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Investigation of the Bonding Performance of Parts Produced by FDM and SLA 3D Printing Methods

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ABSTRACT

In this study, the bonding properties of parts produced using additive manufacturing methods, which are frequently preferred today, were investigated. In this context, parts were produced by Stereolithography (SLA) and Fused Deposition Modelling (FDM) methods. The mechanical properties of the produced materials were determined by tensile test according to ASTM D638 standard. Afterwards, these parts were bonded in different combinations and the mechanical properties of the joints were determined according to ASTM D1002 standard. As a result, the tensile strength of Polylactic Acid (PLA) parts produced by FDM method was 65% higher than that of PhotoPolymer Resin (PPR) parts produced by SLA method, while the strain rates of PPR materials were 85% higher than PLA materials. When the failure load values obtained after the tensile test of the bonded joint specimens were examined, the best mechanical performance was obtained as 3086 N in the combination of PLA and composite material. The lowest damage load occurred in the combination of PPR and PLA material. When the displacement data resulting from the failure load were analysed, the highest values were obtained in the PPR-PPR material combination. In conclusion, bonding can be used for joining parts produced by additive manufacturing, but the choice of material should be based on the application.

Keywords: *Additive manufacturing, Stereolithography (SLA), Fused deposition modelling (FDM), PLA, Adhesive joints, Failure load*

FDM ve SLA 3D Baskı Yöntemleriyle Üretilen Parçaların Yapıştırma Performansının İncelenmesi

ÖZET

Bu çalışmada, günümüzde sıklıkla tercih edilen eklemeli imalat yöntemleri kullanılarak üretilen parçaların yapıştırma özellikleri incelenmiştir. Bu kapsamda Stereolitografi (SLA) ve Eriyik Yığma Modelleme (FDM) yöntemleri ile parçalar üretilmiştir. Üretilen malzemelerin mekanik özellikleri ASTM D638 standartına göre gerçekleştirilen çekme testi ile belirlenmiştir. Sonrasında bu parçalar farklı kombinasyonlarda yapıştırılarak bağlantıların mekanik özellikleri ASTM D1002 standartına göre belirlenmiştir. Sonuç olarak, FDM yöntemi ile üretilen Polylactic Acid (PLA) parçaların çekme dayanımları SLA yöntemi ile üretilen PhotoPolymer Resin (PPR) parçalara nazaran %65 oranında daha yüksek iken, PPR malzemelerinde şekil değiştirme oranlarının PLA malzemeye göre %85 oranında daha yüksek olduğu belirlenmiştir. Yapıştırma ile birleştirme işlemi yapılan bağlantı numunelerinin çekme işlemi sonrasında elde edilen hasar yükü değerleri incelendiğinde en iyi mekanik performans PLA ve kompozit malzeme birleşiminde 3086 N olarak elde edilmiştir. En düşük hasar yükü ise PPR ve PLA malzeme birleşiminde meydana gelmiştir. Hasar yükü sonucunda oluşan yer değiştirme verileri incelendiğinde ise PPR-PPR malzeme birleşiminde en yüksek değerler elde edilmiştir. Sonuç olarak, eklemeli imalatla üretilen parçaların birleştirilmesinde yapıştırma yöntemi kullanılabilir fakat malzeme seçiminin uygulamaya göre yapılması gerekmektedir.

Anahtar Kelimeler: *Eklemeli imalat, Stereolitografi (SLA), Eriyik Yığma Modeleme (FDM), PLA, Yapıştırma bağlantıları, Hasar yükü*

1. INTRODUCTION

In recent years, additive manufacturing (AM) technologies have led to revolutionary developments in many fields from industrial applications to medical applications such as dental and prosthesis. The additive manufacturing method, which can produce the desired products using 3D design (CAD) data, is frequently preferred in many industrial applications today due to its minimum material usage (low volume), acceleration of production processes, direct end use and affordable costs [1]. This method, also known as rapid prototyping, enables the production of parts with improved design and rapid production [2,3]. Also, the more advantages of the method are as follows: (a) the designed parts can be produced directly without any

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process, (b) the internal structures of the parts to be produced can be created in full and hollow forms, (c) the product development stages can be reduced, (d) the parts can be manufactured anywhere without the need for large areas, and (e) instant production can be made according to customer demand [4,5] . In addition to new production, additive manufacturing methods are also used in applications such as part repair and the creation of additional structures to existing products [6].

Today, various additive manufacturing methods such as stereolithography (SLA), selective laser melting (SLE), direct metal laser sintering/melting (DMLS), fused deposition modeling (FDM) are used in industrial applications. These methods differ from each other in terms of the way materials are used, layer formation, part creation and the working process [7]. Some methods create parts by melting layers (such as SLM), while others form layers by solidifying a liquid material [8].

SLA has become one of the most widely used additive manufacturing technologies in recent years due to its superior features. In the SLA technique, photopolymer resin in liquid form is selectively cured layer by layer using a laser beam of a specific wavelength [9]. This process occurs as the laser initiates a photopolymerization reaction in the resin. The material solidifies in the regions where the laser is scanned vectorially, forming layers. These layers stack on top of each other, creating three-dimensional polymer structures with high dimensional accuracy [10,11]. This process enables the production of complex geometries, enabling applications that require high precision in areas such as biomedical, engineering and design. SLA technology offers much higher resolution compared to other 3D printing technologies used in industrial applications, enabling the production of parts with fine details, precise surface features and very low dimensional values [12]. Thanks to this method, parts with very complex geometries that cannot be produced with traditional methods can be easily produced with the desired technical specifications.

The FDM method is based on the principle of manufacturing parts in a layered manner by melting the polymeric material in the nozzle head at a certain temperature set in accordance with the process, and then moving the molten material in the profile defined in the machine to form layers [2]. Depending on the working principle of the FDM method, the production materials must have the ability to solidify by losing heat in a short time after they are melted in the nozzle head and transferred to the production table. Thermoplastic materials are used to meet this requirement in the FDM method. Thermoplastic materials are divided into Polyethylene Terephthalate Glycol (PETG), Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) with different physical and chemical properties [13,14]. The variety of materials provides the opportunity to choose according to the properties of the part to be produced. Among thermoplastic materials, PLA is the most preferred material type in 3D manufacturing applications due to its low deformability in the production of large-sized parts, its complete biodegradability, its lightweight structure and high strength [15].

The assembly of parts produced using SLA and FDM technology is very important for the usability of this method. Considering the production of mechanical components consisting of many parts today, it is necessary to offer comprehensive solutions about joining processes. Problems are often encountered during the joining of polymer structured parts produced using additive manufacturing methods with traditional methods such as rivets and bolts. In riveting processes applied to these parts, the parts break and their structures deteriorate due to the instantaneous force applied suddenly. In bolting processes, while the holes reduce the load resistance of the part, cracks occur in the areas where the nut contacts [16]. Adhesive joints are preferred in applications due to their advantages such as providing solutions to the problems encountered in traditional joining methods, joining materials with different properties, and equal distribution of stresses to occur [17,18]. In order to efficiently utilize the advantages of the bonding method, the selection of the appropriate adhesive material and the geometry design in the bonding area play a critical role [19,20]. The manufacturing materials of the bonded parts and the overlap length of the bonding area are among the most critical factors determining the mechanical properties of adhesive joints [21]. Khosravani et al. [22] investigated the effects of device speed, nozzle temperature, and adhesive thickness on the mechanical properties of adhesive joints. Among the adhesive thickness values used in their study (0.2, 0.3, and 0.4 mm), they determined that a thickness of 0.2 mm provided the best performance. Gültekin et al. [21] examined the effects of manufacturing parameters and overlap length on the mechanical properties of PLA joints with different printing angles and infill ratios. Their study found that an increase in overlap length led to an increase in failure load. Additionally, they observed that increasing the infill ratio from 75% to 100% resulted in tensile strength improvements of 6.3% and 7.4%, respectively. Çoban et al. [23] investigated the mechanical effects of various parameters in adhesive bonding of PLA parts using adhesives with different strength properties. Their study examined factors such as infill ratio, adhesive thickness, and surface abrasion applied to the bonding area. They concluded that the type and thickness of the adhesive, as well as the surface abrasion process applied to the bonding area, significantly influence the mechanical properties of adhesive joints. Atahan and Apalak [24] investigated the effect of bonding process on the strength of single lap joints in PLA specimens. In this context, they performed tensile, three and four point compression tests and observed that the strength increased slightly with the increase in loading rate. Dhilipkumar et al. [25] investigated the mechanical and vibration properties of doped parts with different stress ratios produced by FDM method using graphene doped adhesive in different geometric shapes. They determined that the 0 stress direction has higher tensile strength compared to other stress directions. They also observed that graphene reinforcement of the adhesive content increased the strength of single-lap bonded joints by 61.18%.

Using the bonding process to join dissimilar materials such as PPR and PLA combines the properties of two different materials to create a more functional and durable structure. When fragile parts such as PLA are considered, bonding processes result in less thermal and mechanical stresses than welding, bolted, etc. joining methods. In addition, PPR and PLA parts produced by additive manufacturing often have complex geometries, which can make mechanical joining difficult. Bonding offers an ideal solution to accommodate the different surface structures of both materials, resulting in more aesthetic and functional joints.

When the studies summarized above are examined, it is observed that there are numerous studies involving bonding applications with PLA materials. However, it has been noted that studies comparatively investigating the mechanical properties of parts produced from different materials are quite limited. Therefore, in this study, the mechanical properties of parts produced using SLA technology, which is underrepresented in the literature, were examined in detail by performing bonding processes with other materials. In this context, tensile specimens and joint specimens were produced from PPR and PLA materials using SLA and FDM methods, and bonding processes were applied. Subsequently, tensile tests were conducted to determine the mechanical properties of the bonded parts.

2. MATERIAL AND METHOD

2.1. Material

UV liquid resin is widely used in next-generation 3D printing technologies due to its high precision and surface tolerances. In the conducted study, UV-sensitive resin was preferred for its advantages, such as low surface roughness and high printing accuracy. The UV resin used in this study is the transparent UV Standard liquid resin produced by Anycubic. The technical specifications provided by the manufacturer for the product are presented in the table below.

Table 1. Properties of the used UV liquid resin material

Base material	Resin
Curing Wavelength	405 nm
Viscosity	150-200 mPa.s
Solid Density	1.05-1.25 g/cm^3
Tensile Strength	36-45 MPa
Elongation at break	8-12 %
Shrinkage	4.5-5.5 %
Hardness	82D

PLA material is a type of thermoplastic that is used as a building material in parts produced by FDM method and is produced from renewable resources and has the ability to dissolve in nature. In the study, PLA filament was used for the materials to be produced with 3D printer due to its easy availability, low cost and environmental friendliness. The technical values of the Anycubic brand PLA filament used are given in Table 2.

Table 2. Material properties of the used filament

Diameter	1.75 mm
Density	1.23 g/cm^3
Printing Temperature	190-230 °C
Tensile Strength	61 MPa
Elongation at break	3.8 %
Hardness	81D

In order to produce the joint specimens, carbon fiber fabric reinforced composite plates were used as a different material type in the bonding process and the mechanical properties of the composite materials used are given in Table 3 [26]. The composite materials have a carbon fiber content of 245 g.m^2 3k and were produced using vacuum infusion method.

Table 3. Mechanical properties of carbon fiber composite

E_1 (GPa)	$72^{\pm 2.8}$
E_2 (GPa)	$72^{\pm 2.8}$
G_{12} (GPa)	$5^{\pm 0.3}$
ν_{12}	0.1
σ_{12} (MPa)	$650^{\pm 28}$
τ_{12} (MPa)	$90^{\pm 4.5}$

Araldite 2011 (Huntsman Advanced Materials Co., Ltd.) brand structural adhesive was utilized to bond the joint specimens with varying material properties. Its technical specifications are provided in Table 4 [27]. The two-component Araldite 2011 type adhesive is composed of epoxy and hardener (1:0.8 ratio), and it cures at 60°C [17].

Table 4. Technical properties of the used adhesive

Tensile Strength	33 MPa
Elasticity Modulus	1600 MPa
Poisson's Ratio	0.43
Curing Condition	60 °C-75 min

2.2. Experimental Method

In this study, production was carried out using an Anycubic Photon Mono X brand SLA 3D printer and its associated equipment (Figure 1). Joint samples with dimensions of 25x125x5 mm were produced using Anycubic Standard UV precision resin. The production parameters for the SLA 3D printer were set to a layer thickness of 0.05 mm and a z-axis travel speed of 2 mm/s. After production, the resin residues on the parts were removed by washing them in a cleaning device with agitation using isopropyl alcohol for 6 minutes. Subsequently, the samples were cured under a UV LED lamp, with 3 minutes of clockwise rotation and 3 minutes of counterclockwise rotation.

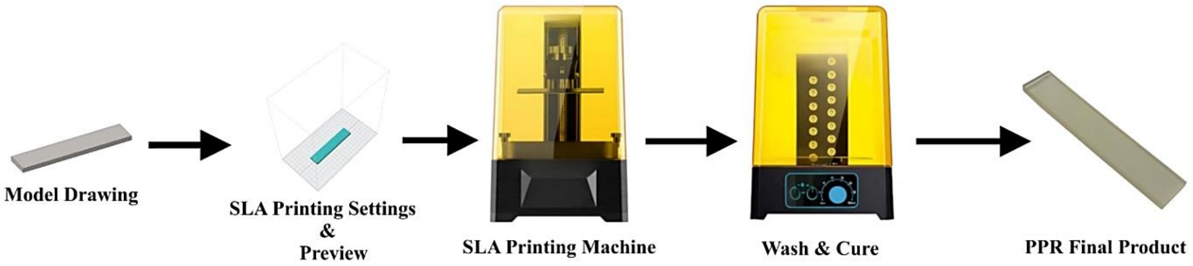

Figure 1. Part production process with SLA method

The PLA plates to be bonded were produced on Anycubic brand Kobra Combo 3 model FDM type printer (Figure 2). In the production of the parts; device nozzle temperature 220°C, layer thickness 0.12 mm, table temperature 70°C were used.

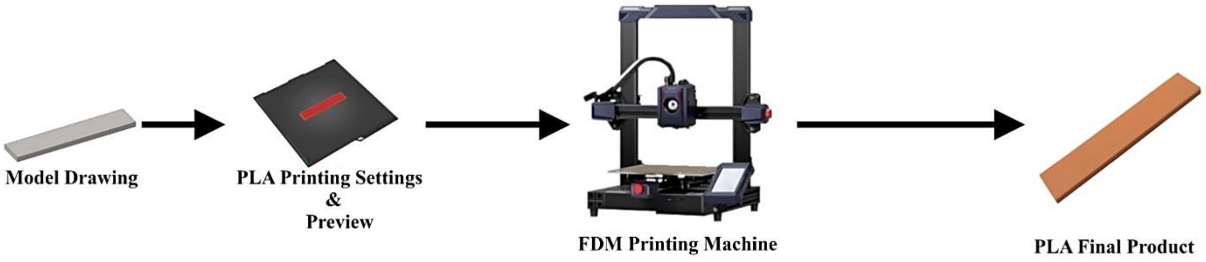

Figure 2. Part production process with FDM method

Care was taken to ensure that the produced PPR and PLA joint specimens were not exposed to external environmental factors (such as humidity and temperature) until the bonding and testing processes were completed.

Figure 3. Production of PPR-PLA bonded plate and tensile bulk test specimens

After the production of PPR and PLA samples, the production phase of adhesively bonded joint was started. The model of the single-lap joint system to be produced is shown in Figure 4. The length, width and overlap length (L_o) of the single-lap adhesive joint specimens to be used in the application were produced as 125 mm, 25 mm and 25 mm, respectively.

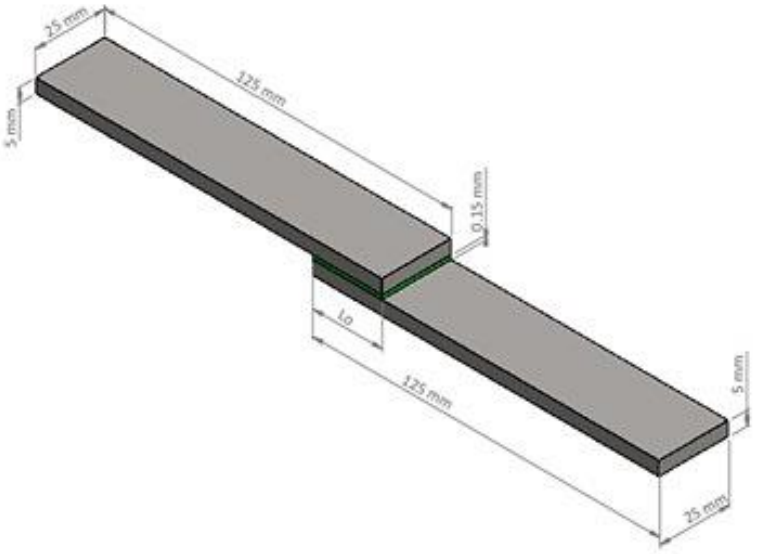

Figure 4. Joint geometry of the adhesion model

During the bonding application, mold and separator equipment were used to adjust the adhesive thickness and the distance of the bonding zone. Silicone lubrication was applied to the equipment to be used and the bonding process started. The bonding area of PPR and PLA plates was cleaned with isopropyl alcohol before the process. The parts were waited for a while to dry after cleaning. Then, the adhesive was applied to the bonding area of the parts with the help of a gun. The adhesive thickness and overlap length of the samples were adjusted using auxiliary equipment. Finally, the bonded parts were placed in an oven at 60°C for 75 minutes for the curing process. After the curing process, the specimens were cooled at room temperature and the overflowing adhesives were cleaned from the joint of the parts (Figure 5).

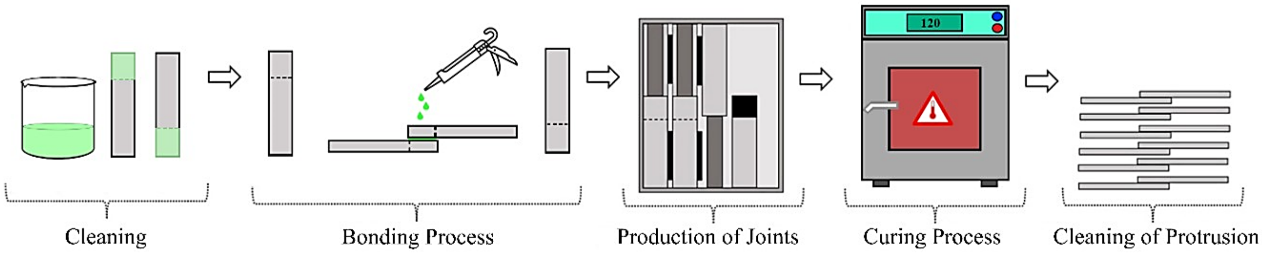

Figure 5. Bonding process

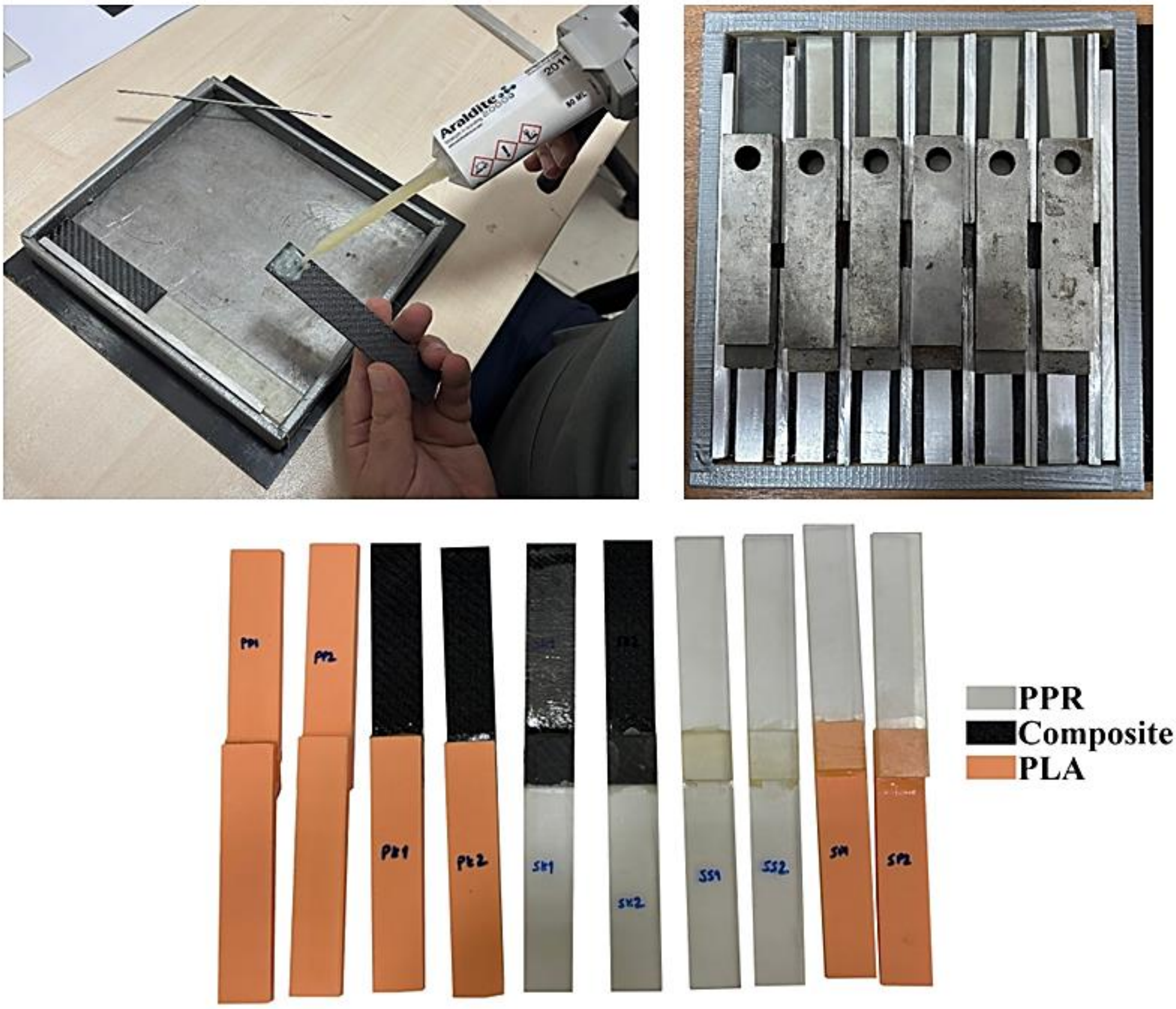

Figure 6. Production of adhesive specimens

The experimental parameters of the fabricated adhesive joint specimens are given in Table 5.

Table 5. Experimental parameters

Material	Sample Code
PPR-PPR	SS
PPR-PLA	SP
PPR-Composite	SK
PLA-PLA	PP
PLA-Composite	PK

The PPR and PLA tensile specimens were tested in Shimadzu tensile testing machine at a tensile speed of 5 mm/min. The bonded joint specimens were tested at a tensile speed of 1 mm/min on the same machine. For each parameter, 3 specimens were tested to obtain more accurate results. The application stage of the tensile testing process is given in Figure 7.

Figure 7. The tensile testing process for tensile and adhesive specimens

3. RESULTS AND DISCUSSION

3.1. Tensile Test Results of PPR and PLA Specimens

The stress-strain results obtained from the tensile tests applied to PPR and PLA bulk tensile specimens are shown in Figure 8.

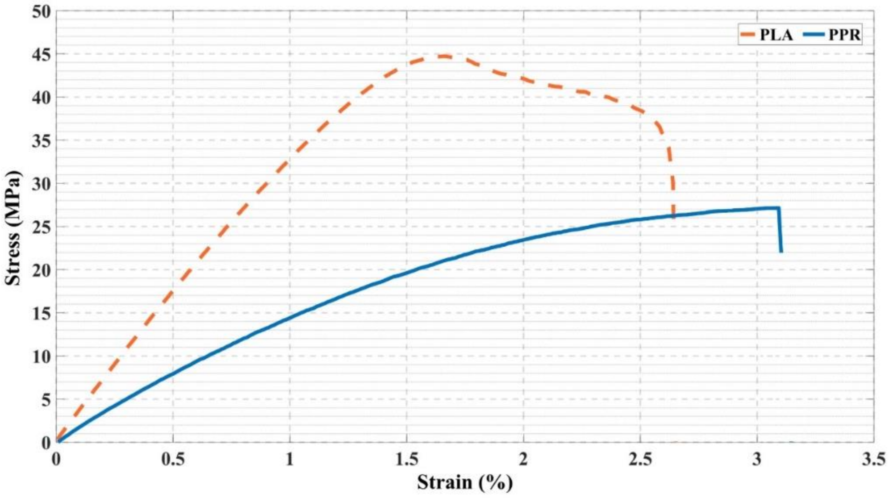

Figure 8. The stress-strain results of the PPR and PLA bulk specimens

The tensile strength, modulus of elasticity, and strain values of the PPR and PLA bulk parts were determined from the true stress-strain graphs obtained after the tensile test. The averages of the data determined as a result of the tensile test are provided in Table 6.

Table 6. The mechanical properties of PPR and PLA bulk specimens

Sample	Tensile Strength (MPa)	Elongation (%)	Elasticity Modulus (MPa)
PPR	27.13	3.09	784
PLA	44.77	1.66	1450

When comparing the mechanical properties of PPR and PLA tensile specimens provided in Figure 8 and Table 6, it is observed that PLA material demonstrates higher mechanical performance compared to PPR material. Upon examining the modulus of elasticity values obtained from the tensile test, it was determined that PLA specimens are 85% higher than PPR specimens. At this point, it is evident that PLA specimens have a more rigid structure due to their high modulus of elasticity. Additionally, the tensile strength of PLA specimens was found to be 65% higher than that of PPR specimens. The higher strength and rigidity of PLA specimens can be attributed to the interwoven bonding of layers with filaments, which enhances the material's overall strength and stiffness. In contrast, PPR specimens lack any binding agent between their internal layers, resulting in lower mechanical properties compared to PLA specimens [22]. Although PLA specimens exhibit higher strength values, they show lower elongation before fracture. Furthermore, a noticeable decrease in strength was observed in PLA specimens after reaching a distinct yield point. Considering this behavior, it can be concluded that parts produced from PLA material undergo brittle fracture. On the other hand, PPR specimens demonstrate 86% higher elongation compared to PLA specimens. Therefore, PPR materials exhibit a more ductile behavior compared to PLA materials. Additionally, the graph indicates that PPR specimens undergo softer deformation. In conclusion, while PLA materials possess higher tensile strength and rigidity, PPR materials are more ductile and have greater deformation capability.

3.2. Tensile Test Results of Single Lap Joint (SLJ) Specimens

The average failure loads and displacement (elongation) values determined after the tensile testing of single-lap joint (SLJ) adhesive joint specimens, produced by bonding PPR and PLA materials with each other and in alternating configurations, are shown in Figure 9. Upon evaluating the findings, it was determined that the failure loads in the joints varied depending on the types of materials bonded.

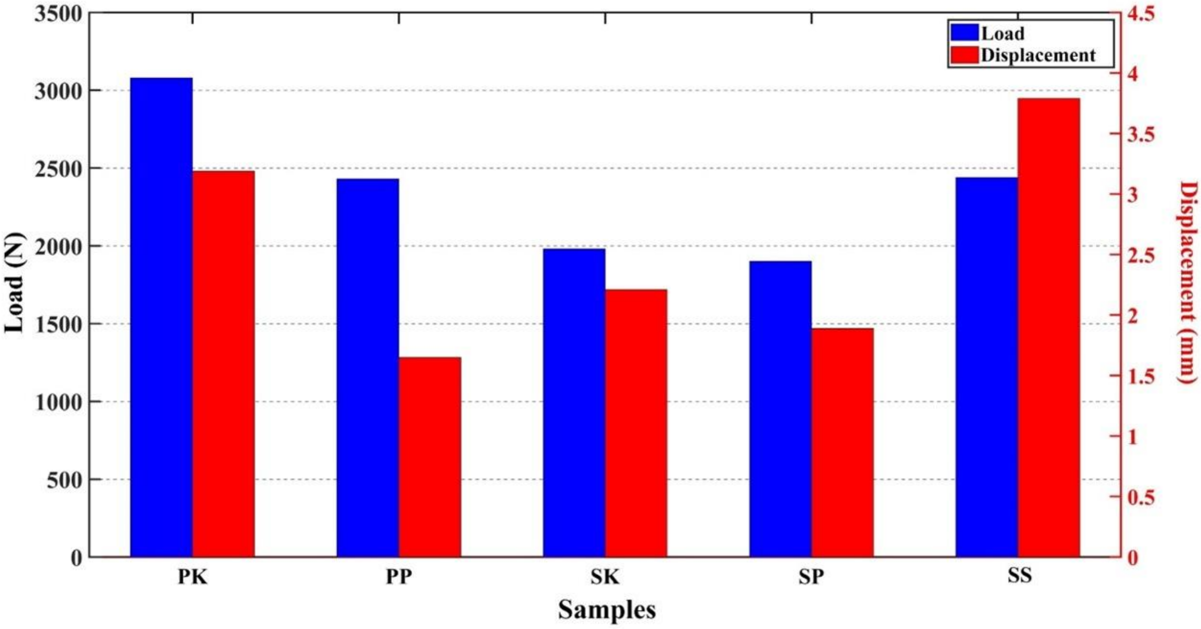

Figure 9. Tensile results of the SLJ adhesive specimens

When examining the results of the single-lap bonded joint specimens provided in Figure 9, it was determined that the PK (PLA-Composite) specimens exhibited the highest strength performance. This high strength performance was achieved due to the high elasticity values of the PLA and composite materials used in these specimens. Additionally, the surface roughness of the PLA and composite materials improved adhesion properties, further enhancing the strength performance. On the other hand, SP (PPR-PLA) specimens showed the lowest strength performance. The failure load values of SK (PPR-Composite) and SP specimens were found to be quite close to each other. It was observed that due to the precise surface properties of SLA-manufactured parts, rapid separation occurred at the bonded joint areas. In general, when comparing strength performance, PK was found to have a 62.2% higher load-bearing capacity than SP. Furthermore, it can be said that the mechanical properties of the materials, such as tensile strength and modulus of elasticity, also significantly influenced the failure loads of the bonded specimens made from different material types [20].

When examining the displacement values of the bonded joint specimens, it was observed that SS specimens had the highest values. Due to the flexible nature of PPR materials, they exhibited better elongation performance under load. In addition to their high load-bearing performance, PK specimens also showed high displacement values. The lowest displacement value was found in PP specimens, which is attributed to the more rigid structure of PLA materials. When analyzing the displacement (elongation) data in the graph provided in Figure 9, it was determined that SS had a 129.7% higher value compared to PP. This is because PPR materials have a higher ability to deform under load and can undergo more significant deformation.

In conclusion, it was determined that the mechanical properties of the bonded materials significantly influence the mechanical strength of the bonded joints. A higher modulus of elasticity contributes to better strength performance.

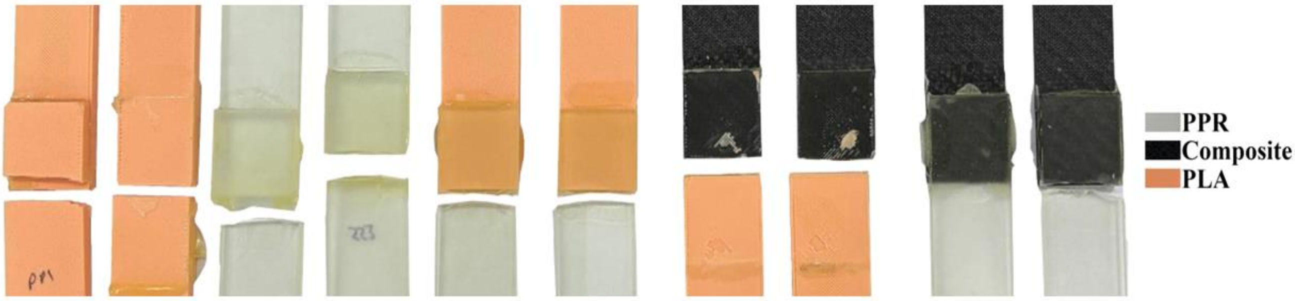

Figure 10. Failure surfaces of the SLJ adhesive specimens

The separation zones and bonding surfaces resulting from the tensile tests of the bonded joint specimens are shown in Figure 10. In some specimens, the parts completely separated at the bonding interface, while in others, failure occurred within the bonding region. It was observed that complete separations occurred in specimens made from more rigid materials, such as PLA and composites. However, the instantaneous stresses generated at the joint regions of the bonded joints reduce the strength of the bonded joints. The proper distribution of stresses in the bonding area is crucial for improving the performance of the bonded joints. In this context, when the failure loads and the mechanical properties of the bonded materials are evaluated together, it can be concluded that the variation in failure loads is due to the stiffness characteristics of the materials [21] .

When examining the surfaces of the bonding area, considering the types of damage in the bonded parts, it was observed that adhesion failure (failure at the interface between the adhesive layer and the bonded material) occurred in the majority of the joint specimens. Additionally, in some areas of the bonding surfaces, cohesive failure (failure within the adhesive layer) was observed due to the non-uniform distribution of the adhesive or its presence on only one surface of the part. In some specimens where PPR parts were bonded, fractures occurred in the bonding region, and the failure was attributed to defects in the base material.These findings highlight the importance of stress distribution, material properties, and surface preparation in determining the failure behavior and performance of bonded joints.

4. CONCLUSIONS

In this study, single-lap adhesive joints with a lap length of 25 mm were produced using different materials produced using SLA and FDM technology, and the mechanical properties of the parts produced by different additive manufacturing methods at the end of the adhesive bonding process were examined. The following results were obtained in the study:

- It was determined that the tensile specimens produced from PLA material have better mechanical properties in terms of tensile strength and modulus of elasticity compared to the specimens produced from PPR material. However, the strain rates of PPR specimens were found to be very high compared to PLA specimens. The modulus of elasticity values of PLA specimens were 85% higher than PPR specimens.
- It was observed that the tensile strength of the samples produced from PLA material was 65% higher than the samples produced from PPR material. PLA tensile specimens offer higher tensile strength and stiffness, while PPR specimens are more flexible and have higher strain capability.
- The damage loads of the bonded joint specimens were found to differ according to the type of material bonded. The highest damage load value was obtained in PK specimens where PLA and composite materials were bonded. For this reason, it was determined that the selection of the materials to be bonded is very important in the applications to be realized.
- PPR materials produced by SLA method performed better than other material types in terms of unit elongation values under load due to their high strain capability.
- When the failure load capacities of the bonded joints were analyzed, it was determined that PK had 62.2% higher value than SP. When the displacement data were analyzed, it was determined that SS had 129.7% higher value than PP.
- In order to improve the performance of adhesive joints, it was determined that homogeneous stress distribution in the adhesion zone contributes positively to the mechanical performance of the parts.
- PLA materials can be preferred in applications requiring high mechanical strength and PPR materials can be preferred in applications requiring flexibility.

The following suggestions are presented for future studies.

Studies can be conducted for different lap lengths and bonding thicknesses in bonding joints. Also, studies can be carried out to increase the bonding surface area by creating recesses in the bonding area. For PPR and SLA materials, different filling ratios can be produced and the effect on bonding performance can be examined.

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