Copper Clad Laminate for High Frequency Printed-circuit Board in 5G era

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ABSTRACT

With the rapid development of the communication industry, the demand for hardware is constantly growing. However, traditional epoxy resin copper clad laminate (CCL) cannot meet the high frequency requirement of 5G (fifth-generation wireless systems) environments.

PTFE is an excellent dielectric material with a low dielectric constant and minimal dielectric loss. It can thus be widely used in mobile communication equipment, radio receivers, transfer devices, base station antennae, and household appliances, and CCL made from PTFE has many applications.

The main purpose of this project was to investigate the use of PTFE to replace epoxy resin. There are several obvious problems with this, such as poor mechanical properties (bending strength, hardness, and so on), the large coefficient of thermal expansion, and the poor bonding force between the copper foil and matrix resin. Those problems greatly affect the promotion of this technique.

To solve the issues with poor mechanical properties, this project investigated the use of different reinforcing materials such as glass fabrics and glass fibre mats while simultaneously seeking and testing a suitable silane coupling agent to increase the fibre strength and the binding forces between the resin and any reinforcing materials.

Alongside investigating a silane coupling agent, this project also researched various copper foil and bonding layer, as these two things are the most important elements affecting bonding force and fulfilling the various purposes of CCL. Based on experiments and comparisons, electrolytic copper foil and FEP film were the technologies selected in this project.

In order to explore the performance of copper foil and a bonding layer, this project utilised the process of hot-pressing and copper cladding. The coefficient of thermal expansion of PTFE is much larger than that of epoxy resin, as the hot-pressing of PTFE board and copper cladding cannot be done together. The pressure curve and temperature must thus normally be designed separately. In this project, an integrated technological approach was designed and tested.

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Declaration of Authorship

"*I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.*"

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1 Introduction

As time goes on, data transmission speeds have become insufficient. The 5G era is emerging, yet the properties of old CCLs cannot meet the requirements of this protocol. CCL technology thus requires reform.

1.1 What is 5G?

Data transmission speeds are rapid in wire media； however, they are not fast enough in the air. The most popular technology in current use is 4GLTE, with a theoretical rate of only 150 Mbps. The most effective way to increase these data transmission speeds is by using higher frequencies.

One of the difficult points about upgrading to 5G is the price. The higher frequency an electromagnetic wave has, the shorter the wave length. This means the diffraction ability and penetration ability of high frequency electromagnetic waves are weak, and it also means that the signal coverage of each base station is minimised. Because of this, the number of base stations in 5G systems is much higher than the number in 4G systems. Information is from reference [1] and [10]. The differences are shown in Illustration 1.1.

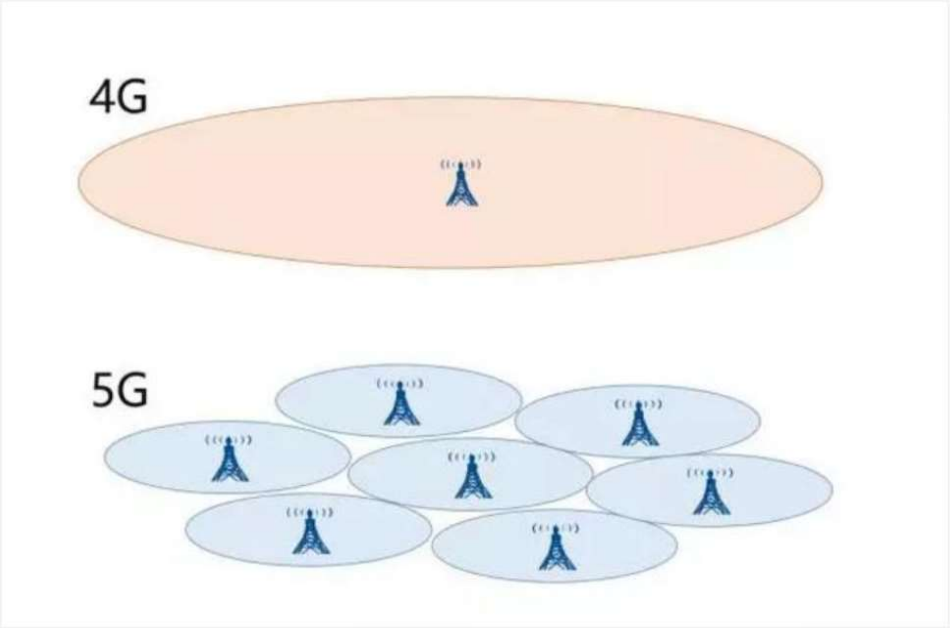


Illustration 1.1 The difference of the station distribution number of 4G and 5G networks in same area [3]

To reduce costs, equipment suppliers have developed several supporting technologies. The first is the use of micro base stations. Compared to normal base stations, a micro base station has a smaller volume and does not need a machine room. However, it puts different PCBs together and this is not good for maintenance.

Compared to 4G, 5G uses millimetre waves as its communication method, which offers a strong advantage in that the antenna also become millimetre-sized. This means that many more antennae could be set in a single micro base station, which makes a second important technology possible, Massive MIMO.

MIMO refers to multiple-input and multiple-output, as multiple antennae receive and send signals at the same time. Strictly speaking, MIMO is not a new technology, and it has been used in 4G LTE; however, each system can only have a few antennae, whereas in 5G, this technology becomes Massive MIMO. The difference is shown in Illustration 1.2.

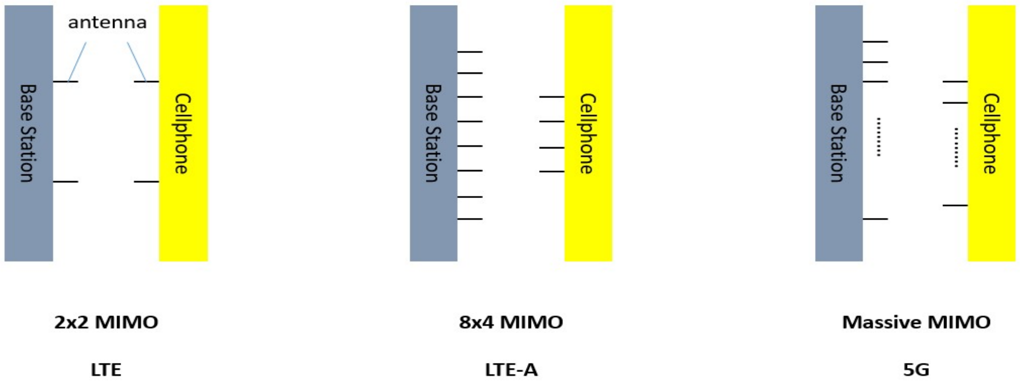


Illustration 1.2 The number requirement of antennas in base station and cellphone of MIMO in LTE, LTE-A, and 5G [2]

Overall, 5G is a complex system and PCB is necessary in every constituent hardware part. The main development directions of PCB in the 5G era are larger sizes, multilayer applications, high frequency, high speed, high density, flex-rigid, and mixed high and low frequencies.

1.2 High frequency CCLs in a 5G environment

A high frequency CCL is a special CCL which can receive high frequency signals. High frequency here can be defined as higher than 1 GHz. High frequency equipment is an inevitable trend in modern electronic equipment, especially in the fields of wireless networking and satellite communications. The development of information products requires higher speed and higher frequency use, and communication product also require high capacity and normalised transmission system. Due to this, new communication equipment such as mobile phones, satellite systems, and base stations must use high frequency CCLs. Over the next few years, the communication arena is likely to continue to develop at top speed, which means that high frequency CCLs will become an important market requirement.

With the increased requirements of high-speed network communication, the development and promotion of 5G technology has become imperative. This 5G technology includes millimetre wave communication, super dense cells, D2D, Co-frequency Co-time Full Duplex (CCFD), Massive MIMO, and New Heterogeneous Networks; the sheer range of needs and solutions poses a big challenge. There are several prerequisites for the development of 5G technology, such as low power consumption, pluralistic terminal forms, and the conglomeration of multiple wireless access methods, as 5G networks must support ultra-high speed and ultra-low delay operations, and the processing ability of 5G terminals will be greatly improved.

At present, the operating frequency range for LTE networks is between 700 MHz and 3.5 GHz; in the 5G era, the currently unauthorized millimetre wave band between 30 GHz and 300 GHz will be put into use and coexist with the LTE network to improve the wireless data capacity. This will generate more requests for processors, base bands, and RF equipment in mobile systems and base station systems. RF chip vendors must be aware that 5G will need to use more technology. One such item is the millimetre wave phased array antenna technology. This technology has previously been used in space and military applications, and it is currently used in automotive radar, 60 GHz Wi-Fi, and the development of 5G. This is not a simple amendment, however; it requires new product design and operational mode design.

In a 5G project, 6 GHz and lower frequencies form the core frequency band, and this is used to create seamless coverage; the frequency band over 6 GHz is the support band, which is used to increase the speed of hot spot regions. As the wave length of the millimetre wave is between 1 and 10 mm, if MIMO or interference coordination is used, it will produce higher paths or result in transmission loss. In addition, the measurement of serried urban environment with controllable beams by the antenna and network extension cellular systems is subject to higher levels of cost and technical difficulty. High frequency CCL is an indispensable part of 5G, and thus research, development and testing of these components is very important. The requirements of PCBs in different frequency ranges are shown in Illustration 1.3.

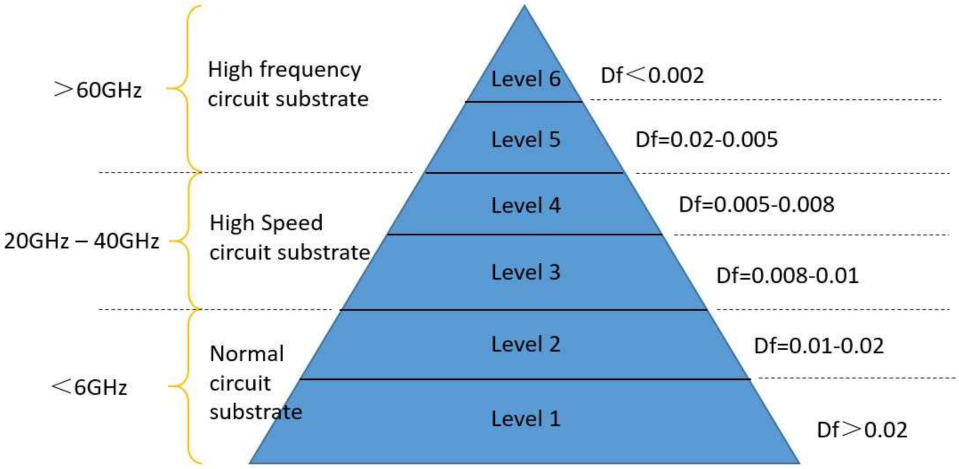


Illustration 1.3 PCB requirements of Df in different frequency ranges (Data is from the 5G seminar in China 2018.10)

1.3 The development and structure of high frequency CCL

Copper Clad Laminate (CCL) is made from a composite material mixed with E-glass fibre cloth or other reinforcing material and resin. The composite material is then covered with copper foil on one or both sides and subject to hot pressing. The resulting material can be used to make PCBs after appropriate etching and drilling of holes [22].

1.3.1 Development tendencies of CCL

CCL is one of main material parts of multiple electronic products. It appeared in the last century and remains under development. Due to modern requirements for miniaturization and lightweight and thin electronic products, modern CCL must have several special quality and technological characteristics to fill its important role in creating electronic information products.

The history of development of CCL can be divided into four stages: budding, initial development, high performance development, and high-density interconnection development.

The budding stage lasted from the beginning of the 20th century to the 1940s. This stage began with the exploration of resin matrices and reinforcing materials, and the development of the substrate manufacturing and metal foil etching processes. This stage laid the foundation for the original structure and characteristics of CCL.

The initial development stage lasted from the 1940s to the 1960s. The main changes in this stage were the use of epikote in CCL production and the introduction of solutions to bonding issues between large areas of copper foil and the insulating substrate. In addition, heat resistance and other key properties were improved.

The high-performance development stage occurred from the 1960s to the 1990s. The invention and application of integrated circuits and the requirements of smaller and higher performance electronic products demanded higher performance from CCLs. In the mid of 1980s, surface mounting technology (SMT) was invented, which was revolutionary as compared with classical through-hole packaging technology; surface mounting technology also meant that the density of electronic components became higher and the quality requirements of CCL thus also needed to increase.

The high-density interconnection development stage began in the 1990s. Since the beginning of 1990s, the electronic and information industry has developed very rapidly, and the use of computers and mobile phone has become exponentially broader; because of this, PCB technology has undergone an important evolution to provide high-density, fine wire conductors using narrow spacing techniques to provide high speed, low loss, high frequency, high reliability, multiple stratification, low cost, and automatic services.
A sedimentary method multilayer board has been invented in Japan that represents a new stage of high-density interconnection multilayer board manufacturing technology. This technology is another a big challenge for classical PCB technology, as high density interconnection multilayer board manufacturing technology offers new and improved product categories, performance characteristics, compositions, and structures. In terms of product function, it offers several new developments. This technology uses light-sensitive insulating resin as an insulating layer, and blind vias and buried vias are used to break the classical modes of structure, base materials, and crafting. The latter factors are the main technology that pushed the high density interconnected multilayer board into the mass market, and these utilise environmentally friendly flame-retardant CCL without bromine and stibium. In order to meet more of the demands of these high frequency microwave PCBs, many kinds of CCLs with special characteristics such as low dielectric constants, low dielectric loss factors, lower thermal expansion, and high heat resistance have also appeared.

2. Raw materials

From the many possible materials, such as ceramics, epoxy resin, and other resin materials, PTFE was chosen as the base material for high frequency CCL because of its excellent electrical properties and chemical stability.

2.1 Fluoropolymer

Since scientists working for Hoechsh AG discovered polytrifluorochloroethylene (PTFCE) in 1934, the number of different kinds of fluororesin has multiplied greatly, and many kinds are widely used in the areas of aviation, spaceflight, petroleum, chemical, mechanical, and construction.

A fluoropolymer is a kind of synthetic polymer material in which the carbon atoms in the main chain or side chain connect with fluorine atoms. In a fluoropolymer, fluorine atoms replace hydrogen atoms and form multiple high energy C-F bonds in which the energy is around 460 KJ per mol. The fluorine atoms spiral around the carbon chain and thus offer a protective coating; due to the shielding effect of the fluorine atoms, which means that the carbon chain is not susceptible to external erosion. This is the reason that fluoropolymers offer excellent performance in many respects such as low-friction, non-stick, oil and water resistance, chemical resistance, heat resistance, and good dielectric performance.

2.1.1 PTFE

PTFE is the abbreviation for polytetrafluoroethylene, also known as Teflon. It was first compound by Roy J. Plunkett in 1938. It has a simple molecular structure and fluorine carbon bonds which have high bond energy. Compared with other polymer resins, it has many excellent characteristics such as heat resistance, chemical resistance, and good dielectric properties. Some dielectric properties of common resinous material are shows in table 2.1 for comparison purposes. The data is from reference [11] “CCL for PCB” chapter 7 and chapter 9 and reference [12].

Resin	**Permittivity**	**Dielectric loss**
Epoxy resin (EP)	3.0-3.4	0.01-0.03
Polyester resin (PAK)	2.8-3.1	0.005-0.02
Phenolic resin (PF)	3.1-3.5	0.03.-0.036
Polyimide (PI)	2.7-3.5	0.005-0.008
Silicone resin (SI)	2.8-2.9	0.002-0.006
Bisphenol A polysulphone (PSF)	3.1	0.003
Polyphenylene sulphide (PPS)	3.0	0.002
Polyetheretherketone (PEEK)	3.2	0.003
Polytetrafluoroethylene (PTFE)	2.1	0.0004

Table 2.1 Dielectric properties of common resinous material

However, PTFE also has some disadvantages, such as high cost, poor stiffness, and large thermal expansion. In order to overcome these disadvantages, a lot of researchers [19], [20] have tried to use SiO2 or other inorganic materials as fillers and reinforcements to improve the stiffness and thermal expansion of PTFE.

Because of its special properties, PTFE is wide using as an anticorrosion and sealing material in the petroleum chemical industry field; as a lubricating antiseptic material in the aerospace field; and as a wire, cable, and outer wall decoration material in the building field.

2.1.1.1 Molecular structure of PTFE

PTFE is the monomer polymer of tetrafluoroethylene (TFE); the formula of its molecular structure is –[-CF2-CF2-] n-., with an average molecular weight of around 5 to 10 million. Within the structure of PTFE, a fluorine atom replaces the hydrogen atom seen in polyethylene. The fluorine atom has larger radius than a hydrogen atom, and because of this, the structure is changed into a sawtooth pattern that is different from the plane structure of PE. The molecular formula and structure of PTFE are shown in Illustration 2.2.

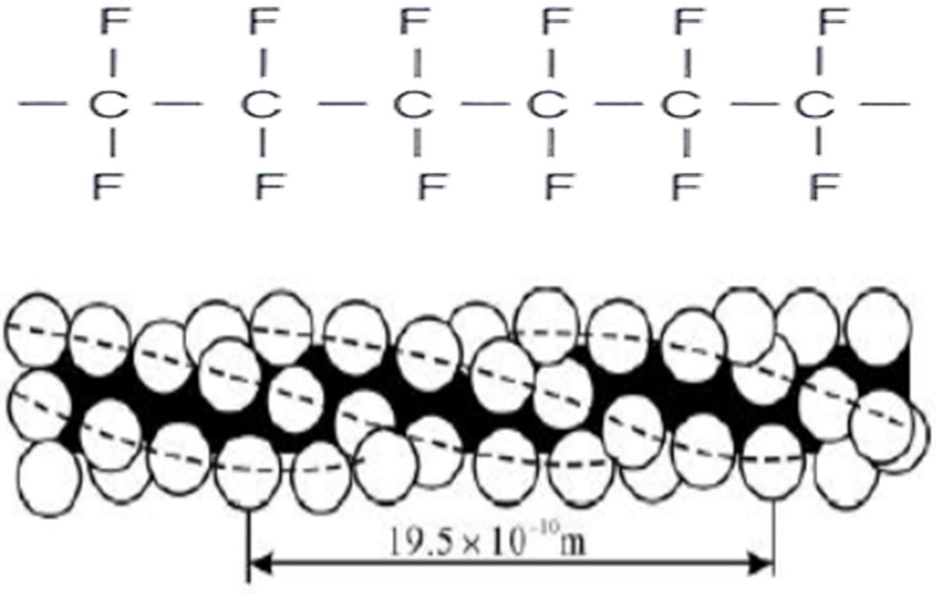


Illustration 2.2 The molecular formula and structure of PTFE [18]

As shown in the picture, the surface of PTFE is covered by many fluorine atoms. A fluorine atom has great C-C bond shielding, much higher than a hydrogen atom, and the fluorine nucleus has a strong binding force and low polarizability. For this reason, PTFE has high dissolution resistance, a low dielectric constant and high levels of insulation. The bond energy of C-F is also up to 460.5 kJ/mol, much higher than that of C-H or C-C. Thus, PTFE has excellent chemical stability and corrosion resistance. Furthermore, the electronegativity of the fluorine atom is very large, which causes the interface energy of PTFE to be very low. This makes it hard for it to bond with any materials which have large polarities.

The helical structure of PTFE changes with temperature. At 19˚C, the helical structure is crystal form II, with 13 -CF2- bonds in the spiral line. Between 19 and 30˚C, the helical structure is crystal form IV, with 15 -CF2- bonds in repeat units in seven spiral lines. If the temperature is higher than 30˚C, the structure changes to crystal form I, and the quantity of disordered organisations increases; however, due to its special helical structure, PTFE still has a higher melting temperature and melt viscosity than other polymer resin materials. For example, at 327˚C the melt viscosity is still up to 1011 Pa.S.

2.1.1.2 Characteristics of PTFE

The special helical structure of PTFE offers many excellent performance benefits, which are clarified below.

(1) Excellent electrical performance

PTFE is a high polymer material which is without linear chains. This means that the structure of PTFE is perfectly symmetric, as the fluorine atoms are distributed symmetrically on the molecular chain. The molecules do not have polarity, and because of that, PTFE has a low dielectric constant and reduced dielectric loss of Dk=2.1 and Df=0.0003 at 10 GHz, respectively. The electrical performance of PTFE is detailed further in table 2.3. [17]

Performance	**Suspension resin**	**Dispersion resin**
Dielectric constant (10 GHz)	2.1	2.1
Dielectric loss (10 GHz)	0.0003	--
Dielectric strength (V/mm)	23600	23600
Arc resistance (s)	>300	>300
Volume resistivity (Ω.cm)	$>10^{18}$	$>10^{18}$
Surface resistivity (Ω.cm)	$>10^{16}$	--

Table 2.3 Electrical performance details for PTFE

The volume resistivity and surface resistivity are both given as at 300°C, and it can be seen that both values are higher than 10^{16} Ω.cm. The value for arc resistance is also excellent.

(2) Excellent corrosion resistance

PTFE is a long chain high crystalline polymer, which means that it has a steady crystalline state. The fluorine atoms cover the long spiral chain, offering PTFE excellent corrosion resistance.

(3) Low water absorption

Water is a high dielectric loss and high dielectric constant substance, and materials vary widely in terms of higher or lower water absorption, which can increase the dielectric constant and dielectric loss of materials and make their dielectric properties unstable. The water absorption of PTFE is lower than 0.01%, which means PTFE is suitable as the matrix of microwave substrate composites.

(4) Wider working temperature range

Between 19°C to 327°C, the dielectric property of PTFE is nearly unchanged, while even at -200°C, PTFE still has good mechanical properties, suggesting that PTFE is suitable as a microwave substrate composite.

(5) Good non-carbonized ablative property

When the temperature rises higher than its decomposition temperature (400°C), PTFE starts to decompose; however, the ongoing ablation happens internally, which means there is no carbonizing layer on the surface, and the products of decomposition volatilize quickly. The dielectric property is thus not affected.

Its special structural feature offers a lot of advantages to the use of PTFE; however, it also has several drawbacks.

(1) Poor mechanical performance

The rebound resilience, material strength, and material hardness of PTFE are weak; details of these parameters are shown in table 2.4. Data from reference [17].

Performance	**Dispersion resin**	**Suspension resin**
Tensile strength (MPa)	17.5-24.5	7.4-28.8
Elongation at break (%)	300-600	100-200
Flexural modulus (MPa)	280-630	350-630
Bending strength (MPa)	6.2-18.7	4.3-19.6
Rockwell hardness (D)	50-65	50-60

Table 2.4 Detailed parameters for PTFE

(2) Large thermal expansion

PTFE has extensive thermal expansion: PTFE will expand by 4% if the temperature rises from 23ºC to 250ºC and shrink by 2% if the temperature lowers from 23ºC to -200ºC.

(3) Poor heat conductivity

The heat conductivity of PTFE is poor, which means that PTFE is prone to thermal deformation and thermal fatigue.

(4) Difficulty in forming and reprocessing

Due to the large shrinking percentage seen in PTFE, injection moulding and calendaring moulding cannot be used for PTFE components.

(5) High cost

Compared to epoxy resin, PTFE is much more expensive. The price of raw materials is an important determinant for the marketization of products, so this is an important factor.

2.1.1.3 PTFE emulsion preparation

PTFE emulsions include PTFE suspension-emulsion and PTFE dispersed-emulsion. The preparation technology for these two emulsions differ, however, being suspension polymerization and dispersed polymerization, respectively.

(1) Suspension polymerization

The steps of suspension polymerization include polymerization, resin washing, comminution, and drying. The polymerization process takes place in a tank reactor. The oxygen content in the tank reactor needs to be controlled under 20 mg/kg by inert gas replacement or vacuum processing before the additive formulation and water are placed into the tank reactor. The pressure must be maintained during stirring and as TFE is added into the tank reactor. Once the polymerization reaction is completed, the reaction product is placed into a mash tank and the mother liquid removed. Deionized water is then added into the mash tank to start the washing and comminution process. After that, the water is removed, and the PTFE sent into the dryer. The final step is using a cyclone separator to remove tiny impurities to produce the final product, PTFE in medium-grained size.

(2) Dispersed polymerization

The main steps of PTFE dispersed polymerization include polymerization, paraffin removal, and agglomeration or concentration. The operation is similar to suspension polymerization, with the main distinction being that dispersed polymerization adds paraffin as a stabilizer and uses a receiving vat to remove the paraffin after the polymerization reaction is completed. The final product is PTFE dispersion resin particles. After processing these PTFE dispersion resin particles with electrophoresis or using a heating concentration method, a PTFE emulsion emerges.

2.1.1.4 PTFE modifications

As described previously, PTFE has many restrictions on its use. In order to expand the application of PTFE in various fields, modifications to PTFE are necessary. The main methods for PTFE modification are surface modification, filling modification, and blending modification.

(1) Surface modification

PTFE is a fluorine-containing refractory polymer material. Materials like this have higher surface chemical inertia, which means they are difficult to bond with ordinary adhesives. Surface modification is an effective method to solve this problem by using the principle of improving surface roughness or surface level by adding polar groups in the molecular chains of PTFE surfaces. The main methods include chemical treatment method, gas thermal oxidation method, low temperature plasma technology, sodium-naphthalene treatment, and coupling modification.

(2) Filling modification and fibre reinforcement

PTFE filling modification refers to the addition of curing additives which offer different compositions and structures. The aims of the process are cost reduction and improving machining performance improvement. Fillers can be classified into organic natural material fillers and inorganic fillers. The inorganic fillers are more common, and these include calcium carbonate, silicon dioxide, carbon black, glass beads, and titanium dioxide.

Fibre reinforcement is the main method of improving the mechanical properties of PTFE. This generally involves mixing polymer with fibre to obtain the combined performance of both. Common fibres used include glass fibre, carbon fibre, finnylon fibre, and crystal whisker.

(3) Blending modification

Mixing two or more polymers together is called blending modification. This can be divided into three types: physical blending, chemical blending, and physical chemical blending.

The current project uses all three different modification types to improve the performance of PTFE CCL.

2.1.2 FEP

FEP is an abbreviation for fluorinated ethylene propylene, which has a density of around 2.12 to 2.17 g.cm^3. It is a copolymer of tetrafluoroethylene (TFE) and hexafluoropropylene (HFP), whose molecular formulas are CF2=CF2 and CF3CF=CF2 respectively. The HFP content can affect the performance of FEP, and the usual mass ratio of HFP for common FEP in the market is around 14 to 25%. The molecular structural formula is shown in Illustration 2.5.

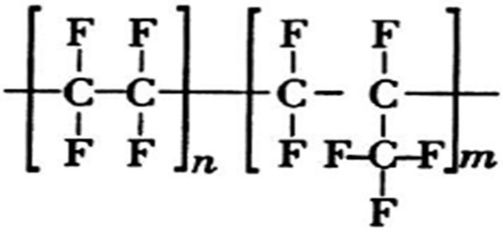


Illustration 2.5 The molecular structural formula of FEP [9]

FEP has similar electrical properties to PTFE, but it has better thermoplastic properties. The melting temperature of FEP is around 260°C [9], much lower than PTFE, which means FEP is an excellent blending modification and binding material. The differences between PTFE and FEP are shown in table 2.6. Data was from reference [18].

	PTFE	**FEP**
Melting point (°C)	327	265-285
Melt viscosity (Pa.S)	10^{11} (350°C)	10^{3}-10^{5} (300°C)
Melt flow index (g.10min)	Immobilization	0.5-3.5 (327°C)
Maximum temperature for long-term use (°C)	250-260	200-210

Table 2.6 Differences between PTFE and FEP about thermal properties

2.1.2.1 Electrical property of FEP

FEP has ideal dielectric loss tangent and dielectric constant and their values only show small changes in wide temperature and frequency ranges. FEP also has high volume resistivity and surface resistivity; only at 200˚C are those two values lower than in PTFE. The electrical properties of FEP are shown in table 2.7. Data is from reference [18]

Dielectric constant	**In 10^3 Hz**	1.9-2.1
	In 10^6 Hz	1.9-2.1
Dielectric loss tangent	**In 10^3 Hz**	$3\text{x}10^{-4}$
	In 10^6 Hz	(4-7) $\text{x}10^{-4}$
Surface resistivity (10^{15}Ω.cm)		>1-10
Volume resistivity (Ω.cm)	**In 20°C**	$>10^{16}$-10^{17}
	In 200°C	$1\text{x}10^{12}$-$5\text{x}10^{16}$
Dielectric constant (kV.mm^{-1})	**Thickness :2mm**	20-35
	Thickness: 50μm	100
	Thickness: 20μm	150
Arc resistance (s)		165

Table 2.7 Electrical properties of FEP

2.1.2.2 Thermophysical properties of FEP

The thermophysical properties also offer important data as the main method for making CCL in this project is the use of hot-pressing technology. The design of the temperature line is thus dependent on the thermophysical properties of the materials used. The thermophysical properties of FEP are shown in table 2.8. Data from reference [9].

Melt viscosity (300°C) (Pa.S)	10^3-10^5
Melt fluid index (g.10min)	0.5-30
Melting point (°C)	265-285
Glass transition temperature (°C)	-90
Decomposition temperature (°C)	>390
Min operating temperature (°C)	-195
Max operating temperature (°C)	200-210
Specific heat capacity (J.g^{-1}.C^{-1})	0.33
Thermal conductivity (W.m^{-1}.K^{-1})	0.26
Coefficient of liner expansion (10^{-5}/°C^{-1})	9
Zero strength temperature (°C)	265-320
Thermal ageing (200°C)	long
No thermal expansion temperature (°C)	19-327

Table 2.8 Thermophysical properties of FEP

2.2 Copper foil

Copper foil is one of the most important elements of CCL. The quality of copper foil thus bears a direct relationship with the durability and electrical properties of the resultant CCL.

2.2.1 Types of copper foil

Copper foil can be classified into different categories based on different characteristics such as production technology, performance, thickness, and colour. This project focuses mainly on the product technology and performance aspects, however.

2.2.1.1 Types of copper foil in product technology

According to the needs of different product technologies, copper foil can be divided into rolled wrought copper foil and electrodeposited copper foil.

(1) Rolled wrought copper foil

Making rolled wrought copper foil has three steps. The first is making copper plate by means of melting. The second step is using a machine to roll the copper plate until it becomes an original foil. The final step is to introduce roughing treatment, heat resistant layer treatment, and anti-oxidation treatment to this original foil.

Rolled wrought copper foil develops a lamellar crystalline structure; because of this, rolled wrought copper foil is better than electrodeposited chopper foil in terms of percentage of elongation, folding strength, and high temperature recrystallization. On the other hand, because of the limits of processing technology, the available breadth of rolled wrought copper foil does not fit the production requirements of rigid CCLs. Due to this, rolled wrought copper foil is mostly used in flexible printed circuits (FPC). However, rolled wrought copper foil has good consistency and a smooth surface, making it effective at rapid transmission of signals, so it can also be used in high frequency circuits and precision line PCBs.

(2) Electrodeposited copper foil

Electrodeposited copper foil is made from a strong solution of copper sulphate. In order to ensure the purity of the electrodeposited copper foil, a copper wire which has the same purity as the final product is used as raw material to make the solution. Subject to direct current, copper will deposit on the surface of a tubular cathode. The rest of the process involves stripping the copper from the surface of the tubular cathode and adding roughing treatment, heat-proof treatment, and anti-oxidation treatment. The manufacturing operation for electrodeposited copper foil is shown in Illustration 2.9 and 2.10.

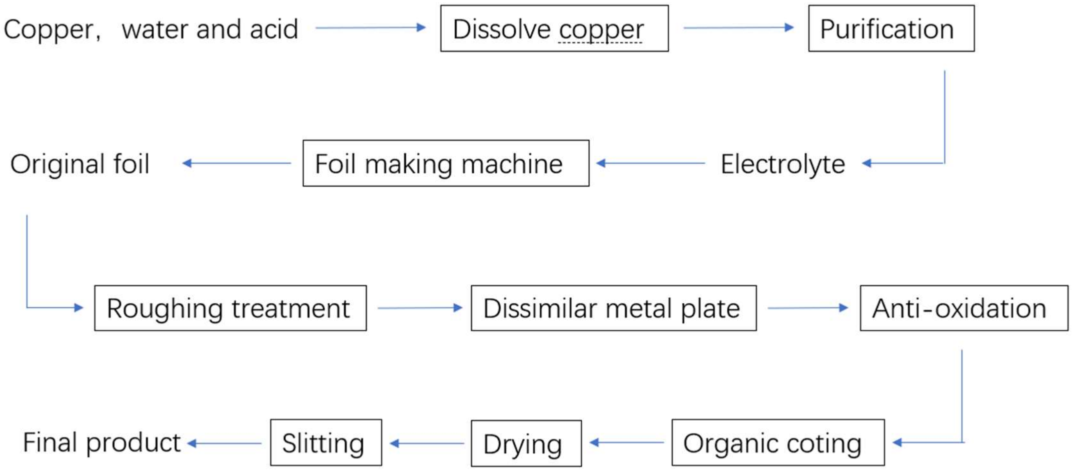


Illustration 2.9 The manufacturing operation for electrodeposited copper foil

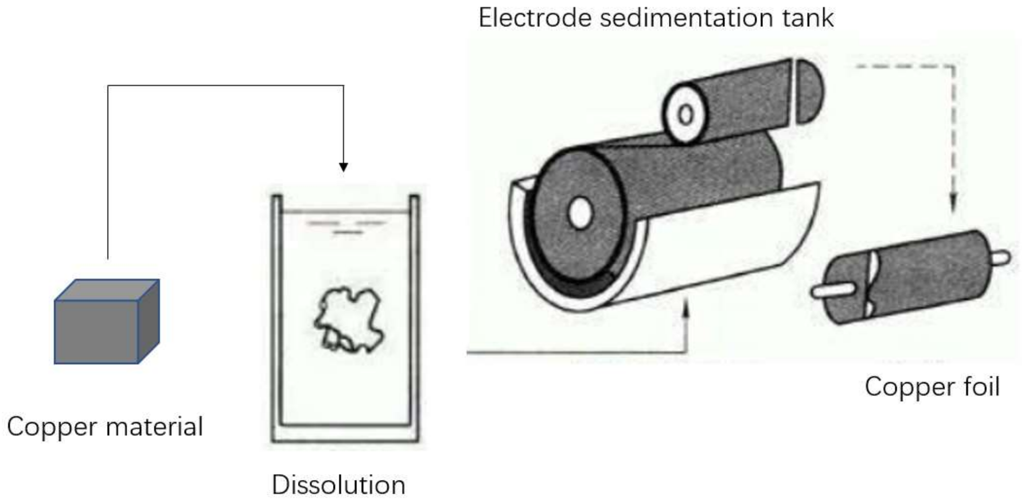


Illustration 2.10 The manufacturing operation for electrodeposited copper foil (This diagram is from reference [11] “CCL for PCB” chapter 5)

Compared to rolled wrought copper foil, electrodeposited copper foil has two different surface crystalline forms on its sides. The side closest to the cathode is smooth, while the other side has an uneven crystal structure and the surface is rough.

The structure of electrodeposited copper foil made by traditional techniques is columnar crystalline. Because of this, the elongation percentage, folding endurance, and high temperature recrystallization are worse than in rolled wrought copper foil. For those reasons, electrodeposited copper foil is mostly used in rigid CCLs. However, with further development of electrodeposit copper foil production technology, many companies have developed special electrolytic copper foils which are more suitable for flexible CCLs, high frequency CCLs and micro circuits.

These special electrodeposited copper foils have similar properties to rolled wrought copper foil; but offer a price advantage. Because of this, more flexible CCLs, high frequency CCLs, and micro circuits now use electrodeposited copper foil instead of rolled wrought copper foil.

2.2.1.2 Performance in types of copper foil

Copper foil can be divided into many types based on its performance, such as standard copper foil; high temperature, high ductility copper foil; high ductility copper foil; transfer proof copper foil; low profile copper foil; and ultra-low-profile copper foil.

(1) Standard copper foil (STD)

Standard copper foil can be used for paper phenolic resin CCL and epoxy resin glass fibre cloth CCL such as normal FR-4 board. This type of copper has greater surface roughness and the thickness is around 18 to 70 µm [11]. It has good binding force and heat-resistance up to 200ºC.

(2) High temperature, high ductility copper foil (HTE)

High temperature, high ductility is usually used in multi-layer circuit boards. These multi-layer circuit boards need high temperatures when processing, and at these temperatures, a recrystallization phenomenon will happen in some copper foil. Thus, these require copper foil with a high ductility at 180ºC to ensure the circuits remain without cracks. Copper foil with 5% or more high temperature elongation and a thickness around 12 of 35 µm is called high temperature, high ductility copper foil.

(3) High ductility copper foil (HD)

High ductility copper foil is widely used in flexible printed circuits that require high consistency and folding performance. High ductility copper foil requires special heat treatment processes.

(4) Transfer proof copper foil

This type of copper foil is often used in CCLs which need high levels of insulating properties. If the copper ion transfers in a CCL, it will affect the reliability of the electronic element. Thus, transfer proof copper foil, which requires special surface treatment such as nickel plating [11], is used.

(5) Low profile copper foil (LP)

Low profile copper foil is often used in multi-layer circuit boards and high-density circuit boards for its low roughness and high peeling strength.

(6) Ultra-low profile copper foil (VLP)

This type of copper foil is often used in flexible printed circuits, high frequency CCLs, and ultra-fine circuit boards. The surface is close to smooth, with a roughness lower than 2 µm [11]. The structure is equiaxed crystal without any columnar crystal.

2.2.2 Copper foil technical requirements

The technical requirements for copper foil focus on five main areas: dimensional requirements, physical properties, processability, technical quality, and surface quality.

(1) Dimensional requirements

The dimensions and weight requirements of copper foil are shown in table 2.11.

Standard thickness/μm	**Mass per unit/(g/m^2)**	**IPC-4562 code**	**Allowable error/%**
5.1	45.1	E	Electrolytic copper foil ≤±10 Rolled wrought copper foil ≤±5
8.5	75.9	Q	
12.0	106.8	T	
17.1	152.5	H	
25.7	228.8	M	
34.3	305.0	1	
68.6	610.0	2	
102.9	915.0	3	
137.2	1220.0	4	
171.5	1525.0	5	
205.7	1830.0	6	
240.0	2135.0	7	
342.9	3050.0	10	
480.1	4270.0	14	

Table 2.11 The dimension and weight requirements of copper foil (Standard is from IPC-4562 and GB/T 5230)

The requirements above are taken from IPC-4562, the most common international technical standard. Alongside meeting the details in the table above, however, the copper foil profile should up to the standards shown in table 2.12.

Copper foil profile	**Max value of copper foil profile**	
Standard	No standard	No standard
Low profile	10.2 μm	0.4 mil
Very low profile	5.1 μm	0.2 mil

Table 2.12 Copper foil profile standards (Standard is from IPC-4562 and GB/T 5230)

(2) Physical properties

The arithmetic mean value of the copper foil's surface roughness must lower than 0.43 μm. Peel strength is related to copper foil and base materials, and the specific standards should be met by supply and requisitioning parties.

(3) Processability

The copper foil after surface treatment should be removed by means if a normal etching process and must thus be of the same uniformity. The copper foil must also have good weldability after the etching process.

(4) Technical quality

The purity of electrolytic copper foil should be higher than 99.8% and the purity of rolled wrought copper foil should be higher than 99.9% before surface treatment.

The IPC mass resistivity requirements of electrolytic copper foil are shown in table 2.13.

IPC-4562 code	**Max mass resistivity/(Ω,g/m^2)**
E	0.181
Q	0.171
T	0.170
H	0.166
M	0.164
10Z and higher	0.162

Table 2.13 Copper foil profile standards (Standard is from IPC-4562)

The IPC mass resistivity requirements of rolled wrought copper foil are shown in table 2.14.

IPC-4562 code	**Max mass resistivity/(Ω.g/m^2)**
AR	0.160
LCR	0.155-0.160
ANN	0.155
LTA	0.160

Table 2.14 Mass resistivity requirements of rolled wrought copper foil (Standard is from IPC-4562)

(5) Surface quality

Copper foil for CCL has strict quality requirements that can be grouped into seven different categories.

- The copper foil cannot have any concave spots or indentations with diameters larger than 1.0 mm. The number of concave spots and indentations with diameters lower than 1.0 mm cannot be more than two in an area measuring 300 cm by 300 cm.
- The copper foil cannot have permanently deformed folds.
- The copper foil cannot have any scratches deeper than 10% of the thickness of the copper foil. The number of scratches cannot, in any case, be more than three.
- The copper foil cannot have notches and tears.
- The copper foil cannot have any dust, feculence, corrosives, salts, grease, or other contaminants which would affect the service life, processability, and

appearance of the foil.

- For 18 µm copper foil, the number of pinholes and breaks cannot be more than five in an area of 300 mm by 300 mm. For copper foil larger than 18 µm, the number of pinholes and breaks cannot be more than three.
- Copper foil should have good micro etching characteristics, which means the surface of the copper foil cannot have any spots or stripes after micro etching.

2.3 Coupling agent

Coupling agent modification is a common method for surface modification. Coupling reagents come in many types such as silane coupling agent, titanate coupling agent, aluminate coupling agent, bimetallic coupling agent, phosphate coupling agent, borate coupling agent, and complex coupling agent. Of these, silane coupling agent and titanate coupling agent are the most widely used.

2.3.1.1 Titanate coupling agent

Titanate coupling agent was invented by the Kenrich petrochemical company in the 1970s [5]. It can react with the surface of inorganic materials and form a monomolecular layer. This layer has a plasticization and adhesive action and is thus widely used for the surface treatment of polymers and inorganic fillers.

Titanate coupling agent has excellent modification effects; however, it is bad for ecological and human health. This is the main reason limiting the application of titanate coupling agent.

2.3.1.2 Silane coupling agent

Compared to titanate coupling agent, silane coupling agent has many advantages; it is non-polluting and low in cost and has a wide application range. The general molecular formula is Y-R-Si-X3, and the structural formula of a silane coupling agent is shown in Illustration 2.15.

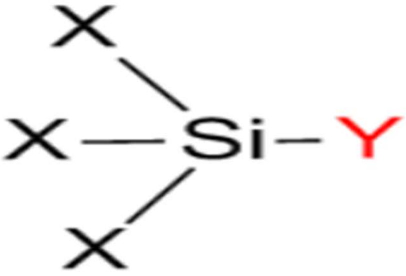


Illustration 2.15 Structural formula of silane coupling agent [21]

In this general molecular formula, Y represents the organic functional group, R is the alkylidene group, and each X is a hydrolysable group. The organic function group reacts with the organic polymer and the hydrolysable group controls the hydrolysis rate. In the same hydrolysis conditions, a bigger group has a slower hydrolysis rate, while in an acid environment, a silane coupling agent with a long hydrolysable group has a lower hydrolysis rate.

2.3.1.3 Functional mechanisms of silane coupling agent

The functional mechanism of a silane coupling agent acting between two materials with different natures is universally accepted as being described by chemical bonding theory. The functional mechanism can thus be divided into four steps:

(1) The hydrolysable group in the silane coupling agent hydrolyses first and reacts to the silanol.
(2) The hydrolysate condenses into an oligomer.
(3) Hydride bonds are formed by the hydride and the hydroxyl groups on the surface of the inorganic materials.
(4) In the drying and curing stages, the hydrogen bonds lose water and form covalent bonds.

Finally, the surface of the inorganic material will be covered by the silane coupling agent and the coupling process will be completed. The flow diagram and surface diagram for this are shown in Illustration 2.16. [6,7]

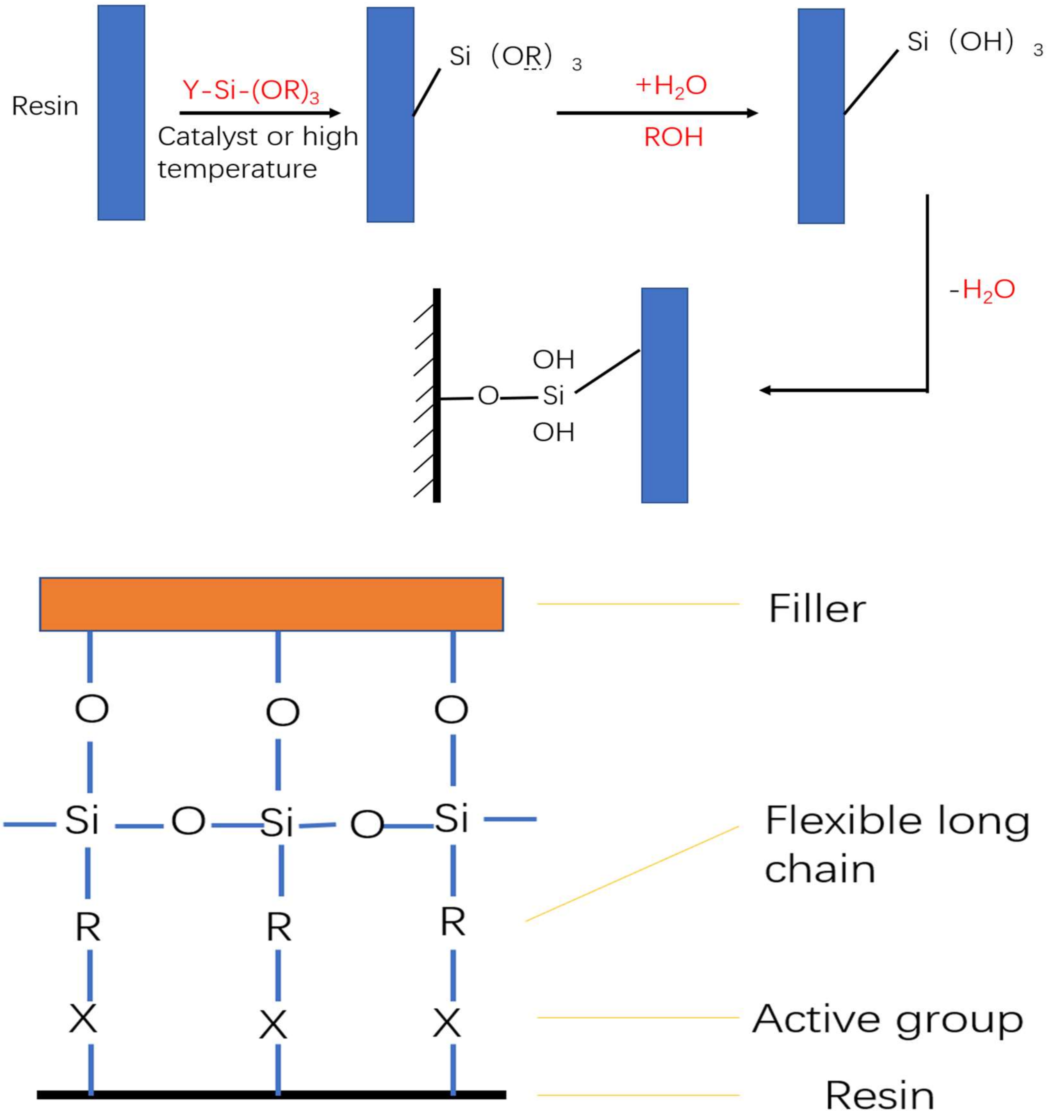


Illustration 2.16 Flow diagram and surface diagram of the coupling process theory

2.3.2 Application of silane coupling agent

Silane coupling agent can be used in many different places, which can be divided into three categories by use: surface treatment, filling plastic, and sealants, adhesives, and thickeners.

2.3.2.1 Surface treatment

Surface treatment of glass fibre with silane coupling agent could improve the adhesion property between the resin and glass fibres. It could also improve the fibre strength, water resistance, and weather fastness. Two SEM photographs of glass fibre before and after surface treatment with silane coupling agent A-1100 are shown in Illustration 2.17.

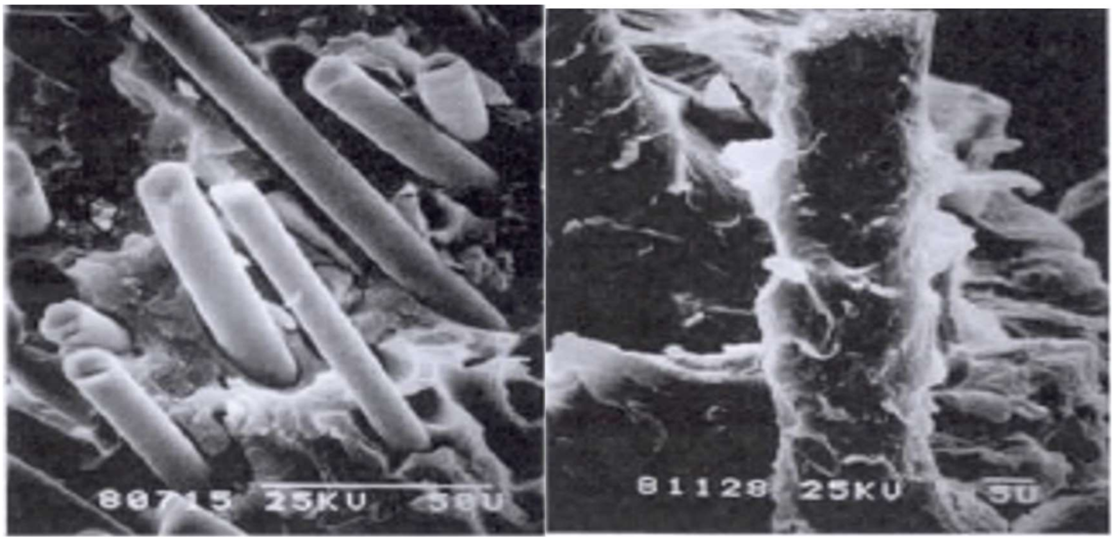


Illustration 2.17 SEM photographs of glass fibre before and after surface treatment with silane coupling agent A-1100

From these photographs, the surface treatment also appears to obviate defects arising from the wire drawing process such as microcracks.

Using silane coupling agent to process glass fibre is quite common. The percentage of silane coupling agent used for this purpose is around 50%, and common varieties include vinyl silane, amino silane, and methyl propyl silane.

2.3.2.2 Filling plastic

There are two methods used to fill plastic. [6] The first one is to pre-treat for filler, while the second is to put silane coupling agent into the resin directly. This processing could improve the dispersibility and adhesive force of the filler in the resin, and the purpose of this processing is to improve the compatibility between filler and resin.

2.3.2.3 Sealants, adhesives, and thickeners

Silane coupling agent can be used to solve the problem caused by the fact that many materials cannot bond directly. The theory is that silane coupling agent can be used as sealant, adhesive, and thickener as silane coupling agent has two different radicals, one of which can bond with the framework material and the other of which can bond with a high polymer material or adhesive. It means that a strong chemical bond can form on the adhesion interface.

2.3.3 Uses of silane coupling agent

Different applications require different processing modes. The main options for different applications are shown in Illustration 2.18. [7]

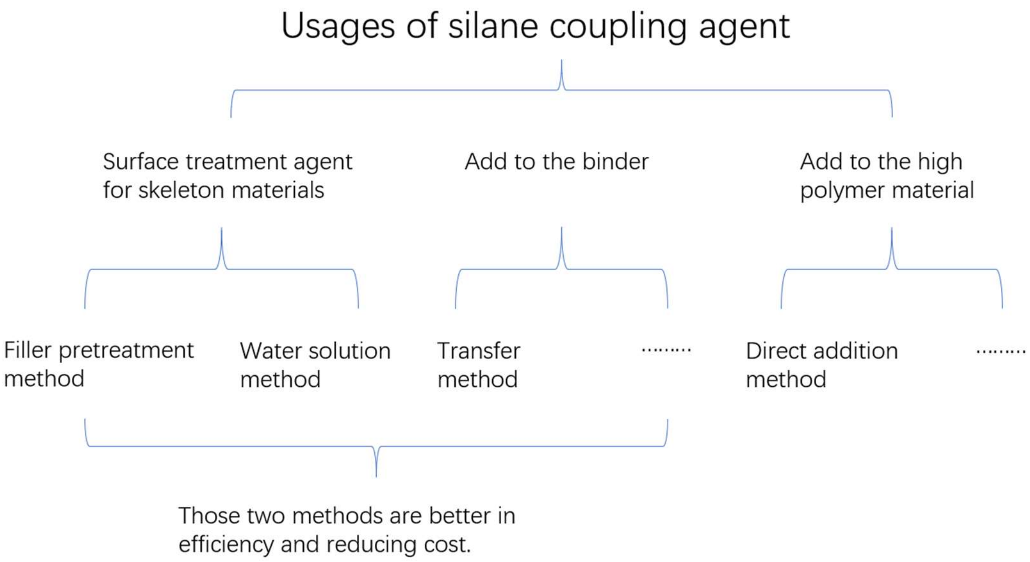


Illustration 2.18 Main options for applications

In practical production, the water solution method is the main use for glass fibre. This method uses silane coupling agent in aqueous solution or stock solution, dispersed onto the surface of materials by dipping, spray coating, or blending. The method can be divided into three types by process: pre-treatment, post treatment, and mixed.

(1) Pre-treatment method

The silane coupling agent in aqueous solution is added into glass fibre impregnating compound in the glass fibre formation stage.

(2) Post treatment method

The glass fibre is dipped into silane coupling agent in aqueous solution after being cleaned of its surface coating of glass fibre.

(3) Mixed method

The silane coupling agent stock solution is added into a high molecular polymer such as resin and rubber. Detailed information on these three methods is shown in table 2.19. Data is from reference [5].

Treatment process	Process complexity	Treatment effect	Application fields
Pre-treatment method	No special equipment required	No loss of fibre strength Low cost	Reinforcing material
Post treatment method	Complex process Special equipment required	30%-60% loss of fibre strength	Electrically insulated glass fibre fabric
Mix method	Simple process No Special equipment required	Poor enhancement effect High cost	Add into fluent material

Table 2.19 The advantages and disadvantage of three different methods

2.3.3.1 Three elements of silane coupling agent usage

The treatment effect can be affected by many environmental factors. There are three main points that play deciding roles. These are solvent, hydrolysis temperature, and pH value.

(1) Solvent
The main solvent for a silane coupling agent includes deionized water and alcohol. If alcohol only is used, this provides poor generation of silanol. Thus, deionized water mixed with alcohol is the best formula.

(2) Hydrolysis temperature
The condensation reaction of silanol is an endothermic reaction. A higher temperature could raise the reaction rate, but the solution is easy to precipitate. Through experimental tests, the range between 15 and 30°C has been found to be the best temperature for silane coupling agents.

(3) pH value
According to experimental tests, when the pH value is between 4 to 6, the speed of condensation reaction is lowest, yet the speed of hydrolysis reaction is highest. At pH value 7, the speed of condensation and hydrolysis are both slow. If the pH value is over 7, the deposition appears quickly, which means the speed of condensation is much higher than that of hydrolysis. Thus, the range between 4 and 6 is the most suitable pH value for silane coupling agents.

2.3.4 Selection principles for silane coupling agent

Of the two different groups within a silane coupling agent, group Y is more important, because it decides the application effect. A silane coupling agent can play a role only when group Y can react with the matrix resin. The type of group Y is thus the first element considered by selection principles for silane coupling agents.

If group Y is an alkyl group or aryl group, it cannot react with polar resin; however, it could react with nonpolar resin such as silicone rubber, polystyrene, and so on. If group Y has reactive functional groups, the reactivity and consistency of the resin used must be considered. If group Y has amidogen, the silane coupling agent could play a catalytic role in the polymerization of phenolic aldehyde, urea formaldehyde, or melamine-formaldehyde. It could also be used as a curing agent for epoxy resin or polyurethane resin.

According to the different group Ys, silane coupling agents can be divided into types such as vinyl silane, amino silane, epoxy silane, and methylallyl silane. These kinds of silane coupling agents are the most popular in use.

2.4 Glass fibre mat

Glass fibre mat is a kind of sheet product made of glass fibres that are divided evenly yet irregularly on a horizontal plane and bonded with a special binder. The basic structure is given in the sketch map in Illustration 2.20.

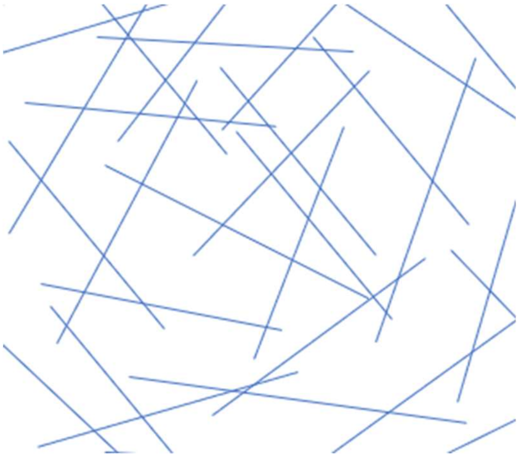


Illustration 2.20 Basic structure of fibre mat

The glass fibre mat has many excellent performance traits such as chemical resistance, fireproofing, waterproofing, retardation, ageing resistant, insulation, and so on. These performance characteristics mean that glass fibre mats are used widely in fibre-reinforced plastic (FRP) base cloth, epoxy CCL, and electrical insulation products.

As with glass fibre cloth; there are three types of glass fibre mat: E-glass fibre mat (no-alkali), C-glass fibre mat (medium-alkali), and alkali glass fibre mat. The main use for E-glass fibre mat is to make epoxy CCL and electrical insulation products. C-glass fibre mat, it is used for different kinds of FRP products, such as sheet material, pipelines, and rowboats. Alkali glass fibre mat is a good material for waterproof antiseptic isolation material.

Glass fibre mat can also be divided into types by purpose; the most common types include copper-clad plate glass fibre mat, pipe wrap glass fibre mat, and roofing glass fibre mat. In this project, copper-clad plate glass fibre mat was chosen as a backing material for high frequency PCBs.

As with glass fibre cloth, copper-clad plate glass fibre mat should be made of no-alkali glass fibres and have good compatibility with dielectric materials. The glass fibre mats chosen in this project were obtained from Nanjing Tianming Fiberglass Products Co Ltd. The performance parameters and product images are shown in table 2.21 and Illustration 2.22.

Item	EMC-E	Loss on ignition (%)	2-6
Standard Weight (g/m^2)	300/450/600	Moisture (%)	≤0.2
Width (mm)	1040-2600	Roll Weight (Kg)	30
Use and Craftwork		Specialized for transformer	

Table 2.21 Performance parameters (Data is from product manual)

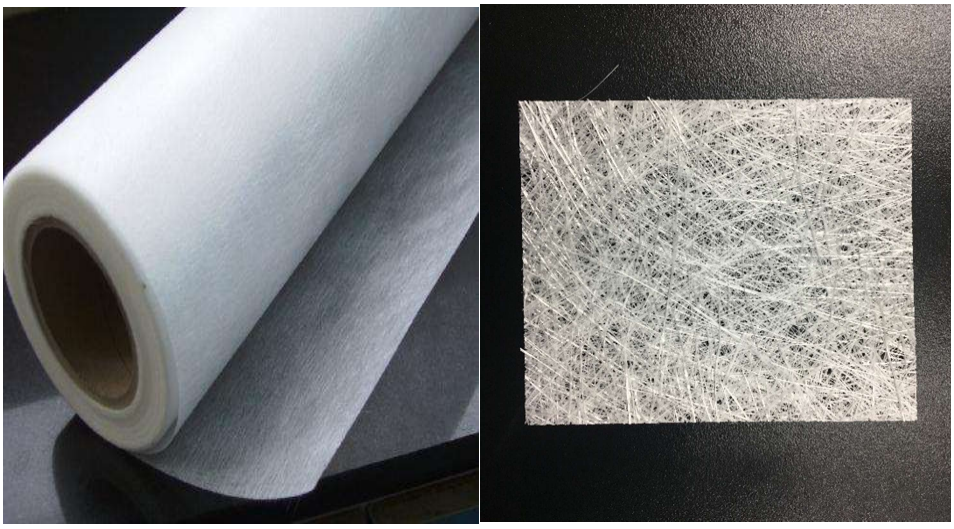


Illustration 2.22 Product image of glass mat

This was an E-glass chopped strand mat made of chopped strands of 50 mm in length and 10 µm in diameter randomly dispersed and bonded together using a polyester binder in powder or emulsion. The industrial preparation process is shown in Illustration 2.23.

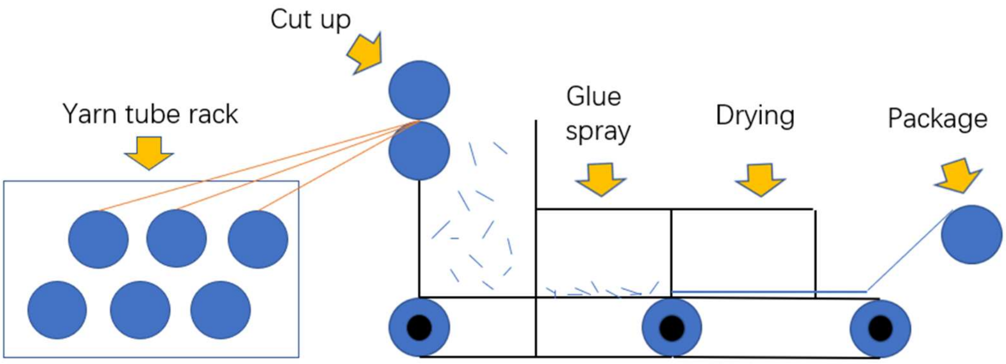


Illustration 2.23 Industrial preparation process

Compare to glass fibre cloth, glass fibre mat has five main advantages:

1. Randomly dispersed fibres with excellent mechanical properties.
2. Excellent compatibility with resin, with clean surfaces and good tightness.
3. Excellent heating resistance.
4. Faster effective wet-out rate.
5. Easily fills moulds and conforms to complex shapes.

2.4.1 Preparation technology and test method for CCL

The copper-clad plate glass fibre mat CCL was made from PTFE emulsion by hot pressing. The main facilities included a vacuum hot press, a safe explosion-proof oven, a Vector Network Analyzer (VNA), a microcomputer control universal material testing machine, a magnetic separation agitator, a precision balance, and precise beakers. The type specification and manufacturers of the main facilities are shown in table 2.24.

Name of facility	Type specification	Manufacturers
Vacuum hot press	VHP-5T-4	Hefei Kejing Materials Technology Co., Ltd
Safe explosion-proof oven	GRX6	Shanghai Jinghong Instrument Technology Co.,Ltd
Vector Network Analyzer （VNA）	Av3672B-S	The 41st Institute of CETC
Microcomputer control universal material testing machine	CTM2050	Shanghai XieQiang Instrument Technology Co.,Ltd
Magnetic separation agitator	MYP11-2A	Shanghai Mei Yingpu instrument and Meter Manufacturing Co., Ltd.
Precision balance	BSM-120.4	Changzhou sanfeng Instrument technology co.,Ltd

Table 2.24 Type specification and manufacturers of main facilities

The main chemical reagents were PTFE emulsion, FEP emulsion, acetone, ethyl alcohol, and ultrapure water. The parameters of the PTFE and FEP emulsions are shown in table 2.26.

Manufacturer:	Daikin industries, Ltd
Name:	PTFE emulsion
Serial number:	D-210C
Facade:	White homogeneous emulsion liquid
Density(20ºC):	1.48-1.53 g/cm^3
Kinematic viscosity(25ºC):	mm^2/s 6-14
pH:	8-10
Resin melting point:	327 ºC
Resin Content %:	60±2

Manufacturers:	Daikin industries, Ltd
Name:	FEP emulsion
Serial number:	ND-4
Facade:	White homogeneous emulsion liquid
Resin Content%:	38
Viscosity：	3.0-7.0

Table 2.25 Parameters of PTFE and FEP emulsions (Data is from product manual of

Daikin industries, Ltd)

3 Technological process

Before placing the glass fibre mat into the PTFE emulsion, the glass fibre mat required surface treatment with a silane coupling agent, as the adhesive force between PTFE particles and glass fibre is weak. The surface treatment with silane coupling agent increase this as well as improving the dielectric properties.

PTFE has higher glutinousness in its molten state. This means it is difficult for it to fill the voids in glass fibre mats, and thus it cannot be used in traditional techniques to create resin CCLs. An impregnation technology was thus chosen for this part. The process flow diagram is shown in Illustration 3.1.

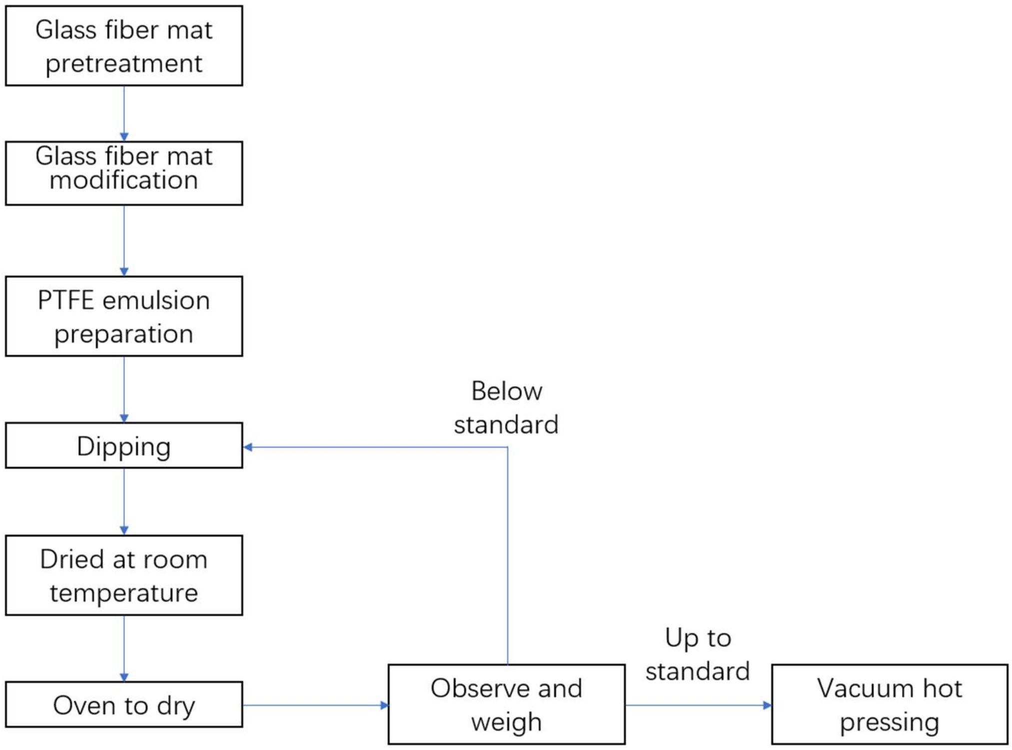


Illustration 3.1 Process flow diagram

3.1 Glass fibre mat pre-treatment

The glass fibre mat has several impurities such as dust and grease. The purpose of this step is thus to remove the impurities from the glass fibre mat that could affect the adhesive strength and results.

This process has three steps. The first step is washing with diluted hydrochloric acid to remove the positive ions. If the quantity of positive ions is too large, it will increase substrate loss. The second step is a rinse in absolute ethyl to remove the dust and any greasy dirt; as the glass fibres in a mat are bonded with a special adhesive and absolute ethyl alcohol could slight dissolve it，however, glass fibre mat can only be douched with absolute ethyl alcohol rather than being dipped. The third step is to wash it in ultrapure water. This step cleans away the residual hydrochloric acid and absolute ethyl alcohol. After these three steps, the glass fibre mat is placed into an explosion-proof drying oven until it is dry.

3.2 Glass fibre mat modification

The main process for glass fibre mat modification is to put the glass fibre mat after pre-treatment into a silane coupling agent diluent. This step has two main purposes. The first is to increase the adhesive force. Chemical bonds cannot form between PTFE and glass fibres, as the adhesive force between them is very small, and this decreases the mechanical properties. The second reason is to reduce the water-absorbing qualities of CCL. The main ingredient of glass fibre mats is SiO_2, which has hydrophilic molecules. This means that glass fibre has high water-absorbing qualities, and the introduction of silane coupling agent diluent could prevent glass fibres' direct exposure to air.

From the many different coupling agents available, Z6269 was chosen in this step. Z6269 is a silane coupling agent from Dow Corning that can be use as adhesive accelerator and glass fibre surface treatment agent. It has many advantages, such as good resin infiltration, high purity organosilane and polyfunctional groups, low turbidity, and few impurities.

A moderate quantity of deionized water was placed into a beaker. Some Z6269 was taken up with a burette and dropped into the beaker. The dosage of Z6269 was around 0.3 to 2% of the total volume. This aqueous solution was then mixed with some glacial acetic acid to control the pH value in the range between 4 and 6, as silane needs to be hydrolysed in the correct acidic environment and temperature. A magneton was placed into the beaker, which was set on the multifunctional magnetic suspension agitator. The temperature was around 60˚C and the speed of the magneton was low. If the time of heating is too long, hydrolysed silane will become siloxane, and the solution will become turbid. Based on these tests, 1 hour is the most suitable time for this process.

After hydrolysis, the solution was poured into a large glass culture dish and the glass fibre mat cut to a 10 cm by 10 cm size. The glass fibre mat was placed into the solution so that the solution flooded the glass fibre mat. After around 20 minutes, the glass fibre mat was removed and placed into an explosion-proof drying oven until it was very dry.

3.3 PTFE emulsion preparation

Before dipping the glass fibre mat into the PTFE emulsion, further preparatory work was required. The PTFE emulsion obtained from Daikin Industries, Ltd is a dispersion made by the heating concentration method. The PTFE granules could thus be reunited by high shearing forces during transport.

To remove any large particles and increase the solution uniformity, the PTFE emulsion was stirred on a magnetic suspension
agitator at low speed, and a filter screen used to take out any precipitated particles. The purpose of this step is to prevent the particles being absorbed by the glass fibres, which would cause unevenness.

3.4 Dipping

When the PTFE emulsion preparation was complete, the emulsion was poured into a large culture dish and any foam removed, as foam residue could affect the morphology of the samples. The glass fibre mat was placed into the emulsion and completely submerged for around 10 minutes.

3.5 Drying at room temperature

The glass fiber mat was taken out of emulsion and hung on a shelf. This step was repeated many times. This involved rotating the direction of the sample each time to enhance the uniformity of thickness as shown in Illustration 3.2.

Illustration 3.2 Drying at room temperature

3.6 Drying in an oven

When no further emulsion dropped from the samples, the samples were placed in an explosion-proof drying oven for step-by-step heating. Due to different structures of glass fibre mat and glass fibre cloth, this step uses different temperature curves. The glass fibre mat is bonded with a special binder, so the temperature of the first few times of heating cannot be higher than the melting temperature of the binder. Further details will be given later.

3.7 Observation and weighing

After the sample was removed from the explosion-proof drying oven and cooled down to room temperature, a precision balance was used to obtain a value for the weight. The thickness was measured with a micrometre and the surface evenness observed. The results were referenced to existing data to determine suitable times before the next step began.

3.8 Vacuum hot pressing

An image and mechanical principle diagram for vacuum hot press are shown in Illustration 3.3.

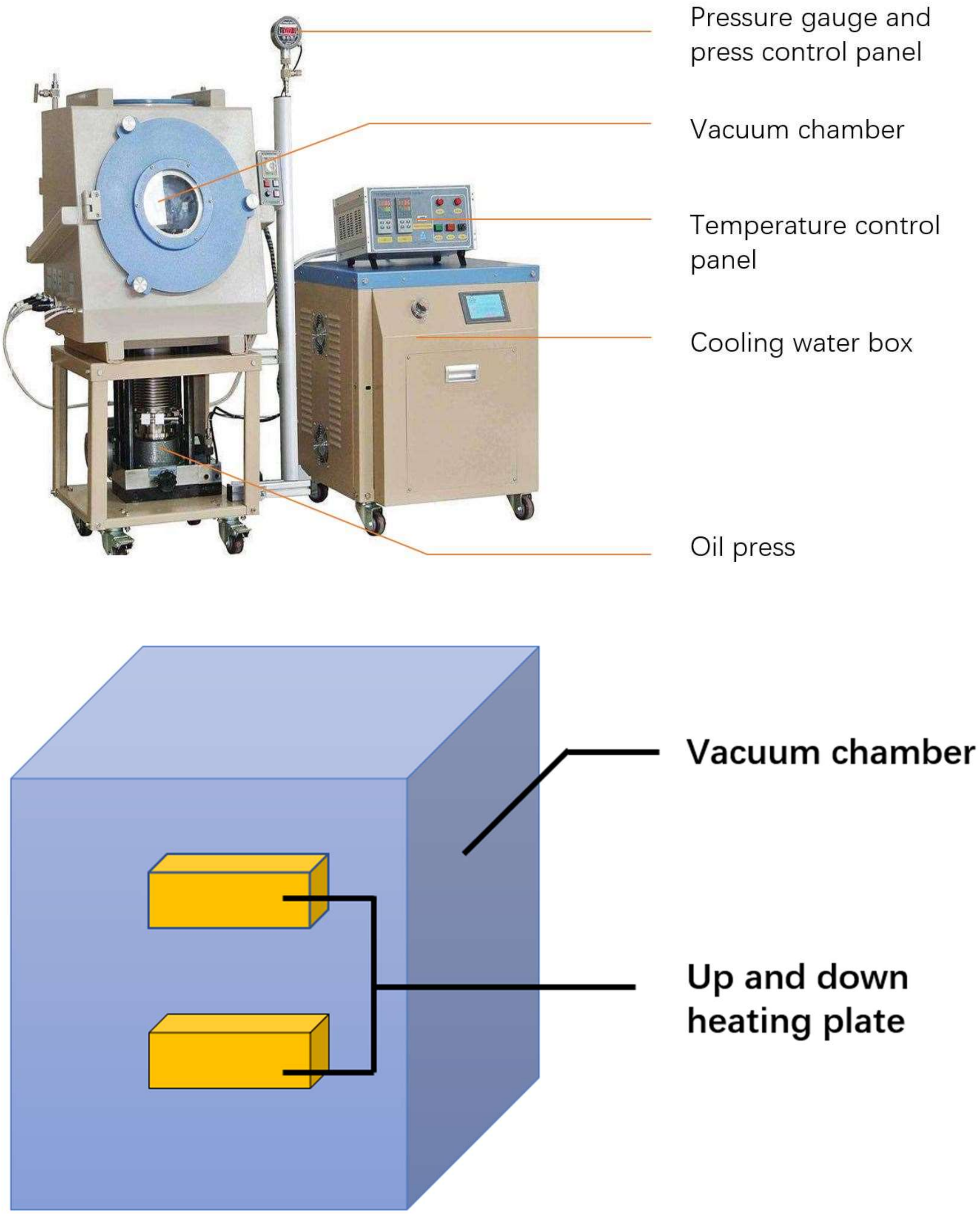


Illustration 3.3 Image and mechanical principle diagram of vacuum hot press

The most important part of the vacuum hot press is a pair of heating plates. These two plates should be completely parallel and the opposing planes should be extremely smooth. Heating tubes and water-cooled tubes are hidden inside both heating plates. The upper heating plate is linked to a hoisting valve and the lower heating plate is linked to a oil hydraulic pump outside of the vacuum chamber.

To set the sample, the sample was placed between two mirror plates that were then placed between the upper and lower heating plate. For the convenience of stripping, it could add isolation layer such as copper foil and aluminium foil between sample and mirror plate. The structure shows in Illustration 3.4.

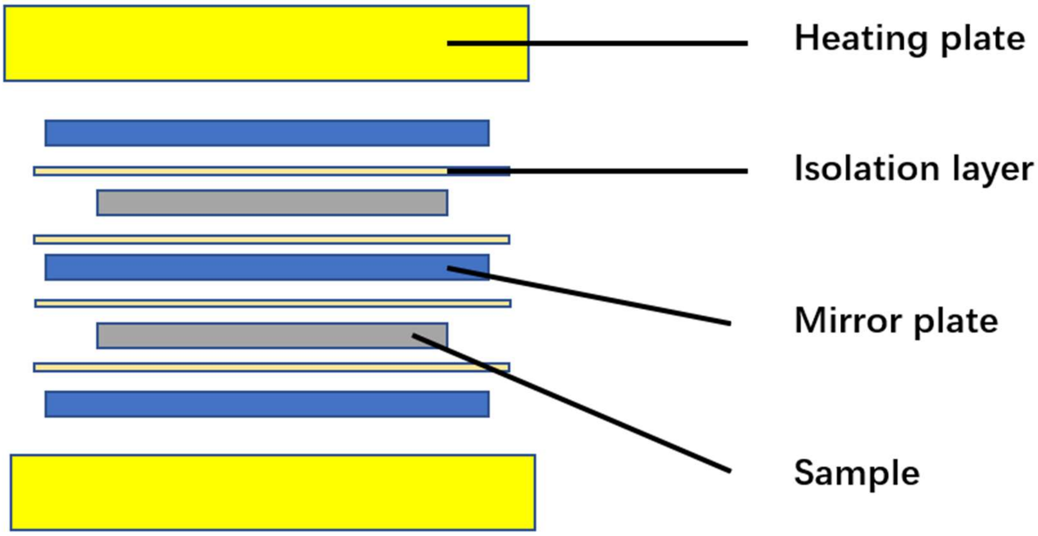


Illustration 3.4 Structure of sample in hot press

More than one sample can be made at a time, but too many layers will cause the heat to not conduct to the middle layers. Too many layers could also create skew, leading to uneven thickness in the sample. Two layers at once achieved the best sample quality.

After finishing the steps above, the air valve of the oil hydraulic pump was opened to bring the lower heating plate to its natural level; then, the hoisting valve was operated to allow the upper heating plate to touch the mirror plate slightly. The pressure at this point requires delicate control, as it is easy to cause sideslip.

After turning off the vacuum chamber and opening the vacuum pump, the temperature of heating plate will rise up to 360°C; at this temperature, the sample will easily react with oxygen, which is why the vacuum environment is necessary. After turning on the oil hydraulic pump and starting heating, different samples display different pressure and temperature curves, which will be described in detail later.

4 Experimental design

To design suitable technological processes. sufficient data is necessary. Thus, multiple attempts were made to examine dipping processes and hot-pressing technology. Based on an analysis of the data acquired, the appropriate ranges and technological parameters were derived.

4.1 Dipping processes

To discover the relationship between dipping processes and the dielectric constant, many pre-tests were done as shown in table 4.1. The test method of dielectric constant is reference to [8].

Number	**Details**	**Thickness**	**Dielectric constant**
1	60%+60% with coupling agent	0.85 mm	3.92383
2	60%+60% with coupling agent	0.77 mm	4.10724
3	60%+60% with coupling agent	0.87 mm	3.88591
4	60%+60% with coupling agent	0.79 mm	4.09301
5	60%+40% with coupling agent	0.69 mm	4.25135
6	60%+40% with coupling agent	0.68 mm	4034417
7	40%+60% with coupling agent	0.67 mm	4.47952
8	40%+40% with coupling agent	0.71 mm	4.30975
9	40%+40% with coupling agent	0.66 mm	4.16878
10	40%+40% with coupling agent	0.68 mm	4.26419
11	60% single without coupling agent	0.66 mm	4.21118
12	60% single without coupling agent	0.67 mm	4.4085

Table 4.1 The result of pre-testing

In this table, the % is the concentration of PTFE solution, where 60%+40% means that the glass fabric was dipped into a solution in which the PTFE concentration was 60%, then after drying, it was dipped into a solution in which PTFE concentration was 40%. All samples from 1 to 10 were dipped twice. Samples 1 and 3 were dipped for 15 minutes, while the rest were dipped for 5 minutes. All samples were made using five-layer glass fabric. From the table, it can be seen that modest increases in the dipping concentration and dipping times could increase the quantity of PTFE.

In order to find the relationship between the resin content and dielectric constant, a plot was made of thickness and dielectric constant, as seen in figure 4.2.

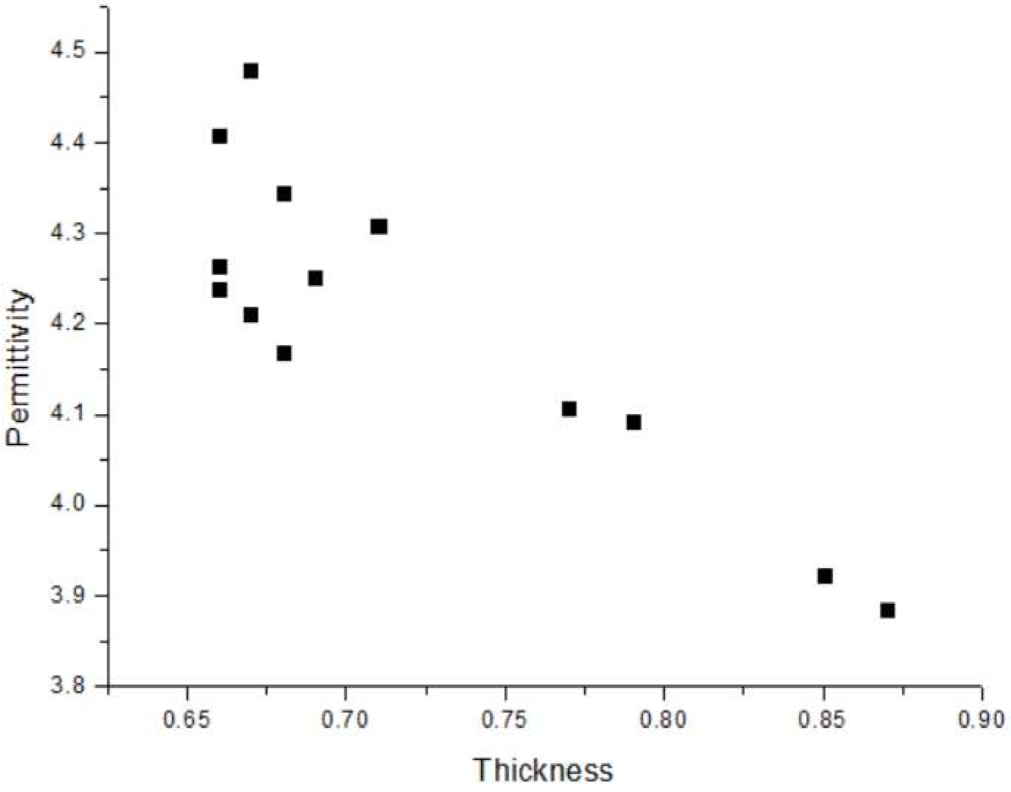


Figure 4.2 The relationship between permittivity and thickness

From this diagram, it is easy to determine that the value of the dielectric constant is inversely proportional to thickness. This means that higher resin content could produce better dielectric properties, within limits.

At the same time, it was found that the lower the resin content, the stronger the water absorption. The reason for this is that PTFE cannot completely fill the gaps in glass fibre, as shown in Illustration 4.3.

Illustration 4.3 Sample before and after hot pressing

The leftmost image is a picture of glass fabric after dipping three time. The right-hand picture is the same sample after hot pressure. In these pictures, the texture of fabric is very easy to see, and the fill of the PTFE is clearly inadequate. An SEM picture of glass fabric after dipping six times is shown in Illustration 4.4. for comparison.

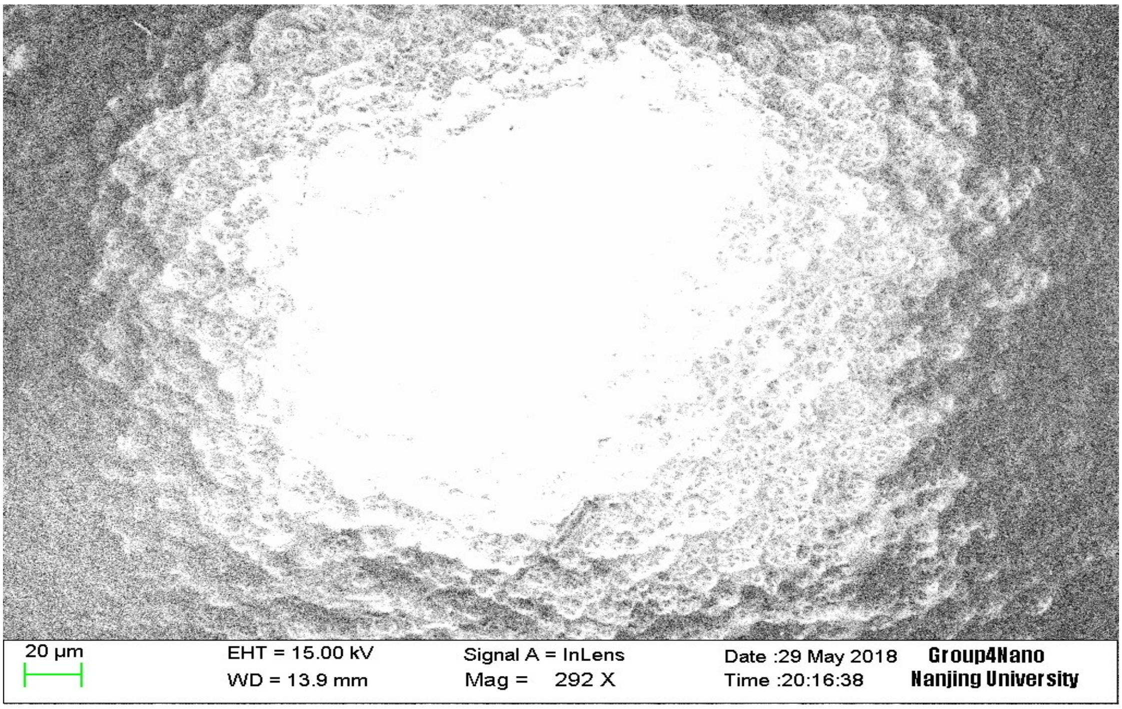


Illustration 4.4 SEM picture of glass fabric after dipping six times

Many micropores can be seen on the surface. Those micropores can greatly increase water absorption and the dielectric constant is thus likely to suffer from instability.

4.2 Technology improvement

From the initial research, two methods were developed to address those problems: the first was blending modification and the second increasing the resin content.

4.2.1 Blending modification

In this research, it was found that blending modification is widely used in baseplate material amendment, including the use of ceramic particles to reduced thermal expansion or FEP to increase surface viscosity. Of all available materials, FEP was the most suitable one for this work for three main reasons.

- The liquidity of FEP is better than that of PTFE in molten condition. Under pressure, FEP could thus fill the gaps between the PTFE and glass fibre.
- The FEP solution can perfectly blend with the PTFE solution unlike ceramic particles; the solution of mixed FEP and PTFE solutions suffers no delamination and this characteristic is good for dipping processes.
- Compared to PTFE solutions, the FEP solution has better adhesiveness.

The maximum concentration of FEP solution found on the market was 38%; because of that, this experiment used a PTFE solution with a concentration of 60% but an FEP solution with a concentration of only 38%. The blending modification had seven steps.

1. Mix the PTFE solution and FEP solution to the desired volume ratio. In this step, two different ratios were produced, 4:1 and 1:1 PTFE solution:FEP solution.
2. Put the mixed solution on the magnetic suspension agitator and set the speed to 100 r/min. Keep stirring for 20 minutes.
3. Dip the glass fabric into the mixed solution for 5 minutes.
4. Hang the glass fabric up at room temperature until the solution flows uniformly.
5. Put the glass fabric into the oven at 250°C for 15 minutes.
6. Take the glass fabric out and cool at room temperature.
7. Repeat steps 3 to 6 above.

The samples were weighed each time after dipping and drying. The data gathered is shown in table 4.5.

Times	**1:1**	**4:1**	**Times**	**1:1**	**4:1**
1	2.10 g	2.33 g	**7**	4.13 g	5.30 g
2	2.55 g	2.78 g	**8**	4.43 g	7.07 g
3	2.71 g	3.10 g	**9**	4.81 g	7.84 g
4	3.09 g	3.29 g	**10**	5.26 g	8.44 g
5	3.42 g	3.87 g	**11**	5.75 g	9.60 g
6	3.84 g	4.40 g	**12**	6.28 g	11.4 g

Table 4.5 Weights of samples after dipping and drying

Using two kinds of samples with different proportions, each was dipped 12 times, and the resulting data are shown in figure 4.6.

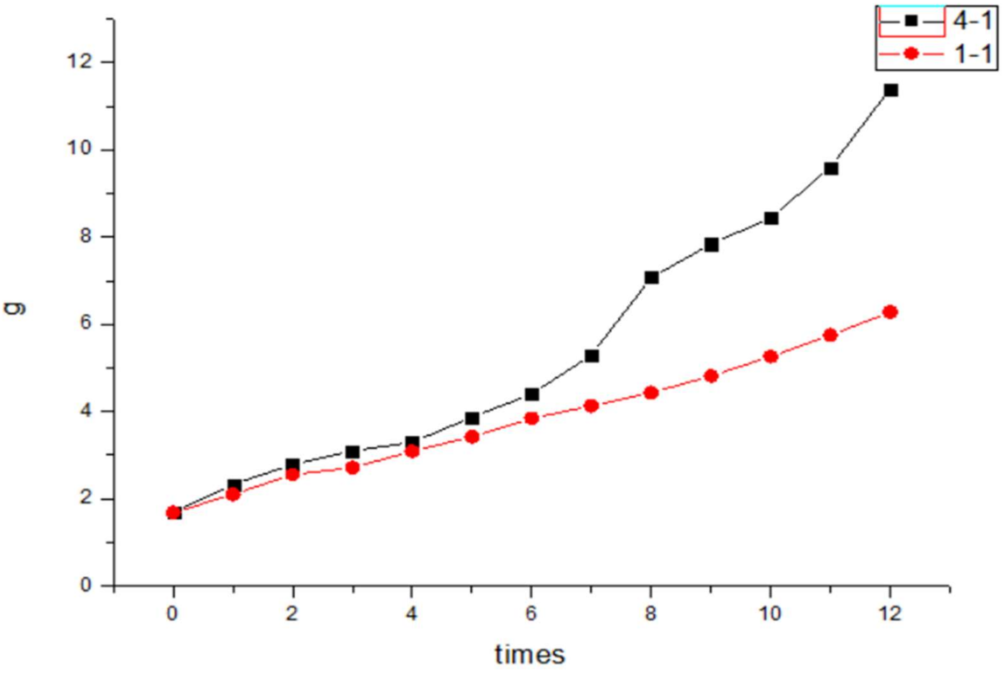


Figure 4.6 The weight of two different samples in 12 dips

It is clear that the growth of the 4:1 ratio is better than that seen in the 1:1 sample, which differs from the previous results. The increase rate of PTFE is much larger than that of FEP. The bonding between one PTFE particle and another is very strong. One possible reason could be that the concentration of FEP solution is too low; however, from the SEM image in Illustration 4.7, it can be seen that FEP does increase the bonding with glass fabric.

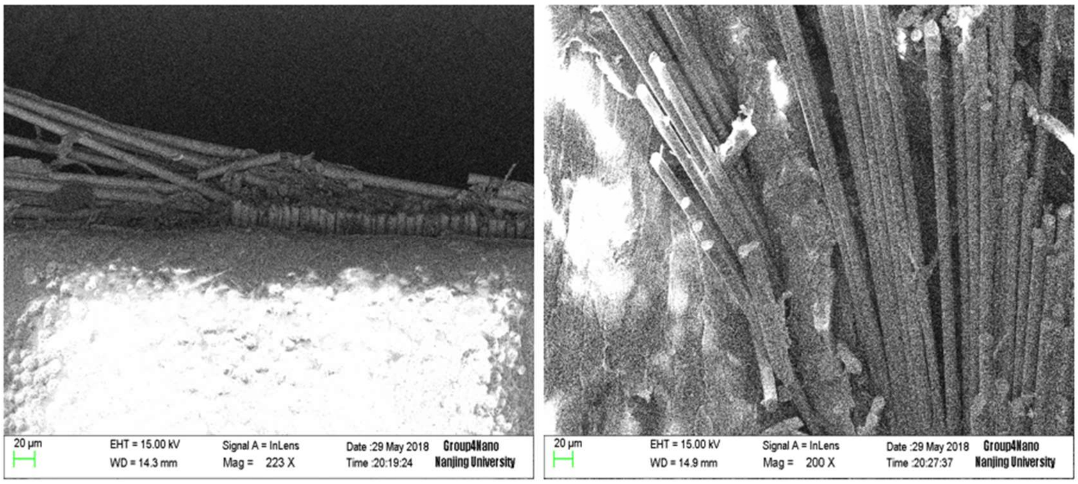


Illustration 4.7 SEM image of the sample after dips

4.2.2 Increasing the resin content

In this project, two methods were used to increase the resin content. The first one was to increase the dipping times and the second was to change the reinforcing material.

Based on prior data, repeat dipping could increase the resin content. Three samples were taken as seen in figure 4.8 and their dielectric constants were tested.

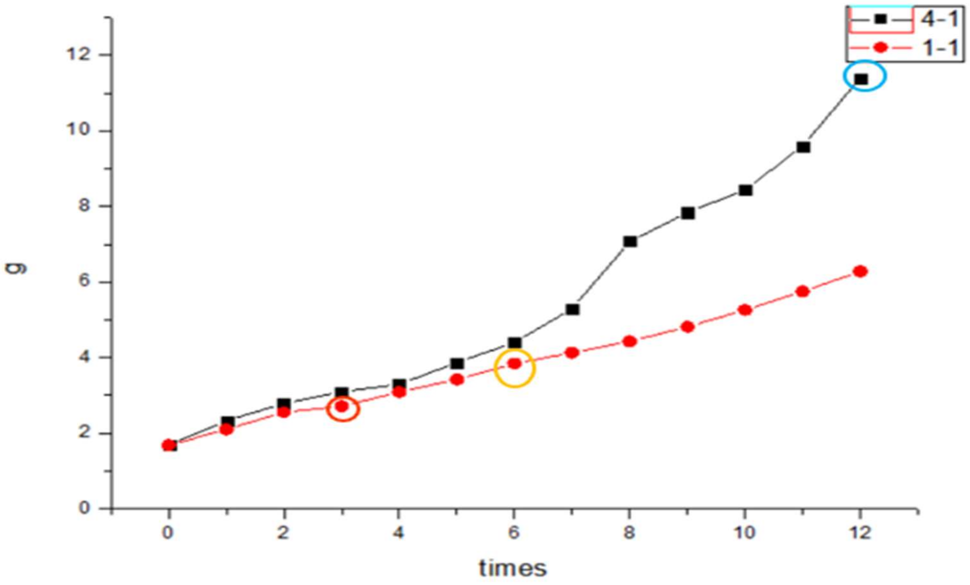


Figure 4.8 Three control tested points

Red point Dielectric constant: 4.39
Resin content: 32.7%
Resin content after dipping and drying: 45.8%
Valid resin content: 71.4%
Yellow point Dielectric constant: 3.36
Resin content: 53.3%
Resin content after dipping and drying: 61.8%
Valid resin content: 86.2%
Blue point Dielectric constant: 2.74
Resin content: 75.7%
Resin content after dipping and drying: 85.3%
Valid resin content: 88.7%

$$\text{Resin content after dipping and drying} = \frac{Weight\ of\ sample\ after\ dipping\ and\ drying - Weight\ of\ glass\ fabric}{Weight\ of\ sample\ after\ dipping\ and\ drying}$$

$$\text{Resin content} = \frac{Weight\ of\ sample\ after\ hot\ pressure - Weight\ of\ glass\ fabric}{Weight\ of\ sample\ after\ hot\ pressure}$$

$$\text{Valid resin content} = \frac{Resin\ content}{Resin\ content\ after\ dipping\ and\ drying}$$

The reason for using the concept of valid resin content is to reduce the overflow of resin. Some samples, as shown in Illustration 4.9, developed a black rim. This rim is the excess resin after pressing, overflow, and heating, and this must be cut off before copper covering, which means the resin in this part is wasted.

Illustration 4.9 Samples with a black rim

From these data, a valid resin content determines the dielectric constant; however, that does not mean resin content should be as high as possible. In the experiment, glass fabric was found to have a maximum valid resin content. If the resin content exceeds the maximum value, the fibre structure of glass fabric will break. An example is shown in Illustration 4.10.

Illustration 4.10 Sample in which fabric was broken

According to multiple experiments, the maximum valid resin content should be around 87%. In order to keep lowering the dielectric constant, the reinforcing material should thus be changed.

4.2.3 Changing reinforcing materials

Many researchers have chosen glass fibre mats to replace glass fabric. The details of the glass fibre mats used can be found in the previous section.
Compared to glass fibre, glass fibre mat has two main advantages.

- The fibre structure of glass fibre mat is similar to a sponge, which allows better resin absorption. In the experiment, one piece of pre-impregnated could made from each piece of glass fibre mat.

- The fibre structure is disordered, and the density is uniform. This gives it a special characteristic for pre-impregnated. Under pressure, the fibre structure is stretched with resin so the density of glass fibre in pre-impregnated is uniform. Two groups of samples were made in this way, and their data is shown in table 4.11.

Times	**PTFE**	**PTFE：FEP 4：1**
0	3 g	3 g
1	4.85 g	5.12 g
2	6.95 g	6.79 g
3	9.02 g	8.12 g
4	11.02 g	9.54 g
5	13.38 g	11.02 g
6	15.64 g	12.52 g
7	18.55 g	13.7 g
8	20.66 g	14.97 g
9	24.38 g	16.02 g
10	28.82 g	17.85 g
11	32.01 g	19.98 g
12	39.17 g	22.67 g

Table 4.11 The weights of samples in two groups over 12 dips

In the first dipping, the resin content of PTFE: FEP 4:1 was higher than that of PTFE. This supported the idea that FEP has good adhesive properties with glass fibre. The resin content after dipping and drying 12 times in the two groups' samples were 92.34% and 86.76%. The same data on 4:1 glass fabric was only 82.45%. The numeric data is made clearer in figure 4.12.

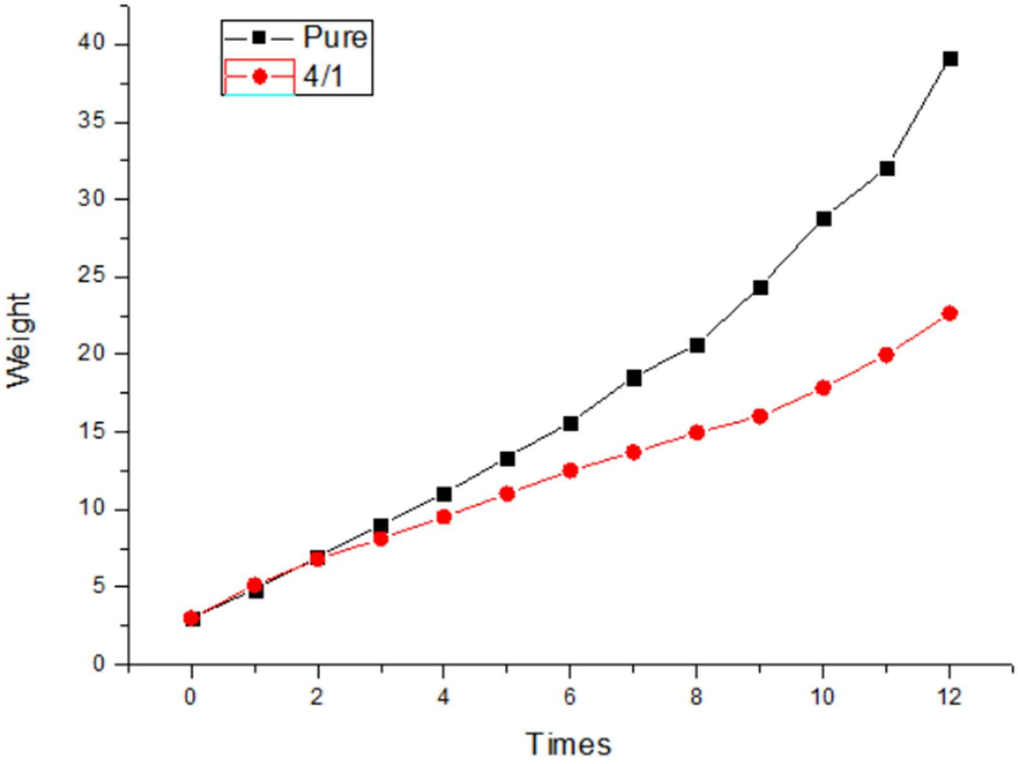


Figure 4.12 The samples weight of two groups in 12 dips

The increase in rate of mass is not uniform. An accelerated rate exists based on contact area. Three examples are shown in Illustration 4.13.

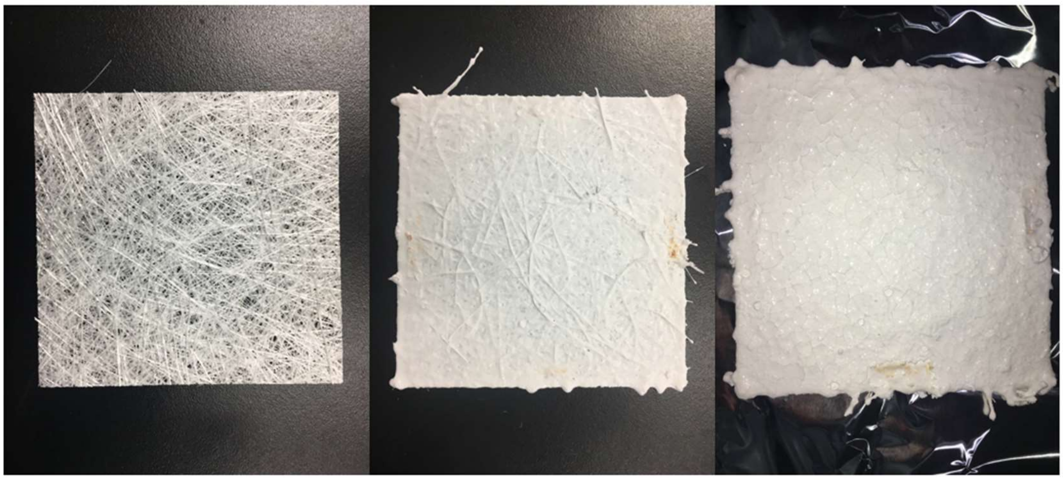


Illustration 4.13 Sample after 0, 6 and 12 dips

The left-hand picture is the original glass fibre mat. At this stage, the resin only covers the surface of the glass fibre. The middle picture shows the sample after six dips. At this stage, no holes exist on the sample. The increase speed of mass undergoes a qualitative change from this point. The right-hand picture is the sample after 12 dips; the fibre structure can no longer be seen.

The two groups of samples were used to make three different prepregs, which were single layer, two layers, and three layers. The dielectric constant and dielectric loss angle of tangent of each are shown in table 4.14.

	Pure PTFE 12 dipping			**Mix PTFE & FEP 12 dipping**		
Number of layers	1	2	3	1	2	3
Dielectric constant	2.25	2.27	2.26	2.36	2.38	2.43
Dielectric loss angle of tangent	0.0073	0.0062	0.0080	0.0083	0.0117	0.0083

Table 4.14 The dielectric constant and dielectric loss angle of tangent of two groups samples

Compared to the glass fabric with the same dipping time, the dielectric properties of the glass fibre mat show obvious advantages; however, the use of glass fibre mats still has some problems that need to be resolved.

In the experiment, it was found if the number of layers was greater than two, the bonding between layers became weak and small cracks appeared. The reason for this could be the glass fibre mat slipping under the heat and pressure.

Another problem arises from the special fibre structure of glass fibre mats. If the resin content is insufficient, the glass fibre will become exposed, as in Illustration 4.15.

Illustration 4.15 Samples with and without sufficient resin

The exposed glass fibre will increase both water-absorbing quality and copper covering difficulty.

4.3 New structure

In order to solve several problems arising while retaining the noted advantages, a new structure is proposed in this paper. The structure diagram is shown in Illustration 4.16.

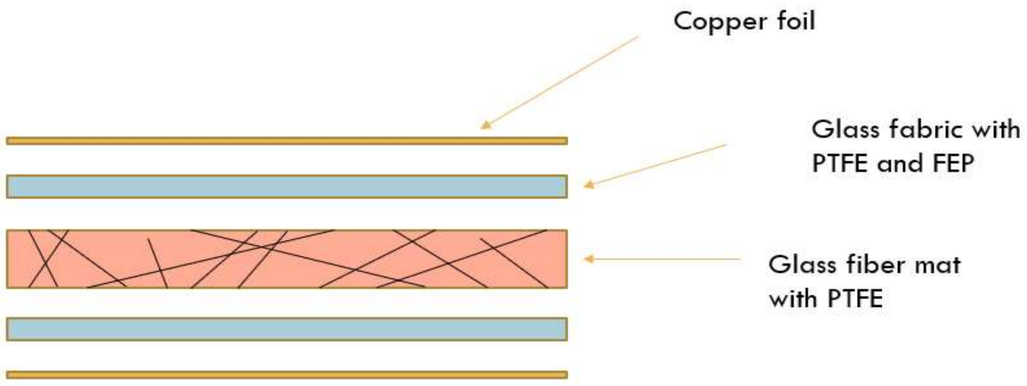


Illustration 4.16 The new structure which mixed with glass mat and glass fabric

The main idea behind this structure is to use the strong resin-absorbing quality to improve the dielectric properties of the material and to use glass fibre to avoid fibre exposure. Compared to glass fibre mats, glass fabric has a strong warp and weft structure, and thus the addition of glass fabric could reduce the deflection induced by thermal expansion. If the FEP content in glass fabric is sufficiently high, the glass fabric could act as a bonding layer between the glass fibre mat and the copper foil.

Some samples were made and tested using this structure. The dielectric constant and dielectric loss angle of tangent showed slight increases at 2.46 and 0.0073, respectively. This data is acceptable.

Furthermore, the special fibre structure of glass fibre mats provides the space for granular modification materials such as ceramic particle. The new structure divides the different performance requirements into different components, offering unlimited possibilities for modification.

The magnitude of force between the copper foil and base material is an important index of any copper covering technology. The standard of evaluation for this is known as peel strength, which can be defined as

$$\frac{The\ force\ required\ to\ peel\ the\ copper\ foil\ from\ CCL}{Width\ of\ copper\ foil}$$

Different countries have different standards, but according to most standards, the peel strength should over 1 N/mm.

Peel strength is determined by many factors, such as the copper foil, the base material, the copper-covering technology and the bonding layer, where present.

The roughing treatment of copper foil and base material are explained in other chapters, so this chapter focuses on copper-covering and the bonding layer.

5 Copper cladding data analysis

The aim of this chapter is to analyse the relationship between the bonding layer and peel strength, in particular, the relationship between the thickness of the bonding layer and peel strength, and to find the best parameters for the bonding layer.

5.1 The relationship between bonding layer and peel strength

Based on the characteristics of PTFE outlined previously, PTFE is difficult to bond directly with copper foil, which makes it necessary to find a suitable bonding layer. FEP and PFA were thus selected as candidates.

Compared to PTFE, PFA has similar mechanical properties and electrical properties; however, PFA has better melting fluidity and viscosity at temperatures over its melting point.

In order to ensure an objective comparison, the two samples were made in same manufacturing conditions. Based on multiple pre-tests, the hot-pressing technology required a vacuum environment; the temperature and pressure curves used are shown in figure 5.1.

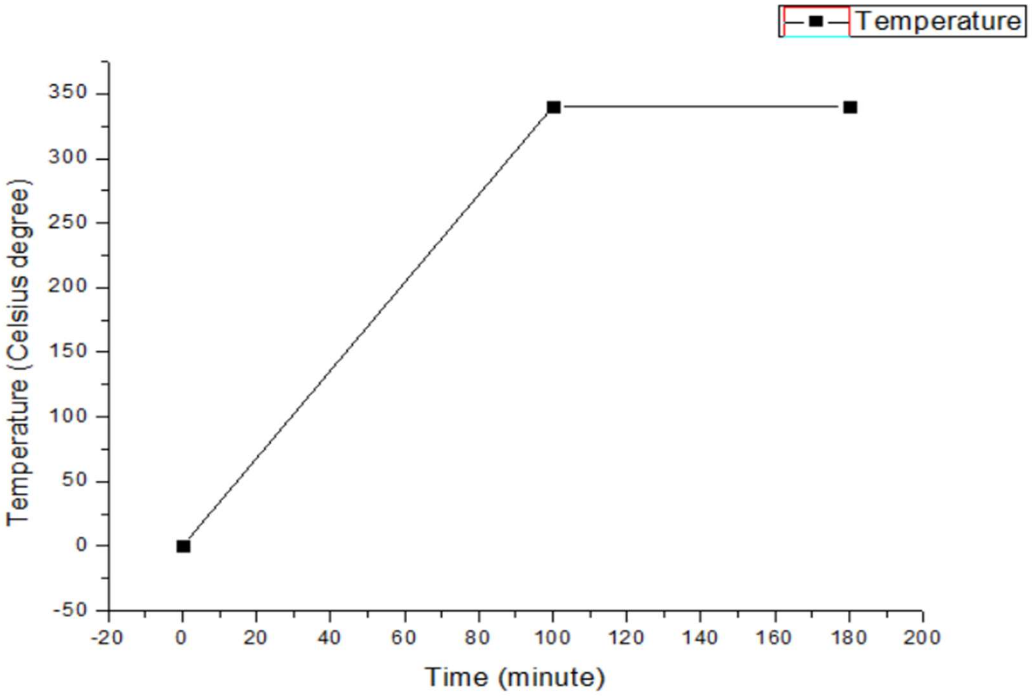
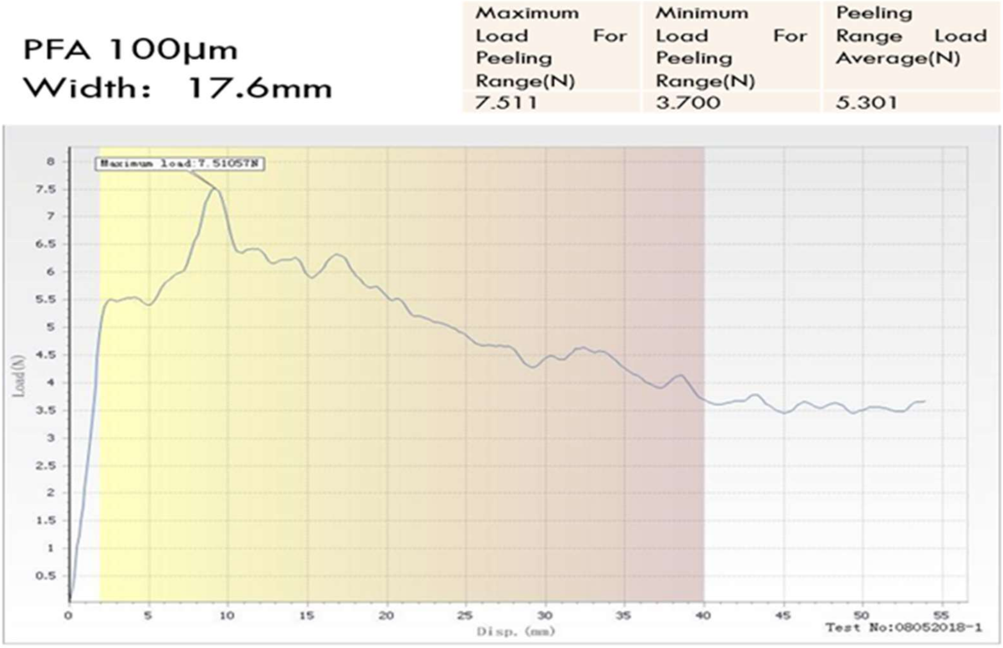


Figure 5.1 The temperature line of Hot-pressing technology in a vacuum environment

For this stage, the base material was PTFE board in a 10 cm by 10 cm square with a thickness of 2 mm. The layer bonding was PFA and FEP thin film of 100 μm thickness. The test results are shown in figure 5.2（a）and（b）.The data will be analysed and contrasted later.



PFA 100μm
Width: 17.6mm

Maximum Load For Peeling Range(N)	Minimum Load For Peeling Range(N)	Peeling Range Load Average(N)
7.511	3.700	5.301

Figure 5.2（a）Peel strength line of two samples with different kinds of bonding layers (PFA)

FEP 100μm
Width: 13.5mm

Maximum Load For Peeling Range(N)	Minimum Load For Peeling Range(N)	Peeling Range Load Average(N)
21.418	10.138	18.588

Figure 5.2 （b）Peel strength line of two samples with different kinds of bonding layers (FEP)

Comparing the range between 5 to 40 of PFA film and FEP film, the curve of FEP is less undulating and value is much higher; that means the FEP film has better flatness and stability. The peel strength of PFA film is around 0.3 N/mm and the peel strength of FEP film is around 1.37 N/mm. PFA film is thus not up to standard as a bonding layer and FEP is a preferable selection.

5.2 Relationship between the thickness of bonding layer and peel strength

According to pretesting, a link exists between the thickness of the bonding layer and peel strength. In order to explore this, many samples bonded with FEP film of different thicknesses were tested. The peel strength test results are shown in figure 5.3.

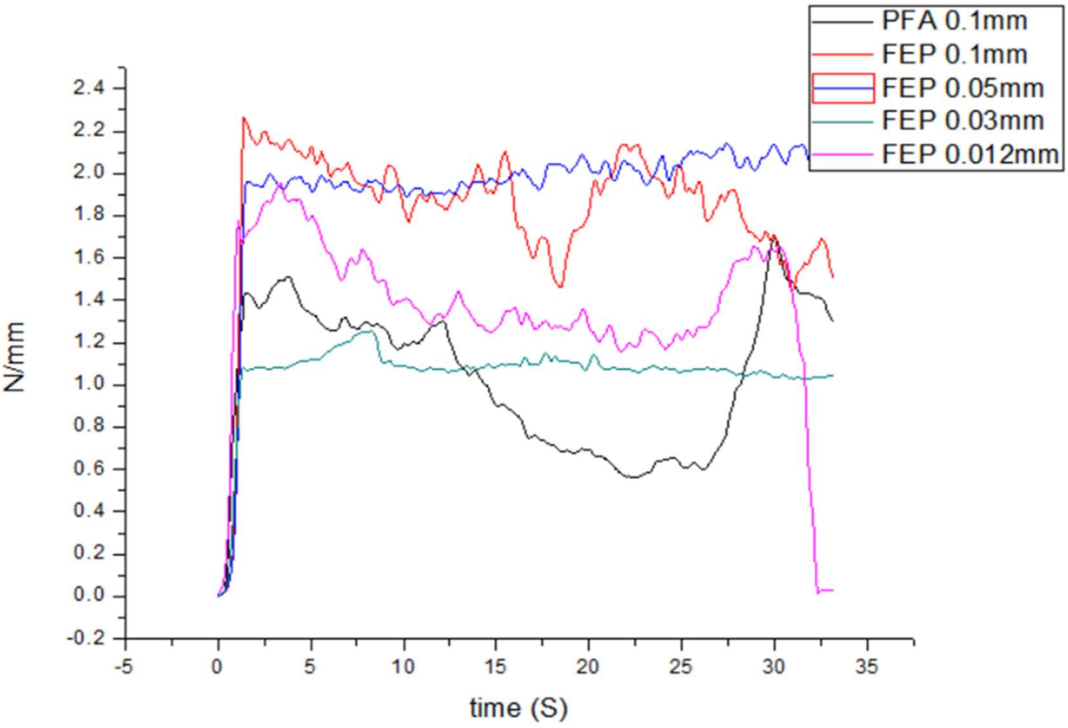


Figure 5.3 Peel strength test results of different bonding layers after plot

In this diagram, the ordinate is peel strength, and the abscissa is peel time. All samples were made with the same temperature and pressure curves.

From this diagram, it is apparent that the peel strength lines of 100 µm and 50 µm are apparently higher than those of the others. This suggests they have better bonding capacities, with both being over 2 N/mm; however, the peel strength line of the 50 µm FEP film is smoother, suggesting that in terms of bonding stability of bonding layer and cost, 50 µm FEP film is better than 100 µm.

5.3 The relationship between copper-covering technology and peel strength

Copper-covering technology is the most important stage of CCL, it is in direct relation to the quality of peel strength. The adjustable parameter includes vacuum degree, temperature curve and pressure.

(1) Vacuum degree

Compared with epoxy resin, PTFE and FEP have better heat stability, but this does not render a vacuum environment unnecessary. There are three main reasons that copper covering must take place in vacuum.

Oxidation of materials

Copper foil is the most easily oxidizable of all materials used in this process. At 200ºC, copper will react with oxygen and produce copper oxide, which could affect the binding force with the base material. In addition, FEP film will crinkle and react with oxygen and the surface of production will become irregular.

Bubble residual

In a non-vacuum environment, air will exist the gaps between the copper foil, FEP film, and basal plate. If the material deforms, some air bubbles will be generated at the surface. Illustration 5.4 is a picture of a sample which was not subject to vacuum.

Illustration 5.4 Sample not subject to vacuum

In this picture, the black section is formed of carbonization isolation materials. The copper foil in this picture has lost its gloss and been oxidized, and there are many air bubbles in the middle of the CCL.

Equipment damage

At high temperatures, the metal of equipment can undergo oxidation reactions that may break the surface evenness of critical planes. At the same time, the air can also make the cavity temperature increase more rapidly, which could cause damage to electric wires and tubes.

(2) Temperature curve

FEP and PTFE have different melting points. It was found by experiment that maintaining pressure in the melting point for a while could improve the copper covering quality. At the melting point of FEP, FEP could flow and fully integrate with the copper foil and PTFE under pressure. Based on several tests, the best temperature was found, as shown in figure 5.5.

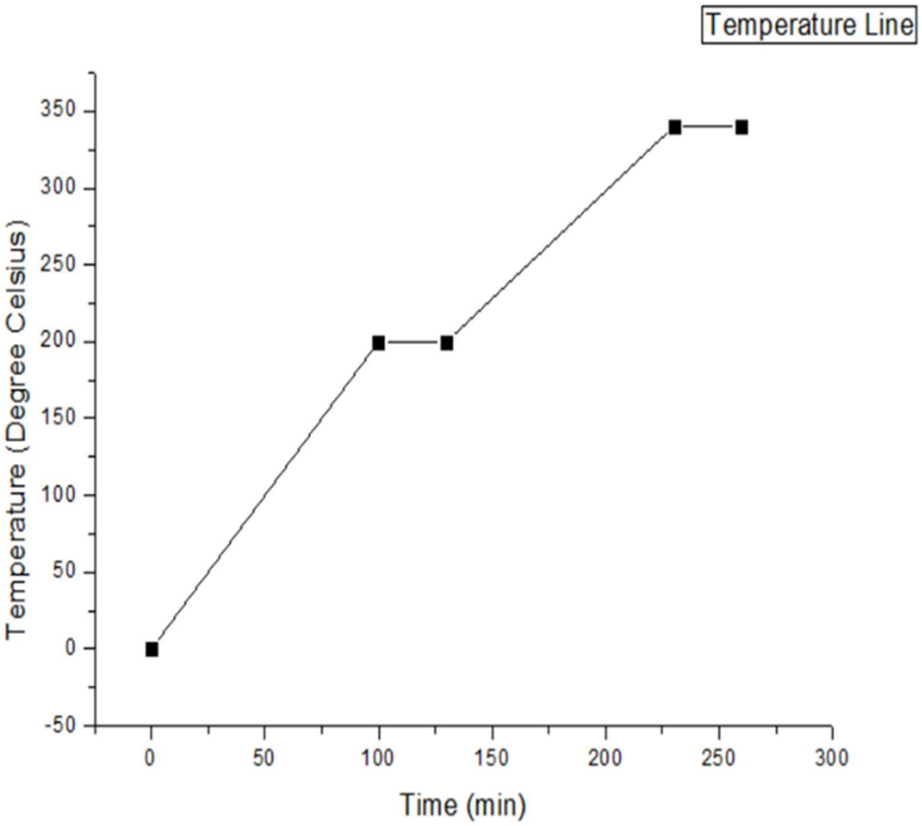


Figure 5.5 Temperature line of copper clad process with FEP bonding layer

(3) Pressure

In the experiment, it was found that at different pressures, the effects of copper cladding were also different. Compared to epoxy resin basal plate, PTFE suffers larger deformation under pressure. If the pressure is removed, the PTFE will resume its original form; however, due to the different mailabilities of copper foil and PTFE, if the pressure is too large, bumps will form, as in the picture in Illustration 5.6.

Illustration 5.6 Bumps on sample

This sample was made at 1 MPa, and the image clearly shows the many bumps that emerged.

To find the most suitable pressure, three samples were made under different pressures of 0.5 MPa, 0.3 MPa, and 0.1 MPa. The test results are shown in figure 5.7. The bonding layers of the three sample were 50 μm FEP film.

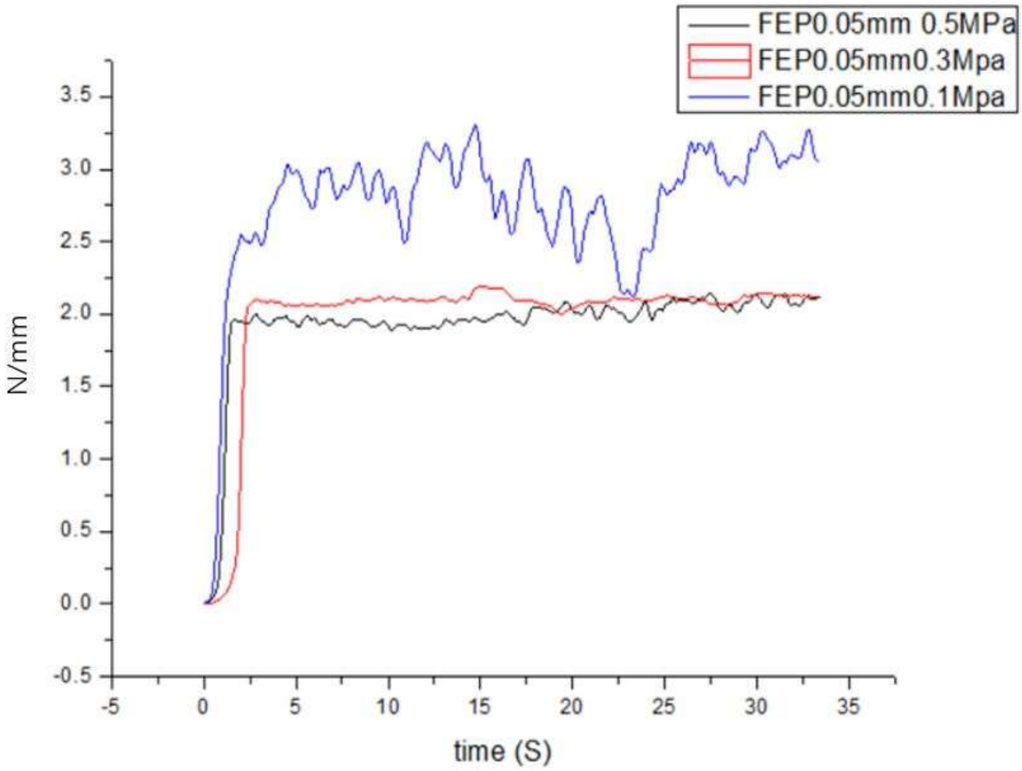


Figure 5.7 Test results of FEP bonding layers with three different thickness

The ordinate of the diagram is peel strength, and the unit is N/mm. In this diagram, the line for 0.1 MPa is higher than the others, but it is extremely unsmooth, which suggests that the bonding layer is uneven. The line for 0.3 MPa is a little higher than the line for 0.5 MPa, however, and it is the most even line. Thus, 0.3 MPa is the most suitable pressure.

6 Industrial producing of PTFE high-frequency substrate

There are three main manufacturing techniques used for three different PTFE substrates in factories. Those types are pure PTFE board, PTFE board with filling materials such as ceramic powder, and PTFE board with reinforcing materials such as glass fabric. They are summarized from reference [13], [14], [15] and [16].

6.1.1 Manufacturing techniques for pure PTFE board

The physical characteristics of PTFE mean that the usual processing methods to make PTFE into boards include compression moulding, cutting moulding, and tape casting. For pure PTFE board, cutting moulding is the most suitable and easiest processing method. A flow diagram of this process is shown in Illustration 6.1.

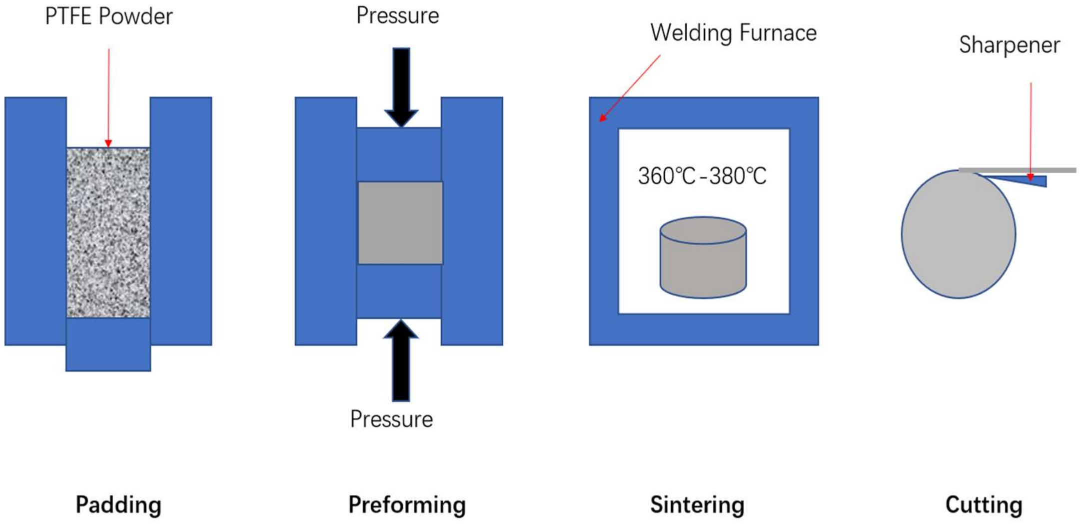


Illustration 6.1 Process flow diagram of cutting moulding

Cutting moulding for PTFE has four main steps: padding, preforming, sintering, and cutting.

Padding: This step requires placing the PTFE powder into a special mould; the dosage of PTFE powder varies depending on the breadth of board required.

Preforming: The purpose of the second step is to make the gap between PTFE powder particles as small as possible, to get the air out and to form a singular whole.

Sintering: The step requires placing the PTFE cylinder into a welding furnace. The PTFE melts in the temperature range between 360℃ and 380℃ to form a single unit.

Cutting: This step decides the thickness of the PTFE board.

The processing setup described above is a classic manufacturing technique, but it is not suitable for PTFE with inorganic padding such as ceramic particles. There are three difficulties with this classic manufacturing technique: first, the PTFE and inorganic padding powder must be mixed evenly; second, the material has no crack or cavity after the preforming mush is completed; and third, the thickness and surface roughness need to be controlled more precisely.

6.1.2 Manufacturing technique for PTFE with inorganic padding

To solve the previously highlighted issues, a rolling process was chosen to make the PTFE board with inorganic padding. The equipment is shown in Illustration 6.2.

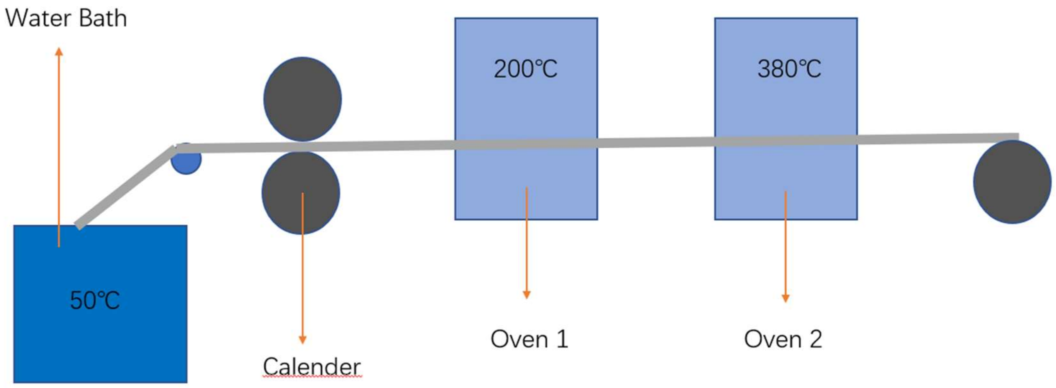


Illustration 6.2 Process flow diagram of rolling process

The key point of the manufacturing technique for PTFE with inorganic padding is the control of filler dispersion and air voids. If this control is poor, the dielectric properties in each part will be uneven, and the number of air voids will increase with the increase in percentage of padding. This is undesirable, as more air voids lead to higher water-absorbing qualities.

The manufacturing technique here is derived from a US Patent, number US4335180. This manufacturing technique mixes the PTFE dispersion liquid with padding materials and dries it until a good blend is achieved. Some accessory ingredients such as lubricant are added on the surface of the material which is then sent to be calendered. The thickness of board can be controlled by the space between the calendar rollers.

The material should then be baked twice, at two different temperatures, 200℃ and 380℃. The accessory ingredients will disappear at 200℃ and the PTFE particles will melt and blend together at 380℃.

6.1.3 Dip cloth production process

The dip cloth production process is the most popular method for the creation of epoxy resin basin body PCB boards, though it can also be used for PTFE boards. In this project, the dip cloth production process was thus chosen as the main research direction.

The key equipment for this technology is a gluing machine. The process flow diagram is shown in Illustration 6.3.

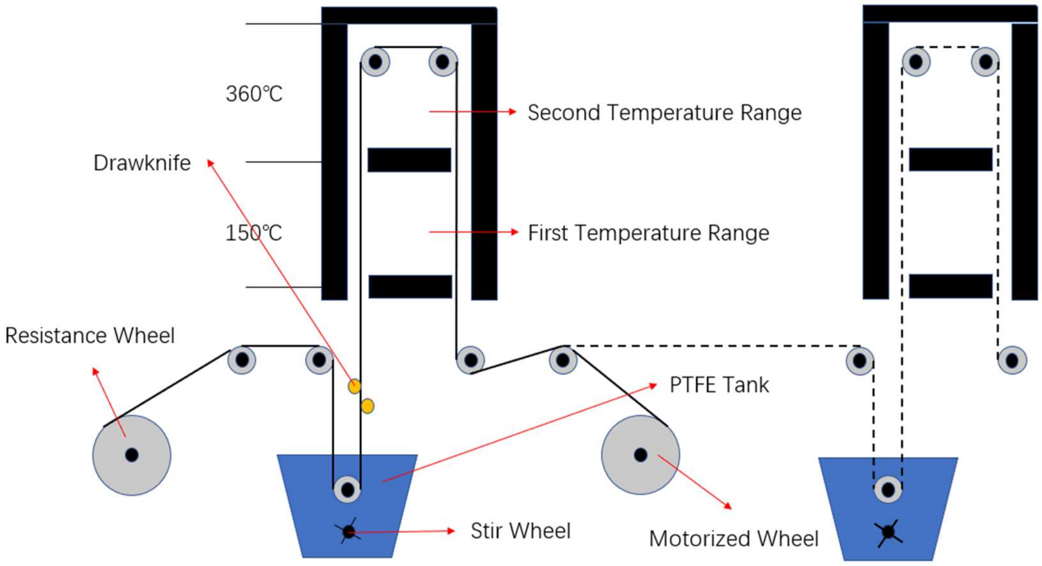


Illustration 6.3 Dip cloth production process

The gluing machine used was from Wujiang City Tai Sheng Oven Factory; it has two temperature ranges, though three temperature ranges would be better, because the transition region helps reduce the strong deformation caused by large temperature changes. In a factory, it is better to have many gluing machines to process a cloth. However, this project only had one gluing machine, and thus the cloth needed to be reset after each operation.

The pulling force was created by a motorized wheel. The cloth passed across the PTFE tank and dips into it on both surfaces. The idler wheel must dip into the PTFE solution, or the cloth may have only one side toughened with PTFE solution as in Illustration 6.4.

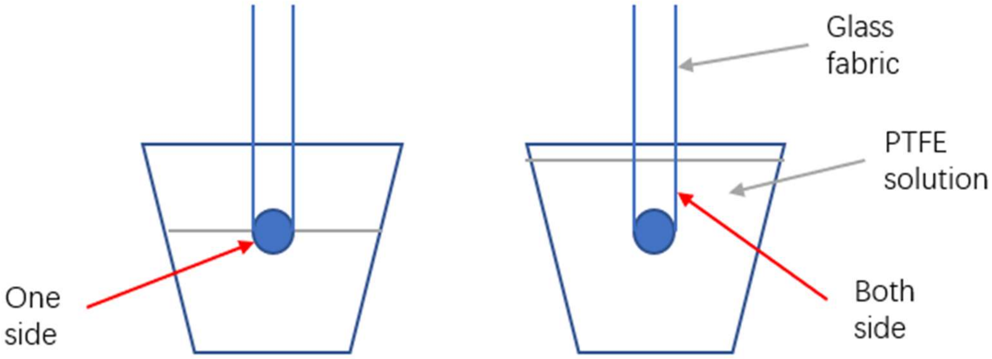


Illustration 6.4 Effect of immersion depth

The glass fabric after dipping crossed a pair of drawknives. The space between the two drawknives thus decides the thickness of the PTFE layer; however, if the gap is too big, it is difficult to get smooth surface. The resulting fabric was dried at 150℃ and sintered at 360℃.

6.2 Testing

For testing, the concentration of the PTFE solution was 60% and the glass fabric used was TGFC-1080-1270N from the Taijia glass fibre limited company. The experimental results for the first process were good. The average thickness increased by 0.008 mm and the surface was smooth. However, the adhesive force decreased after the second time of processing, and many extraneous particles appeared as in the picture in Illustration 6.5.

Illustration 6.5 Sample with particles

According to additional experiments, the reason for this is that PTFE after sintering has high water permeability, and the PTFE solution cannot uniformly distribute itself on the surface. In order to solve this problem, the equipment should be changed as shown in Illustration 6.6.

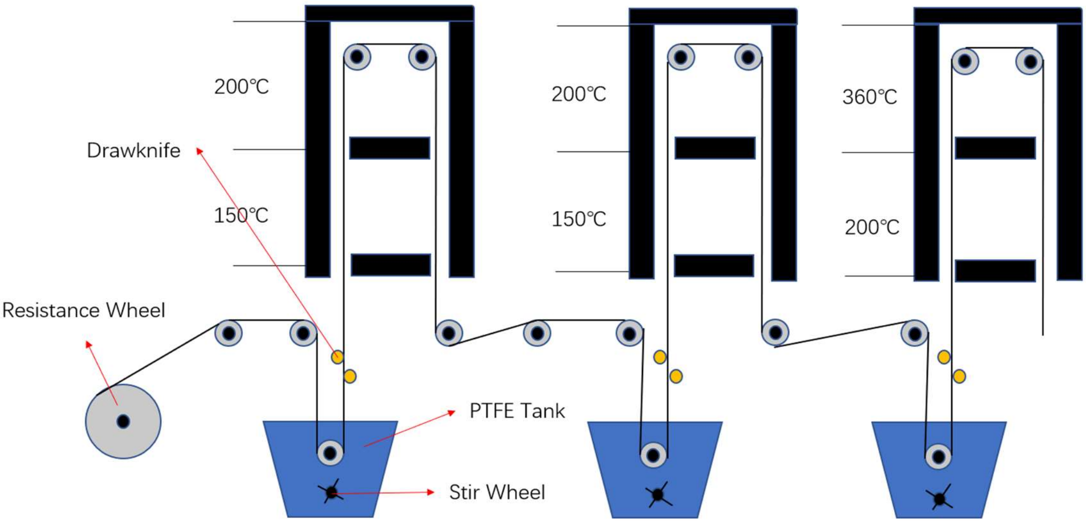


Illustration 6.6 Equipment after improvements

The design intent is to remove the sintering process after each dipping, replacing it with drying, and only sintering once, at the end. The gap between the drawknives should be noted, as each gap needs to be a little bigger than the gap before it. According to testing, the surface became better after this process.

6.3 Industrial copper clad process

A few pieces of glass fabric were taken from the roll after the gluing process， and the copper foil used to cover these before they were sent to the hot press. A second group was also created with two thin PFA films between the glass fabric and copper foil. The structure is shown in Illustration 6.7.

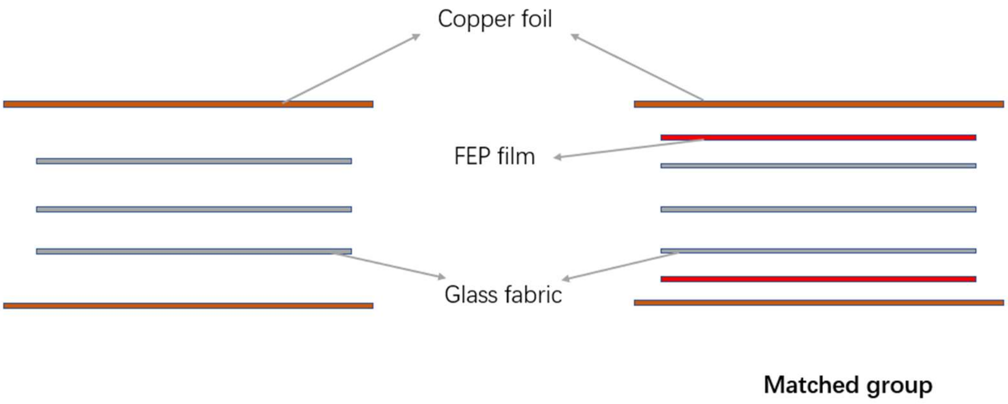


Illustration 6.7 CCL structure with bonding layer

The peel strength test results are shown in figure 6.8.

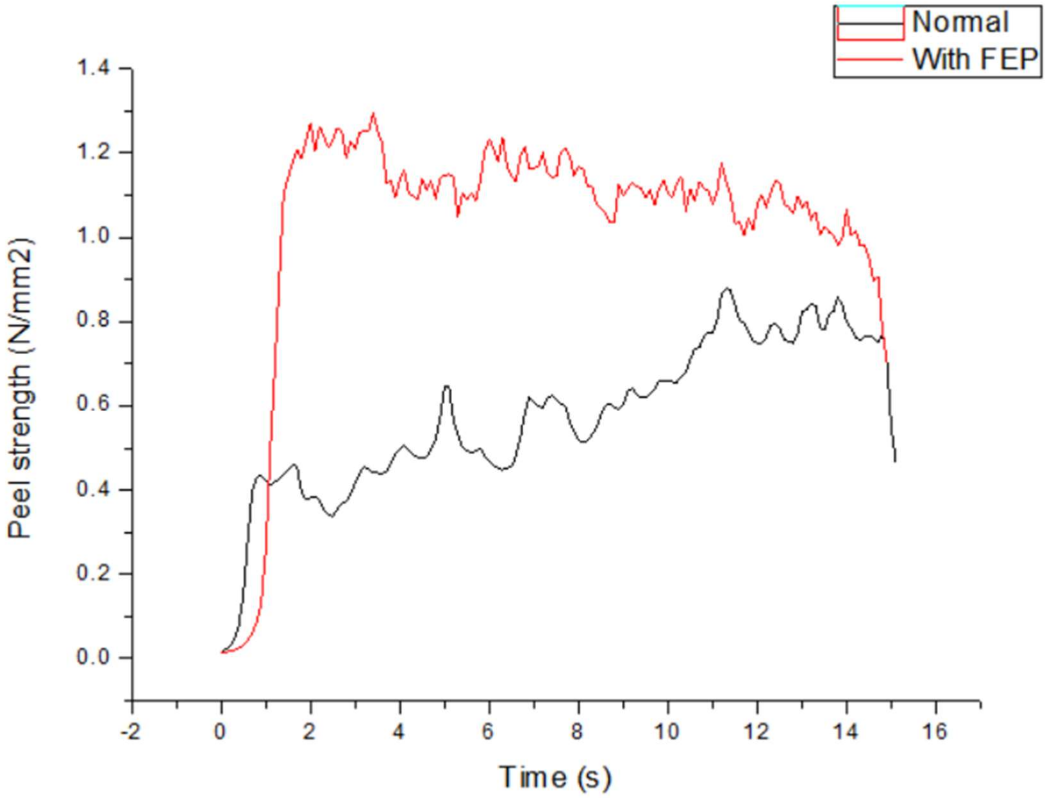


Figure 6.8 Peel strength test result with and without FEP layer

The peel strength of the sample without FEP solution is unqualified and shows large fluctuations. The FEP film is thus necessary and improves efficacy.

This project also examined the addition of a process which treated the glass fabric with FEP solution prior to hot-pressing. The results are shown in figure 6.8. It is clear that the stability improved, but the peel strength did not show a large improvement overall.

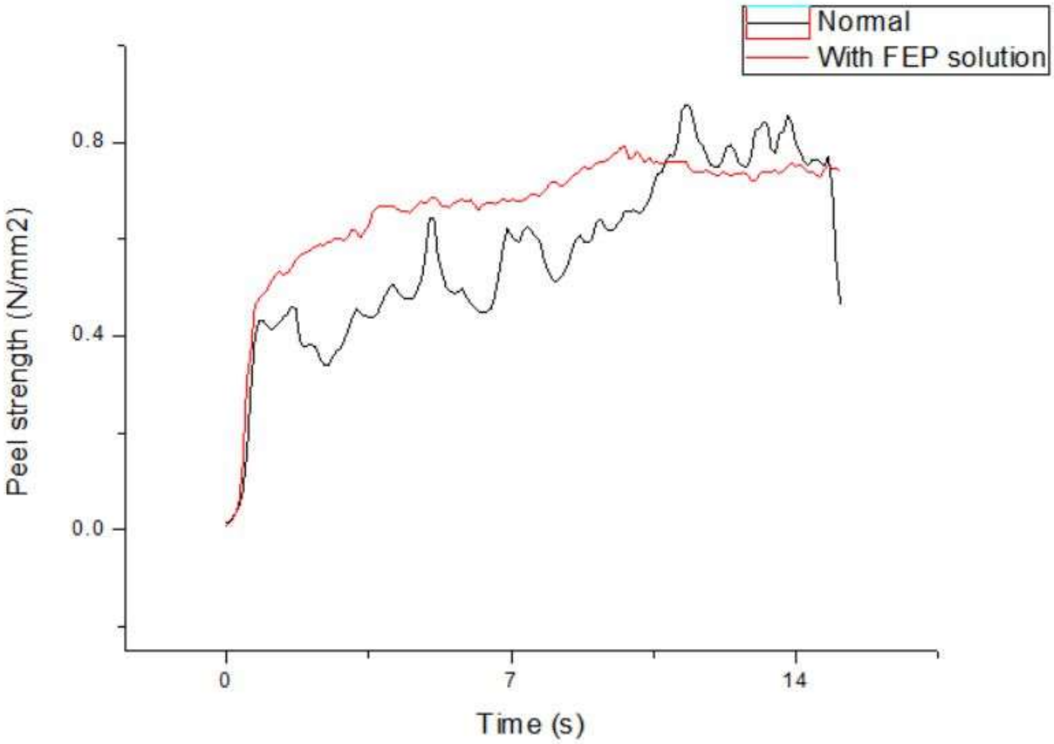


Figure 6.9 Results with and without FEP solution

This step will increase the cost of production, but the results with the FEP film are better; thus, this step may not be appropriate.

7 Conclusion

This project focused on research into the required materials for the nascent 5G technology. Based on data gathered prior to the start of the project, this project used PTFE as a base material, glass fibre mats and glass fabric as reinforcing materials, FEP film as a bonding layer, FEP solution as a modifying material, and electrolytic copper foil as a conducting layer. A set of mature technologies which included impregnation technology, pre-treatment technology, and vacuum hot-pressing technology was used to develop a PTFE composite substrate to be used in the microwave frequency band. It thus required the creation of a material with a suitable dielectric constant, low dielectric loss, low water absorption, low coefficient of thermal expansion, and stable temperature coefficient of dielectric constant.

Furthermore, the project designed a process for industrial manufacture of such components using a gluing machine, as well as testing and improving the process.

7.1 Impregnation technology

This project used PTFE solutions with different concentrations and PTFE and FEP mixed solution to dip glass fabric and glass fibre mats to discover the most suitable soaking concentrations and soaking times. These were identified as 60% PTFE solution for 10 times for glass fabric, and 60% PTFE solution for 12 times for glass fibre mats. There were also signs that the proper addition of FEP solution could help with the bonding of resin; however, high concentrations of FEP solution were not available during the research, so this issue will require further investigation.

7.2 Hot press sintering process

Different technical formulae need different technological parameters. This project thus designed different temperature curves for glass fabric and glass fibre mat prepreg.

Due to the large coefficient of thermal expansion and large deformation under pressure, the hot press actions for prepreg and copper covering must usually be done separately. This project tested different pressures and found a suitable pressure for both prepreg and copper covering, however.

7.3 Bonding layer

As PTFE is difficult to bond directly with copper foil, the selection of a bonding layer is very important. This project tested FEP and PFA films in different thicknesses and compare the peel strength and effect of copper cladding on of them. After this testing, 50 μm FEP film was selected as a bonding layer based on considerations of effectiveness and cost.

7.4 Glass fabric and glass fibre mat composite structure

To remedy the gel content issues arising from the glass fabric and the surface problems of the glass fibre mat, this project designed a composite structure that offered the advantages of both glass fabric and glass fibre mats and compensated for their disadvantages. After testing, the indices reached the application standard.

7.5 Industry produce

In this project, a PTFE board with reinforcing material was chosen as the design object. A traditional glue machine was tested and transformed to adjust the manufacturing technique to make it suitable for industry production and to save on costs.

The project also tried to improve the formula for the dipping solution and thus increase the adhesive force with the copper foil. The experimental results showed that the use of FEP solution for the last few times of dipping appeared to make the peel strength greater.

7.6 Future work

This project designed a complete production process and formula; however, this cannot be used to make high frequency microwave substrates on a commercial scale. as further works need to be done before volume production can commence.

7.6.1 Product test

CCL is the raw material of for PCBs, and the percentage of passing PCBs made by the CCL arising from the project is an important indicator of success. The CCL should thus be tested by etching and drilling and the creation of sample electronic components.

7.6.2 Environment test

The service environment of high frequency PCBs is complex, and therefore the CCL should be tested for extreme environmental performance indicators. This is the most important reference for PCB manufacturers.

7.6.3 Adjustments and modifications

The use of glass fibre mats gives more space for adjustment and modification, as they can be easily modified by adding ceramic powder and other nanometre materials. In the future, this characteristic could be used to design different formulae for different application environments. Many groups have done some research for pure PTFE such as reference [4],[19] and [20]. It is worth a try with glass fibre mats.

7.6.4 Equipment design

Compared to traditional glass fabric CCL, glass fibre mats are more breakable before dipping, and thus the equipment needs to be redesigned. Because of the price of PTFE is much more expensive than epoxy resin, the repeating utilization factor is an important question need to be considered.

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