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Assessment of Carbon Black Weight Fraction on the Shear Strength of Polyurethane Adhesive Joints

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Abstract

Adhesive bonding has become one of the most widely used joining techniques in engineering due to its ability to provide uniform stress distribution, minimize structural weight, and avoid the thermal distortion during welding processes. This study examines the effect of carbon black weight fraction on the shear strength of aluminum single-lap joints bonded with polyurethane adhesive. Aluminum 6061 specimens were prepared following ASTM D1002 standards and were reinforced with carbon black at weight fractions of 0, 8, 16, and 24 wt%. Fourier Transform Infrared (FTIR) spectroscopy was conducted to identify any chemical interactions, and lap shear testing was performed using a Universal Testing Machine (UTM). The results indicated that increasing the weight fraction of carbon black enhanced the shear strength and gradually shifted the failure mode from adhesive failure to cohesive failure. The specimen containing 24 wt% of carbon black exhibited the highest shear strength of 2.81 MPa, with 88% of the failures occurring cohesively. FTIR analysis revealed that carbon black did not introduce any new functional groups but functioned as a physical reinforcing filler within the polyurethane matrix. Therefore, carbon black is an effective reinforcing material for improving the mechanical performance of polyurethane adhesive-bonded aluminum single-lap joints.

***Keywords**: Polyurethane adhesive; Carbon black; Shear strength; Failure mode*

Abstrak

Perekat adalah salah satu teknik penyambungan yang banyak digunakan dalam bidang teknik karena kemampuannya untuk memberikan distribusi tegangan yang seragam, meminimalkan berat struktural, dan menghindari distorsi termal selama proses pengelasan. Studi ini mengevaluasi pengaruh fraksi berat *carbon black* terhadap kekuatan geser sambungan tumpang tindih tunggal aluminium yang direkatkan dengan poliuretan dengan penambahan *carbon black* 0, 8, 16, dan 24 wt%. Spesimen aluminium 6061 disiapkan mengikuti standar ASTM D1002. Spektroskopi Fourier Transform Infrared (FTIR) digunakan untuk mengidentifikasi gugus fungsi pada perekat sambungan, sedangkan kekuatan geser diidentifikasi melalui Mesin Uji Universal. Hasil studi menunjukkan bahwa semakin tinggi fraksi berat karbon hitam, maka semakin tinggi kekuatan geser sambungan. Secara bertahap terjadi pergeseran mode kegagalan dari kegagalan adhesif ke kegagalan kohesif. Spesimen dengan kandungan 24 wt% karbon hitam memiliki kekuatan geser tertinggi sebesar 2,81 MPa. Analisis FTIR mengungkapkan bahwa karbon hitam tidak memperkenalkan gugus fungsional baru apa pun, tetapi berfungsi sebagai pengisi penguat fisik di dalam matriks poliuretan. Karbon hitam merupakan bahan penguat yang efektif untuk meningkatkan kinerja mekanik sambungan tumpang tindih tunggal aluminium yang direkatkan dengan perekat poliuretan.

Kata kunci: Perekat polyuretan; Carbon black; Kekuatan geser sambungan; Mode kegagalan

1. PENDAHULUAN

Adhesive bonding has become one of the most widely used joining techniques in engineering due to its numerous advantages over conventional methods such as welding, riveting, and bolting. In contrast to mechanical fastening, adhesive bonding offers a more uniform distribution of stress, reduces structural weight, enhances fatigue performance, and allows for the joining of both similar and dissimilar materials. Oetomo et al. [1] This study compares the shear strength of joints bonded with white PVAc, yellow PVAc, and a combination of adhesives. The results indicate that white PVAc exhibits the best performance among the adhesives tested. However, when joints bonded with PVAc adhesive are exposed to distilled water, seawater, and vegetable oil, there is a noticeable reduction in their shear strength [2].

Wang et al. [3] reported that using polyurethane adhesive can achieve high shear strength in engineered wood flooring. Similarly, Winkler et al. [4] demonstrated that polyurethane adhesive shows strong adhesion and mechanical performance in structural bonding applications. These benefits have led to the widespread adoption of adhesive bonding in industries such as automotive, aerospace, marine, and manufacturing [5, 6].

Polyurethane (PU) adhesive is one of the most commonly used structural adhesives due to its excellent flexibility, high toughness, impact resistance, and strong adhesion to a variety of engineering materials. According to Akindoyo et al. [7], polyurethane has unique mechanical and chemical properties that make it suitable for a wide range of industrial applications. Das and Mahanwar [8] further explain that polyurethane is highly durable and can maintain its bonding performance under various service conditions. However, despite these advantages, the mechanical properties of polyurethane adhesive, especially its shear strength and fracture resistance, still need improvement to meet the increasing demand for lightweight, high-strength structures.

One of the most effective methods for enhancing the mechanical performance of polyurethane adhesives is the incorporation of reinforcing fillers. Carbon black has gained significant attention due to its high carbon purity, nanoscale particle size, and large specific surface area, which facilitate efficient stress transfer between filler particles and the polymer matrix. Marhoon [9] reported that carbon black greatly improved the mechanical and physical properties of polyurethane composites. Similarly, Tyczkowski et al. [10] found that carbon black nanoparticles enhanced the adhesion properties of polymer surfaces by increasing interactions between the filler and the polymer matrix. According to Ramly and Setiyo [11], carbon black also enhances stiffness and overall mechanical performance due to its reinforcing characteristics. Robertson and Hardman [12] further explained that carbon black serves as an effective reinforcing agent in polymer nanocomposites.

In addition to filler reinforcement, the quality of adhesive bonding is influenced by several processing parameters, including surface preparation, adhesive thickness, overlap length, and bonding dimensions. Surface roughness has a significant influence on the strength of the joint between steel and aluminum plates [13]. Chen et al. [5] investigated the shear strength of adhesively bonded single lap joints and reported that bonding parameters have a significant impact on joint performance. Similarly, Guo et al. [6] demonstrated that proper surface treatment and the appropriate adhesive thickness markedly improve lap shear strength. Furthermore, Abbasi et al. [14] showed that bonding dimensions directly affect the mechanical behavior of joints made with epoxy and polyurethane adhesives. Therefore, optimizing both adhesive composition and bonding parameters is essential for achieving high-performance adhesive joints.

In addition to mechanical testing, material characterization is essential for understanding how carbon black reinforces the polyurethane matrix. FTIR spectroscopy is a commonly used technique for identifying functional groups and investigating chemical interactions within polymer materials. Schmidt [15] noted that FTIR is an effective analytical tool for determining the molecular structure of polymers. The incorporating fillers enhances polymer performance through physical reinforcement, rather than by creating new chemical bonds. Therefore, combining FTIR characterization with shear strength testing offers a comprehensive evaluation of the impact of carbon black on polyurethane adhesives [16, 17, 18].

Previous studies have demonstrated the potential of polyurethane and carbon black to improve the mechanical performance. However, most research has focused solely on composite materials or the influence of bonding parameters, without simultaneously evaluating the relationships among carbon black weight fraction, shear strength, and failure modes in polyurethane adhesive-bonded aluminum single-lap joints. While Feng et al. [19] reported that enhancing the bonding interface can significantly increase the shear strength of adhesive joints, there is still a lack of studies exploring the combined effects of carbon black weight fraction on both mechanical performance and fracture behavior.

Moreover, Rodrigues et al. [20] highlighted the effectiveness of numerical approaches in understanding material behavior, indicating that comprehensive experimental data are essential for validating adhesive performance. Therefore, this study aims to investigate how varying the carbon black weight fraction affects the shear strength of polyurethane-adhesive-bonded aluminum single-lap joints. This will be achieved through FTIR characterization, lap-shear testing in accordance with ASTM D1002, and failure mode analysis. The findings are expected to provide scientific insights into the reinforcing mechanisms of carbon black and contribute to the development of stronger and more reliable polyurethane adhesive systems for engineering applications.

2. RESEARCH METHOD

2.1 Materials

The materials used in this study included 6061 aluminum plates as the adhered, a commercial one-component polyurethane adhesive (JUKU) as the bonding agent, commercial carbon black powder as the reinforcing filler, and 70% alcohol for cleaning the aluminum surfaces before bonding. Aluminum 6061 was selected for its excellent mechanical properties, corrosion resistance, and widespread applications in engineering structures. The polyurethane adhesive was chosen because of its high flexibility, strong adhesion, and good impact resistance. Additionally, carbon black was incorporated to enhance the mechanical performance of the adhesive joint by reinforcing the filler.

2.2 Specimen Preparation

The aluminum specimens were prepared following ASTM D1002 standards for single-lap joint shear testing. Aluminum plates measuring 120 mm × 20 mm × 2 mm were cut and cleaned with 70% alcohol to eliminate any contaminants from the bonding surface. Surface roughness measurements were taken before bonding to ensure uniform surface conditions across all specimens, as shown in Figure 1.

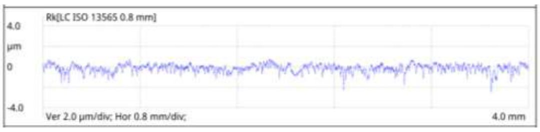


Figure 1. Surface roughness of aluminum plate

A polyurethane adhesive was mixed with carbon black at four different weight fractions: 0, 8, 16, 24 wt%. The adhesive mixture was manually stirred until it reached a homogeneous consistency. It was then uniformly applied to the overlap area of the aluminum specimens, which featured an overlap length of 12.5 mm and an adhesive thickness of 0.2 mm. After assembly, the bonded specimens were compacted with a hydraulic press at 3 MPa for 10 minutes to create a uniform adhesive layer and reduce entrapped air. All specimens were cured at room temperature for 24 hours before characterization and mechanical testing.

Figure 2 demonstrates the sequence of preparing the polyurethane adhesive-bonded aluminum single-lap joint specimens. The aluminum 6061 specimens were initially prepared, followed by mixing the polyurethane adhesive with carbon black in the specified weight fractions. The adhesive was then applied to the overlap region of the aluminum specimens before using a hydraulic press.

Figure 2. polyurethane adhesive-bonded aluminum single-lap joint specimens

2.3 Material Characterization

2.3.1 Fourier transform infrared (FTIR)

FTIR spectroscopy was performed using a Bruker Alpha II Platinum ATR spectrometer operating within the wavenumber range of 4000–400 cm⁻¹. The analysis was conducted on adhesive samples collected after shear testing to identify the functional groups present in polyurethane adhesive and to determine whether the addition of carbon black introduced chemical interactions within the adhesive matrix. The ATR (attenuated total reflectance) technique enabled direct characterization of solid adhesive samples without additional sample preparation, allowing efficient identification of molecular functional groups.

2.3.2 Shear strength

The mechanical performance of the adhesive joints was evaluated using UTM GD-1100-100B with a maximum loading capacity of 100 kN. The test was conducted according to ASTM D1002, which is the standard method for determining the apparent shear strength of single lap adhesive joints. The maximum load obtained during testing was converted into shear strength using Equation (1).

$$\boldsymbol{\tau} = \frac{\boldsymbol{F}}{\boldsymbol{A}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (\mathbf{1})$$

Where, τ is shear strength (MPa), F is maximum applied load (N), and A is bonded overlap area (mm²).

2.3.3 Failure mode analysis

After the shear test, the fractured surfaces of all specimens were visually examined to determine the failure mechanism. The fracture surfaces were classified into three categories:

(a) Adhesive failure, where separation occurred at the interface between the adhesive and aluminum substrate.

(b) Cohesive failure, where fracture occurred within the adhesive layer.

(c) Mixed failure, where both adhesive and cohesive failures were present simultaneously.

The percentage of adhesive and cohesive failure was determined through visual observation of the fractured overlap area. The failure mode analysis was subsequently correlated with the shear strength results to evaluate the influence of carbon black on the bonding performance of polyurethane adhesive joints.

3. RESULTS AND DISCUSSION

3.1 FTIR Spectrum

FTIR analysis was conducted to determine whether the incorporation of carbon black resulted in any chemical interactions within the polyurethane adhesive matrix. The FTIR spectra for all adhesive compositions are presented in Figure 4.

The 1400 cm⁻¹ region shows a significant decrease in transmittance compared to other areas of the polyurethane (PU) sample. This suggests that there is considerable infrared energy absorption in this region. This peak is a key characteristic of polyurethane, as it exhibits a higher absorption intensity than other peaks on the graph.

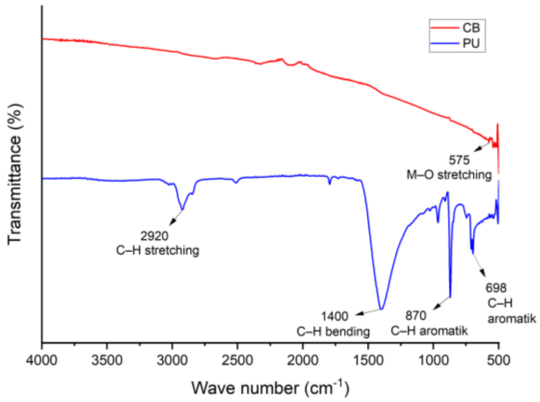


Figure 3. FTIR spectra

Additionally, the regions at 870 cm⁻¹ and 698 cm⁻¹ display several peaks with sharper, narrower profiles. The presence of multiple small peaks in the lower wavenumber range indicates more complex molecular interactions within the polyurethane. The relatively sharp curve in this region further suggests that the material has a stable and homogeneous structure.

In contrast, the carbon black (CB) sample exhibits characteristics that differ from those of polyurethane. Its main peak appears at 2113 cm^{-1} and has a less sharp shape, tending to broaden. This indicates that carbon black possesses a more complex and less homogeneous absorption structure than polyurethane. Moreover, the overall transmittance intensity of the carbon black sample is higher than that of the polyurethane sample, signifying different infrared absorption capabilities due to the dominant carbon structure in the material.

In the low wavenumber region, specifically around 575 cm^{-1} and 540 cm^{-1}, a small peak is observed in the carbon black sample. Although its intensity is not particularly high, the presence of this peak is indicative of the characteristic carbon structure in the material. The relatively small and narrow shape of the peak suggests that absorption in this region is not particularly dominant, yet it remains characteristic of carbon black.

Overall, the differences in curve shape, peak intensity, and wavenumber position between polyurethane and carbon black signify that the two materials have distinct structural characteristics. These variations are thought to influence the adhesive's mechanical properties when carbon black is mixed with polyurethane.

The similarity in the FTIR spectra across all samples suggests that carbon black primarily serves as a reinforcing filler through physical interaction rather than through a chemical reaction with the polyurethane matrix. This finding indicates that the improvements in mechanical performance are mainly due to enhanced stress transfer and filler reinforcement, rather than chemical modification of the polymer network.

These results align with previous studies that report carbon black typically acts as an inert reinforcing filler, improving load distribution while preserving the original chemical structure of polyurethane.

3.2 Shear Strength Analysis

The lap shear test was conducted according to ASTM D1002 to assess the mechanical performance of polyurethane adhesive reinforced with varying weight fractions of carbon black. The average shear strength results are illustrated in Figure 4.

The findings demonstrate that carbon black has a significant impact on the shear strength of polyurethane adhesive joints. The specimen without carbon black (0 wt%) exhibited the lowest bonding performance, as the adhesive layer consisted solely of polyurethane and lacked any reinforcement. As carbon black was added, the mechanical behavior of the adhesive improved gradually due to enhanced stress transfer within the polymer matrix.

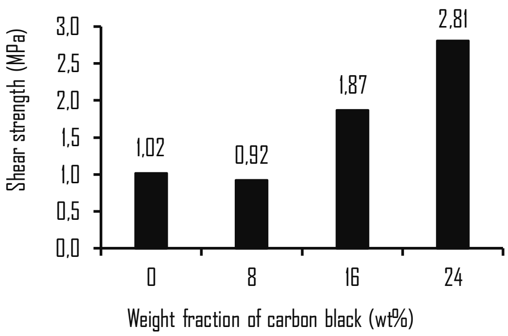


Figure 4. Effect of carbon black weight fraction on shear strength

When 8 wt% of carbon black was incorporated, there was only a slight improvement in bonding performance. At this level, the reinforcing particles were not well-distributed throughout the adhesive matrix, resulting in limited enhancement of the internal strength.

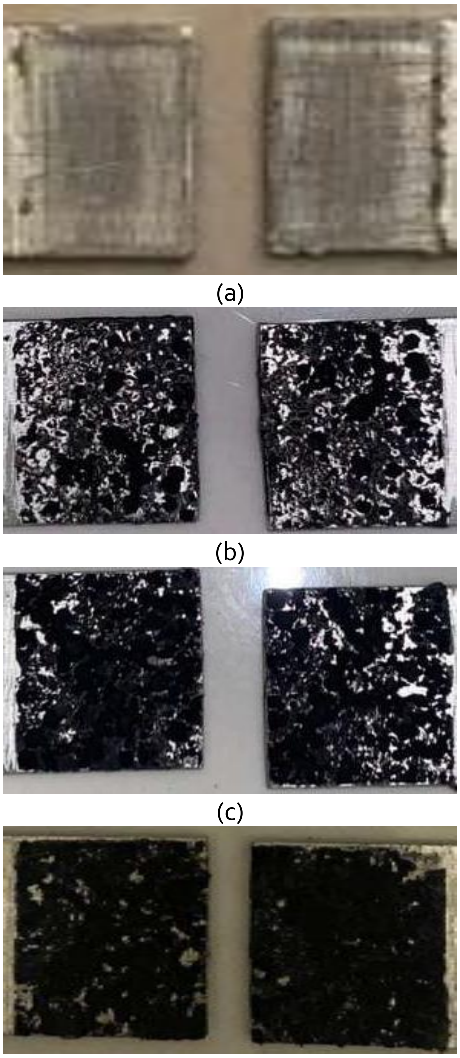
A notable increase in shear strength was observed in the specimen containing 16 wt% of carbon black. This improvement indicates that the dispersion of carbon black became more effective, allowing the filler particles to reinforce the polyurethane matrix and improve load distribution during shear loading.

The specimen with 24 wt% of carbon black achieved the highest shear strength at 2.81 MPa. In this composition, carbon black effectively reinforced the adhesive layer, leading to stronger interfacial bonding and greater resistance to shear loading. The enhanced performance suggests that this specific filler content provided the most efficient reinforcement among all compositions tested.

In summary, increasing the weight fraction of carbon black improved the mechanical performance of polyurethane-adhesive-bonded aluminum joints. The addition of carbon black particles enhanced the internal cohesion of the adhesive and facilitated more efficient stress transfer throughout the bonded interface, resulting in higher shear strength.

3.1 Failure Mode Analysis

Failure mode analysis was conducted after lap shear testing to investigate the fracture mechanism of each adhesive joint. The fracture surfaces were visually examined and classified as adhesive failure, cohesive failure, or mixed failure. Representative fracture surfaces are shown in Figure 5.



(a)
(b)
(c)
(d)

Figure 5. Fracture surfaces following shear testing on samples with added carbon black: (a) 0 wt%, (b) 8 wt%, (c) 16 wt%, and (d) 24 wt%.

The percentages of adhesive and cohesive failures for each specimen are summarized in Table 1. Fracture observations revealed a gradual transition in failure modes as the carbon black content increased. The specimen without carbon black showed 100% adhesive failure, indicating weak adhesion between the polyurethane adhesive and the aluminum substrate. In this case, the fracture occurred entirely at the adhesive-substrate interface, resulting in relatively low shear strength.

Table 1. Percentage of failure modes

Weight fraction of carbon black (wt%)	Adhesive failure (%)	Cohesive failure (%)
0	100	0
8	46	54
16	23	77
24	12	88

For the 8 wt% specimen, the failure mode shifted to mixed failure, consisting of 46% adhesive failure and 54% cohesive failure. This shift suggests that carbon black started to improve the internal strength of the adhesive, even though interfacial failure still occurred in a significant portion of the bonded area.

A more pronounced improvement was evident in the 16 wt% specimen, where cohesive failure rose to 77%, while adhesive failure dropped to 23%. These results indicate stronger adhesion between the polyurethane adhesive and the aluminum surface, allowing most fractures to occur within the adhesive layer rather than at the bonding interface.

The 24 wt% specimen displayed the highest percentage of cohesive failure (88%) and only 12% adhesive failure, corresponding to the highest shear strength recorded in this study (2.81 MPa). The predominance of cohesive failure indicates that the adhesive-substrate interface became stronger than the internal strength of the adhesive itself. Consequently, fractures occurred mainly within the adhesive layer, demonstrating excellent bonding quality.

The gradual increase in cohesive failure from 0% to 88% shows that increasing the carbon black weight fraction significantly improved the bonding performance of the polyurethane adhesive. These results align with the shear strength measurements and confirm that carbon black effectively enhanced both the interfacial adhesion and the internal cohesion of the adhesive layer.

4. CONCLUSION

The impact of the carbon black weight fraction on the shear strength of aluminum single-lap joints bonded with polyurethane adhesive has been examined using FTIR characterization, lap-shear testing, and failure mode analysis.

The FTIR analysis indicated that adding carbon black did not create new functional groups within the polyurethane adhesive matrix. This suggests that carbon black mainly functions as a physical reinforcing filler. Nonetheless, incorporating carbon black significantly improved the mechanical performance of the adhesive joints. As the carbon black content increased, there was a notable rise in shear strength, with a corresponding shift in the failure mechanism from adhesive failure to cohesive failure.

Among the compositions tested, the specimen containing 24 wt% of carbon black showed the best overall performance, achieving the highest shear strength of 2.81 MPa and the largest cohesive failure percentage at 88%. These findings demonstrate that carbon black effectively enhances both the interfacial adhesion between the polyurethane adhesive and the aluminum substrate, as well as the internal cohesion of the adhesive layer.

Therefore, carbon black is an effective reinforcing filler that improves the mechanical performance of polyurethane-adhesively bonded aluminum single-lap joints, indicating its significant potential for lightweight structural bonding applications.

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