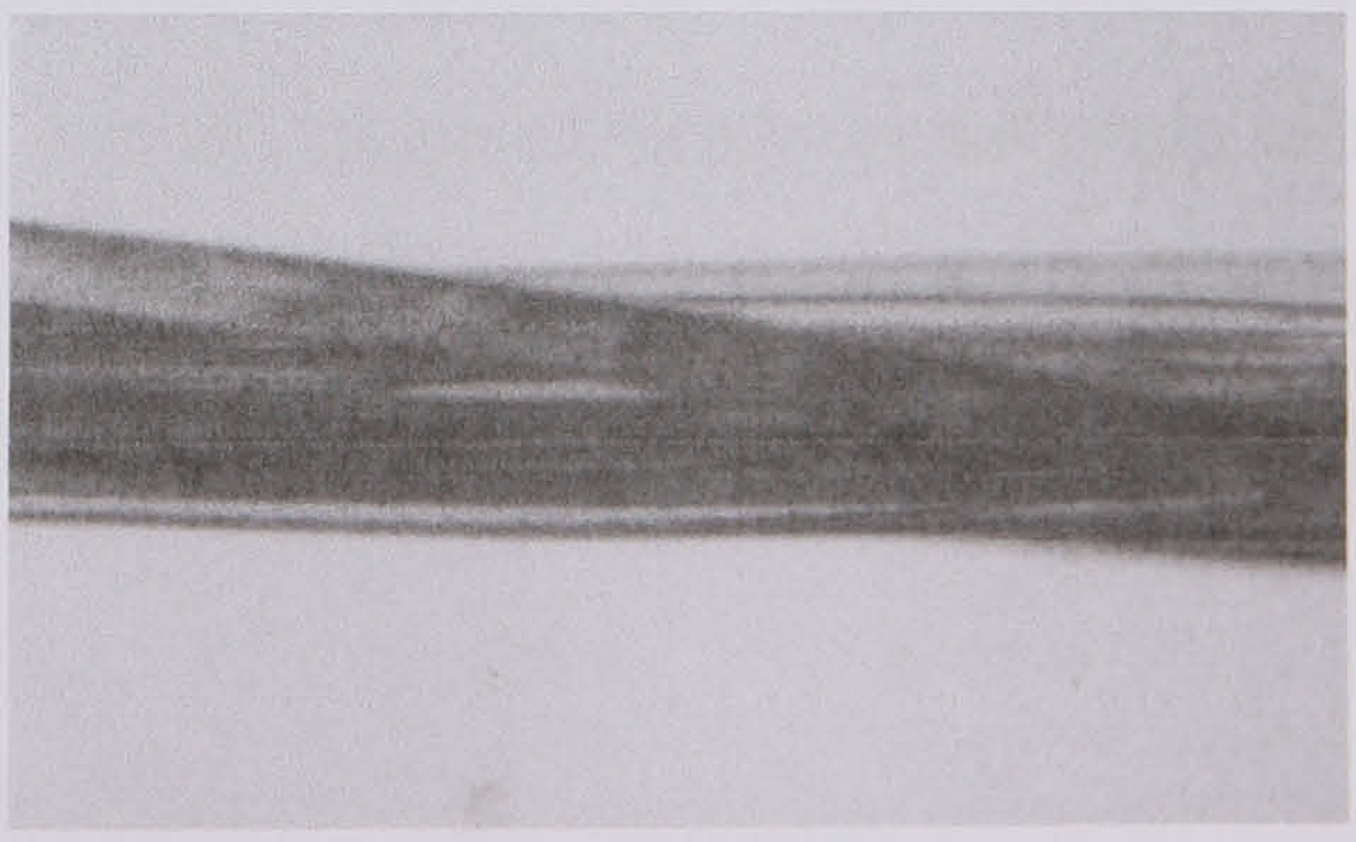
Resistat F9301 (5x magnification)

Yarn diameter 0.10mm



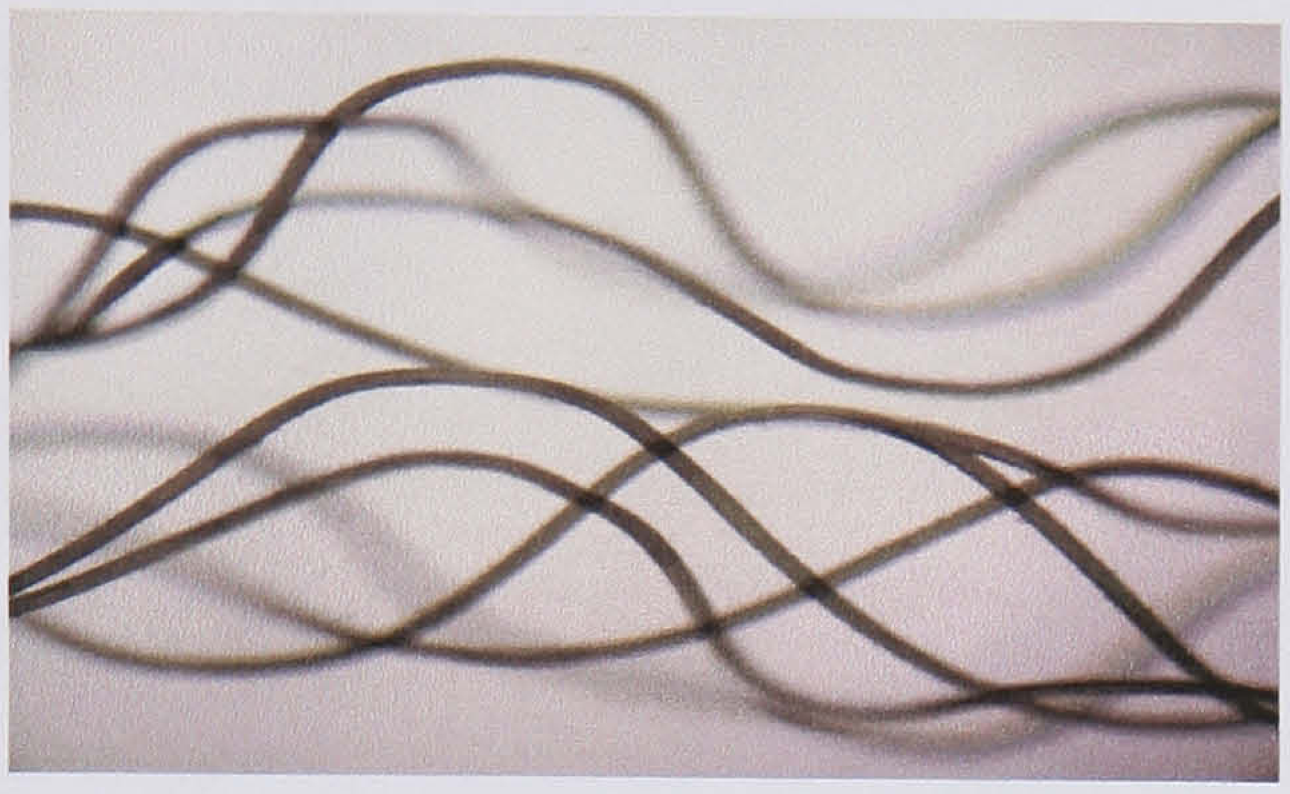
Resistat F9306 (10x magnification)

Yarn diameter 0.3mm



R.Stat/N (5x magnification)

Yarn diameter 0.7mm (no crimp)

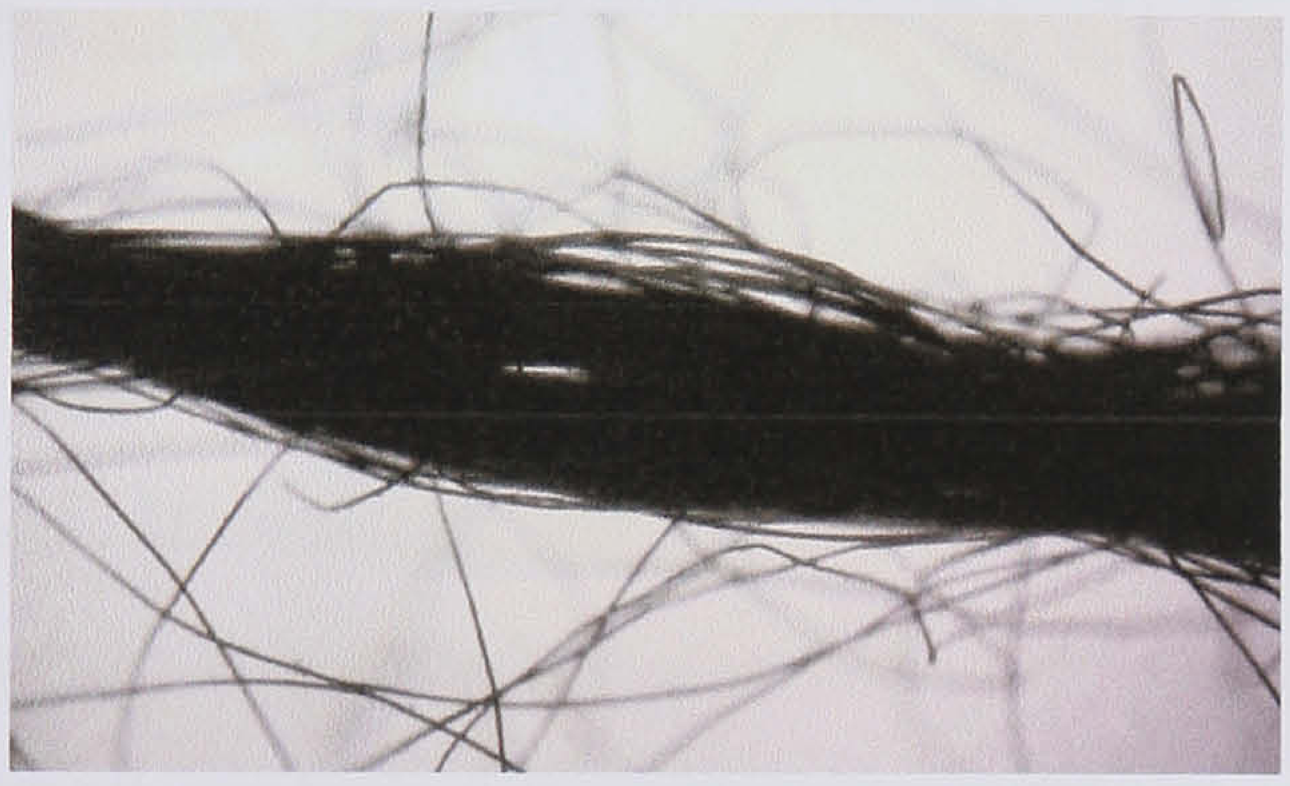


R.Stat/P (Digital image)

Yarn diameter 0.68mm

R.Stat/S (5x magnification)

Yarn diameter 0.52mm



Stainless Steel Wire (Digital image)

Yarn diameter 0.06mm

Figure 3.7 Images of Conductive Yarn Structure

3.4.2.5 Elastomeric Yarn Specific Stress-Strain

The strain at break values for the elastomeric materials in Table 3.4 show that, as expected, they all exhibit very high levels of extensibility. The CV values are fairly high, most likely due to the somewhat irregular structure of the yarns, with the covered yarns having the greater degree of variation.

The specific stress at break values are relatively low, especially when compared to the values for some of the conductive yarns, but the range of values is not wide and the CV values are similar showing that for most yarns these results are relatively repeatable, with the exception of the double covered Lycra which exhibits high variability.

Table 3.4 Elastomeric Yarn Physical and Mechanical Behaviour

Parameter \ Material	Linel 156dtex	Lycra 78dtex	Lycra E2569	Lycra E276B	Stretch Magic
Count (Tex)	15.6	7.8	20.7	12.3	232
Strain at break	7.2	7.4	7.2	6.6	4.8
Strain CV	7.18	8.53	13.19	11.06	14.75
Specific Stress at Break (mN/tex)	68.42	90.25	65.83	49.39	49.99
Specific Stress CV	13.32	14.50	35. 80	14.92	17.11

A comparison of the stress-strain curves for the elastomeric yarns is shown in Figure 3.8. It confirms the expectation that in general elastomeric yarns exhibit very high strain at break characteristics, typically greater than 600% extension, yet the stress at break performance can vary. Whilst it is understood that the polymer type [122] has a significant effect on this tensile behaviour, as opposed to the yarn structure, it can be seen that the covered Lycra yarns (276 and 2569) share similar strain behaviour in that there is a degree of straightening out of the highly twisted covered yarns on straining prior to the start of the specific stress increase, an effect which can also be seen in the initial stages of the specific stress increase (around 40-50% extension).

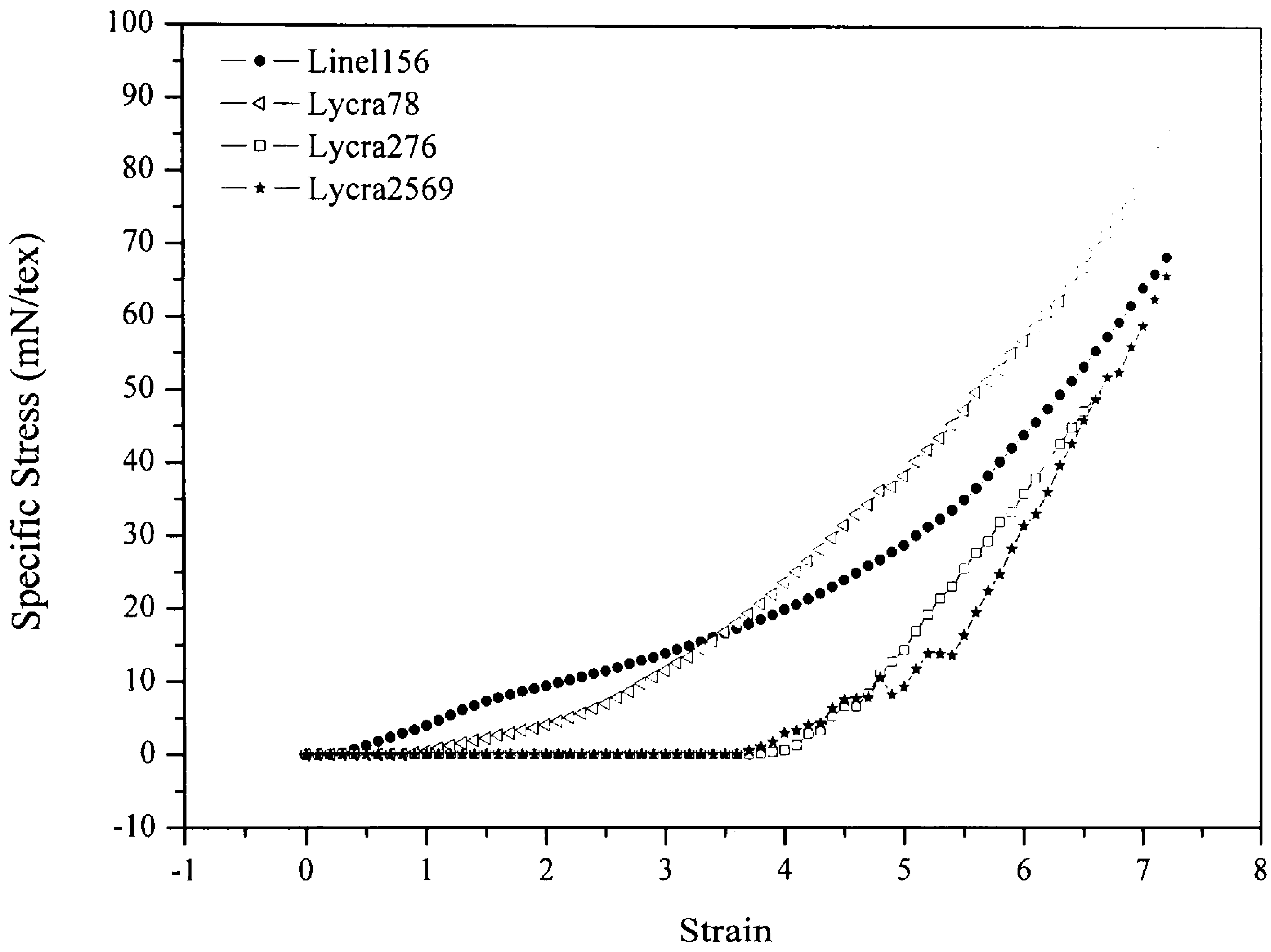


Figure 3.8 Elastomeric Yarn Average Stress-Strain Curve Comparison

3.5 Discussion

The results of the mechanical tests performed on the conductive and elastomeric yarns have highlighted the complexity in analysing and comparing the structure-property relationships of the yarns. Assessment of these results alone did not give sufficient information by which it was decided which of the yarns was suitable for mechanical-electrical characterisation, however potential deficiencies in certain yarns' suitability for use as a strain sensor, such as low strain at break, was noted.

Chapter 4

Electrical Characterisation of Conductive Yarns

Chapter 4

Electrical Characterisation of Conductive Yarns

Following the physical and mechanical tests described in Chapter 3, preliminary electrical testing was carried out in order to determine the electrical resistivity of each conductive yarn. This information will then be used to determine which yarns are suitable for further mechanical-electrical characterisation.

4.1 Electrical Performance

There are a variety of ways to define the electrical performance of a conductive textile material.

4.1.1 Electrical Conductivity

Electrical conductivity (σ) is the capacity of a material to allow the passage of an electrical current and it is defined as "The charge transported across a unit cross-sectional area per second per unit electrical field applied" [123] and measured in siemens/unit length. It can be calculated according to equation 4.1 using the length of the conductor (*l*), the cross-sectional area (*A*), the current (*I*) and the applied voltage (*V*).

$$\sigma = \frac{l}{A} x \frac{I}{V} \qquad \text{----------------------- (4.1) [123]}$$

For most commercially available conductive fibres, yarns and fabrics the electrical resistance or resistivity, rather than the conductivity, of the material is stated in the technical specifications, particularly for those conductive materials used in the production of anti-static products.

4.1.2 Electrical Resistivity

Electrical Resistivity (ρ), the inverse of conductivity, is the resistance per unit length of a material, thus the SI unit is ohm centimetre (Ω.cm) or ohm metre (Ω.m). It can be calculated according to Equation 4.2, using the resistance (R), the sample length (l) and the cross-sectional area (A).

$$\rho = \frac{RA}{l} \quad \text{------------------ (4.2) [124]}$$

4.1.3 Electrical Resistance

Electrical resistance (R), measured in Ohms, is determined by the geometry of a material and is directly proportional to the length of the conductor yet inversely proportional to the area of the cross section of the conductor. R can be calculated according to equation 4.3 using the resistivity (ρ), the length of the conductor (l), and the cross-sectional area (A).

$$R = \rho\frac{l}{A} \quad \text{---------------------- (4.3) [123]}$$

Figure 4.1 which illustrates the range of resistivities spanned by traditional textile fibres, conductive textile fibres (Thunderon; Copper Sulphide coated nylon) and metallic fibres, showing that the resistivity of natural fibres such as wool and acrylic is so high as to render them unsuitable for use as sensor materials.

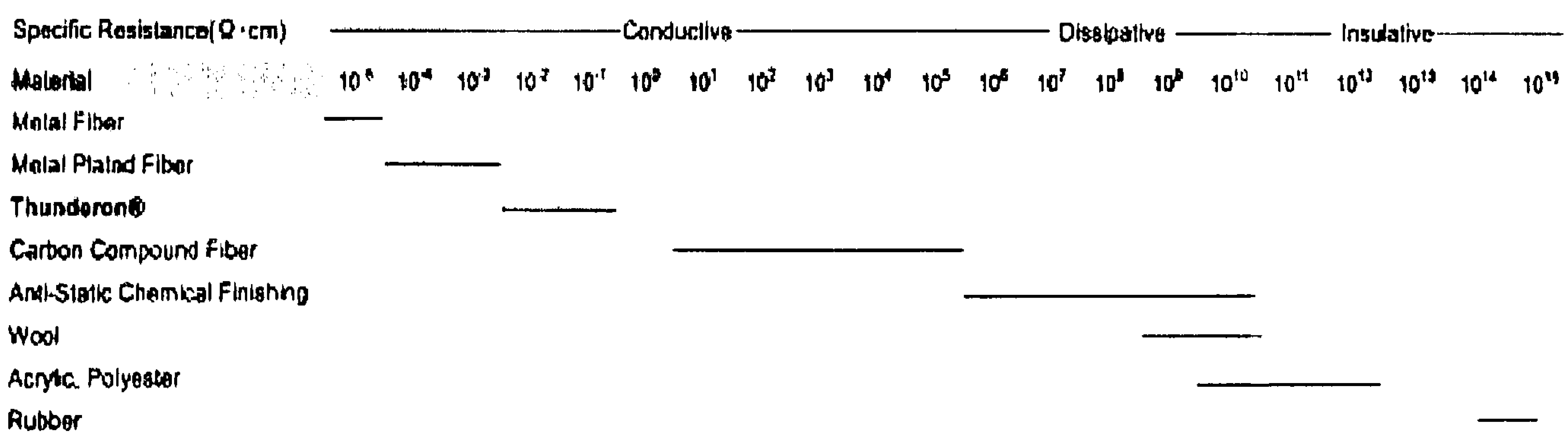


Figure 4.1 Resistivity of Textiles Fibres [125]

4.2 Determination of the Conductive Properties of the Yarns

4.2.1 Test Standards

A suitable test methodsfor measuring the resistance of the yarns was sought but a direct measuring test standard was not found. Many test methods were specific only for solid forms, for surface resistivity only or for testing metal materials only. A sample of these test standards and the reasons for their unsuitability are shown in Table 4.1.

Table 4.1 Electrical Conductivity Test Standards

Standard Number	Description
AATCC 84-2000 [126]	This method was unsuitable as; "Due to the mechanism of conductance, this method is not applicable to yarns containing randomly situated stainless steel or highly conductive fibers."
DIN 54345-1 [127]	This test standard was available only in German (funds to translate it were not available within the researcher's budget).
ASTM D 4496-04 [128]	This standard contained information on measuring the volume resistivity of materials and testing materials for shielding, however it required the use of the test apparatus which was not available within the department.
JIS L 1094:1997 [129]	This standard described the testing methods for determining the electrostatic propensity of woven and knitted fabrics, but not yarns.
GOST 6433.2-71 [130]	This standard required the use of flat, circular samples of film in order to measure the resistance

	under DC voltage.
BS EN 61340-2-3:2000 [131]	The test method could only be carried out on the surface of materials and required apparatus which was not available within the department for use.
BS EN 3466:1962 [132]	This method was contrived for use on metallic materials only using a Kelvin double bridge or a Wheatstone bridge.

4.2.2 Non-standard Test Methods

The electrical conductivity of conducting polymer fibres was determined by Bowhon et al [133] using a 'two-probe test technique' and a Keithley 617 electrometer as an ammeter. The Keithley 617 electrometer generated a variable DC voltage power supply when connected to the conductive fibres and at the same time it measured the electric current. The electrometer was connected to a PC which controlled the voltage and measured the current as shown in Figure 4.2.

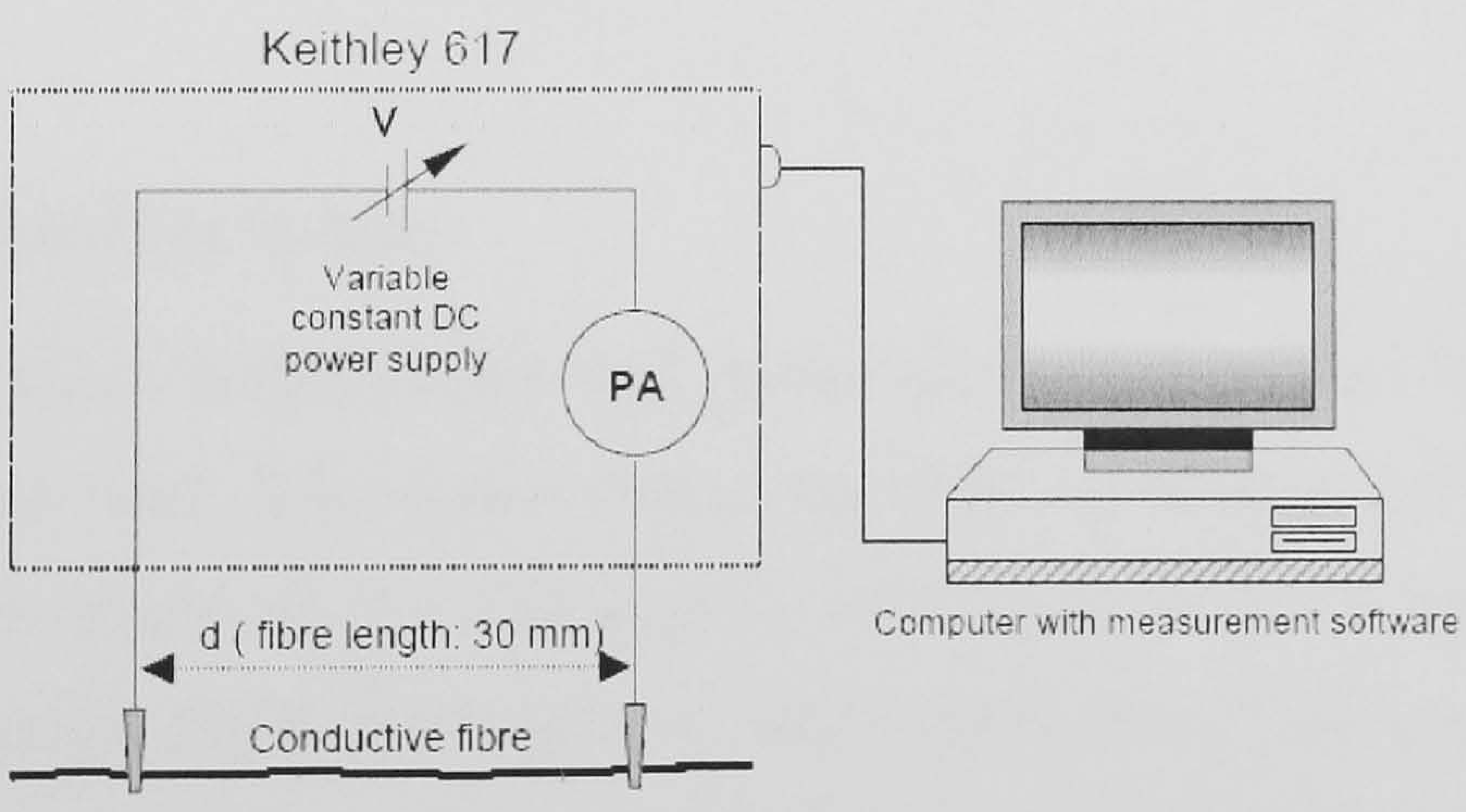


Figure 4.2 Schematic View of Geometry and Circuit for Making Resistivity Measurements [133]

Researchers at the University of Belgrade [134] measured the electrical resistance of yarns produced from a mixture of cotton and metal fibres directly by means of a sensitive digital multimeter. Electrodes were used as sample supports, these having been formerly set up for the measurement of electrical resistance of yarns consisting only of textile fibres. Xue et al [73] measured the resistance of PPy coated fibres using the four-probe method [135] with a Keithley 2010 multimeter with the extended yarn samples attached to cardboard frames and strained at a speed of 5mm/min.

Based on the information gathered from these non-standard test methods, it was decided that measuring the resistivity of yarns directly, using a highly sensitive multimeter, would be a suitable method and, if the multimeter were to be connected to the clamps of the Instron, the change in resistance during yarn straining could be measured. This method also enabled the use of equipment already available within the department and only required the purchase of one piece of equipment (the multimeter).

4.2.2 Electrical Resistance Measuring Devices

Sensitive multimeters are available either as hand-held (digital or analogue) devices or bench devices, all exhibiting varying degrees of measuring accuracy.

4.2.2.1 Hand-held Multimeter

For initial resistance measurements and on-the-spot testing, a hand held DVM890L Multimeter was used. This has a measuring range of 0.1Ω (±0.8%) to 200MΩ (±5%). Resistor testing of the multimeter confirmed its accuracy showing that the multimeter measured the resistances to well within their own tolerances. Initial resistance measurements of the conductive yarns were made using the handheld multimeter in order to determine the required range of the bench multimeter. A gauge length of 300mm was used and the results are compared to the resistivity values given in the manufacturers' data sheets, as shown in Table 4.2.

Table 4.2 Measured Resistivities of Conductive Yarns using Hand-held Multimeter at 300mm Gauge Length

Material	Manufacturers' Resistivity (Ω.cm)	Measured Resistivity (Ω.cm)	% Difference	Standard Deviation
Bekinox VN	0.71	0.55	22.5	0.008
BK 50/1	100	13,501	-13,401	9,657
BK 50/2	50	90,194	-180,288	179,903
Epitropic OE Rotor Spun	10 – 80 (MΩ)	Immeasurable	-	N/A
Epitropic Plied	Not available	Immeasurable	-	N/A
Resistat F902	400,000	250,666	37.3	3,183
Resistat F9301	300,000	614,733	-104.9	20,029
Resistat F9306	300,000	585,978	-95.3	5,164
R.Stat/N	100,000	19,026	80.9	13,016
R.Stat/P	1,0000	176	98.3	20
R.Stat/S	60-80	0.73	98.9	0.10
Stainless Steel Wire	Not available	2.5	239.3	0

It can be seen that many of the yarns' measured resistivity value differed significantly from the values given by the manufacturer. For example, the BK 50/1 and 50/2 yarns measured values are very much higher than those specified, and as the standard deviation values show there a high degree of resistivity variability between the five samples measured (for BK 50/2 the values measured ranged from 0.76Ω/cm to 450kΩ/cm). This disparity may be attributed to the yarn structure whereby the staple conductive metallic fibre is surrounded by insulating polyester fibres which may inhibit the measured conductivity, a theory which could also be applied to the Epitropic OE Rotor Spun and Plied yarns.

Conversely, the measured resistivity values of the Resistat continuous multifilament yarns are much closer to those specified, although more so for the F902 yarn which contains fewer non-conductive polyester filaments and the standard deviation results of the F902 yarn indicate that the measured results are very repeatable as the spread of results from the mean is no greater than ±3%. This differentiation in results may also be due to the differing test methods and conditions under which the manufacturers tested their yarns compared to the test method used (as described).

For the R.Stat yarns, however, the measured resistivity values are much lower than those specified, and the standard deviation values are relatively high, particularly for the R.Stat/N yarn equating to a spread of results about the mean of ±68%. This again could be a consequence of the yarn structure as the R.Stat/N and R.Stat/P yarns are irregularly crimped and twisted, thus it was impossible to gauge the degree of strain under which the yarns were measured, either in these tests or by the manufacturer, which could have significantly affected the results. As such the yarns with the greatest spread of results about the mean were re-tested at a shorter gauge of 50mm in order to determine if this minimised the difference between the specified results and the measured values, as shown in Table 4.3.

Table 4.3 Measured Resistivity of Conductive Yarns using Hand-held Multimeter at 50mm Gauge Length

Material	Manufacturer's Resistivity (Ohms/cm)	Measured Resistivity (Ohms/cm)	% Difference	Standard Deviation
Bekinox 50/1	100	127	-27	82.7
Bekinox 50/2	50	26.7	46.6	9.33
R.Stat/N	100,000	12,196	87.8	5043

The results show that whilst an improvement was seen in terms of a reduction in the difference between the specified and measured resistivity results, the standard deviation values are relatively similar, and it is important to note that the Bekitex 50/1 yarn resistivity values given by the manufacturer were also measured with an electrode distance of 5cm. This information had a bearing on the gauge lengths used during further electrical-mechanical testing of the yarns (Chapter 5). These results indicated that the bench multimeter needed to be capable of measuring up to 600kΩ/cm.

4.2.2.2 Bench Multimeter

Based on the results gained from using the handheld multimeter, a Thurlby Thandar Instruments TTi 1604 Multimeter [136] was purchased in order to test the resistances of the yarns. It has a measuring range from 0.1Ohms (±0.15%) to 40MOhms (±2%), specification: 110-120V or 220-240V AC ± 10%, 50/60Hz, 3VA max.

4.2.3 Connecting the Yarn to the Electrical Resistance Measuring Device

A sturdy connection was needed between the conductive yarn and the multimeter cables as crocodile clips did not give a secure, reliable connection. To ensure that an immovable connection to the maximum number of conductive filaments was achieved, a variety of clamping methods were considered.

4.2.3.1 Cardboard Frame Clamping

This method is similar to that used for supporting yarns when carrying out the stress-strain tests in the Instron. Xue et al [73], when testing the electromechanical behaviour of fibres coated with an electrically conductive polymer, used the set-up up shown in Figure 4.3 to support the yarns. The yarn was attached vertically with adhesive into a paper frame with a rectangular hole in the centre with the electrodes being 60mm apart. The cardboard edges of the paper frame were cut prior to the load being exerted on the yarn. This method, however, required the use of a suitable adhesive which may have affected the resistance values measured or contaminated the yarns.

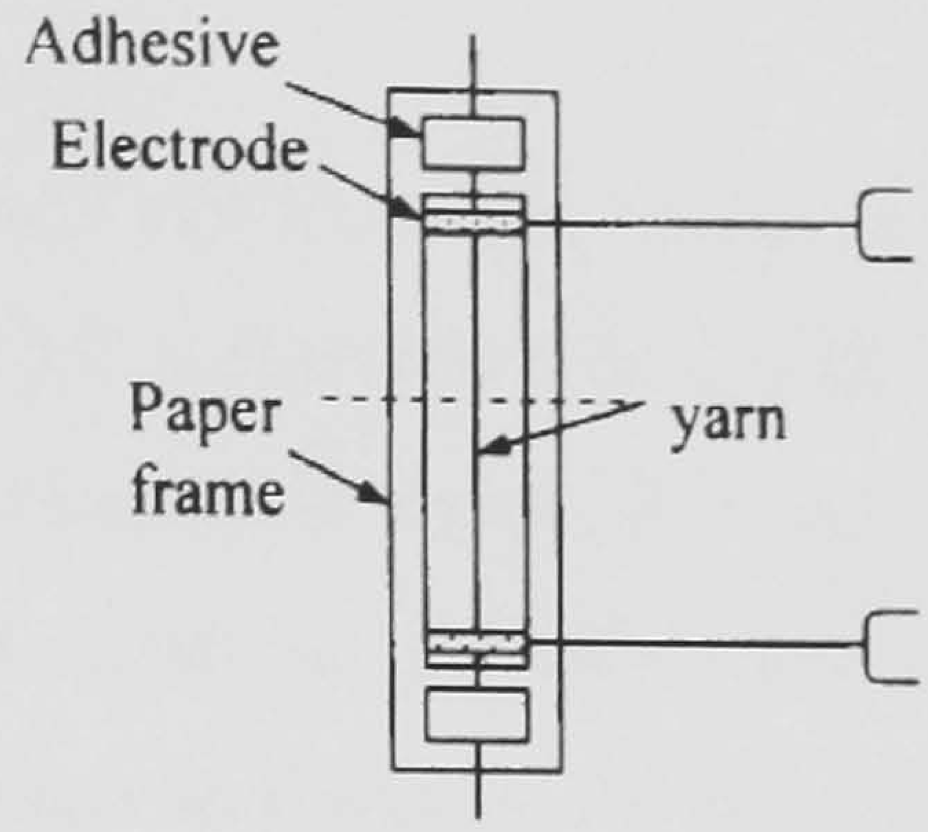


Figure 4.3 Schematic Drawing of a Cardboard Clamping Test Set-Up [73]

4.2.3.2 Soldering

Yarns can be soldered to a thin copper plate using a lead solder whilst making the electrical connection to the copper plate. By applying solder to both the copper strip and the yarn, then pressing them together, a good connection is made and a minimum of solder used. A potential configuration for this soldering method is shown in Figure 4.4. Lead solder contains resins which should dissolve any oxidation on the materials and promote a closer connection between the soldered materials however it may be necessary to scrape any thin layers of oxidation off the copper strip before use. The preferred method of soldering however is to pre-tin the materials, which could put light flexible textile yarns under stress, and if solder is used then it should be compatible with stainless steel, which is not present in all of the conductive yarns tested, hence this method was deemed unsuitable.

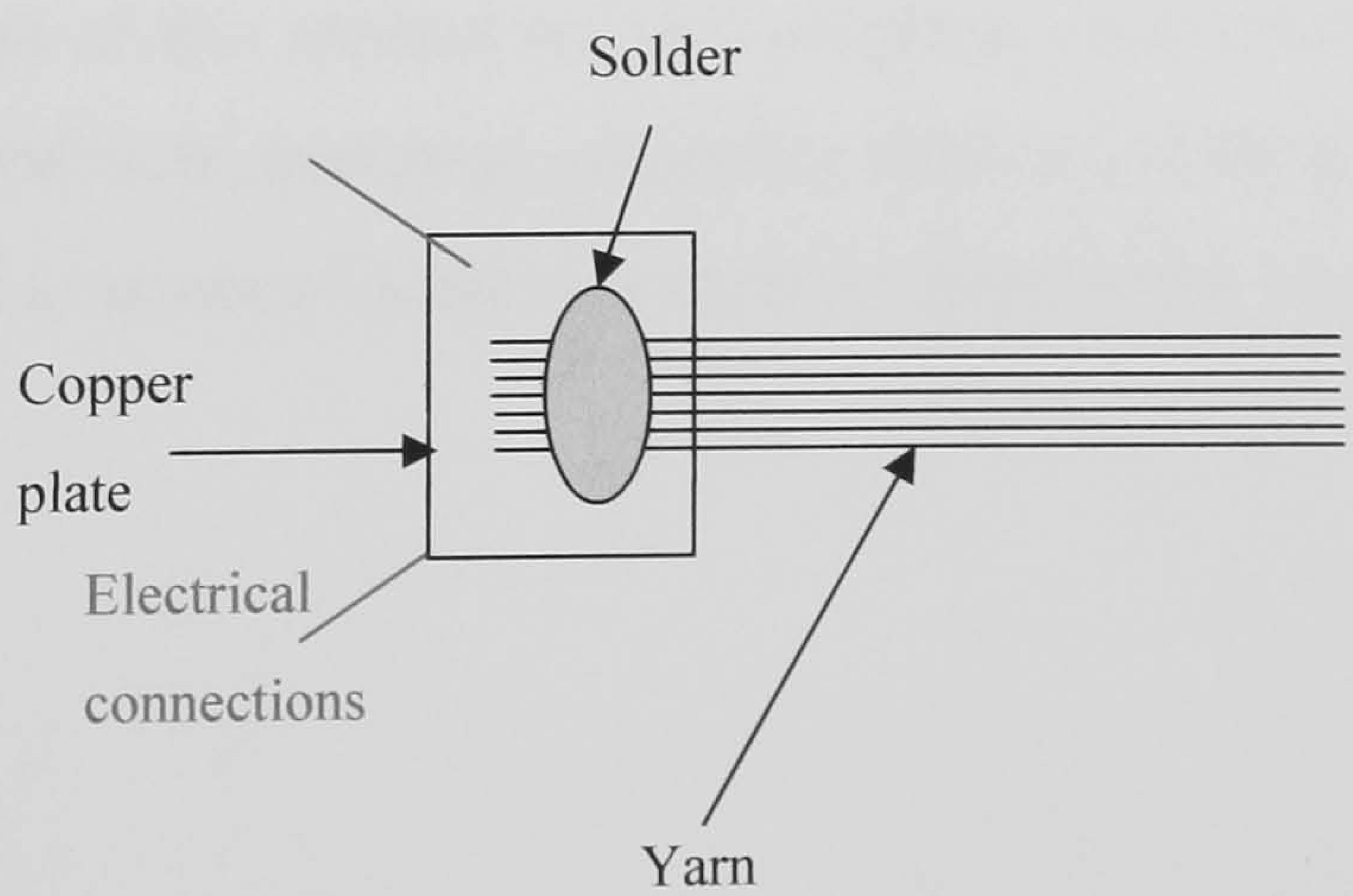


Figure 4.4 Potential Solder Connection Configuration

4.2.3.3 Clamping

Clamping the conductive yarn between two sheets of copper foil and applying an even pressure via an electrical connector was another method considered, and an example of this type of connection is shown in Figure 4.5. This method, however, was not easily realised as it would be difficult not to crush or damage the material whilst applying enough pressure to minimise the risk of yarn slippage.

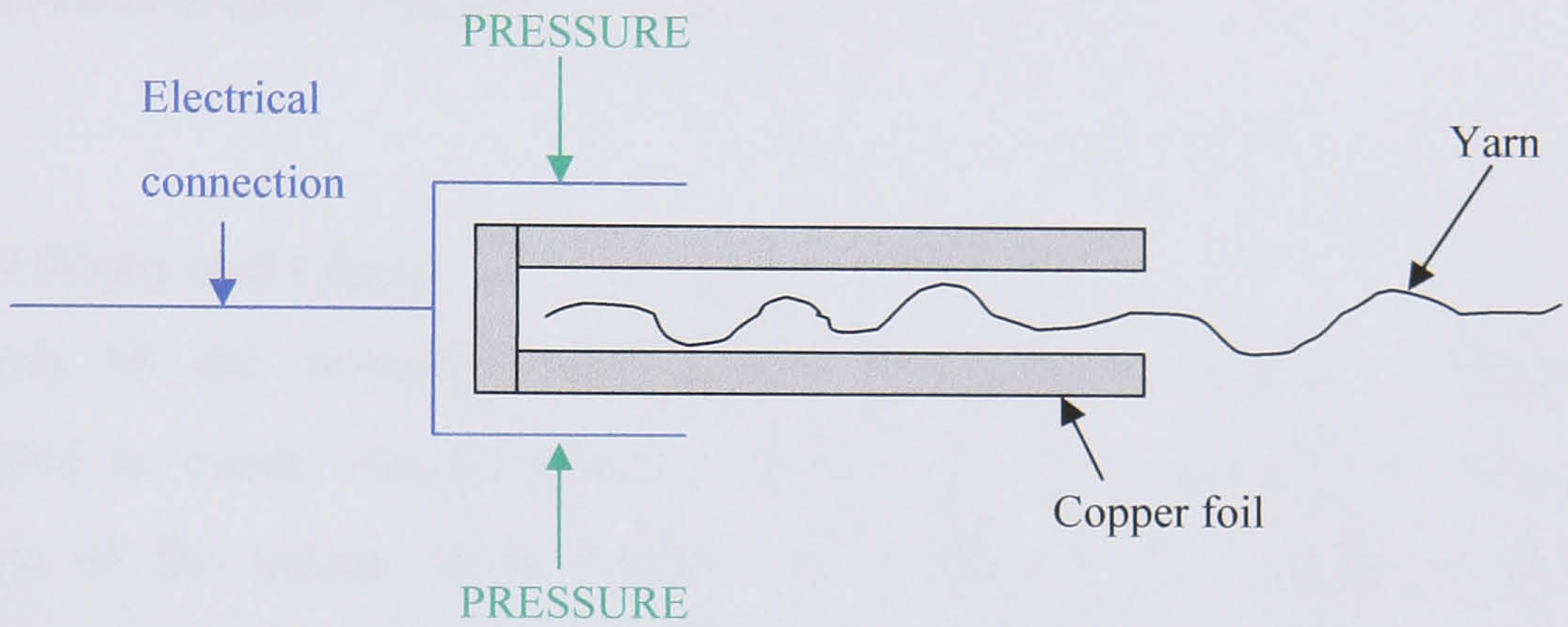


Figure 4.5 Potential Clamping Connection Configuration

4.2.3.4 Wrapping

Another method considered was wrapping the conductive yarn around a brass pin and then inserting it into a brass housing which would hold it in place, thus making the electrical connection with the brass housing, as illustrated in Figure 4.6. Once again, the realisation of this method was not simple as each conductive yarn had a different diameter and bulk, thus issues regarding tightness of fit in the brass housing were raised, as well as issues of complexity and accuracy in the wrapping process.

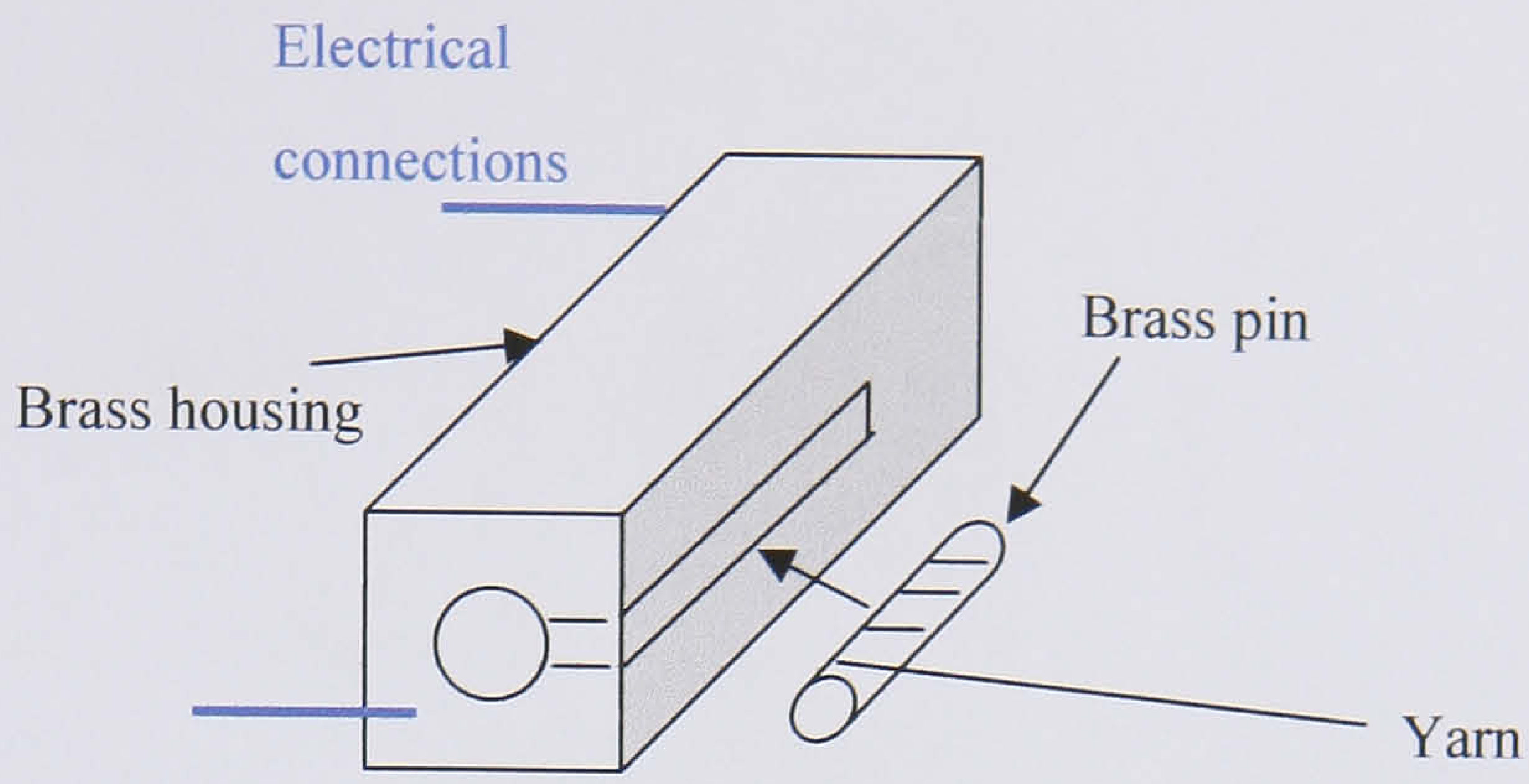


Figure 4.6 Potential Wrapping Connection Configuration

4.2.3.5 Wrap and Clamp

Elements of the potential connection configurations already considered were combined to create clamps which would ensure an even pressure with minimal slippage of the yarns during testing. The clamp created, shown in Figure 4.7, consisted of a 1.5mm depth brass plate, a 1mm depth copper plate and 2 brass screws, all housed on a insulating Tufnel base. The yarn was wrapped around the copper plate which was then screwed down to ensure a secure connection, and the electrical connection was soldered to the edge of the brass plate. 4mm brass plates connected to the edge of the Tufnel base were gripped between the jaws of the Instron. Optimally the internal resistance of a connection system should be so small as to not interfere unduly with the results gained from the sensor measurements. The internal resistance of the clamps, measured using resistors and the bench multimeter to compare the resistance values measured, was only 0.8 Ohms which is essentially negligible and therefore could be discounted in all of the resistance measurements.

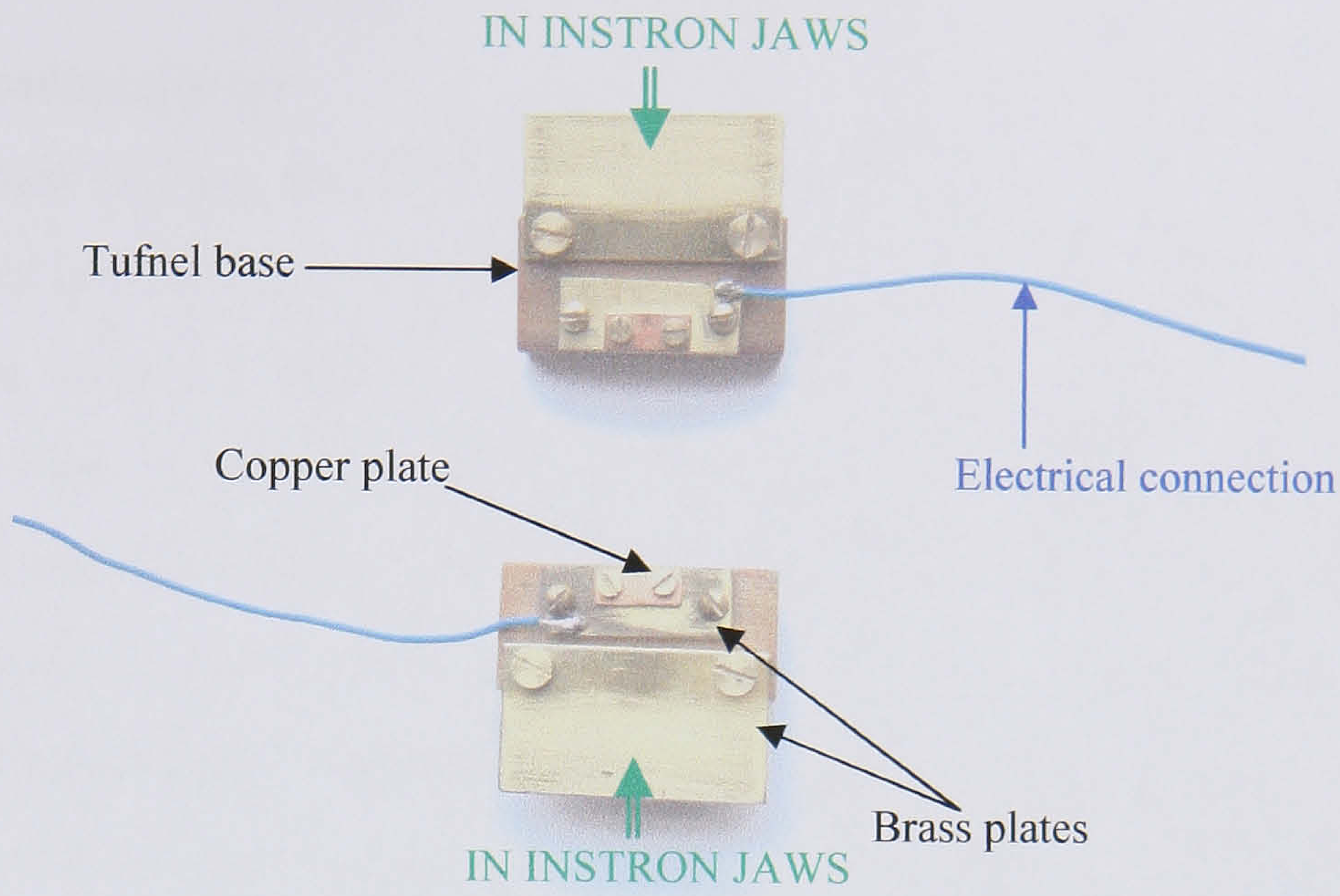


Figure 4.7 Yarn Clamps Used for Measuring Conductive Yarn Resistance

4.2.4 Conductive Yarn Test Set-Up

4.2.4.1 Test Set-Up and Equipment

The equipment used to measure the resistance of the yarns was a Thurlby Thandar Instruments TTi Digital Multimeter which was connected to a PC to automatically log the resistance data as it was measured. The Instron CRE 1122 was used to strain the yarns and measure the stress imposed on them, the physical set-up of the tests can be seen in Figure 4.8.

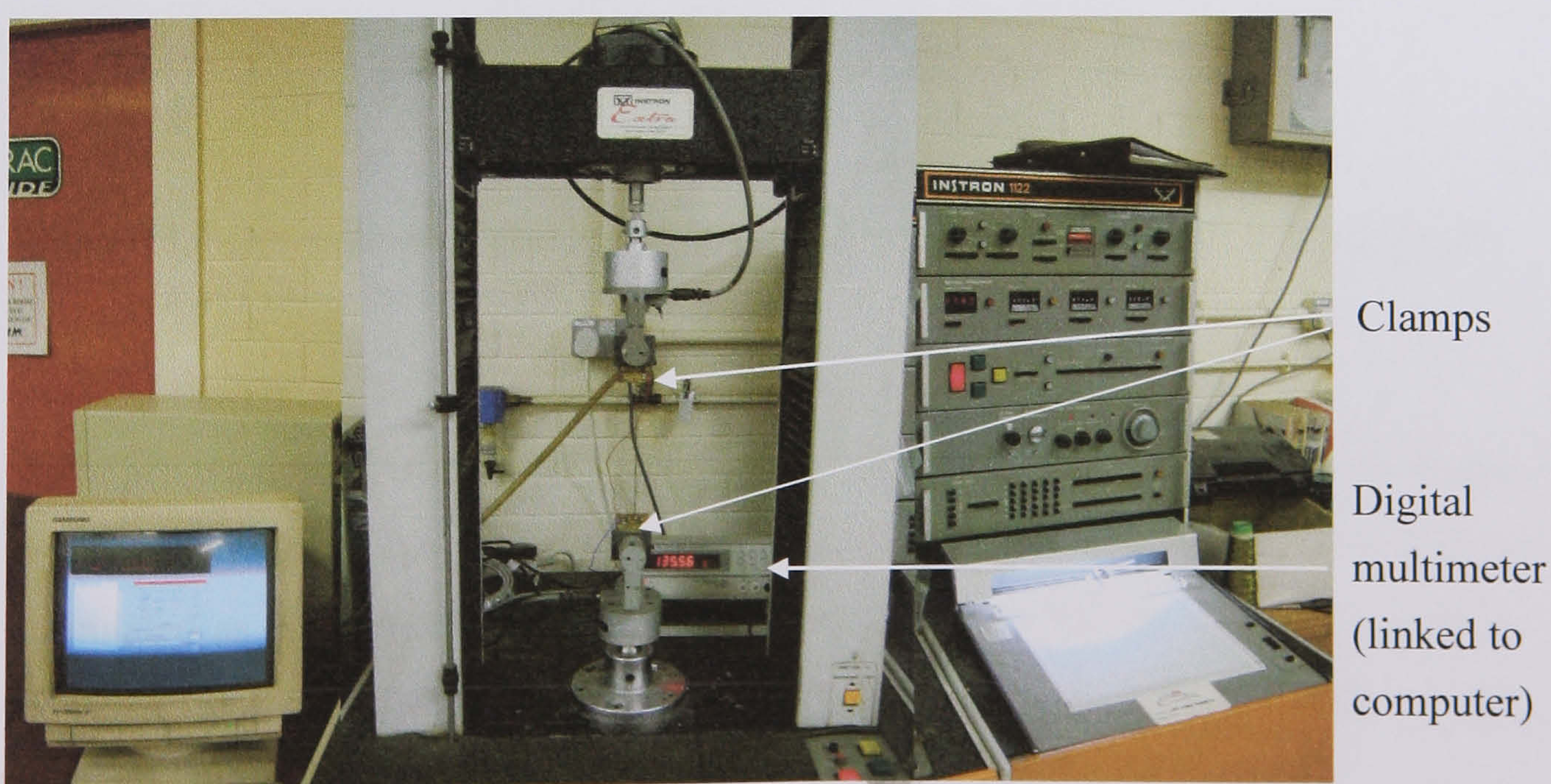


Figure 4.8 Equipment Set-up for Mechanical-Electrical Tests

4.2.4.2 Pre-tensioning

It is important to note the relevance of pre-tensioning the yarns for the resistance tests carried out using the Instron. Theory states that the electrical resistance of staple yarns increases under strain, due to a reduction in the cross-section surface caused by load increase (axial dilation strain), and this phenomenon has been observed in both textile yarns and metal fibre yarns. In contrast, Mihajlidi et al [134] discovered that the electrical resistance of staple yarns consisting of cotton and metal fibres decreases slightly with rising axial strain, this effect being more accentuated for yarns containing lower proportions of metal fibres, as seen in Figure 4.9. This phenomenon occurred because the cross section of the yarns decrease with rising axial strain, there is another dominant influence causing the decrease in resistance at higher values of load and it was proposed that this effect was based on the establishment of better contacts between the metal fibres, thus inducing an increase in the yarn conductivity.

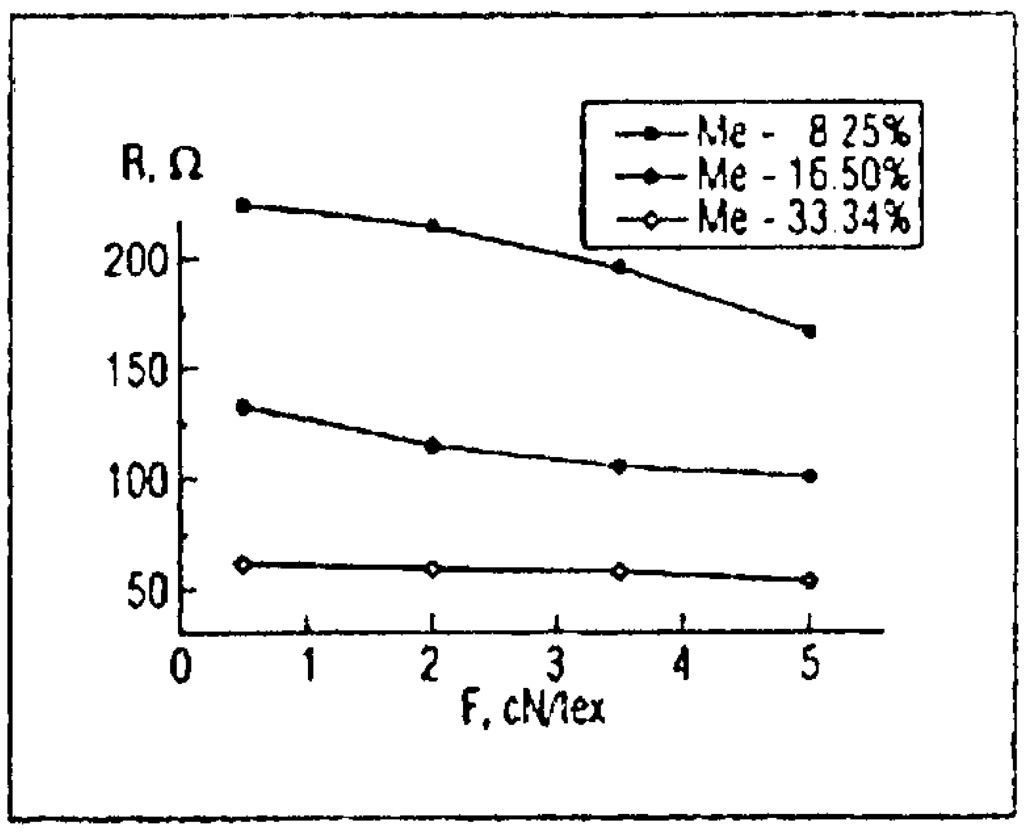


Figure 4.9 Dependence of Electrical Resistance of Yarns Consisting of Cotton and Metal Fibres on Pre-Loading [134]

Thus pre-tensioning of the yarns was deemed important in order to try and eliminate such effects from the recorded results and, as such, the pre-tension level was calculated as 0.5cN/tex based on the count each yarn [137]. For the textured yarns, however, the crimp was just removed, without stretching the yarn due to the difficulty in determining the exact pre-tension level.

4.3 Conductive Yarn Electrical Resistance Test Results

4.3.1 Conductive Yarn Resistivity

The yarns were clamped between the jaws of the Instron (300mm gauge length) and stretched to their pretension level before the resistance reading was taken. Table 4.4 shows the measured resistivity compared to the value given by the manufacturer.

Table 4.4 Resistivity of Conductive Yarns

Material	Manufacturer's Resistivity (Ω.cm)	Measured Resistivity (Ω.cm)	% Difference
Bekinox VN	0.71	0.67	-5.6
BK 50/1	100	111	11
BK 50/2	50	36	-28
Epitropic OE Rotor Spun	10-80 (MΩ.cm)	Unmeasurable	N/A
Epitropic Plied	10-80 (MΩ.cm)	Unmeasurable	N/A
Resistat F902	400,000	266,366	-33
Resistat F9301	300,000	603,322	-101
Resistat F9306	300,000	755,942	151
R.Stat/N	100,000	20,566	-79
R.Stat/P	10,000	464	-95
R.Stat/S	60-80	473	491
Stainless Steel Wire	170	2	-98

It can be seen that whilst some of the measured values are close to the manufacturer's given values (Bekinox VN, BK 50/1 and 50/2), others vary significantly either positively or negatively (i.e. higher or lower resistivity). This is most likely due to differing measurement methods or conditions, or it could be an indication of the inherent variability of electrical resistance along the length of the yarn. For example, a resistance reading could not be made for either of the Epitropic yarns, even when the gauge length was reduced down to 5cm, however the manufacturers are able to take a measurement.

4.4 Discussion

From the measured resistivity results shown in Tables 4.2 and 4.4, it is clear that the conductive yarns chosen span the spectrum of conductivity ranging from metal-like to those very high in the MΩ range. Some of the yarns' resistance levels were too high or too variable to be measured, such as the Epitropic yarns, thus rendering them unsuitable inclusion in a textile-based strain sensor. The benefit of using specially constructed clamps for connectors was illustrated by the improvement in results of the measured yarn resistivity compared to the manufacturers' values. In the majority of cases, percentage difference between the resistivity values for each yarn was decreased when the clamps were used.

However, a significant difference between the measured resistivity and the values supplied by the manufacturer was still encountered both when using the specially constructed clamps and when using the standard multimeter clamps. These discrepancies could be due to a number of different parameters, in particular the tension under which the yarns were tested, the connection/clamping method, the measurement equipment and the overall test specifications used (i.e. sample length etc). Unfortunately a direct comparison of these various parameters could not be made as the manufacturers were not prepared to make their test specifications available.

Thus it was deemed appropriate to narrow down the selection of conductive yarns to a small cross-section that covers a range of base materials, yarn compositions and yarn structures. The yarns chosen for further electrical-mechanical characterisation were Bekinox VN (metal multifilament yarn), Bekitex 501 (metal-polyester blend staple yarn), Resistat F9301 (carbon-based continuous filament yarn), R.Stat/P (copper-sulphide continuous multifilament textured yarn), R.Stat/S (metal staple yarn) and the Stainless Steel Wire (continuous monofilament yarn). These will be subject to mechanical-electrical characterisation with respect to assessing their potential strain sensor capabilities.

The extent of the effect of yarn structure on mechanical-electrical behaviour is a prime consideration when striving to attain a near-linear response for both the mechanical behaviour and the change in resistance on straining. The yarn structures already characterized in this report are illustrated in Figure 4.10.

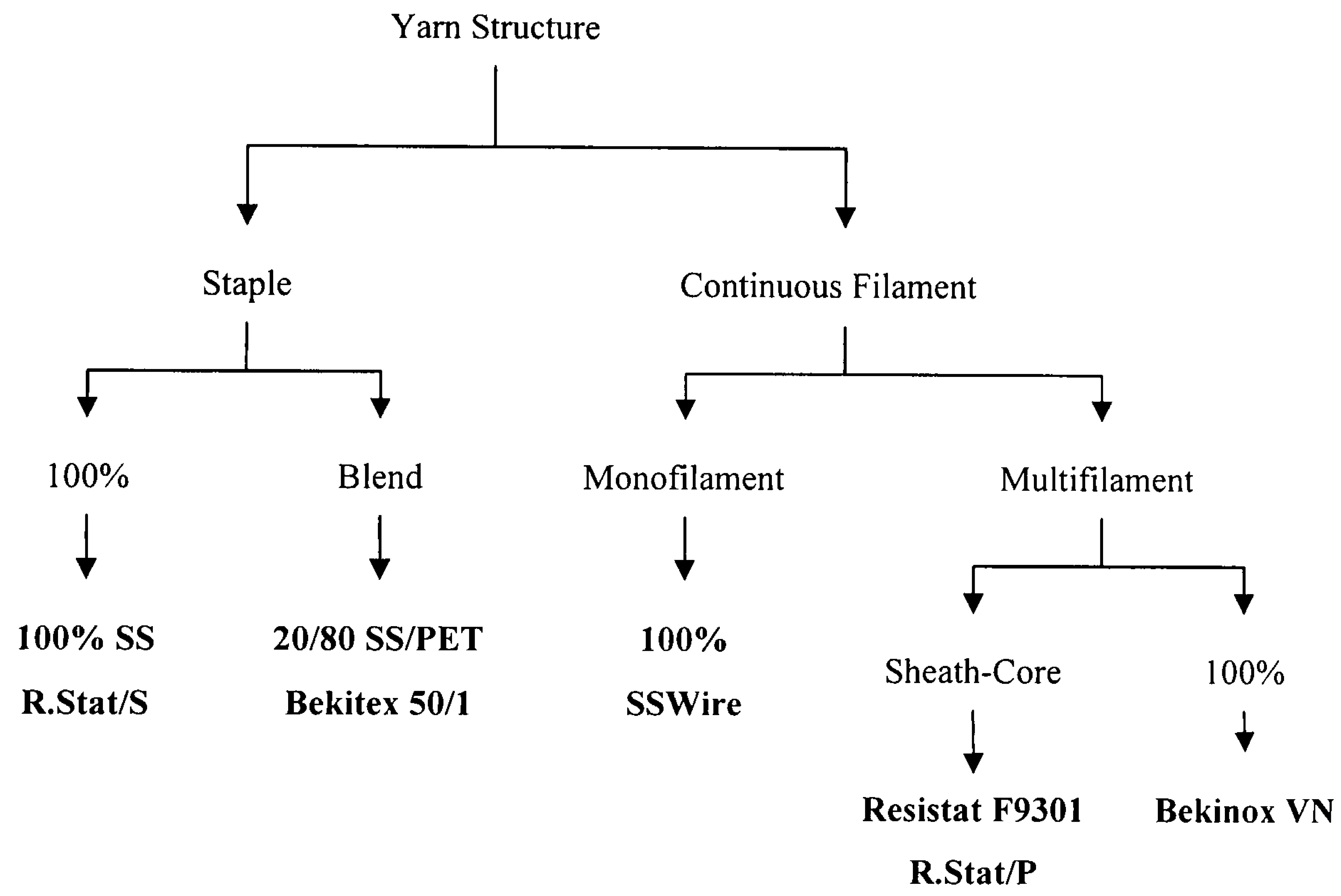


Figure 4.10 Yarn Structure Flow Chart

The mechanical performance of the staple yarns (Bekitex 50/1, R.Stat/S) was not repeatable under cyclic loading, the strain at break values were low and the yarns exhibited poor elastic recovery properties. In terms of staple yarn electrical behaviour, the increase in electrical conductivity on straining has been attributed to the compaction of, and therefore improved connections between, the conductive fibres as the yarn cross-section decreases. However, these advantageous electrical properties were negated by the variable mechanical behaviour in the testing carried out, thus discounting staple yarns from further investigation.

The Stainless Steel Wire, the only continuous monofilament yarn tested, did not respond well to continuous cyclic loading as the yarn yield point was exceeded at a relatively low strain level, which affected the yarns elastic recovery properties. In terms of its electrical behaviour, the resistance increased on straining due to the filament cross sectional area decreasing. This behaviour is predictable using the equation $R=\rho l/A$ where R is the resistance, ρ is the resistivity, l is the yarn length and A the cross sectional area. If, however, a different material were to be used with a higher yield point and better elastic recovery properties, this structure would be suitable for use as a textile strain sensor.

The individual filaments of both continuous multifilament yarns were similar in structure to core-sheath bicomponent fibres as they had polymer cores with conductive fillers/coatings on the fibre surface. In this structure the polymer core provides the yarn elasticity whilst the surface conducts electricity, however as the filaments are stretched the conductivity decreases as the surface filler particles/coating are pulled further apart. The mechanical behaviour of the R.Stat/P yarn was the most variable of all the yarns tested, due to the textured and twisted yarn structure, and correspondingly the changes in electrical performance were unpredictable and unrepeatable. The Resistat F9301 yarn, however, performed predictably in the mechanical testing and the electrical performance results were repeatable. This may be due, in part, to the uncomplicated two-strand, low level twist yarn structure as well as the Carbon particle filler.

Chapter 5

Mechanical-Electrical Characterisation of Conductive Yarns

Chapter 5
Mechanical-Electrical Characterisation of Conductive Yarns

Following the physical, mechanical and electrical characterisation of the commercially available conductive and elastomeric yarns, six yarns with differing base materials, compositions, configurations, conductivity levels and mechanical behaviour were picked for further investigation based on the resistivity results gathered in Chapter 4 and the Yarn Structure Flow Chart developed (Figure 4.2). These are Bekinox VN, Bekitex 50/1, Resistat F9301, R.Stat/P, R.Stat/S and the Stainless Steel Wire yarn, and they were subjected to further tests in order to assess their potential for use as textile strain sensors.

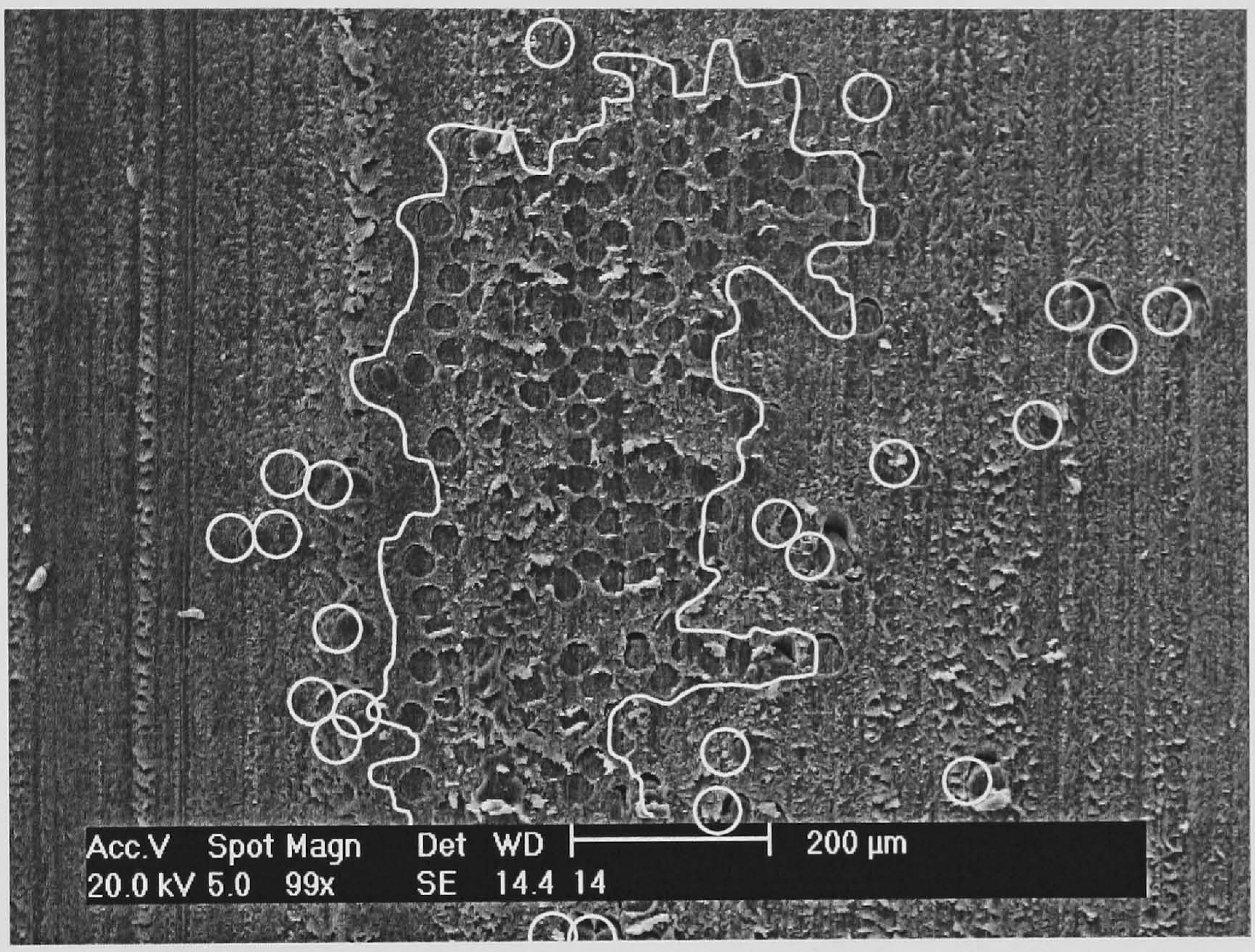
5.1 Physical and Mechanical Property Test Methodologies

5.1.1 SEM Analysis of Yarn Structure

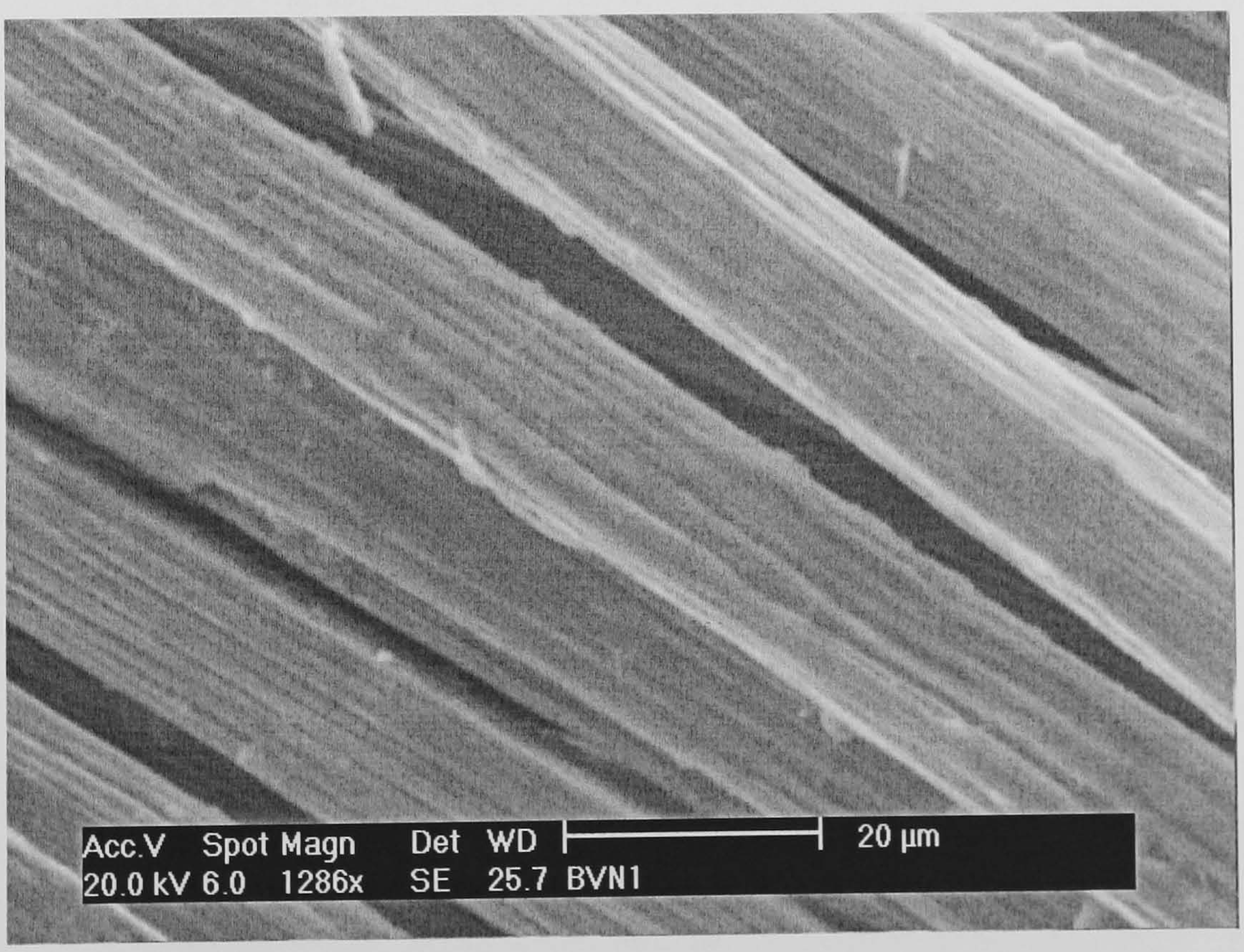
Whilst the yarn structural appearance had been documented through digital images or microscope images, SEM analysis of the yarns surface structure and cross-section was undertaken in order to determine whether the mechanical-electrical behaviour exhibited could be attributed to yarn morphology (i.e. the structure of the yarn). Images of the resinated yarns [138] were taken using a Philips XL30ESEM.

5.1.1.1 Metal yarns

The cross sectional spatial distribution of the 100% stainless continuous filament Bekinox VN yarn is illustrated in Figure 5.1. The distribution of the metal fibres is illustrated in the cross-sectional area image (I), such that the spatial distribution of the majority of the fibres is circled, whilst any fibres that are separate from the main body of the yarn are highlighted. Although there are 90 filaments in total in the yarn, approximately 22% of them are floating around the periphery. These floating filaments extend quite far from the centre of the yarn core, in effect almost doubling the yarn diameter, however this may change at any point along the length of the yarn as it twisted (100 turns/m). The surface image (II) of the yarn shows the surface striations along the length of each filament, which is typical for metal fibres.



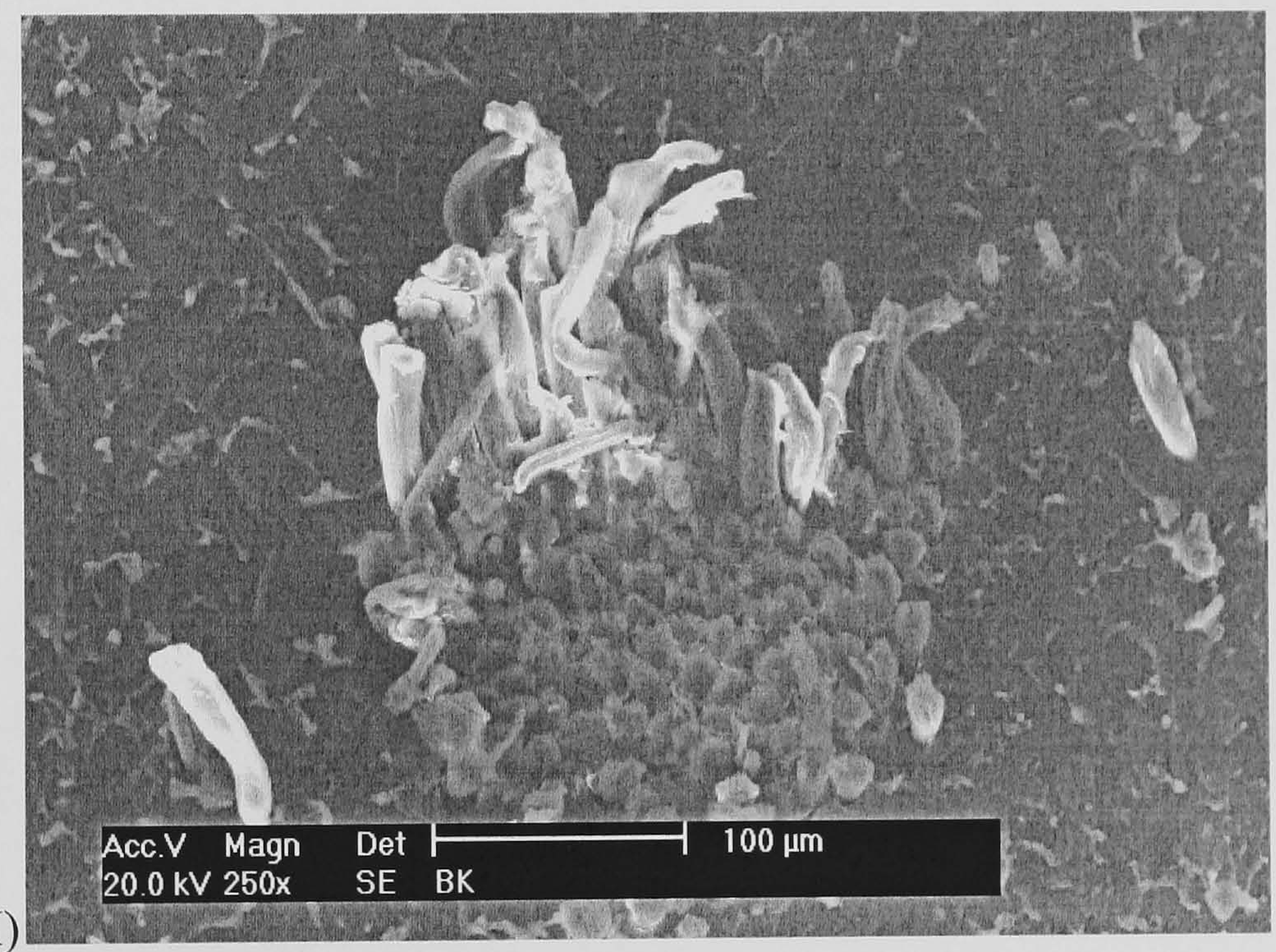
I)



II)

Figure 5.1 Bekinox VN Yarn Cross Section (I) and Surface Structure (II)

The 20/80 Stainless Steel/Polyester staple Bekitex 50/1 yarn cross-sectional spatial distribution is shown in the backscattered electron image (I) Figure 5.2, wherein the contrast between the fibres with different chemical compositions is highlighted. The conductive metal fibres appear paler compared to the darker non-conductive polyester fibres. The metal fibres are mainly distributed towards one side of the yarn, with only two visible floating around the periphery of the yarn, and the spatial distribution of the yarns is such that the only 5 fibres in total are floating around the yarn periphery. In the yarn surface image (II), it is easy to differentiate the metal fibres from the polyester filaments due to their longitudinal striations.

I)


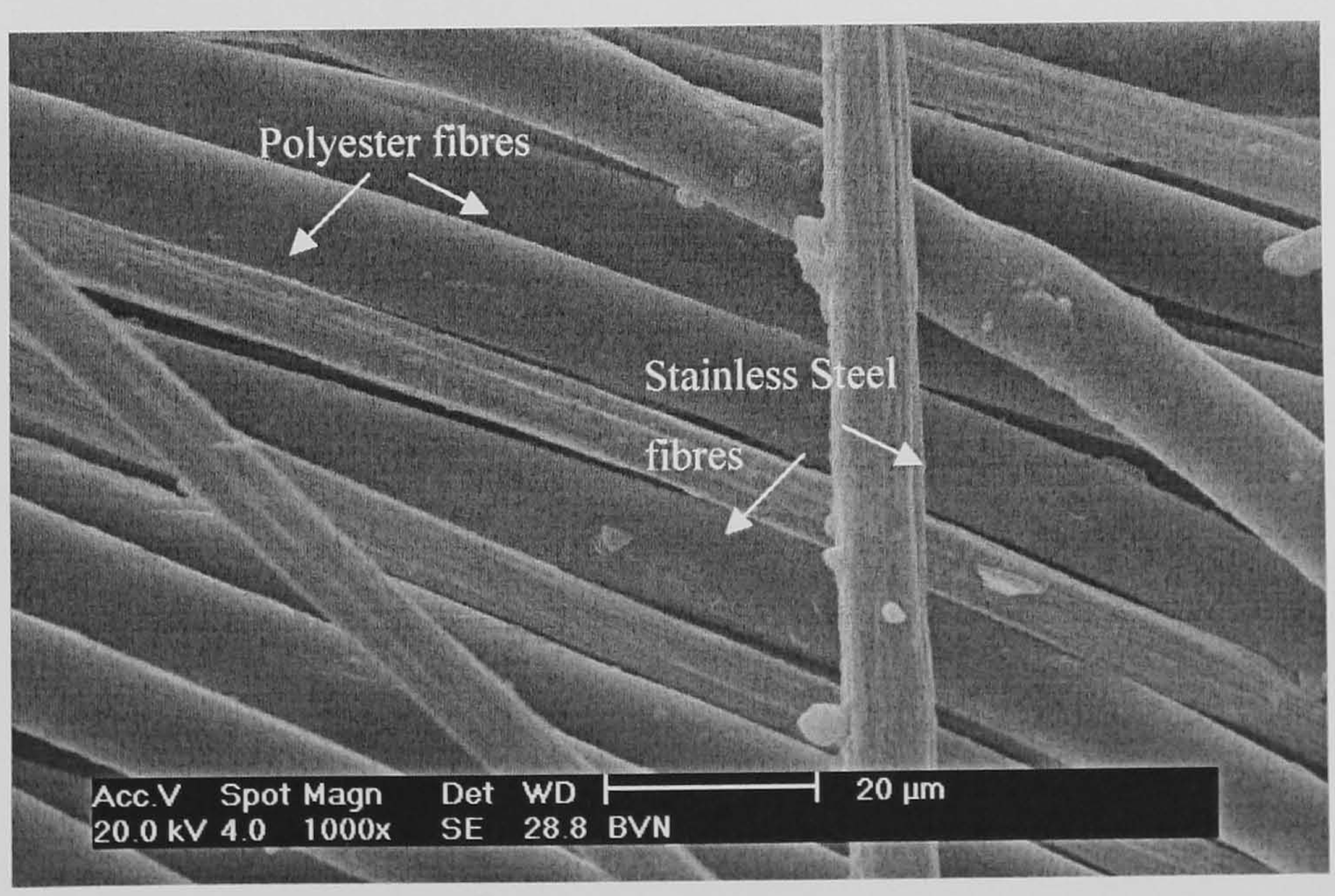
II)


Figure 5.2 Bekitex 50/1 Yarn Cross Section (I) and Surface Structure (II)

Figure 5.3 shows the cross sectional spatial distribution of the 100% Stainless Steel staple R.Stat/S yarn, with the spatial distribution of the fibres highlighted in the cross-sectional image and in this instance, it can be seen that only a small proportion of the fibres are not bound up within the bulk of the yarn diameter. As common with the other metal yarns, there are longitudinal striations visible on the metal fibre surfaces.

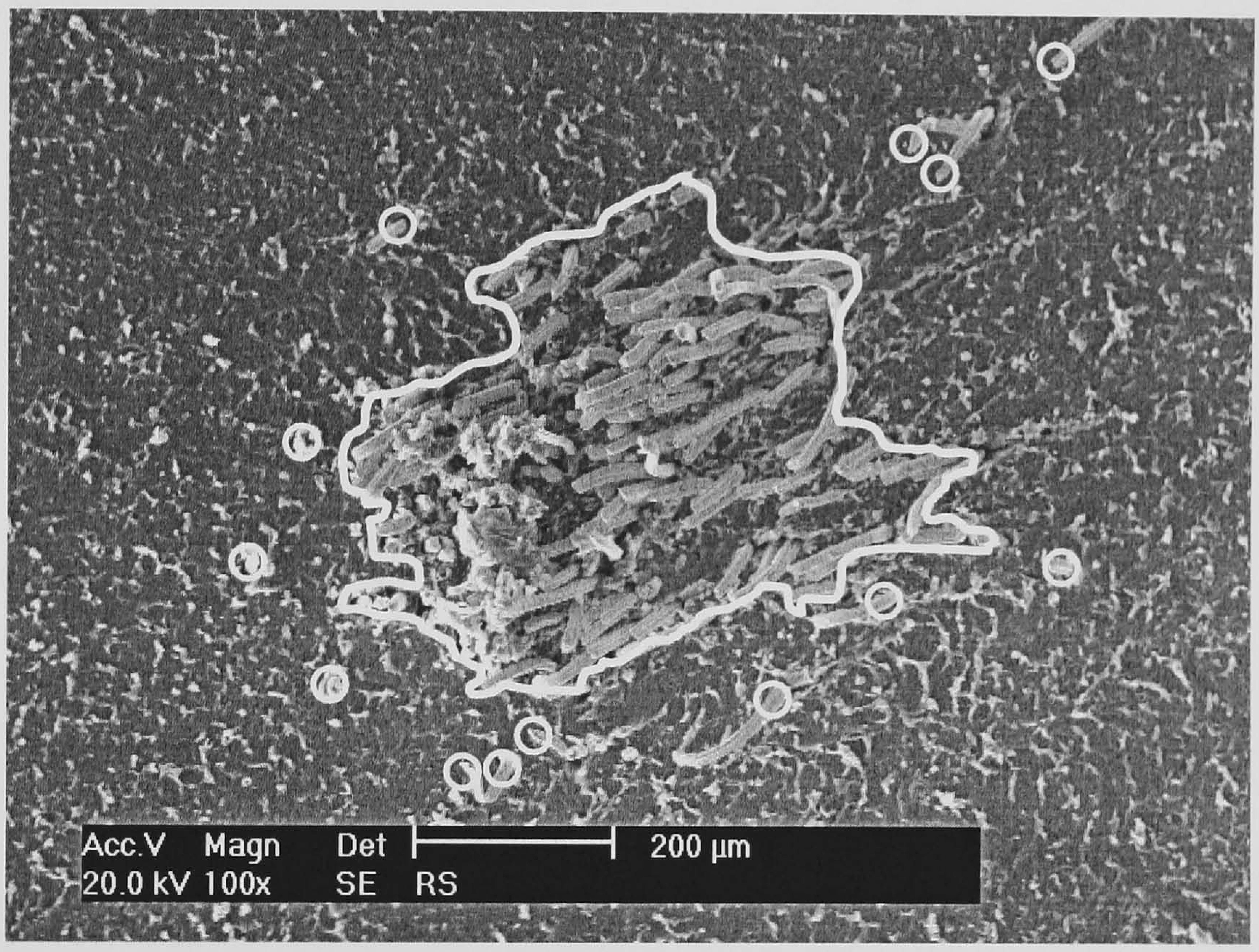


Figure 5.3 R.Stat/S Yarn Cross Section

The cross-sectional shape of the stainless steel wire is slightly more circular than that of the metal fibres used in the Bekitex 50/1 and the R.Stat/S yarns, and the surface longitudinal striations less prominent, as shown in Figure 5.4, however these identifying elements of a metal fibre are still present.

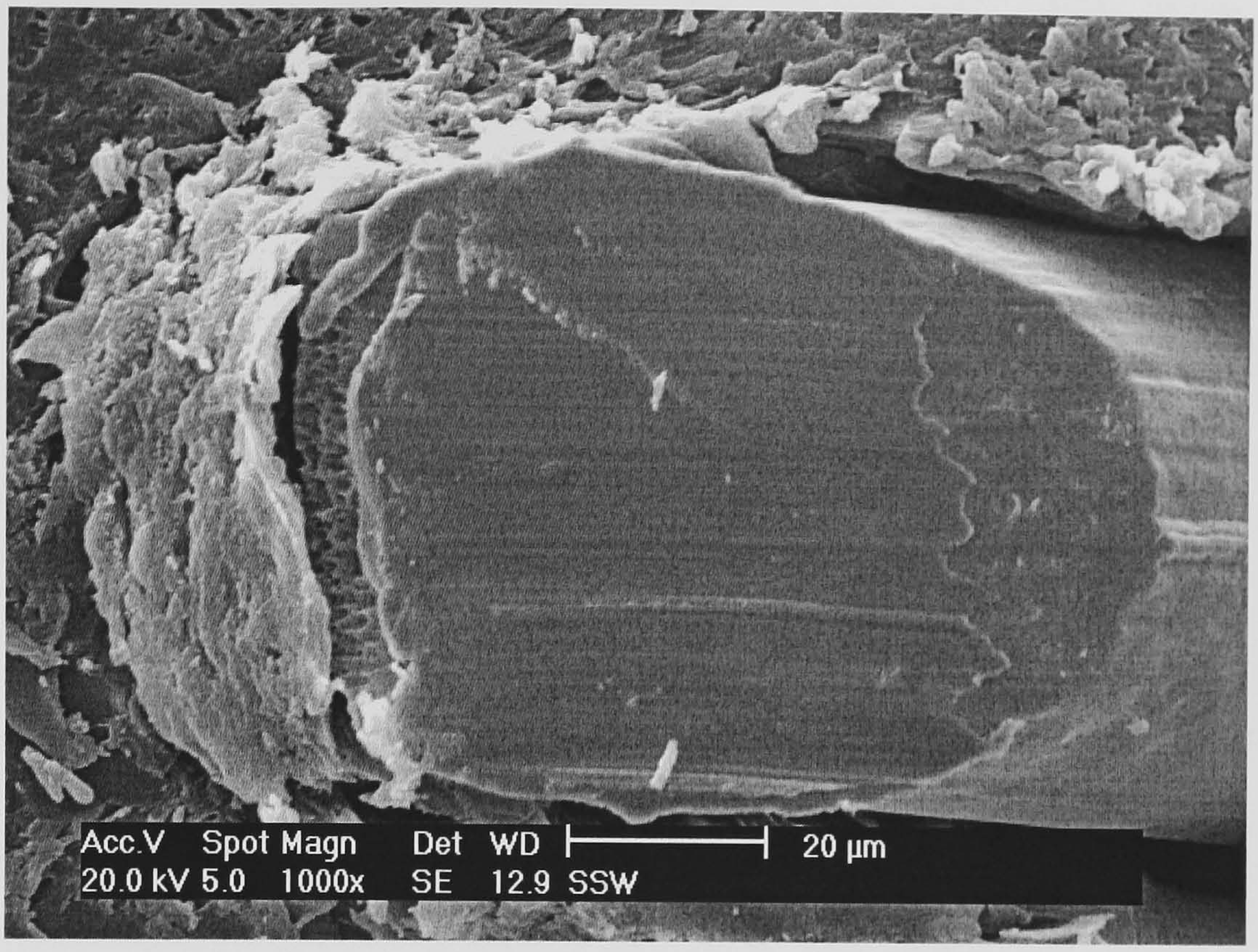
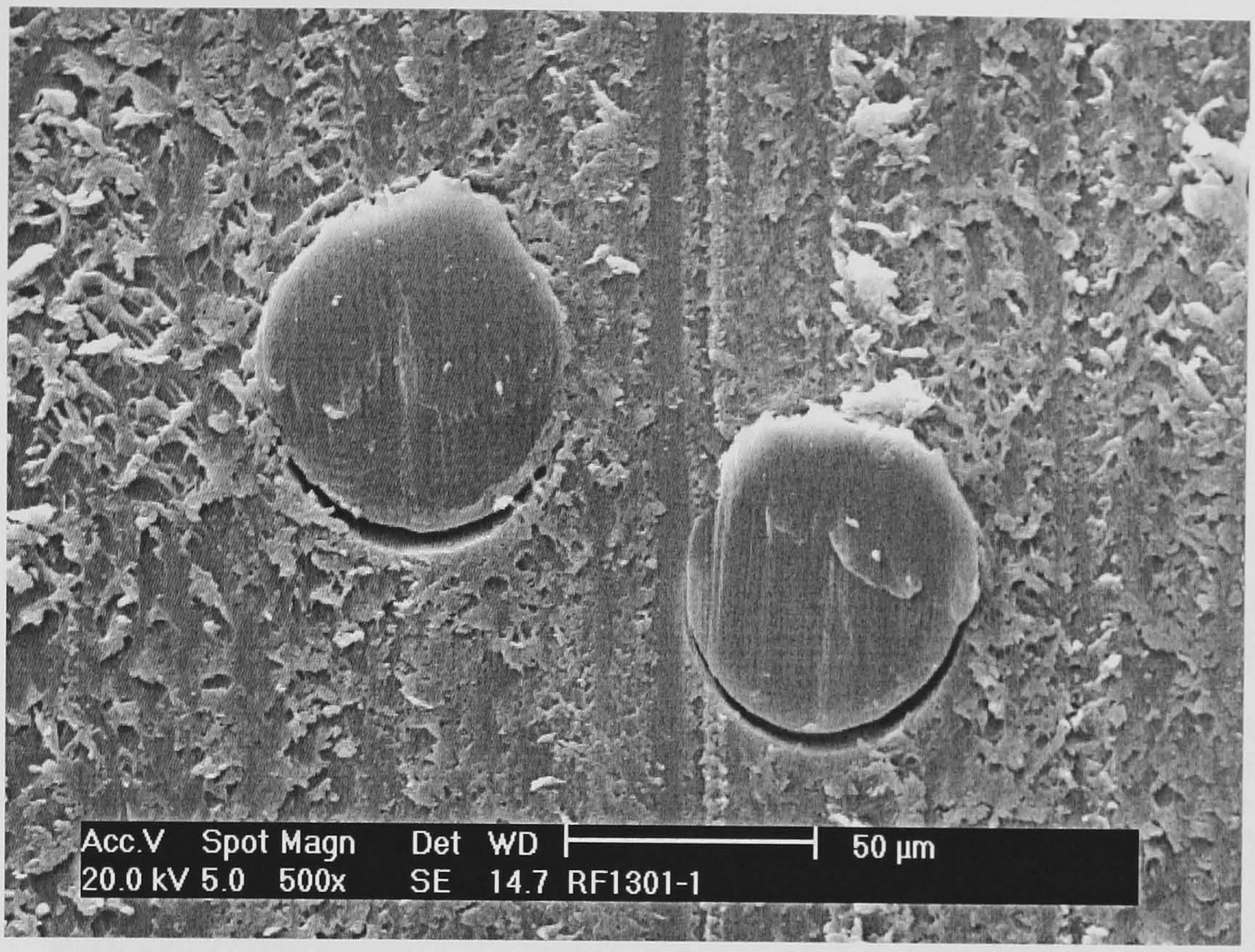


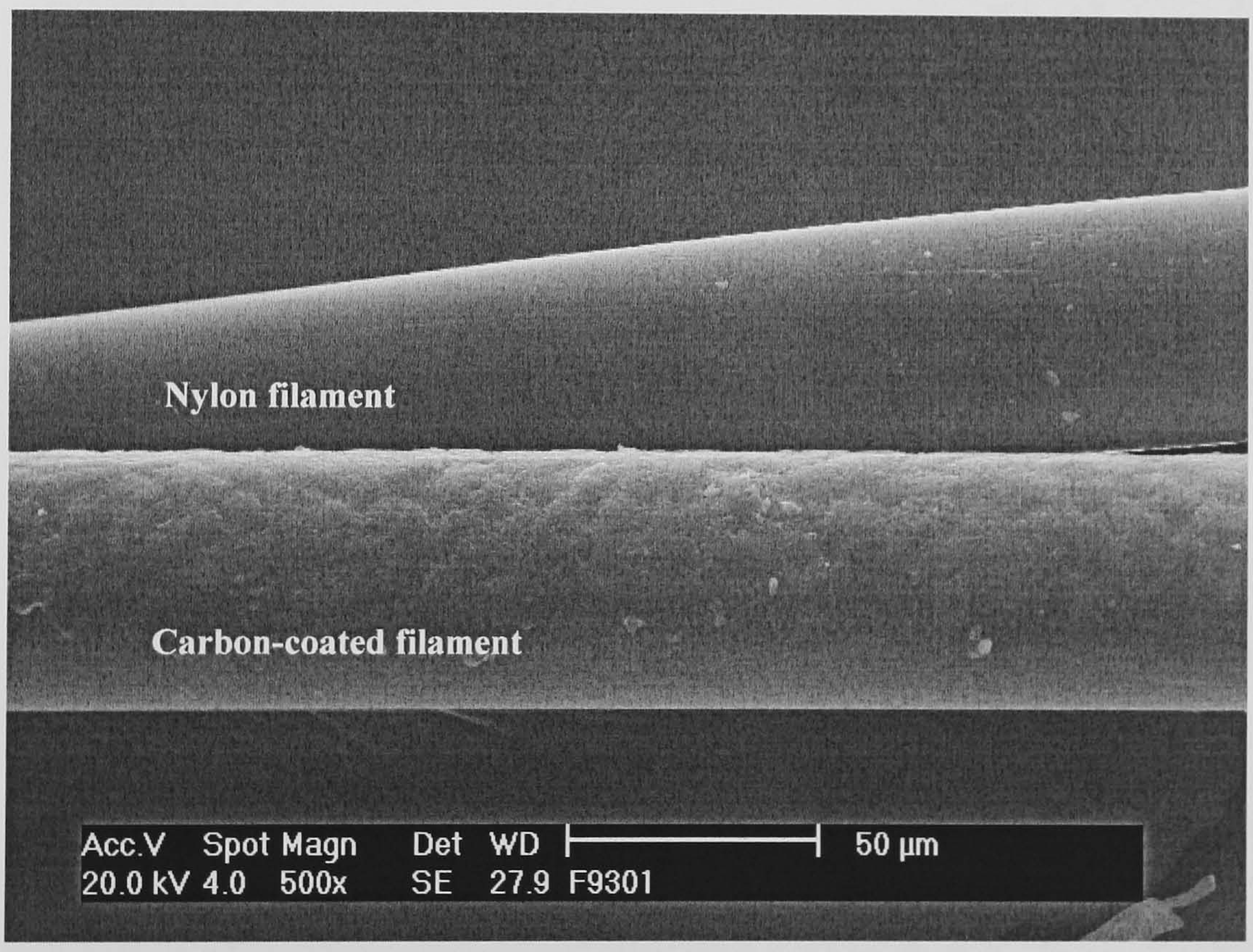
Figure 5.4 Stainless Steel Wire Cross Section

5.1.1.2 Carbon yarns

The Resistat F9301 yarn morphology is shown in Figure 5.5 with the fibre cross section image (I) showing the spacing between and the shape of each continuous filament. From this image, it is difficult to differentiate between the plain nylon and the carbon-coated nylon filament. At this point along the length of the yarn, the two filaments are approximately 32µm apart, however as this yarn is twisted they may at any other point along the yarn be closer or further apart than this. In the filament surface image (II) the differences can clearly be seen whereby the carbon-coated filament has an uneven surface texture compared to the smooth texture of the uncoated nylon.



I)

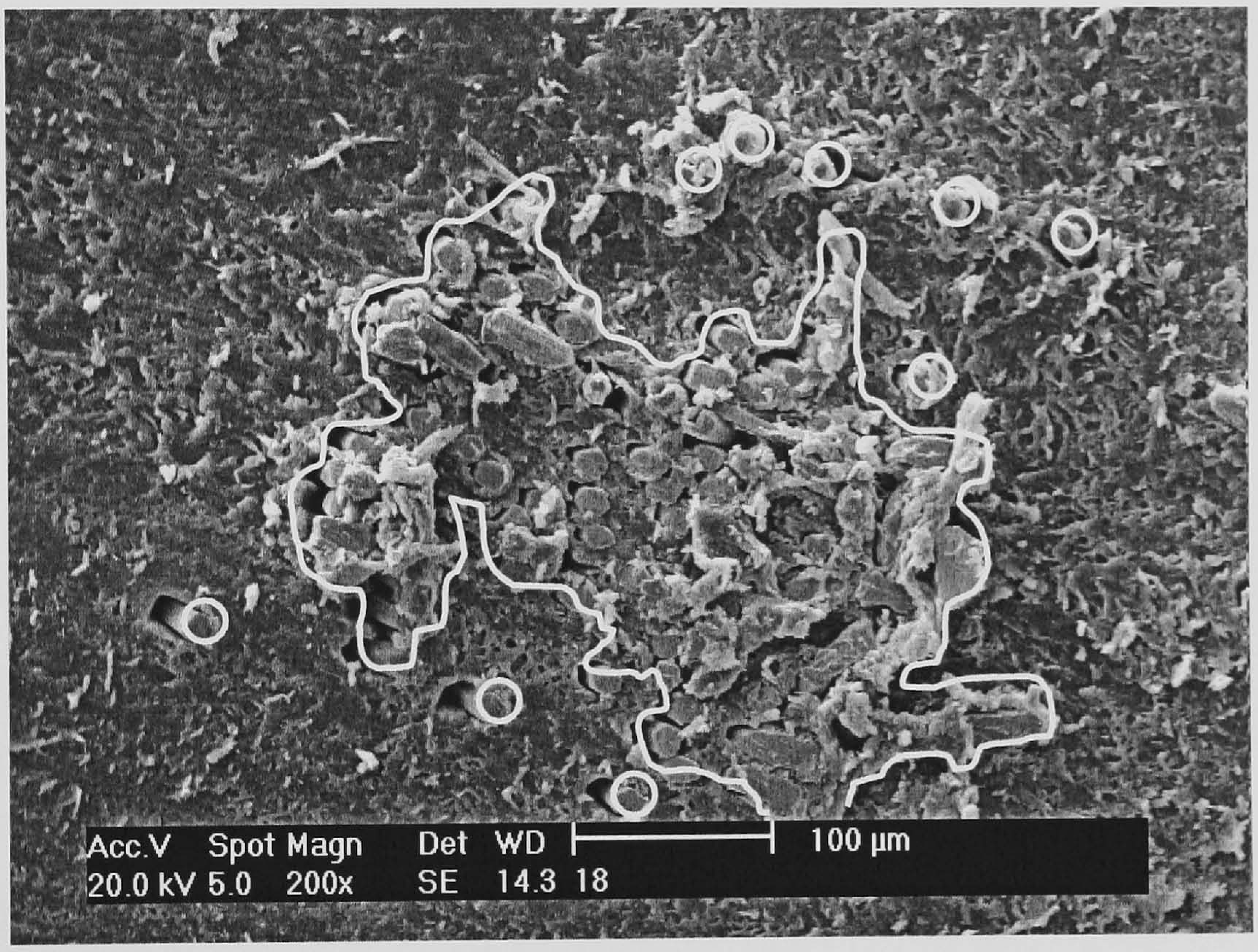


II)

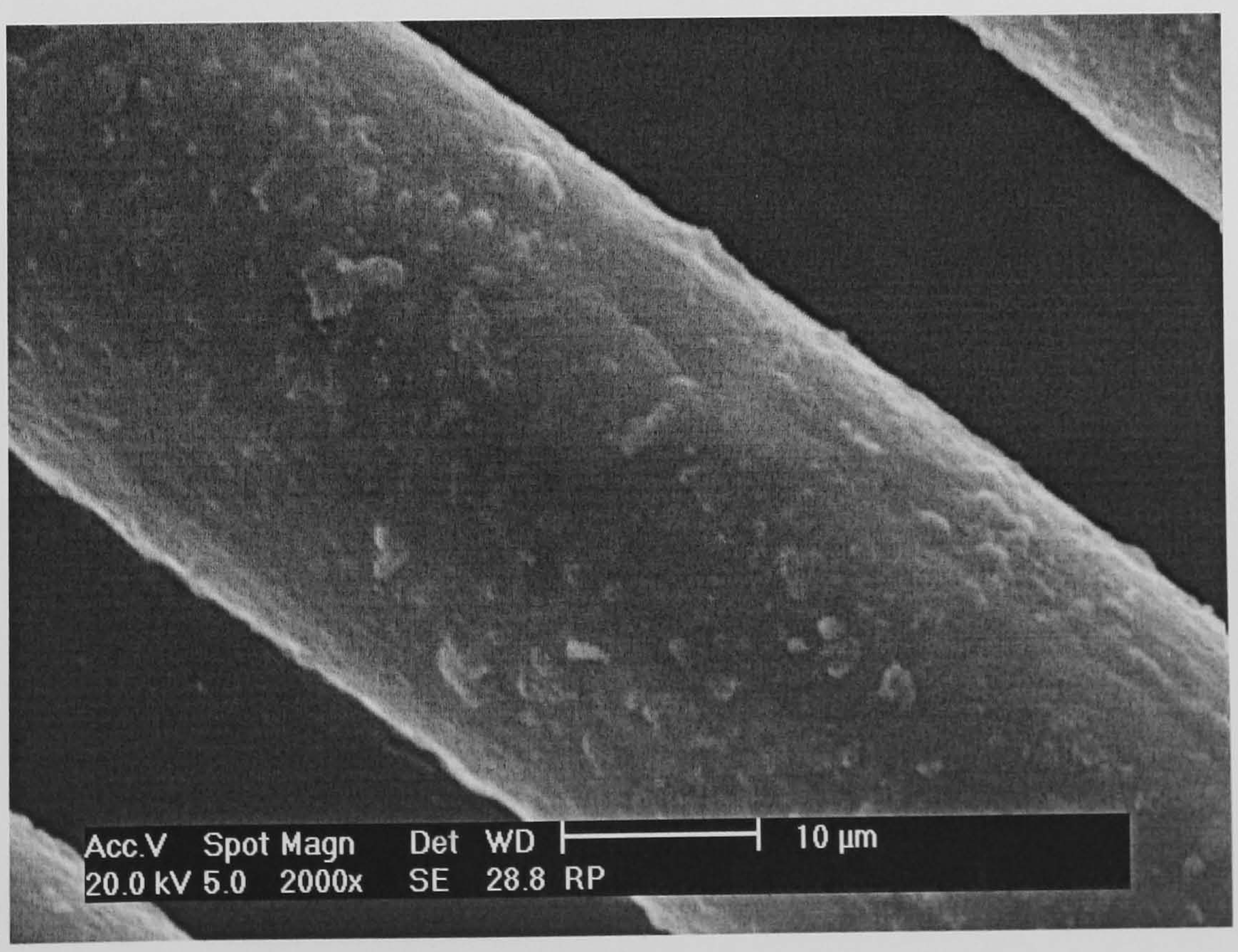
Figure 5.5 Resistat F9301 Yarn Cross Section (I) and Surface Structure (II)

5.1.1.3 Metal-Salt Yarn

Figure 5.6 shows yarn morphology of the twisted continuous filament R.Stat/P yarn, with the cross-sectional image (I) detailing the spatial distribution of the filaments. Due to some pull-out of the filaments during the microtoming process of the resinated yarn, it is difficult to see the exact distribution of the individual filaments, however the general shape of the main body of the yarn and any satellite filaments can be seen. As such, it is apparent that the yarn cross-section is very uneven, however less than 0.5% of the 200 filaments are floating outside the periphery of the yarn. The copper sulphide coating on the polyester filaments can be seen on the fibre surface structure image (II) as an uneven texture.



I)



II)

Figure 5.6 R.Stat/P Yarn Cross Section (I) and Surface Structure (II)

5.1.2 Yarn Diameter

The diameter of each yarn was measured using a Vision Engineering Micro Dynascope and Quadra Chek 200, with 20 measurements taken and averaged from along 1m length of yarn. This was done both in a pre-strained and post-strained state (yarns taken to 75% of their breaking load) in order to calculate the Poisson's ratio of each yarn. It was not possible to separate the individual filaments of the R.Stat/S or Bekitex 50/1 yarns sufficiently to measure them accurately. Due to the crimped nature of the R.Stat/P yarn it would not lie flat, thus a 10g weight was used to tension the yarn for all measurements. The standard deviation of each diameter measurement was calculated to give information on the evenness of the yarn along the length.

5.1.3 Initial Modulus

The value of the Initial Modulus is important as it is a measure of the yarn's resistance to extension under low forces. It is graphically represented by the slope of the curve after the removal of crimp [122] and can be measured as the specific stress at a given strain value, or the specific stress at 100% extension extrapolated from the tangent to the initial curve [139] as illustrated in Figure 5.7.

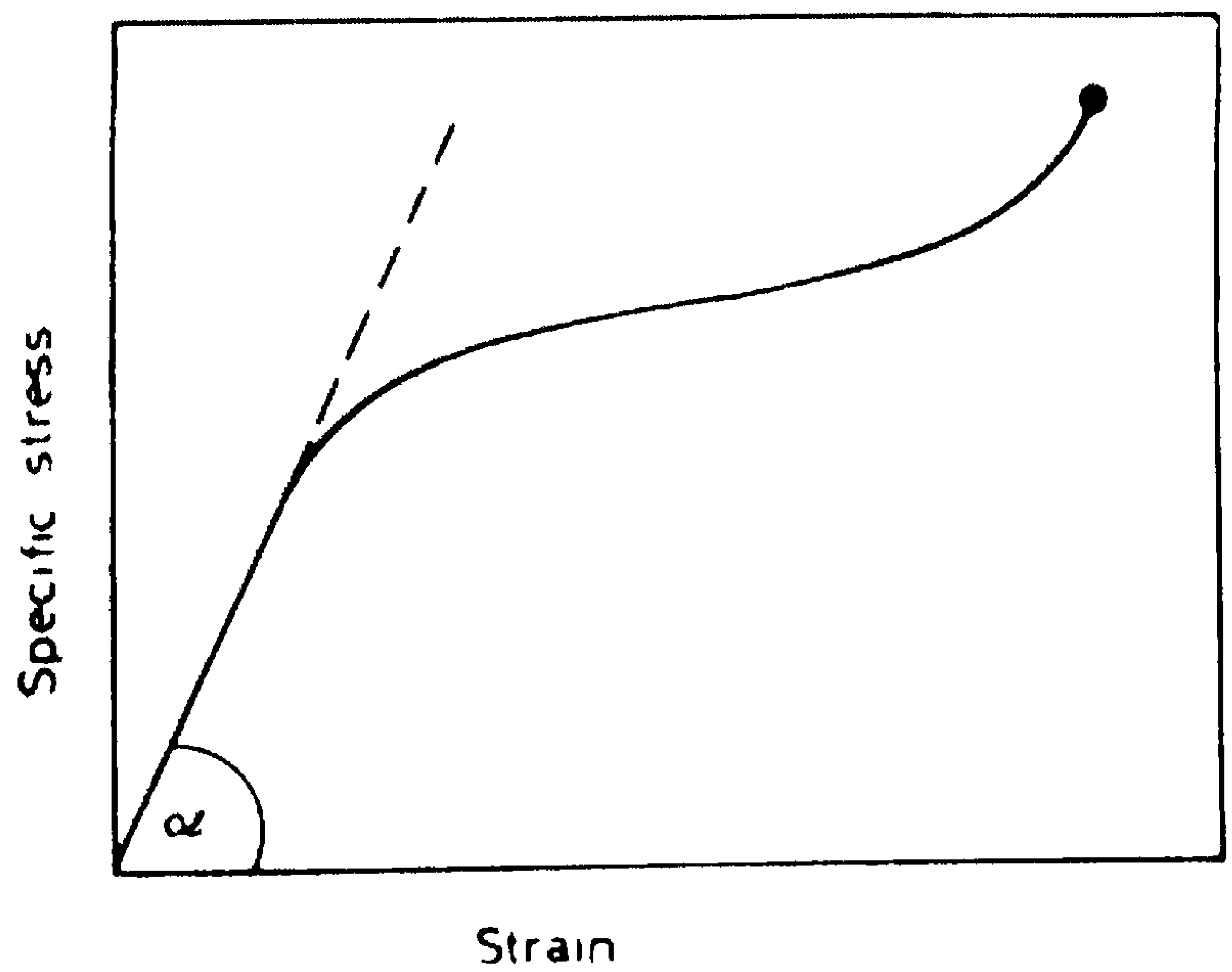


Figure 5.7 Initial Modulus of Stress-Strain Curve

5.1.4 Yield Point

The Yield Point indicates the end of the elastic region of each yarn and can be ascertained using either Coplan's construction theory or Curve Regression. According to Coplan's construction the yield point is "at the stress given by the intersection of the tangent at the origin with the tangent having the least slope" [122] as shown in Figure 5.8.

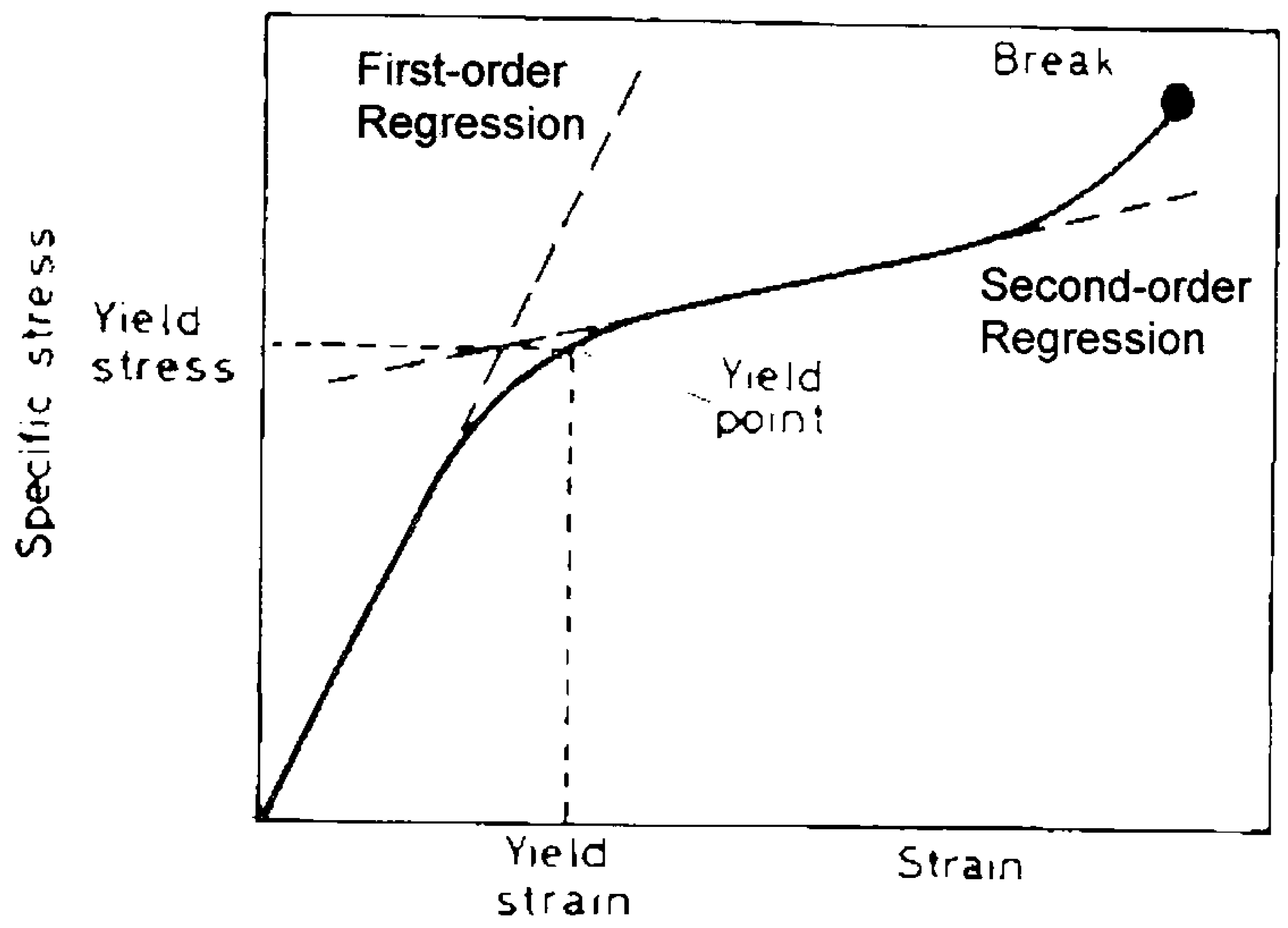


Figure 5.8 Determination of the Yield Point using Coplan's Construction [122]

The slope of the curves used to determine the intersection point can be calculated using first and second order regression equations, with the first order equation determining the linear portion of the curve of the tangent at the origin, and the second order equation determining the tangent of the curve having the least slope. In order to determine whether to use a first or second order regression equation for the portion of the curve with the least slope, both a first and second order regression curve is fitted to this portion and the curve which produces a Regression (R^2) value closest to 1 is used. Equations 5.4 and 5.5 show the first and second order regression equations where x and y are the coordinates of the points that satisfy the function, m is the gradient of the line and c is the y-axis intercept.

First Order Regression $y = mx + c$ -------------------- (5.4) [122]

Second Order Regression $y = m_1x^2 + m_2x + c$ --------------------- (5.5) [122]

The Yield Point is also important in assessing the elastic recovery of the material. which is normally good up to the yield point, and it also indicates the point at which permanent deformation of the material takes place.

5.2 Physical and Mechanical Property Test Results

5.2.1 Yarn Diameter and Poisson's Ratio

The pre-strain and post-strain yarn diameter results indicate that, as expected, most of the filaments and yarns exhibit a decrease in diameter after straining, as shown in Table 5.1. The mean Standard Deviation (SD) of the filament/yarn diameters measured was calculated and this figure indicates the eveness of the yarn along its length and, as such, the uneven nature of the plied R.Stat/S staple yarn is highlighted as is the uneven nature of the loosely twisted and crimped R.Stat/P yarn, even though the diameter of the individual filaments is fairly uniform along their length.

Table 5.1 Conductive Yarn Diameter measurements and Poisson's Ratio

Material	Single filament Poisson's ratio	Mean filament diameter SD	Whole yarn Poisson's ratio	Mean yarn diameter SD
Bekinox VN	6.410	0.002	74.494	0.475
BK 50/1	-	-	0.329	0.033
Resistat F9301	0.380	0.002	2.495	0.030
R.Stat/P	0.601	0.002	0.684	0.064
R.Stat/S	-	-	2.302	0.135
Stainless Steel Wire	-	-	0.974	0.002

The exceptional results is from the Bekinox VN yarn which increased in diameter after straining - it was observed that during straining the filaments consolidated, however once the tension was released they spread apart again as the consolidated form could not be maintained and the Poisson's ratio results confirm this phenomenon.

5.2.2 Initial Modulus and Yield Point

The Initial Modulus values, shown in Table 5.2, highlight the complexity in determining the effect of yarn composition and morphology on the mechanical properties. For example, the 100% Stainless Steel multifilament Bekinox VN yarn and the staple R.Stat/S yarns exhibit the greatest resistance to extension under low forces. Conversely, the 100% Stainless Steel Wire monofilament and the 20/80 Stainless Steel/Polyester Bekitex 50/1 yarns are the most extensible under small loads. In the middle ground lie the multifilament continuous coated nylon and polyester yarns (Resistat F9301 and R.Stat/P) exhibiting very similar Initial Modulus results. The end-use of the strain sensor would determine whether a relatively elastic or inelastic yarn under low forces would be required.

The Yield Point values, also shown in Table 5.2, show that all of the 100% Stainless Steel Wire yarns (Bekinox VN, R.Stat/S and the Stainless Steel Wire) reach their Yield Point at very low strain levels (<0.01). The staple Bekitex 50/1 yarn extends a little further before the yarn yields, but the continuous multifilament coated polymer yarns (Resistat F9301 and R.Stat/P) are those which extend the most before the Yield Point is attained. Although some of the Specific Stress Yield Points are high (Bekinox VN, R.Stat/P), it is important to analyse the stress-strain curve to determine whether or not these figures translate into useable yarns.

Table 5.2 Initial Modulus and Yield Point

Material	Initial Modulus (mN/tex)	Yield Point	
		Specific Stress (mN/tex)	Strain
Bekinox VN	18.13	117.182	0.004
BK 50/1	2.21	88.820	0.019
Resistat F9301	7.68	410.017	0.050
R.Stat/P	5.81	109.915	0.032
R.Stat/S	11.97	32.33	0.004
Stainless Steel Wire	0.19	77.24	0.009

Thus as can be seen in Figure 5.9, the Bekinox VN (and the R.Stat/S yarn which has a similar graph, see Appendix 1) shows only three graph points prioer to yarn break, meaning that this yarn is unsuitable for use in an application requiring a high degree of elasticity. As such, the Yield Point of both these yarns was calculated using First order regression equations only and, in fact, it could be argued that the Yield Point is not even reached before the yarn breaks once the standard error bars are taken into consideration.

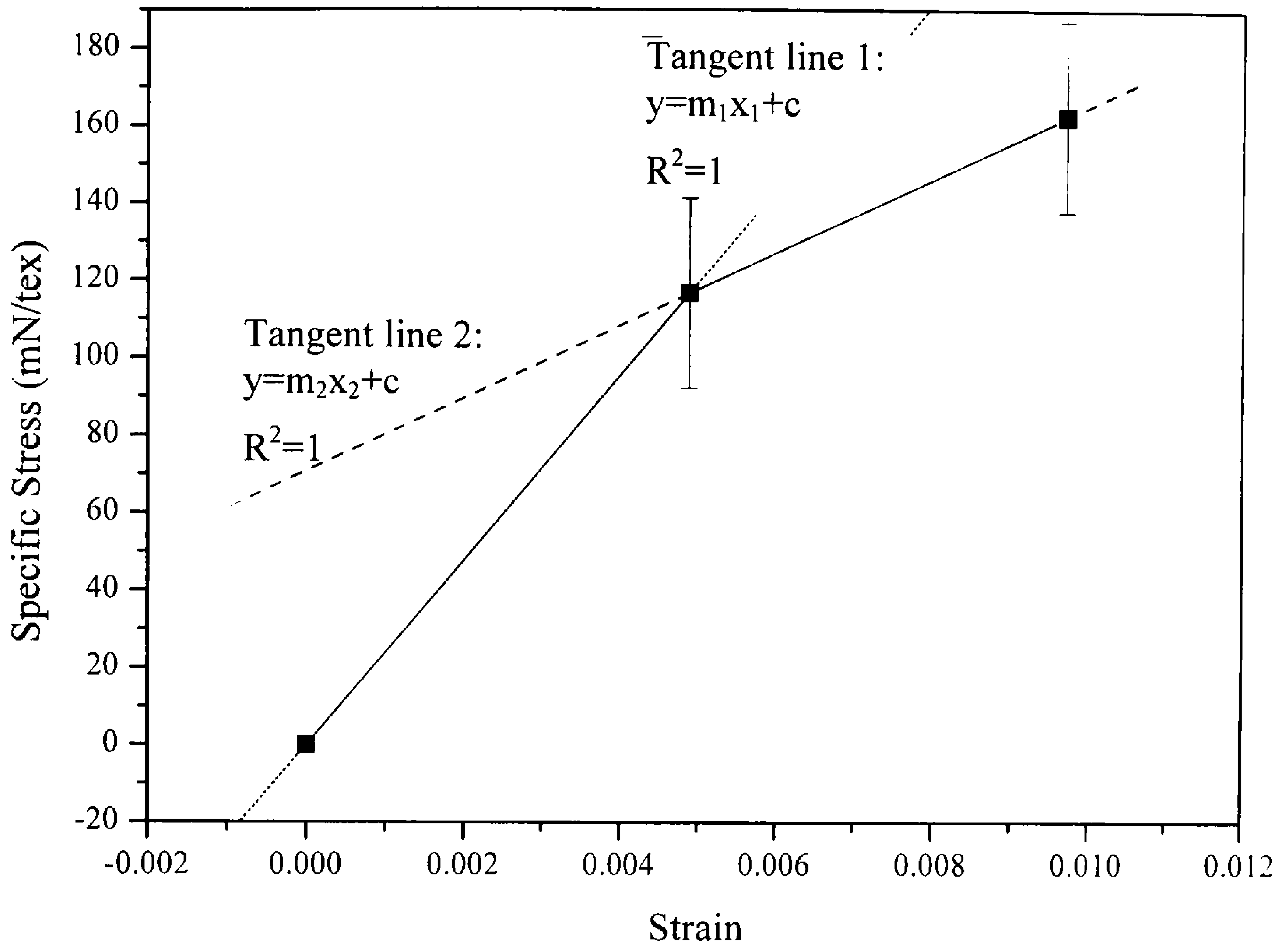


Figure 5.9 Bekinox VN Specific Stress Yield Point

First order regression equations of each tangent line and Standard Error of each strain point indicated.

Although the Bekitex 50/1 and Stainless Steel Wire yarns have a greater number of points on their curves (see Appendix 1), their low Yield Point strains may exclude them from consideration as an elastic strain sensor. The polymer-based coated yarns, Resistat F9301 (Appendix 1) and the R.Stat/P yarn, as illustrated in Figure 5.10, exhibit a more usable level of elasticity before their yield point is reached.

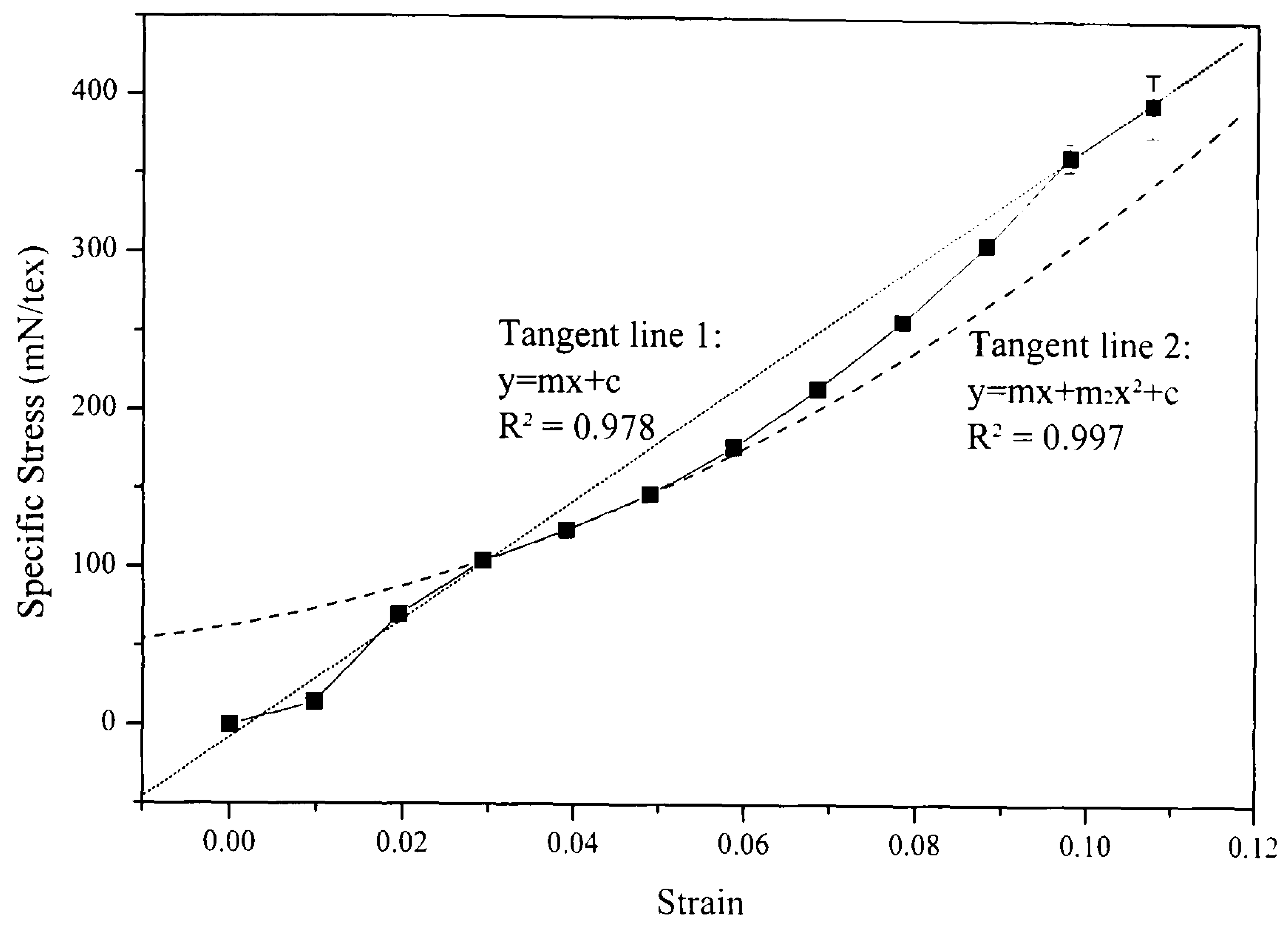


Figure 5.10 R.Stat/P Specific Stress Yield Point

First order regression equation of tangent line 1 and second order regression equation of tangent line 2 and Standard Error of each strain point indicated.

5.3 Electrical Property Test Methodologies

5.3.1 Change in Resistance with Yarn Relaxation

The test set-up was the same as for the Linear Resistivity tests; the yarns were clamped between the jaws of the Instron and connected to the bench multimeter. The yarns were taken to their pretension level then extended to 2% and 5% of the gauge length. That level of strain was then held for 1000 seconds whilst the rate of change of the resistance was logged whilst the relaxation of yarn stress was measured. All tests were carried out under test conditions of 20°C ± 1°C and 65% RH ± 2% and two samples were tested of each yarn type.

5.3.2 Dynamic Resistance-Strain Testing

The yarns were connected to the Instron via the clamps and strained at a rate of 200mm/min using the relevant load cell. The yarns were strained to break with the resistance change being logged at a log time interval of 3 seconds between each reading. All tests were carried out under test conditions of 20°C ± 2°C and 65% RH ± 4% [139] and ten samples were taken of each yarn. A matrix of the test conditions is shown in Table 5.3, including the individual yarn pretension levels as calculated at 0.5cN/tex (refer to section 4.2.4.2).

Table 5.3 Conductive Yarn Dynamic Resistance-Strain Test Matrix

Material	Gauge length	Pretension	Load cell (kg)	Stepwise Strain interval
Bekinox VN	20cm	56.1g	500	5mm
BK 50/1	5cm	10.2g	2	1mm
Resistat F9301	20cm	2.35g	2	1mm
R.Stat/P	20cm	340g	500	2mm
R.Stat/S	20cm	92.8g	500	5mm
Stainless Steel Wire	20cm	11.57g	2	5mm

5.3.2.1 Gauge Factor

The objective of these mechanical-electrical tests is to identify a usable linear region of the resistance-strain curve where the change in resistance reacts linearly to the change in strain. The gauge factor (GF) indicates the sensitivity of the sensor yarn by expressing the ratio of fractional resistance change to the fractional length change. It is calculated using Equation 5.6 where ΔR is the change in resistance, R_o is the original resistance value and ε is the strain. The ± indicates that for certain yarns the result is positive, whereby the resistance increases with strain, and for others it is negative, whereby the resistance decreases as the strain increases.

$$GF = \pm \frac{\Delta R}{\varepsilon R_O} \qquad \text{------------------ (5.6) [113]}$$

The strain and resistance values used in the calculation are determined using the linear portion of each curve as judged by eye, and for certain yarns it can be observed that there are several linear portions to each curve, thus a number of gauge factor values can be calculated.

5.3.3 Stepwise Resistance-Strain Testing

Each yarn was connected to the Instron via the clamps and strained at a rate of 200mm/min using the relevant load cell. Each yarn was stretched at different strain intervals depending on the stretch capability of the yarn and then left for 60 seconds before being strained again. The change in resistance was simultaneously logged at a log time interval of 3 seconds between each reading. This was continued up to the yarn break point. All of the tests were carried out at 18°C and 38% RH.

5.4 Electrical Property Test Results

5.4.1 Change in Resistance with Yarn Relaxation

The relationship between the change in resistance on relaxation of the yarn stress over time was measured at 2% and 5% extension for each yarn. For most of the yarns, the initial decrease in stress after the extension is applied is greater at 5% extension than it is at 2% extension. Morton & Hearle expounded the theory using acetate yarn as an example, deducing that;

> "A rapid extension beyond the yield point, with a large energy loss, causes a rise in temperature of the order of 11°C for a 20% extension. It takes several seconds for the excess heat to be lost from the specimen, so that the initial part of the relaxation curve could be considerably affected." [122]

Contrary to the theory however, is the performance of the Resistat F9301 yarn as shown in Figure 5.11, whereby there is a 43.2% initial decrease in the specific stress at 2% extension compared to a 28.7% decrease at 5% extension. In addition, contrary to the behaviour exhibited by the five other yarns tested in this manner, the variation in resistance over time is different as, at 2% extension the resistance increases and peaks at 300 seconds then decreases, eventually returning to the value measured after the initial extension, and at 5% extension the resistance continues to increase over the time period.

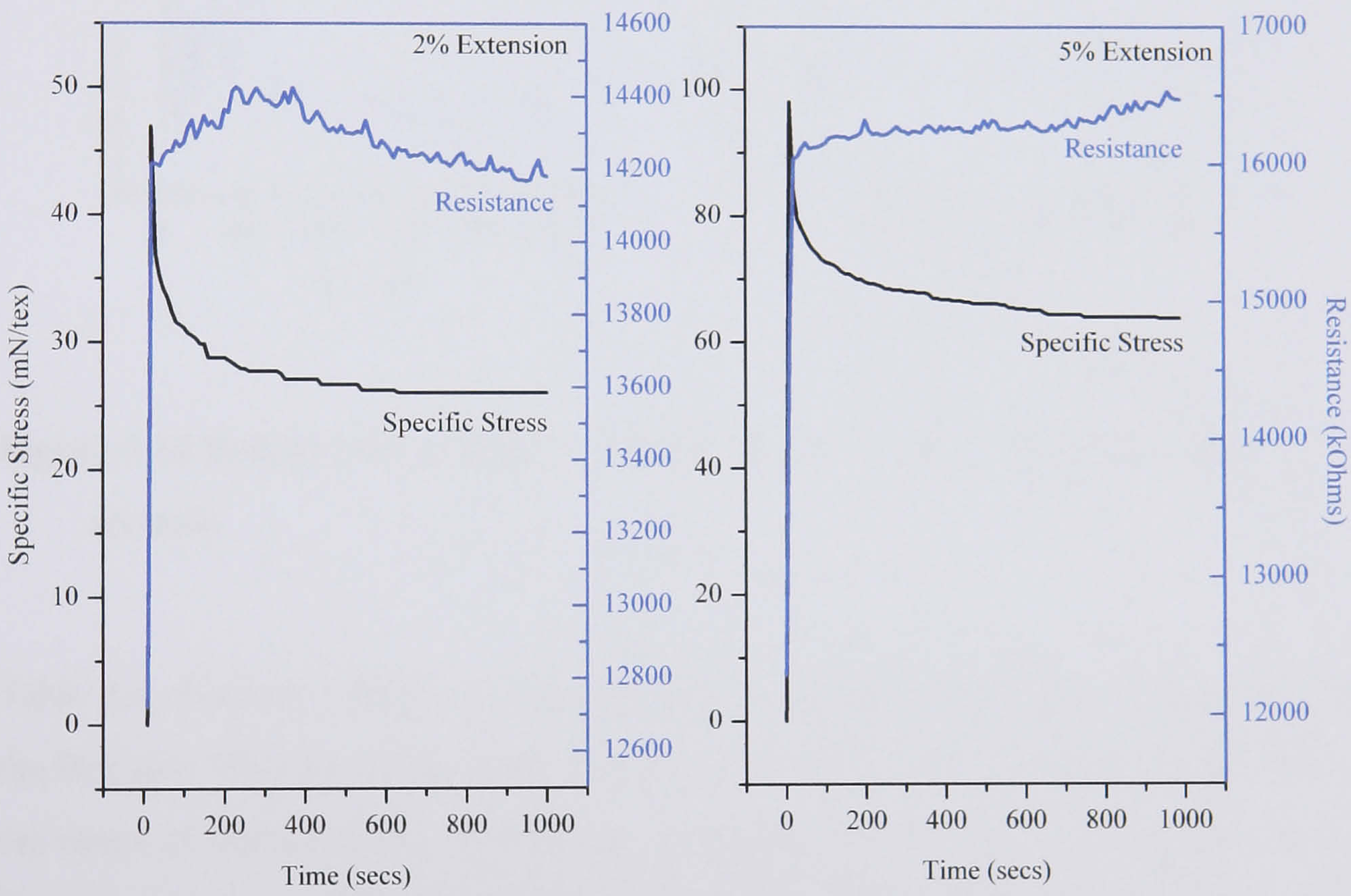


Figure 5.11 Resistat F9301 Change in Specific Stress and Resistance with Yarn Relaxation

For each graph, the y-axis scales are maximised so that the change in results can be clearly seen.

For the other yarns tested, as the yarn relaxed over time the resistance decreased thus making the yarns more conductive. The results for the Bekitex 50/1 yarn is shown in Figure 5.11 (the graphs for the staple R.Stat/S, and multifilament Bekinox VN and R.Stat/P yarns are in Appendix 2).

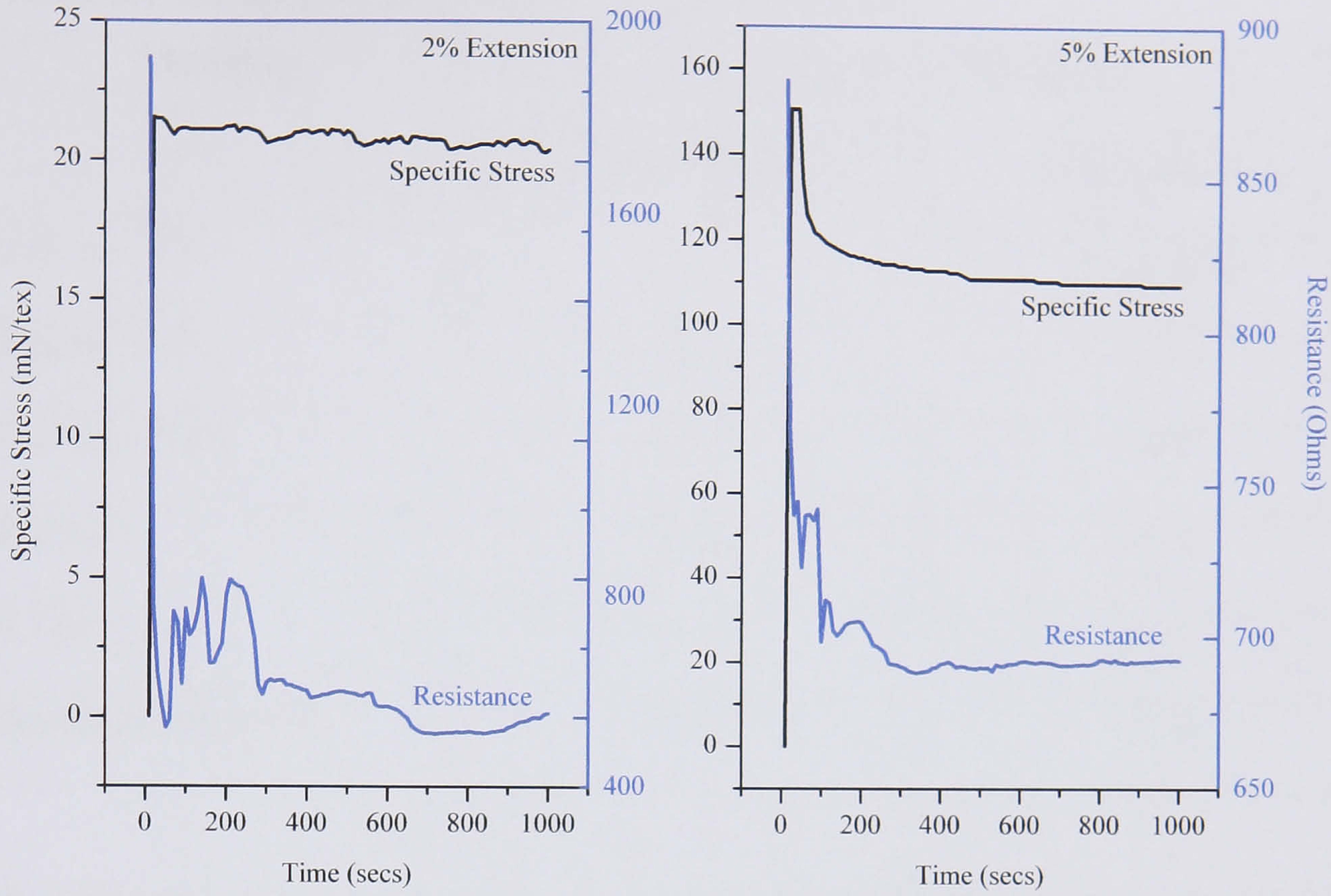


Figure 5.12 Bekitex 50/1 Change in Specific Stress and Resistance over 1000 seconds

Table 5.4 shows the degree of change in the resistance of the yarns, indicating that the Bekinox VN yarn changes are so small as to render them insignificant and within the range of normal usage variation, similarly the R.Stat/S yarn experiences a small drop in resistance with the R.Stat/P yarn experiencing a slightly larger decrease at both extensions. The decrease in resistance is greatest overall for the Bekitex 50/1 yarn, however the variation in resistance over time varies so much that the performance could not be considered predictable.

Table 5.4 % Change in Resistance with Yarn Relaxation

Material	% Change in Resistance	
	2% Extension	5% Extension
Bekinox VN	3.3	Negligible
Bekitex 50/1	-71.2	-21.5
Resistat F9301	11.4	34.0
R.Stat/P	-29.6	-35.5
R.Stat/S	-14.4	-3.0
Stainless Steel Wire	1.40	10.13

The difference between the behaviour of the Resistat F9301 yarn compared to the other yarns, in both the change in specific stress and the change in resistance, must be attributed to a combination of the yarn morphology and the yarn composition, as there is no clear division between the performance of one type of yarn morphology or composition between the other yarns. In terms of the Resistat F9301 yarn change in specific stress behaviour, this can be attributed to the fact that contrary to Morton & Hearle's theory, the yield point of the yarn is not exceeded at either 2% or 5% extension, whereas it is for the other yarns and in some cases by a significant amount.

As for the resistance increase (rather than decrease) on straining, the cross-sectional area of the Resistat F9301 conductive monofilament decreases and the carbon particles in the coating may be pulled further apart, thus reducing the conductive pathways and hence the conductivity of the yarn. In comparison, the coated polyester yarn (R.Stat/P) is multifilament, thus as the yarn is strained the filaments may be pulled closer together, resulting in an increase in the connection between the conductive pathways within the yarn.

5.4.2 Dynamic Resistance-Strain Results

There is a split in the metal-based yarns' behaviour on straining. Two of the metal yarns; Bekitex 50/1 and R.Stat/S, experience a decrease in resistance on straining whereas the Bekinox VN and Stainless Steel Wire yarns display an increase. This difference in behaviour can be attributed to the morphology of the yarns as both the Bekitex 50/1 and R.Stat yarns are staple, and the Bekinox and SSW are continuous filament yarns. Hence, on straining the fibres of the staple yarns are pulled closer together, thus increasing the number of available conductive pathways, and as the cross-sectional area of the continuous filaments decreases on straining (as evidenced by the Poisson's Ratio results), the flow of free electrons enabling conduction becomes limited.

The variability of consistency in the resistance change on strain for the BK50/1 yarn was high (as reflected with the large error bars; the maximum result being 400Ω ±140 which is equivalent to 35%), as illustrated in Figure 5.13. This correlates with the findings of Mihajlidi et al [134] who tested cotton yarns blended with Bekinox fibre and found that the electric resistance varied strongly along the yarn length, due potentially to the insufficiently compact structure of the yarns and hence the lack of stable contacts between the metal fibres. The R.Stat/S results (Appendix 2) exhibit far lower error levels (around 14%), however the inflexibility of the yarn means that there are only three points on each of the graphs which, much like the Bekinox VN yarn, might limit the operational range of a potential strain sensor

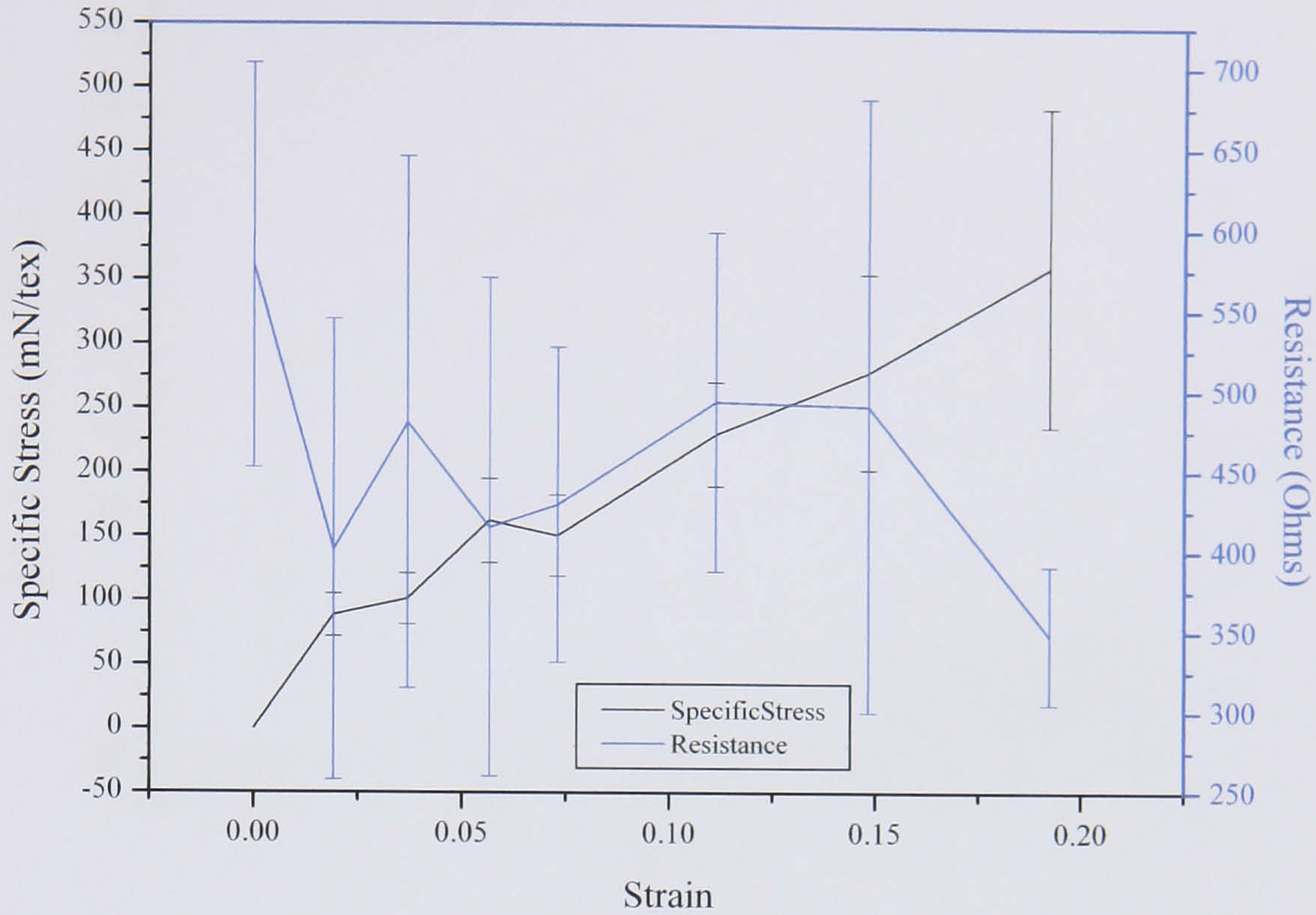


Figure 5.13 Bekitex 50/1 Dynamic Stress and Resistance-Strain Curve

Figure 5.14 shows the change in specific stress and resistance on strain of the Stainless Steel Wire, highlighting the decrease in conductivity with decrease in the filament cross-sectional area; it is important to observe that the marked increase in the specific stress of the Stainless Steel Wire on initial straining does not affect the gradual increase in yarn resistance. The error levels (shown as error bars) for these results are so small as to be considered insignificant demonstrating that, based on the ten tests carried out, the performance of this yarn is highly consistent. It must be noted, however, that for the Bekinox VN yarn (Appendix 2) the resistance only increases by 0.3Ω which is considered within the normal tolerance of the yarn. This may be due to the combination of a decrease in conductivity due to the filament cross-section decrease together with a corresponding pulling together of the filaments resulting in an increase in conductivity. Also, due to the inflexibility of the yarn, there are only three points on each of the graphs which would limit the operational range of a potential sensor.

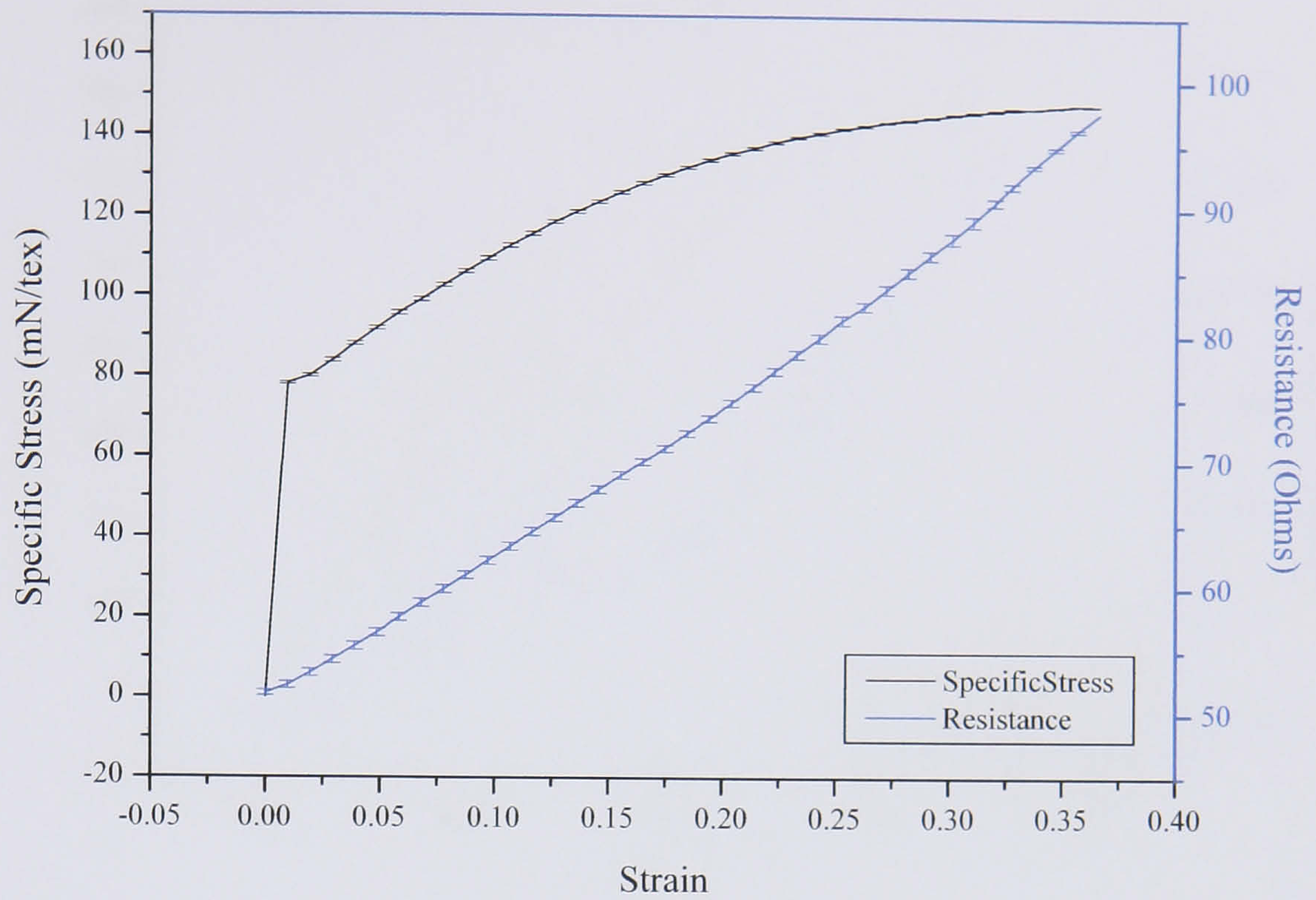


Figure 5.14 Stainless Steel Wire Dynamic Specific Stress and Resistance-Strain Curve

As with the continuous filament metal yarns, the copper sulphide covered R.Stat/P yarn and the carbon-based Resistat F9301 exhibit an increase in resistance on straining, and these results are illustrated in Figure 5.15. The pattern of increase in resistance for the Resistat F9301 yarn almost exactly mirrors the pattern of increase in specific stress on straining and, from the ten samples tested, the maximum resistance variation about the mean is low at ±2967Ω (10%) indicating that these results are repeatable. This increase in resistance is most likely due to the conductive particles in the respective yarn coating being pulled further apart on straining, along with a decrease in the filaments' cross-section.

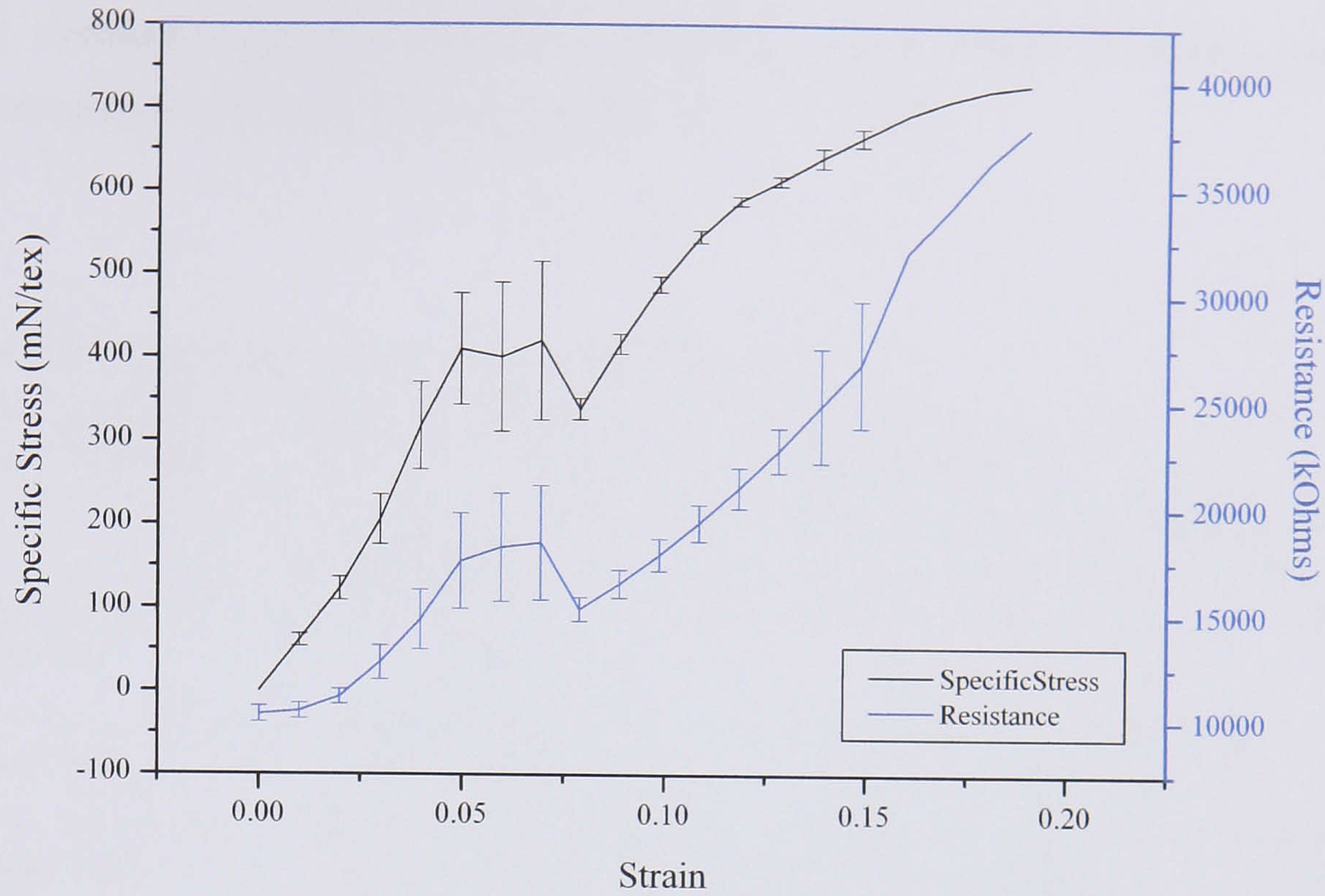


Figure 5.15 Resistat F9301 Dynamic Specific Stress and Resistance-Strain Curve

For the R.Stat/P yarn (Appendix 2) the variation of the results about the mean for the specific stress is minimal, peaking at 5%, whilst the variation about the mean for the resistance is greater, ranging from 30-60% (after the initial strain region), indicating that these measurements are not reproducible due to the irregularly crimped/twisted nature of the yarn.

5.4.2.1 Gauge Factor

The gauge factors (strain sensitivity) of the conductive yarns can be seen Table 5.5 whereby a negative result indicates that the resistance increases as the strain increases, and a positive result indicates that the resistance decreases as the strain increases. Whilst a gauge factor for the overall decrease in resistance with strain has been calculated for the Bekitex 50/1 yarn, it is important to bear in mind that the resistance-strain curve fluctuates between increasing and decreasing resistance, thus this result is not indicative of the real-time behaviour of the yarn. The Bekinox VN gauge factor is negative and low, indicating that the yarn is not very sensitive to strain as there is only an increase 0.25Ω when the yarn is extended by 1% which could eventually provide measuring difficulties when integrated into a sensor product attached or integrated into a technical textile fabric.

Table 5.5 Conductive Yarn Resistance Gauge Factor

Material	Gauge Factor(s)			
	1	2	3	4
Bekitex 50/1	0.00377	-	-	-
Bekinox VN	-0.14886	-	-	-
Resistat F9301	-0.00109	-0.00033	-0.00003	-
R.Stat/P	-561.323	-2.25722	-0.00004	-2.10444
R.Stat/S	2.52948	-	-	-
Stainless Steel Wire	-0.0472	-	-	-

The three different gauge factors calculated for the Resistat F9301 yarn were calculated from the points on the curve as shown in Figure 5.16. Although the gauge factor values are low, which would indicate that the yarn is not very sensitive to strain, the actual difference in resistance measured per curve section are of the order of 8kΩ (1), 11kΩ (2) and 5kΩ (3), indicating that it is in fact sensitive to strain. Thus, as this curve shows marked areas of differing yarn behaviour it is important to decide which one is most suitable depending on the performance required or the application and this is determined by the elastic behaviour of the yarn at each stage.

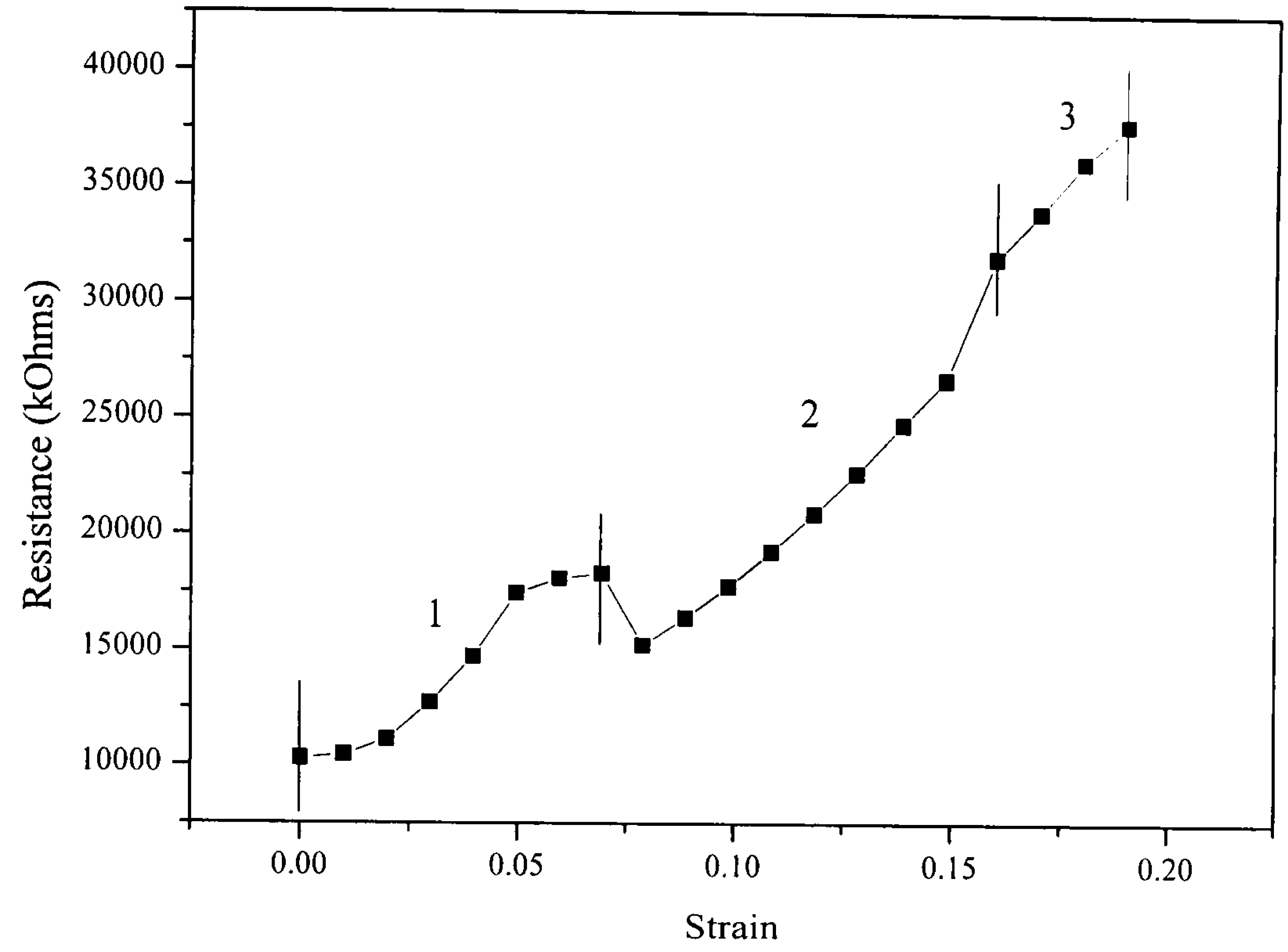


Figure 5.16 Resistat F9301 Resistance-Strain Curve

Linear portions of curve used for gauge factor calculations indicated (1-3).

The R.Stat/P yarn showed a large degree of variation in gauge factor along the length of yarn, most likely due to the effect of crimp removal on straining. This variability of behaviour would make it difficult to predict the behaviour of the yarn under stress-strain conditions unless there was a method of ensuring that the starting condition (tension, twist level, crimp level etc) was the same for every smart structure made and every test carried out. R.Stat/S exhibited th gauge factor closest to that of a typical metallic strain gauge which is normally around two, although as with the Bekitex 50/1 yarn, the result is positive as the resistance decreases as the strain increases, and the overall change in resistance at 1% strain is only 15Ω. The Stainless Steel Wire yarn gauge factor is low with the corresponding change in resistance being only 45Ω, thus indicating that in using this yarn there would only be a narrow conductivity window for the resultant sensor to operate.

5.4.3 Stepwise Resistance-Strain Results

These curves give an indication of the effect of viscoelasticity on the yarns' conductive behaviour, that is the effect of time on the change in strain, specific stress and resistance of the yarns. For the staple Bekitex 50/1 yarn, the pattern of resistance change with strain change is inconsistent and only loosely follows that of the rising specific stress of the yarn, as shown in Figure 5.17, rendering it almost impossible to derive any meaningful information from the graph. Also, the degree of yarn relaxation with each 'step' becomes greater as the stress increases, due perhaps to the yield point being exceeded. Alternately, with the Bekinox VN yarn (Appendix 2), the change in resistance mirrored the change in specific stress exactly, with very little variation from the maximum result during the rest period, although due to the stiffness of the yarn only two 'steps' are achieved before the yarn break point is reached.

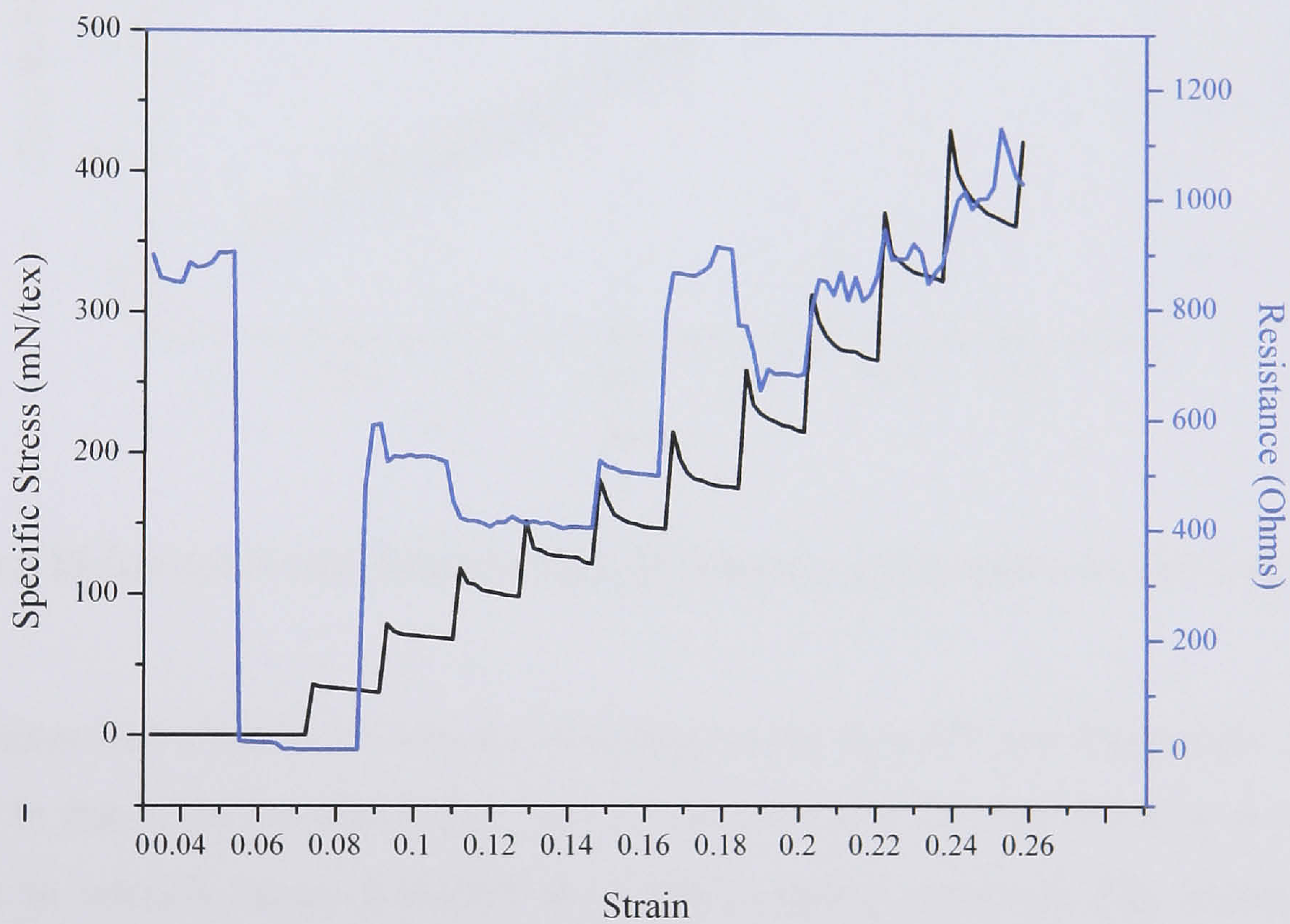


Figure 5.17 Bekinox 50/1 Stepwise Specific Stress and Resistance-Strain Curve

For the Resistat F9301, Bekinox VN, R.Stat/P and Stainless Steel Wire yarns, again the increase in specific stress is accompanied by an increase in resistance, however there are slight differences in the resistance variation during the rest periods. The Resistat F9301 results are fairly consistent in terms of the resistance change mirroring the specific stress change, however it can be seen in Figure 5.18 that there is a peak followed by a sharp decrease in specific stress after each increase in strain, however the resistance doesn't show such marked changes after straining and the resistance gently increases as the stress in the yarn relaxes and this effect is more pronounced the more the yarn is strained. This behaviour mirrors that of the resistance and specific stress change during yarn relaxation when extended (see 5.4.1)

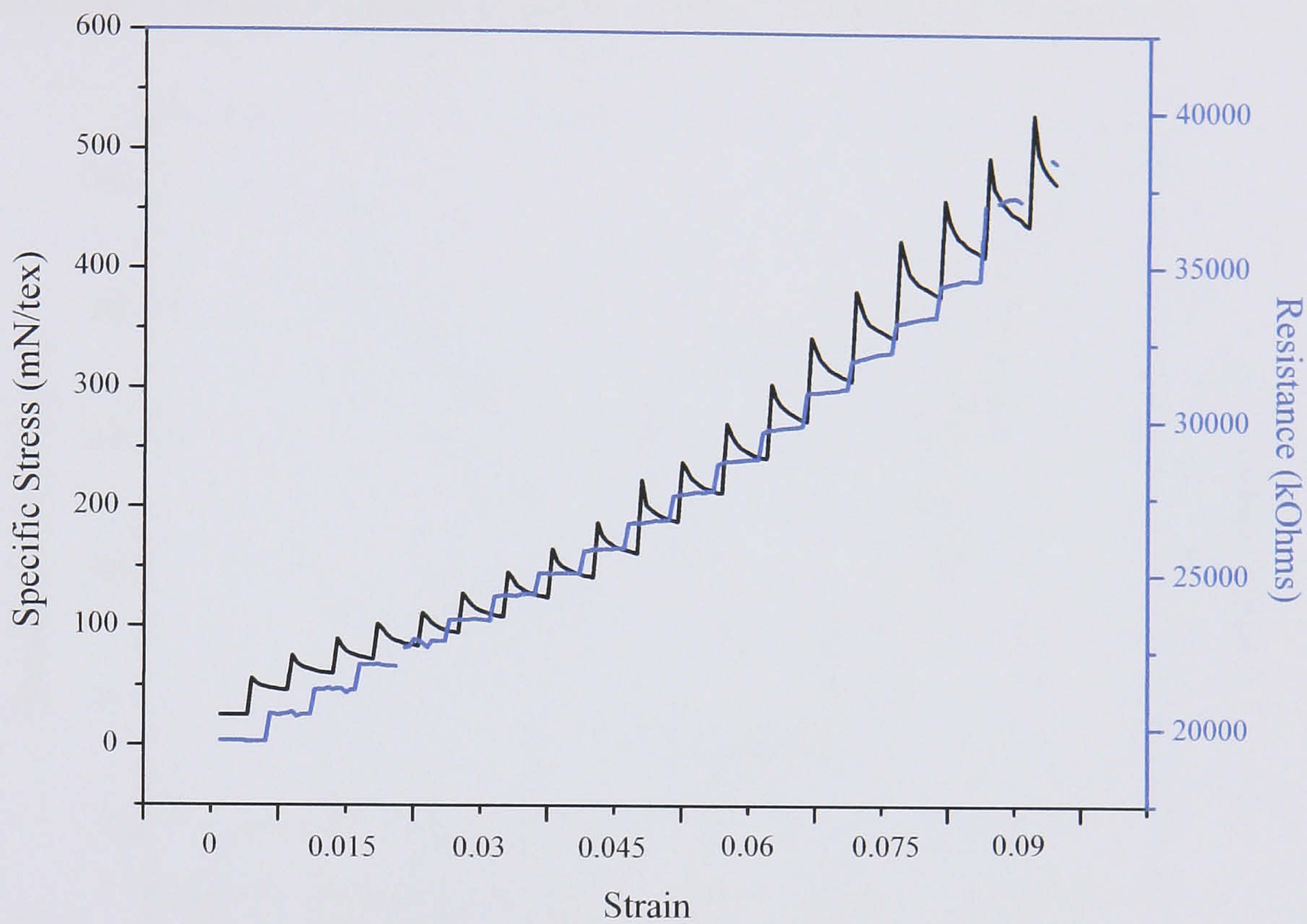


Figure 5.18 Resistat F9301 Stepwise Specific Stress and Resistance-Strain Curve

The change in resistance on stepwise straining for the R.Stat/P yarn (Appendix 2) is similar to that of the Resistat F9301 yarn in that, after each increase in strain, there is a peak in specific stress followed by a sharp decline, however this change in resistance mirrors the specific stress changes more readily and this effect is more apparent the more the yarn is strained, possibly due to all of the crimp being removed from the yarn and the 'real' yarn pretension level being reached. With the Stainless Steel Wire (Appendix 2), although the specific stress increases sharply after the first increase in strain, the increase in resistance is not so marked and, over the course of the test, the rate of change in resistance remains constant showing little variation during the 60 second rest periods, whilst the specific stress exhibits a series of peaks and troughs after each strain increment. This follows previous test results showing that the overall change in resistance for the Stainless Steel Wire is low.

The R.Stat/S yarn results follow the behaviour exhibited in previous tests in that the resistance decreases as the strain increases, and the timing of these changes are fairly consistent with the timing of the changes in specific stress. For this yarn, there is no relaxation of specific stress during the 60 second rest period between straining whereas there is a slight decrease in the resistance, as shown in Figure 5.19.

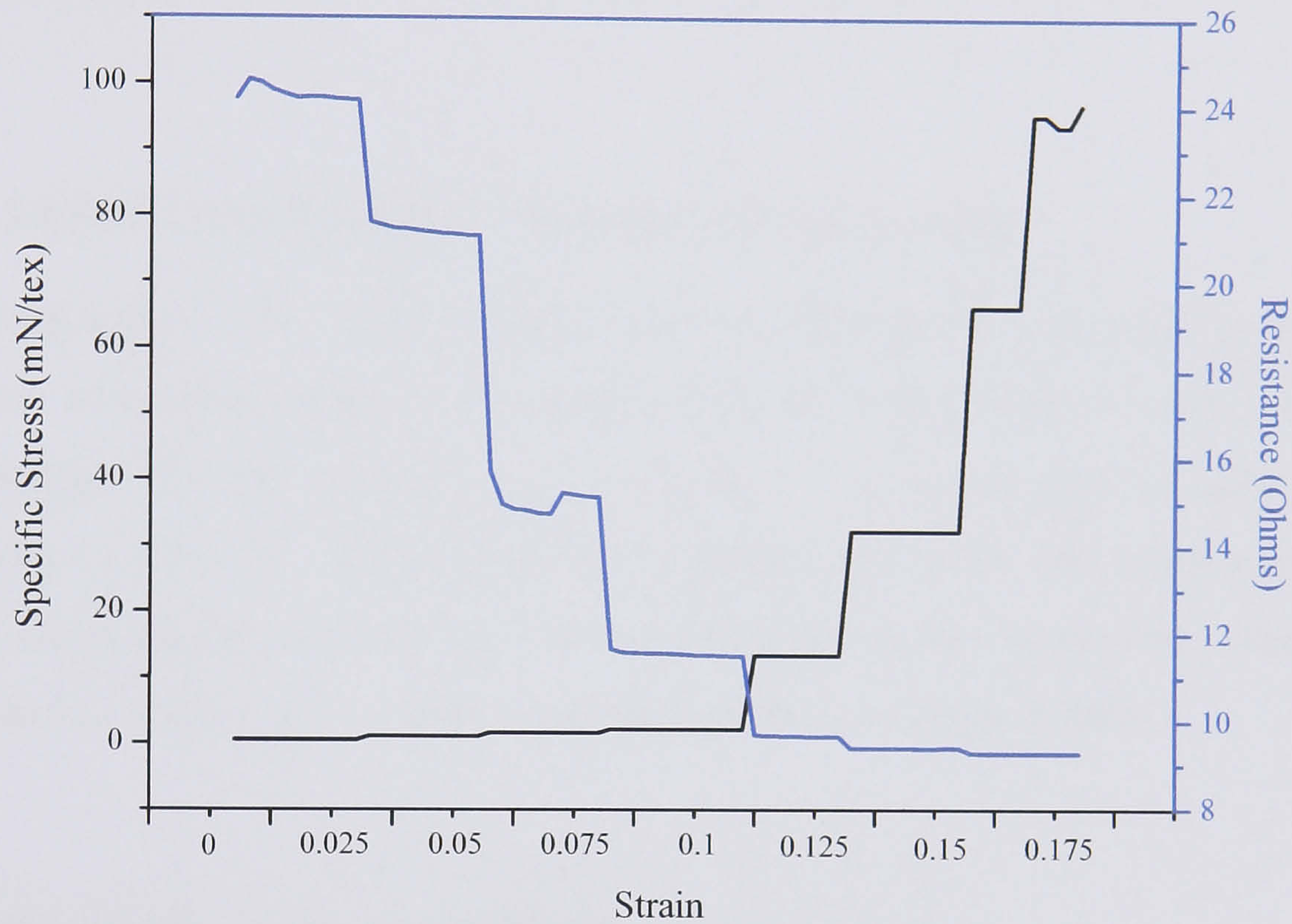


Figure 5.19 R.Stat/S Stepwise Specific Stress and Resistance-Strain Curve

This behaviour can most likely be attributed to both the staple yarn morphology and to the 100% stainless steel material whereby, on straining, the filaments are pulled closer together, thus resulting in an increase in the conductive pathways.

5.5 Characterisation of Conductive Yarn Stretch Behaviour

Based on the results gained from all of the tests carried out so far it was deemed appropriate to eliminate the yarns R.Stat/S and Bekinox VN due to their lack of extensibility and stiffness, and the Bekitex 50/1 yarn due to the irregularity of the measured resistance values on straining, which meant that this yarn could not demonstrate acceptably repeatable or predicatable behaviour. Further tests were carried out on the remaining yarns; R.Stat/P, Resistat F9301 and the Stainless Steel Wire in order to further characterise their resistance-strain behaviour. The experimental work included the use of elastomeric yarns in hollow-spindle wrap-spun yarn configurations, and assessing the elastic recovery behaviour - an important factor when considering the reproducibility of results and the long-term behaviour of a sensor in-situ.

5.5.1 Coiled Yarns Dynamic Resistance-Strain Testing

The conductive yarns were coiled around an elastomeric yarn core to try and improve upon their elastic performance. 10cm of Wykes 2569C double covered elastomeric yarn was stretched to 25cm using a twist tester, then 30 coils of the conductive yarn was wound around this extended core yarn. The yarns were then tested using the same Instron and multimeter set-up as for the dynamic resistance-strain tests, except with the differentce between the jaws being 100mm.

5.5.2 Elastic Recovery Timed Hold

The method used was based on BS 4029:1978 [140] which involved extending the yarns to a pre-set strain, holding this strain for 30 seconds, then releasing the strain and holding for a further 60 seconds before repeating the test. The same Instron and multimeter set-up was used as for the other dynamic resistance tests. The yarn gauge length was 100mm, the test speeds were 50mm/min and the yarns were extended to 2% and 5% of their gauge length.

5.5.3 Elastic Recovery Immediate Reversal

Similar to the Timed Hold tests, the method used was based on BS 4029:1978 [140] in which a repeat of the strain and release of strain conditions is used but without the holding time in-between. Again, the same Instron and multimeter set-up as for the other dynamic resistance tests was used and the yarn gauge length was 100mm, the test speeds were 50mm/min and the yarns were extended to 2% and 5% of their gauge length

5.5.3.1 Elastic Recovery and Work Recovery

It is important to know the extent to which a fibre becomes permanently deformed when it is stretched, particularly for the potential applications of a strain sensor as it is essential to know what its usable range is, especially if it is intended for repeated use. The Elastic Recovery can be calculated using Equation 5.7 shown below.

$$\text{Elastic recovery} = \frac{\text{Elastic extension}}{\text{Total extension}} \qquad \text{------------------ (5.7) [122]}$$

The equation is based on the illustrative graph shown in Figure 5.20 and, according to this equation, complete recovery will have the value of 1 (or 100%) and no recovery will have the value of zero.

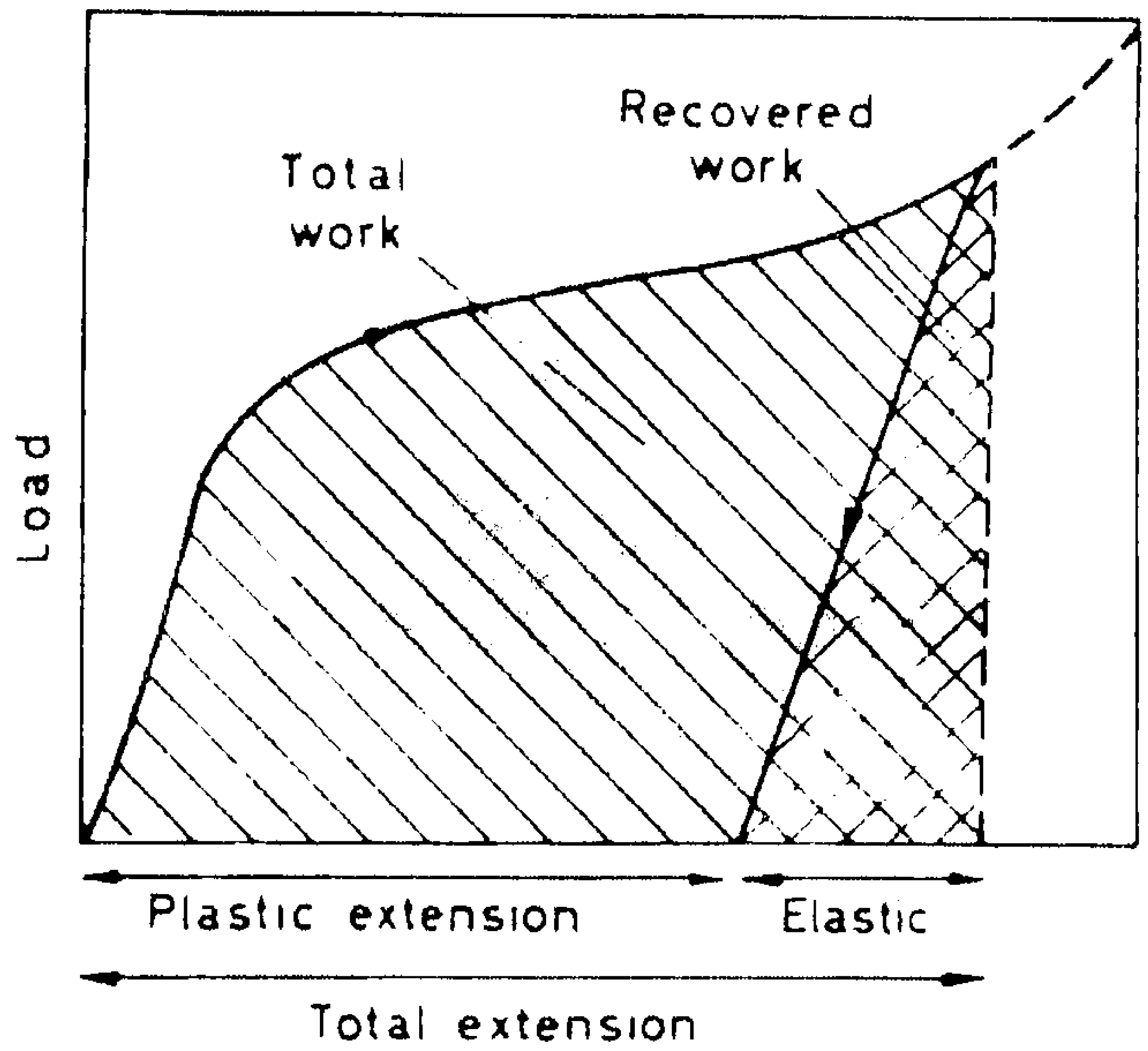


Figure 5.20 Elastic and Plastic Extension [122]

As well as determining the Elastic Recovery properties of a yarn, the levels of yarn hysteresis are also of importance when considering yarns that are to be subjected to repeated loading as it gives a measure of the energy used up by internal friction. One method of presenting this information is to determine the Work Recovery of the yarn by calculating the energy lost from stretching and relaxing the yarn, and comparing the results of the first and the tenth cycle. The area under the load and unload curve was calculated using Origin Software and the results of the unload curve (work returned during recovery) was divided by the area under the load curve (total work done during extension) and multiplied by 100%. Calculating 1-Work Recovery, the proportion of the total work that is dissipated as heat is given, as shown in Equation 5.8.

$$\text{Work Recovery} = 1 - \left(\frac{\text{work returned during recovery}}{\text{total work done in extension}} \times 100\%\right) \quad \text{---------} \ (5.8)\ [122]$$

5.6 Characterisation of Conductive Yarn Stretch Behaviour Test Results

5.6.1 Coiled Yarns Dynamic Resistance-Strain Results

The lengths of conductive yarns coiled around the elastomeric core are shown in Table 5.6, measured by hand after unwinding the coiled yarn from around the elastomeric core. It was observed that the crimped nature of the R.Stat/P yarn made it difficult to wrap the yarn at either a consistent relaxed or tensioned state, leading to the differences in yarn lengths measured. Whilst the Resistat F9301 yarn was easily wrapped around the elastomeric core yarn, the Stainless Steel Wire yarn was so inflexible and stiff that, in effect, the elastomeric yarn becomes wrapped around the wire, hence the very small increase in length of yarn used.

Table 5.6 Length of Conductive Yarn Coiled Around Elastomeric Core

Material	Length of yarn (mm)
Resistat F9301	260
R.Stat/P	260 (relaxed) or 250 (yarn taut)
Stainless Steel Wire	252

The whole graph of the Resistat F9301 yarn, Figure 5.21, appears to show a close correlation between the increase in the specific stress of the coiled yarn and the increase in resistance of the conductive yarn, however on closer inspection, strain region (I) shows that there is actually a high degree of resistance variability whilst the coils of the conductive yarn are being stretched apart. In strain region (II), once the conductive yarn is becoming strained itself, it can be seen that the resistance change is less variable, except for a break in measurement when there is a significant dip in the yarn specific stress.

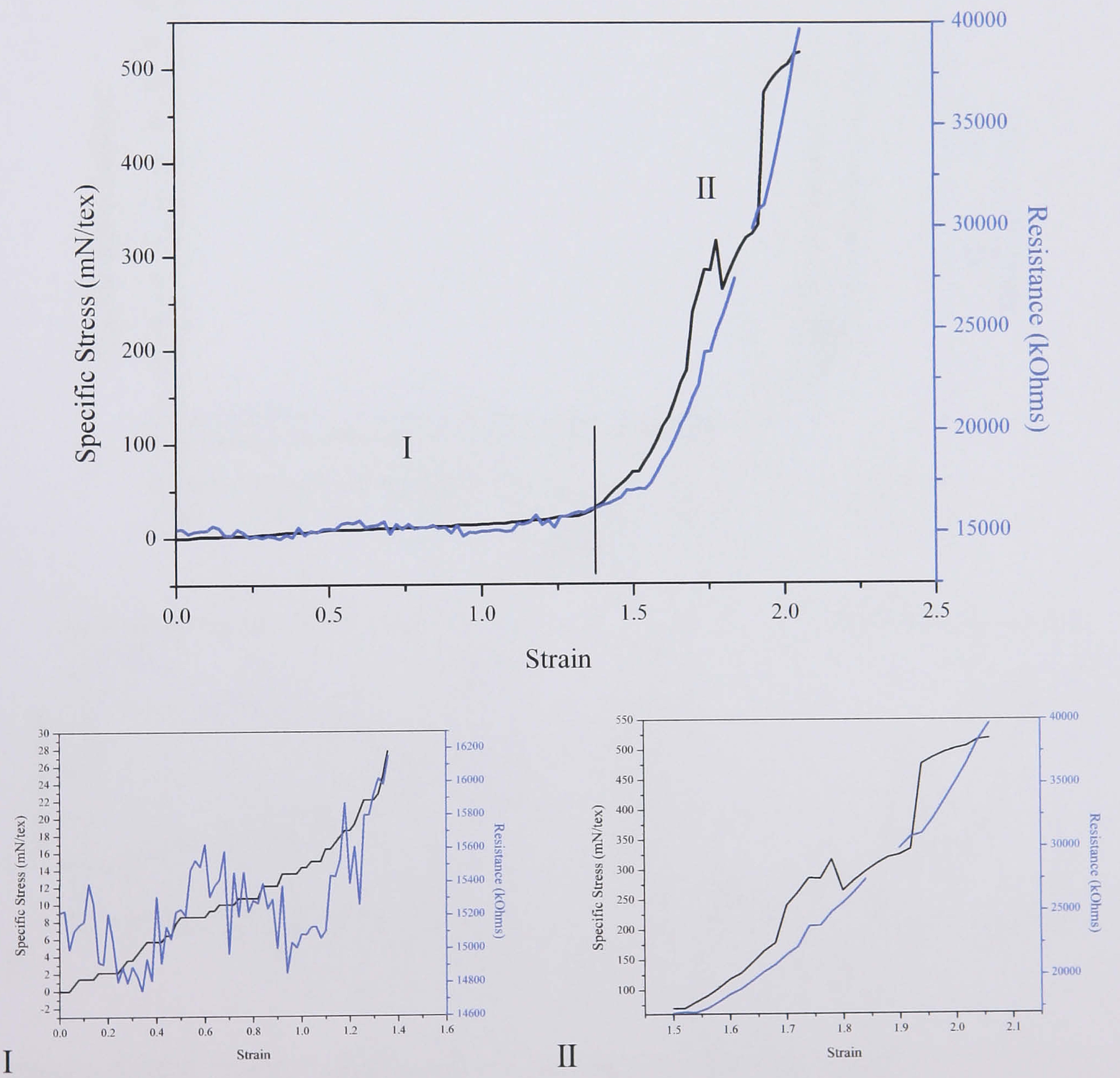


Figure 5.21 Resistat F9301 Coiled Yarn Dynamic Resistance-Strain Curve

(I) strain region 0 - 1.5 and (II) strain region 1.5 – 2.0

The change in specific stress and resistance for the coiled R.Stat/P yarn, Figure 5.22, also initially appears to follow a similar pattern, however when strain region (I) is analysed it can be seen that there is a decrease in the resistance whilst the coils of the yarns are being stretched, although this is only of the order of approximately 1.5Ω. Once the conductive yarn itself starts being strained, as seen in strain region (II), it can be seen that the change in resistance follows the pattern of the change in specific stress fairly closely, except for the portion where there is a spike increase in the specific stress.

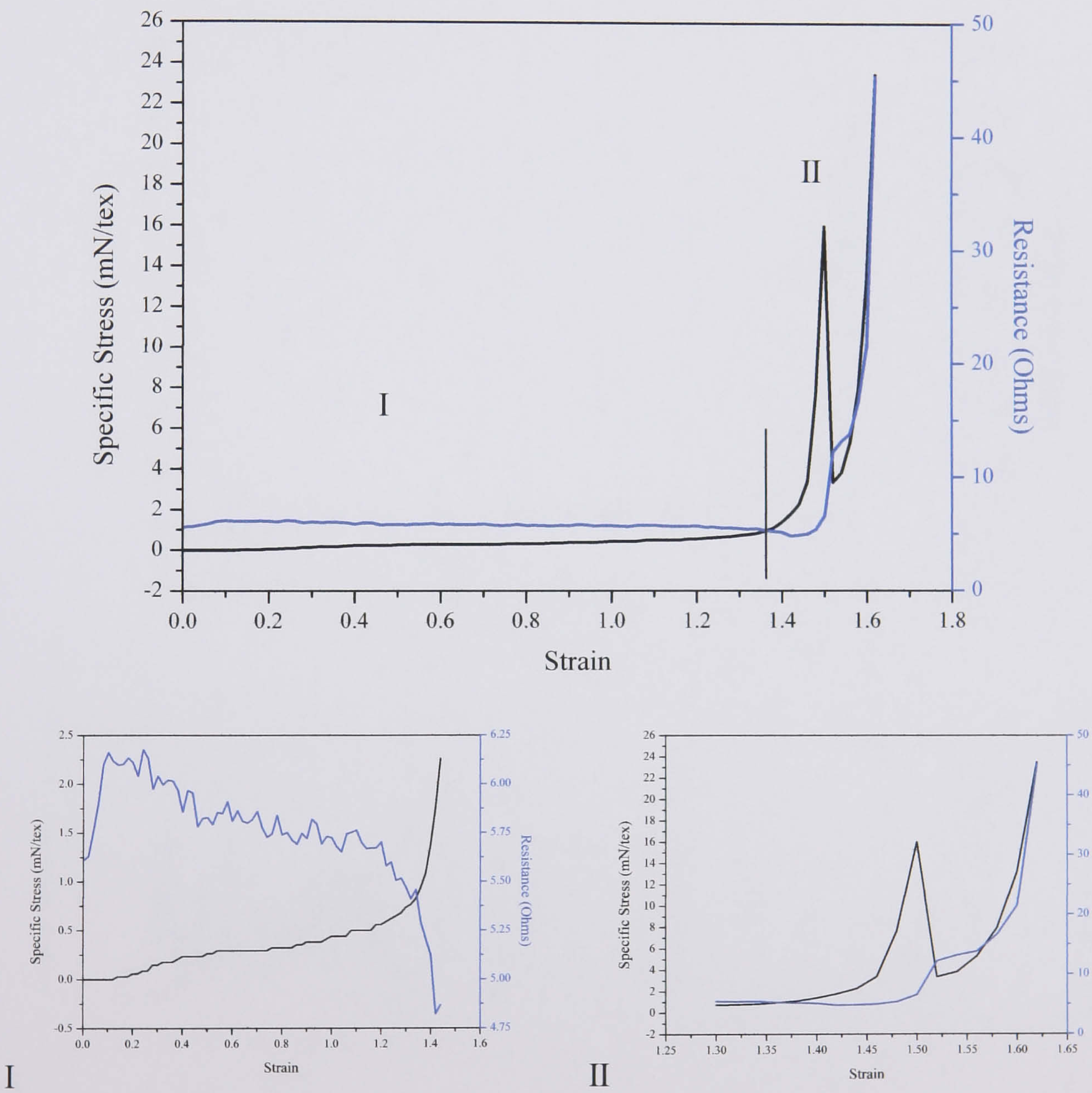


Figure 5.22 R.Stat/P Coiled Yarn Dynamic Resistance-Strain Curve

(I) strain region 0 – 1.3 and (II) strain region 1.3 – 1.6

The coiled Stainless Steel Wire, Figure 5.23, like the Resistat F9301 and the R.Stat/P yarn, appears to experience resistance change with specific stress change in a simultaneous pattern, however strain region (I) highlights that there is a significant variability of the resistance whilst the coils are separating with an approximate range of ±200Ω. Even once the specific stress of the yarn starts increasing significantly (strain value 1.47) there is no real increase in the resistance; this does not happen after there is a change in the inclination of the specific stress curve which happens at the point where the yield point of the Stainless Steel Wire is approaching in strain region (II).

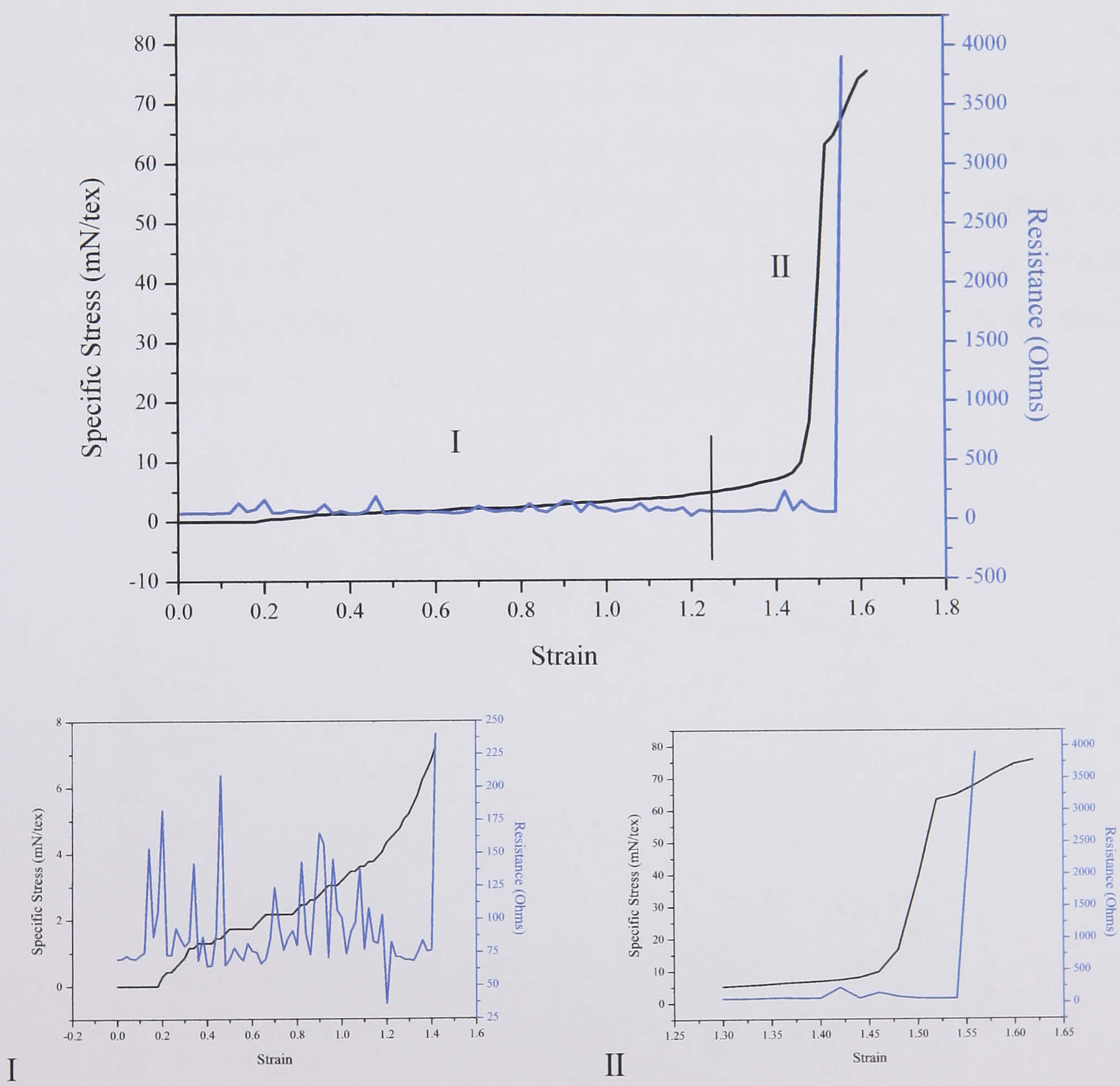


Figure 5.23 Stainless Steel Wire Coiled Yarn Dynamic Resistance-Strain Curve

(I) strain region 0 – 1.25 and (II) strain region 1.25 – 1.6

5.6.2 Elastic Recovery Timed Hold

For all yarns tested the rate of cyclic straining was ½ cycle/min, and the numerical results were used to determine the immediate elastic recovery and the residual elongation of the yarns.

As the Resistat F9301 yarn is strained, both the specific stress and resistance increase, and decrease when the strain is released as shown in Figure 5.24. The specific stress graph shows the decay in yarn elastic recovery over time as exemplified by the decrease in the maximum specific stress value reached with each subsequent cycle and the time it takes to reach that maximum level. For example, the time it takes to go from zero to the maximum specific stress value is 12.5 seconds for cycle 1, whereas it takes 17 seconds for cycle 8, and the maximum specific stress values reached are 117.7mN/tex and 98.4mN/tex respectively.

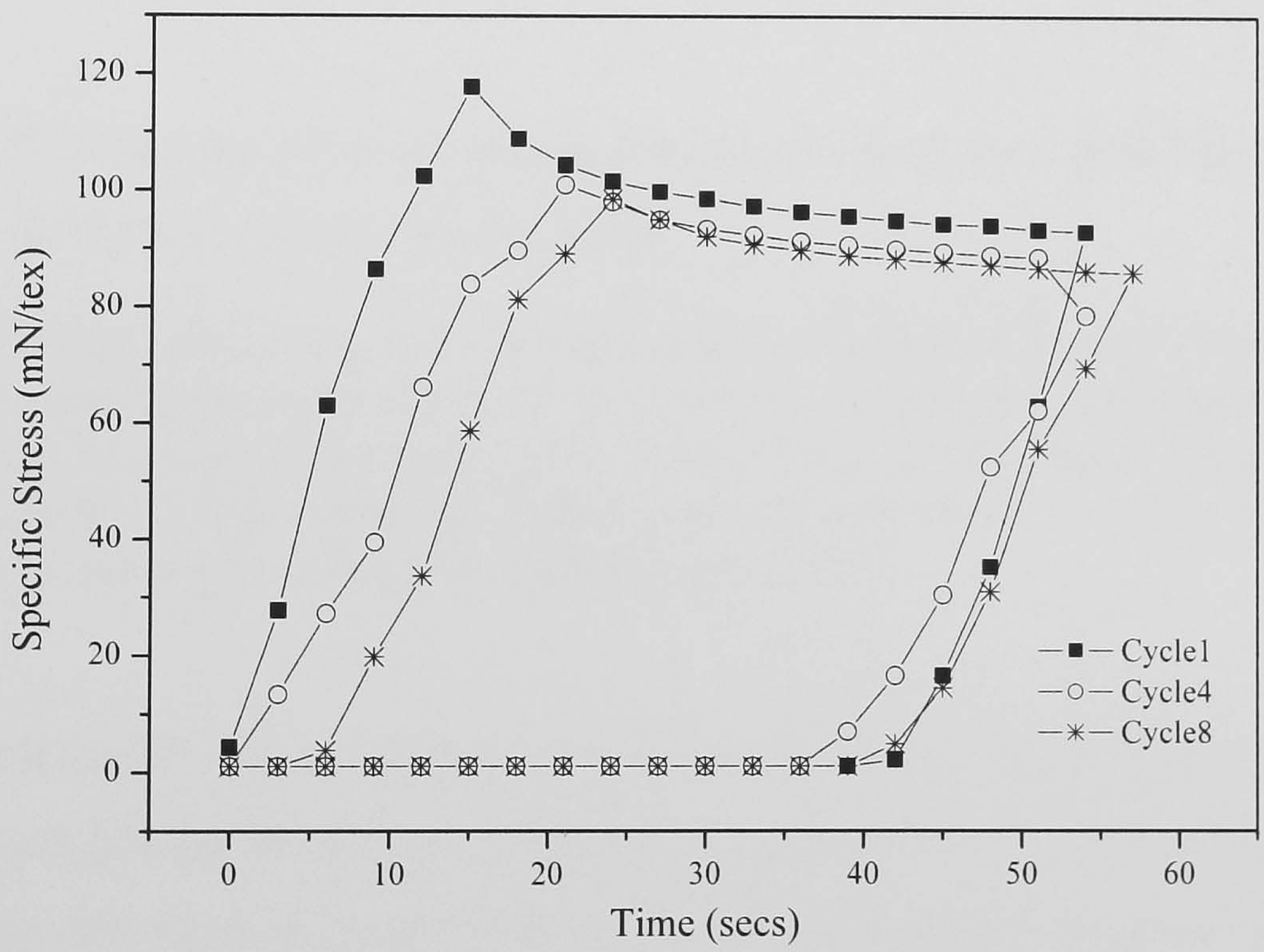


Figure 5.24 Timed Hold Cyclic Loading of Resistat F9301, Specific Stress

The peak resistance value reached for the Resistat F9301 yarn does not change significantly from cycle 1 to 8 (0.3% at 2% extension and 0.6% at 5% extension) and although there is some creep evident in the recovery resistance values, it is less than 1% for both extensions, as shown in Figure 5.25. As the timings of these increases and decreases mirror the timings of the specific stress changes, it can be deduced that these results are repeatable.

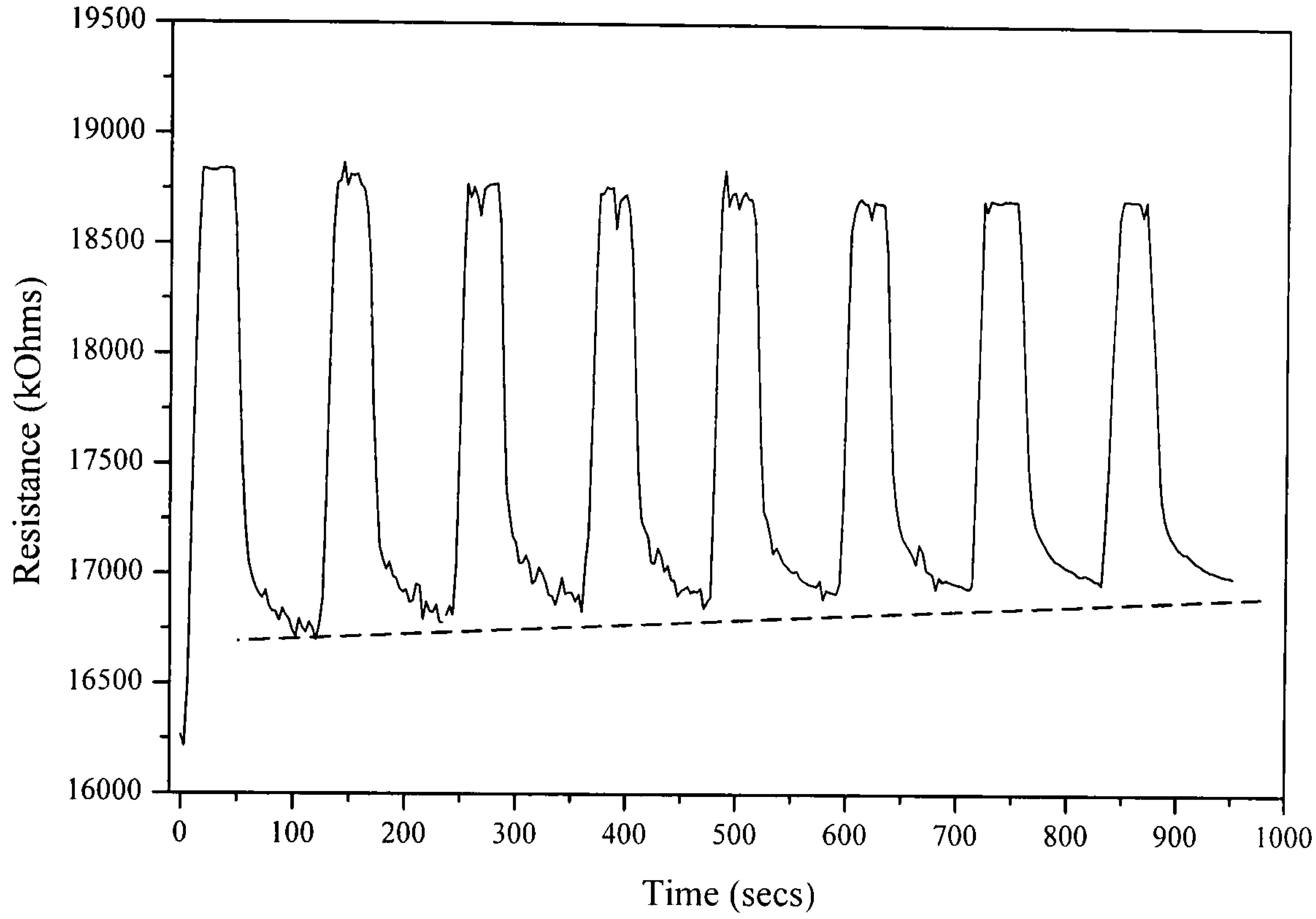


Figure 5.25 Resistat F9301 Change in Resistance with Yarn Cyclic Elastic Recovery with Holding Time at 5% Extension.

A single 120-second cycle is highlighted on the Specific Stress-Time graph, comprising strain increase, 60 second strain-hold region, strain release and final 60 second relax-hold region. Dotted lines on Resistance-Time graph indicate increase trend in Ω baseline return level after each cycle and decrease in resistance level reached on each strain cycle.

For the R.Stat/P yarn the change in specific stress with strain differs as the cyclic loading progresses, as shown in Figure 5.26, in which it can be seen that the timing of the specific stress increase (from zero to maximum value) starts at 9.3mN/tex/sec for cycle 1, decreases to 6 mN/tex/sec for cycle 4 and then increases again to 13mN/tex/sec for cycle 8. Once again, this highlights the irregular and non repeatable behaviour of this yarn.

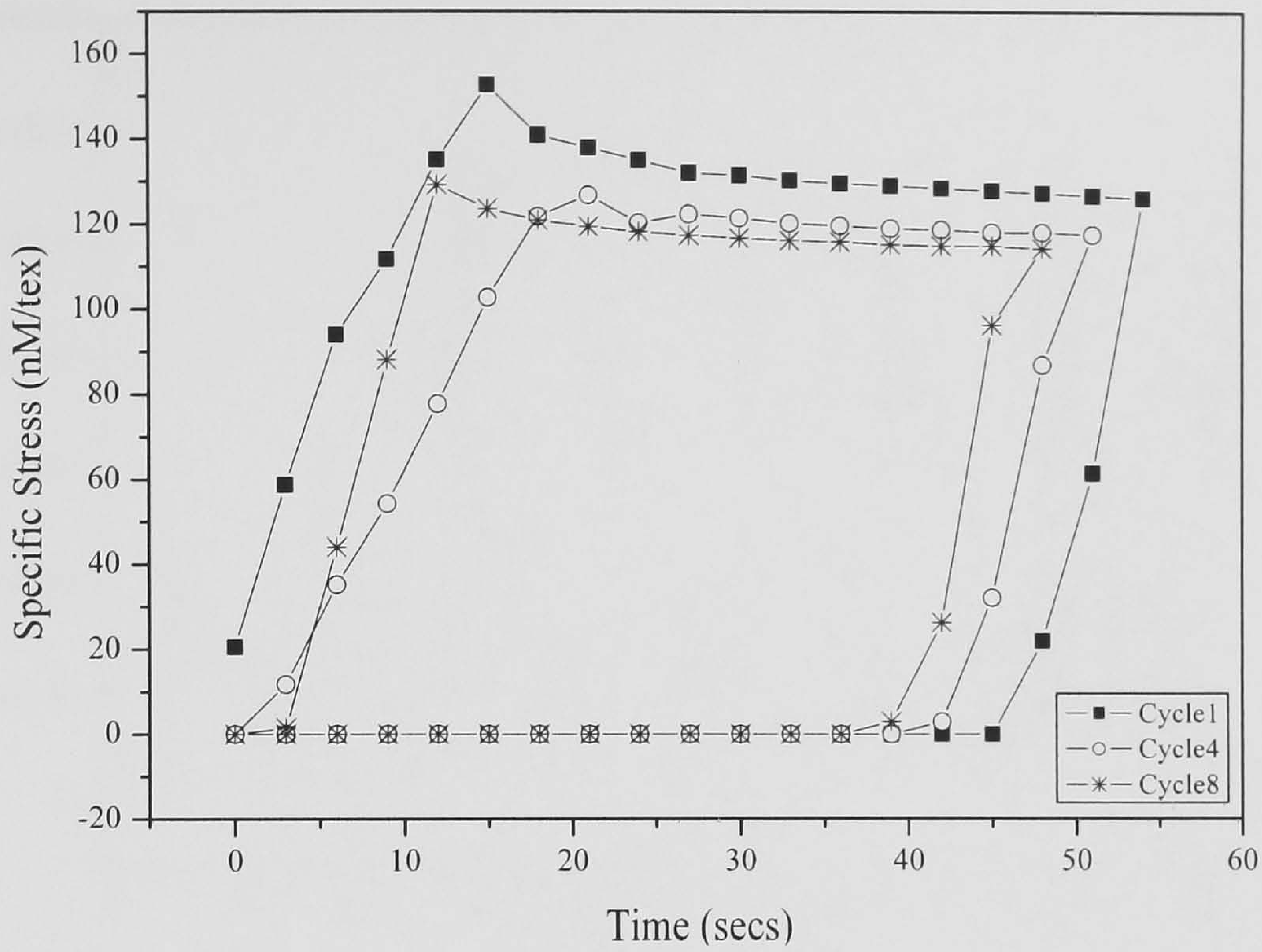


Figure 5.26 Timed Hold Cyclic Loading of R.Stat/P, Specific Stress

For the R.Stat/P yarn no discernible pattern can be observed from the change in resistance with cyclic loading graph (Figure 5.27). Not only is there a variability between the cycles, but within each cycle there are significant peaks and troughs which would make predicting the behaviour of the yarn almost impossible.

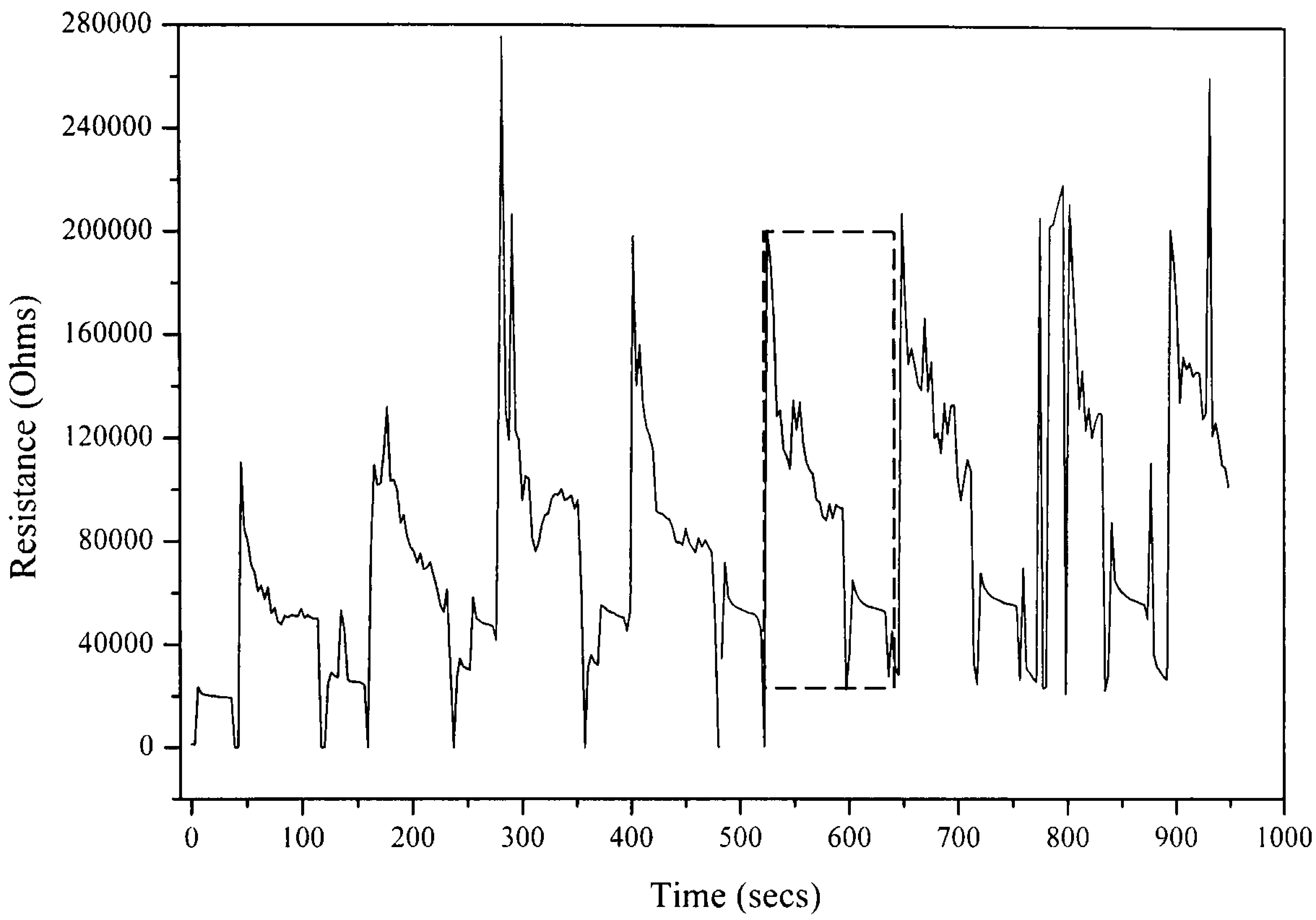


Figure 5.27 R.Stat/P Change in Resistance with Yarn Cyclic Elastic Recovery with Holding Time at 5% Extension

A single 120-second cycle is indicated on the Resistance-Time graph, illustrating the erratic nature of the yarns resistance response.

The elastic recovery limitations of the Stainless Steel Wire can be seen in Figure 5.28, where the difference in the timing of the successive specific stress cycles is significant at both 2% and 5% extension. Following the first cycle there is little elastic recovery, such that the time before an increase in specific stress commences increases from zero seconds for cycle 1 to 35 seconds by cycle 8.

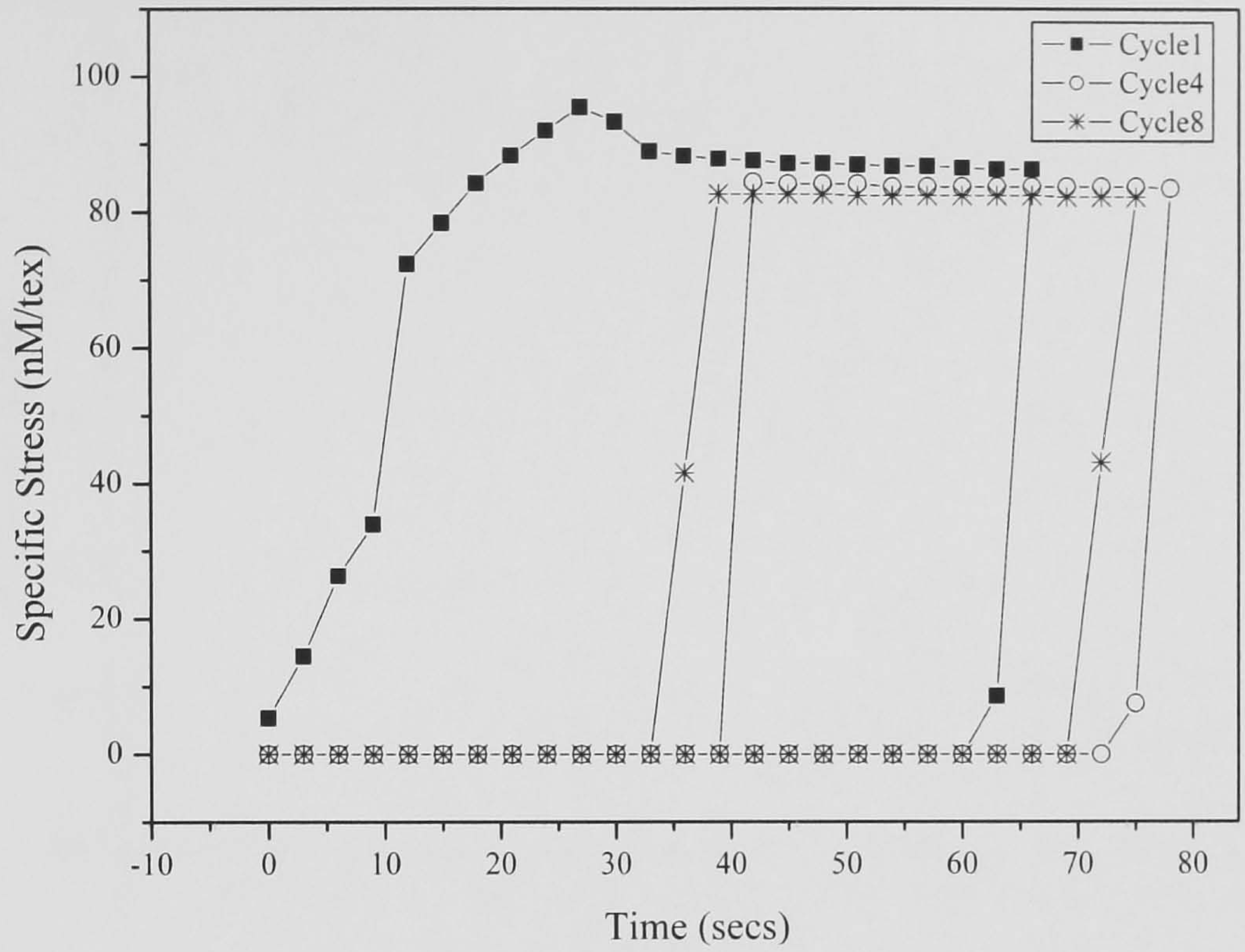


Figure 5.28 Timed Hold Cyclic Loading of Stainless Steel Wire, Specific Stress

Although the repeatability of the resistance change is satisfactory, as illustrated in Figure 5.29, the amount of change is very small at less than 0.5Ω, allowing little room for error in a real-life usage situation.

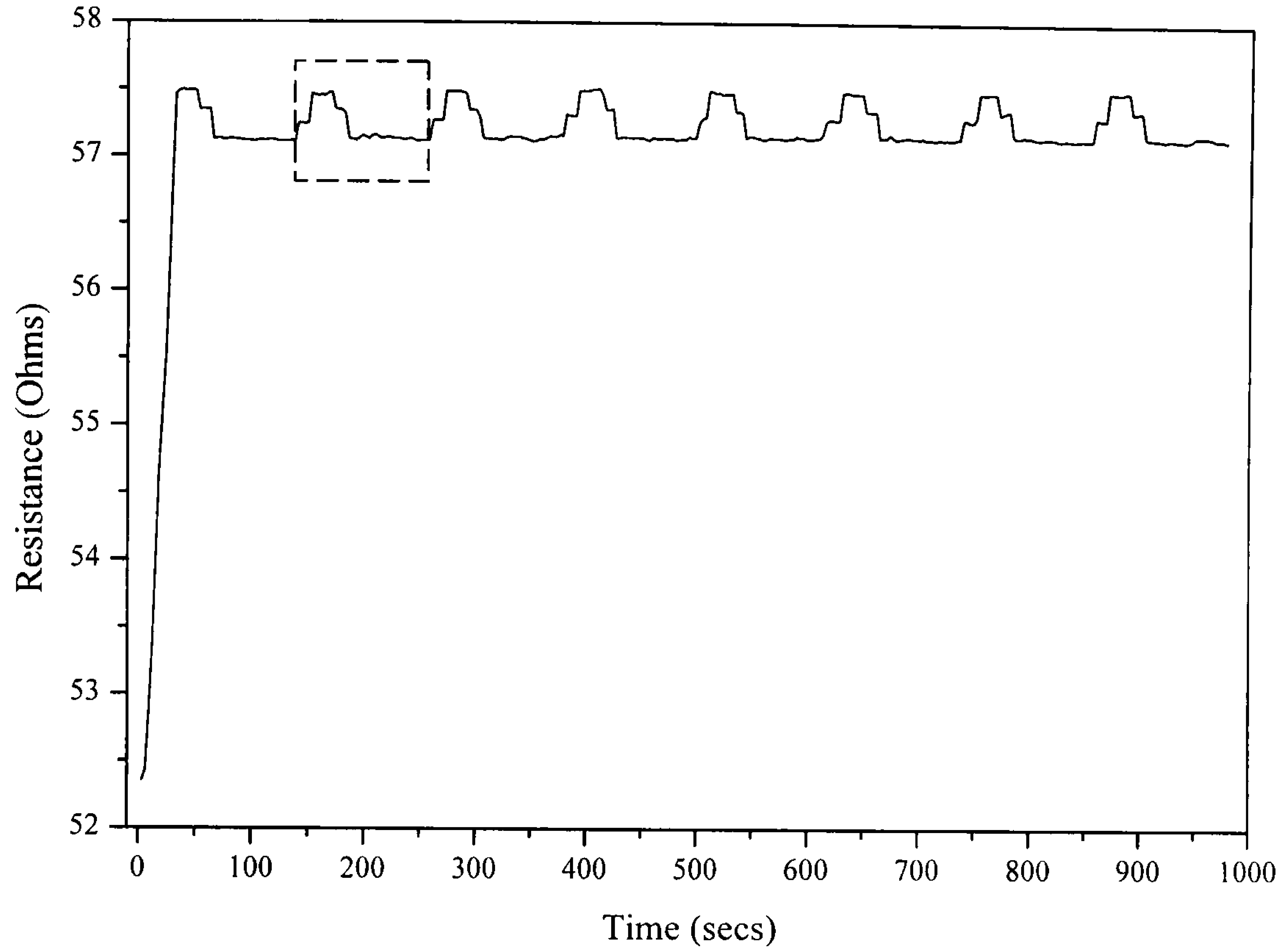


Figure 5.29 Stainless Steel Wire Change in Resistance with Yarn Elastic Recovery with Holding Time at 5% Extension.

A single 120-second cycle is indicated on the Resistance-Time graph.

By calculating the CV of the resistance values, as shown in Table 5.6, the variation between the minimum and maximum resistance results from the mean can be compared. This statistical analysis illustrates the variability (or otherwise) of the resistance values achieved per cycle. As expected, it can be seen that the yarn with the greatest degree of variation in resistance results about the mean is the R.Stat/P yarn, and the Resistat F9301 yarn has the most repeatable behaviour, with the variation typically being less than 0.5%.

Table 5.7 Statistical Analysis of Elastic Recovery Resistance values; Timed Hold

Material	Extension	Min. Recovery Resistance		Max. Elongation Resistance	
		Mean	CV%	Mean	CV%
Resistat F9301	2%	14,467	0.12	15,104	0.15
Resistat F9301	5%	16,794	1.37	18,780	0.33
R.Stat/P	2%	1,033	110.31	10,865	106.73
R.Stat/P	5%	8,869	134.03	200,749	28.23
Stainless Steel Wire	2%	53	0.90	53	1.11
Stainless Steel Wire	5%	56	2.99	57	0.01

5.6.3 Elastic Recovery Immediate Reversal

In analysing the immediate reversal elastic recovery curves, the repeatability of the yarn behaviour can be deduced from the resistance-strain graphs and the trends in the yarns' resistance variability with each successive cycle can be deduced from the resistance-time graphs.

Zhang et al. [141] proposed that there are two types of hysteresis occurring during conductive fibre/knitted fabric immediate reversal elastic recovery tests, as shown in Figure 5.30. The first hysteresis is an inter-cycle drift caused by the resistance differences between elongation and recovery stages in one cycle of testing, and this type of hysteresis can be predicted in practical use by specifying either the elongation or recovery strain stages. The second type of hysteresis occurs between the cycles, reflecting the cycle differences, and this type of hysteresis affects the readability of the data. If the between-cycle hysteresis is significant, it means that the strain gauge is impractical for use when trying to gain accurate measurements.

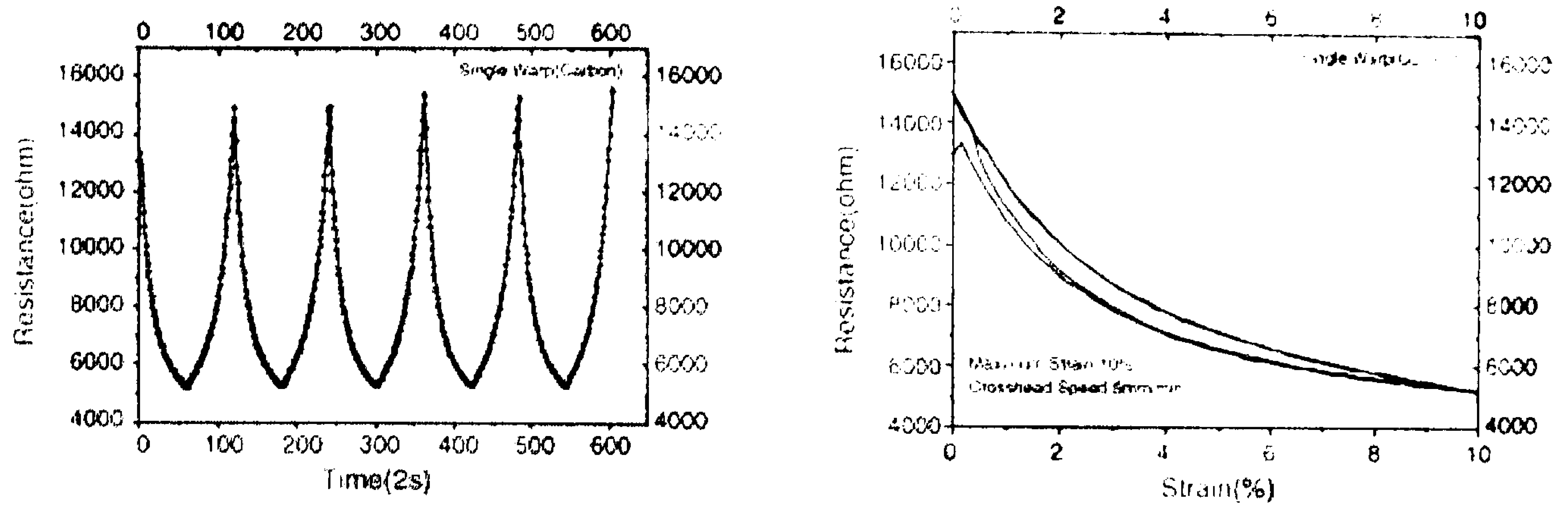


Figure 5.30 Resistance-Time and Resistance-Strain Relationships of Samples [141]

The inter-cycle hysteresis (effectively, the symmetry of each cycle about the strain elongation/recovery reversal point) of the Resistat F9301 yarn (5% elongation) is small after the initial elongation cycle (1), as shown in Figure 5.31. From cycle 2 to cycle 10, the recovery resistance increases by 7% overall and the resistance creeps by only 1.2%. In terms of the between-cycle hysteresis, it can be seen that there is a slight change in timing between the cycles in terms of the strain value at which the maximum resistance is reached. For example maximum resistance is reached at 0.05 strain for cycle 1, but at 0.03 strain for cycle 7, however this variability is minimal, and although there is a variability in the maximum resistance value reached during each cycle, this differs by only ±1.25% between cycles.

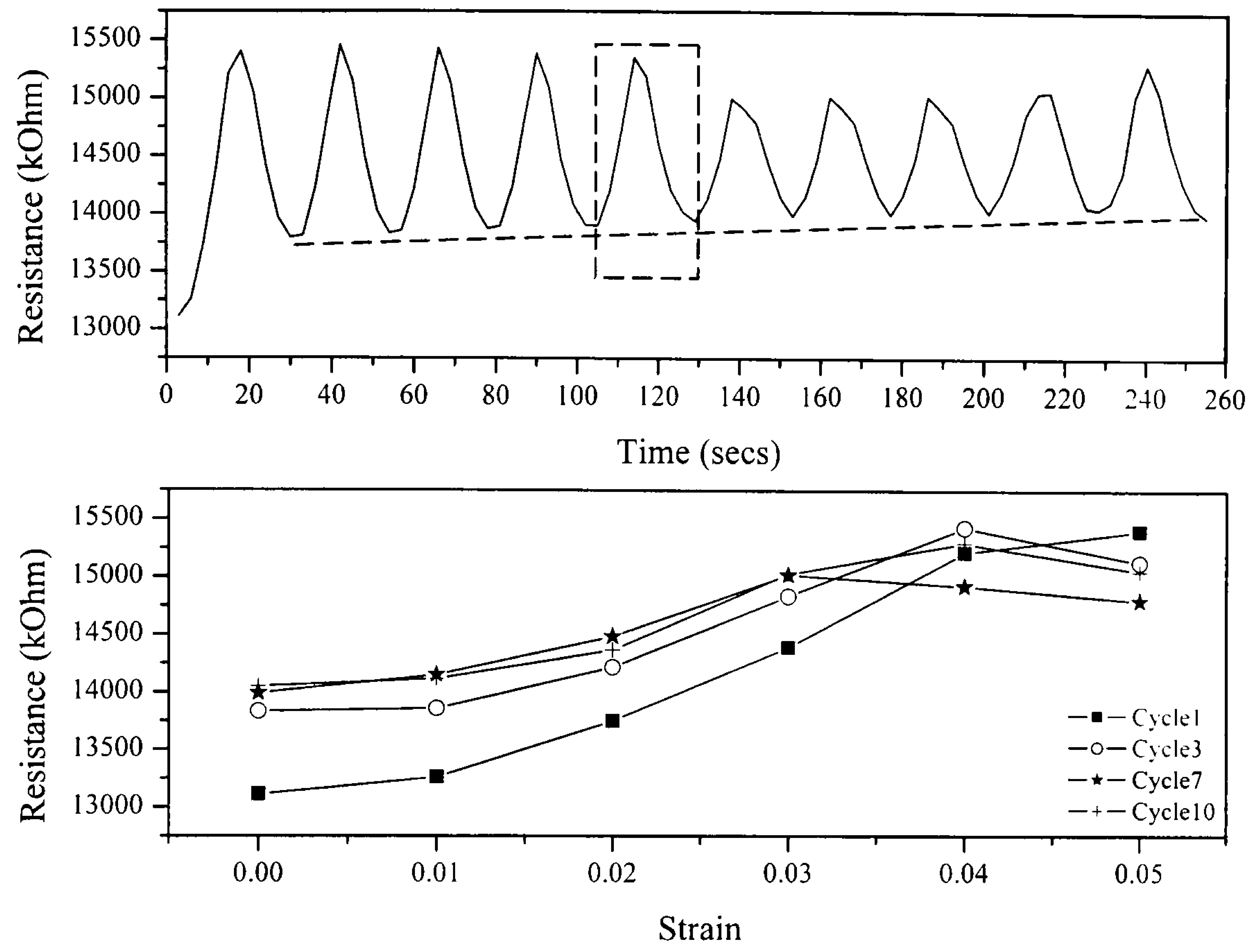


Figure 5.31 Resistat F9301 Resistance-Time and Resistance–Strain Relationships at 5% Extension; Immediate Reversal

A single 25-second cycle is represented on the Resistance-Time graph indicating the increase in strain followed immediately by the reversal. The dotted line on the Resistance-Time graph shows the trend for the baseline Ω-level increase after each cycle.

The inter-cycle variability of the R.Stat/P yarn (5% elongation) is highlighted in Figure 5.32, wherein there is no mirroring of the resistance change in the elongation and recovery portions of each cycle. In terms of between cycle hysteresis, from cycle 1 to cycle 9 there is a 46% increase in the recovery resistance and the maximum elongation resistance value reached varies by ±10% between cycles 1 and 10, thus indicating that the yarn behaves inconsistently.

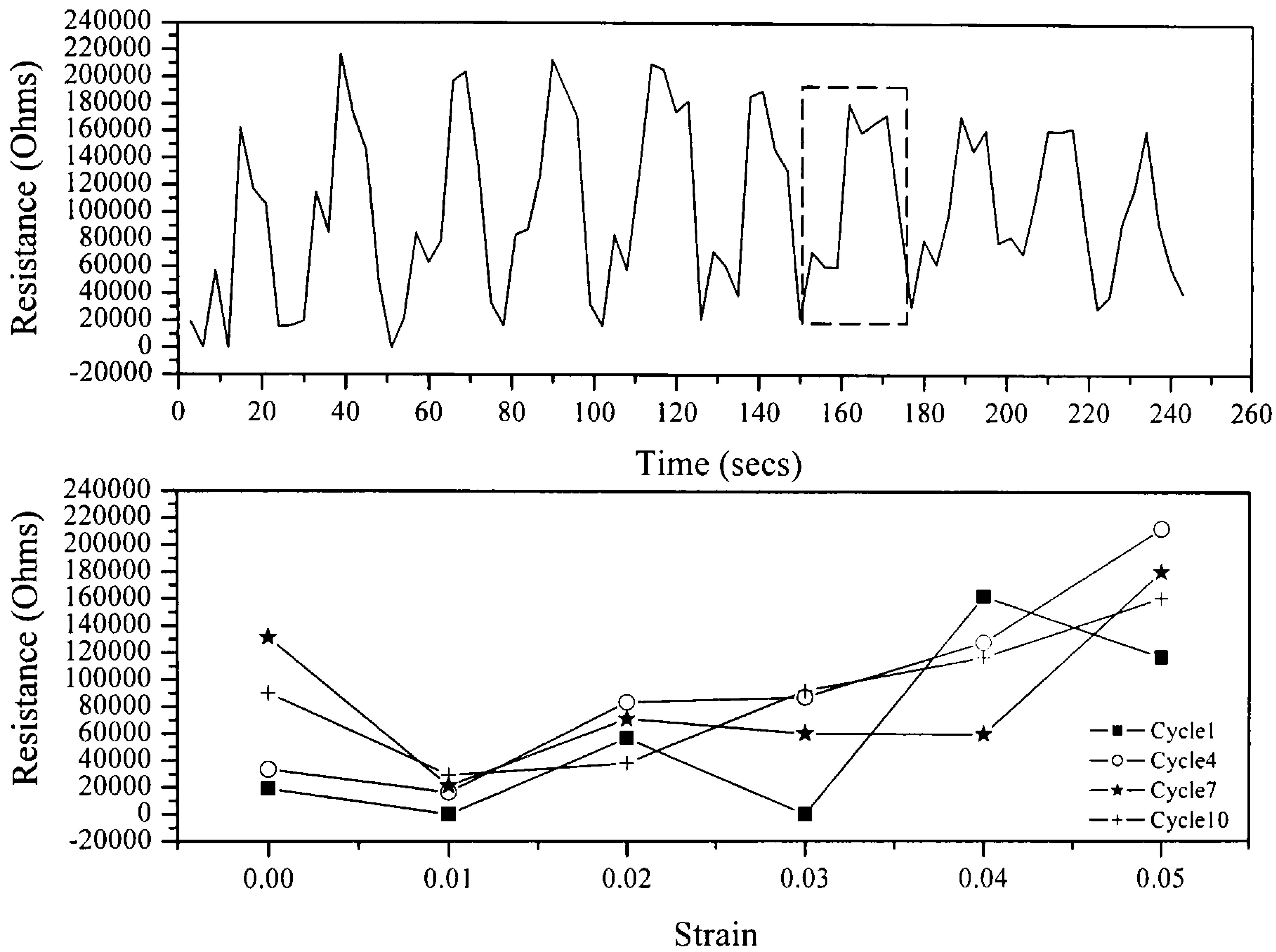


Figure 5.32 R.Stat/P Resistance-Time and Resistance–Strain Relationships at 5% Extension; Immediate Reversal

The inter-cycle hysteresis experienced by the Stainless Steel Wire is significant and is highlighted by the degree of plastic extension undergone by the yarn as seen in Figure 5.33, whereby after the first elongation and recovery cycle (1), any inherent elasticity has been almost entirely removed. This is highlighted when assessing the between-cycle hysteresis; although the overall increase in recovery resistance is only 8% from cycle 1 to 10, there is no elastic recovery of the yarn when the strain is removed.

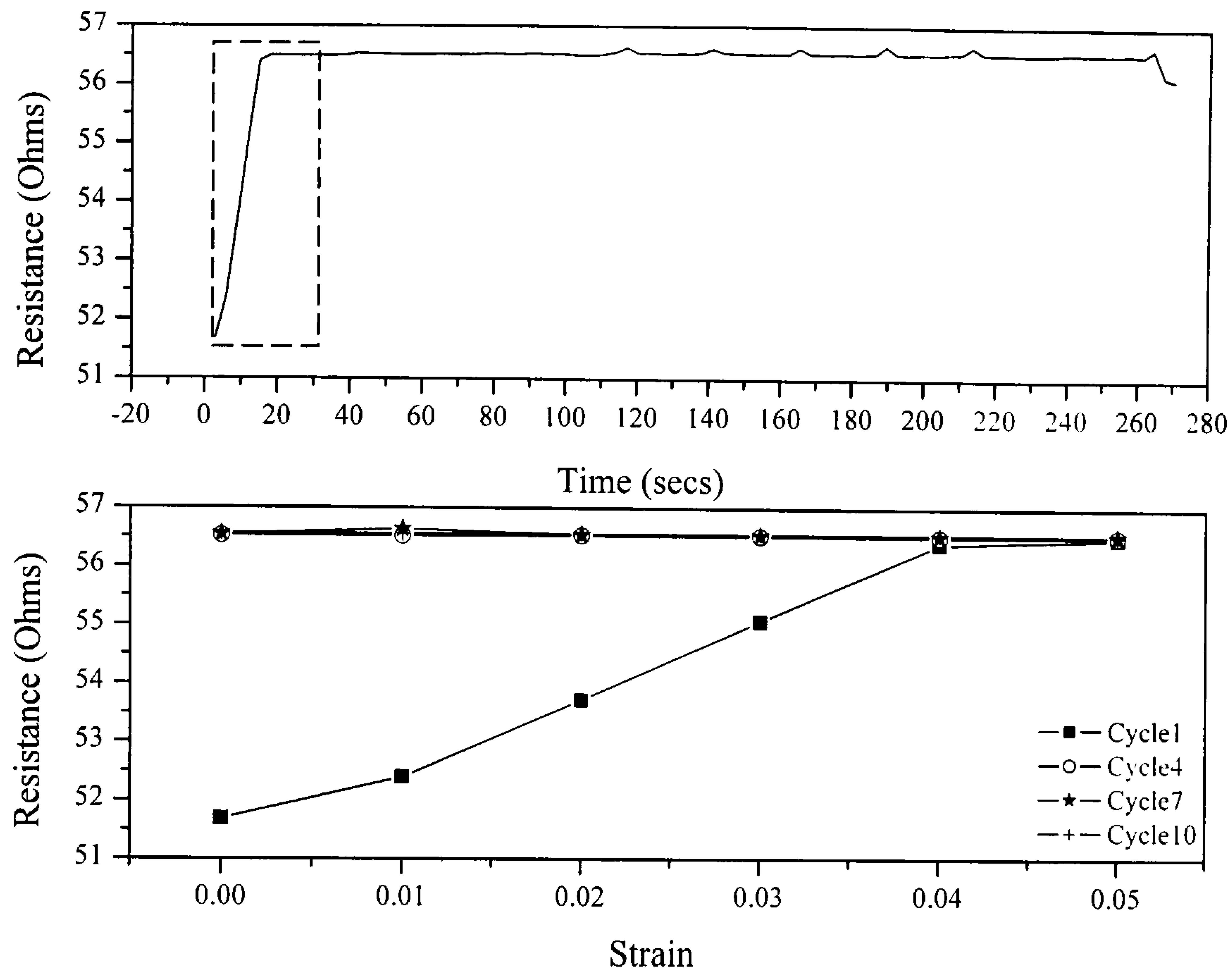


Figure 5.33 Stainless Steel Wire Resistance-Time and Resistance–Strain Relationships at 5% Extension; Immediate Reversal

The statistical analysis of the elastic recovery immediate reversal results, as shown in Table 5.8, confirm that the R.Stat/P yarn exhibits the most variable behaviour. Unlike for the Timed Hold tests, the Stainless Steel Wire performs less variably than the Resistat F9301 yarn however, as before, the range of resistance variation is so small as to render it unsuitable for use as an elastic strain sensor.

Table 5.8 Statistical Analysis of Elastic Recovery Resistance values; Immediate Reversal

Material	Extension	Min. Recovery Resistance		Max. Elongation Resistance	
		Mean	CV%	Mean	CV%
Resistat F9301	2%	13,120.43	10.96	13,549.33	0.47
Resistat F9301	5%	13,851.43	1.97	15,244.77	1.25
R.Stat/P	2%	13.75	27.31	19.44	6.29
R.Stat/P	5%	18,072.78	59.78	189,793.8	10.75
Stainless Steel Wire	2%	53.35	1.01	53.56	0.09
Stainless Steel Wire	5%	56.04	2.73	56.59	0.12

5.6.3.1 Elastic Recovery and Work Recovery

In order to determine the elastic recovery values of the Resistat F9301 and the R.Stat/P yarns, it was necessary to fit regression lines along each section of the curve with differing gradients in order to accurately determine the point of intersection between the elastic and plastic regions.

It can be seen from Table 5.9 that the monofilament Stainless Steel Wire exhibits smaller levels of elastic recovery than the multifilament Nylon and Polyester based Resistat and R.Stat/P yarns. As expected, the elastic recovery results for the 2% extension samples are higher than for the 5% extension samples, given that the yarns are less likely to have been stretched beyond their plastic extension regions. As the number of cycles increases, the elastic recovery of each yarn decreases, however this decrease is much greater for the Nylon based Resistat yarn than for the polyester based R.Stat/P yarn.

Table 5.9 Conductive Yarn Elastic Recovery Results

Material	Extension	Elastic Recovery %			
		Cycle 1	Cycle 3	Cycle 7	Cycle 10
Resistat F9301	2%	66	67	69	68
Resistat F9301	5%	68	46	50	50
R.Stat/P	2%	68	67	60	57
R.Stat/P	5%	45	44	43	42
St. Steel Wire	2%	25	25	25	25
St. Steel Wire	5%	20	20	20	20

The work recovery results (Table 5.10) show that for the Stainless Steel Wire there is no work recovered after straining to either 2% or 5% after cycle 1 and, as with the elastic recovery behaviour. the Nylon and Polyester based yarns perform better. For both the Resistat and the R.Stat/P yarns the work recovered is greater at 2% extension than at 5% extension, and in general the % work recovered increases as the number of cycles increase.

Table 5.10 Conductive Yarn Work Recovery Results

Material	Extension	Work Recovery %			
		Cycle 1	Cycle 3	Cycle 7	Cycle 10
Resistat F9301	2%	85.2	89.8	95.9	97.6
Resistat F9301	5%	57.1	66.7	63.4	64.9
R.Stat P	2%	70.5	93.4	91.3	89.3
R.Stat P	5%	35.3	72.5	76.4	83.9
St. Steel Wire	2%	14.7	0	0	0
St. Steel Wire	5%	13.3	0	0	0

5.7 Theoretical Considerations

In order to fully understand the results gained, it is important to relate them to conduction theories and to assess whether the changes observed are due to the base polymer, the conductive filler or the structure of the yarn.

The theory of metal conduction is well known in terms of the flow of free electrons between metal atom orbital rings [102] and it is understood that the smaller the cross-sectional area of a metal wire (i.e. the smaller the count), the greater the resistance of that sire will be for any given length. This explains why, for the Stainless Steel Wire yarn, the resistance increased when subjected to strain forces under all conditions (dynamic, stepwise and elastic recovery) and these results are exemplified by the behaviour of the Bekinox VN continuous multifilament stainless steel yarn. The differences in behaviour of the staple metal-based yarns (Bekitex 50/1 and R.Stat/S) can be attributed to the yarn structure with the resulting decrease in resistance on strain occurring as a result of the fibres being compressed into closer contact on straining, thus improving the conductivity.

Both the R.Stat and Resistat yarns have conductive material absorbed into the surface of a traditional polymeric fibre; R.Stat/P yarn is a metal salt in a polyester base and Resistat F9301 is carbon in a nylon base. By mixing together polymers and electrically conductive fillers such as carbon black or metal particles [142], the charge is carried via electrons or holes and the conductivity of the material is dependent on the electrical charge on the carrier, its mobility (which is dependent on the size and material structure) and the concentration of charges as well as being dependent on mutual contacts between the conductive filler particles.

Morton & Hearle [122] expounded the theory that for hygroscopic (moisture absorbing) filaments such as nylon the resistance is inversely proportional to the cross sectional area, indicating that conduction is predominantly a volume effect, with the current flowing through the bulk of the material. Thus, in hygroscopic fibres volume conduction is the dominant effect with surface conduction having a negligible effect, hence the requirement for a conductive surface filler. As the volume of the yarn remains constant during testing, the increase in resistance on elongation of the monofilament yarn can be attributed to the carbon particles being pulled further apart, thus reducing the number of connections and hence the conductivity.

Morton & Hearle also proposed that in synthetic fibres of higher resistance and negligible moisture absorption, such as polyester, surface conduction is likely to be more significant and may be the dominant conduction mechanism. As such if conduction was a surface effect, the resistance of the yarn would be inversely proportional to the circumference. This is evidenced by the results of the R.Stat/P yarn, and again the effect of the metal salt particles being pulled further apart during elongation is a factor in the increase in elongation on straining.

From the elastic recovery behaviour results, in particular the Immediate Reversal tests, it can be seen that the Resistat F9301 yarn shows a smaller between-cycle hysteresis compared to the stainless steel wire yarn and the irregular metal-salt R.Stat/P yarn, thus indicating good repeatability and potential use as a strain gauge. It is theorised that the pleated striations on the stainless steel fibre surface create large levels of surface friction which prevent the fibres from recovering their original configurations completely. The elastic recovery behaviour of the nylon and polyester-based conductive yarns follow the accepted pattern [122] whereby nylon exhibits superior elastic recovery behaviour ascompared to polyester.

5.8 Discussion

Throughout the course of this preliminary experimental work assessing the physical properties and mechanical performance (Chapter 3), electrical properties (Chapter 4) and the change in electrical resistance behaviour on mechanical manipulation (Chapter 5) of a range of commercially available conductive yarns, it has been possible to discard a number of yarns from the test matrix. The initial stress-strain results combined with the linear resistivity values of the yarns highlighted some conflicting yarn properties with respect to designing a textile strain sensor. For example, the R.Stat/N yarn, Decorative Thread and Resistat F9306 yarns had exhibited high breaking strains, but very high or barely measurable levels of conductivity. Similarly yarns such as Bekitex 50/2, Epitropic Plied and Epitropic OE Rotor Spun have very high specific stress at break values but low breaking strain values and very high resistance values.

Of the six yarns chosen for further testing, it was observed that the Bekinox VN and R.Stat/S yarns had very high levels of conductivity but are very stiff and have very small elasticity ranges, limiting their potential use as a sensor in a flexible and potentially highly extensible textile product. The Bekitex 50/1 staple yarn showed variable results in all the tests for both specific stress and resistance changes (with strain or over time) due in part to the morphology of staple yarns and to the fact that the conductive elements were not always on the yarn surface.

The R.Stat/P yarn results were often the most variable of each set of tests and, as such, the results were deemed to be non-repeatable and unrepeatable, rendering this type of yarn unsuitable for use as an accurate measure of strain or resistance variation. In addition it has been known for metal salt coating yarns to present adhesion and corrosion resistance problems [72] which would limit this type of yarn for use if exposed to the elements. Whilst the Stainless Steel Wire yarn showed a wide strain and change in specific stress range, the resulting change in resistance was very small, often $<1\Omega$, potentially making it too sensitive for use with a highly extensible textile product. In addition, it has been found that when using conductive yarns that contain exposed metallic components, there is a heightened propensity for them to become damaged due to exposure to moisture and fatigue during use [143].

The remaining yarn, Resistat F9301, exhibited properties and behaviours that displayed significant advantageous properties and performance levels that indicated the potential for modification (by altering the material composition or choosing a different yarn morphology) which may create a more suitable textile strain sensor.

The Nylon base polymer ensured a moderately wide strain range and the relatively high specific stress at break values were achieved. In addition the repeatability of the resistance variation was acceptable through all of the mechanical-electrical tests. This repeatability of results could be attributed to the simple morphology of the yarn (two-strand continuous filaments, one conductive one non-conductive), and the use of a Carbon filler when the theories of Quantum Tunnelling are applied. Thus in the Chapter 6, the potential to exploit Quantum Tunnelling mechanics will be overviewed along with assessing a range of Carbon-based fillers, polymeric materials and a number of yarn morphologies in order to determine the optimum choice for the desired strain sensor.

Chapter 6

Sensor Development

Chapter 6
Sensor Development

Based on the experimental work carried out in Chapters 3, 4 and 5, and the deduction that the yarn type with the greatest potential for investigation as an optimised textile sensor yarn was the Resistat F9301, it was decided to further investigate conductive carbon fillers dispersed into polymeric materials in order to create a textile strain sensor. This would require an assessment of the achievable strain sensitivity and usable region, the types and properties of conductive carbon particle fillers and carrier polymer, and the resultant yarn structure. The 'optimised' yarn would then be spun and the resulting yarn characterised mechanically and electrically, prior to the design paradigm being created.

6.1 Designing the Performance of a Textile-Based Strain Sensor

An important factor to consider when designing a textile based strain sensor is how the change in resistance reacts to the changing strain as, whilst an ideal strain sensor would react linearly, this behaviour may not be attainable when using textile materials. It can be seen from Figure 6.1 that the already developed strain sensors (as reviewed in Chapter 2) have different modes of behaviour and operate at different strain levels, for example, whilst most of the strain sensors developed exhibit an increase in resistance on straining, the Respibelt and PPy-coated fabric exhibit a decrease. In addition, the PPy and CFR covered fabric sensors operate at the lower end of the strain range, from 0 - 20% extension whilst the Respibelt works at the upper end from 35% – 90% extension.

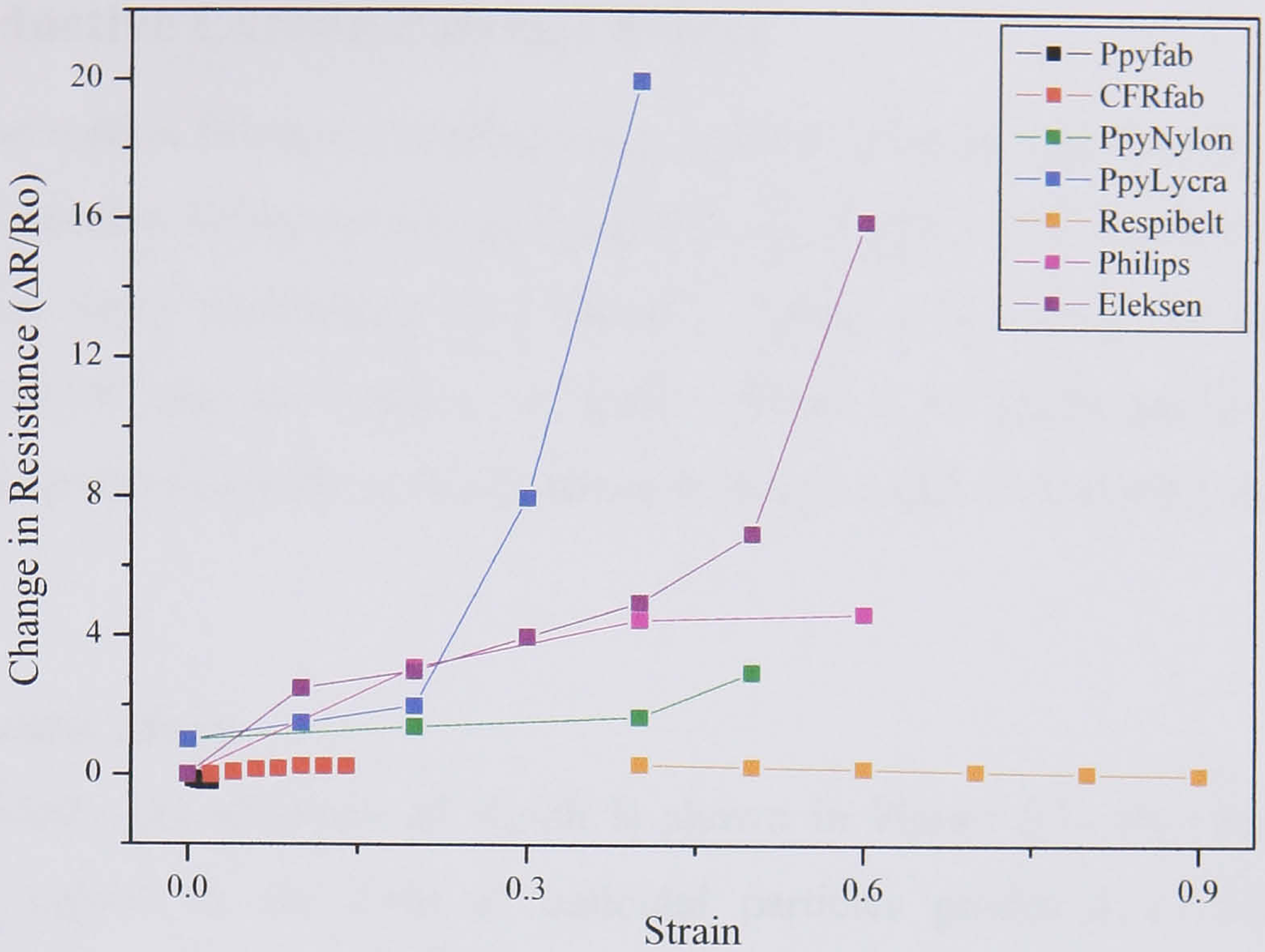


Figure 6.1 Comparison of Strain Sensor behaviour

Illustrative graph composed from the graphical information presented in Chapter 2.

The degree of change in resistance ($\Delta R/R_o$) also varies between the sensors from 0 to -3% up to 20%, but of specific interest is the strain sensitivity of the yarns, as it is clear that some sensors exhibit a far smaller change in resistance on straining than others, as typified by the Respibelt compared to the PPy-coated Lycra monofilament. It can also be seen that some of the materials, such as PPy-coated Lycra fibre and the Eleksen yarn exhibit two distinct regions of strain sensing, prompting the decision over which of the areas should be considered usable.

Of the myriad variables that can be defined and optimised in order to reach the required level of performance, the most easily controllable within the scope of this project are the yarn structure (as discussed in section 4.4), the conductive particles used and the carrier polymer (sections 6.2 and 6.3).

6.2 Conductive Carbon Polymer Fillers

Conductive carbon fillers are available in a number of forms with Carbon Black and Carbon Nanotubes being commonly integrated into polymers to induce conductivity. Carbon has many advantages over metallic fillers in that it is not sensitive to oxidation [144] and the addition of carbon fillers to polymers can improve the mechanical properties such as tensile strength (below a certain loading level).

6.2.1 Carbon Black

Carbon blacks, the structure of which is shown in Figure 6.3, are virtually pure elemental carbon in the form of colloidal particles produced by hydrocarbon dehydrogenation. Base particles of carbon black are typically <300nm however during processing they coalesce into aggregates, the basic indivisible entities of carbon black, and strong electrical forces maintain the bond between aggregates to form agglomerates [145].

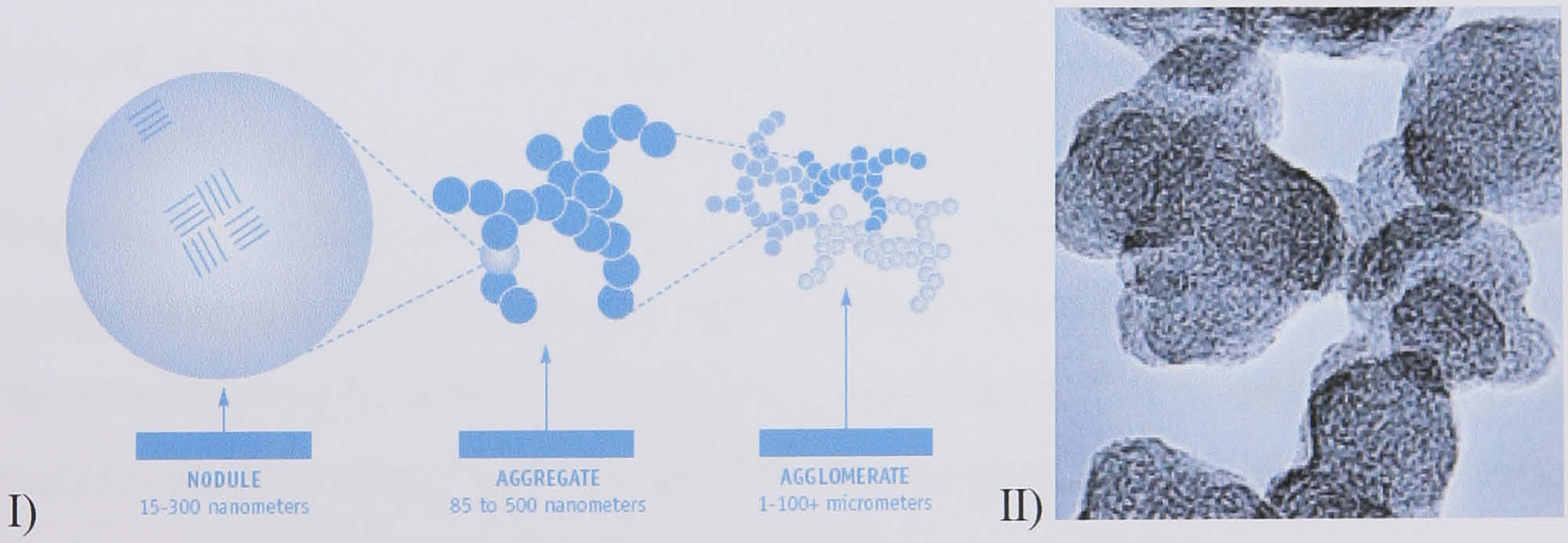


Figure 6.2 I) Sequence of Carbon Black Structure Development [145] II) Carbon black agglomerate [146]

It is important to note that there are a variety of factors to consider when choosing a Carbon Black for filler use, particularly the particle size, particle porosity and particle surface chemistry, as well as aggregate structure and distribution, as illustrated in Figure 6.4.

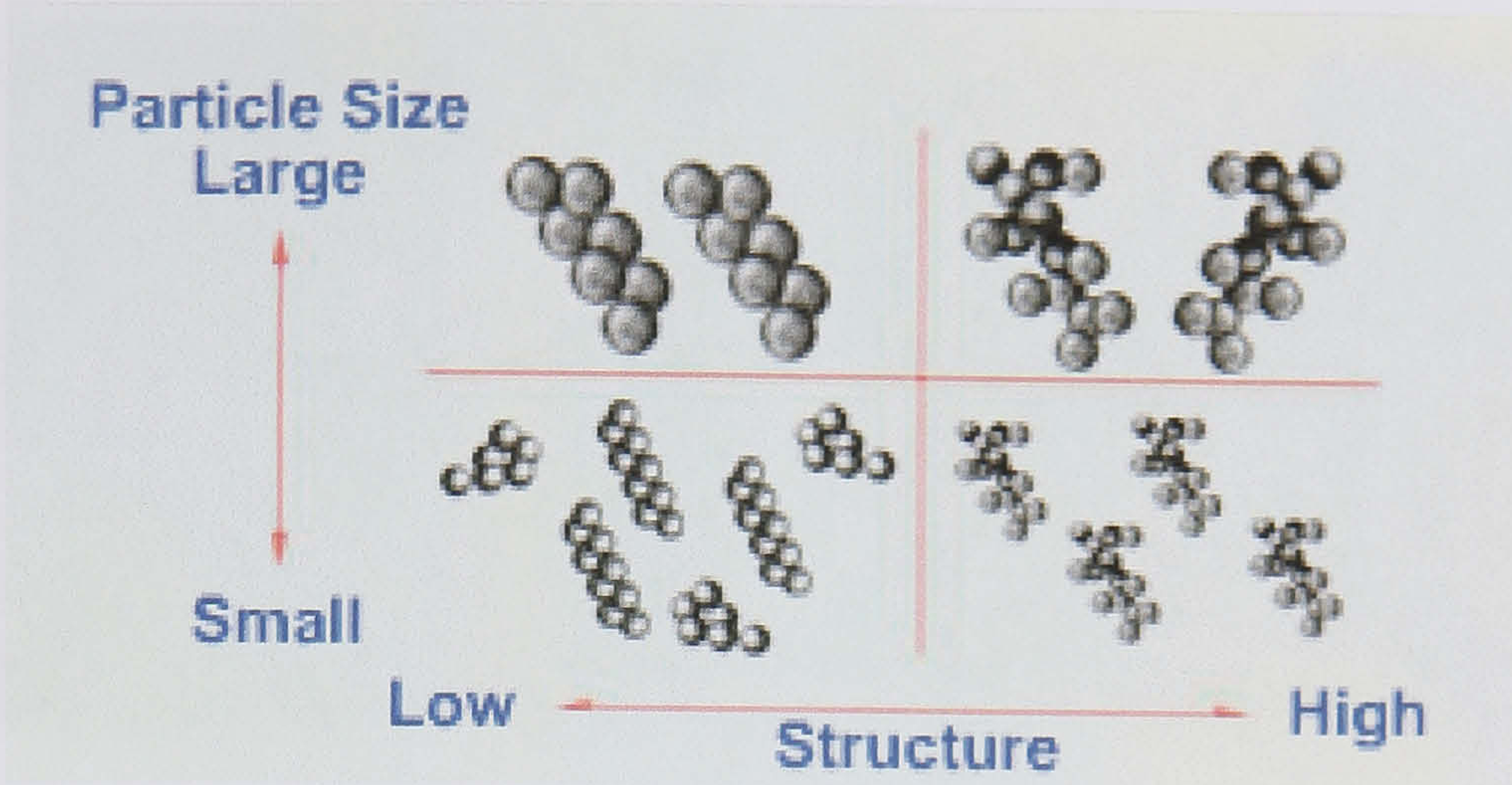


Figure 6.3 Variations of carbon black particle size and aggregate structure [147]

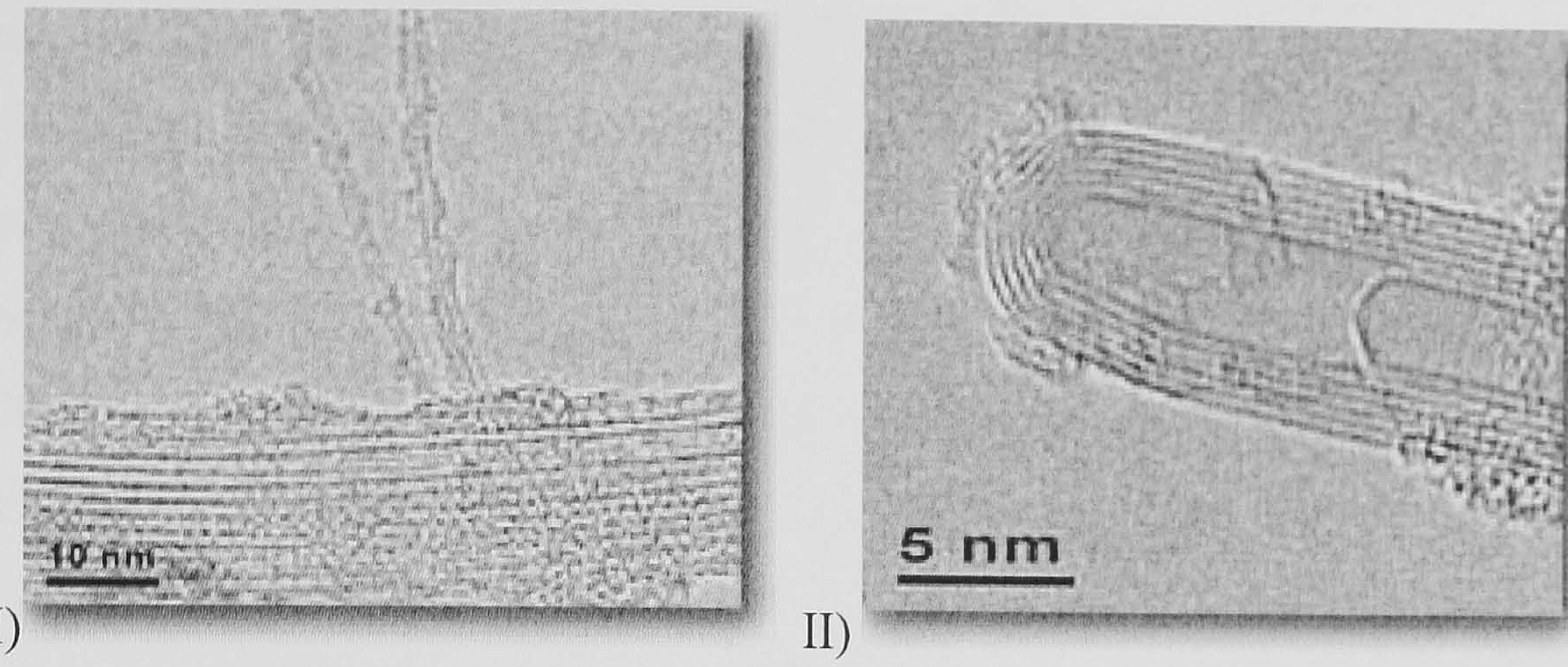
In order to achieve maximum conductivity, small particles should be used as these form aggregates with high surface area and high structure (i.e. high branching and chaining of the particles within the aggregate). The porosity of the carbon black particles is significant as increased particle porosity leads to decreased aggregate density [146]. Thus, if the particle porosity is high, the aggregate density will be reduced, leading to a greater number of aggregates formed and a resultant higher conductivity. Linked to the particle porosity is the void volume which can originate from the interstices between the carbon black particles due to their complex arrangement and porosity. Carbon black materials with a high void volume enables the manufacture of a carbon network at low filler content [148]. Also, in terms of the particle surface chemistry, the higher the volatile content (i.e. the surface functionality) the lower the conductivity.

6.2.2 Carbon Nanotubes

Carbon nanotubes (CNTs) consist of carbon atoms connected in a cylindrical manner [149], and Ko [150] defined them as follows;

> "A single-walled carbon nanotube is a capped, close-ended tubular structure with a wall thickness of one graphene sheet layer (one layer of carbon atoms arranged in a hexagonal manner) assuming various orientations/chirality"

Single walled carbon nanotubes (SWNT) comprise only one cylinder, whereas multiwalled nanotubes (MWNT) contain two or more concentric graphene cylinders as shown in Figure 6.5.



I) II)

Figure 6.4 Carbon Nanotubes; I) single walled II) multi-walled [151]

SWNTs can be classified according to three crystallographic configurations - zigzag, armchair and chiral, depending on how the graphene sheet is rolled up [152] and this configuration determines the properties of CNTs, for example 100% of armchair SWNTs and ⅓ of all zigzag nanotubes are "metallic" whereas the rest are semiconducting.

CNTs exhibit very high aspect ratios whereby SWNTs are found to grow up to several centimetres long (i.e. 109 times their diameter) whilst MWNTs can attain lengths of up to 1cm whilst having diameters ranging from 5-100nm. The electronic transport properties of CNTs are dominated by a quantum size effect and the mechanical properties indicate bending flexibility. The resultant properties of CNTs include high tensile strength, thermal conductivity and the electrical conductivity performance is similar to that of copper, however CNTs are able to carry much higher currents.

6.2.3 Percolation Theory

Percolation theory has already been studied extensively by researchers [146-150] and it can be defined as being used to;

> "Predict the mechanical, rheological and kinetic properties of colloidal dispersions and polymeric materials and coatings" [153]

It concerns the phenomenon of a percolation threshold (Pc) being reached at a critical weight concentration of Carbon Black (CB) is achieved within a polymer. In samples where the CB content is below the Pc, samples act as insulators, whilst near to and above the threshold, samples act as conductors. In Percolation theory when the CB and the polymer are at Pc, a continuous infinite percolating network develops creating physically connected conductive pathways. It has been studied widely [153-157] with equations, expressions and graphical illustrations having been developed in order to explain the theory surrounding the exact level of carbon particle loading required to reach the percolation threshold in a number of polymers and materials. For example, the model shown in Figure 6.15, as developed by Balberg, illustrates an idealised high structure carbon black agglomerate structure embedded within a polymer, illustrating the close physical links required to enable tunnelling and subsequently electrical conductivity.

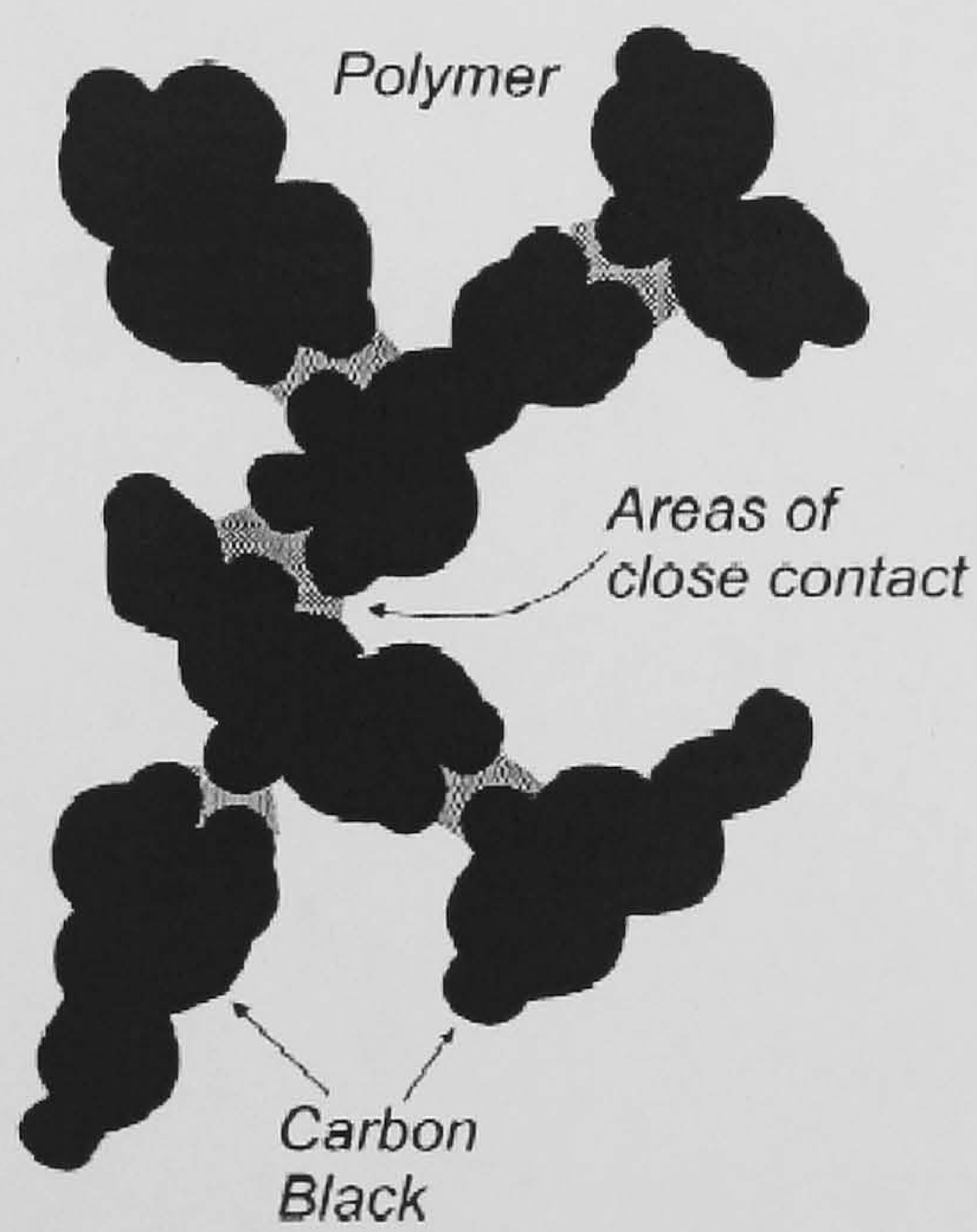


Figure 6.5 An illustration of [sic] model of a high-structure CB-polymer composite

Here, the distance between the nearest-neighbour closest inter-particle surfaces have narrow enough distribution to cause non-diverging distribution of the tunnelling-resistor values in the network .

When the CB and the polymer are at Pc, charge carriers are allowed to tunnel from one conductive cluster to another without being physical connected in order to create conductive pathways, and the effect of CB loading on the conductivity of a polymer being shown in Figure 6.7. This figure also shows the Pc when CNT particles

(Nanocyl 7000) are added to a polymer, which is significantly lower than for standard or highly conductive CB, and this also relates to the theory of tunnelling effects [158].

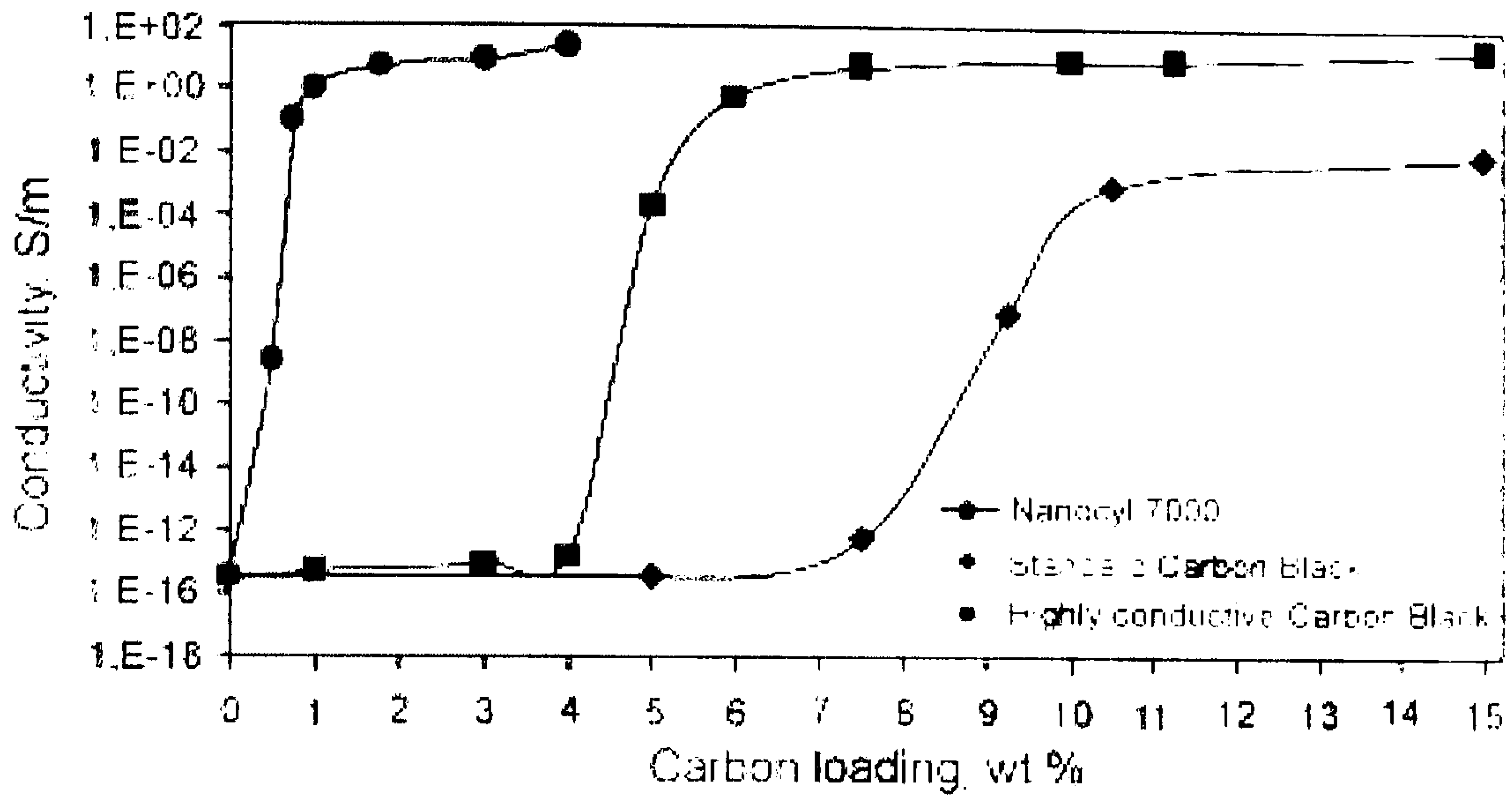


Figure 6.6 Comparison of percolation thresholds for Carbon Nanotubes (Nanocyl 7000), CB and highly conductive CB [158]

This difference in percolation thresholds between CNT and CB can be explained by the different geometric aspect ratios of CNT (<100) compared to CB (>1), however it must be noted that percolation behaviour is also dependent on a variety of issues, such as the polymer polarity and the polymer surface tension, whereby both properties are proportional to the critical content required to reach the percolation threshold. The viscosity of the polymer not only determines the quantity of work that has to be input to achieve a certain level of dispersion [159], but it also affects the percolation threshold as the carbon black structure degrades as the shear viscosity during processing increases, thus increasing the percolation threshold. Whilst processing carbon filled yarns, carbon black aggregates are 'rejected into interspherulitic boundaries' [155] during crystallization, hence in semicrystalline polymers the aggregates tend to concentrate in the amorphous regions.

6.3 Carrier Polymer

In order to fulfil the performance requirements of the strain sensor, the carrier polymer should exhibit strain capabilities compatible with the technical textile fabric onto which it is integrated (the fabric strain would be dependent on the product application, material used and method of construction), high elastic recovery properties and reasonable force at break values. It is also desirable that it should be resistant to the effects of moisture, chemicals, temperature fluctuations and UV light however these are idealised properties not all of which are normally achievable with textile polymers. A number of polymers with properties approaching the ideal were assessed, including Polyester, Polybutylene Terephthalate (PBT), Polypropylene (PP) and Thermoplastic Polyurethane (TPU), all of which possess advantages and disadvantages with respect to the required sensor performance characteristics, and eventually it was deduced that Nylon possessed the most appropriate mix of physical and mechanical characteristics.

There are several types of Nylon available, from Nylon 3-12 [160], and they are typically strong, elastic, chemically stable, abrasion resistant and have low moisture absorbency and, as discussed in Chapter 5.7, the electrical resistance of nylon yarns is inversely proportional to the cross sectional area thus the main method of electrical conduction is volume conduction. The properties of PA 4.6 [161], including its high melting point and glass transition temperature (Tg), means that it is used typically for tyre cords, sewing threads, filters and felts. Nylon 6 and 6.6 are the most commonly used in traditional textile applications, with Nylon 6 being available in either regular or high tenacity grades. Both polymers have high breaking elongation, excellent recovery from deformation (part instantaneous, the remainder taking several hours), high abrasion resistance, high flex resistance and relatively low initial modulus meaning that it's particularly sensitive to stretching under low loads, however they are both sensitive to UV light and may undergo yellowing and degradation after prolonged exposure to sunlight. Nylon 6.10 [161] is primarily extruded into monofilaments and, when mixed with Nylon 6 or Nylon 6.6, the high wet knot tenacity and water transparency make it useful for fishing lines and nets. The higher initial modulus of Nylon 11 [161] means it is more rigid which gives better dimensional stability to repeated strain and better resistance to creep than the other polyamides and it has excellent abrasion resistance and a silk-like hand, however it is not commonly manufactured, whilst Nylon 12 is thermally stable and has already been used in conjunction with CNTs to produce a conductive yarn [162].

A comparison of Nylon 6 (24dtex), Nylon 6.6 (92dtex) and Nylon 6.10 (21dtex) yarns stress-strain behaviour is shown in Figure 6.8. Nylon 6.10 exhibits regions of stress-strain linearity at both low (0-10) and high (10-30) strain levels, and its low initial modulus means that it is easily deformable under low load, it exhibits good elastic recovery and it has better fatigue resistance than Nylon 6 and 6.6. As such, it was decided to utilise Nylon 6.10 polymer as the carrier.

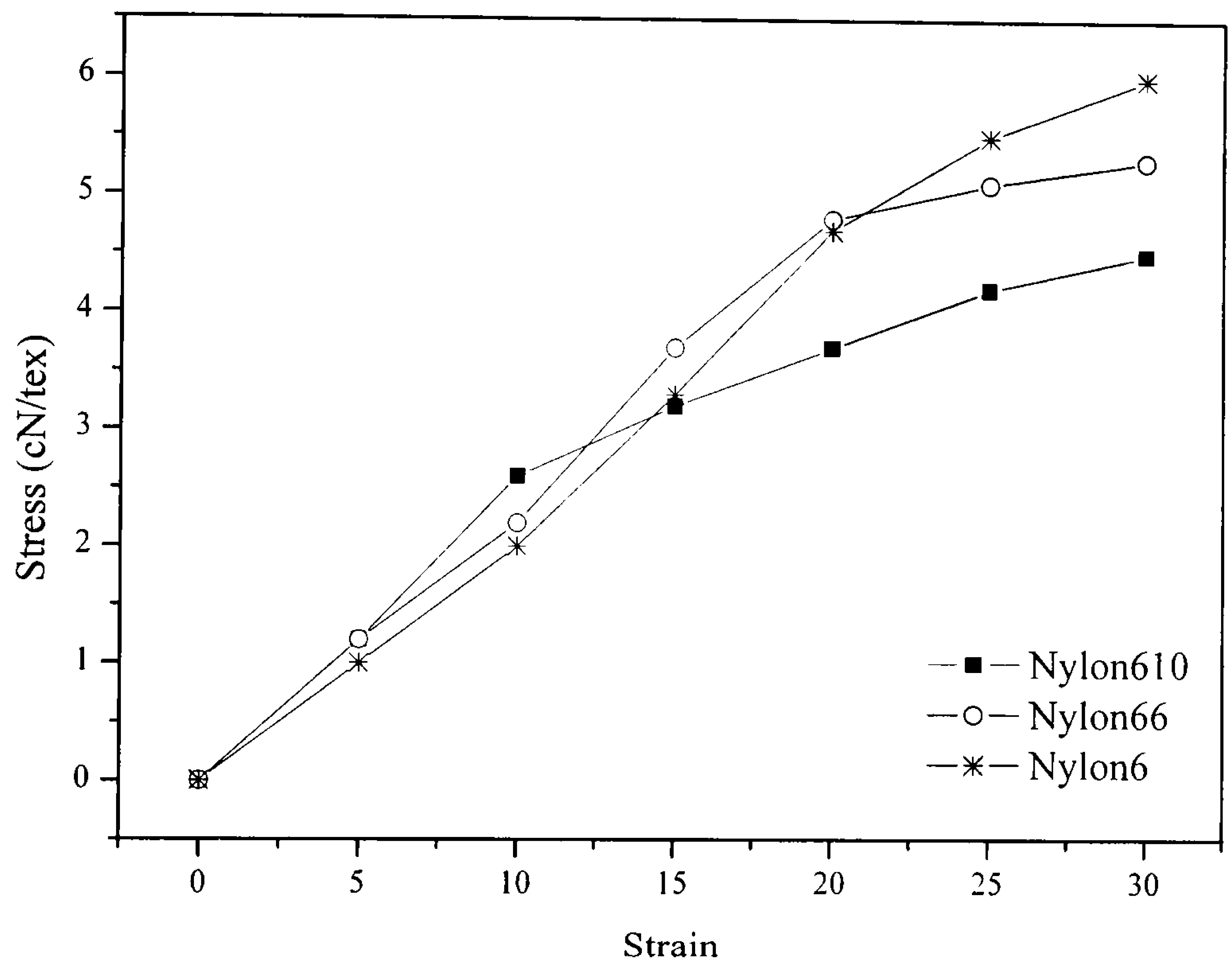


Figure 6.7 Stress strain behaviour of Nylon 6, Nylon 6.6 and Nylon 6.10
Graph comprised from values given in manufacturers [163] specifications.

Nylon 6.10/MWCNT composites have been developed using an *in situ* interfacial polymerisation method to minimise the aggregation of the MWNT and thus improve the particle dispersion, and the resulting changes in the Nylon 6.10 can be seen in Table 6.2. As expected, there is an increase in the conductivity of the material, as well as an increase in the tensile strength and stiffness, although there is an accompanying reduction in the elongation at break.

Table 6.11 Properties of Nylon 6.10 and Nylon 6.10/MWCNT (0.1 wt.%) composites [164]

Material	Tensile strength (MPa)	Young's modulus (MPa)	Elongation at break (%)	Conductivity (S/cm)
Nylon 6.10	33.5±1.2	886±12.4	11.9±1.4	2.1×10^{-17}
Nylon 6.10/MWNT	43.9±1.1	1352±11.8	4.5±0.8	6.1×10^{-12}

6.4 Experimental Manufacture of Textile-Based Strain Sensor Yarns

It was decided to spin monofilament yarns using a Nylon 6.10 carrier polymer and a mixture of CB and CNT. The aim of mixing CB and CNT was to maximise the conductivity whilst minimising the amount of each filler that needs to be added; in the hope that the CNT would act as a bridges between the CB particles, thus reducing the likelihood of the particles separating and losing contact and so reducing the conductivity.

The conductive element of the Resistat F9301 yarn had a Carbon Black content of 4% (concentrated at the fibre surface) and a Teijin Monofilament conductive bicomponent yarn [165] comprises up to 20% of CNTs in the sheath around a non-conductive core. Work carried out Lee et al. [166] using CNT and CB in HDPE, showed that at least 15% CB was needed to induce conductivity in the polymer, and that between 20-25% CB allowed the formation of tunnels for electricity transfer, as shown in Figure 6.9. Harlin et al [142] concluded that in order to reach percolation and produce polymers/yarns with good conductivity approximately 15-35% carbon filler and 2.5% SWNT would be required to ensure good conductivity.

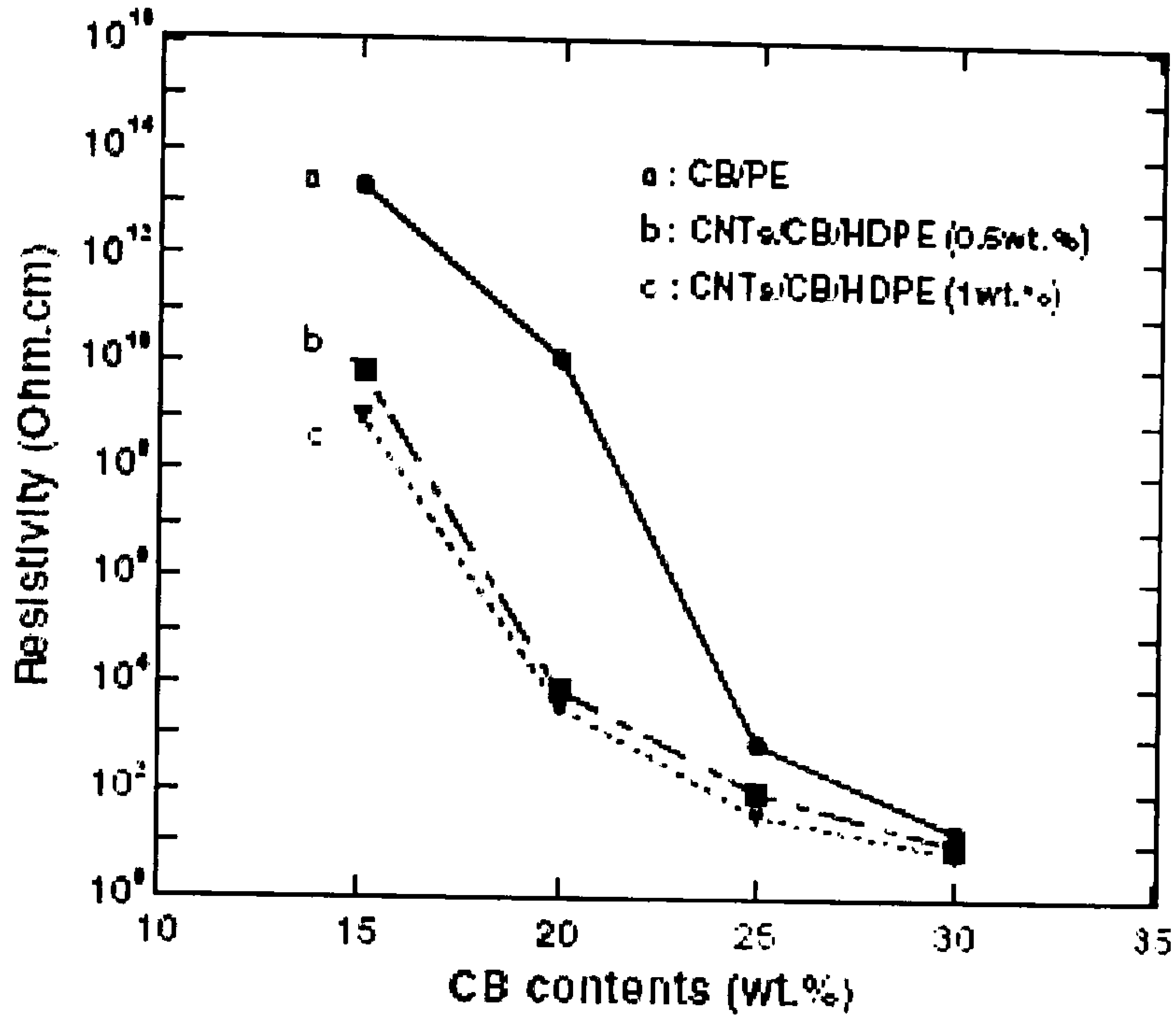


Figure 6.8 The resistivity of nanocomposites with and without MWTs at room temperature [166]

However, it is understood that the addition of CB to a polymer creates difficulties in spinning, and as such it was hoped that by reducing the amount of CB used and slightly increasing the amount of CNT used, it would still be possible to achieve conductivity. Also, it remained to be seen whether the effects shown in Figure 6.8 would be amplified or minimised due to the different filler loading and carrier polymer.

6.4.1 Materials

Nylon 6.10 was mixed with Carbon Black VXC72R (particle size range 10-20nm, aggregate size range 170-210nm) and the CNT (as chosen from the materials available by the researcher in the School of Physics and Astronomy who carried out the compounding) was a vapour grown carbon nanofibre, VGCNF Pyrograf III PR-19PS [167] which is smaller than continuous or milled carbon fibres (5-10μm) but significantly larger than carbon nanotubes (1-10nm). The properties of a number of Pyrograf III grades can be seen in Table 6.3.

Table 6.12 Vapour Grown Carbon Nanotubes - Pyrograph III properties

Nano-fibre Type	**Nano-fibre Grade**	**N_2Surface Area, (m^2/gm)**	**Dispersive Surface Energy, (mJ/m^2)**	**Moisture Content (%)**	**Iron Content (ppm)**	**PAH Content (mg PAH/g fibre)**	**Density (gm/cm^3)**
PR-19	AG	10-20	20-40	<5	<14,000	<1	1.95
PR-19	**PS**	**20-30**	**120-140**	**<5**	**<14,000**	**<1**	**1.95**
PR-19	LHT			<5	<14,000	<1	
PR-19	HHT	15-25	265-285	<5	<100	<1	
PR-24	AG			<5	<14,000	<1	
PR-24	PS	50-60		<5	<14,000	<1	
PR-24	LHT			<5	<14,000	<1	
PR-24	HHT			<5	<100	<1	

6.4.2 Compounding Methodology

The compounding was performed on a Eurolab 16 co-rotating twin screw extruder and the temperature profile was flat (i.e. the heated zones of the extruder were at the same temperature). The feed port was water cooled to the 260°C and the extruder was fitted with a cylindrical die with a diameter of 3mm. The extruded strand was drawn off through a water bath before being chopped into pellets.

The components of each batch were pre-weighed to give the required percentages (i.e. 90g of PA6.10 and 10g of VGCNF for 10w/w% VGCNF). Where both VGCNF and Carbon Black were used together, they were mixed together by shaking in a sealed polyethylene sample bag.

The extruder ran at a screw speed of 100 rpm and the PA6.10 pellets were fed in by a single screw feeder at the feed port. The feeder is a volumetric design so the feed rate is not constant but was initially set to 7g per minute. Once the nylon was extruding in a stable manner the carbon powder was fed into the feed port by hand using a spatula and once all the carbon powder had been fed into the machine the nylon was allowed run until the feeder was empty.

The collected pellets were composed of a mixture of both unfilled and filled nylon. This mixture was then shaken in the bag and fed into the single screw feeder once more so that the pellets could be blended again, with the hope that this would result in a homogeneous final product having the required ratio of components. The equipment used to compound the materials is illustrated in Figure 6.10.

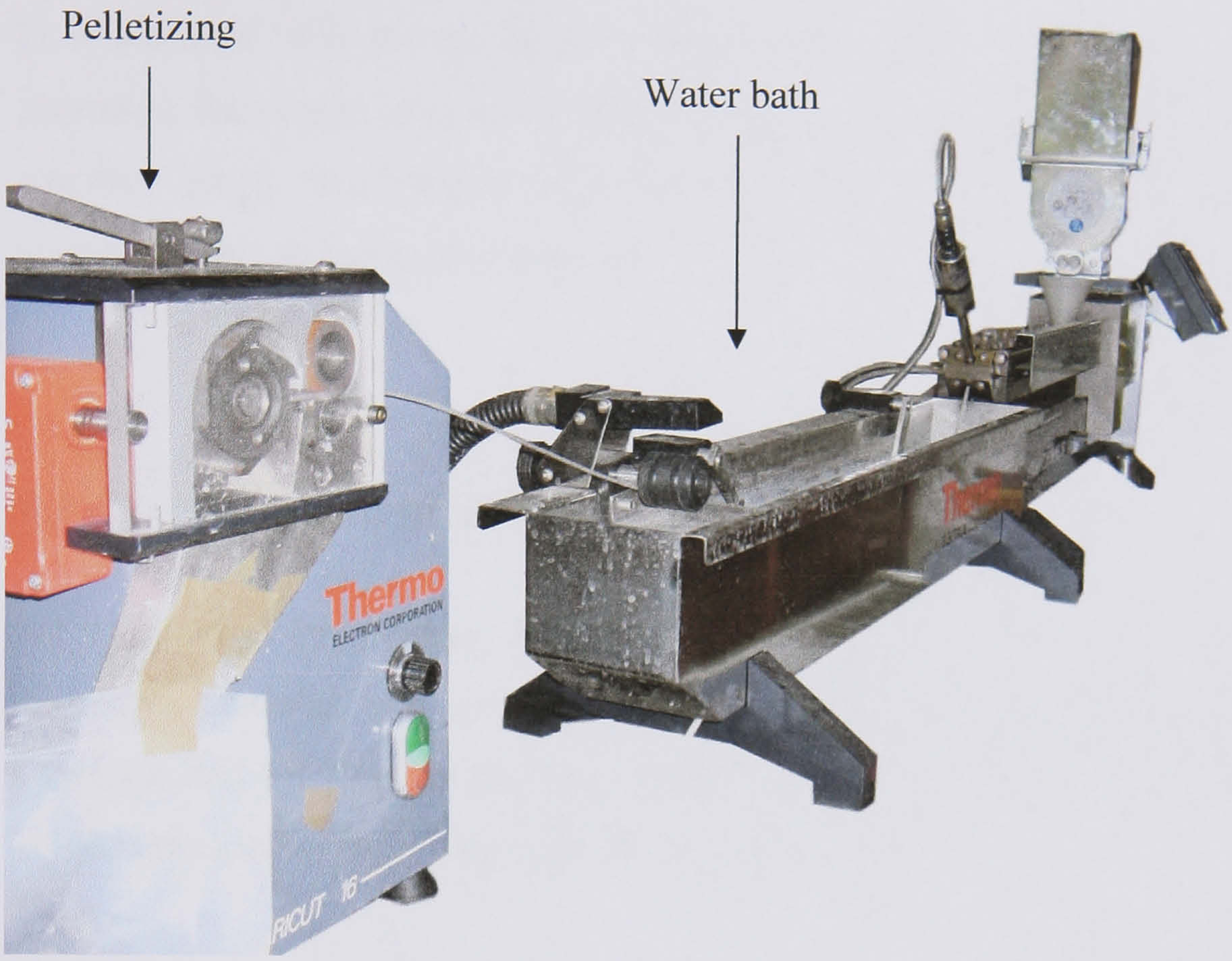


Figure 6.9 Eurolab 16 equipment used to compound PA6.10, Carbon Black and Carbon Nanofibres.

Based on information given from a variety of CB and CNT loaded polymers [144, 165, 166, 168-171] it was decided to create yarns with varying proportions of CB and CNF, ranging from 0 – 10%w/wt. The compounded pellets were manufactured and delivered in the ratios shown in Table 6.4.

Table 6.13 Compounded pellets of PA6.10, Carbon Black and Carbon Nanofibres manufactured

Sample	% PA6.10	% CB	% CNF
1	90	-	10
2	85	10	5
3	90	5	5
4	95	-	5

6.4.3 Spinning Methodology

In accordance with the equipment available within the department, a Davenport Extrusion Rheometer (Serial No. 406/58) with a 0.5mm capillary radius and 20mm capillary length was used to spin the yarns. The yarns were spun at 270°C at 1.5cm/min and undrawn after take-off.

6.5 Characterisation of Sensor Yarns

6.5.1 Physical Properties of Yarns

The yarns produced were very brittle, so much so that it created difficulties during extrusion and winding. As the yarns could be broken on stretching by hand, stress-strain testing using an Instron could not be carried out.

6.5.2 Electrical Properties of Yarns

The yarn electrical resistance results, as shown in Table 6.5, are the values as measured with the equipment used in previous Chapters (4 & 5). For the yarns whose resistance was off-the-scale (OFL), they were re-tested using a Keithley 614 Electrometer, capable of measuring up to $2x10^{11}\Omega$, however these yarns could not be measured with sufficient accuracy even on the Giga-ohm scale.

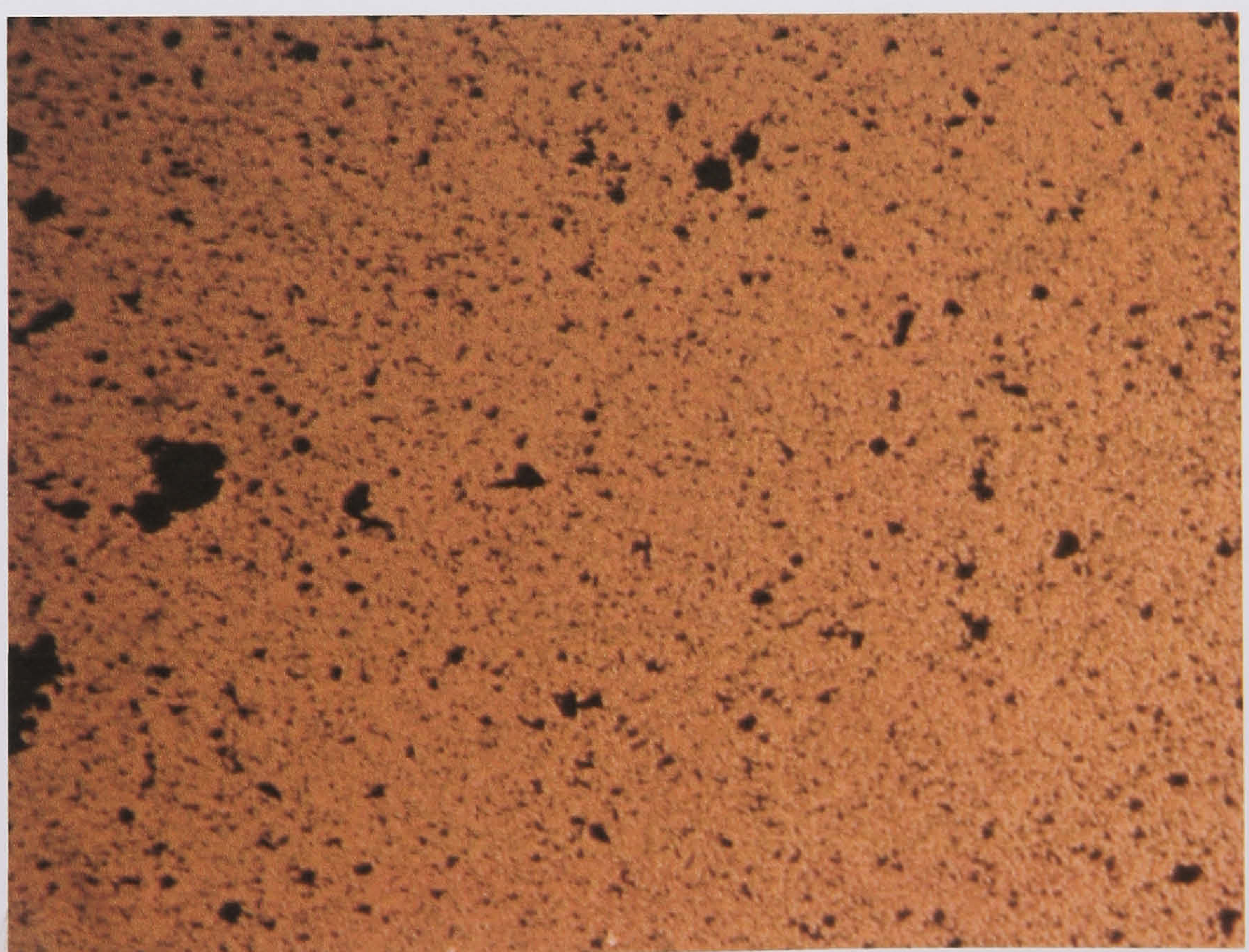
Table 6.14 Resistivity of Yarns Test Results

Sensor Yarn	Resistivity	Sample gauge length
5% CNF	OFL	<5cm
10% CB	OFL	<5cm
5% CB	OFL	<5cm
5% CNF, 5% CB	OFL	<5cm
5% CNF, 10% CB	OFL	<5cm

6.5.3 Conductive Particle Dispersal

In order to determine the cause of the yarns' electrical performance, the dispersion of the CB and CNF within the PA6.10 was determined visually using a test methodology based on BS ISO 11345:2006 section 6.3.2 [172], 3mm long sections of yarn or 1-2 polymer pellets were heated between two microscope slides under constant pressure to 230ºC degrees for 10 minutes. The melted polymer was then evaluated under the microscope and digital images taken for particle dispersion observation.

Visual analysis of the digital images indicate that there are clear areas of significant conductive element agglomeration, as shown in Figure 6.11, suggesting that the conductive particles have not been sufficiently dispersed throughout the polymer during the compounding process and/or that the method of yarn manufacture contributed to the agglomeration of the conductive particles.



I)

II)

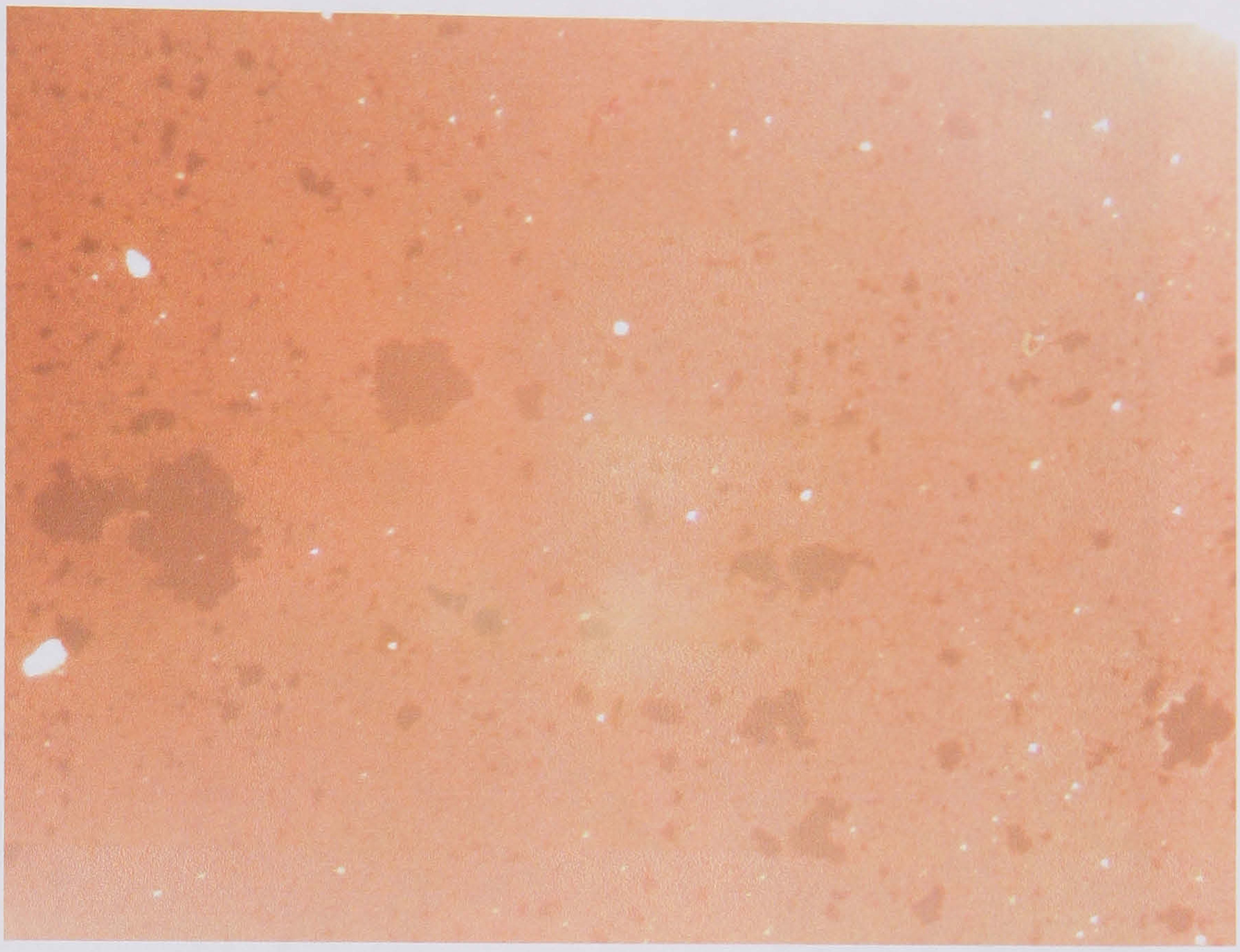


Figure 6.10 Visual analysis of the conductive element dispersal in I) 5% CNT in PA6.10 and II) 5%CB/5%CNF in PA6.10 yarns

This phenomenon is also seen in the digital images of the 10%CB / 5%CNF and 5% CB samples (Appendix 3).

Visual analysis of the conductive element dispersal within the polymer in Figure 6.12 shows another common observation along the length of a number of the yarns spun, this being a lack of conductive particles within the polymer and again this is a significant hinderance to the attainment of electrical conductivity. The same phenomenon can be seen in the 5% CB sample (Appendix 3).

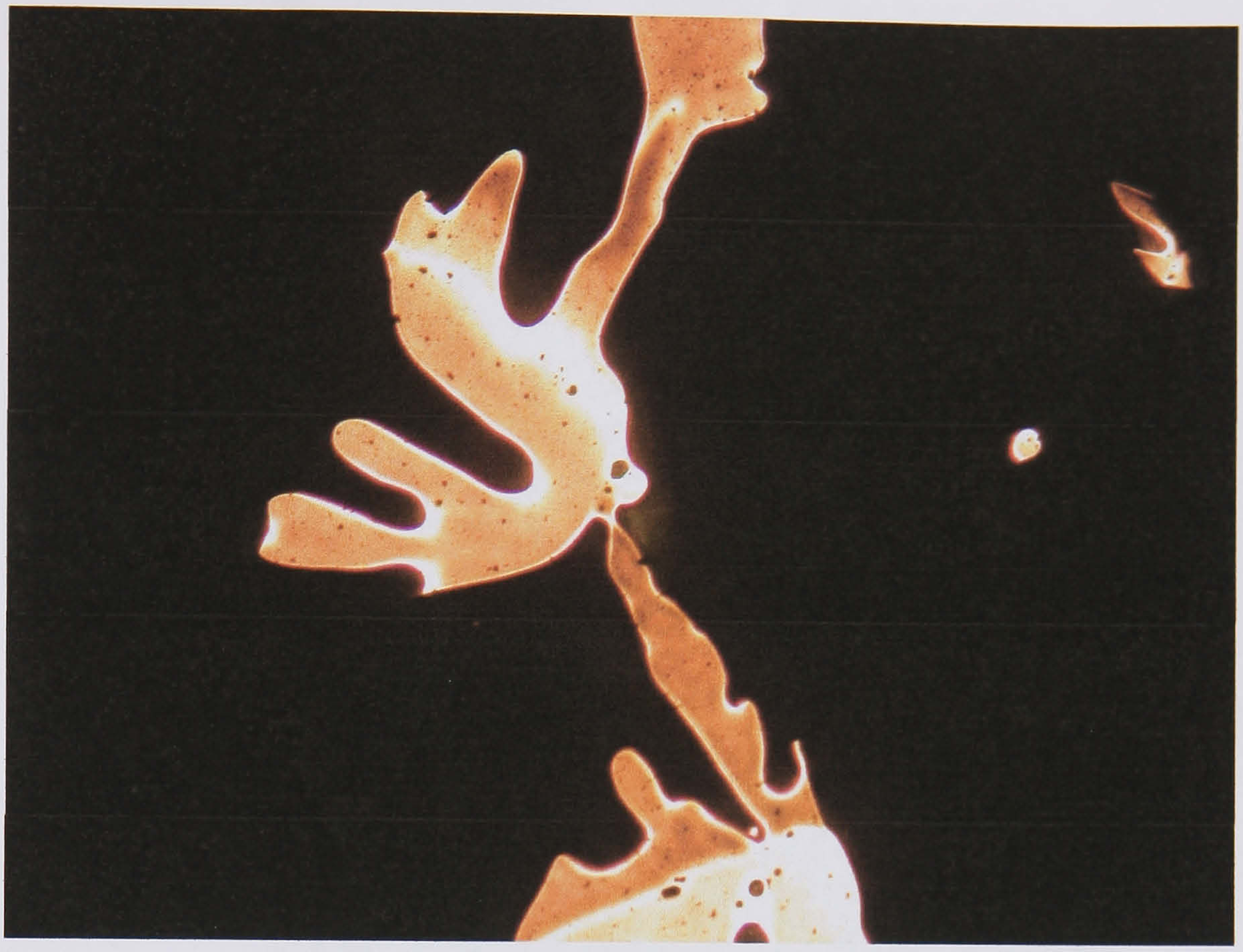


Figure 6.11 Visual analysis of the 10% CB in PA6.10 conductive element dispersal

6.5.4 TEM Analysis of Yarns

TEM analysis was carried out on the samples, with images taken of the longitudinal cross-section of the yarns in order to determine whether there is connection between the conductive tubes and particles. The samples were prepared using the acrylic resin LR White [173] and sectioned longitudinally using a microtome. 31 images in total were taken using a Philips CM10 Transmission Electron Microscope at a variety of magnifications (as indicated on each image descriptor).

As can be seen from the longitudinal cross section images in Figure 6.13 (I) and (II), whilst there are areas where there is concentrated grouping of the CNF or areas where they are physically close, these conductive pathways are not continuous, hence the lack of formation of an electrically conductive network.

I)

II)

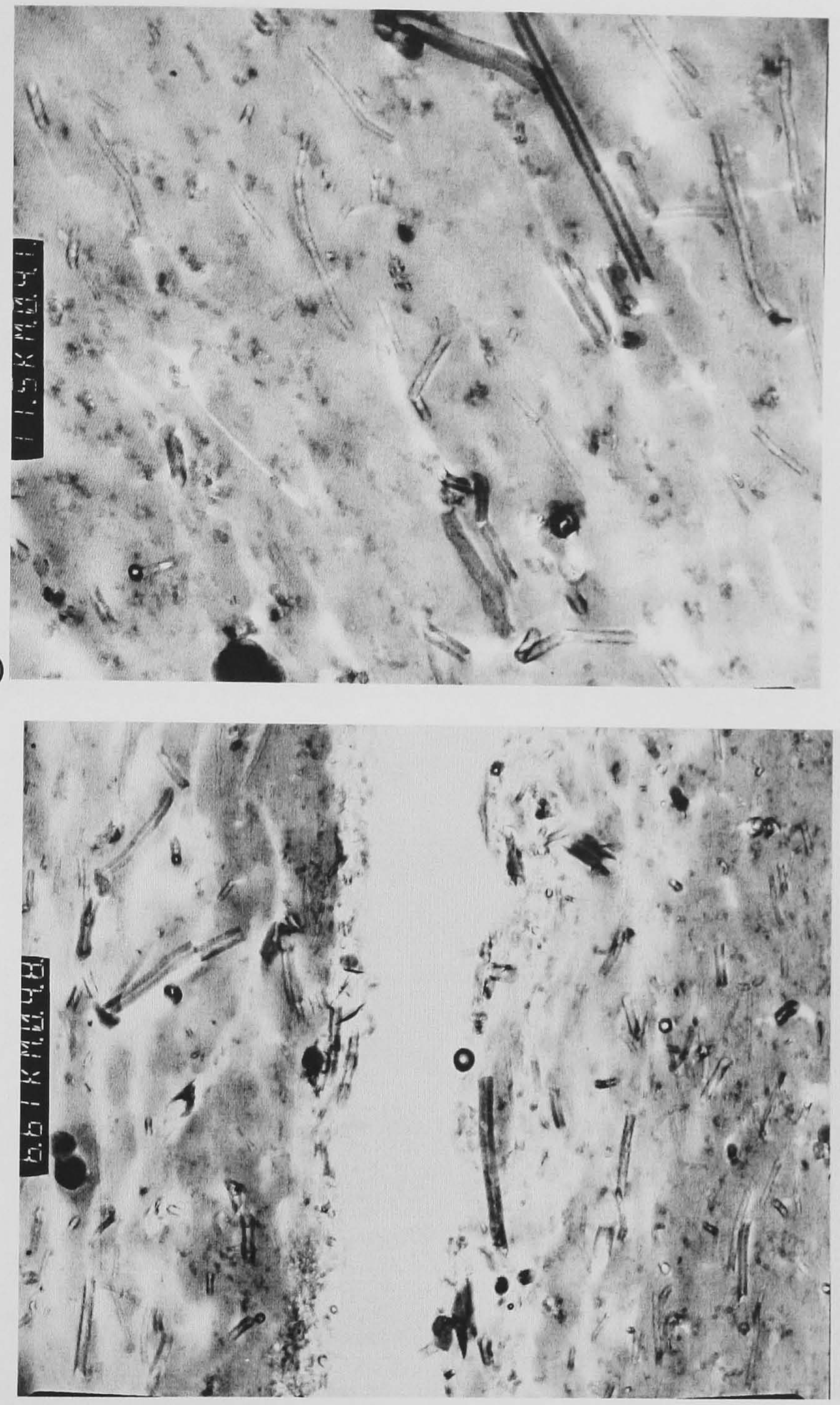
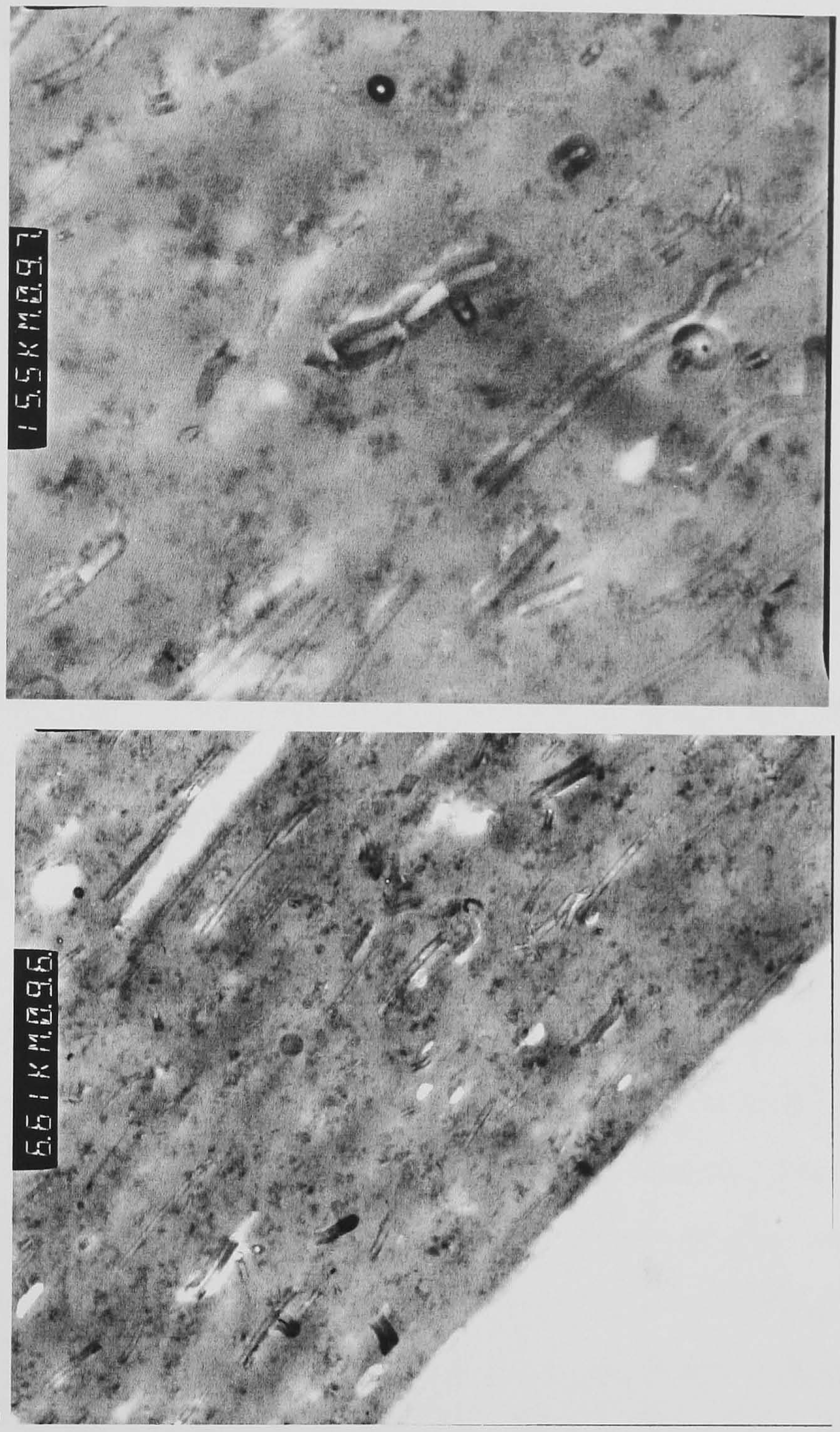


Figure 6.12 TEM images of longitudinal cross-sections of the10% CNT, 90% PA6.10 yarn at I) 11,500x and II) 6,600x

Figures 6.14 (I) and (II) are the longitudinal cross-sections of the 10% CB, 5%CNF particles embedded in PA6.10. In this instance, it can be observed that the CB particles are unevenly dispersed, leaving gaps unfilled by conductive particles, and there are few connective pathways formed between the CNF particles.

I)



II)

Figure 6.13 Longitudinal cross-section of the 10% CB, 5% CNT and 85% PA6.10 yarn I) 15,500x and II) 6,600x

The TEM imaging results for the 5% CB, 5% CNF, 90% PA6.10 yarn and the 5% CNF, 95% PA6.10 yarn are similar, as can be seen in Appendix 3.2 where again the dispersal of the conductive particles is observed to be insufficient for the establishment of continuous conductive networks to have formed.

6.6 Discussion

The objective of constructing an electrically conductive textile sensor yarn was not met through this experimental stage, a fact that may be attributed to a number of different issues reliant upon the carbon particle mix, the polymer matrix and the method of construction.

Visual analysis of the microscope images and the TEM images appears to indicate that there was a degree of insufficient dispersal of the conductive particles (CNF and CB) throughout the PA6.10 polymer which may have contributed to the yarns exhibiting no measurable electrical conductivity. When analysing the method of compounding the conductive carbon particles with the nylon, it could be deduced that, in lieu of the prolonged and thorough mixing of conductive materials prior to compounding that might ideally be required, shaking the separate materials together may not have provided enough of a mix. In addition, the compounding method used involved neither the use of other additives, such as supercritical carbon dioxide [174], to aid dispersion of particles throughout the polymer, nor were the conductive particles dissolved into a solution to aid mixing and increase the formation of conductive chains. Hence continuous conductive pathways may not have been formed either through physical connections or close particle tunnelling, and this lack of measurable conductivity was experienced when resistance testing the unspun polymer chips. This information will form an element of the design paradigm being created that would seek to avoid such issues occurring by ensuring that optimal material and processing conditions are used.

Another contributing factor to the unmeasurable electrical conductivity may have been the conventional method of extrusion coupled with the basic production equipment. Processing of carbon loaded polymers becomes increasingly difficult as the carbon content increases, due to the increased viscosity of the polymer and the increase in shear properties. As conductive networks and pathways are formed randomly using conventional extrusion methods [175], a higher carbon content is required to ensure pathways are made. Thus, this is something of a circuitous situation, as even if the resultant yarns are conductive, the mechanical properties, particularly in terms of stretch, will have been severely degraded (as was experienced with the 10% CB/90% PA6.10 yarn). According to Yanagizawa and Kodiara [176] the average volume resistivity for fibres decreases when winding speeds increase, however the yarns extruded were so viscous and brittle that they could not be wound up or drawn on exiting the spinneret, thus any latent conductivity could not be induced. This outcome will also inform the design paradigm relating to the processing parameters and can be linked to the decision making process when deducing which polymer to use. Given the resultant difficulties in extruding the yarns, optimising the viscosity and shear properties of each polymer type will also be addressed by the design paradigm.

Whilst the samples spun did not exhibit measurable levels of electrical conductivity, despite there being research papers available stating that this aim is achievable [153] [154-156, 164, 166, 176], there are sufficient differences in the compounding methods and materials, and processing methods to ensure that the results were not due simply to researcher error. As such, the design paradigm will cover the parameter associated with; conductive particle properties, polymer properties, compounding methodology and yarn manufacture and structure.

Chapter 7

Conclusion and Further Work

Chapter 7
Conclusions and Further Work

Following the conductive yarn characterisation (Chapter 5) and the conductive yarn spinning (Chapter 6), it can be concluded that whilst Carbon Nanofibres and Carbon Black are conductive elements in their own right, the amount of these elements, their dispersal throughout the polymer and the yarn processing method will significantly affect the mechanical and electrical properties of the resultant yarn. Whilst the samples prepared exhibited no measurable electrical activity, the parameters that were assessed contributed to the development of the design paradigm.

7.1 Conclusions

In order to close the loop in terms of determining whether or not the research philosophy and principles were met, the results gained from all of the testing and observations will be analysed against the initial objectives.

7.1.1 Relationship between Research Objectives and Achievements

Objective 1: Critically review the current literature relating to yarn sensors in order to determine what work has already been done in this area and to determine where there are gaps in the knowledge.

A critical review of current literature was carried out in Chapter 2, highlighting that whilst research was being carried out on the development of electrically smart structures (yarns and fabrics) and products for a wide range of application areas and products, that a number of different technologies were being employed and each encountered their own advantages and limitations. In terms of the methods used to measure the electrical resistance of yarns, it was deduced that measurement of yarn resistance as opposed to capacitance (complex issues surrounding textile dielectric material), impedance or inductance (both of which produced noise artefacts which need to be filtered from the results) would be most suitable and would allow the use of equipment already available within the department.

Objective 2: Test and analyse the physical, mechanical and electrical properties of a number of commercially available conductive yarns such that those worthy of further characterisation can be determined.

The physical and mechanical properties of a number of commercially available yarns were tested in Chapter 3, in order to determine which yarns would be suitable for further investigation. The yarns tested covered a broad spectrum of material types (i.e. metallised polymers, carbon loaded polymers, 100% stainless steel) and compositions (i.e. continuous filament, staple, textured) and performance levels. Given that the research was focussed on developing a yarn with stress-strain and elastic/recovery properties similar to those of a technical textile substrate, yarns which could not be stretched or with minimal recovery potential were discarded, as were the yarns whose strength properties were not in the range of standard technical textile yarns.

In terms of the electrical conductivity, assessed in Chapter 4, the resistivity of each yarn was calculated and two comparisons were made. The resistivity results were compared against the values supplied by the manufacturer, the results of which highlighted disparities, and indicated that the method of testing and the parameters used (i.e. yarn tension, sample length, clamping method, test methodology) could influence the measurements gathered. The results were evaluated to determine which yarns were more or less electrically conductive, indicating that the yarns chosen span the spectrum of resistivity, from near conductors to near insulators.

Objective 3: Determine the relationship between the mechanical properties and the electrical properties of the yarns.

The experimental work of the mechanical-electrical characterisation of the commercially available yarns is documented in Chapter 5. A number of tests were carried out in order to determine the behaviour of the yarns under a variety of stress-strain conditions, and the resulting changes in electrical conductivity. Of the results gathered, one of the most important issues to be considered was the consistency of the yarns' reaction under the changing conditions. For example, whilst some of the yarns' resistivity values were favourable, their physical structure limited their usable regions in terms of elasticity and/or recovery, issues which might affect the choice of potential application for such sensor yarns. Other yarns' behaviour was erratic and unrepeatable, issues that would eventually affect the ability to predict the performance of a strain sensor as well as the repeatability and reliability of results.

Objective 4: Construct an electrically conductive textile yarn capable of sensing strain.

The experimental work carried out in the attempt to attain this objective is documented in Chapter 6 and, whilst the objective was not met, the reasoning behind why is a source of information to be fed into the design paradigm. In this experimental work, all elements of the design process were considered – the types of electrically conductive filler, the carrier polymer, the compounding method, yarn extrusion techniques and the yarn structure. Adjusting all or only one of the parameters might have resulted in the objective having been met and, as many of the parameters were beyond the control of the researcher to choose or change, these issues are reflected in both the design paradigm and the considerations for further work.

Objective 5: Derive a design paradigm from the information gathered to inform the design and construction of a textile sensor.

The attainment of this objective is discussed in greater details in Section 7.1.2 wherein Table 7.1 sets out a number of design considerations and their solutions relating to the construction of an electrically conductive textile sensor yarn.

7.1.2 The Design Paradigm

Design paradigms [177] are models of designed solutions to problems and can be used either to describe a design solution or as an approach to design problem solving. One of the Aim 3 / Objective 5 of this research was to develop a design paradigm for constructing a conductive textile sensor yarn such that the materials, yarn morphology and structure can be optimised prior to the commencement of manufacture. A summary of the desired properties of a textile based strain sensor is given in Table 7.1, the summation of which was based upon current literature and the surmised product/application requirements highlighted in Chapter 1.

Table 7.1 Desired properties of a textile based strain sensor

Parameter	Requirements
Operational resistance range	As long as the resistance range is measurable, the strain sensitivity (GF) of the sensor is of paramount importance.
Strain level	The strain level required would depend upon the product/application and it could be high or low as long as the recovery level was high and the results repeatable for cyclic testing.
Force at break	The required strength of the material would depend both on the application/product and the intended method of use (i.e. strain to break or cyclic testing).
Behaviour under different conditions (temperature, moisture, UV)	Ideally the sensor yarn would remain unaffected under changing environmental conditions or on exposure to UV or chemicals etc. otherwise hopefully the resulting change would be insignificant.
Yarn construction	The construction of the yarn should be such that the effect of damage, leading to issues of redundancy during use, can be avoided

The resultant design paradigm is detailed in Table 7.2, giving a summation of the most significant polymer and conductive carbon particle properties, as well as the processing parameters, required to construct electrically conductive textile yarns capable of detecting strain. The design considerations are split into sections for ease of understanding and, as textile strain sensors might be required to operate at any operation range, no specific values have been attached in order to avoid limiting its use.

Table 7.2 Design Paradigm for the design and construction of smart structures for technical textiles

Desired Property	Design Solution
Conductive particles	
Maximise the potential number of conductive particle aggregates	Ensure they have high porosity
Maximise conductive particle network potential using minimum loading	Ensure they have high void volume
Maximise surface conductivity of particles	Minimise the volatile content
Maximise the surface area of the particles to maximise aggregate surface area and high structure (i.e. branching and chaining)	Choose small particles
Greatest possible electrical conductivity levels	Use SWNT rather than MWNT
Polymer	
Ease of spinning even once loaded and minimisation of damage to conductive particles	Low viscosity
Tensile strength matches that of the technical textile to which it is attached/integrated	Well orientated – semi crystalline
Stretch properties match those of the technical textile to which it is attached/integrated	Inherent elasticity
Recovery properties match those of the technical textile to which it is attached/integrated	High tensile strength
Smart structure reacts to strain at low strain levels	Low initial modulus
Minimise excess energy produced at polymer-carbon interface	Low surface tension

Reduced conductive particle loading levels required	Low polarity
Minimise effect of moisture on resistance in different environments	Hydrophobic / low moisture regain
Minimise effect of temperature on resistance in different environments and during use	High temperature resistance
Compounding	
Ensure different particles equally dispersed in matrix	Thorough and repeated mixing
Ensure adequate dispersion through polymer matrix	Particle dispersal aids
Yarn manufacture and structure	
Minimise attrition (wear/abrasion) and degradation of conductive particles	Core-sheath structure (conductive core with protective polymer outer layer)
Improve orientation of particles within yarn and yarn itself	Slightly draw yarn
Engage conductivity of yarn during spinning process	Use electrospinning or similar method to produce yarn
Avoid redundancy issues	Multifilament yarn configuration
Repeatability and predictability	Avoid staple yarn configuration
Minimise conductive particle loading and therefore effect on yarn properties	Core-sheath structure
Aid stretch properties and strength of smart structure	Twist at regular intervals

Part of the difficulty experienced in developing a textile engineering design paradigm is that there is an inherent multi-level complexity due to the nature of the materials being used such as the behaviour of the materials during production. the effect of temperature and other variables (discussed in Section 7.2) The often unpredictable nature of fibre and yarn behaviour and performance. combined with the integration of conductive elements on a micro and nanoscale widens the number of variables to be taken into account, and the adjustment of one variable may result in the need to adjust all other variables or a significantly different performance from the yarn. Thus, these parameters and their solutions are neither exhaustive nor guaranteed to produce a yarn that operates at all performance levels, however it covers the main considerations to be taken into account and should aid researchers and developers to avoid timely and potentially costly unsuccessful experimental work.

7.2 Further Work

7.2.1 Dispersal of Nanoparticles

Investigation of methods of improving nanoparticle dispersal, both at the chip preparation stage and during yarn preparation could be carried out. During the course of this research project, a thorough investigation of the compounding was beyond the scope of this thesis as the compounding facility was not at my disposal and I depended on the time and convenience of the Physics Department to prepare a limited amount of material, and there was insufficient time to conduct a more intensive set of trials.

7.2.2 Other Conductive Fillers

Given the number of the commercially available conductive yarns characterised in Chapters 4 and 5, the potential for incorporating highly conductive nanoparticles such as metals (Copper, Silver) and Metal oxides, could be further investigated to determine whether lower levels of CB or CNF would be required in order to further increase the yarn conductivity.

7.2.3 Yarn construction

A secondary conclusion surrounds the preferred strain sensor yarn configuration. Difficulties were encountered using a simple extrusion method to produce a monofilament yarn, and potentially by using a bicomponent configuration, the electrically conductive elements could be concentrated in one part of the yarn, thus increasing the potential for conductive flow to be achieved. There are a variety of bicomponent configurations that can be spun, a number of which are shown in Figure 7.1. One of the most common types available is sheath-core which is typically used in binder fibres with a low-melting sheath around a higher-melting core. A bulked or crimped yarn can be produced using the eccentric sheath-core configuration if two different polymers with differing shrinkage rates are used and this crimping behaviour can be replicated and heightened using the side-by-side configuration. The pie wedge configuration is created such that the 'wedges' can be split to form microfibres, as is the islands-in-the-sea configuration where the 'sea' polymer is dissolved leaving the microfibre islands.

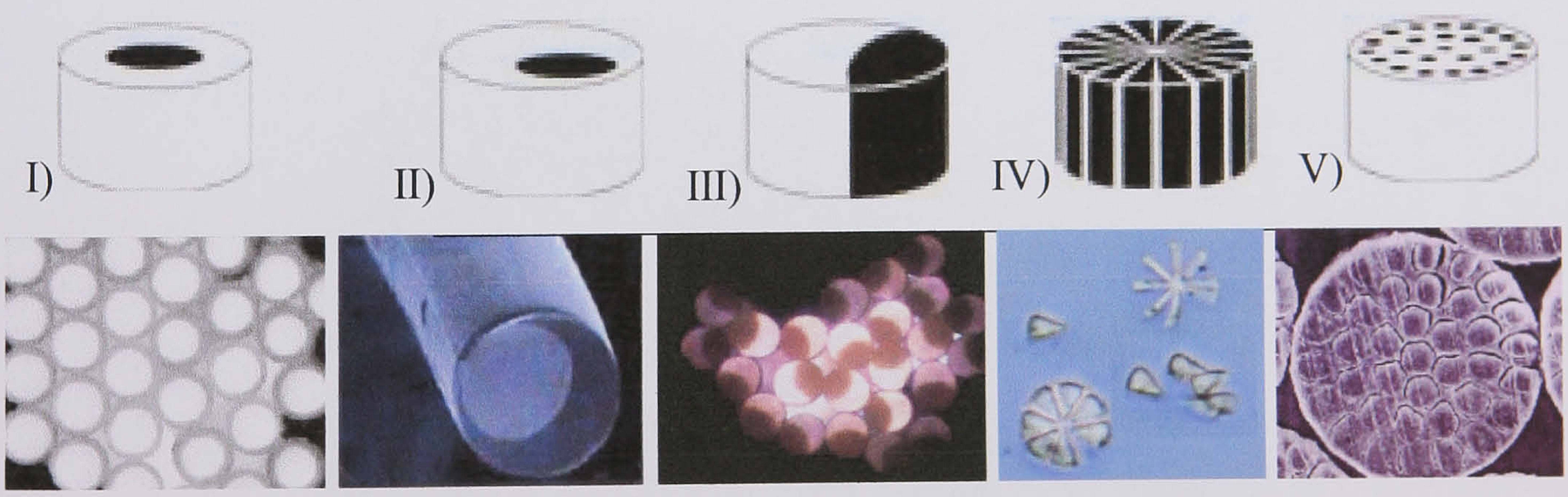


Figure 7.1 Bicomponent Fibre Configurations I) Sheath-Core, II) Eccentric Sheath-Core, III) Side by Side, IV) Pie Wedge and V) Islands in the Sea [178]

Of the bicomponent yarn types described, the most suitable for use as a strain sensor would be the sheath-core configuration with a conductive sheath (carbon filler in polymer) and a non-conductive polymer core. This would provide the yarn with an inherent elasticity and ensure that conductivity flow along the length of the yarn without overloading the whole yarn with carbon filler which would create stiffness and brittleness. Also, issues of redundancy may be overcome whereby, having a number of filaments in the yarn may mean that, in the event of one of the filaments breaking, the current will still flow through the yarn, and the bicomponent yarns resistance to abrasion and flexing will be improved.

7.2.4 Assessment of the Environmental Behaviour of Yarns

Two very important issues which must be taken into consideration when developing a textile sensor are those of the effects of moisture and relative humidity. Studying the effects on the durability and stability of sensor yarns with changes in temperature and moisture effects, as well as chemical and UV degradation would give further information for their characterisation.

7.2.4.1 Moisture and Relative Humidity

As can be seen in Figure 7.2 moisture is one of the most important factors in determining the resistance of textile materials as it can cause a variation of resistance over a range of at least 10^{10} times.

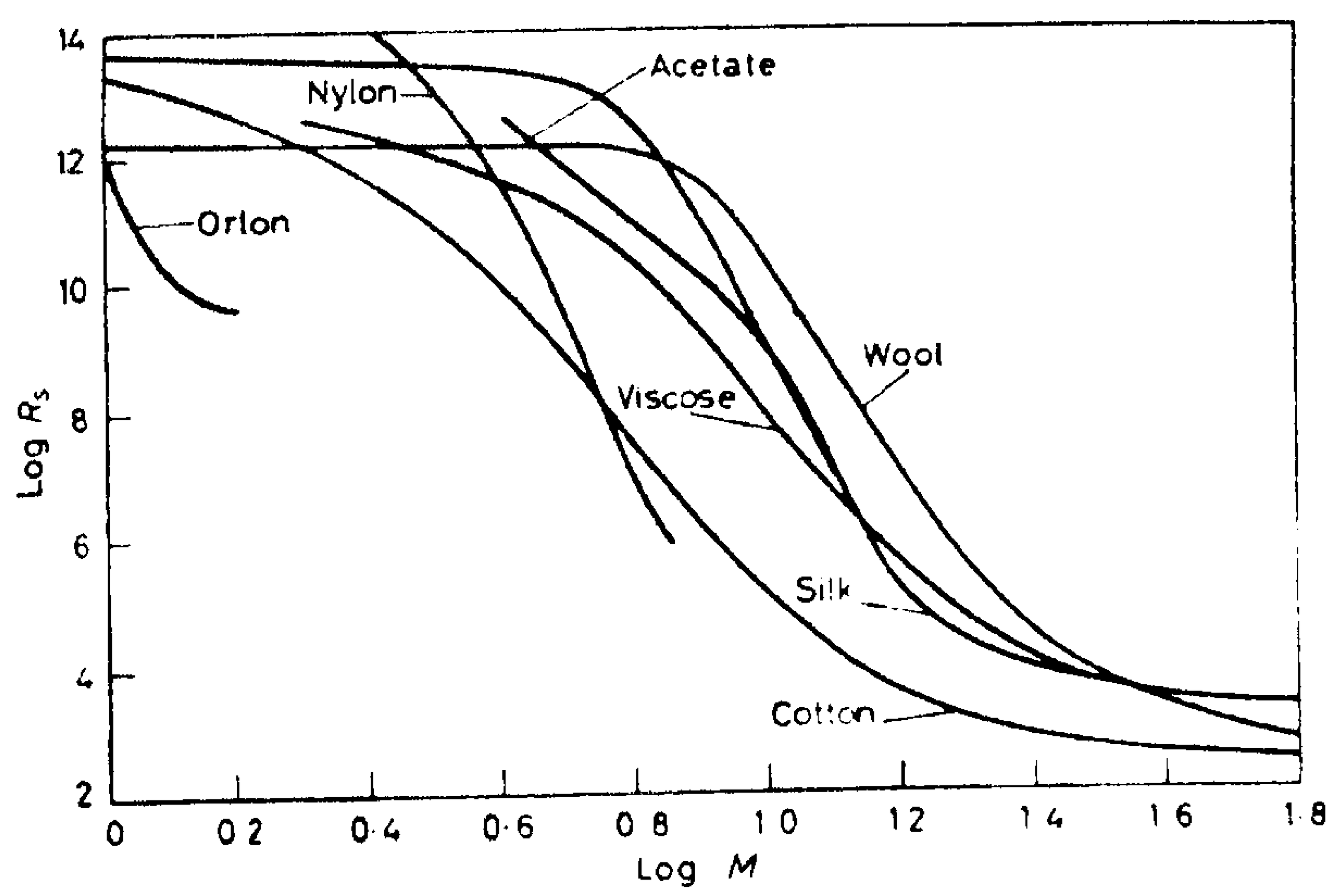


Figure 7.2 Variation of Electrical Resistance of Fibres with Moisture Content

The relative humidity is equally important, as the difference between 10% and 90% relative humidity causes a million-fold difference in the resistance, namely a tenfold decrease in resistance for every 13% increase in relative humidity, as illustrated in Figure 7.3.

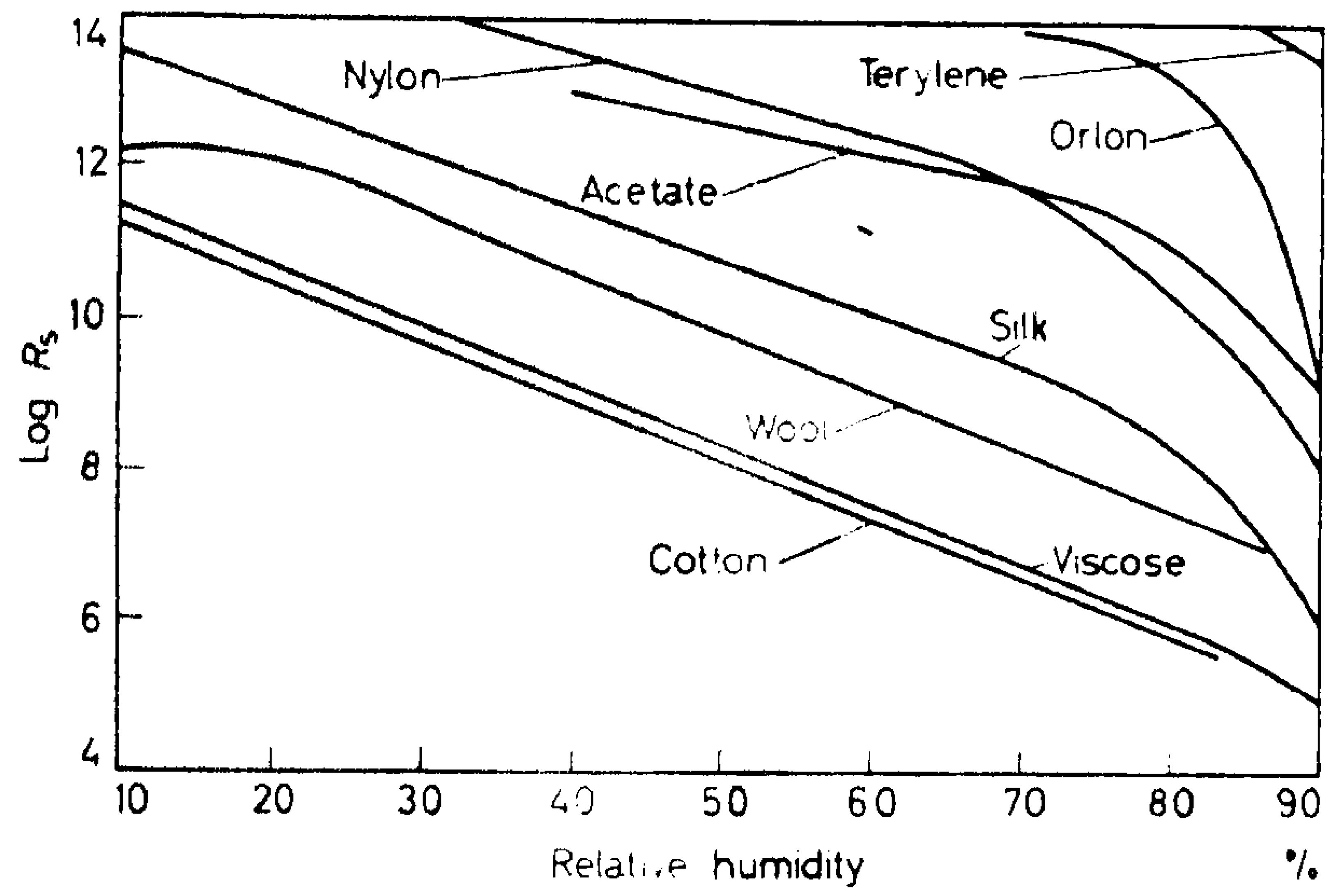
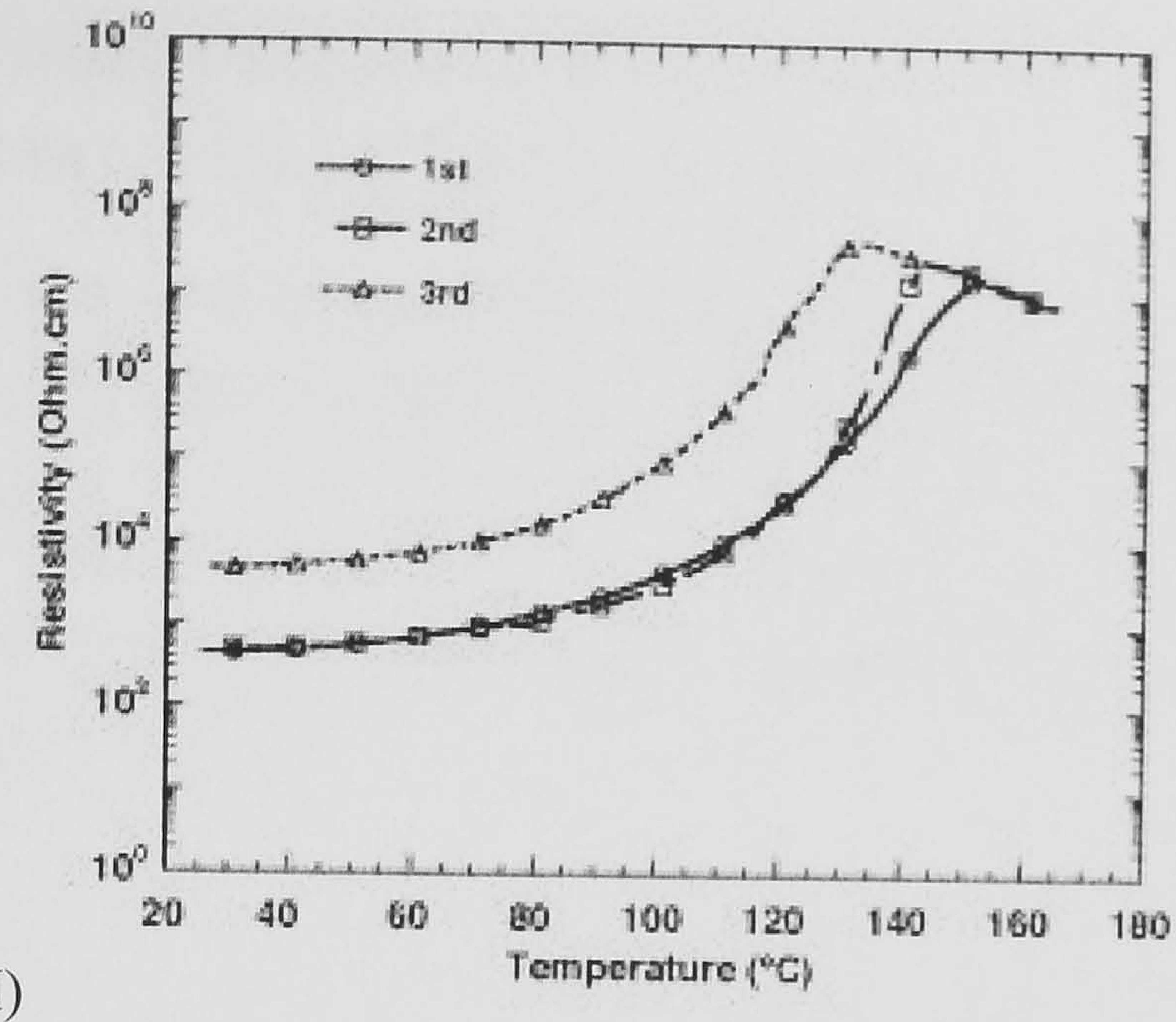


Figure 7.3 Variation of Electrical Resistance of Fibres with Relative Humidity

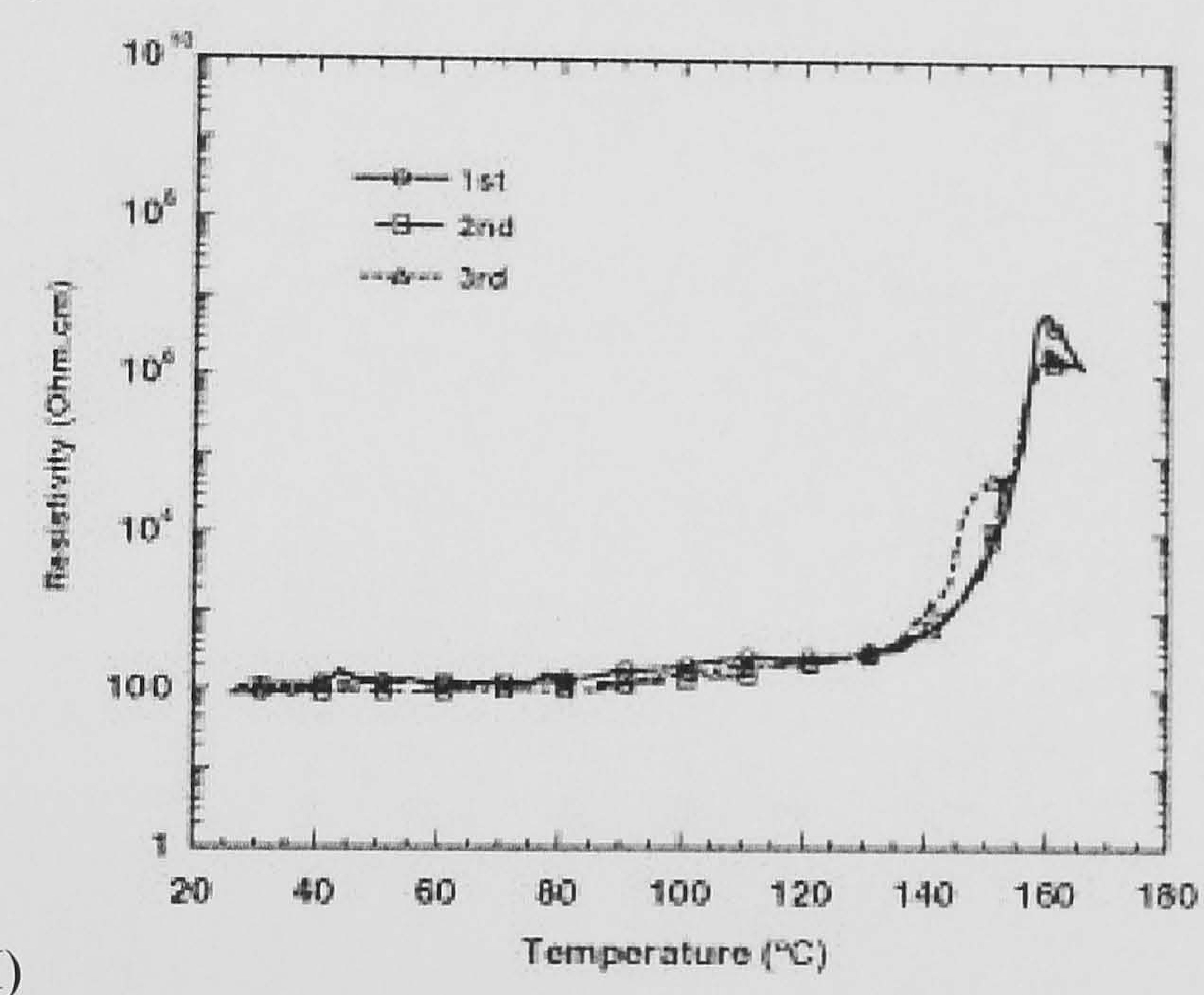
The effect of these issues should be considered of importance with regard to the characterisation of the sensor, repeatability of results, and assessing the longevity of a component.

7.2.4.2 Temperature

The effect of temperature on the performance of a textile sensor has been researched [166], as shown in Figure 7.4, however this work was not concerned with monofilament yarns. Hence issues over the design of sensor yarns such that they will be able to expand (if necessary), and therefore suffer no constriction, would need to be addressed.



I)



II)

Figure 7.4 Temperature Dependence of Electrical Resistivity of the Nanocomposites with CB Content of 25 wt.% for the Three Heating Cycles I) without MWNTs and II) 1.0 wt.% MWNTs [166]

7.2.5 Application of Sensor

The final area of further work would inevitably be the application of the sensor to a technical textile fabric and testing under a variety of conditions (laboratory, environmental, in-situ). This would give the greatest indication of the success of a textile sensor's strain sensing ability, durability and repeatability. There are several issues surrounding the application process, including:

- Method of applying the sensor to fabric – best practice for seamless integration of electronic functionality into a textile substrate
- By what means will there be signal acquisition and the conversion of resistance to voltage for easier reading of results, and how will this conductivity be controlled?

How to minimise the current carried through the textile yarn in order to prevent the yarns overheating.

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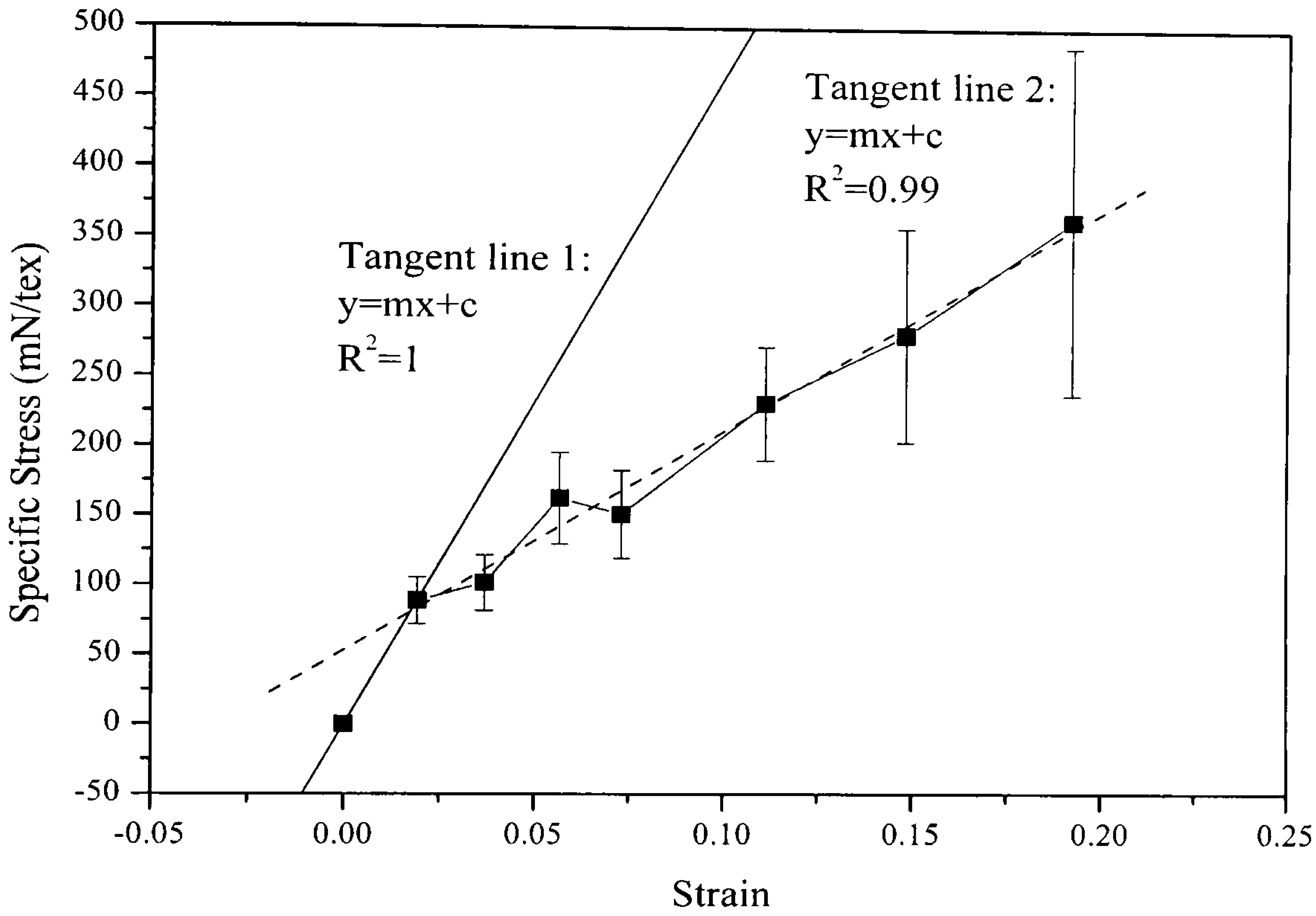
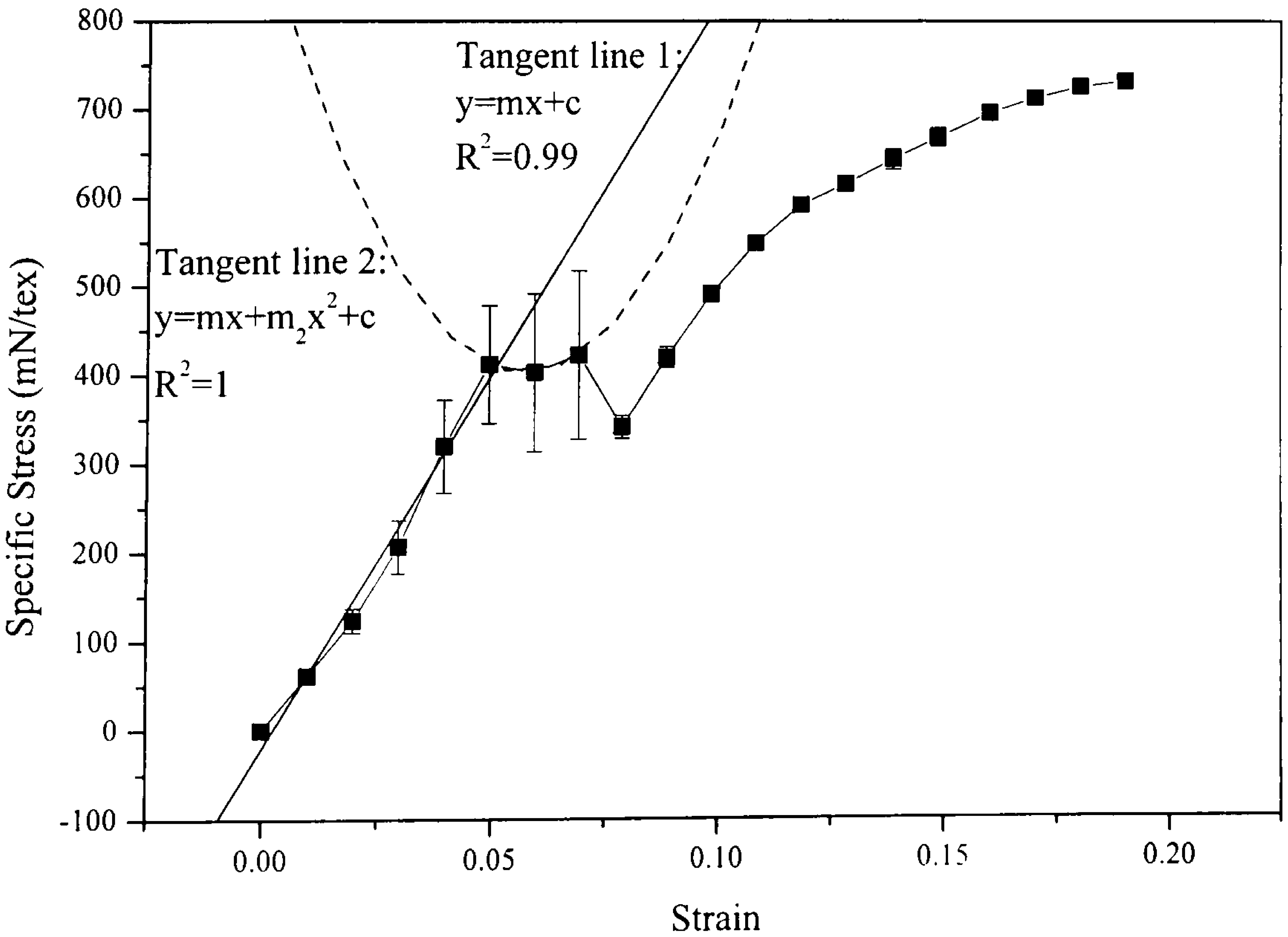
Appendix 1
Mechanical Behaviour

A1.1 Yield Point

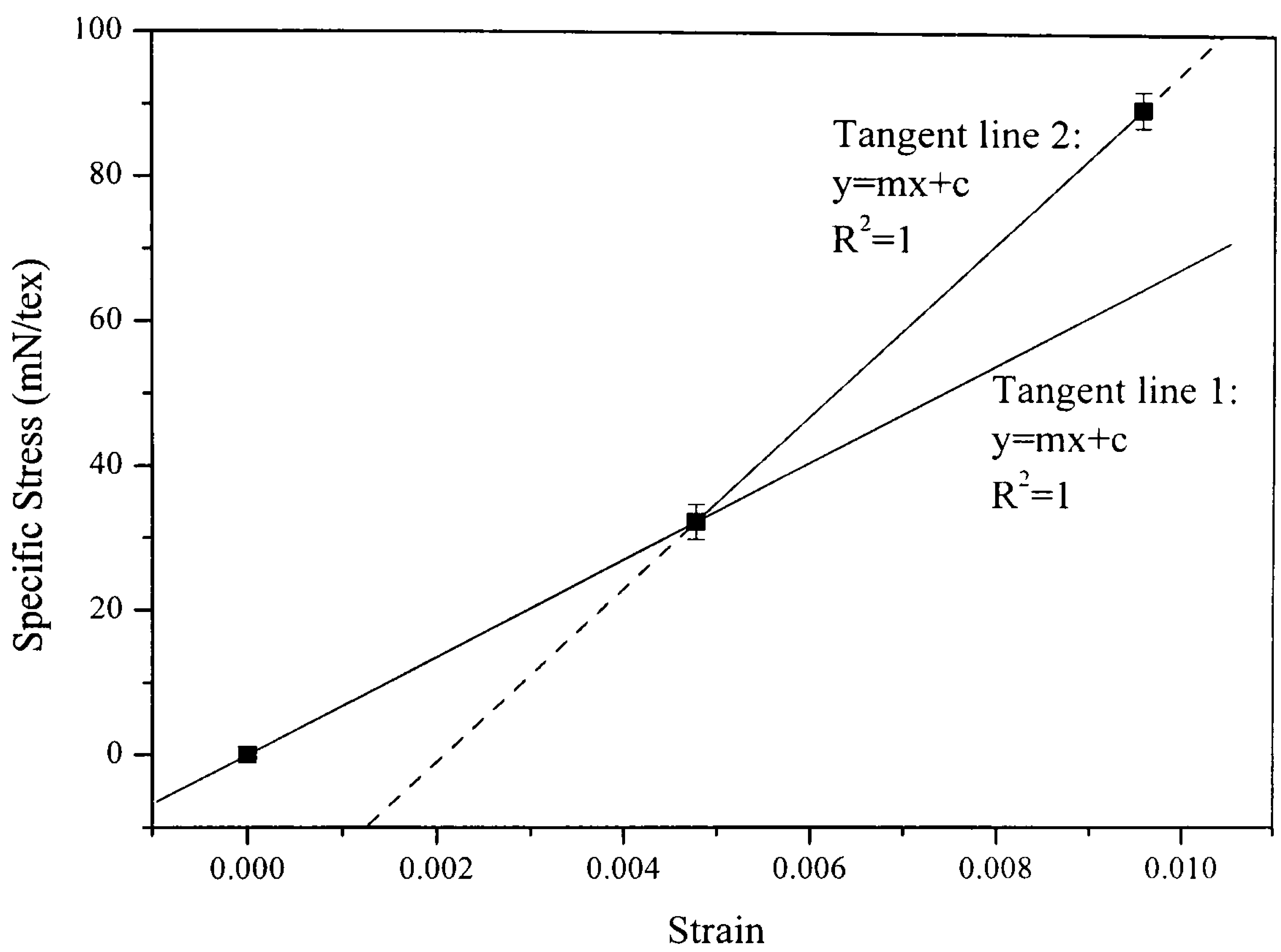
Bekitex 50/1 Yield Point



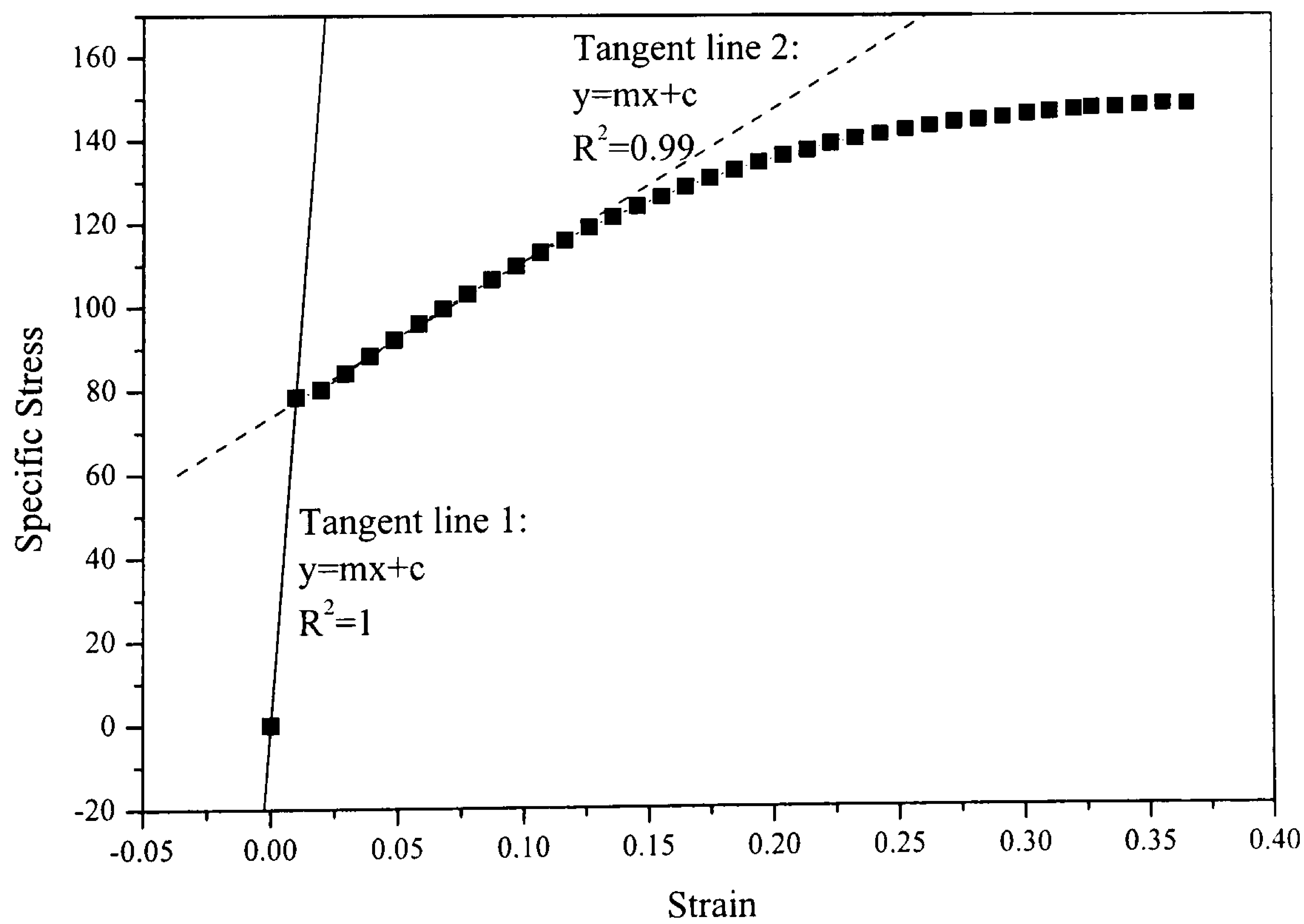
Resistat F9301 Yield Point



R.Stat/S Yield Point



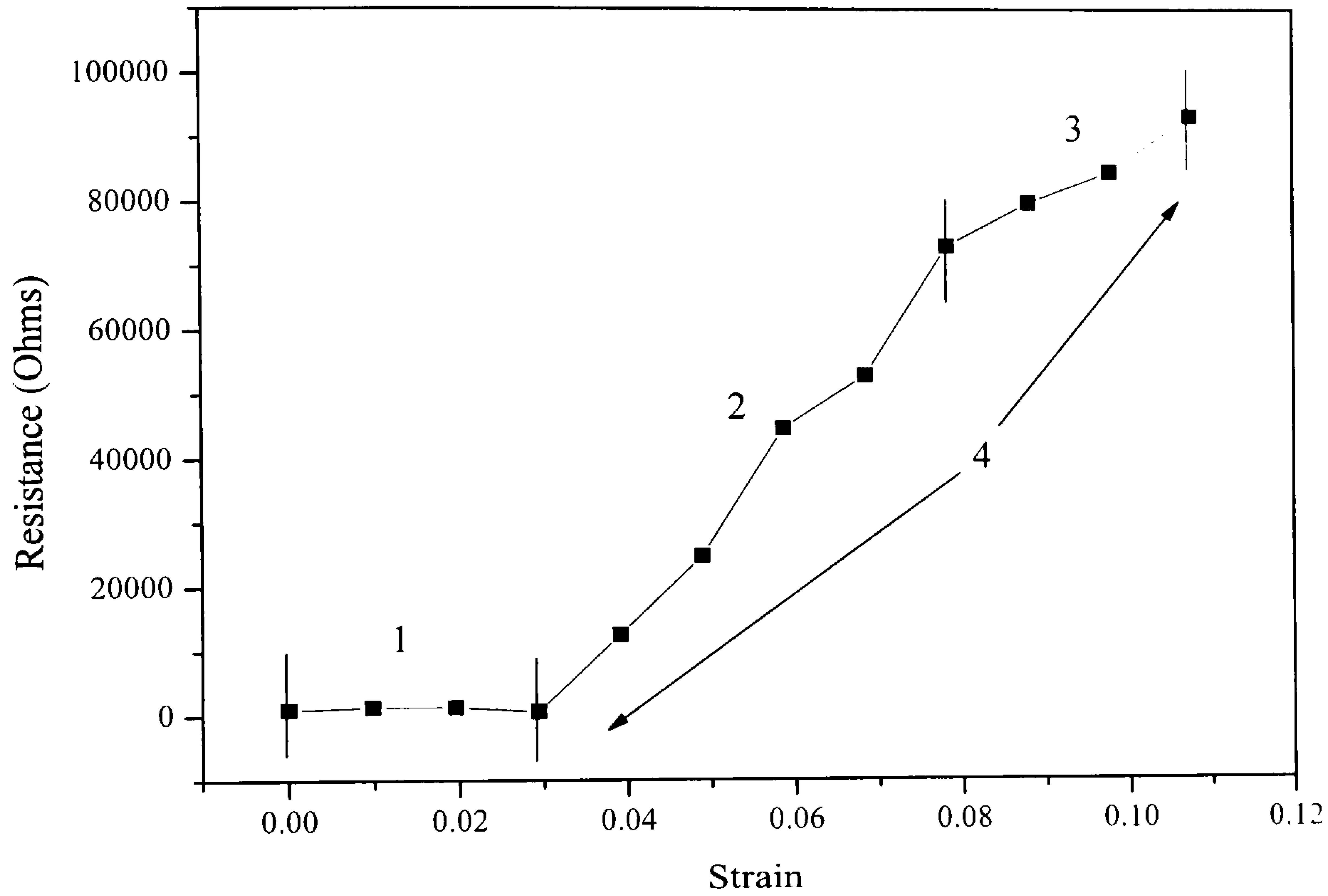
Stainless Steel Wire Yield Point



A1.2 Gauge Factor

R.Stat/P

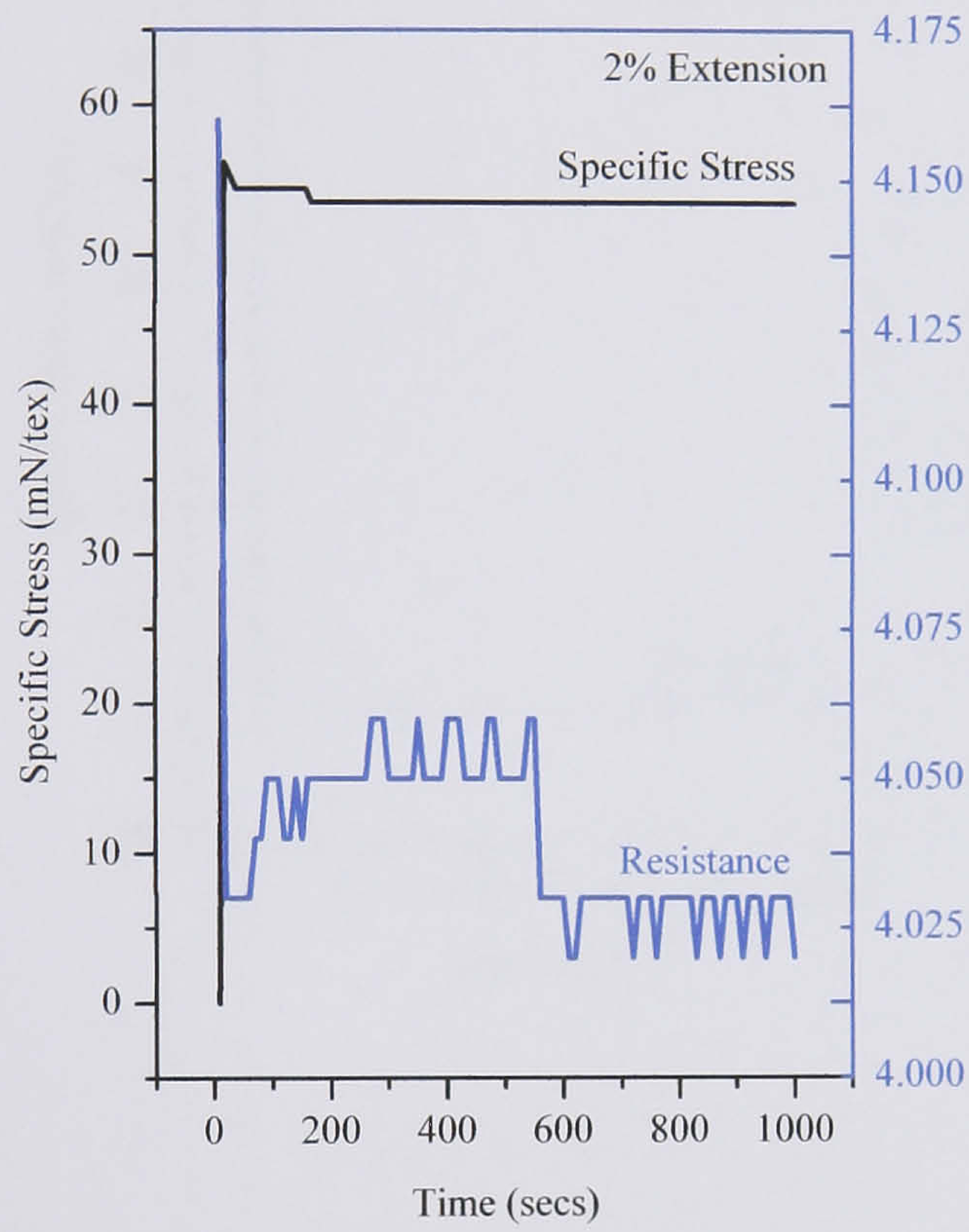
Linear portions of graph used for Gauge Factor calculations

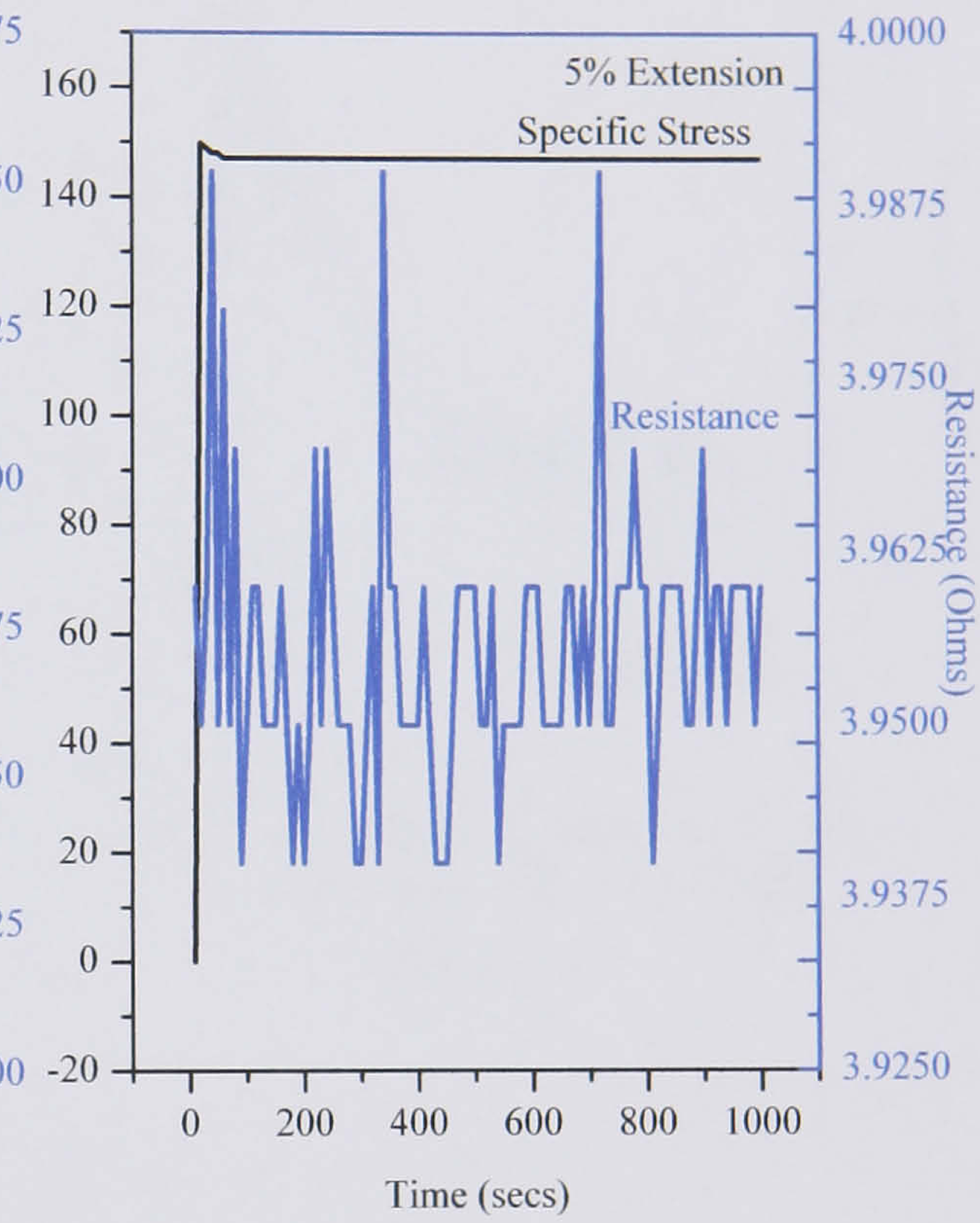


Appendix 2
Mechanical-Electrical Behaviour

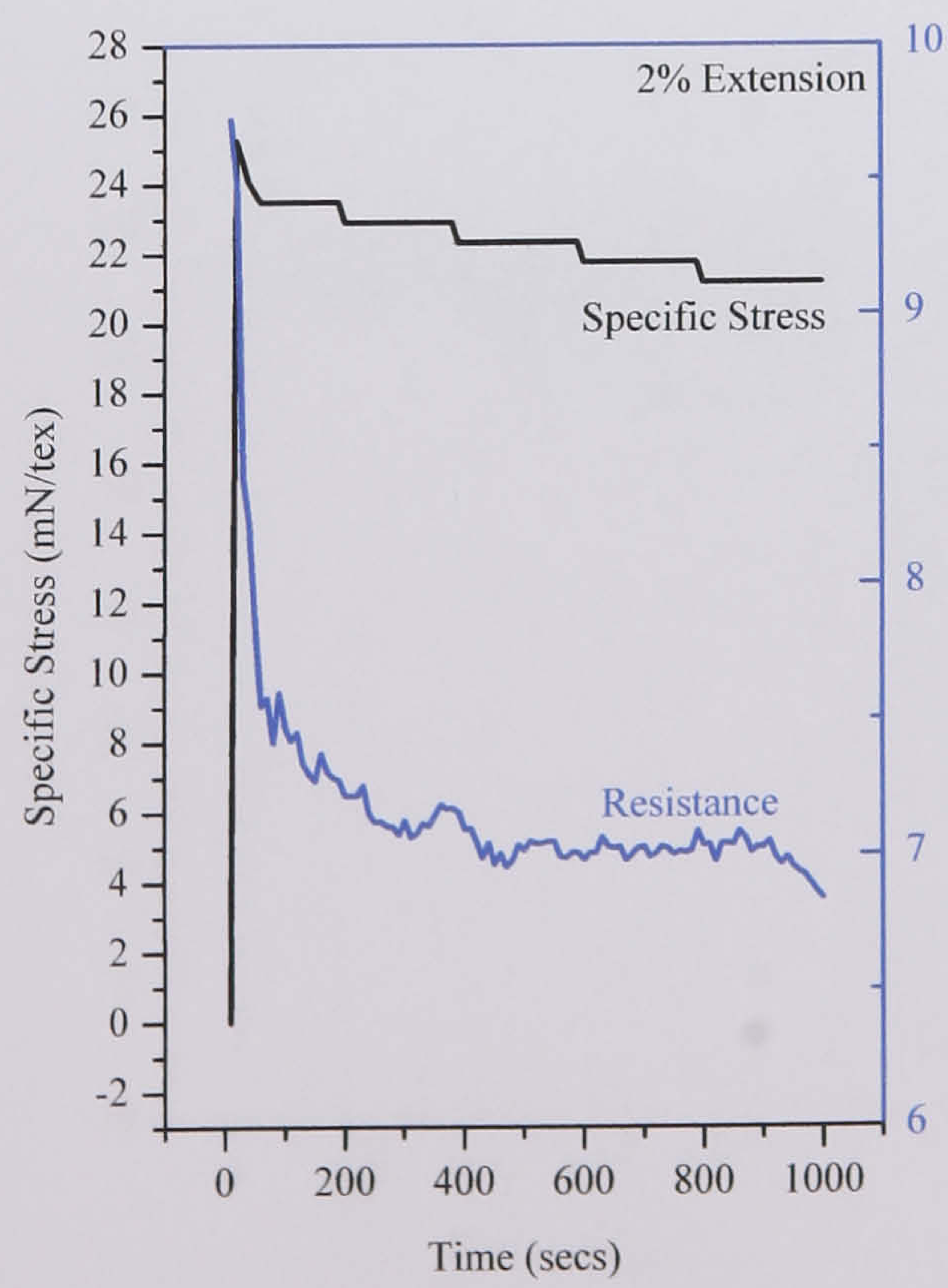
A2.1 Change in Resistance with Yarn Relaxation

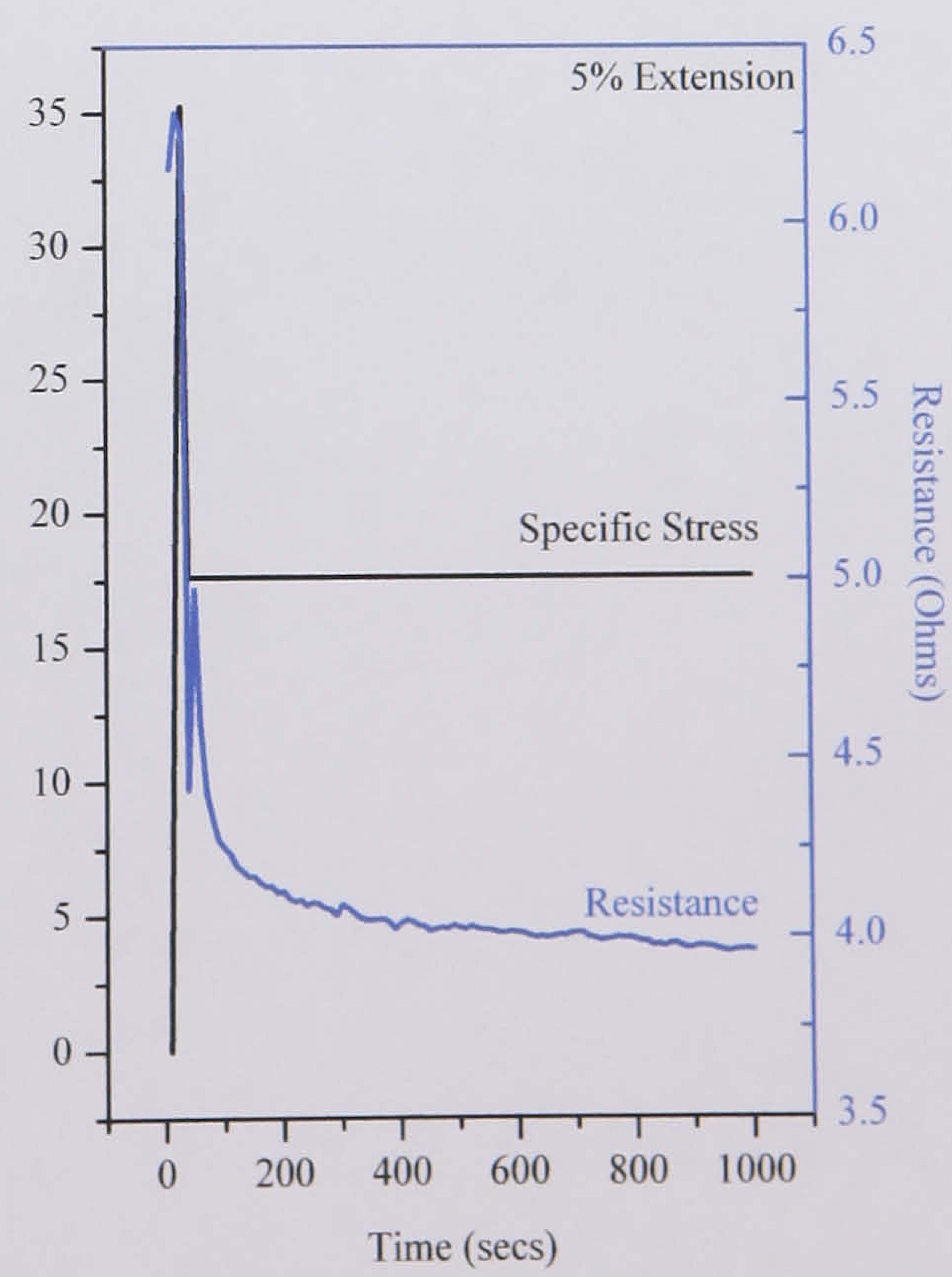
Bekinox VN



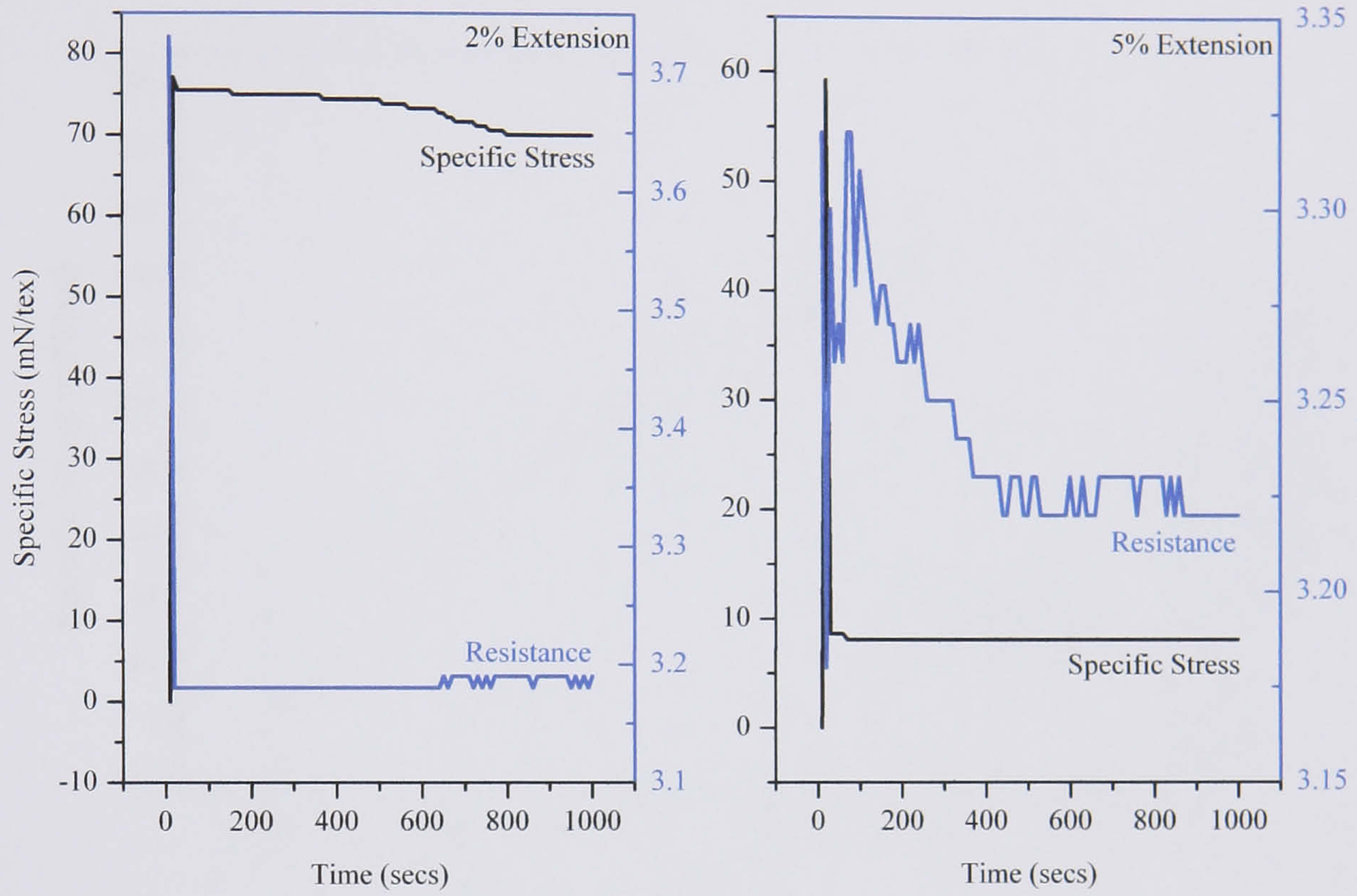


R.Stat/P

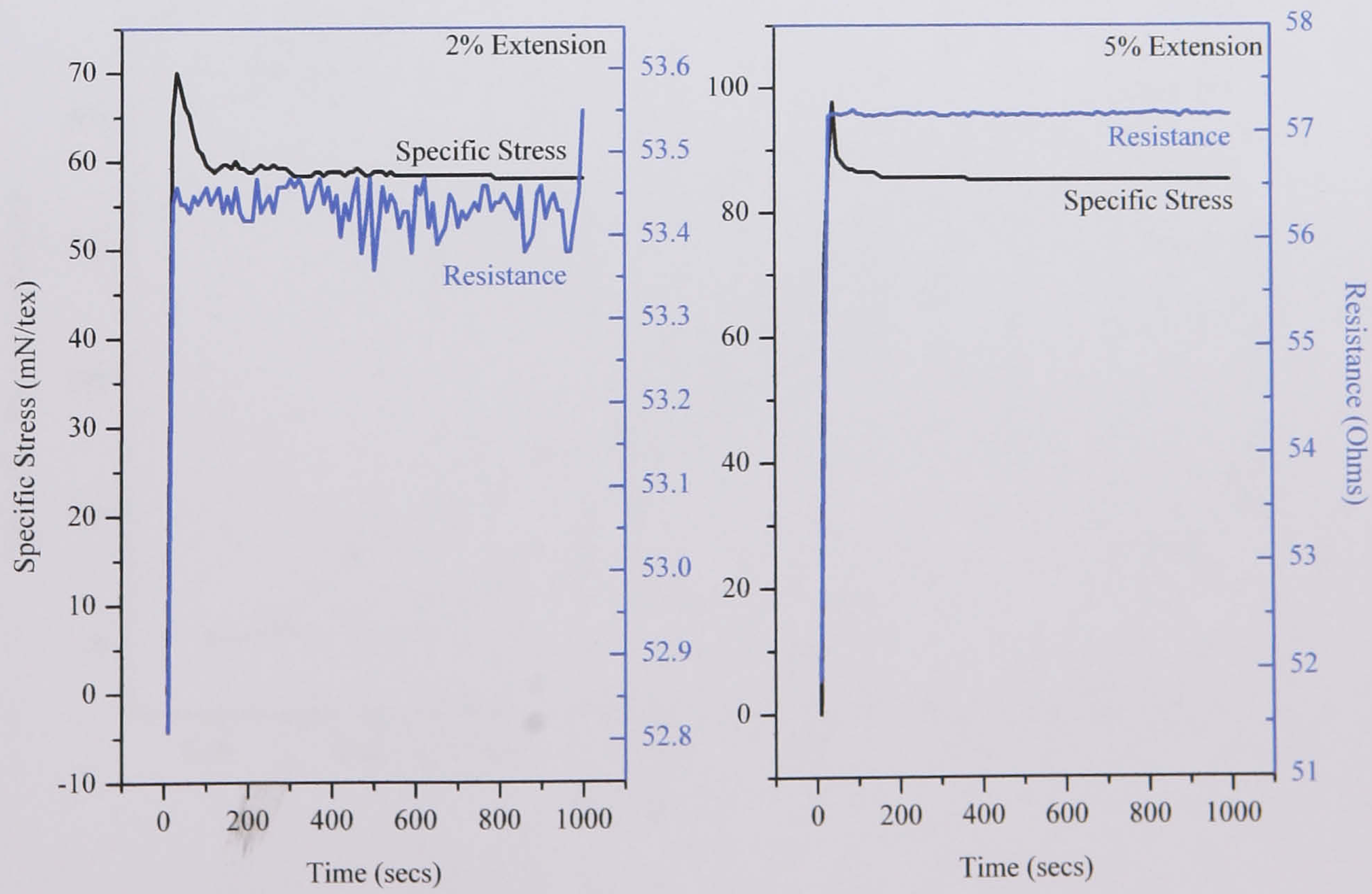




R.Stat/S

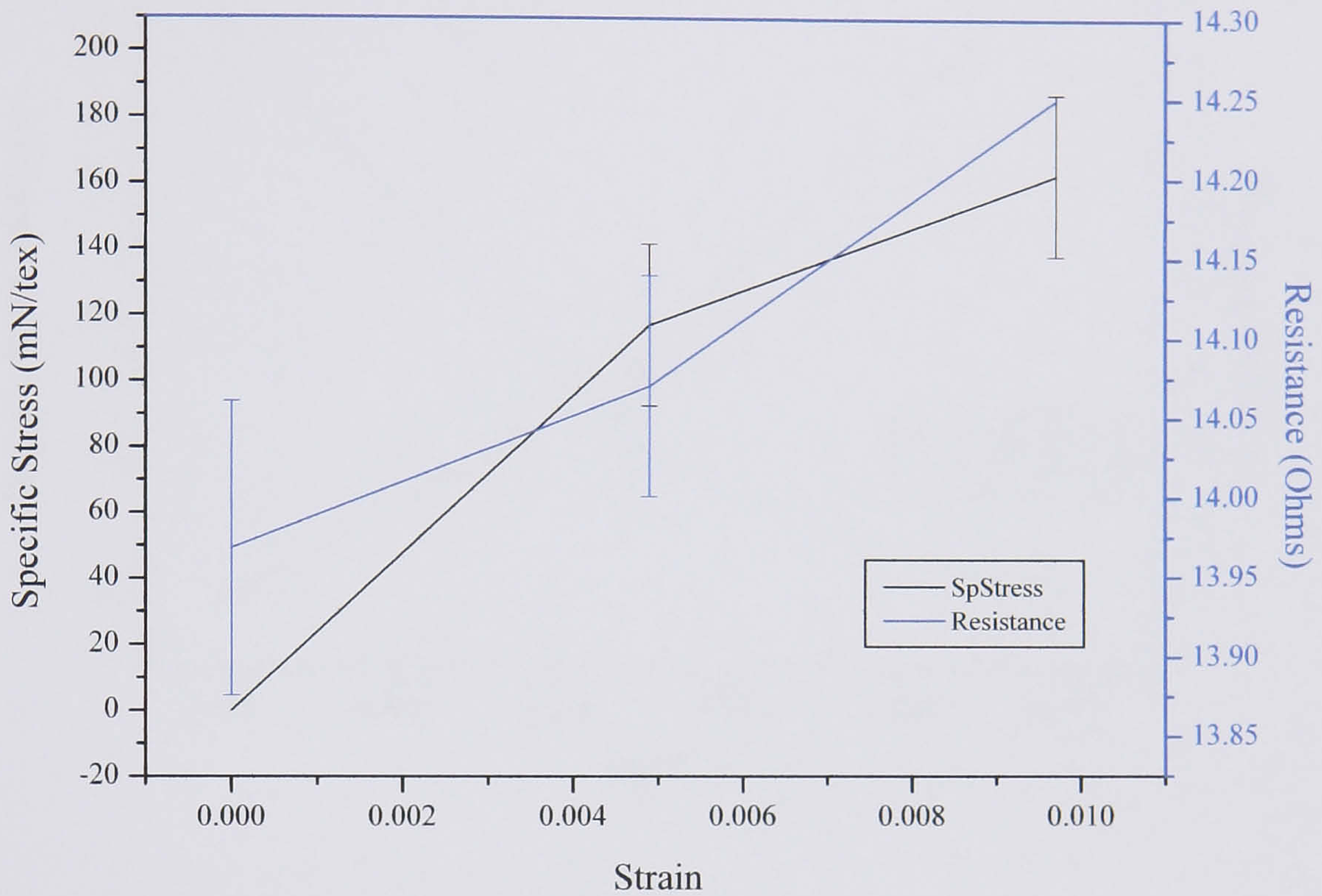


Stainless Steel Wire

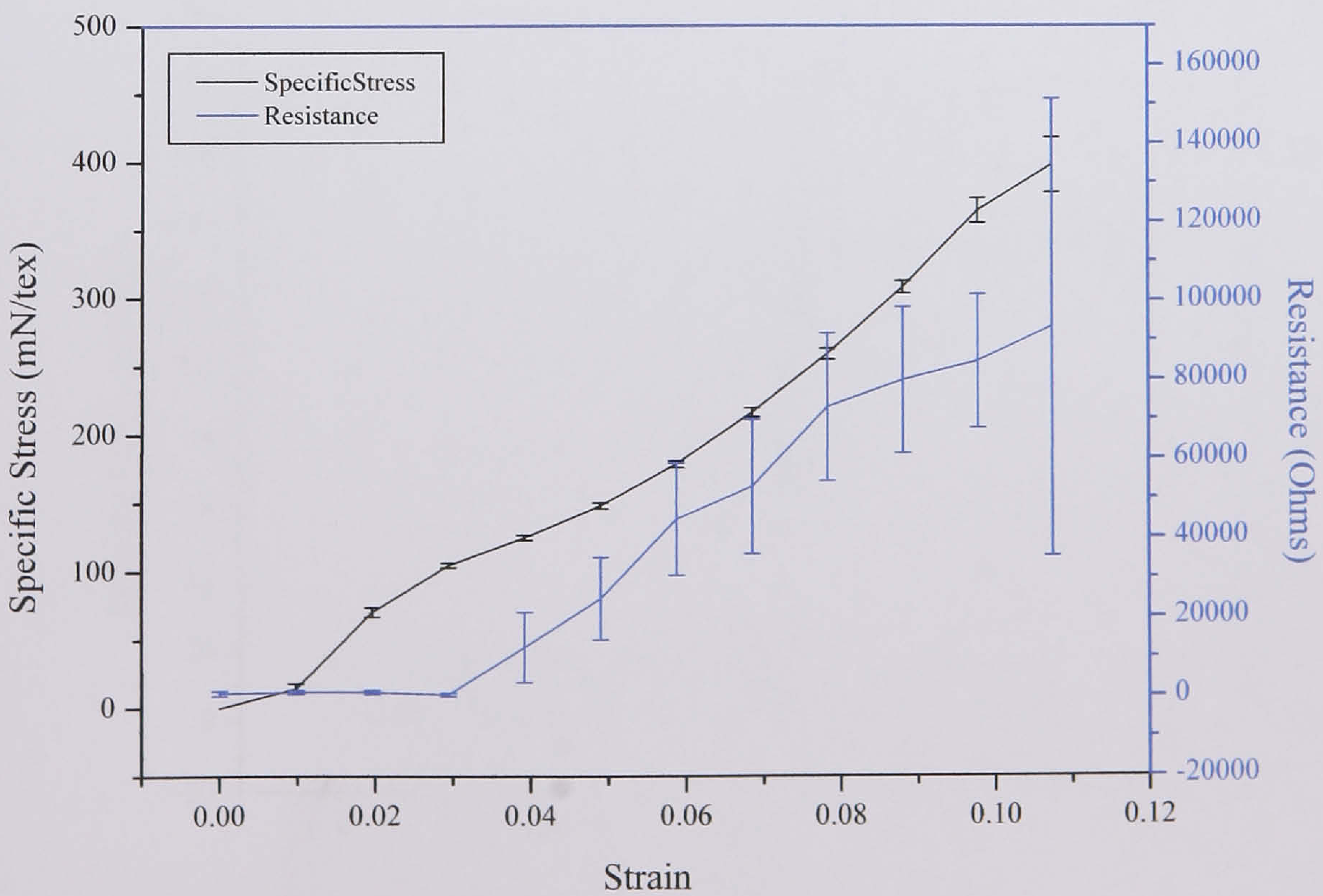


A2.2 Dynamic Resistance-Strain Curves

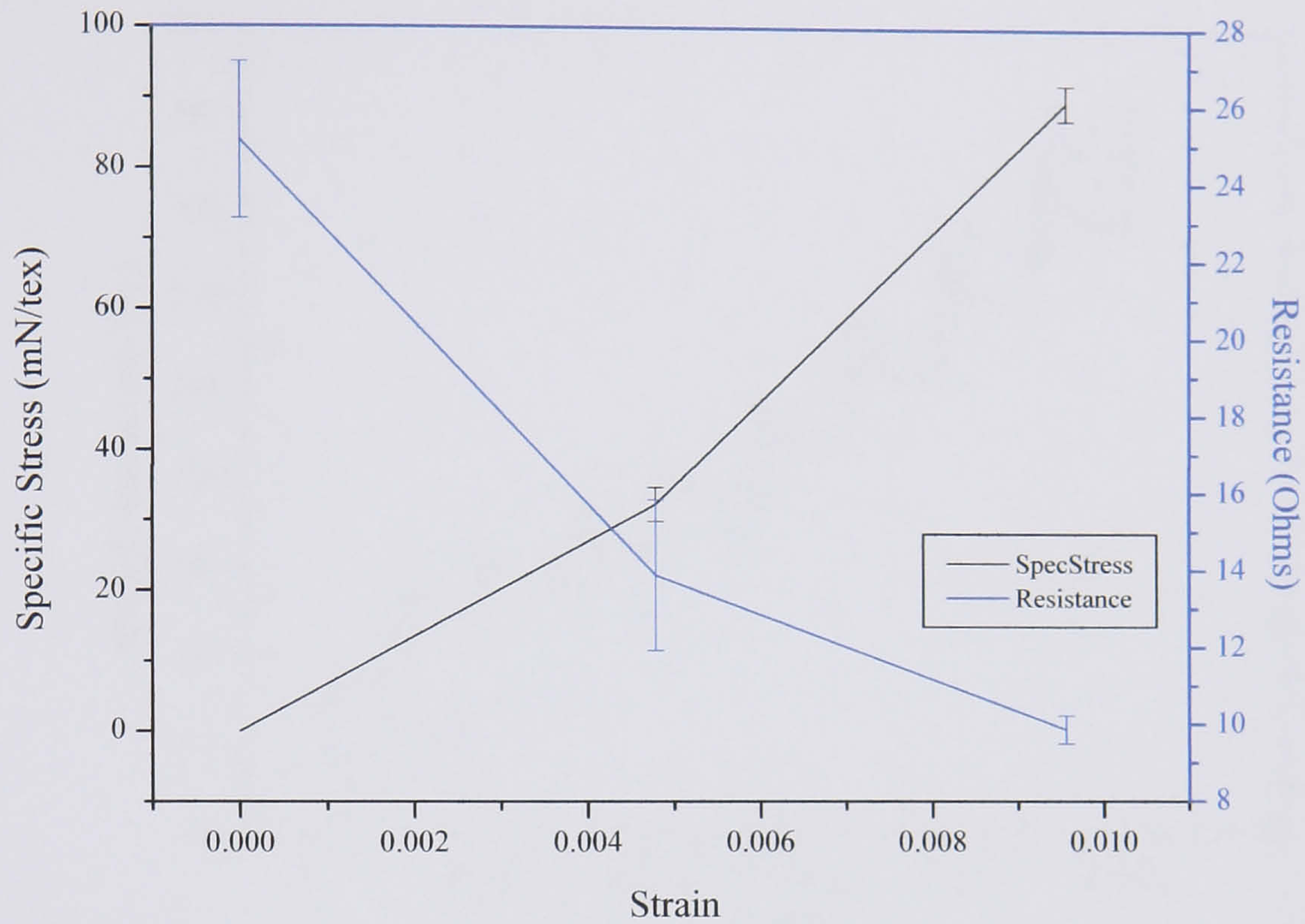
Bekinox VN Dynamic Resistance-Strain



R.Stat/P Dynamic Resistance-Strain

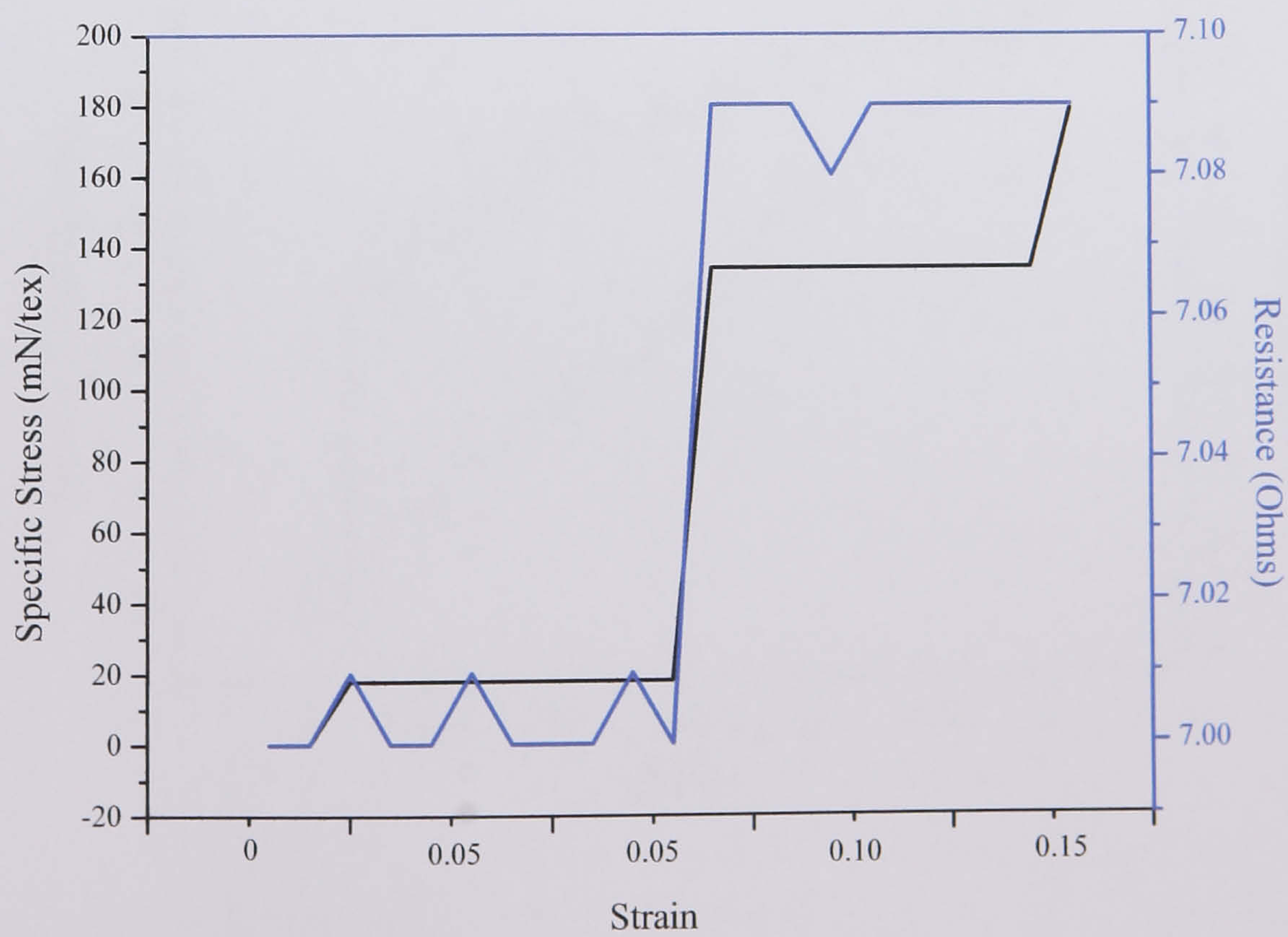


R.Stat/S Dynamic Resistance-Strain

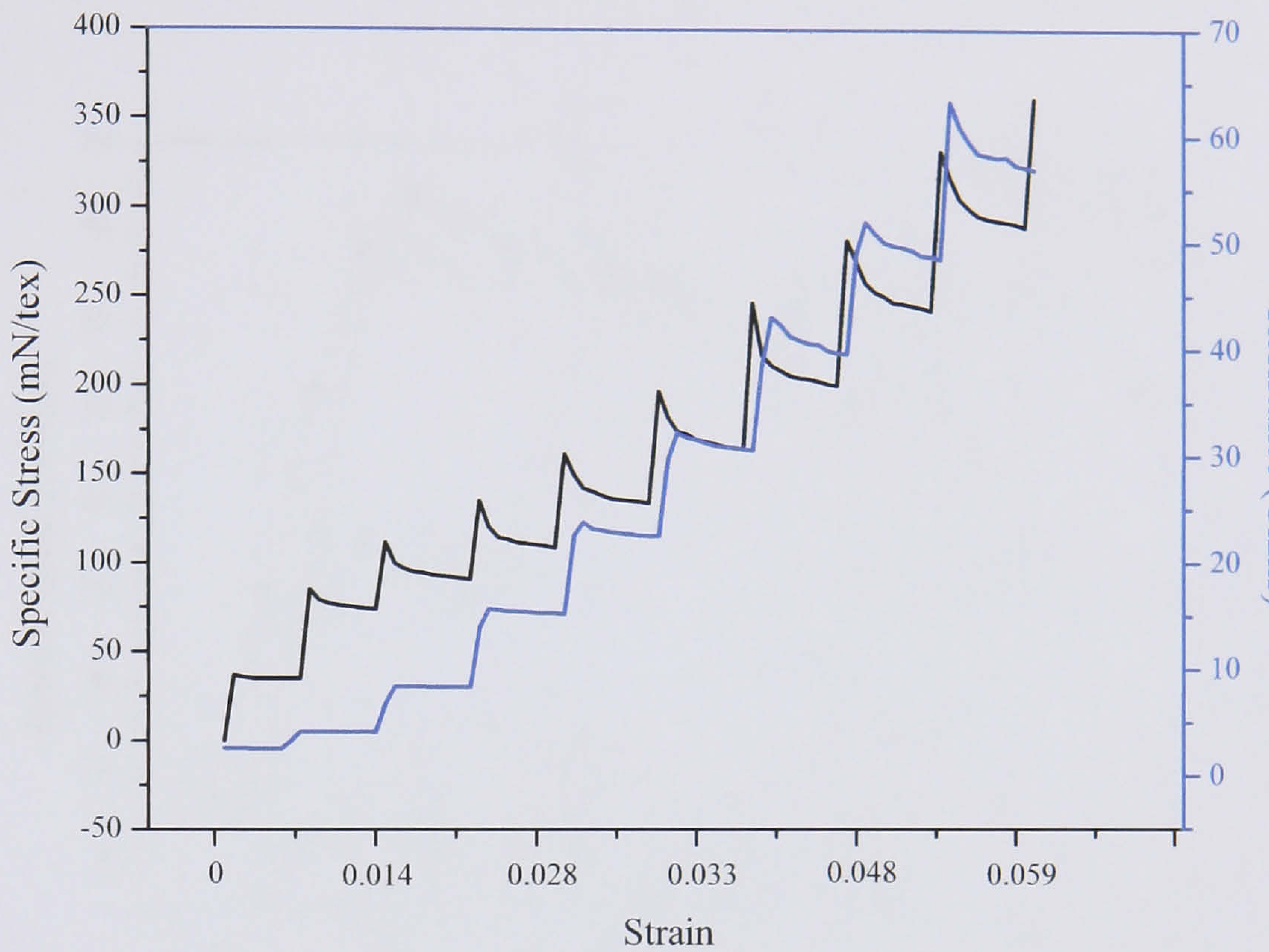


A2.3 Stepwise Resistance-Strain

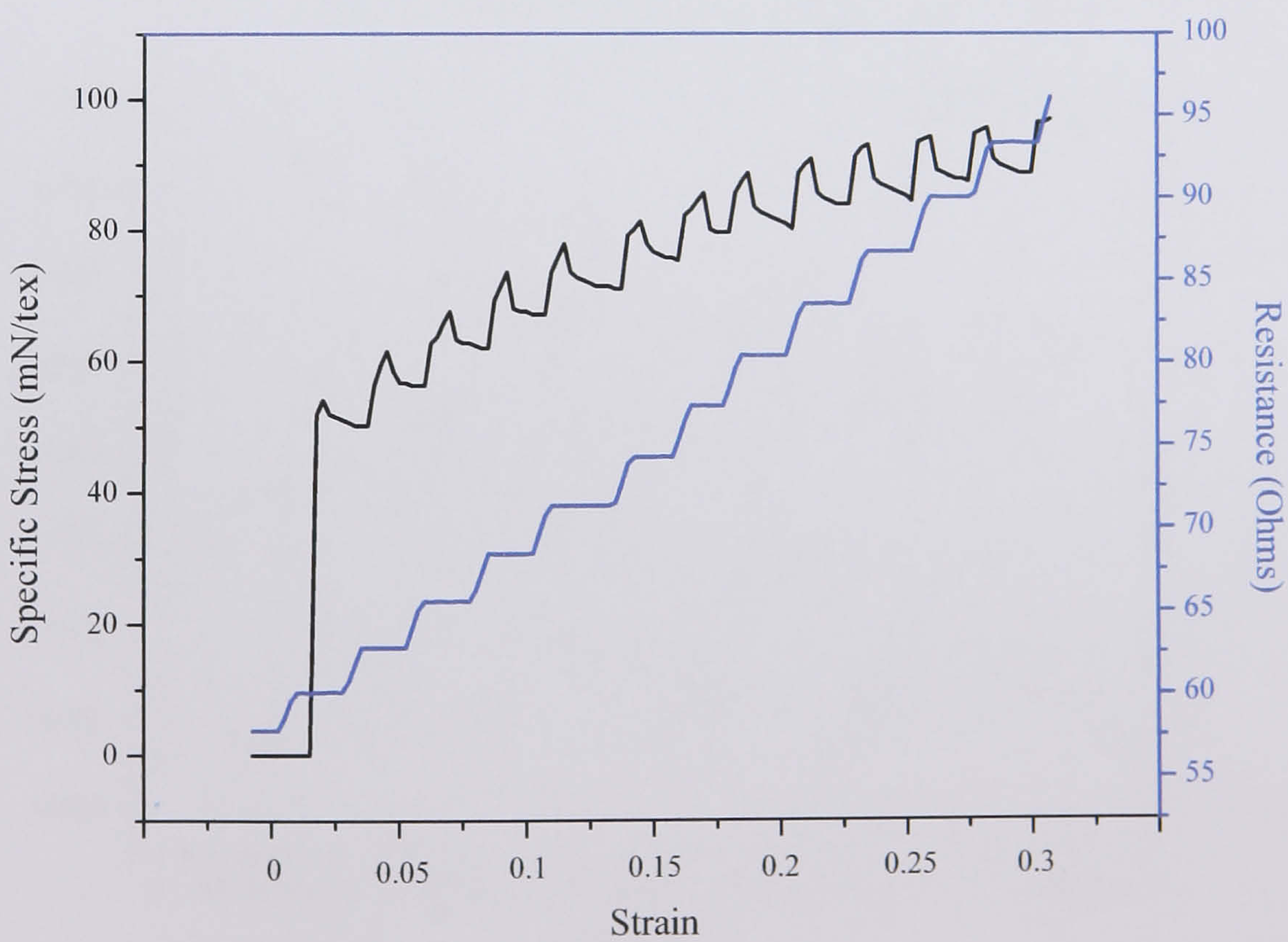
Bekinox VN Stepwise Resistance-Strain



R.Stat/P Stepwise Resistance-Strain

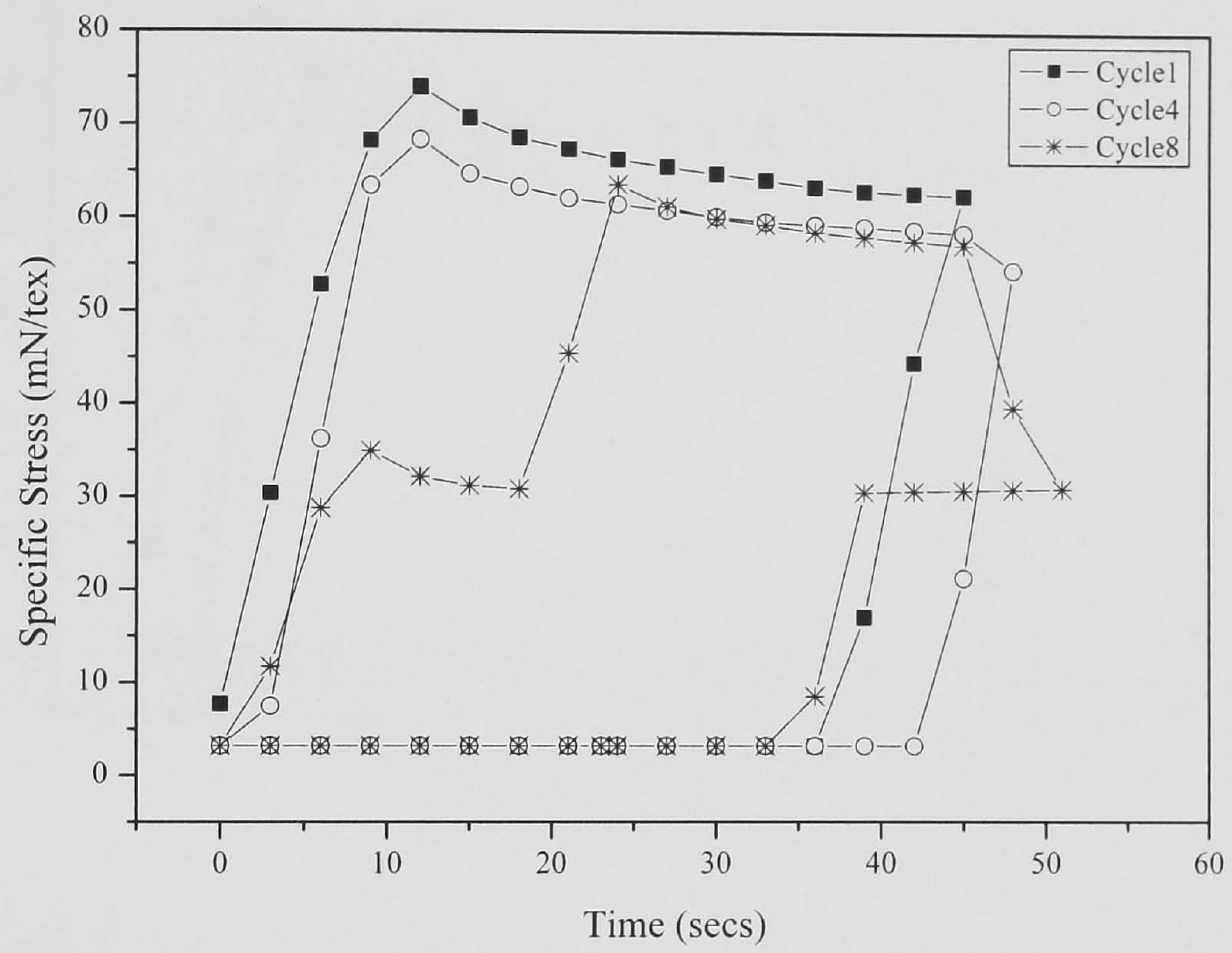


Stainless Steel Wire Stepwise Resistance-Strain

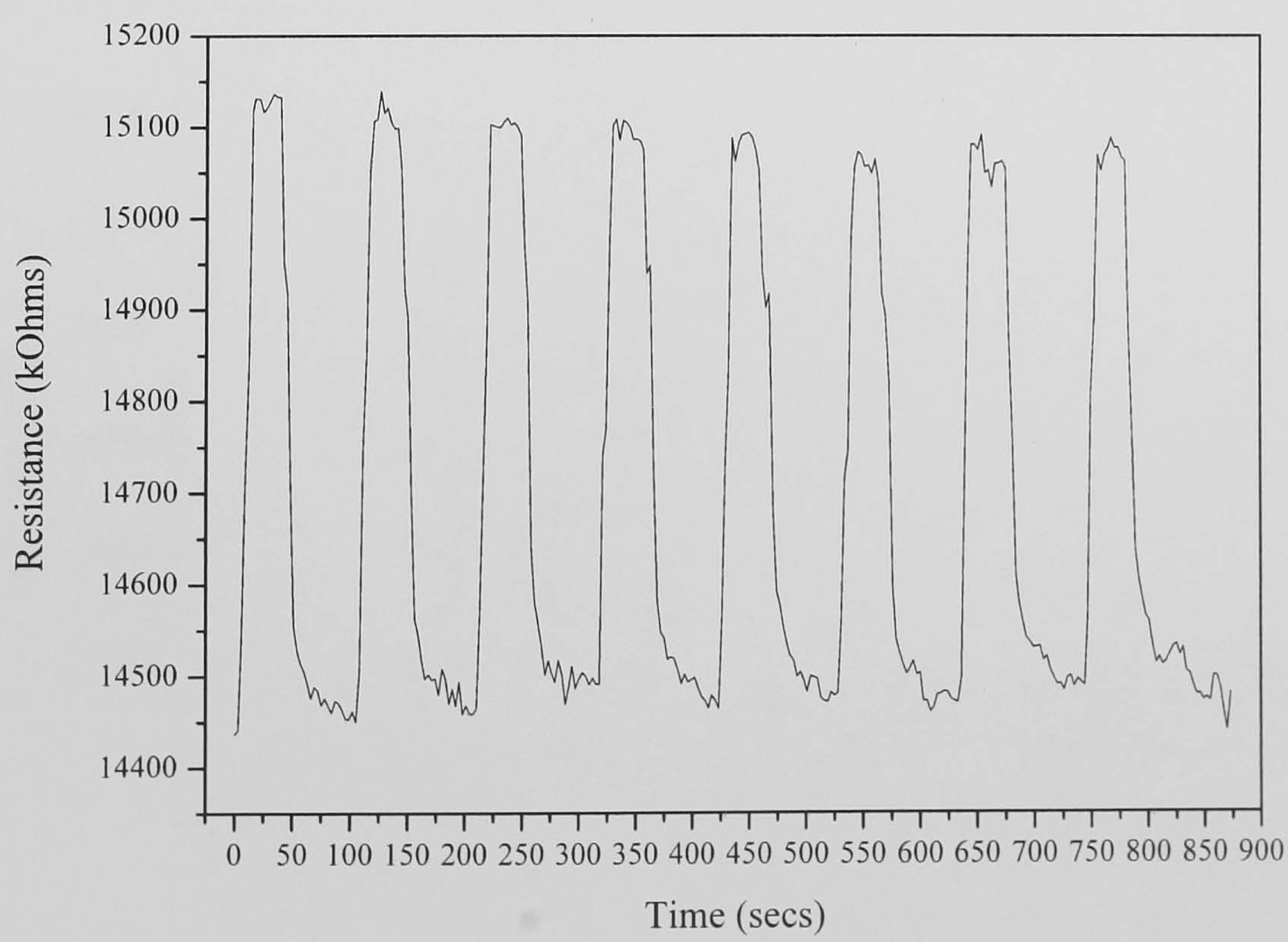


A2.4 Elastic Recovery – Timed Hold

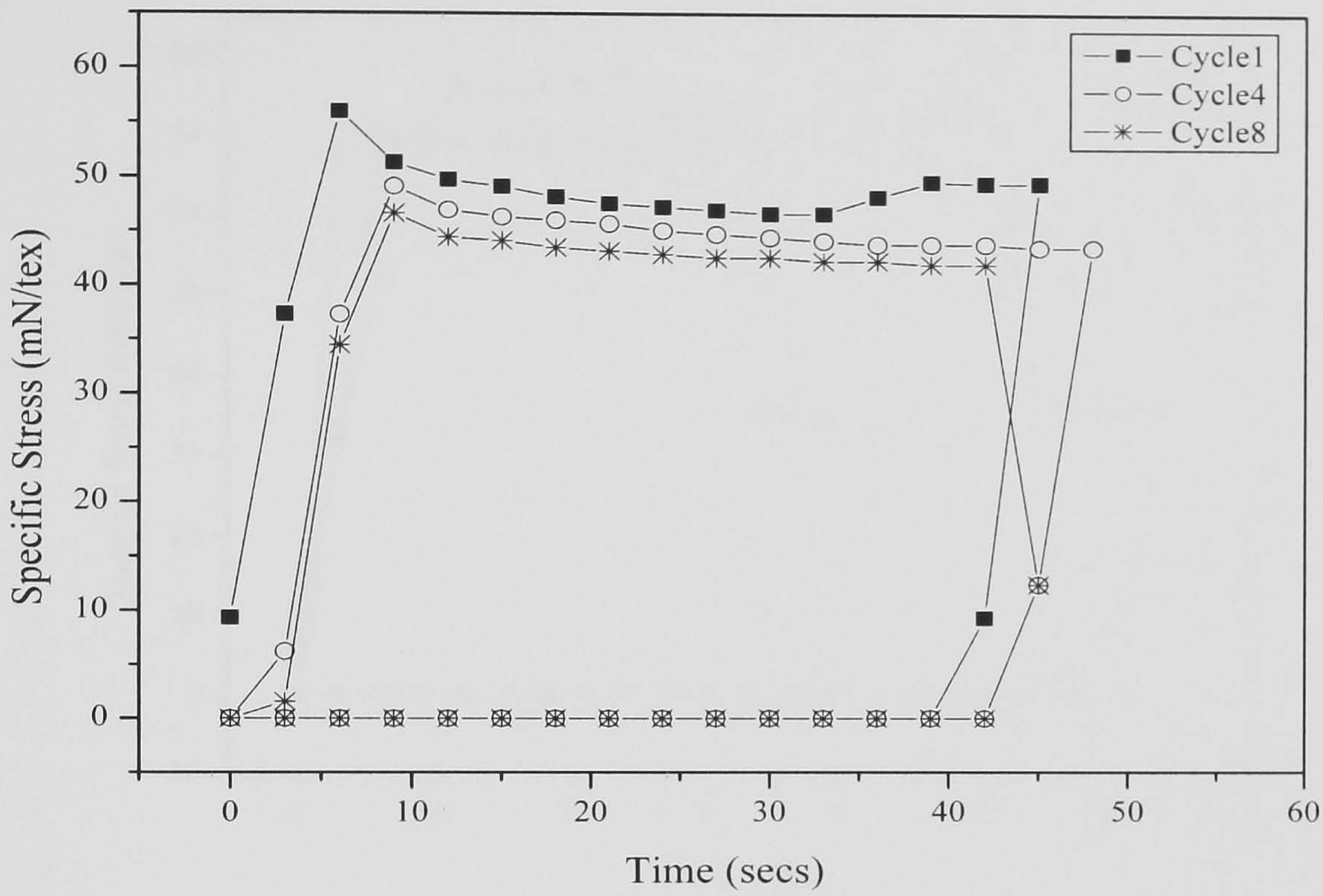
Resistat F9301 Specific Stress Elastic Recovery at 2% Extension, Timed Hold



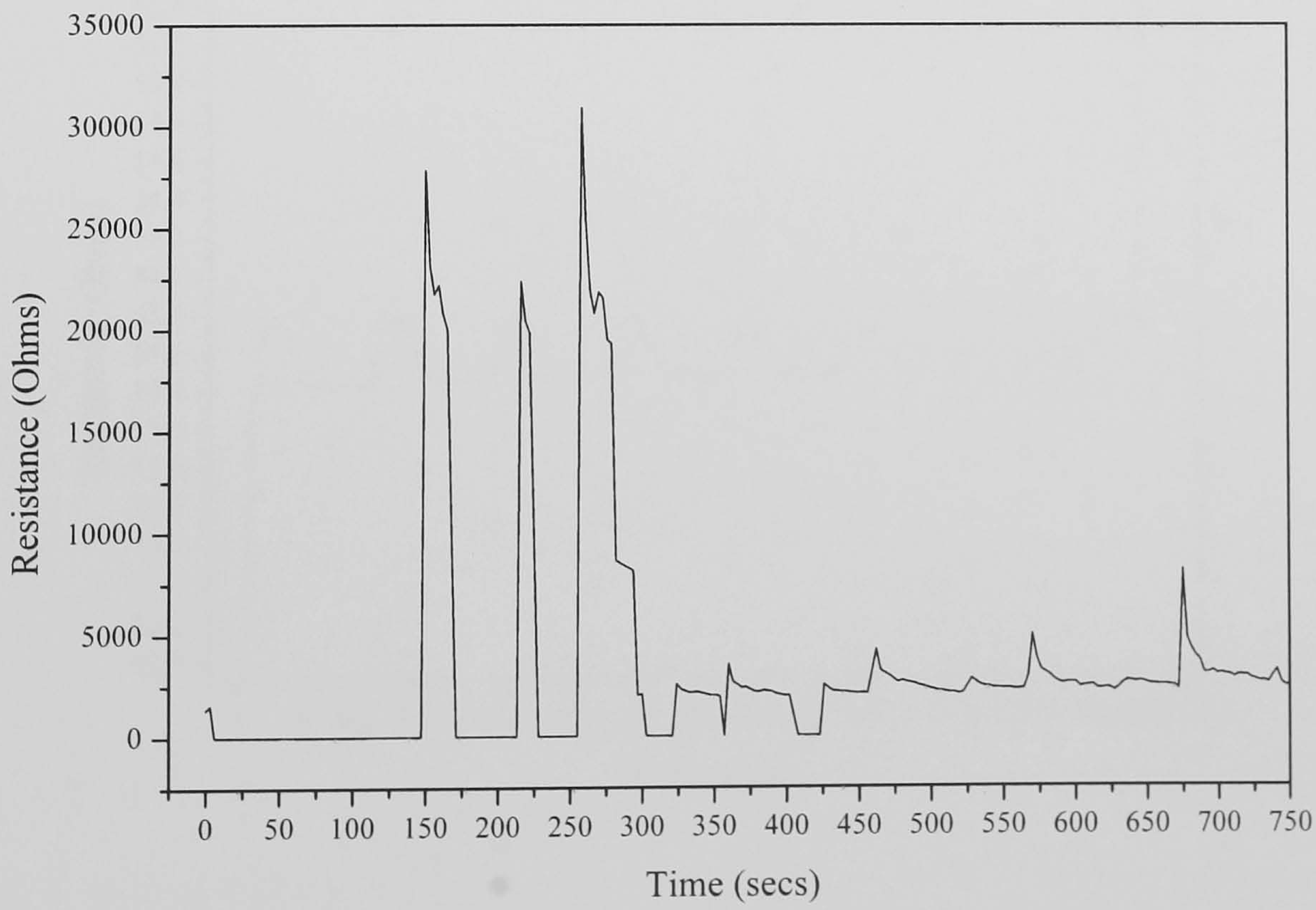
Resistat F9301 Resistance Elastic Recovery at 2% Extension, Timed Hold



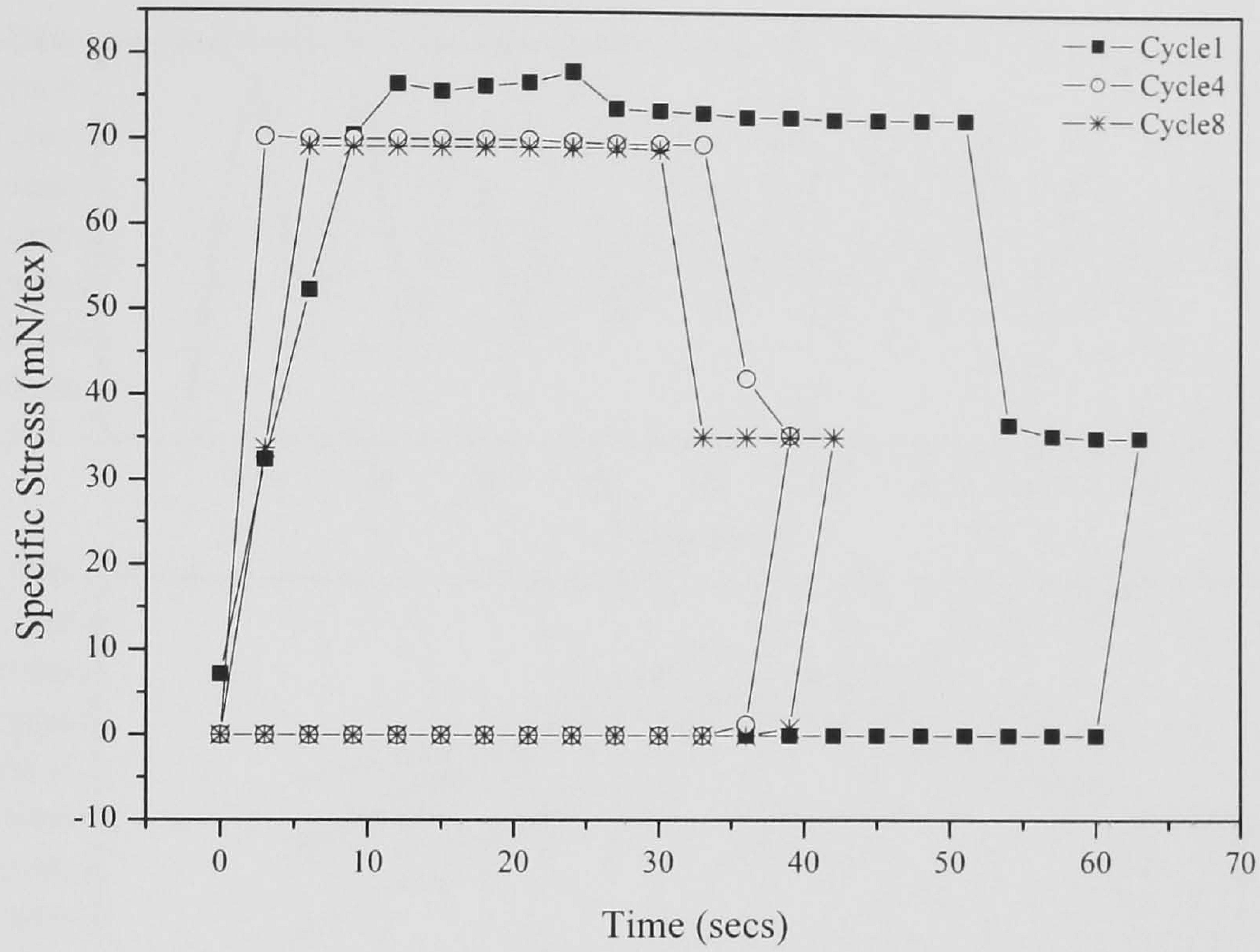
R.Stat/P Specific Stress Elastic Recovery at 2% Extension, Timed Hold



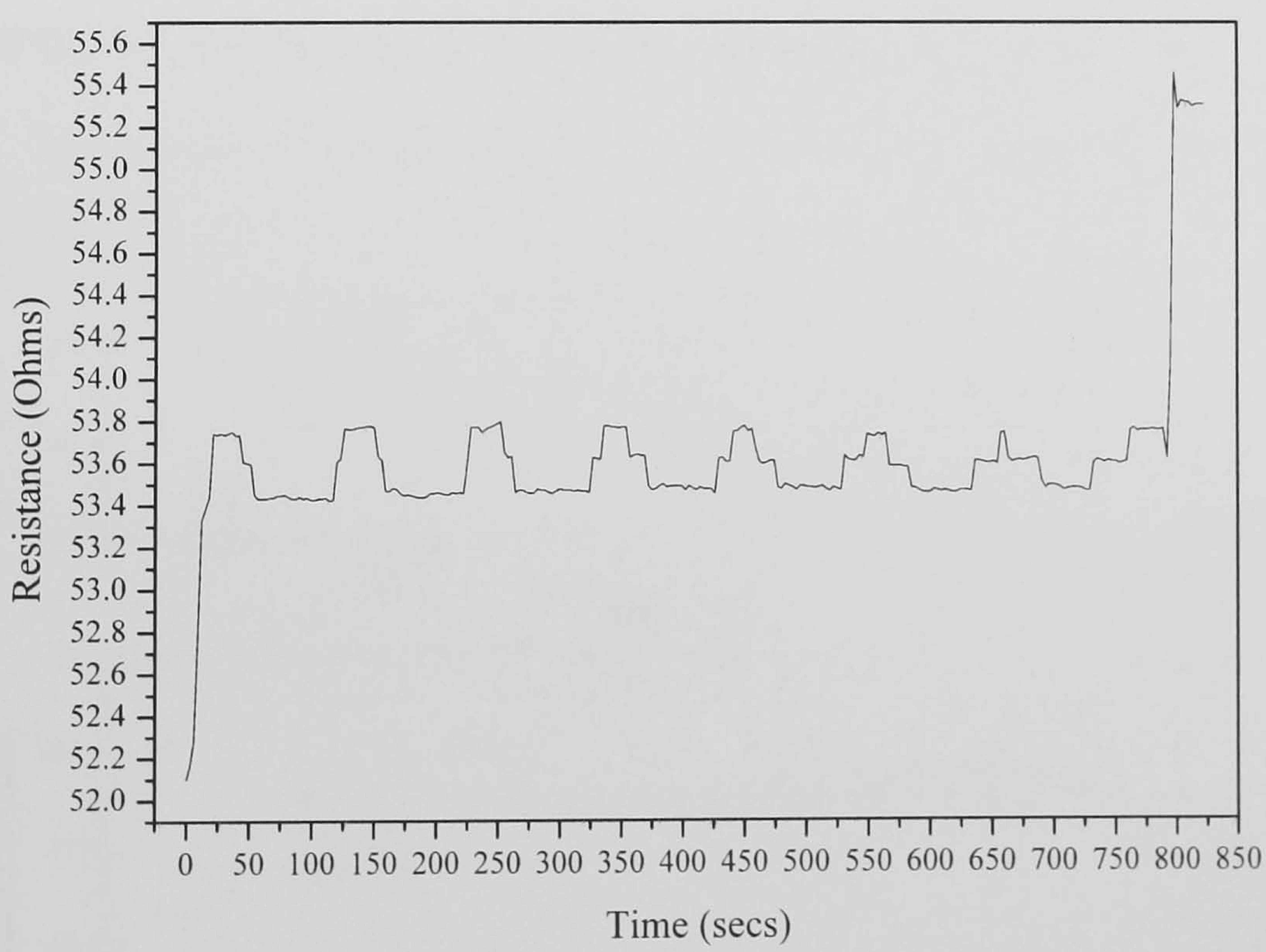
R.Stat/P Resistance Elastic Recovery at 2% Extension, Timed Hold



Stainless Steel Wire Specific Stress Elastic Recovery at 2% extension, Timed Hold

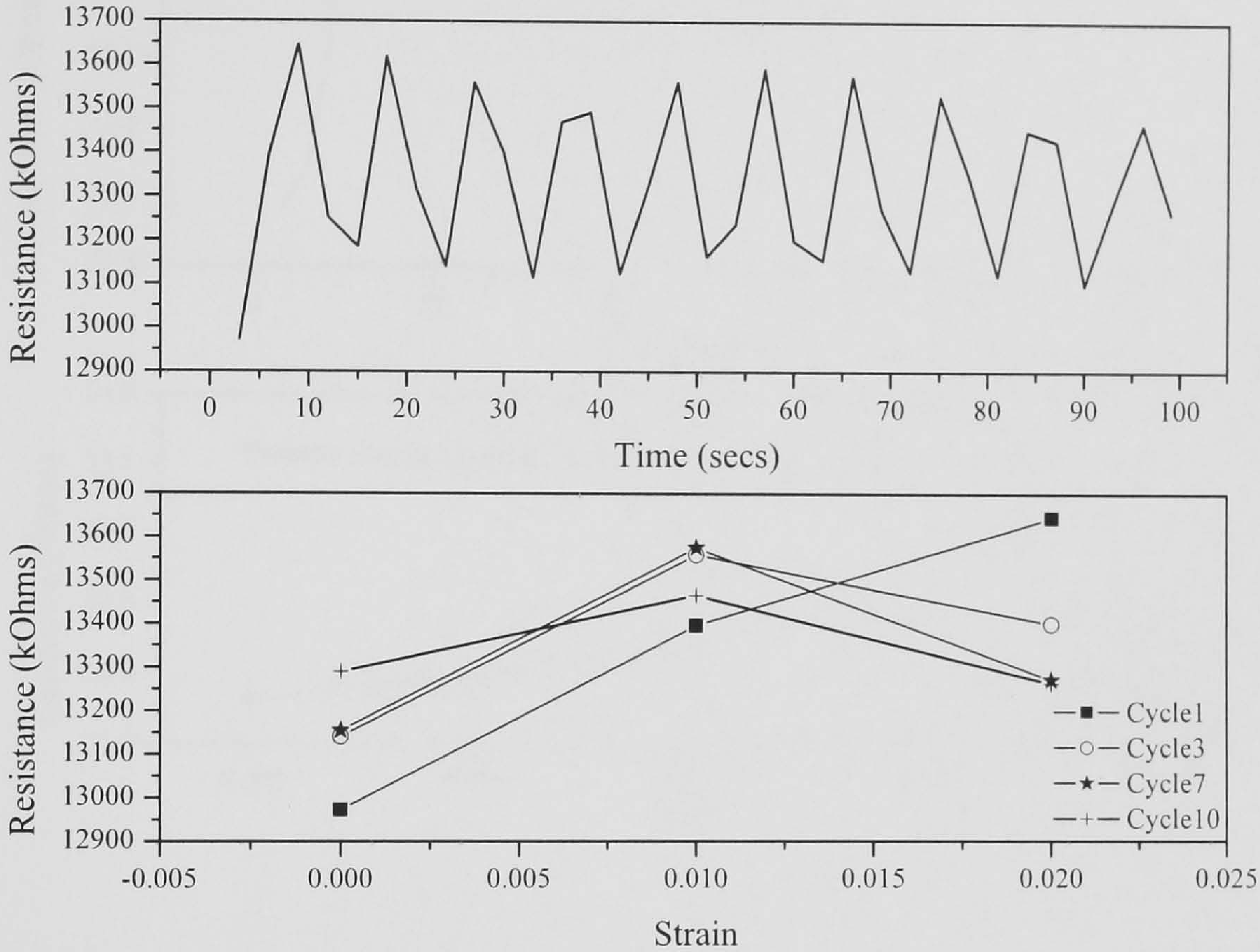


Stainless Steel Wire Resistance Elastic Recovery at 2% extension, Timed Hold

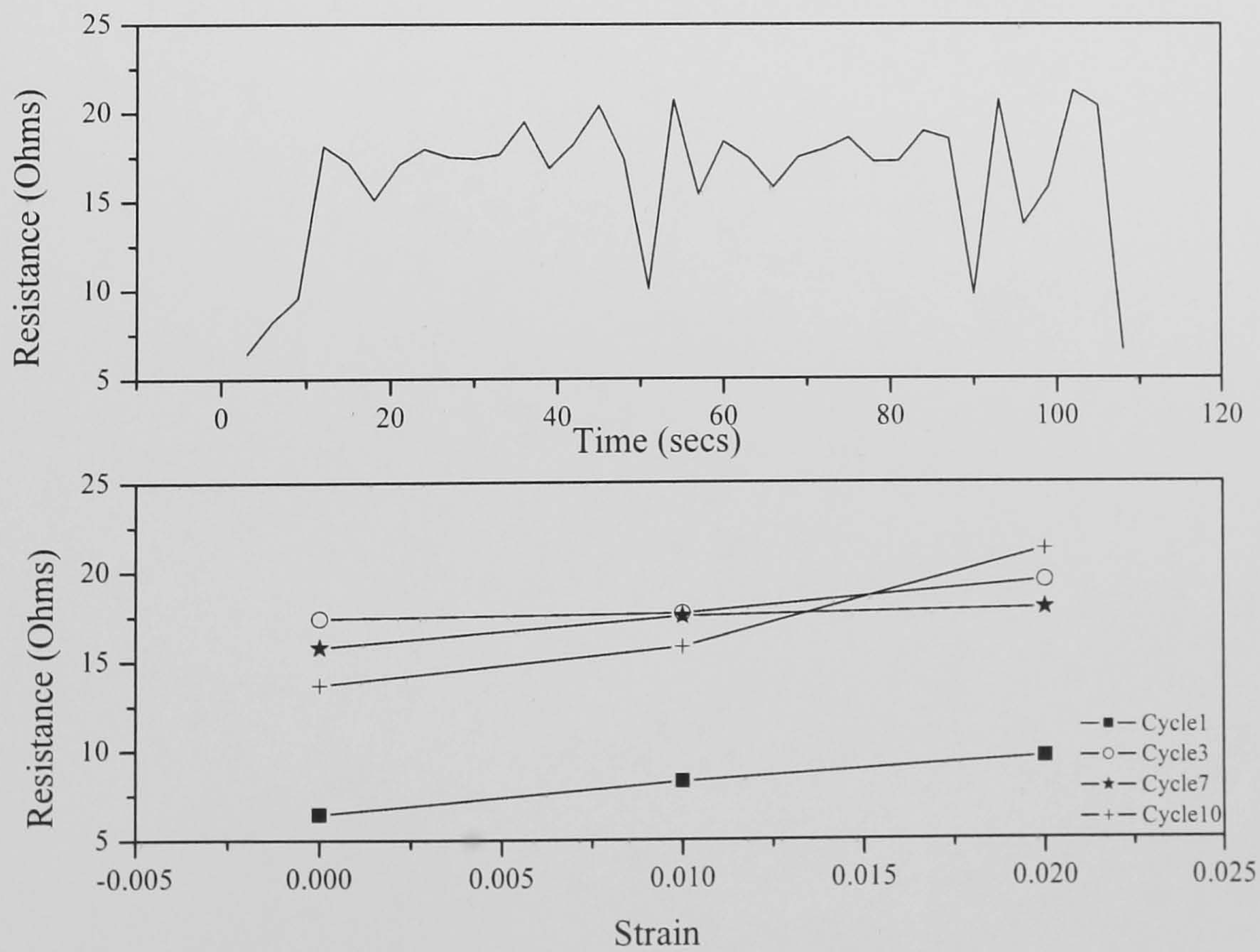


A2.5 Elastic Recovery – Immediate Reversal

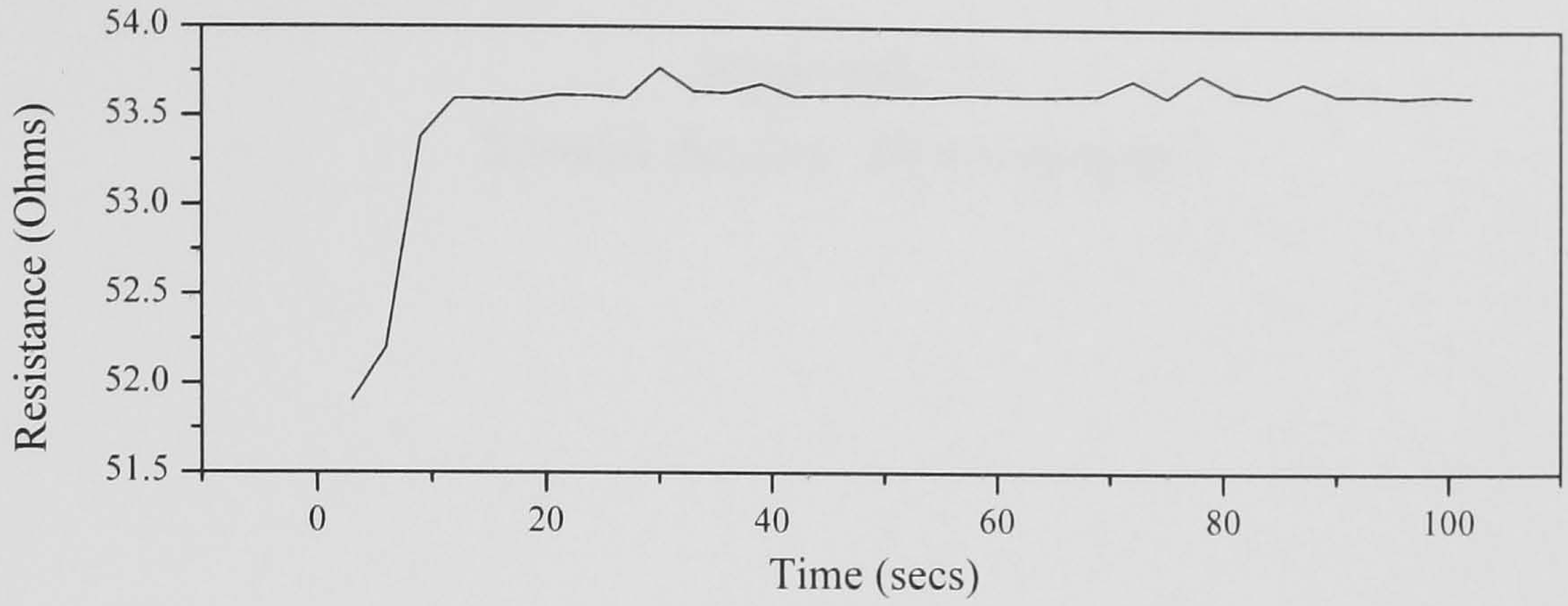
Resistat F9301 Elastic Recovery at 2% Extension, Immediate Reversal

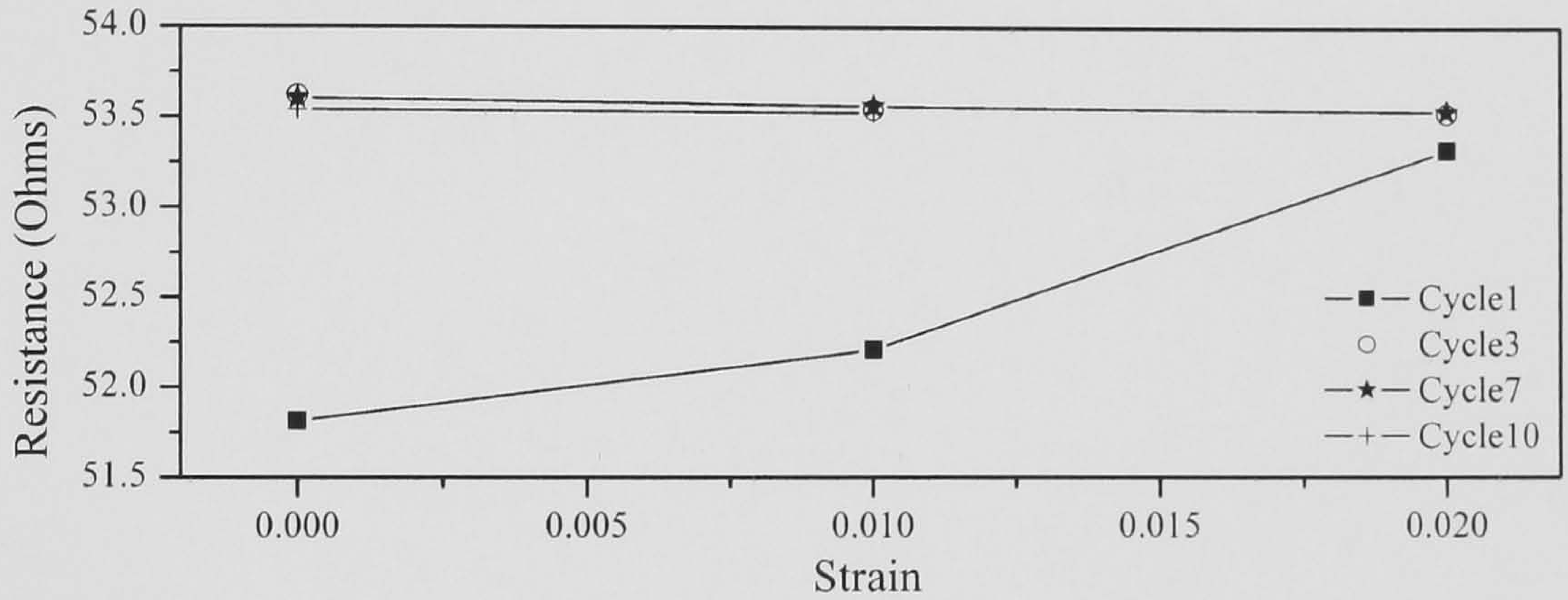


R.Stat/P Elastic Recovery at 2% Extension, Immediate Reversal



Stainless Steel Wire Elastic Recovery at 2% Extension, Immediate Reversal

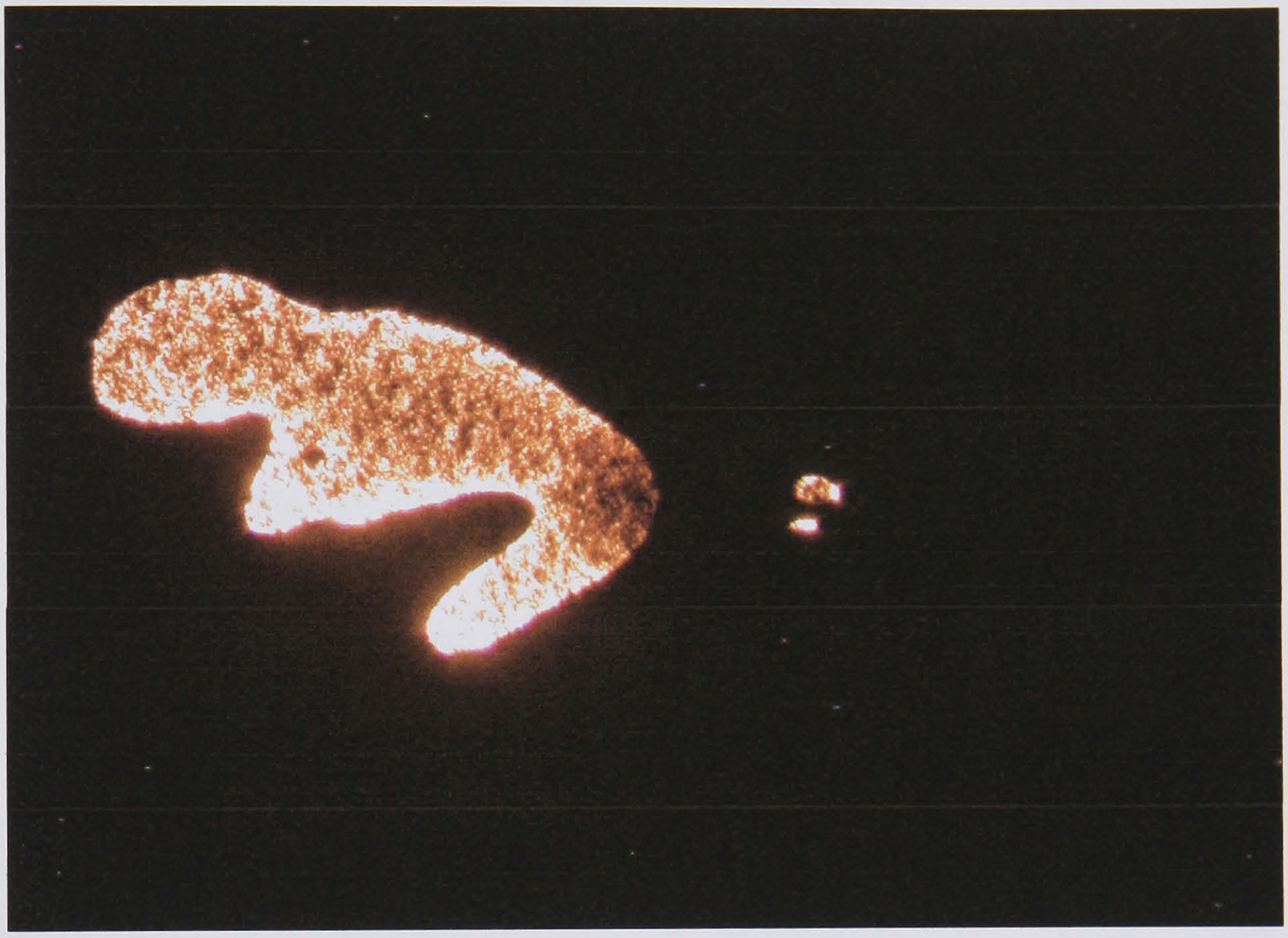




Appendix 3
Strain Sensor Development

A3.1 Particle Dispersal Microscope Images

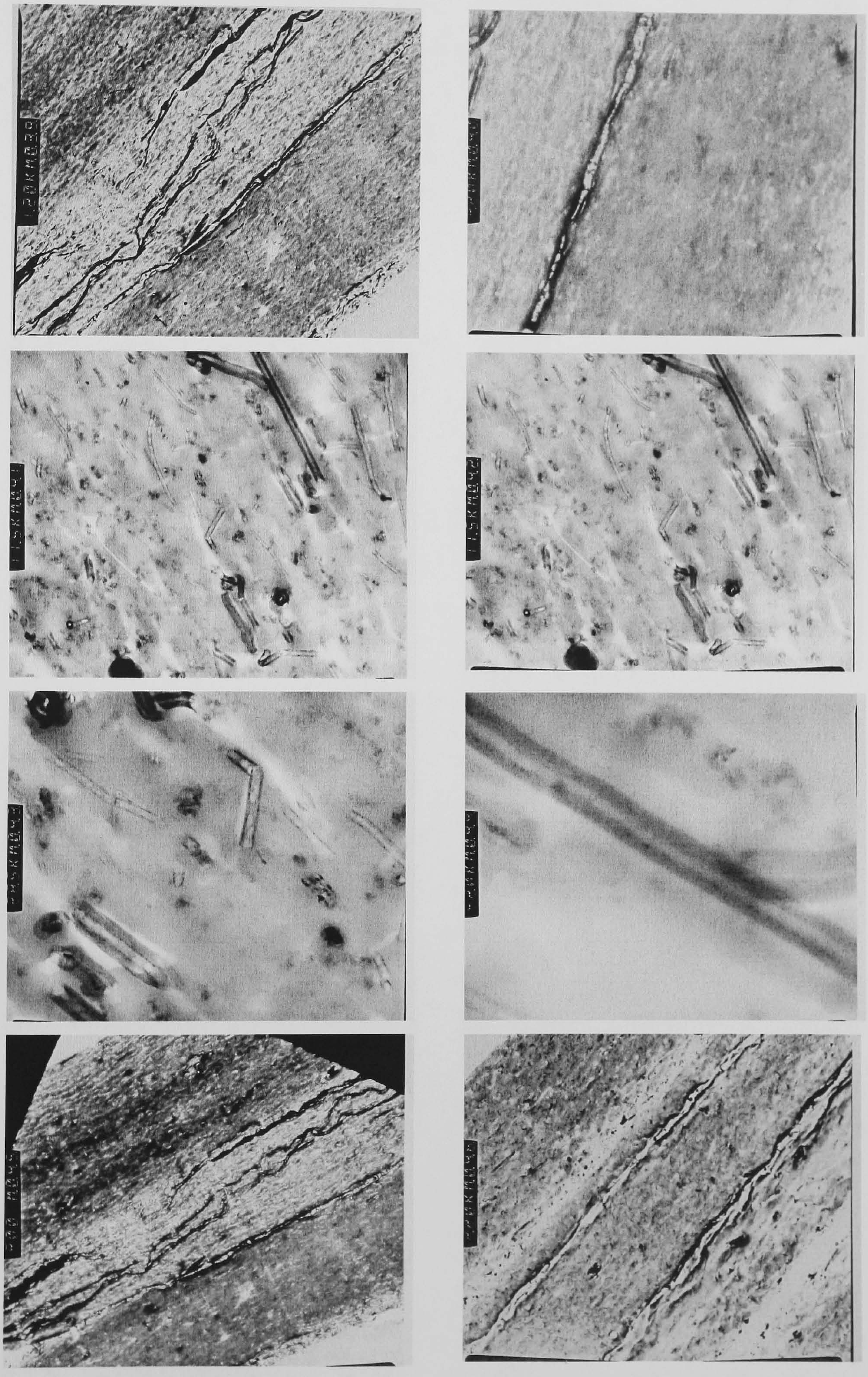
10% CB, 5% CNF

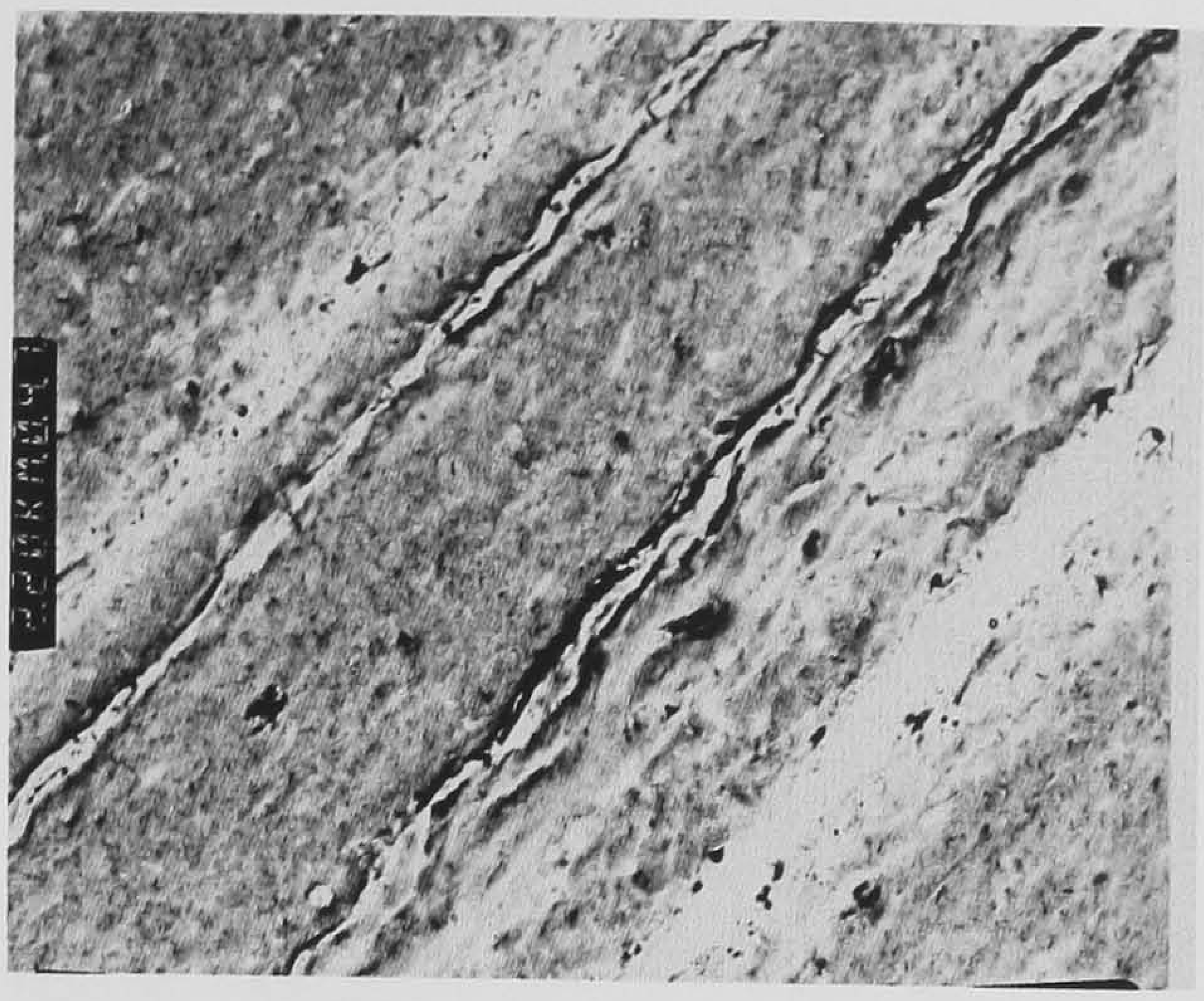


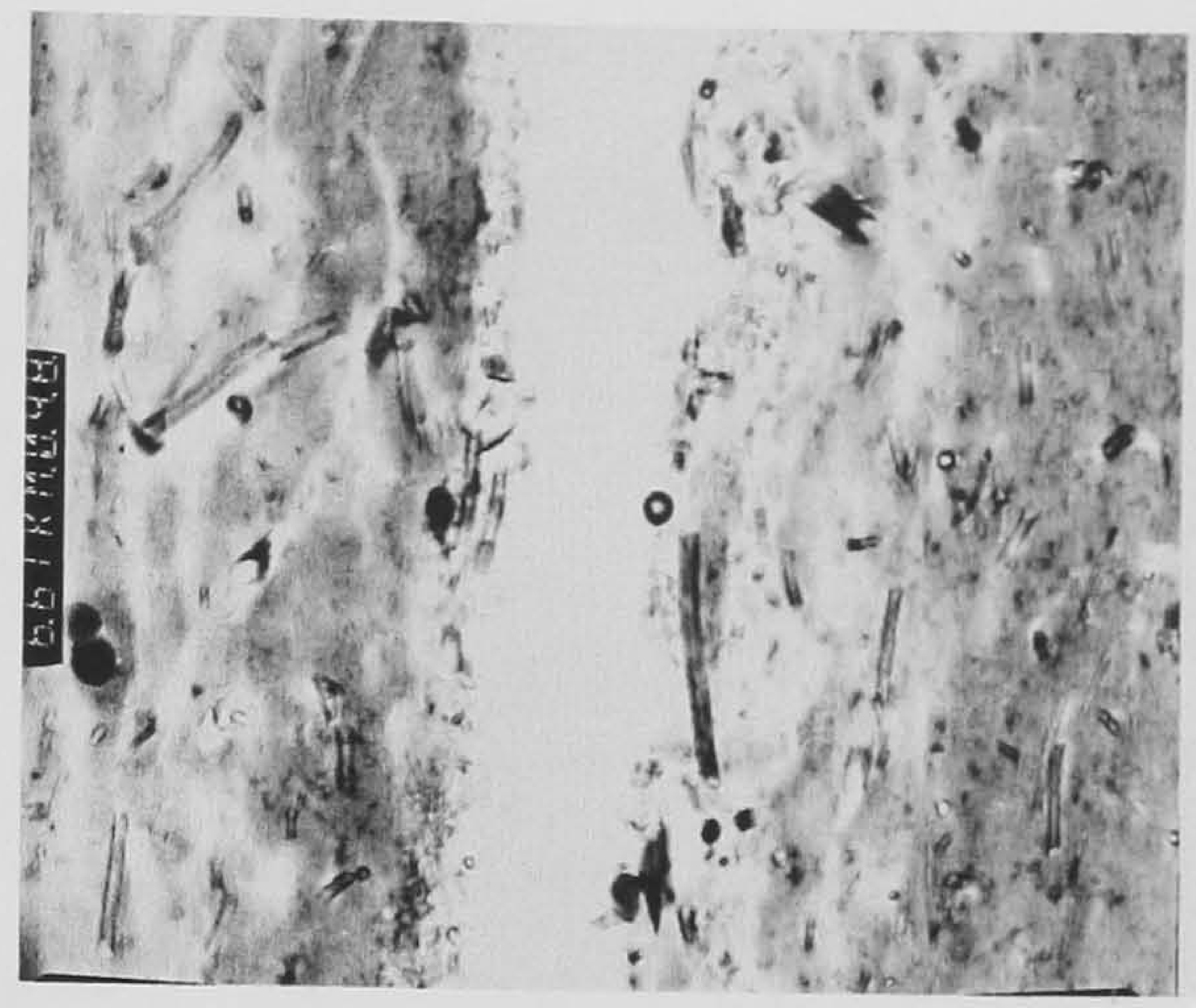
5% Carbon Black

A3.2 TEM Imaging

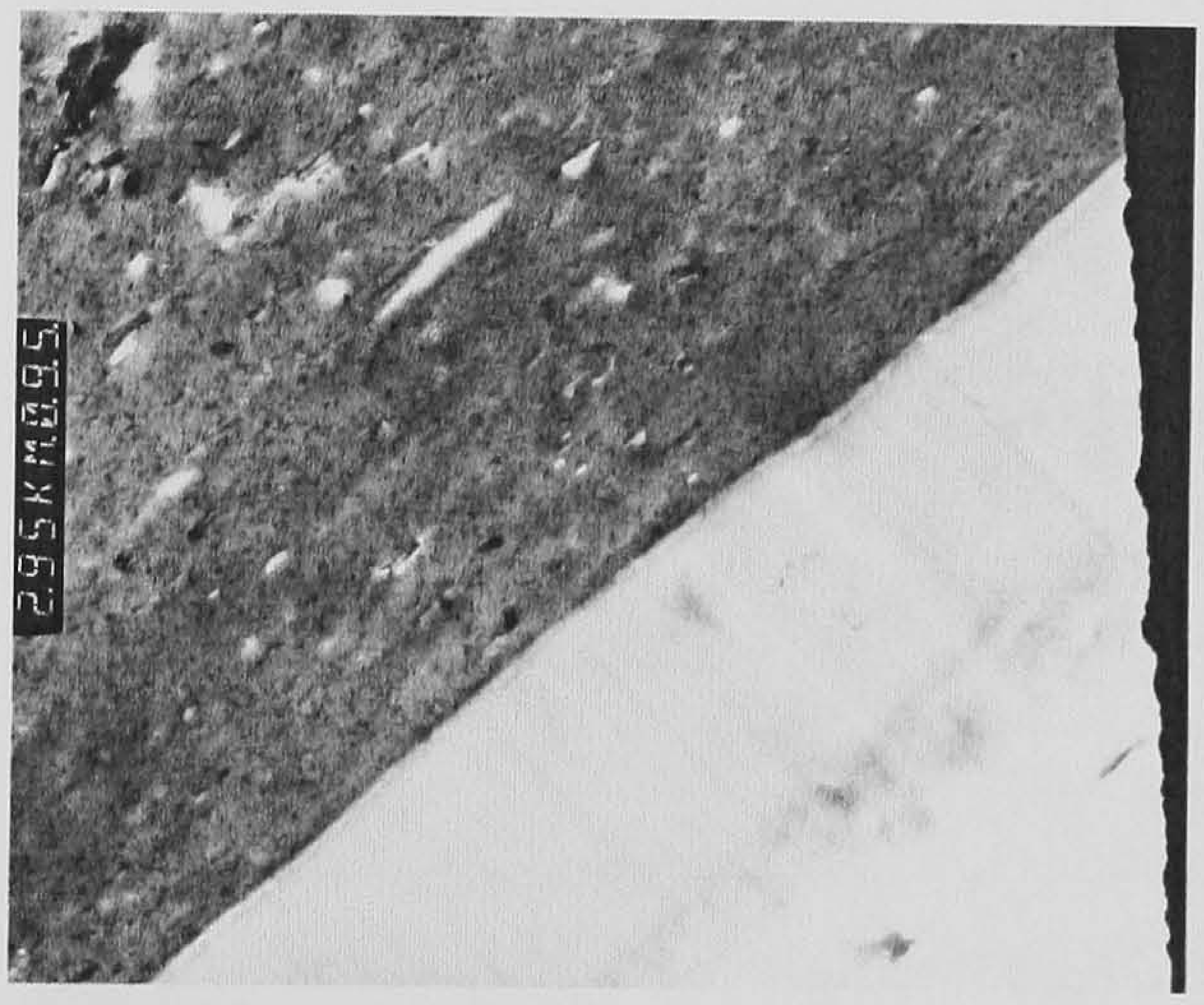
10% CNF, 90% PA6.10

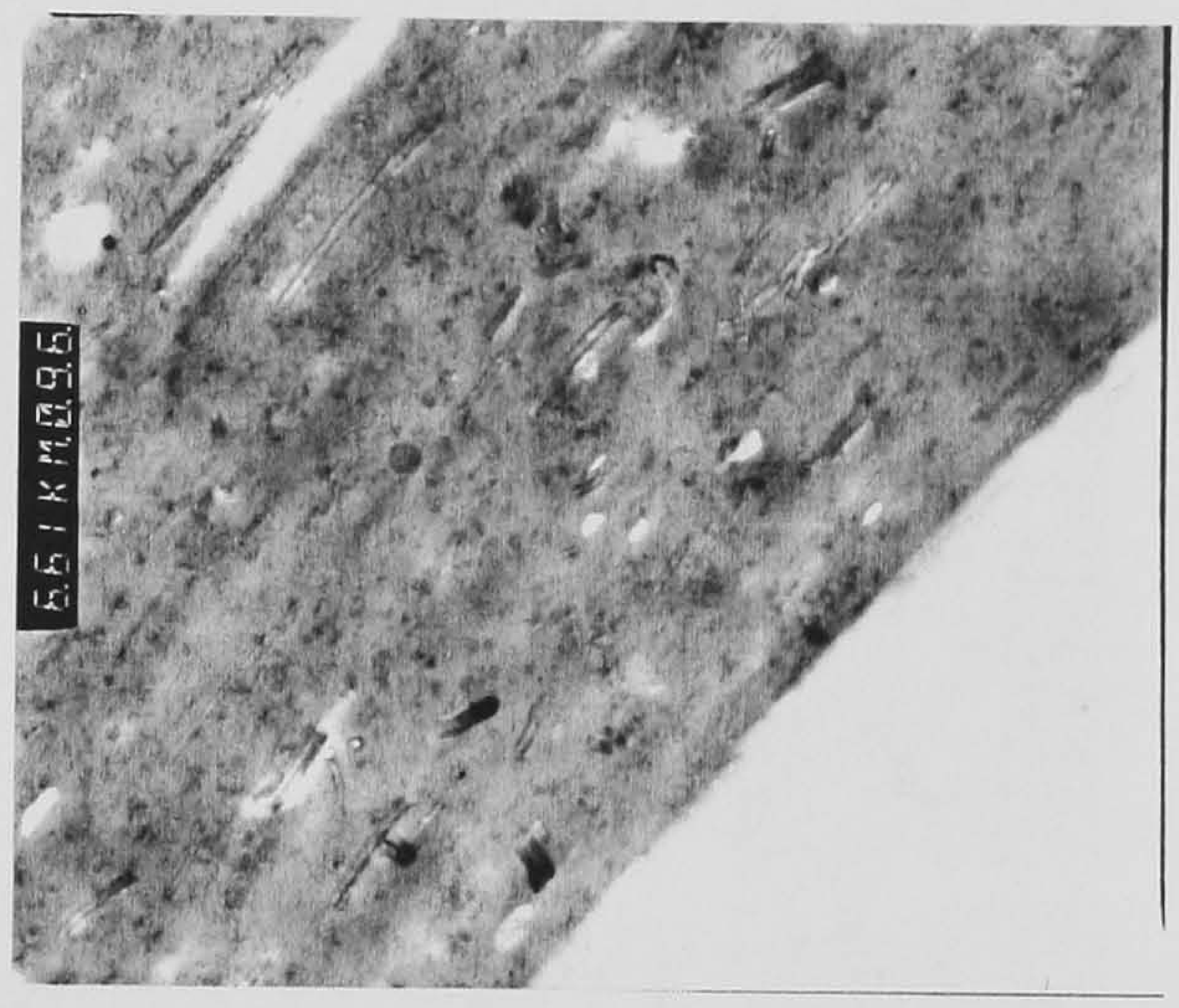


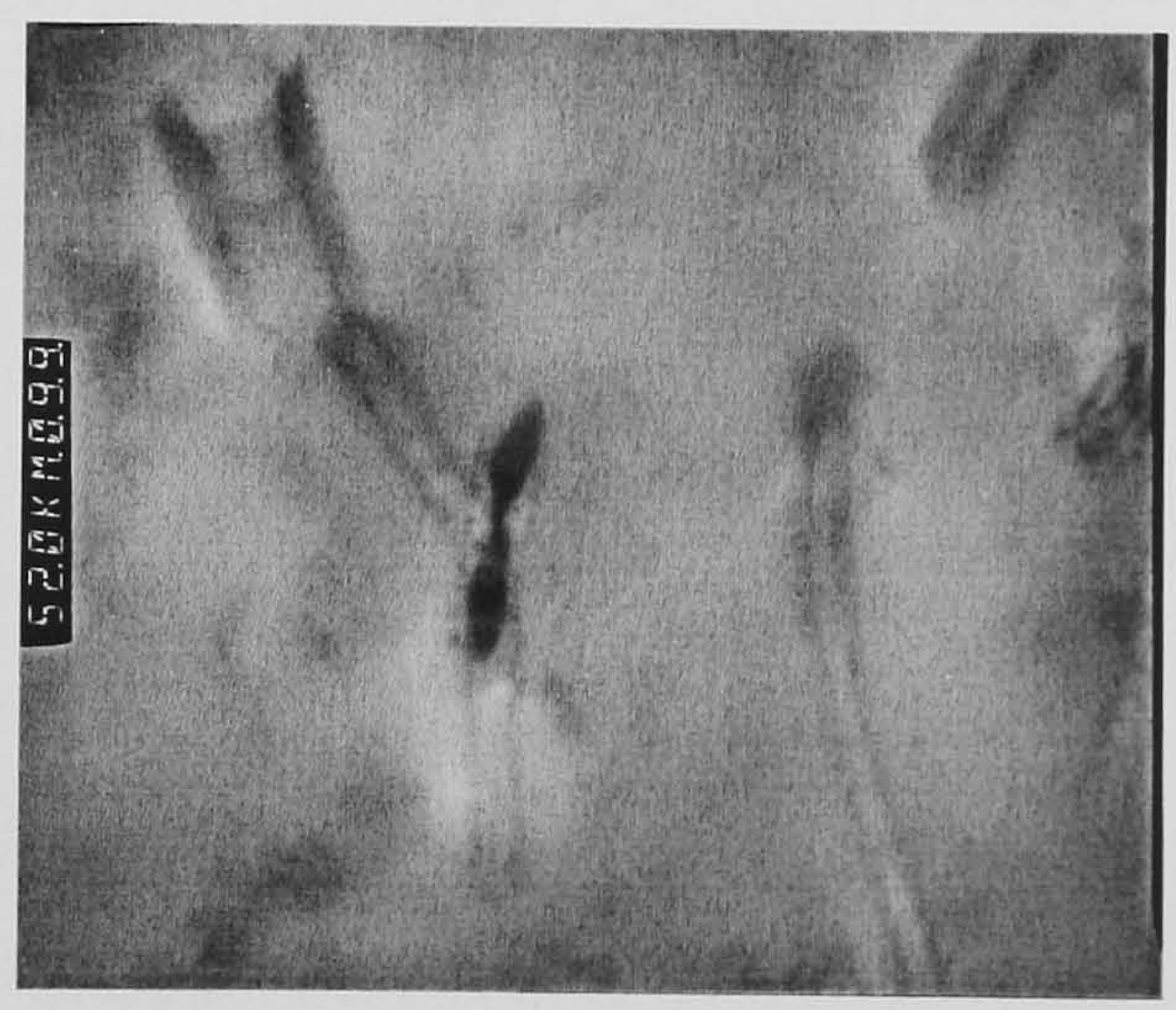


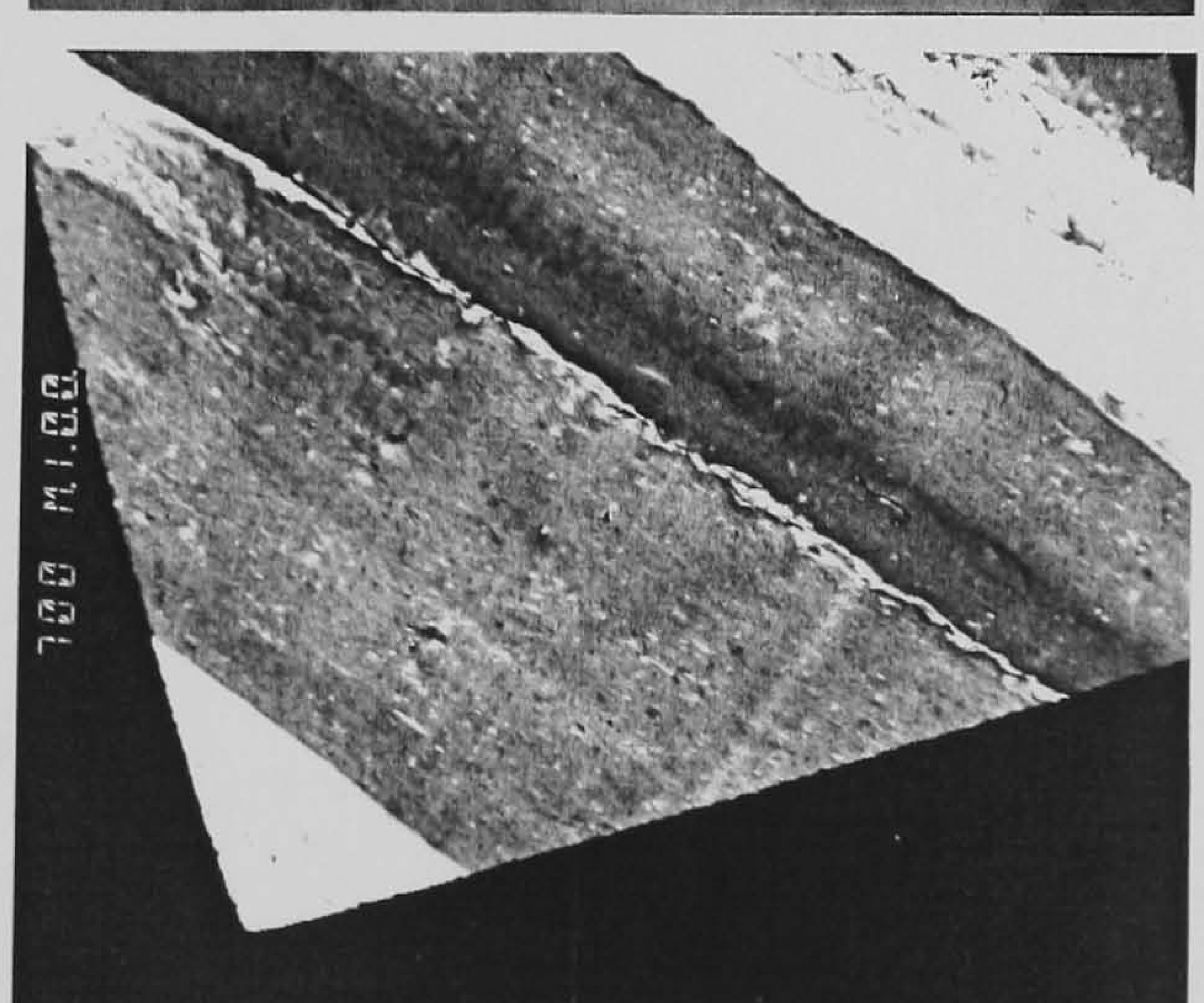


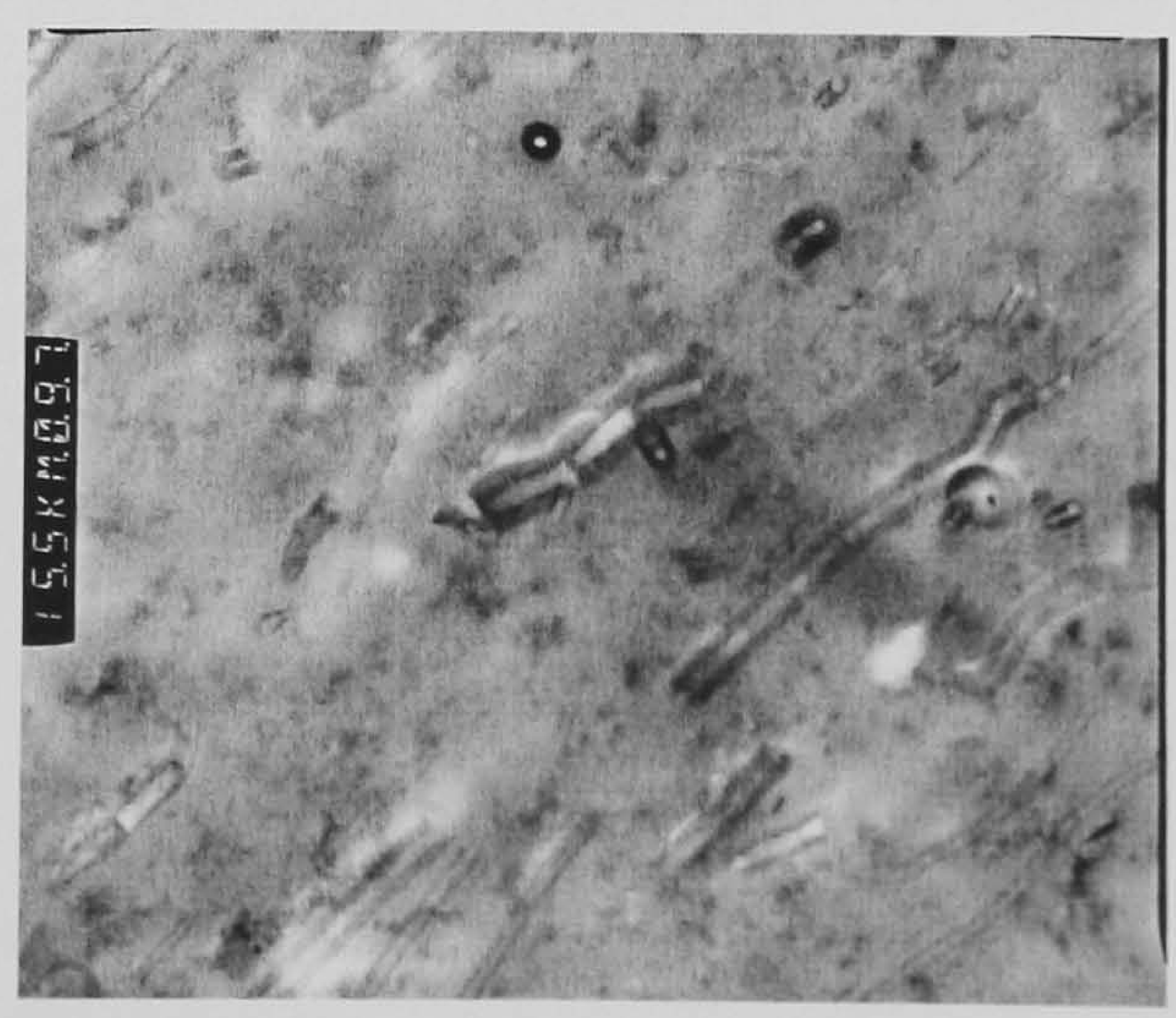
10% CB, 5% CNF, 85% PA6.10



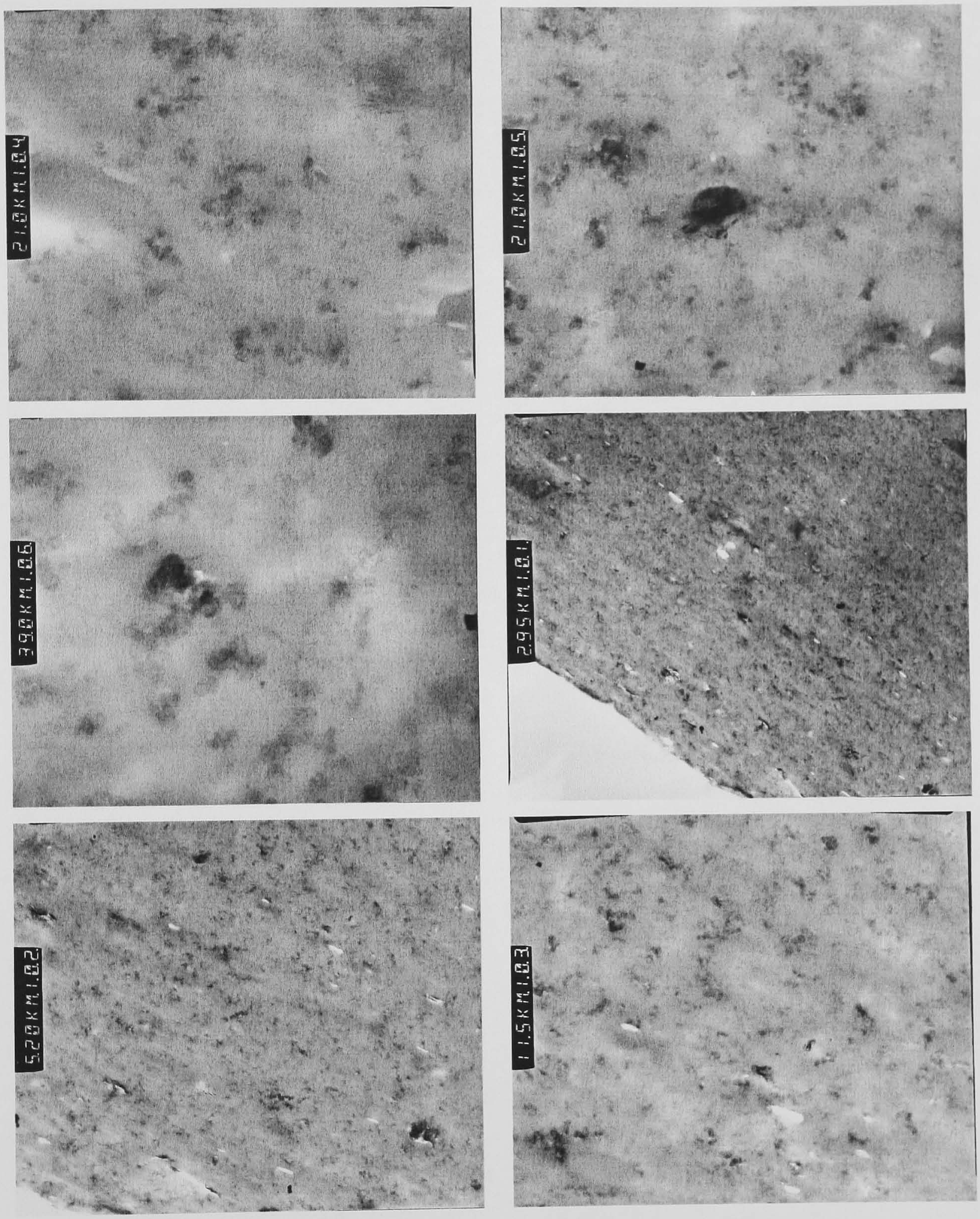








5% CB, 5% CNF, 90% PA6.10



5% CNF, 95% PA6.10