

SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

**ADHESION PERFORMANCE OF SOLVENT-BASED ADHESIVE IN
MEDICAL TUBE**

By

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DECLARATION

I hereby declared that I have conducted completed the research work and written dissertation entitled “**Adhesion Performance of Solvent-based Adhesive in Medical Tube**”. I also declared that is has not been previously submitted for the award of any degree or diploma or other similar of this for any other examining body of University.

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TABLE OF CONTENTS

Contents	Pages
DECLARATION	II
ACKNOWLEDGEMENTS	III
TABLE OF CONTENTS	IV
LIST OF TABLES	VIII
LIST OF FIGURES.....	X
LIST OF ABBREVIATIONS.....	XIII
LIST OF SYMBOLS.....	XV
ABSTRAK.....	XVII
ABSTRACT.....	XIX

CHAPTER 1	INTRODUCTION.....	1
1.1	BACKGROUND TO THE RESEARCH.....	1
1.2	CONTEXT AND RATIONALE.....	6
1.3	RESEARCH AIMS & DIRECTION.....	7
CHAPTER 2	LITERATURE REVIEW.....	8
2.1	ADHESION.....	8
2.1.1	Adhesive Bonding.....	8
2.1.2	The Function of the Adhesives	10
2.1.3	Bond types in Adhesive Joints	12
2.1.4	Strength in Adhesive Joints	16
2.1.5	Theories of Adhesion and Adhesion Mechanism.....	17
2.1.6	Surface Treatment	24
2.1.7	Joint Design.....	27
2.1.8	Joint Failure	32
2.1.9	Selection of Adhesives	33
2.2	ADHESIVE	37
2.2.1	Physical adhesives	41
2.2.2	Solvent-based adhesive	42
2.2.3	Solvent-based adhesive used in PVC.....	44
2.3	FACTORS THAT AFFECT THE ADHESION AND ADHESIVE	49
2.3.1	Compatibility and Miscibility.....	49
2.3.2	Viscosity of adhesive	50

2.3.3	Wettability and Surface Energy.....	51
CHAPTER 3	METHODOLOGY	54
3.1	MATERIALS	54
3.2	PREPARATION OF PVC SOLVENT-BASED ADHESIVE.....	55
3.3	TESTING PROCEDURE FOR PVC SOLVENT-BASED ADHESIVE .	58
3.3.1	Viscosity	58
3.3.2	Fourier Transform Infra-Red Spectroscopy (FTIR)	58
3.3.3	Specimen Preparation	59
3.3.4	Preparing the surface	59
3.3.5	Lap Shear Test	60
3.3.6	Optical Microscopy (OM)	60
CHAPTER 4	RESULT AND DISCUSSION	61
4.1	EFFECTS OF DIFFERENT COMPOSITION OF PVC/CYC RATIO ...	61
4.2	EFFECT OF DIFFERENT SOLVENT RATIO (PVC/CYC/SOLVENT: 15/35/50)	65
4.3	EFFECT OF DIFFERENT SOLVENT USED IN ADHESIVE TO FTIR ANALYSIS.....	68
4.4	EFFECT OF COMPOSITION PVC/CYC RATIO ON LAP SHEAR STRENGTH.....	72
4.5	EFFECT OF DIFFERENT SOLVENT ON LAP SHEAR STRENGTH.	76

4.6	EFFECT OF COMPOSITION PVC/CYC RATIO ON FAILURE SURFACE MORPHOLOGICAL.....	78
4.7	EFFECT OF DIFFERENT SOLVENT ON FAILURE SURFACE MORPHOLOGICAL.....	80
CHAPTER 5 CONCLUSION AND FUTURE RECOMMENDATIONS		82
5.1	CONCLUSION.....	82
5.2	RECOMMENDATIONS FOR FUTURE RESEARCH.....	84
REFERENCES.....		85

LIST OF TABLES

Table 1-1: Some of polymer that used in medical industries	2
Table 1-2: Parameters and the corresponding performance some of medical device adhesives.....	3
Table 2-1: Forces at the Interface or Within the Bulk of a Material (Petrie, 2000)	15
Table 2-2: Surface preparation for plastics (PVC) (Shields, 1984).....	26
Table 2-3: Failure Mode as an Inference to Bond Quality (Petrie, 2000)	33
Table 2-4: Lap shear strength for common engineering adhesive (Heidarpour et al., 2018)	39
Table 2-5: The applications of common type of adhesive based on their curing system.....	40
Table 2-6: The lap shear strength (psi) of different type of physical curing adhesive.....	42
Table 2-7: Types of solvent-based adhesive suitable for bonding polymer materials (Pinner and Simpson, 2013)	43
Table 2-8: Some of Typical Solvents for Solvent Cementing of Plastics (Petrie, 2000)	45
Table 2-9: The contact angle affects the wettability and adhesive bond	53
Table 3-1: Original formulation of solvent-based adhesive (PVC/CYC: 10/90)	56
Table 3-2: Other formulation of solvent-based adhesive composition.....	57
Table 3-3: Formulation of different composition of PVC/CYC	57
Table 3-4: Formulation of different solvent of PVC/CYC/other solvent.....	57

Table 4-1: Time taken for PVC to dissolve in solvent, viscosity of adhesive with different composition PVC/CYC ratio and defect on medical tube	62
Table 4-2: Time taken for PVC to dissolve in solvent, viscosity and molecular weight of adhesive with different solvent and defect on medical tube	66
Table 4-3: Lap shear strengths and type of failure of adhesive for different composition of PVC/CYC	74
Table 4-4: Lap shear strengths and type of failure of adhesive for different solvent	77

LIST OF FIGURES

Figure 1-1: Part of Laryngeal Tube Suction Disposable (LTSD)	5
Figure 2-1: Substrate (adherend) and adhesive bonding	9
Figure 2-2: Difference between adhesion forces and cohesion forces	9
Figure 2-3: Specific and mechanical adhesion (Adhesion strength).....	11
Figure 2-4: Contributions to the cohesion strength of an adhesive	12
Figure 2-5: Bond types in adhesive joints	13
Figure 2-6: Development of adhesion forces due to dipole action between the molecules	14
Figure 2-7: Principle of the action of hydrogen bonds (Example: Polyamides)	15
Figure 2-8: Structure of an adhesive joint	16
Figure 2-9: Adhesion mechanism of adsorption theory	18
Figure 2-10: Good and Poor Surface Wettability	19
Figure 2-11: Adhesion Mechanism of Physisorption (Physical absorption) and Chemisorption (Chemical adsorption)	19
Figure 2-12: Adhesion Mechanism of Mechanical Interlocking	20
Figure 2-13: Adhesion Mechanism of Diffusion Theory	22
Figure 2-14: Adhesion Mechanism of Weak Boundary Layer Theory	23
Figure 2-15: Adhesion Mechanism of Electrostatic Theory	24
Figure 2-16: Experimental apparatus used for the plasma treatment of the PVC (Rangel et al., 2011).....	26
Figure 2-17: Types of stress common to adhesive joint	28
Figure 2-18: The four basic types of joints; (a) angle; (b) tee; (c) butt; (d) surface	30

Figure 2-19: Various types of joint design various types of joint designs suitable for various loa.....	30
Figure 2-20: Common joint designs for flat adherend (Petrie, 2000).....	31
Figure 2-21: Adhesion Failure	32
Figure 2-22: Cohesion Failure.....	32
Figure 2-23: Mixed Failure	32
Figure 2-24: Classification of adhesive	37
Figure 2-25: Molecular structure of cyclohexanone (CYC).....	46
Figure 2-26: Molecular structure of tetrahydrofuran (THF).....	47
Figure 2-27: Molecular structure of methyl ethyl ketone (MEK).....	47
Figure 2-28: Molecular structure of acetone.....	48
Figure 2-29: Molecular structure of xylene	49
Figure 2-30: The differences between low viscosity and high viscosity of liquid	51
Figure 2-31: The effect of surface roughness on wettability (Asgharifar et al., 2014)	52
Figure 2-32: Different contact angle gives different wettability quality	52
Figure 3-1: Overall process to analyzed adhesion performance	55
Figure 3-2: Adhesive Lap Joint Shear Test Specimen	60
Figure 4-1: Effect of adhesive with different composition PVC/CYC (a) 5/95 (b) 10/90 (c) 15/85 (d) 20/80 and (e) 25/75 on medical tube	64
Figure 4-2: Effect of adhesive with different solvent (a) CYC (b) THF (c) MEK (d) Acetone and (e) Xylene on medical tube	68
Figure 4-3: Comparison of FTIR spectra between (a) pure PVC/CYC and (b) PVC/CYC/THF	69

Figure 4-4: Comparison FTIR spectra between (a) pure PVC/CYC and (b) PVC/CYC/MEK.....	70
Figure 4-5: Comparison FTIR spectra between (a) pure PVC/CYC and (b) PVC/CYC/acetone.....	71
Figure 4-6: Comparison FTIR spectra between (a) pure PVC/CYC and (b) PVC/CYC/xylene	72
Figure 4-7: Shear stress vs. shear strain of different composition of PVC/CYC	73
Figure 4-8: Chemical structure of polyvinyl chloride (PVC)	75
Figure 4-9: Type of failure in adhesive application	75
Figure 4-10: Amorphous and semi-crystalline structure of polymer	76
Figure 4-11: Shear stress vs. shear strain of different solvent.:	77
Figure 4-12: Mechanical interlocking between the molecule in the polymer chain	78
Figure 4-13: Lap shear bonding and cohesion failure	78
Figure 4-14: Morphological of surface at interface of PVC substrate of different composition PVC/CYC ratio (a) 5/95 (b) 10/90 (c) 15/85 (d) 20/80 and (e) 25/75.....	80
Figure 4-15: Wettability of the adhesive	80
Figure 4-16: Morphological of surface at interface of PVC substrate of different solvent (a) CYC (b) THF (c) Acetone (d) Xylene and (e) MEK ...	81

LIST OF ABBREVIATIONS

AIBN	Azobisisobutyronitrile
ASTM	American Society For Testing and MAterials
C	Carbon
Cl	Chlorine
cP	Centipoise
CYC	Cyclohexanone
F	Fluorine
FTIR	Fourier Transform Infrared
H	Hydrogen
IPA	Isopropyl alcohol
LTSD	Laryngeal Tube Suction Disposable
MEK	Methyl ethyl ketone
MW	Weight average Molecular weight
O	Oxygen
OM	Optical microscopy
PA	Polyamide

PC	Polycarbonate
PCL	poly- ϵ -caprolactone
PE	Polyethylene
PEEK	Polyether ether ketone
PMMA	Polymethyl Methacrylate
PS	Polystyrene
PSA	Pressure sensitive adhesive
PUR	Polyurethane
PVC	Polyvinyl chloride
SBR	Styrene butadiene rubber
SPI	soy protein isolate
THF	Tetrahydrofuran
VOCs	Volatile organic compounds

LIST OF SYMBOLS

$^{\circ}$	Degree
$^{\circ}\text{C}$	Degree celcius
$^{\circ}\text{F}$	Degree Fahrenheit
Min	Minutes
E_b	Elongation at break
mm	Milimeter
ml	Mililiter
cm	Centimeter
cm^3	Cubic centimeter
W_f	Weight fraction
MPa	Megapascal
KJ/m^2	Kilojoule Per square Meter
KJ/mol	Kilojoule Per Mole
μm	Micrometer
g	Gram
mg	Miligram

g/cm^3	Gram per cubic centimeter
g mL^{-3}	Gram per cubic liter
%	Percent
wt%	Percent by weight
T_g	Glass transition temperature
T_m	Melting temperature
rpm	Revolution Per minute
psi	Pounds per square inch
θ	Angle
ρ	Density

PRESTASI PELEKATAN PELEKAT BERASASKAN PELARUT DALAM TIUB PERUBATAN

ABSTRAK

Tujuan penyelidikan ini adalah untuk mengkaji prestasi pelekatan pelekat berasaskan pelarut dalam tiub perubatan. Polivinil klorida (PVC) dalam pelarut yang berbeza seperti sikloheksanon (CYC), tetrahidrofolat (THF), metil etil keton (MEK), aseton dan xylene disediakan. Kesan komposisi PVC / CYC komposisi yang berlainan dan pelarut yang berbeza digunakan sebagai parameter pemprosesan untuk menilai prestasi lekatan. Lima nisbah yang berbeza dipilih iaitu 5:95, 10:90, 15:85, 20:80 dan 25:75 untuk kesan nisbah komposisi PVC / CYC yang berlainan manakala untuk pelarut yang berlainan, lima lagi nisbah yang berbeza dipilih 15:85 (PVC / CYC), 15:35:50 (PVC / CYC / THF), 15:35:50 (PVC / CYC / MEK), 15:35:50 (PVC / CYC / aseton) dan 15:35:50 (PVC / CYC / xylene). Sampel akan dicirikan pada masa yang diambil untuk larutan PVC dalam pelarut dan kelikatan untuk mengaitkan parameter pemprosesan dan prestasi melekat. Dalam kes ini, suhu (suhu bilik) dan kelajuan pengaduk mekanik (600 rpm) digunakan secara berterusan. Kelikatan dan masa yang diambil untuk PVC terlarut dalam pelarut telah diukur kerana ia diandaikan bahawa kedua-dua parameter adalah faktor yang mempengaruhi prestasi melekat. Prestasi lekatan dianalisis menggunakan tiga ujian berbeza iaitu FTIR, ujian kekuatan ricih pusing dan mikroskop optik. FTIR digunakan dalam penyelidikan ini untuk menyiasat jenis ikatan dan kumpulan berfungsi terdiri daripada rantai molekul pelekat. Kekuatan ricih pelekat diukur dengan menggunakan ujian kekuatan ricih pusingan mengikut ASTM D3163. Kajian morfologi dilakukan melalui kajian analisis permukaan patah semua sistem pelekat selepas ujian

ricih putaran dengan menggunakan mikroskop optik. Nisbah antara polimer dan pelarut juga penting kerana penyebaran antara pelekat dan pelekat bergantung kepada interaksi antara molekul substrat dan lapisan pelekat. Kajian ini akan menonjolkan pengaruh formula dan parameter pemprosesan ke atas prestasi lekatnya.

ADHESION PERFORMANCE OF SOLVENT-BASED ADHESIVE IN MEDICAL TUBE

ABSTRACT

The purpose of this research is to investigate the adhesion performance of solvent-based adhesive in medical tube. Polyvinyl chloride (PVC) in different solvent such as cyclohexanone (CYC), tetrahydrofuran (THF) methyl ethyl ketone (MEK), acetone and xylene were prepared. The effects of different composition PVC/CYC ratios and different solvents are used as the processing parameters to assess the adhesion performance. Five different ratios are selected which are 5:95, 10:90, 15:85, 20:80 and 25:75 for the effect of different composition PVC/CYC ratio whereas for the effect of different solvent, another five different ratios were selected which are 15:85 (PVC/CYC), 15:35:50 (PVC/CYC/THF), 15:35:50 (PVC/CYC/MEK), 15:35:50 (PVC/CYC/acetone) and 15:35:50 (PVC/CYC/xylene). The sample will be characterized in time taken for PVC to dissolved in solvent, and viscosity to correlate the processing parameter and adhesion performance. In this case, the temperature (room temperature) and speed of mechanical stirrer (600 rpm) used is constant. The viscosity and the time taken for PVC to dissolved in solvent were measured as it is postulated that both parameters are the factor that affected the adhesion performance. The adhesion performance was analyzed by using three different tests which are FTIR, lap shear strength test and optical microscopy. FTIR was used in this research to investigate the type of bond and functional group consists in the molecular chain of the adhesive. The shear strength of the adhesive was measured by using lap shear strength test according to ASTM D3163. The morphology study is done via the study of the fracture surface analysis of the all adhesive systems after lap

shear test by using optical microscope. The ratios between polymer and solvent also are important as the inter-diffusion of adherend and adhesive depends on the interaction between substrate molecule and adhesive layer. This study highlighted the influence of formulations and processing parameter onto its adhesion performance.

CHAPTER 1

INTRODUCTION

1.1 Background to the research

The joining of materials has been used in industry or manufacturing since the beginning of mankind and has become one of the key technologies in many manufacturing industries. Joining is achieved through rivets, clamping, seaming, welding, soldering, brazing and the use of adhesives. According to Zhou and Breyen (2013), the medical-device industry is no exception. Medical devices are ending up more confounded, both in execution determinations and auxiliary many-sided quality. Medical devices typically consist of components and materials that must be joined in some way, whether used outside the body (in the form of instrumentation or surgical tools) or inside the body (for diagnostic monitoring or therapeutic purposes). Recently other joining methods besides stitching are also being applied for tissue bonding and skin closure.

Medical devices which are manufactured in a variety of materials such as metals, polymers and ceramics can be joined by using mechanical fastening where parts are joined through clamping and riveting, welding where parts are joined by fusion welding, brazing and soldering, and solid-state welding, and adhesive bonding where parts are joint by applying an adhesive to the surfaces (Zhou and Breyen, 2013). All these three methods mention above are used in medical devices although the materials, the size of these devices and these devices limit the strict limits on the scope of the process with potential use.

The uses of polymer and plastic engineering to the design and produce of medical hardware are developing at a quick pace not seen before in the medical device industry (Modjarrad and Ebnesajjad, 2013). The development of polymers enabled the development of medical devices that overtook and eventually replaced the foundation materials with newer and better materials such as polyvinyl chloride (PVC) for IV bags and tubing, silicone tubing for catheters and balloons, polyolefins for trays and bottle and fluoropolymers for IV catheters. **Table 1-1** below shows some common polymers that may be used in medical application. Polymers have been used in many medical application and devices because of the special properties itself. The characteristics of polymer are flexible, biocompatibility, sterilization resistance, chemical inertness, resistance to physical forces, ability to modified using additive, high heat resistance and flame retardant properties for PC, withstand high temperatures, and pressures for extended periods of time for PEEK (Modjarrad and Ebnesajjad, 2013).

Table 1-1: Some of polymer that used in medical industries

Polymer	Application
Silicone	Adhesive, wound care, catheters and medical tubing, seals, masks and valves
Polycarbonate (PC)	Respiratory therapy devices, high-pressure syringes, surgical device handles and housings
Polyether Ether Ketone (PEEK)	Medical tubing and implants
Polymethyl Methacrylate (PMMA)	Diagnostic equipment and implants
Polyurethane	Heart valves, blood filter, vascular tubes, artificial hearts

Polyvinyl chloride (PVC)	Disposable syringe, medical tubing
Polyethylene (PE)	Wear-bearing surface of hip and knee arthroplasty
Polystyrene (PS)	Tissue culture component, flasks, pipettes

Performance of adhesives in medical devices depends on the application of the product. For example, some medical devices need to be temperature resistance, environmental resistance, chemical compatibility, corrosion resistance and good mechanical properties. Choosing wearable medical device adhesives requires a strong comprehension of essential adhesive that will be discuss later in this research. **Table 1-2** shows example of adhesive that commonly used in medical devices. The fast cure speed and high performance of cyanoacrylates and light curing acrylic adhesive regularly make them the adhesive frameworks of decision for rapid, robotized get together of medical devices (Courtney and Serenson, 1998).

Table 1-2: Parameters and the corresponding performance some of medical device adhesives.

Performance considerations	Medical device adhesive category			
	Cyanoacrylates	Epoxies	Silicones	Urethanes
Benefits	Wide range of bonding applications	Wide range of formulations	Excellent temperature resistance	Excellent toughness/flexibility

Temperature resistance	-65°F to 180°F	-65°F to 300°F	-65°F to 350°F	-65°F to 250°F
Environmental resistance				
Polar solvents	Poor	Very good	Good	Good
Non-polar solvent	Good	Excellent	Poor to fair	Good
Sterilization	Very good	Excellent	Excellent	Very good
Adhesions to substrate				
Plastics	Excellent	Fair	Good	Very good

Laryngeal Tube Suction Disposable (LTSD) as shown in **Figure 1-1** is one of the medical device produced by CCB Medical Devices Sdn Bhd. According to Asai and Shingu (2005), the laryngeal tube (VBM Medizintechnik, Sulz, Germany) is relatively new extraglottic (supraglottic) airway, designed to secure a patient airway during either spontaneous breathing or controlled ventilation. The device consists of an airway tube with small cuff attached at the tip (distal cuff) and larger balloon cuff at the middle part of the tube (proximal cuff) (**Figure 1-1**). The cuffs are normally inflated through a single pilot tube and balloon, through which cuff pressure can be monitored. There are three black lines on surface of the tube near a standard 15-mm connector, which indicate adequate depth of insertion when align with the teeth. The device is made PVC and re-usable, after sterilization in autoclave, up to fifty times.

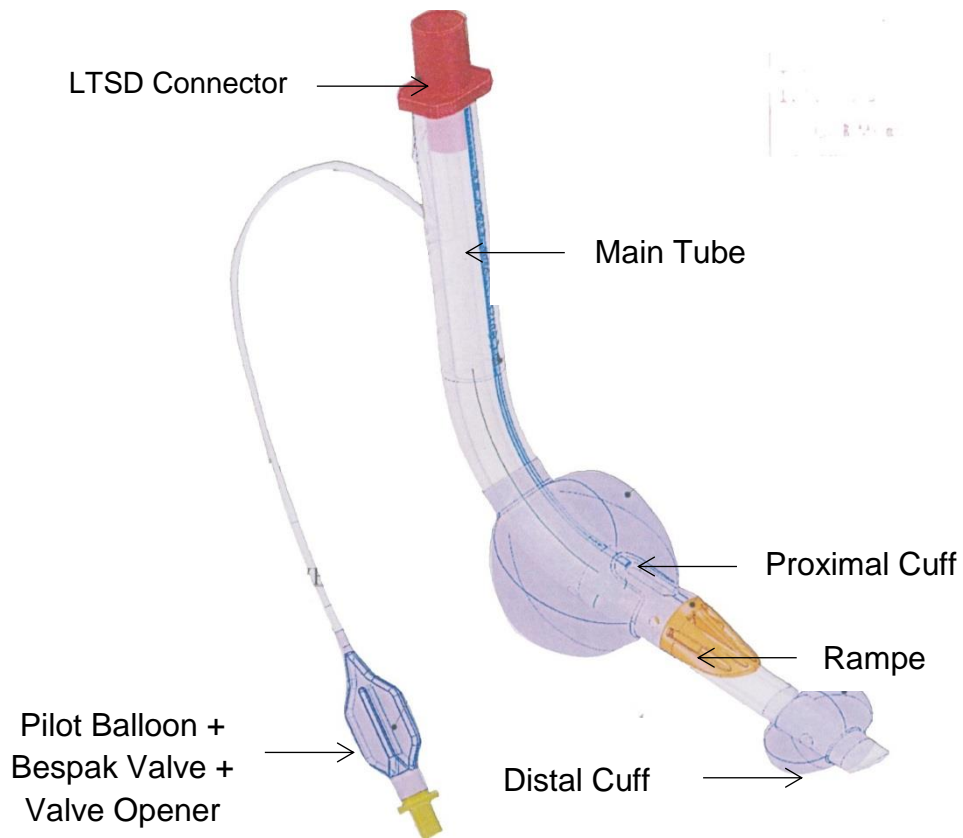


Figure 1-1: Part of Laryngeal Tube Suction Disposable (LTSD)

The solvent-based adhesive was used to join each part in the LTSD. Each part of the joining includes:

- i. The LTSD connector with main tube
- ii. The upper and lower of proximal cuff with main tube
- iii. The rampe with main tube
- iv. The upper and lower of distal cuff with main tube
- v. The upper of pilot balloon with bespak valve + valve opener and lower part of pilot balloon with inflation tube

Although this type of adhesive is well-used for medical devices such as LTSD, however it leads to several failure modes such as adhesive failure, cohesive failure and structural failure. These failure modes can be contributed by many factors such as

material itself, adhesive bonding, type of solvent used, processing condition of plastic and adhesive and lack of surface preparation of substrate.

In this research, the solvent-based adhesive will be study further on their properties, formulations including ratio composition of PVC/CYC and different type of solvent used, their processing and also their performance to bind the substrates (materials).

1.2 Context and rationale

Solvent-based adhesive is a large group of adhesives which all consist of polymeric resin dissolved in an organic solvent. The different types of solvent used will affect the adhesion properties itself including mechanical and physical.

In this solvent based adhesive, the formulation used is very important because it lead to formation of different viscosity that will affect the adhesion performance especially on their strength. According to Kim and Sun (2015), viscosity is one of the most critical factors that affects the flow property and penetration of adhesive through substrate, which directly influence adhesion strength. The viscosity of adhesives has a strong influence on the quality, rate of dispensing and adhesion performance itself (Christina R. Hicks, 2015). They found that increase in viscosity was material dependent (solvent used). Too thick (high viscosity) of a material is hard to dispense, requiring higher pumping force or increased heating in the adhesive line. High viscosity at the time of dispensing may also cause difficulty in spreading the adhesive uniformly across the surfaces to be joined.

While too thin (low viscosity) of an adhesive, the faster it flows. The difference in viscosity are also caused by molecule in the adhesive. This is essentially how molecules are bonded in adhesive. The looser the molecular bonds, the weaker the inter-molecular

forces. This equates to a lower viscosity. The tighter the molecular bonds, the stronger the inter-molecular forces. This equates to a higher viscosity.

1.3 Research aims & direction

The purpose of this research is to investigate the adhesion performance of solvent-based adhesive in medical devices. This research aimed to overcome the problem arises from the surface of medical tube and other materials in contact with it which is involved the solvent-based adhesive. The specific research objectives are as follows:

- i. To assess the effect of different types of solvent used on its mechanical properties.
- ii. To establish optimum formulation of solvent-based adhesive used in joining PVC medical tube.
- iii. To correlate the processing parameter and formulation in order to develop a reject-free material.

CHAPTER 2

LITERATURE REVIEW

2.1 Adhesion

2.1.1 Adhesive Bonding

Adhesive bonding is a process of joining two or more solid parts with an adhesive substance which undergoes a physical or chemical hardening reaction causing the parts to join together through surface adherence (adhesion) and internal strength (cohesion). The serviceability and strength of adhesive-bonded joints are mainly the result of the play of forces of intermolecular interaction between the adhesive and the substrate. The forces of interaction between two condensed bodies at distances on the atom size scale produce high adhesion strength (Veselovsky and Kestelman, 2002). Adherend is a material or part that is held to another by an adhesive. The material of the adhesive layer is commonly a polymer (natural or synthetic). Through definition by ASTM D907-06, an adhesive as “a substance capable of holding materials together by surface attachment”. According to DIN EN 923, an adhesive is defined as a non-metallic binder that acts via adhesion and cohesion. Adhesion is the joining between one material to another, namely an adhesive to a substrate, due to a variety of possible interactions while cohesion is defined as the internal strength of an adhesive as a result of a variety of interactions within the adhesive.

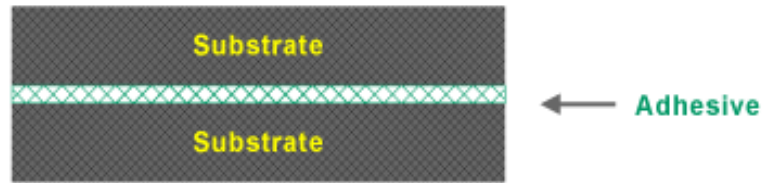


Figure 2-1: Substrate (adherend) and adhesive bonding

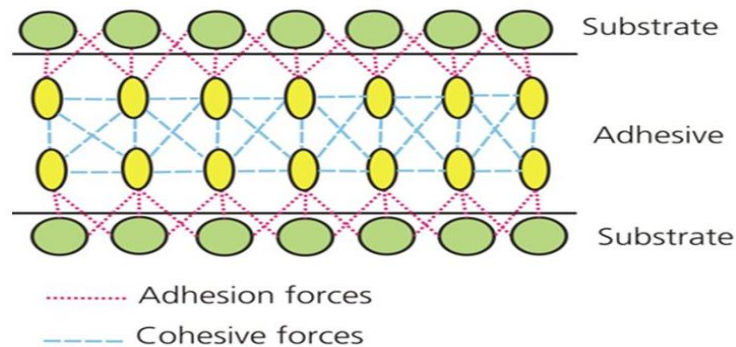


Figure 2-2: Difference between adhesion forces and cohesion forces

Veselovsky and Kestelman (2002) reported that the adhesive contacts the substrate via a layer of substances that frequently differ from the adhesive in composition. If the cohesion strength of these substances is less than that of the adhesive, this will determine the failure stress of the adhesive-bonded joint. Adhesive joint may fail either adhesively or cohesively. The major forces involved in adhesion are adhesive and cohesive forces. Adhesive forces hold two materials together at their surface while cohesive force hold adjacent molecules of a single material together. Adhesive failure is failure at the interface between adherend and the adhesive while cohesive failure is failure within the adhesive or one of the adherends. The function of the joint is more important criterion than the mode of joint failure (Petrie, 2000).

2.1.2 The Function of the Adhesives

The main function of adhesive is for sticking materials together. The other functions of adhesive are for wet the surface (adhesion) and to form cohesively strong solid upon solidification. The joints involved mechanical interlocking and it was this which took the stress imposed during use. Adhesive was added to lock the joint in place, to give it rigidity and to fill gaps. Wake (1982) stated that the modern use of adhesives is very different and involves the direct transfer of major stresses from one body to another through the adhesive. If the function of the adhesive is to transfer stress then it must react to the stress in a controller manner, remaining in a stable configuration. It is convenient at this point to consider the stress applied to the adhesive as comprising four types which are Tension, Compression, Shear and Cleavage or Peel. Any of these stresses can be applied to the body of the adhesive existing between the adherends if the interface between the adherend and adhesive does itself fail.

Adhesion is defined as the adhesive forces acting between the adhesive and the surface of the material. This force comes from the result of mechanical interlocking between adhesive and the material surface roughness which is mechanical adhesion as well as the physical and chemical interaction between the adhesive and the material which is specific adhesion. Bonding between adhesive and substrate is due to a combination of specific and mechanical adhesion. Cohesion is the strength of the adhesive itself, results of the interlocking of the adhesive molecules and mechanical entangling and their physical and chemical affinity for each other.

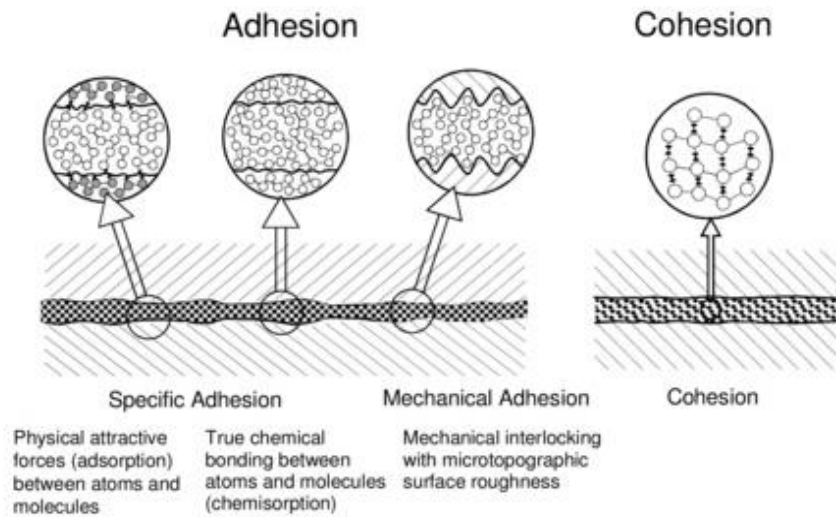


Figure 2-3: Specific and mechanical adhesion (Adhesion strength)

The cohesive strength of an adhesive is determined by a number of molecular forces:

1. The chemical bonds within the polymer molecules.
2. The chemical bonds resulting from the use of crosslinking agent reacting with the polymer molecules within the adhesive.
3. The intermolecular interactions between the polymer molecules within the adhesive.
4. The mechanical adhesion between the polymer molecules within the adhesive.

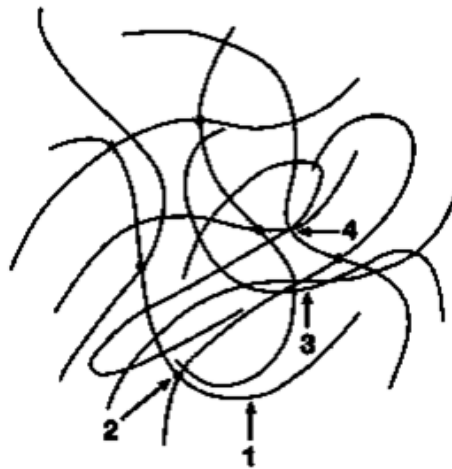


Figure 2-4: Contributions to the cohesion strength of an adhesive

The properties of the non-cured adhesive and determine for example the viscosity of the adhesive effected by all four cohesive forces stated in above. The curing of the adhesive chiefly involves solidification of the adhesive via bonds between the molecules in the adhesive. This involves new bonds being formed for example, long chained molecules formed from crosslinking of short chained molecules) and existing bonds being strengthened.

2.1.3 Bond types in Adhesive Joints

Bond types in adhesive joints basically divided into two major parts which are chemical bonds and intermolecular bonds. According to Skeist (1977), chemical bonds may be either primary or secondary. Primary bonds include electrovalent, covalent and metallic bonds. The intermolecular bonds (secondary valency bonds) act between the adhesive molecules as well as between adhesive and the surfaces on the joining parts and are thus relevant for the cohesion and adhesive strength (**Figure 2-5**).

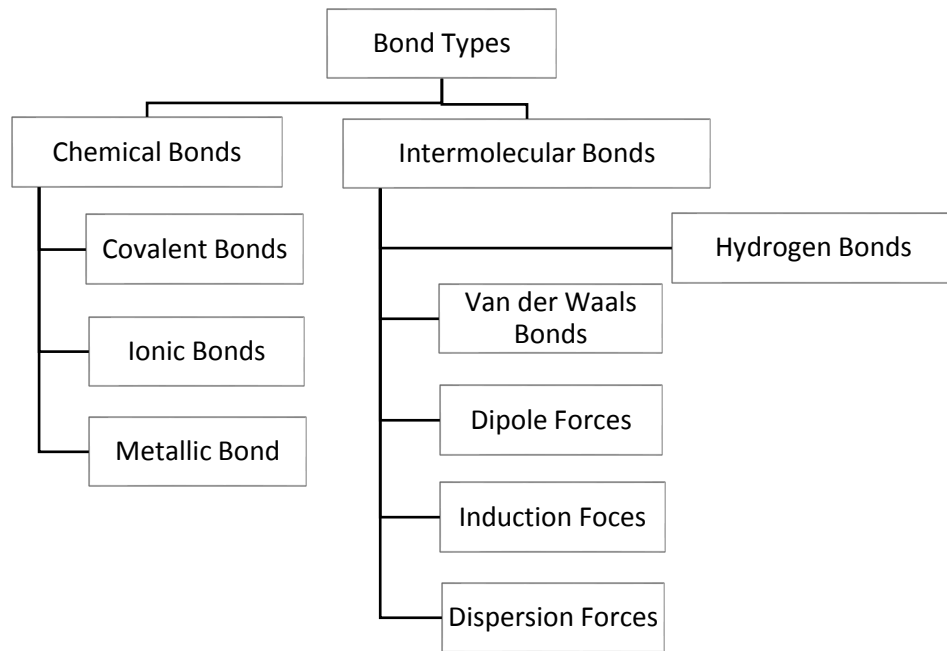


Figure 2-5: Bond types in adhesive joints

Short-range molecular interactions or primary bonds include electrovalent, covalent and metallic bonds. Covalent or homopolar bonds results from chemical reactions such as may play a part in some finishing treatments for fiber glass. Electrovalent or heteropolar or ionic bonds may be a factor in protein adhesives. The metallic bond is formed by welding, soldering and brazing. The most important bond relative to adhesion are the secondary or Van der Waals' bonds that give rise to attraction between molecules. Most significant of these are London or dispersion forces. They are responsible for virtually all the molar cohesion of nonpolar polymers such as natural rubber, SBR, polyethylene and butyl rubber (Skeist, 1977).

Polar molecule groups (dipoles) contain in numerous adhesives which have a strong polarizing action on the metallic joining parts, the latter being non-polar in them. The dipole forces can operate effectively only if these molecule groups can approach to within 0.1mm of the surface of joining parts (**Figure 2-6**). It is only possible if the adhesive can wet the solid surfaces optimally. Skeist (1977) states that interaction of permanent dipoles results in strong bonds, especially if the positive dipole is an H-atom.

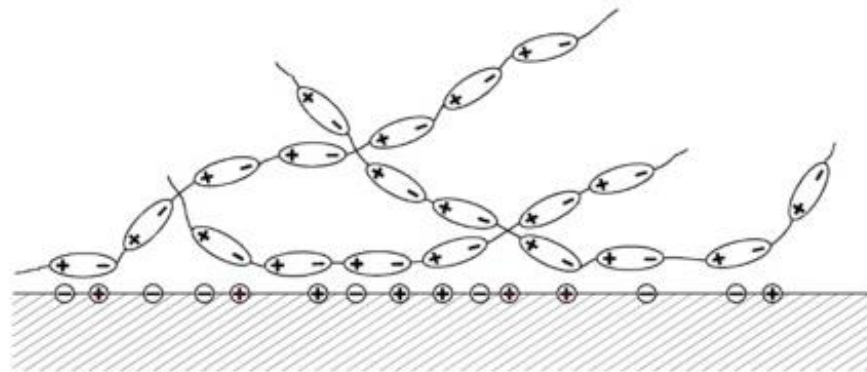


Figure 2-6: Development of adhesion forces due to dipole action between the molecules

Hydrogen bonds are a special form of intermolecular bonds. These are, for example, responsible for the relatively high cohesion strength of PUR and PA adhesives (**Figure 2-7**). Byun and Lee (2017) stated that due to hydrogen bonding between the electron accepting site and the electron donating site in the functional groups, the polymer and solvent molecules can solvate or self-associate. It is well known that such association, especially a solvation such as self- and cross-association, has a remarkable effect on the phase behavior of polymer solutions. Hydrogen bonds also can be formed between adhesives and solid surfaces parts when the latter are oxidized or contain adsorbed hydrogen molecules.

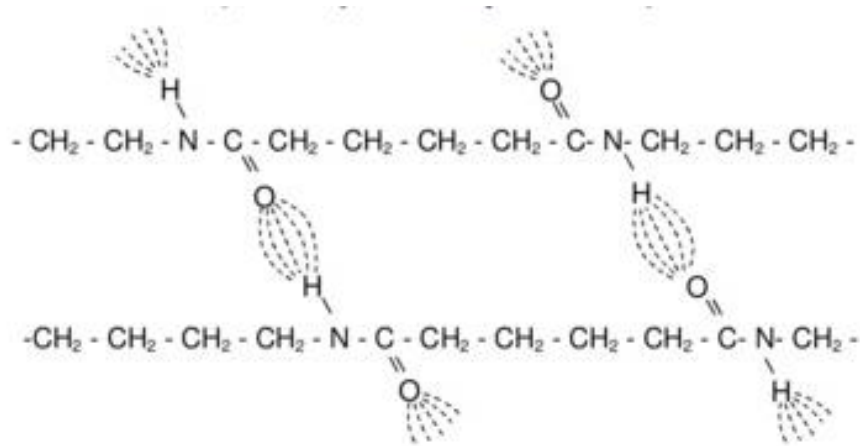


Figure 2-7: Principle of the action of hydrogen bonds (Example: Polyamides)

Table 2-1: Forces at the Interface or Within the Bulk of a Material (Petrie, 2000)

Types of Force	Source of force	Bond Energy (KJ/mol)	Description
Primary or Short-Range Forces	Covalent forces	60-700	Diamond or cross-linked polymers. Highly directional.
	Ionic or electrostatic	600-1000	Crystals. Less directional than covalent.
	Metallic	100-350	Forces in welded joints.
Secondary or Van der Waals Forces	Dispersion	0.1-40	Arise from interactions between temporary dipoles. Accounts for 75-100% of molecular cohesion. Forces fall off as the 6 th power of the distance.

Polar	4-20	Arise from the interactions of permanent dipoles. Decrease with 3 rd power of distance.
Hydrogen bonding	Up to 40	Results from sharing of proton between two atoms possessing loan pairs of electrons. Longer range than most polar and dispersion bonds.

2.1.4 Strength in Adhesive Joints

Adhesive joints are one of composite systems whose strength depends on both the loading type and geometrical design as well as on the schematically illustrated. As in every composite system consisting of different members, the overall strength is limited by weakest member (**Figure 2-8**).

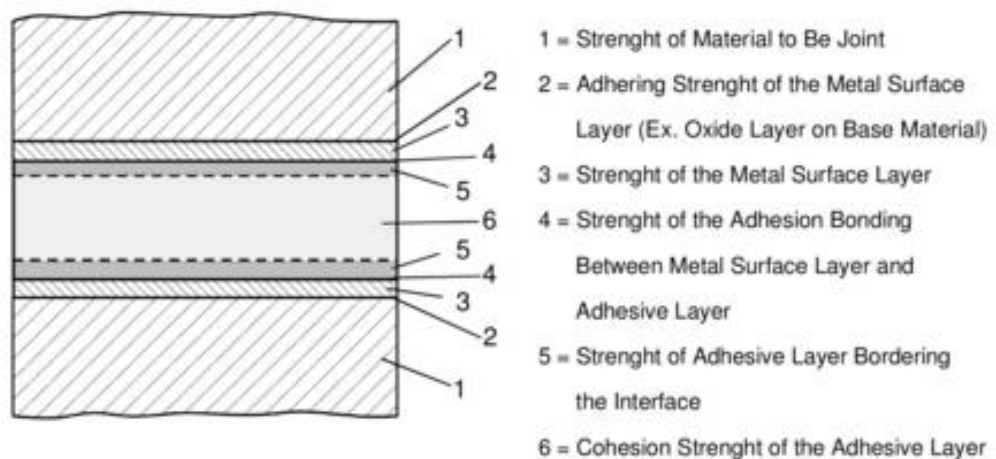


Figure 2-8: Structure of an adhesive joint

2.1.5 Theories of Adhesion and Adhesion Mechanism

Petrie (2000) stated that there is not explicitly of the actual mechanism of adhesive attachment. No single theory explains adhesion in a general, comprehensive way. The most common theories of adhesion are based on adsorption, chemisorption, simple mechanical interlocking, diffusion, electrostatic, interactions and weak-boundary layer. Three main types of theory have been advanced in attempts to explain the formation of adhesive bonds (Pinner and Simpson, 2013):

1. Adhesion arises from physical or possibly chemical, adsorption at the interface
2. Adhesion is due to the inter-diffusion of adhesive and substrate
3. An electrical double layer is formed at the interface and this result in electrostatic attraction between the charges and in adhesion.

However, each theory contains certain concepts and information that are useful in understanding the basic requirements for a good bond. Each of these theories will be considered separately.

2.1.5.1 The Adsorption Theory

According to this theory, the intermolecular attractive forces which are operative over very short distances (of order of 0.3-0.5 mm) are responsible for adhesion. The adsorption theory states that adhesion results from molecular contact between two materials and the surface forces that develop (**Figure 2-9**). Secondary or van der Waals forces usually designated a bond that develops from the adsorption molecules on the substrate and the resulting attractive forces.

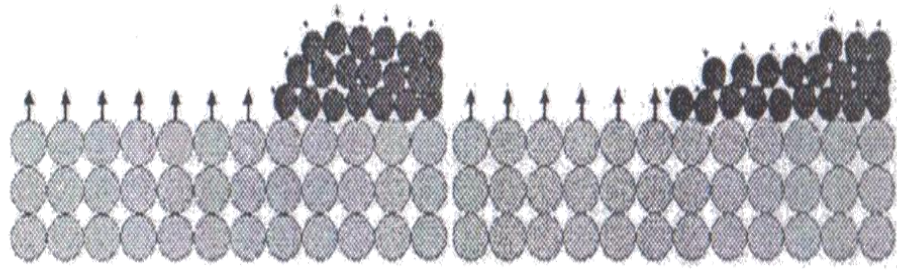


Figure 2-9: Adhesion mechanism of adsorption theory

The process of establishing continuous contact between a liquid adhesive and the substrate surface is known as “wetting”. **Figure 2-10** illustrates good and poor wetting of an adhesive spreading over a surface. The adsorption theory or model explains the phenomenon of adhesion based on concepts such as contact angle, wettability and surface tension. The adhesive capable of wetting the surface, generating a contact angle less than 90° when it has lower surface tension compared to the substrate surface energy, thus generating the adhesion between the adhesive and substrate. Good wetting results when the adhesive flows into the valleys and crevices on the substrate surface while poor wetting results when the adhesive bridges over the valleys formed by these crevices. Poor wetting causes less actual area of contact between the adhesive and adherend and this results in lower overall joint strength (Petrie, 2000).

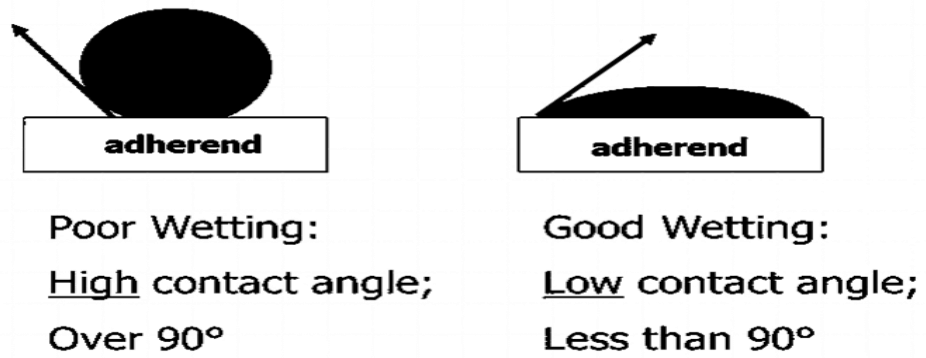


Figure 2-10: Good and Poor Surface Wettability

2.1.5.2 The Chemisorption Theory

The chemisorption theory is an extension of the adsorption theory of adhesion. The adhesive has properly wet the substrate which is the adhesion phenomenon arises when generating chemical bonds between the adhesive and substrate (**Figure 2-11**). Wake (1982) states that chemisorption may occur and is believed by many to occur where adhesion is particularly strong even though, physical adsorption could, in theory, provide for more than the observe strength of adhesive joints.

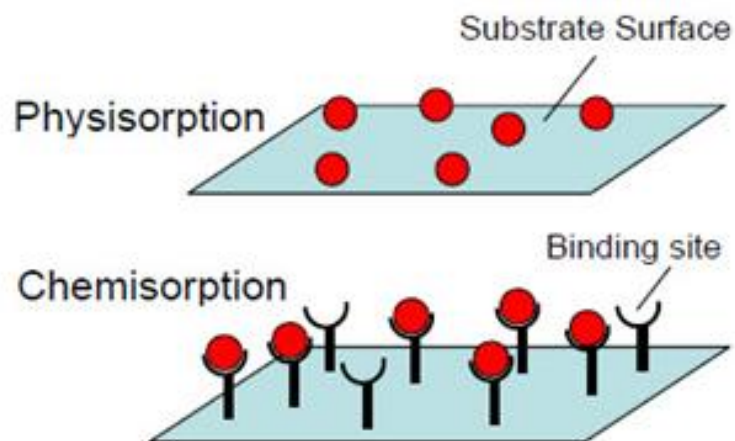


Figure 2-11: Adhesion Mechanism of Physisorption (Physical adsorption) and Chemisorption (Chemical adsorption)

2.1.5.3 The Mechanical Theory

The third adhesion mechanism is mechanical interlocking. The substrate's surface is never truly smooth but consists of a maze of peaks and valleys. In this case, the liquid adhesive penetrates the cavities of a rough or porous adherend; displace the trapped air at the interface and upon solidification the adhesive forms effective "hooks" holding the phases together (Petrie, 2000). It is directly linked to the surface roughness and porosity of the substrate with the degree of adhesion that can be obtained.



Figure 2-12: Adhesion Mechanism of Mechanical Interlocking

According to Petrie (2000), one way that surface roughness aids in adhesion is by increasing the total contact area between the adhesive and the adherend. The increase in the effective surface area can be attributed when the "roughness" of a substrate surface is increased. If interfacial or intermolecular attraction is the basis for adhesion, increasing the actual area of contact will increase the total energy of surface interaction by a proportional amount. This theory also states that joint designs that have large bonding areas are better than joint designs that have smaller area.

2.1.5.4 The Diffusion Theory

The fundamental concept of the diffusion theory is that adhesion arises through the inter-diffusion of molecules in the polymeric adhesives and adherends (**Figure 2-13**) and having compatible long-chain molecules capable of movement. The mobile adhesive molecules (not locked into a tightly cross-linked or crystallized structure) can diffuse into the solid surface, leading to the formation of an interphase of some thickness if there is adequate mutual solubility and adequate contact time between the adhesive and the surface. Pinner and Simpson (2013) suggested that, during the bonding process, inter-diffusion of the adhesive and substrate occurs, leading to the entanglement of the molecular chains of substrate and adhesive and the formation of a diffuse boundary layer in which a gradual change one molecular species to another occurs. The key is that the adhesive and substrate must be chemically compatible in terms of diffusion and miscibility (Petrie, 2000).

Wake (1982) reported that film formation from dried emulsion involves a stage of phase inversion after which the previously disperse phase generally continuous and substantially free of surface active material which itself become disperse phase. At this stage the long chain molecules start a process of inter-diffusion which eliminates the particle boundaries and this stage only occur if the material is above its glass transition temperature. According to Adams (2005), the diffusion theory takes the view that polymers in contact may inter-diffuse, so that the initial boundary is eventually removed. Molecular diffusion is likely also to be important in the combination of films of adhesives above glass transition temperature. Such inter-diffusion will occur only if the polymer chains are mobile (the temperature must be above the glass transition temperature) and compatible. The diffusion theory of adhesion can be applied in only a limited number of cases.



Figure 2-13: Adhesion Mechanism of Diffusion Theory

2.1.5.5 The Weak-Boundary-Layer Theory

The weak boundary layer theory propose that clean surfaces can give strong bond to adhesives, but some contaminants such as oil or greases and dust give a layer which is cohesively weak. It was agreed by Petrie (2000), when bond failure seems to be at interface (**Figure 2-14**); usually a cohesive rupture of a weak boundary layer is the real problem. Weak boundary layers can originate from the adhesive, adherend, the environment, or a combination of any of the three. Adams (2005) stated that not all contaminants will form weak boundary layers, as in some circumstances they will be dissolved by the adhesive. However, in some cases, contaminants such as oils and greases can actually be eliminated by the adhesive dissolving them. If an impurity concentrates near the bonding surface, weak boundary layers can occur on the adhesive or adherend and forms a weak attachment to the substrate. So, when failure occurs, somehow failure may seem to occur at the adhesive-adherend interface, but the reality was shown that it is the weak boundary layer that fails. The most important task before application of the adhesive is to remove the weak boundary layers. The most common material to be removed is atmospheric air (Petrie, 2000).

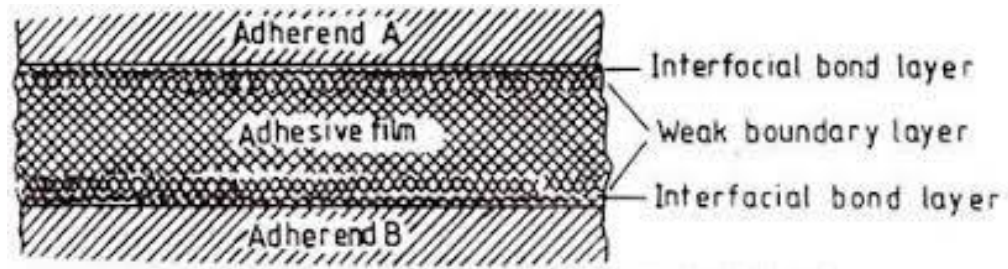


Figure 2-14: Adhesion Mechanism of Weak Boundary Layer Theory

2.1.5.6 The Electrostatic Theory

The electrostatic theory is if two metals are placed in contact, electrons will be transferred from one to the other so forming an electrical double layer, which gives a force of attraction. Electrostatic theory states that electrostatic forces in the form of an electrical double layer are formed at the adhesive and adherend interface (**Figure 2-15**). In fact, electrical discharges have been noticed when an adhesive is peeled from a substrate (Petrie, 2000). Wake (1982) concludes that particle adhesion can result from electrical charges as well as dispersion forces but that when films of adhesive substances adhere to substrates, the electrical phenomena observed when they are peeled otherwise separated do not contribute appreciably to the force required and may even.

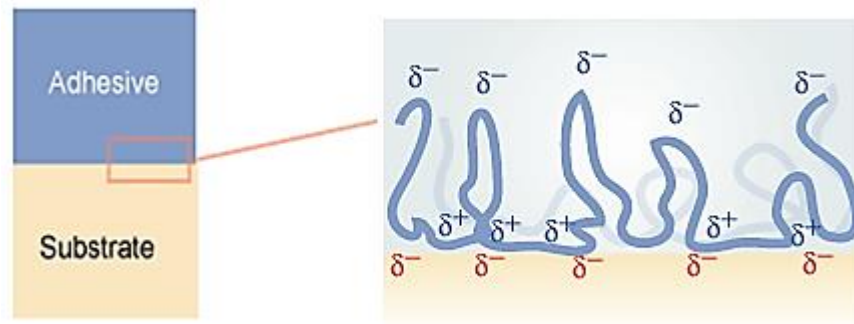


Figure 2-15: Adhesion Mechanism of Electrostatic Theory

2.1.6 Surface Treatment

According to Petrie (2000), the major purpose of surface treatment is to ensure that adhesion develops to the extent that weakest link in the joint is either in adhesive or in the adherend. For optimum adhesion, the surfaces to which any adhesive is applied must be cleaned or converted to a suitable condition before bonding. As a general rule, all adherends must be treated in some manner prior to bonding if not to remove or prevent the formation of weak boundary layers then to provide a constant surface. Shields (1984) stated that, the simplest treatment relies on the cleaning action of abrasive or solvent to remove surface contaminant. Other surface treatments are more involved and tend to increase adhesion such as chemical treatments which modify the surface physically and chemically to increase its specific adhesion properties, whereas mechanical roughening creates a surface which interlocks with the adhesive to provide better mechanical adhesion. Surface treatment can range from simple solvent wiping to a combination of mechanical abrading, chemical cleaning and acid etching.