Mechanical Properties Characterization of Adhesively Bonded T-joint at Elevated Temperature

by

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

T_g	-	Glass transition temperature
$T_{g\infty}$	-	Glass transition temperature fully cured network
${}_{gel}T_g$	-	Gelation glass transition temperature
$T_{g,o}$	-	Initial glass transition temperature
T_{cure}	-	Post-cure temperature
t	-	thickness
p_w	-	Extent of weight loss
w	-	Weight of the samples
w_i	-	Initial weight of the samples
w_f	-	Final weight of the samples
$\sigma_{T-joint}$	-	Critical stress of adhesively bonded T-joint
$\sigma_{adhesive}$	-	Maximum yield stress of adhesive
σ_{FEA}	-	Maximum equivalent (Von-misses) stress in FE model

Abbreviations

FE	-	Finite element
FEM	-	Finite element method
FEA	-	Finite element analysis
TTT	-	Time-temperature transformation isothermal
UTM	-	Universal tensile machine
SEM	-	Scanning electron microscopic
DSC	-	Differential scanning calorimetric
TGA	-	Thermo-gravimetric analysis

DTA - Differential thermo-gravimetric analysis

MPC - Multi point constrains

DIY - Do it yourself

ASTM - American Society for Testing and Materials

Pencirian Sifat-Sifat Mekanikal Hubungan Perekat Sendi-T Pada Suhu Ternaik

ABSTRAK

Satu kajian eksperimen dan analisis tingkah laku mekanikal perekat bersendi-T pada suhu ternaik telah dibentangkan. Analisis awal mewujudkan pembolehubah utama dalam hubungan perekat dan membenarkan satu kajian eksperimen dibangunkan. Kajian analisis perekat bersendi-T dibangunkan untuk meramalkan kekuatan hubungan perekat dan proses menentukan kegagalan mekanisma ke atas pengagihan tegasan sepanjang permukaan sentuh lapisan perekat. Tujuan kajian ini adalah untuk mengenal pasti sifat-sifat mekanikal perekat yang mempunyai rintangan yang baik pada suhu manakala dapat menyediakan kekuatan hubungan yang tinggi terutamanya dalam daya tarikan. Kesan parameter asas penghubung terhadap kekuatan hubungan ditubuhkan daripada eksperimen secara bersiri yang dijalankan pada suhu ternaik. Bersama-sama dengan penilaian sifat-sifat fizikal morfologi struktur perekat dan sokongan kajian terhadap mikro struktur epoksi perekat, maklumat ini juga digunakan sebagai cadangan kepada faktor berlakunya kegagalan perekat. Kekuatan perekat membuktikan mempunyai kaitan ke atas rencana zarah pada tahap suhu yang berbeza. Kekuatan perekat yang tinggi juga didapati apabila menghampiri suhu peralihan kaca pada sembuhan sepenuhnya rangkaian. Di sebalik suhu peralihan kaca pada sembuhan sepenuhnya rangkaian, $T_{g\infty}$ degradasi haba dimulakan pada perekat di mana perubahan sifat fizikal mula berlaku. Dalam hasil eksperimen, 2.0 mm adalah kekuatan berkesan bagi suhu linkungan 55 °C sehingga 100 °C. Selain itu, 1.0 mm dan 1.5 mm didapati mempunyai kekuatan maksima pada suhu bilik dan 35 °C masing-masing. Tekanan tegangan paling maksima, 1.9063MPa yang di dirujuk pada 35 °C bagi semua julat ketebalan garisan perekat. Hujah ini telah disokong pada ciri-ciri fizikal manakala pada keadaan ini, perekat mencapai nilai suhu peralihan kaca pada sembuhan rangkaian sepenuhnya $T_{g\infty}$. Akhirnya, jangkaan hubungan dari pengiraan FEM telah dijalankan. Oleh itu, tanggapan mengenai kegagalan hubungan berlaku di lakukan apabila tekanan Von-Misses diperolehi pada analisis FEM ke atas perekat bersendi-T yang mencapai kekuatan perekat maksima dan dianggap sebagai kekuatan hubungan. Oleh yang demikian, satu hubungan yang ringkas antara sifat-sifat mekanikal sendi perekat, perekat kekuatan pada tahap ketebalan perekat yang berbeza dan peningkatan suhu dipersembahkan. Kekuatan perekat menunjukkan lebih sensitif pada $T_{penjagaan} < T_{g\infty}$. Pada 35 °C, perekat menunjukkan kekuatan tertinggi berbanding pada ke semua ketebalan perekat. Peningkatan suhu sembuhan akan meningkat tahap degradasi haba yang disebabkan oleh perubahan sifat-sifat fizikal dan komposisinya. Oleh itu, kemerosotan kekuatan perekat akan mengurangkan. Penilaian suhu terhadap kekuatan hubungan dibandingkan dari pelbagai suhu bersama nilai kekuatan pada suhu bilik. Pembinaan model finite elemen telah dibina, dipastikan dan ramalan pada perekat bersendi-T-joint tertakluk pada bebanan statik telah dilaksanakan. Keputusan menunjukkan kekuatan sendi dipersembahan dengan elastic-plastik FEM dimana mempunyai kepentingan secara consisten di antara ramalan dan keputusan yang diambil.

Mechanical Properties Characterization of Adhesively Bonded T-Joint at Elevated Temperature

ABSTRACT

Both experimental and analytical studies on mechanical behaviour of adhesive T-joint at elevated temperature are presented. Preliminary analyses established the main variables in adhesive bonding and allowed an experimental study to be developed. The analytical study of adhesive T-joint was developed to predict the adhesive bonding strength and to determine failure mechanism on the stress distribution along interfaces of adhesive layer. The purpose of this study was to identify mechanical properties of adhesive that have good temperature resistance while providing high bond strength to the adhesively-bonded T-joint. The effects of the adhesive thickness and environmental on the bonded strength were established from a series of experiments conducted in elevated temperature. Together with the assessment of physical properties of the adhesive structure morphology and with the supporting studies of the microstructure of epoxy adhesive, this information was also used to propose the adhesive failure factors occurs. The strength of adhesive was related to the cross-linked of particles at different levels of temperatures. The higher strength of adhesive joint also was proposed, in which near glass transition temperature of the fully cured network. Beyond the glass transition temperature of the fully cured-network, $T_{g\infty}$ the thermal degradation initiate on the adhesive whereby the changes of physical properties occurs. In experiment outcomes, 2.0 mm is an effective adhesive thickness of adhesively bonded T-joint for temperature ranging from 55 °C up to 100 °C. Besides that, 1.0 mm and 1.5 mm obtained had optimum strength at room temperature and 35 °C respectively. The highest tensile stress of 1.9063 MPa was obtained at 35 °C would refer to all ranges of bond line thicknesses. This argument has been supported in physical properties, where at this condition; adhesive reached the optimum glass transition temperature of the fully cured network $T_{g\infty}$ value. The joint prediction from FEM calculation was made. It is found that the rupture occurs when the Von-misses stress obtained on the FEM of the T-joint reaches the adhesive strength and concluded to be the joint strength. Therefore, a simple relationship between the mechanical properties of the adhesive joint, adhesive strength at different level of adhesive thickness and thermal conditions was presented. Adhesive strengths shows more sensitive when $T_{cure} < Tg_{\infty}$. At 35°C, adhesive shows the highest strength for all range of adhesive thickness. Increasing cure temperature will increased the thermal degradation level due to the changes of physical properties and its composition. Thus, the degradation will reduce the adhesive strength. The evaluation of the temperature dependence of joint strength by comparing them at various temperatures with the value at room temperature has been accomplished. The development of finite element models, validation and prediction of adhesively bonded T-joint models subjected to static uniaxial loading has been accomplished. The results show the joint strength prediction performed by using elastic-plastic FEM which have significant consistence between the prediction and measured results.

CHAPTER 1

INTRODUCTION

1.1 Overview

In recent times, adhesive bonding has been extensively used in the industry and become important as the other joining techniques (Kah, Suoranta, Martikainen, & Magnus, 2014). Joining techniques for specific applications can be achieved by brazing, flanged, welding and adhesive bonding. Among of the techniques, adhesive bonding has provided many advantages as compared to the other techniques (Thakare & Dhumne, 2015). Besides that, a great design flexibility provided by adhesive bonding and its simple integration found useful as they can be found directly into almost all available manufacturing sequences when it comes to single-piece work. This chapter aims to give a brief introduction of adhesive bonding technology.

1.2 Fundamental of adhesive bonding

Adhesive bonding is a material joining process where an adhesive is placed between the adhered surfaces to make a great adhesive joint. For instance, bonding refers to the crosslink structure of the adhesive, which bonds to the surface on the two adherents to be joined, transferring the forces from one adherent to the other. These physical attractions are mainly due to the interfacial force of the attraction between two materials involving different physical phenomenon, some of those are Van der Waal forces, chemical bonding, mechanical interlocking and electrostatics forces.

1.3 Adhesive bonding as joining technique

According to a spread of adhesive used in the world has been reported by Adams, Lucas, & Andreas, (2011). A statistical graphic in Figure 1.1 shows the market sectors for adhesive bonding used. A projection shows that, the construction and transportation areas are the largest market areas for adhesives. Moreover, the applications involved also include footwear, paper and packaging, retail labelling, woodworking, transport, construction, DIY, electronic/electrical assemble etc. All these applications have metal joining with the exception of the footwear, woodworking and packaging sectors.

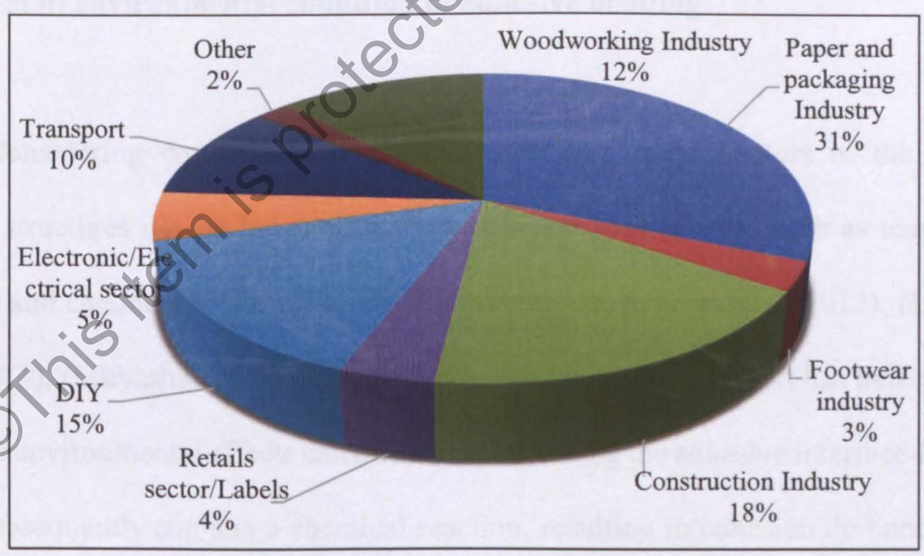


Figure 1.1: Adhesive bonding application

In the automotive industry, there are challenges in maximizing performances while minimizing weight and cost. Adhesive bonding is one of the approaches used to improve the vehicle performance by reducing the weight consequentially in the enhancement of fuel efficiency and high absorption of energy that are offered during crash. Other than that, the effectiveness of adhesive bonding reported as six to eight times safer than a structure built with metals (Divakara H Basavaraju, 2005). Therefore, the adhesive bonding is a safer approach, which always has a main factor in the consideration for automotive sector.

In recent years, adhesive was used in a wide range of temperature exposure such as removing the heat generated in many electronic applications, heat transfer applications, fabrication of heated, plastic forming tools and molds (Sarvar, Whalley, & Conway, 2006). Therefore, various research had been conducted to identify the factors involved in influencing the strength of adhesive with temperatures exposure. However, in adhesive study, some of the enhancement work is focused in several aspects; adhesive-adherent properties, surface preparation, environmental condition etc.

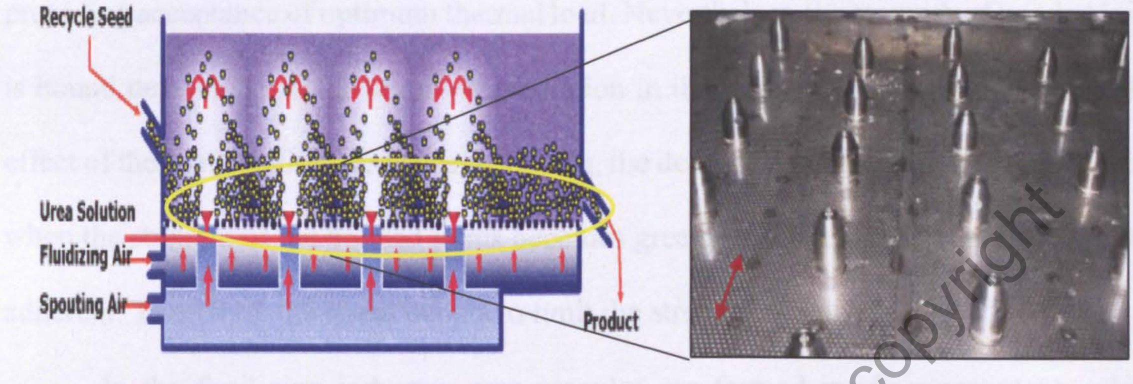
1.4 Effect of environmental condition in adhesive bonding

Considering environmental conditions is one of the factors in the adhesive bonding structures design for environment exposure applications, such as temperature, moisture and chemical solvent (Shokrieh, Torabizadeh, & Fereidoon, 2012); (Loguercio *et al.*, 2011); (Mubashar, Ashcroft, Critchlow, & Crocombe, 2009). It has been observed that these environmental effects can diffuse rapidly along the adhesive interface-adhesion, which subsequently triggers a chemical reaction, resulting in adhesion de-bonding. The study the effect of thermal condition on their mechanical properties (Gan, 1988). They found that the adhesive strength would decrease as the temperature increased. This result was supported by Anderson, (2011) where the thermal degradation of individual epoxy adhesives were found to have an independent behaviour. Thus, the effects of environmental conditions are very important to be considered in the configuration of adhesive joints to give an effect to the adhesive properties.

1.5 Granulator fluidization bed

Temperature is often used in the granules process chamber to control the level of humidity and the mass of granulated formations. Many researchers have investigated the effect of temperature on the size of the granule for sufficient hardness in various applications. (Rostam & Said, 2014) studies the granule size and hardness formed at different levels of heating process from (i.e. 35 °C to 110 °C) of temperature. Similar with the findings operating temperature (i.e. 35 °C to 55 °C) in fluidization bed is directly proportional to the dissolution rated coated of granule, showing the both studies focused on the effect of temperature on the granule formation (Suherman & Anggoro, 2011). Hence, the size differences and hardness of the granule formations is crucial based on the type of the applications and their usage. Eventually, the variation of the thermal condition will affect the mechanical structure in granulator fluidization bed system. Therefore, the study of elevated temperature levels is required for testing the durability of structural support in granulator fluidization bed.

In this study, adhesive is used in joint structures in granulator fluidization bed system as shown in Figure 1.2(a). The joints structure involving two parts of components which are base plate and perforated plate. On the other hand, the frame structure or base plate and thin plate are made of stainless steel that is more resistant to corrosion as compared to other materials. In this study, perforated plate is used to evaporate the feeding of urea solution while producing the urea granules by the spouting air. Therefore, a preliminary research is conducted to find out the possibility the uses of adhesive joint technique in this application. Using the mechanical properties of adhesive T-joint studies is the most significant approach to evaluate the capability of this technique in the real industry cases (Silberschmidt, V.V. and Casas R. J. P., 2008).



(a) (b)

Figure 1.2: (a) Schematic diagram of granulator fluidization system (Toyo Engineering Corporation, 2016) and (b) Actual fluidization bed

In this research, epoxy adhesive are utilized as an alternative approach of joint technique. Adhesive is applied along the perforated plate contact area as compared to a 100 mm gap specified for plug welding as shown in Figure 1.2(b). For instance, applying adhesive in this way will distribute stress load evenly over a long strip rather than concentrated area, hence reducing stress on the joint. Other than that, adhesive bonding is a 'cold joint technique' that will not affect mechanical properties of the perforated plate versus thermal joining such as plug welding.

1.6 Problem statement

The thermal conditions allow an undesirable adhesive strength of the joining. It is possible to determine the bonded strength with mechanical properties of adhesive, i.e. providing acceptance of optimum thermal load. Nevertheless, the strength of bonded joint is bound depending on the stress concentration in the adhesive bonding of T-joint. The effect of thermal condition and tensile loading, the deformation of adherents occur exactly when the strength of the bonded joints becomes greater than the proportional limit of the adherent. Therefore, the stress occurs to limit the strength of joints.

In the fertilizing industry, urea granules are formed inside a granulator while floating on air cushion. Thin stainless steel perforated plate 1.25 mm of 304L Stainless Steel is an essential component of this process, as spot welding is normally used to join perforated plate to its supporting frame with a 100 mm gap specified for plug welding. However, a specific amount of heat and welding rate is required when conducting a plug welding which can cause mechanical damage, i.e. burn through, cracking, porosity and plate distortion. These are some of the drawbacks of plug welding that causes excessive metal melting.

For instance, the adhesive joint technique is normally applied to the flat surface of adherent, as mentioned by Afendi (2011) and Andreas (2007). There is limited study on the adhesively bonded joint involving perforated plate. Even so, there has been a challenge with the application of perforated plate as an adherent. Therefore, it is necessary to develop a study on the perforated plate, where it is contribute to the reducing adhesive durability on the adhesively bonded joint.

In addition, the effects of adhesive strength concerning the variation on geometry (i.e. adhesive thickness) and material properties at elevated temperature are investigated by conducting a parametric study. The analyses are also carried out to determine the failure characteristic of adhesively bonded T-joint. Concerning these problems, this present study aims to numerically investigate the behaviour of adhesively bonded T-joint under axial loading at elevated temperature condition and validated by experimental works. The research objectives and research scopes of this present study are outlined in the subsequent section.

1.7 Research Objective

This research project is primarily conducted to grasp the understanding of the mechanical behaviour of adhesively bonded at T-joint at elevated temperature. The effect of temperature for variation of adhesive thickness and materials parameter together with the adhesive strength under the tensile loading is investigated. The findings obtained from this research project are used to facilitate further the development of joining technique in achieving the lightweight design for joining application. The objective of this study embarks as follows:

i. To examine a series of adhesive thickness of the adhesively bonded T-joint in tension at elevated temperature (i.e. 25 °C (room temperature) to 100 °C).
ii. To evaluate the temperature dependence of joint strength by comparing adhesive properties with the value at room temperature.
iii. To develop finite element models of adhesively bonded T-joint subjected to static uniaxial loading.

1.8 Research scope

In this study, the effects of elevated temperature on the adhesive strength of T-joint concerning the variation on geometry in terms of bondline thickness are investigated in parametric studies. These parameters vary between 0.5 mm to 2.0 mm, room temperature to 100 °C for adhesive thickness and testing temperature, respectively. The materials of stainless steel 304L and Araldite Standard epoxy adhesive are assessed at various thickness at elevated temperature. The material selected for adherent selected is based on the study cases application of real structural joining in fluidization bed.

Several test specimens made from actual perforated plate are used to simulate the real structure of fluidization bed equipment. The experiment is conducted on a T-joint specimen and bulk specimen subjected to uniaxial tension loading using Universal Tensile Machine (UTM). Uniaxial of static tests, performed on adhesive bulk specimens in order to define accurately the constitutive behaviour in the FE models.

Besides that, the finite element model of adhesively bonded T-joint with different bondline thicknesses at elevated temperature are evaluated and validated with experimental results. Finite element (FE) analysis software, ANSYS 14.5 is used to analyse the stress on the adhesive bondline of the T-joint model.

In general, this report can be categorized into three main sections:

i. Parametric study concerning the variance in geometries (i.e. adhesive thickness), physical and mechanical properties of adhesive at elevated temperature conditions. The developed experiments test for four different thicknesses (i.e. 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm).

ii. The experimental tests under tension loading on T-joint specimen and bulk specimen at elevated temperature by using ASTM 638 and ASTM D1002-10.

iii. The development of Finite element (FE) modelling, analysis of validation and prediction.

1.9 Thesis outlines

This thesis comprise of five chapters. Chapter 1 discuss of the overview of the introduction of the fundamental of adhesive joining and research project involving problem statement and objectives and scope of research.

Chapter 2 describes a details review of the literature. To begin with, the mechanics of tensile loading and mechanical behaviour of adhesive are addressed. Following this, the adhesive strength and the effect of geometry are also discussed. These details comprise of studies that have been conducted previously analytically and experimentally.

Chapter 3 describes the development of experiments for bulk and adhesively bonded T-joint specimen. The methodology for model development and simulation under tensile loading at elevated temperature is proposed. For validation of the experimental conducted, a series of model developed is also summarized in the chapter and the comparison between the FE and experimental result are then discussed. Next, further evaluation of the correlation between the experiment and results and the FE model, value of tensile strength, and the deformation are assessed, followed by the validated FE model that is used to treat the parametric studies of adhesive thickness at elevated temperature condition under tensile loading analyses.

Chapter 4 explains the experimental results obtained from the parametric studies that have been conducted under tensile loading. The relative effect of the parametric studied on the adhesive strength under tensile loading is described. Based on the critical stress on the adhesive layer, the effectiveness of adhesive thickness and operating temperature is evaluated based on adhesive strength, and a suitable parametric combination is used to demonstrate the effectiveness of adhesively bonded of T-joint proposed.

Chapter 5 summarizes the main findings and recommendations for future works. It was suggested that this study contribute for new knowledge and further improvement of the structural adhesive T-joint for application.