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Thermal Effects on the Mechanical Performance of Adhesively Bonded T-Joints for Structural Applications to Support Sustainable Development Goals (SDGs)

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ABSTRACT

This study investigates the thermal effects on the mechanical performance of adhesively bonded T-joints, with a focus on optimizing bond strength under elevated temperatures. Using tensile testing, four adhesive thicknesses (0.5, 1.0, 1.5, and 2.0 mm) were examined across five temperatures (room temperature to 100°C). Results reveal that tensile strength peaked at 35°C, aligning with the adhesive's glass transition temperature (Tg), with 1.5 mm thickness yielding optimal performance. Thicker bonds (2.0 mm) exhibited superior strength at higher temperatures (55–100°C), while thinner bonds performed best at lower temperatures. Differential Scanning Calorimetry and SEM analyses confirmed thermal degradation and morphological changes as key factors influencing strength. These findings highlight the relationship between adhesive thickness, thermal exposure, and structural integrity, providing critical insights for the aerospace and automotive industries. The study aligns with SDG 9 (Industry, Innovation, and Infrastructure) by supporting durable design practices and contributes to the bibliometric discourse on epoxy-based adhesive technologies under thermal stress.

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1. INTRODUCTION

Adhesive bonding has gained substantial attention across engineering industries due to its capacity to deliver high durability under both static and dynamic loading conditions. This technique supports lightweight structural design by ensuring homogeneous stress distribution, making it particularly advantageous for aerospace and automotive applications (Guofeng *et al*., 2023). Moreover, adhesive bonding avoids the mechanical damage typically associated with conventional fastening methods. However, its long-term durability remains uncertain, especially under environmental factors such as moisture, temperature fluctuations, and thermal aging (Xu *et al*., 2004; Budhe *et al*., 2017). Bonded joints often fail suddenly rather than progressively, which poses challenges for structural integrity assessment and predictive design.

T-joint configurations, particularly those involving perforated plates, are widely used in automotive and industrial applications due to their ability to reduce weight and enhance performance (Xing *et al*., 2011). Perforated plates offer functional benefits in filtration, separation, and thermal management, as well as sound insulation in exhaust systems and aircraft structures (Ji & Zhao, 2014; Ozalp *et al*., 2003; Blanco *et al*., 2014). The design allows precise control over open area, promoting material efficiency without compromising mechanical strength. Despite their widespread application, predicting joint strength in these configurations remains complex due to the influence of multiple variables such as adhesive properties, joint geometry, bonding technique, and environmental exposure.

Adhesively bonded joints are often exposed to elevated temperatures in practical settings, such as in electronic packaging, heat transfer devices, and forming tools (Budhe *et al*., 2017). While previous research has identified several factors affecting adhesive performance under heat, further investigation is needed into critical parameters such as adhesive–adherent interactions, surface preparation, and environmental degradation.

Elevated temperatures are known to cause degradation in epoxy adhesives, leading to reduced failure stress and changes in failure modes (Berthe *et al*., 2014; Anderson, 2011; Torabizadeh, 2013). Studies on sandwich T-joints under pull-off loading have shown that increased temperature accelerates adhesive degradation and adversely affects joint strength, particularly as the adhesive thickness varies (Nguyen *et al*., 2012). Thermal conditions also influence the elastic and plastic behavior of epoxy polymers, which are highly sensitive near the glass transition temperature (Tg) (He, 2011; Reis *et al*., 2015). The failure of adhesively bonded joints under thermal loading has been attributed to thermos-oxidative degradation, thermal stress due to mismatched coefficients of thermal expansion, and altered stress distributions (Petrova *et al*., 2007). Variations in mechanical properties, such as Young's modulus and Poisson's ratio under heat, play a significant role in these changes, and studies have demonstrated that the adhesive modulus tends to decrease as Tg is approached (Carbas *et al*., 2014).

The failure behavior of T-joints with different joining techniques has also been investigated, revealing that stress tends to concentrate in the horizontal section of the joint. Variations in joining methods (such as the use of gussets or angle reinforcements) have led to significantly different failure modes and strengths (Lopes *et al*., 2019). However, these findings are mostly empirical and may not be directly applicable to adhesively bonded T-joints with perforated adherends.

The long-term performance of adhesively bonded joints, especially under thermal conditions, remains insufficiently understood. In particular, the relationship between adhesive properties (such as modulus and Tg) and the stress distribution under thermal

loading has not been comprehensively analyzed, making it difficult to predict joint strength accurately.

This study aims to evaluate the mechanical performance of adhesively bonded T-joints under elevated temperatures, focusing on four adhesive thicknesses (0.5, 1.0, 1.5, and 2.0 mm). Tensile tests were conducted across temperatures ranging from room temperature to 100°C to explore the relationship between thermal conditions, adhesive thickness, and mechanical strength. The novelty of this work lies in its application of perforated adherends and its integration of thermal, morphological, and mechanical analyses to develop optimized joint designs. The findings are expected to support design improvements in aerospace and automotive applications, where high-strength, thermally stable adhesive joints are critical. This study supports Sustainable Development Goals (SDGs), especially SDG9 (Industry, Innovation and Infrastructure), by addressing the need for thermally reliable and structurally optimized adhesive joints in engineering applications. The integration of advanced bonding techniques contributes to the innovation of lightweight, energy-efficient components in industrial sectors such as automotive and aerospace.

2. METHODS

2.1. Materials and Sample Preparation

Proper surface treatment is essential for achieving optimal adhesive joint performance. In this study, the adherend surfaces were cleaned with acetone to remove all traces of oil and dirt before bonding with the epoxy adhesive. The joint assembly consisted of a stainless steel 304 base plate and a stainless-steel perforated plate, as presented in **Figure 1**. Two types of plates were used: the base plate (**Figure 1a**) and the perforated plate (**Figure 1b**).

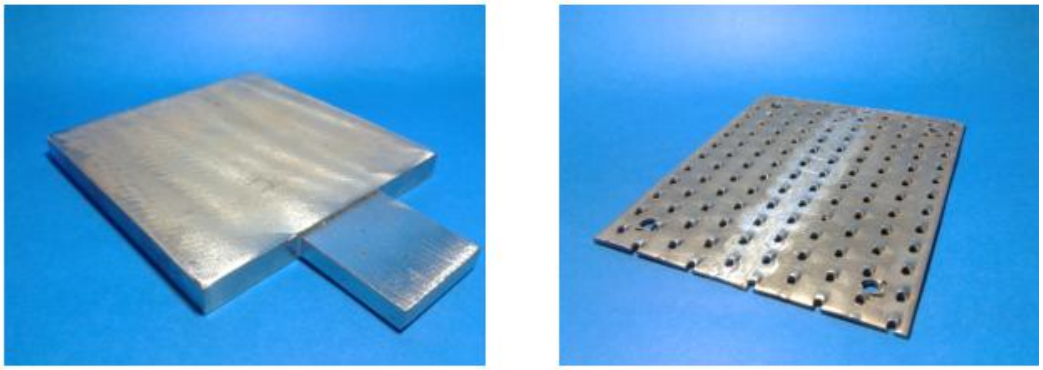


Figure 1. Image of plates: (a) Stainless steel base plate and (b) Stainless steel perforated plate.

A multipurpose epoxy adhesive (Araldite Standard) manufactured by Huntsman Advanced Materials was used. This adhesive is a two-component system comprising resin and hardener. The components were hand-mixed for 10 minutes. After application to the adherends, the joint was cured at room temperature for 18 hours. The adhesive thicknesses (0.5, 1.0, 1.5, and 2.0 mm) were selected based on common industrial practices to ensure relevance to real-world automotive and aerospace applications.

2.2. Experimental Procedure

A 5 mg sample of the epoxy adhesive was prepared for Differential Scanning Calorimetry (DSC) analysis. Each sample was pre-cured for 24 hours under laboratory conditions (T = 25 ±

3°C; RH = 50 ± 5%), then post-cured at varying temperatures. A non-isothermal scan was conducted from room temperature to 300°C at a heating rate of 10°C/min in a nitrogen atmosphere with a purge rate of 50 ml/min. The glass transition temperature (Tg) of each specimen was determined from the scan.

For Thermogravimetric Analysis (TGA), five samples of 10 mg each were prepared under the same conditions as the DSC samples. The TGA was performed in a nitrogen atmosphere, with the temperature scanned from 25 to 700°C at a rate of 10°C/min. TGA was used to observe weight changes in relation to time and temperature.

Additionally, five samples were prepared for Differential Thermal Analysis (DTA), each weighing 10 mg. DTA was used to measure the temperature difference (ΔT) between the sample and a reference material. The resulting curves provided insights into endothermic and exothermic processes, particularly those associated with melting and phase transitions.

Scanning Electron Microscopy (SEM) was employed to analyze the surface morphology of the adhesive under different thermal conditions. A HITACHI TM3000 SEM was used after sputter-coating the samples with platinum. Adhesive samples cured at various temperatures were examined to observe microstructural changes before and after thermal exposure.

2.3. Fabrication of Bulk and T-Joint Specimens

A mold was fabricated to produce standardized bulk specimens according to ASTM D638 dimensions. **Figure 2a** shows the schematic of the mold, while **Figure 2b** displays the setup with a clip-on extensometer used to measure longitudinal strain. The extensometer had a gauge length of 50 mm with a minimum accuracy of ±0.5%.

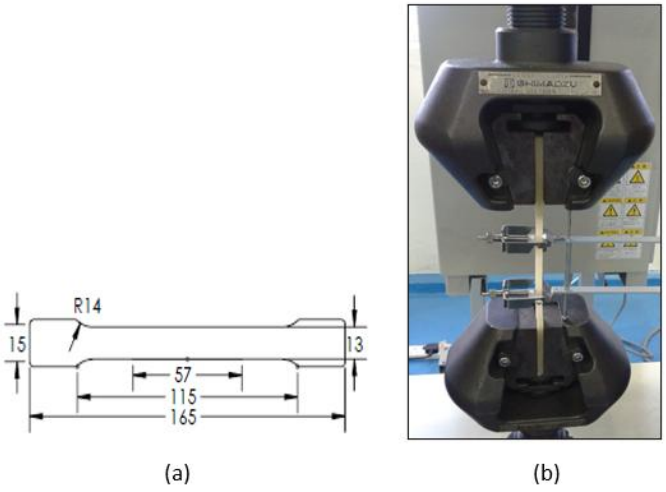


Figure 2. (a) Dimensions of tensile test specimen and (b) Clip-on extensometer

The bulk specimens were pre-cured for 18 hours under ambient conditions (T ≈ 27°C; RH ≈ 50%). Post-curing was then conducted at various temperatures (room temperature, 35, 55, 75, and 100°C) for 30 minutes to evaluate the effect of cure temperature on mechanical properties. These temperature levels were selected to reflect realistic service conditions and to assess performance near and beyond Tg. **Figure 3** presents the pre- and post-curing process.

Tensile testing was conducted using a universal testing machine (UTM), with loading applied longitudinally at a constant rate of 1 mm/min, as specified in ASTM D1002-10. For each temperature and thickness condition, five specimens were tested, excluding any with visual defects or tab failures.

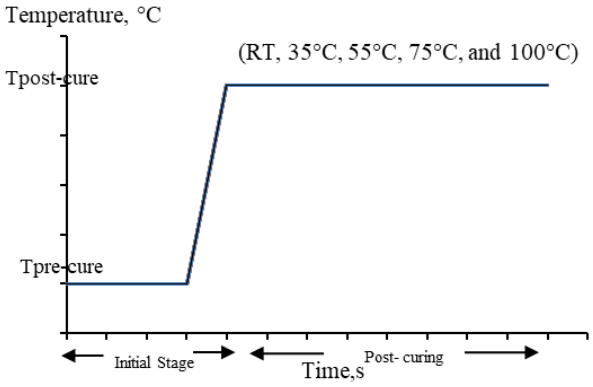


Figure 3. Curing process of the adhesive.

2.4. T-Joint Specimen Fabrication and Testing

The adhesive T-joint was prepared for tensile testing, as shown in **Figure 4**. A customized jig was developed to align the base and perforated plates precisely and to control adhesive thickness during the bonding process. **Figure 5a** presents the schematic of the fixture, and **Figure 5b** shows the assembled Teflon jig. The adjustable Teflon spacer ensured consistent adhesive thickness (t) across all specimens.

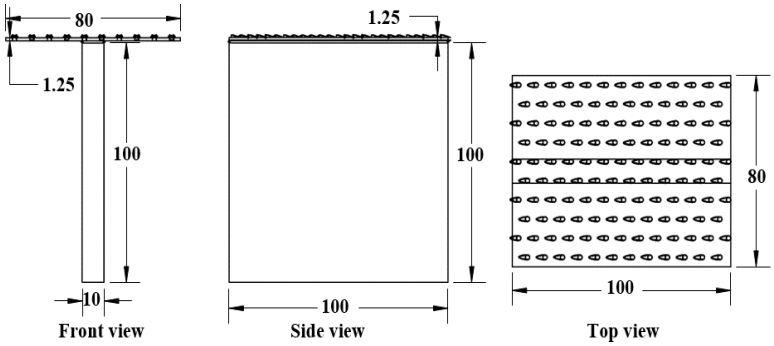


Figure 4. Dimension for T-joint specimen.

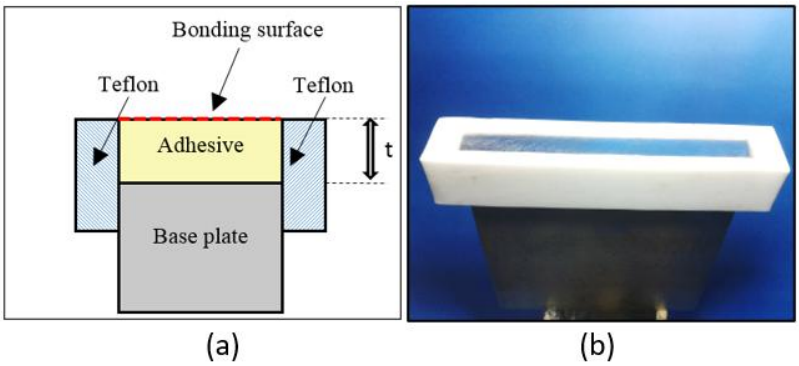
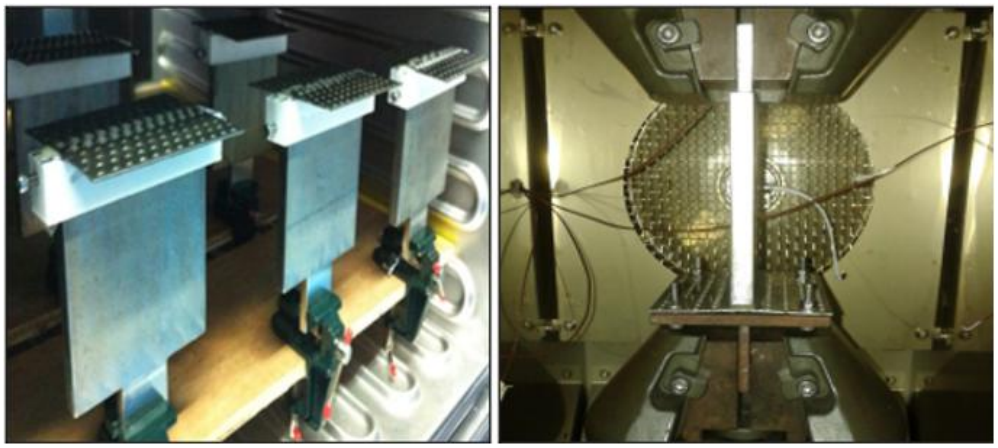


Figure 5. (a) Schematic of fixture and (b) Assembled Teflon jig.

The T-joint specimens were pre-cured in a furnace at 27°C for 18 hours, as shown in **Figure 6a**. They were then post-cured within Teflon molds at different adhesive thicknesses (**Figure 6b**). To address any potential misalignment between the base and wide plates, a T-shaped jig was mounted on the UTM for testing. Environmental temperature was controlled during testing using a thermostatic chamber, and thermocouples were used to monitor temperature at the adhesive layer and the surrounding area.



(a) (b)

Figure 6. (a) Pre-cure of adhesive T-joint in furnace and (b) Tensile test in thermostatic chamber.

The tensile test was performed by moving the base plate upward after thermal equilibrium was reached. The average failure stress was calculated based on five specimens for each adhesive thickness (0.5, 1.0, 1.5, and 2.0 mm). This range of thicknesses was chosen to align with industrial applications and design requirements. The test adhered to ASTM D1002-10 standards, with a loading rate of 1 mm/min.

3. RESULTS AND DISCUSSION

3.1. Physical Investigation

This section represents the effect of the thermal condition on the physical properties of the epoxy adhesive. This study aims to enhance the comprehension of the influence of curing temperature on the glass transition temperature, Tg, and adhesive stiffness. There are two stages of the curing process, which are the pre-curing and post-curing processes. The beginning stage, pre-curing process, where the same conditions were applied to all test specimens, while post-curing temperature was uniformly performed at elevated temperature (i.e., room temperature, 35, 55, 75, and 100°C) until completely cured.

3.1.1. Differential Scanning Calorimetric (DSC)

Figure 7 represents the results of the DSC test for epoxy adhesive at room temperature. Based on the plot, thermal degradation of the adhesive passes through three stages, which are separated by temperature range: 30°C-100°C, 100°C-200°C, and 200°C-300°C. The beginning stage represents the glass transition temperature range, rather than occurring at a specific temperature, due to a linked polymer chain that has multiple degrees of freedom in response to the applied thermal energy. In other words, it shows the compatibility of epoxy adhesive to start yielding during heating and undergoes its transformation to a soft and rubbery phase. The second stage refers to the crystalline phase, where the fraction of the epoxy adhesive becomes smaller. The last stage is the melting temperature range at which the adhesive epoxy starts to melt and decay at diverse temperatures. **Table 1** and **Figure 8** show the relationship between the post-cured temperature and the glass transition temperature. From the results, 47.3˚C is a high value of glass transition of all temperature ranges and is known as the glass transition temperature of the fully cured network, Tg_{∞}. If the curing temperature approaches the glass transition temperature of the fully cured network Tg_{∞}, Tg gradually increases. If the curing temperature is beyond the glass transition

temperature of the fully cured network Tg∞, Tg slowly decreases. The increase of adhesive strength until it achieves the maximum glass transition temperature for the entire temperature range.

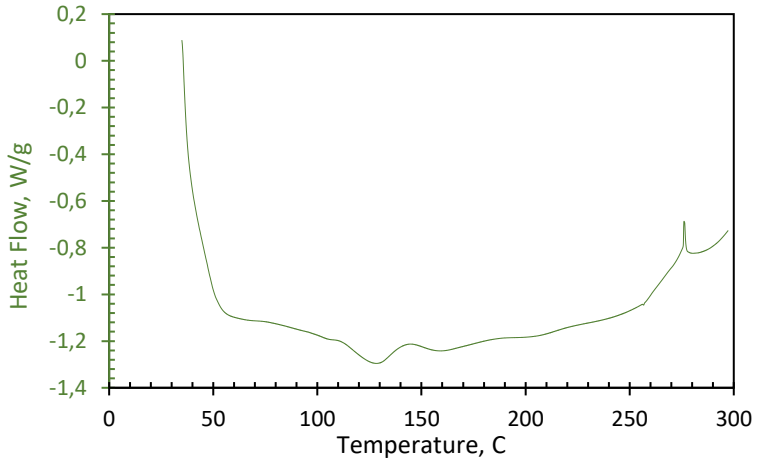


Figure 7. Differential Scanning Calorimetry (DSC) for epoxy adhesive.

Table 1. Relationship between Post-cure Temperature and Glass Transition Temperature

	Post-Cure Temperature (Tcure), °C	Glass Transition Temperature (Tg), °C
Epoxy	Room Temperature	45.0
adhesive	35	47.3
(Araldite	55	43.8
Standard)	75	42.7
	100	42.1

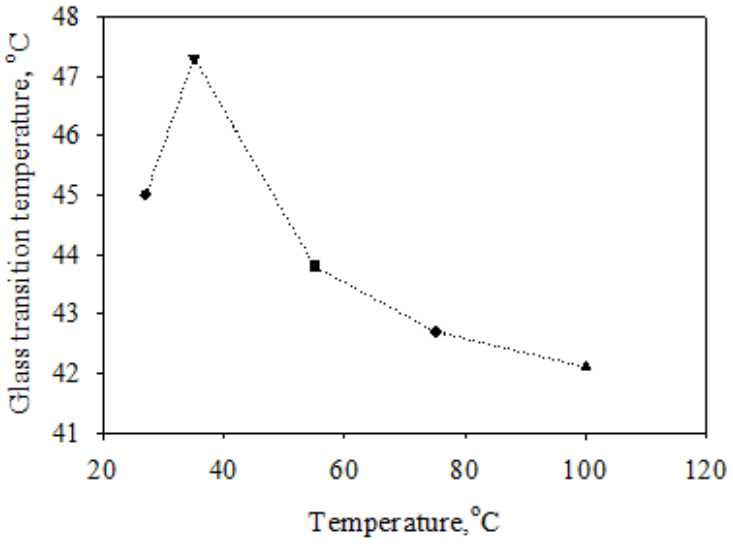


Figure 8. Measured Tg vs. Cured Temperature.

The output parameters of the adhesive properties and the Tg were obtained with the corresponding post-curing temperature. From the results, the adhesive strength is proposed to be increased as the Tg value obtained is higher than the post-curing temperature. Besides that, cured adhesive above Tg∞ can show thermal degradation and can alter the adhesive behaviour.

3.1.2. Thermo-gravimetric (TGA) and Differential Thermo-gravimetric Analysis (DTA)

TGA analyses were performed to examine the thermal decomposition of the epoxy adhesive. Generally, the matrix of decomposition of material should be specified chemically as the difference in mass residue in the thermal decomposition. The normalized extent of weight loss as a function of time is shown in **Figure 9**. The percentage of weight loss, p_w, is defined as (see equation (1)).

$$p_w = (w_i - w)/(w_i - w_f) \quad (1)$$

where w is the weight of the samples, w_i is the initial weight, and w_f is the final weight. The percentage of weight loss is normally used as a measure of the extent of degradation. The plotted curve shows a few stages of degradation for the epoxy adhesive. The mass loss rapidly drops between 350 and 500°C, and a small additional mass loss of approximately 2-3% between 500 and 700°C. The TGA suggests that decomposition temperature is about 276.12˚C. According to the analysis, it can be stated that 276.12˚C is the crystallization temperature of epoxy adhesive. At this point, the weight of the sample is 9.366 mg, which was about 5-10% of the initial weight. Adhesive strength and TGA measurement show that weight loss and adhesion loss due to chemical bonding degradation over the temperature range (Anderson, 2011).

The epoxy adhesive undergoes thermal degradation beginning at 380.31˚C with a mass loss of 73.07% of the total mass. At this stage, the adhesive undergoes moisture vaporization. The degradation of the adhesive is determined after a gradual drop in weight loss during the test. At 444.05 ˚C, the weight of the epoxy adhesive is approximately 33.02% of the initial weight at the lowest peak of differential weight in the DTA test, which is shown as the melting point of the epoxy adhesive. After the melting point, the sample exhibits endothermic behavior as it absorbs heat and regains its way to the maximum peak level. There is a small amount of inert residue remaining of 5.872%.

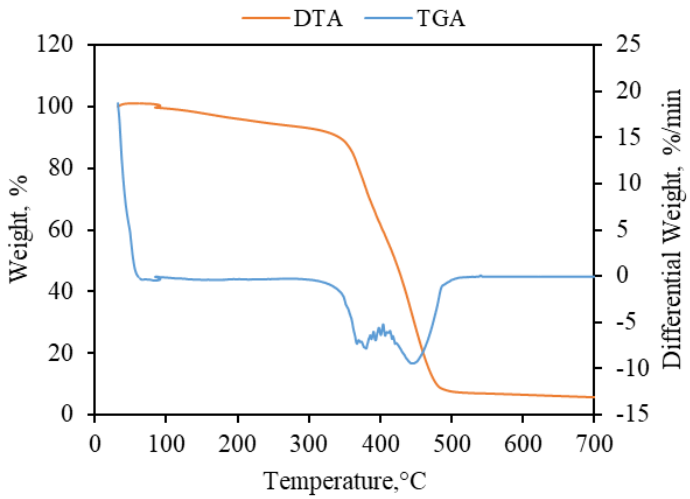


Figure 9. Differential thermal analysis.

3.1.3. Scanning Electron Microscope (SEM)

The effects of thermal exposure on the microscopic structure of adhesive samples are presented. Scanning electron microscopy offers an effective tool in determining the morphology of carbon-based and low-conductivity samples, such as adhesive surfaces. **Figure 10** depicts the area before and after thermal exposure at room temperature, showing minimal

changes in the surface morphology. In contrast, **Figure 11** shows the scanned area before and after heating to 35˚C. The pre-heating image clearly reveals the presence of tackier resin particles, which appear as distinct bumps in the topological image. These particles are differentiated as distinct features in the scanned area. Upon heating, the degree of cross-linking in the epoxy structure increases, leading to noticeable changes in the adhesive morphology. The individual adhesive particles become smaller, as observed in the post-heating images. After thermal exposure, the scanned area shows a loss of resolution in distinguishing the particle edges, indicating significant changes in the adhesive's microscopic structure.

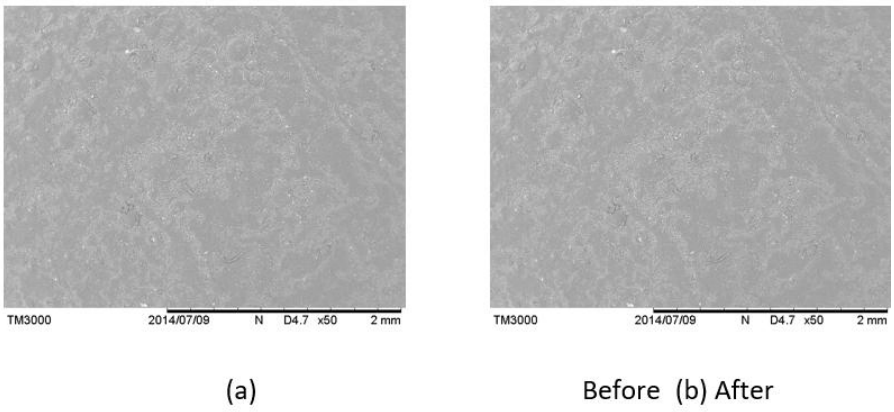


Figure 10. Phase image of adhesive before (a) and after (b) exposure at room temperature.

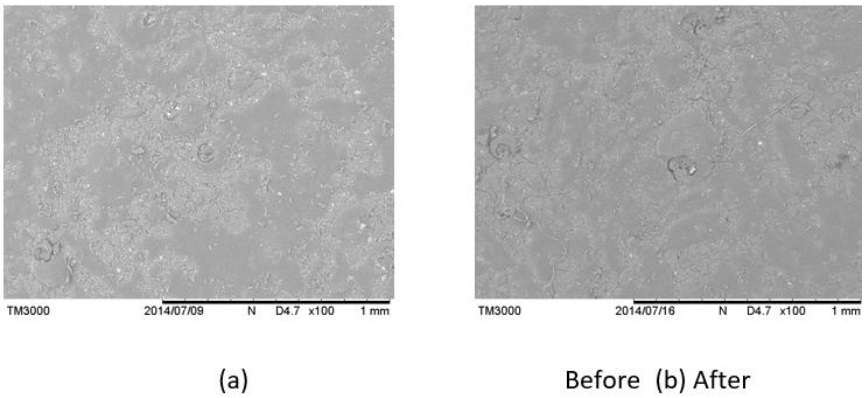


Figure 11. Phase image of adhesive before (a) and after (b) exposure to 35˚C.

Figures 12 and 13 show the effects of thermal exposure on the adhesive surface. Upon heating, the individual tackier resin phase appears to diminish and fade. This suggests that the diminished tackier resin dissolves into the modifier, creating voids where the particles were previously located. The thermal effect and the dissolution of the modifier in the epoxy can be correlated with the composition of the adhesive epoxy (Zhang *et al*., 2023a). The partial dissolution leads to a reduction in the size of the tackier resin particles, which eventually disappear completely.

Recent studies also support the observation that the adhesive surface becomes smoother as the temperature increases. For instance, a previous study on the effects of temperature on epoxy resin with modifiers demonstrates a similar phenomenon, where the surface smoothness improves with thermal exposure (Zhang *et al*., 2023b). This study further confirms that optimizing the level of tackier resin in the adhesive enhances its overall strength.

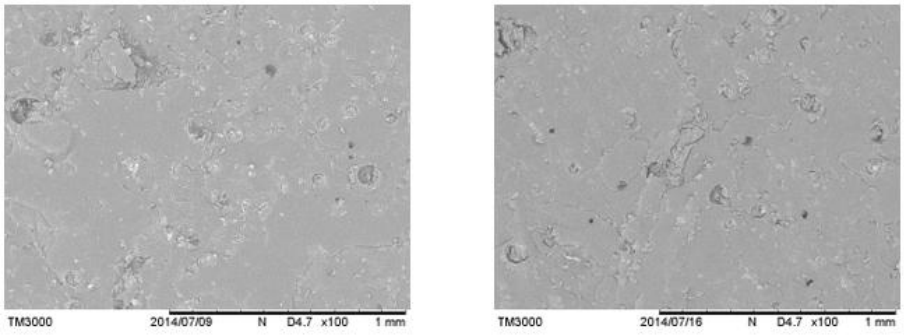


Figure. 12. Phase image of adhesive before (a) and after (b) exposure to 55˚C.

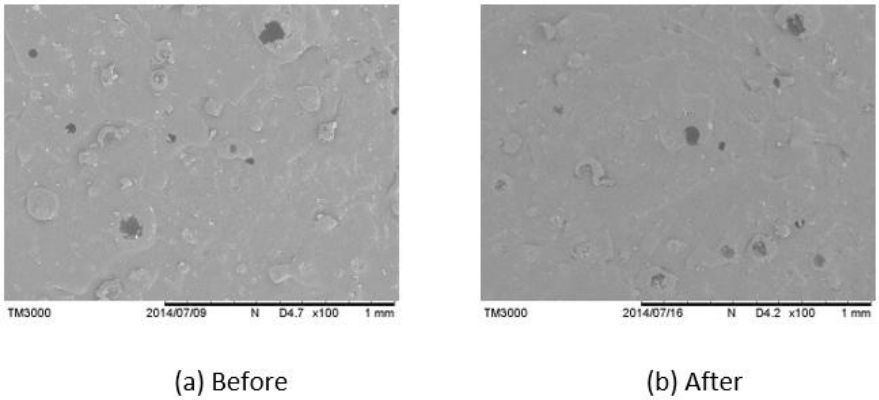


Figure 13. Phase image of adhesive before (a) and after (b) exposure to 75˚C.

Figure 14 shows a micrograph of the adhesive before and after exposure to 100˚C. The individual tackier resin phase seemed to completely dissolve, and evidence in **Figure 15** shows that a microcrack formed on the adhesive surface. Therefore, thermal conditions have a significant effect on the composition of the adhesive. At this stage, the adhesive experiences extremely thermal exposure.

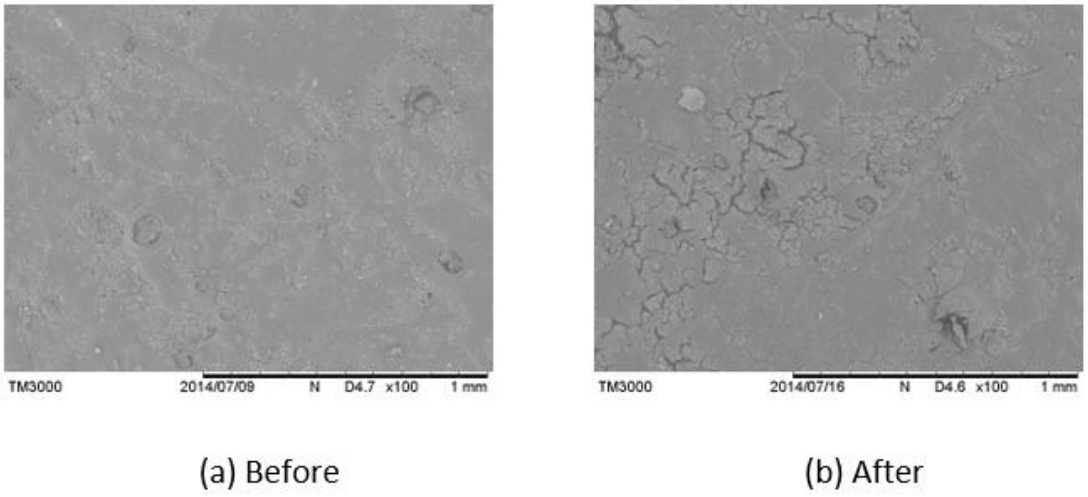


Figure 14. Phase image of adhesive before (a) and after (b) exposure to 100˚C.

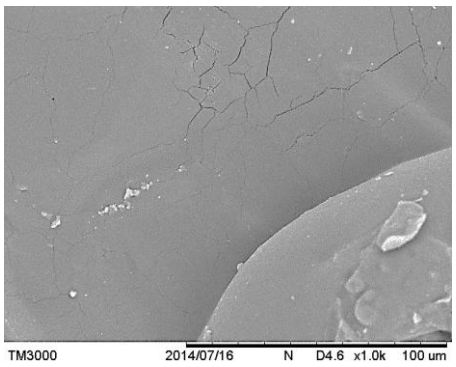


Figure 15. Enlarge the phase image of the adhesive.

3.2. Mechanical Investigation

Mechanical properties of the bulk adhesive at elevated temperature (i.e., room temperature, 35, 55, 75, and 100°C) were determined from the stress-strain graph as shown in **Figure 16**. From the results, room temperature has recorded the optimum failure stress compared to other temperatures (i.e., 35, 55, 75, and 100°C). In general, it is noted that the tensile strength decreases with the increase in temperature. At room temperature, the highest value of stress was obtained due to the adhesive possessing brittle and linear elastic behaviours. Instead, when temperatures of 35 and 55°C were applied, the adhesive slowly changed to become ductile and exhibited non-linear viscoelastic behaviours. In contrast to 75 and 100°C temperatures, the adhesive shows its visco-plastic and elastic behaviour, respectively.

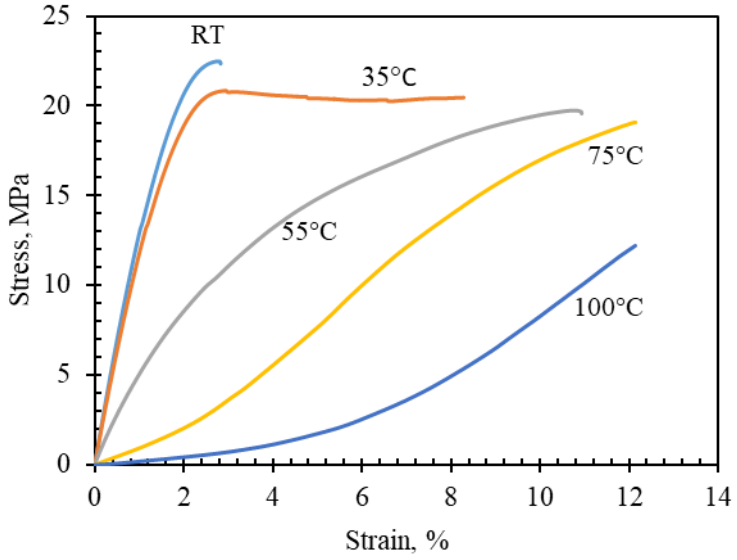


Figure 16. The stress against displacement of the bulk specimen at elevated temperature.

In addition, the percentage of strain at elevated temperature was examined. The results indicate that the percentage of strain increase corresponds to the stress applied to the adhesive. The percentage of elongation increased due to changes in adhesive behaviours from brittle, ductile, to elastic behaviour, eventually experiencing elongation before it fails. Thus, the observations were made on the failure, and the result shows that the failure often occurs between the gage length of the adhesive specimen due to the

high stress concentration region. The highest elongation at 100°C obtained because of adhesive behaviour was completely changed to elastic. The results show that the elastic region for adhesive at 100°C, as a function of polymer type, could not be linear, and it was difficult to determine the value of the stress equivalent to the start of yielding. However, an exact position has been proposed for the yield point as the maximum point on the stress-strain curve. The validation of the procedure was accepted due to the adhesive's behavior as an elastomer-plastic.

Mechanical properties of the adhesive at elevated temperature were determined from the stress-strain graph. As a result, the elastic modulus decreased as the temperature increased, while Poisson's ratio had less effect on the increment of temperature. The nominal transition glass temperature of 45°C was determined from the data sheet of the adhesive, and it was validated with the transition between the brittle and the elastic state of the adhesive. The value of transition glass temperature (T_g) was validated with the previous section of DSC test results, which was in the range of 42.1 to 47.3°C.

Table 2. Adhesive properties (Araldite Epoxy) at elevated temperature.

Temperature (°C)	Elastic Modulus (GPa)	Poisson's ratio
Room Temperature	1.392	0.380
35	1.257	0.392
55	0.426	0.463
75	0.227	0.480
100	0.185	0.484

As shown in **Figure 8**, we represented the different levels of cured temperature affecting the mechanical properties of the adhesive, especially on the elastic modulus and the yield strength. The results show that the elastic modulus and the yield strength rapidly decrease as the cured temperature increases. The findings supported by the study on the effect of adhesively bonded joints are mainly affected by the variation of adhesive properties. The adhesive strength shows the temperature dependence, especially near the glass transition temperature (Tg) of the adhesive.. However, the trends of elastic modulus and yield stress of the adhesive at different levels of cured temperature are expected to be similar. These results are in complete agreement with the findings of similarities in the adhesive behaviour for both the strength and stiffness upon the cure temperature (Moussa *et al*., 2012). Thus, the decrement elastic modulus is also referred to as relaxation modulus, where the adhesive is strained rapidly to a pre-determined strain and stress required to maintain this strain over time, measured at a constant curing temperature. The decrease in stress occurs due to the molecular relaxation process.

3.3. Adhesively Bonded T-joint

In this section, the results of the durability of different thickness adhesively bonded T-joints at elevated temperature are presented. Therefore, a series of adhesive thicknesses of the adhesively bonded T-joint specimens (i.e., 0.5, 1.0, 1.5, and 2.0 mm) in tensile loading at elevated temperature (i.e., Room temperature to 100°C) is investigated. **Figure 17** shows the result of a method to evaluate experimental stress by performing tests at different temperatures. At room temperature conditions, the results show that the strength of the adhesive T-joint gradually increased from 0.5 to 1.0 mm, and it reached the optimum strength at 1.0 mm for room temperature testing. With a further increment of bond line from 1.0 to 2.0 mm, there is a slight decrease in strength. Thus, the thicker

bond line thickness at room temperature conditions will reduce the adhesive strength. Besides, the result also shows that a temperature of 55°C achieved the highest strength compared to 75 and 100°C temperatures tested. However, there was a slight increase in strength when the bond line thickness increased from 0.5 to 1.5 mm in the temperature range 55 to 100°C. The optimum strength was obtained for these three temperatures at 2.0 mm of adhesive thickness. The highest tensile stress was obtained at 35°C in the entire range of bond line thicknesses. The tensile stress increases as bond line thickness increases until the optimum tensile stress of 1.9063 MPa is reached at a bond line thickness of 1.5 mm. Under these conditions, the adhesive reached the optimum glass transition temperature of the fully cured network Tg_{∞} value. Thus, the higher adhesive strength was obtained under this condition for all adhesive thicknesses. From the results, the post-curing temperature below the glass transition temperature fully cured the network$_{\infty}$, the adhesive strength increased, and the Tg value obtained was higher than the post-curing temperature. Besides that, cured adhesive above Tg_{∞} shows opposite behaviours (i.e., the adhesive strength decreases as the curing temperature increases) and obtained Tg higher than the cure temperature. These results agree with the findings by Carbas *et al*. An argument in which the glass transition of an epoxy adhesive is affected by the cured temperature (Carbas *et al*., 2014).

Tensile test results of the adhesive T-joint under different temperatures are presented in **Figure 18**. The result shows the effect of temperature on the adhesive strength at various bond line thicknesses. It was noted that the decrement trend of failure stress increases with the temperature from 35 to 100°C. Whenever the Tg is fully cured of adhesive, the changes in the adhesive behaviours can be observed. The adhesive becomes less brittle and consequently reduces the tensile strength. Our findings demonstrate that 2.0 mm adhesive thickness performs optimally at elevated temperatures (from 55 to 100°C), a critical insight for designing durable joints in automotive exhaust systems and aerospace components. For room and moderate temperatures, 1.0- and 1.5-mm thicknesses yield superior performance, offering weight reduction without compromising strength.

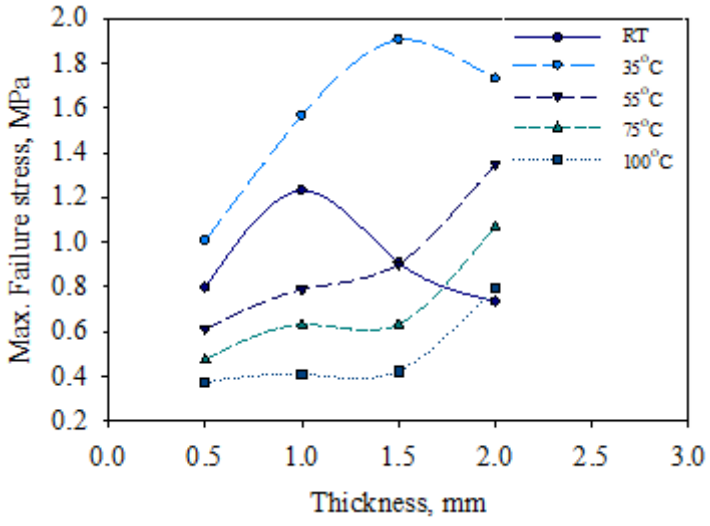


Figure 17. Effect of bond line thickness on the failure stress at elevated temperature.

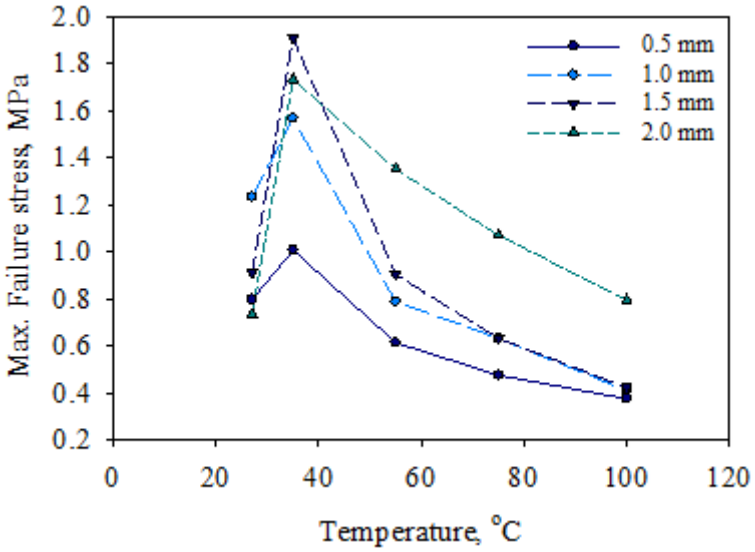


Figure 18. Temperature dependence on maximum failure stress at different levels of bond line thicknesses.

3.4. Adhesive Failure Analysis

The observation results of adhesive T-joint failure were examined to identify the type of failure and critical area that promotes fracture. **Figure 19** represents a type of failure of an adhesively bonded T-joint that occurs at different adhesive thicknesses. Based on **Figure 19a**, 0.5 mm of thickness shows a mixed-mode factor where cohesive failure and adhesion failures occur. There are thin layers of adhesive remaining on the surface of the perforated plate. The failure starts to initiate at the end of the adhesive bond line. **Figure 19b** shows that the failure occurs only at the adhesive interface for 1.0 mm of thickness. In this result, some adhesive remains in the hole on the perforated plate. From the result in **Figure 19c and 19d**, the failure also occurs at the adhesive interface.

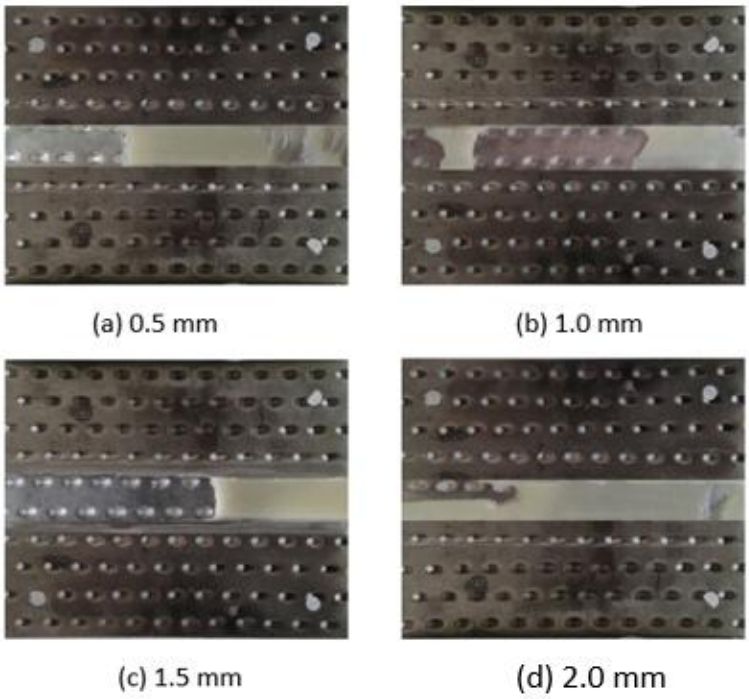


Figure 19. Adhesive failure of adhesively bonded T-joint.

Figure 20 shows that the failure occurs at the interface between the adhesive and adherend. The results show that the increment of adhesive thickness can cause the adhesive degradation mainly in the interface regions. The joining performance depends on the environmental condition because it is achieving the plasticization that may cause the suitability of non-linear elastic fracture mechanics criteria. The rupture of the adhesive T-joint always initiated from the edge of the 304L stainless steel perforated plate interface, as shown in. It noted that the high stress concentration was reported on the edge of the 304L stainless steel perforated plate interface. Thus, it was noted that the end of the bond was expected to be a critical area to promote the fracture. The observed trends in adhesive strength and failure modes are attributed to changes in adhesive morphology. SEM analysis revealed a significant reduction in resin particle size at elevated temperatures, correlating with increased void formation and reduced stress transfer efficiency.

(a) Adhesive failure (b) Crack occurs at the end of the bond line.

Figure 20. Adhesive failure.

3.5. Contribution to Sustainable Development Goals (SDGs)

The results of this study offer practical contributions to SDG 9: Industry, Innovation and Infrastructure, which promotes inclusive and sustainable industrialization, as well as the adoption of resilient infrastructure and innovative technologies. By examining the thermal performance of adhesively bonded T-joints at various adhesive thicknesses and curing temperatures, this research provides essential knowledge for designing thermally stable, lightweight, and durable bonding systems for high-performance applications.

The findings demonstrated that optimized adhesive thicknesses (e.g., 1.0 mm at room temperature and 2.0 mm at elevated temperatures) significantly enhance mechanical performance while reducing material waste. These results are particularly relevant in automotive and aerospace industries, where lightweight and temperature-resistant materials are vital for improving energy efficiency and reducing fuel consumption. The use of epoxy-based adhesives, rather than mechanical fasteners, also supports modular and low-impact manufacturing, which aligns with sustainable engineering practices.

Moreover, the integration of thermal analysis techniques (DSC, TGA, SEM) in this study promotes scientific innovation by linking morphological and thermal degradation behavior with mechanical failure characteristics. This multidisciplinary approach encourages the development of smart material systems that are not only efficient in performance but also sustainable in lifecycle.

Through this contribution, the study advances the body of knowledge required to build resilient industrial infrastructure, reduce maintenance costs, and extend the service life of structural joints, all of which are key priorities under SDG 9. The results can inform future

guidelines and industrial standards for adhesive joint design under fluctuating thermal environments, fostering long-term sustainability and technological innovation.

4. CONCLUSION

The experimental results of this study demonstrate the impact of thermal exposure on the strength of adhesively bonded T-joints at varying adhesive thicknesses, providing valuable insights into adhesive performance under different thermal conditions.

The adhesive strength was found to be more sensitive to temperatures below the glass transition temperature (Tg) of the fully cured network (Tg∞) than to temperatures above Tg∞. At elevated temperatures above Tg, significant thermal degradation occurs, leading to changes in the adhesive's physical properties, primarily driven by the glass transition temperature. These changes are a critical factor in understanding the adhesive's performance under various thermal conditions.

In this study, a detailed examination of the adhesive's microscopic structure provided valuable insights into the effects of thermal exposure on the chemical composition of the adhesive. Unlike previous studies, which focused primarily on the chemical structure, our findings highlighted the role of tackier resin particles and surface morphology. The presence of tackier resin particles and their dissolution during thermal exposure resulted in the formation of voids in the adhesive, which in turn reduced thermal stress transfer within the adhesive matrix.

Further analysis revealed that increased thermal loading conditions led to a decrease in Young's modulus, which correlated with the observed reduction in adhesive strength. The yielding stress of the adhesive followed similar trends to the elastic modulus, and the reduction in elastic modulus was interpreted as a relaxation modulus. This refers to the adhesive's tendency to relax over time under constant strain, resulting in a decrease in stress as the molecular structures undergo relaxation processes.

The adhesive strength of the T-joint was strongly influenced by both adhesive thickness and thermal conditions. As adhesive thickness varied, distinct physical and mechanical behaviors were observed, particularly with respect to adhesive stiffness and stress concentration in the bonded joint. These changes in adhesive stiffness are crucial for understanding the adhesive's performance and failure modes at different thermal loadings.

This study underscores the importance of selecting optimal adhesive thickness and thermal conditions for achieving reliable bond strength in adhesively bonded joints. The findings have significant implications for industries such as automotive and aerospace, where temperature fluctuations are common and adhesive joints must maintain their strength and durability. Understanding the relationship between adhesive thickness, thermal loading, and adhesive properties will contribute to more effective design and material selection for adhesive joints in high-performance applications.

Overall, this study aligns with SDG 9, offering practical strategies for improving the durability and efficiency of adhesive bonding in thermally demanding environments. The outcomes support the advancement of sustainable engineering solutions that enhance resilience and innovation in industrial infrastructure.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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