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Enhancement of Shear Strength in Lap Joints with Different Surface Patterns

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ABSTRACT

In this study, surface patterning with CNC vertical machining center was applied to the aluminum surface for the enhancement of the shear strength of the epoxy-bonded lap joints. It was found that the pattern shape affected shear strength and among vertical, square, horizontal, 45 degree and diamond patterns, 45-degree provided the highest shear strength of 24.6 MPa. Moreover, the pattern features also affected the shear strength. A decrease in the depth led to slightly lower shear strength, whereas an increase in the depth gave a slight enhancement. The optimum depth was found as 300 µm and the obtained shear strength was calculated as 25.5 MPa. Additionally, an increase in the width length led to lower shear strength. On the other hand, a decrease in the width length provided higher shear strength. The increment became smaller as the width length increased. Also, after a point, the trend reversed and the shear strength decrease slightly. The optimum width length and the corresponding shear strength were found as 1.0 mm and 28.0 MPa, respectively.

Farklı Yüzey Desenli Bindirmeli Bağlantılarda Kesme Mukavemetinin İyileştirilmesi

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ÖZ

Bu çalışmada, epoksi ile bağlanmış bindirmeli bağlantıların kayma mukavemetinin arttırılması amacıyla, alüminyum yüzeylere CNC ile yüzey desenleme işlemi uygulanmıştır. İşleme şeklinin kayma mukavemetini etkilediği görülmüş ve dikey, kare, yatay, 45 derece ve baklava şekillerinden 45 derece şeklinin 24,6 MPa ile en yüksek mukavemeti verdiği gözlenmiştir. Ayrıca şekil özelliklerinin de mukavemeti etkilediği anlaşılmıştır. Derinlikteki azalma daha düşük kayma mukavemetine yol açarken, artma ise daha yüksek değerler sağlamıştır. Optimum derinlik 300 µm olarak bulunmuş ve elde edilen kayma mukavemeti 25,5 MPa olarak hesaplanmıştır. Bunların yanı sıra, şekil genişliğinin artması daha düşük mukavemete yol açmıştır. Diğer yandan genişliğin azalması ise daha yüksek mukavemet sağlamıştır. Ayrıca, bir noktadan sonra trend tersine dönmüş ve mukavemette azalma gözlenmiştir. Optimum genişlik ve sağladığı kayma mukavemeti sırasıyla 1,0 mm ve 28,0 MPa olarak bulunmuştur.

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1. Introduction

Lap joints are more advantageous than traditional methods such as welding, riveting, or bolt joints since they provide lighter structure designs, good stress distribution, and short application time with lower costs (Hunter et al., 2017). Unlike the lap joints, the biggest disadvantage of bolted nut connections is that the fasteners increase the weight of the system. In addition, since the fasteners are generally made of steel and its alloys, they are subject to corrosion according to the working environments. This reduces the life of the connection system (Böhm et al., 2022).

In lap joints, epoxy adhesives have been utilized to join the metal parts in various industries such as civil infrastructure, automotive, marine engineering, and aerospace (Ayatollahi et al., 2017). They have ease of application and can apply to large surface areas (Wang et al., 2016). However, they suffer from cracking both in the epoxy layer and between epoxy-substrate interfaces when they are exposed to shear strength. The most common cracking occurs in the interface. Hence, it is important to enhance the epoxy-substrate surface interaction to increase the shear strength. Since it is well known that surface features and treatments play an important role in this interaction, various studies have been conducted on the surface treatments such as sandblasting, sandpaper polishing, sanding, shot blasting, surface patterning (longitudinal grooves, transverse grooves, dimples and grids), grit blasting, electrical discharge, plasma treatment, chemical (acid (HCl, nitric acid, sulfuric acid/sodium dichromate, chromic acid etchings), NaOH etching, photopolymerization grafting, polymer coating), electrochemical phosphoric acid anodizing, forest product laboratory etching, sulfuric acid anodizing, laser treatment (laser surface texturing, laser-induced line patterning, fiber laser treatment), zirconium conversion treatment, silane treatment, alkaline degreasing, vibratory shot peening, anodizing with vibrational shot peening, aluminum patching, composite layer production by an in-situ reaction synthesis, embedding a wavy net-like thermoplastic insert, micro-mesh printing, surface functionalization (Wang et al., 2017; Nemati et al., 2018; Coban et al., 2019; Feng et al., 2019; Kwon et al., 2019; Mehr et al., 2019; Morfini et al., 2019; Pizzorni et al., 2019; Rudawska et al., 2019; Shokrian et al., 2019; Akiyama et al., 2020; Baby et al., 2020; Bangash et al., 2020; Bora et al., 2020; Delzendehrooy et al., 2020; Kanani et al., 2020; Li et al., 2020; Mandolfino et al., 2020; Pawlik et al., 2020; Sim et al., 2020; Sorrentino et al., 2020; Sun et al., 2020; Van Dam et al., 2020; Xie et al., 2020; Yudhanto et al., 2020; Zhang et al., 2020; Suzuki et al., 2021; Tuovinen et al., 2021; Safari et al., 2022). They have focused on increasing the surface roughness of the substrate and enhancing the mechanical interlocking between epoxy and substrate to improve their interaction by increasing the surface area of the substrate. Among these treatments, surface patterning is advantageous due to ease of application, high precision control on parameters, reproducibility, and cost-effectiveness. It has been observed that generally sandblasting and chemical abrasions are used to increase the surface roughness. It was determined that the method of increasing the surface roughness with the surface pattern was not used. Surface patterning can be easily obtained by surface machining with a computer numerical control (CNC) machine. Moreover, by CNC, different patterns can be applied to the surface. Furthermore, pattern features should be optimized since very small features prevent thick and viscous adhesive solution from penetrating microcavities on the surface during the curing period of the adhesive. Thus, dilution or pretreatment of the adhesive solution should be needed for these surfaces (Wang et al., 2017). To avoid this extra treatment, the feature size could be adjusted and full penetration of the adhesive into these features can be acquired.

In this study, various surface patterns were processed with a CNC machine onto the aluminum surface to achieve high shear strength for the lap joints bonded with epoxy adhesives. The dependency of the shear strength to epoxy/hardener ratio, the pattern shape and features were also evaluated. The most suitable epoxy/hardener ratio and the most suitable surface pattern were determined.

2. Materials and Methods

2.1. Materials

Lap joint test specimens were made from Al 7075-T6. Its chemical and mechanical properties can be seen in Table 1. The Demarin Epo 300 brand epoxy-based adhesive was utilized for the adhesion of the lap joints. Ethanol and acetone were obtained from Sigma-Aldrich (Merck) and used as received.

Table 1. The chemical and mechanical properties of Al 7075-T6

Mechanical Properties		Chemical composition (%)	
Tensile stress (MPa)	570	Zn	5.50
Yield stress (MPa)	505	Si	0.13
Density (kg m-3)	2810	Mn	0.30
Elongation (%)	11	Cr	0.28
Hardness (HB)	102	Ti	0.20
Elastic modulus (N mm-2)	72000	Cu	2
Poisson Ratio	0,33	Mg	2.9
		Al	88.69

2.2. Substrates and Surface Preparation

The shear strength test specimens were produced from Al 7075-T6. The dimensions of the specimen can be seen in Fig. 1.

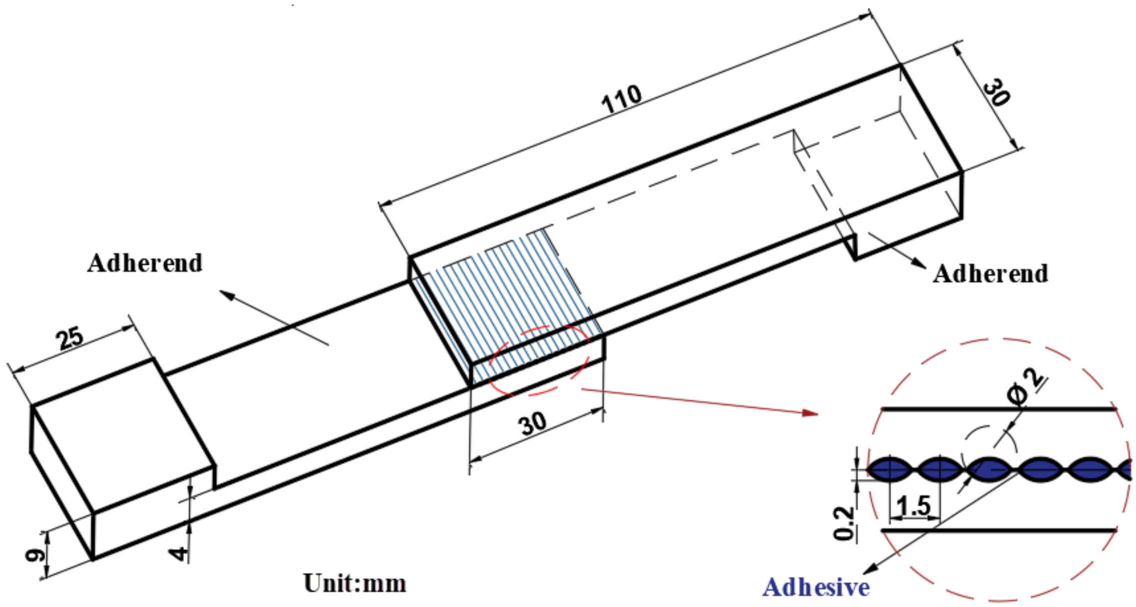

Figure 1. The sketch of the shear strength test specimen

To achieve enhanced bonding strength, substrate surfaces were processed with Pro-X PPF-22020 2F spherical carbide end mill cutter having a diameter of 2 mm. For the cutting parameters, the cutting speed was adjusted as 58 m.min$^{-1,}$ and the feed rate in the x, y, and z axis was utilized as 350, 350 and 300 mm.min^{-1}. The depth of the end mill cutter indentation was 0.2 mm. The surface patterns were processed with TAKUMA JVH-710 CNC vertical machining center (Fig. 2). The sketches of the surface patterns can be seen in Fig. 3. Burnishing was applied to the test specimen surface after surface patterning. The surface of the specimen was cleaned with ethanol and acetone before utilization to prevent dirt and oil occurrence on the test specimen surface.

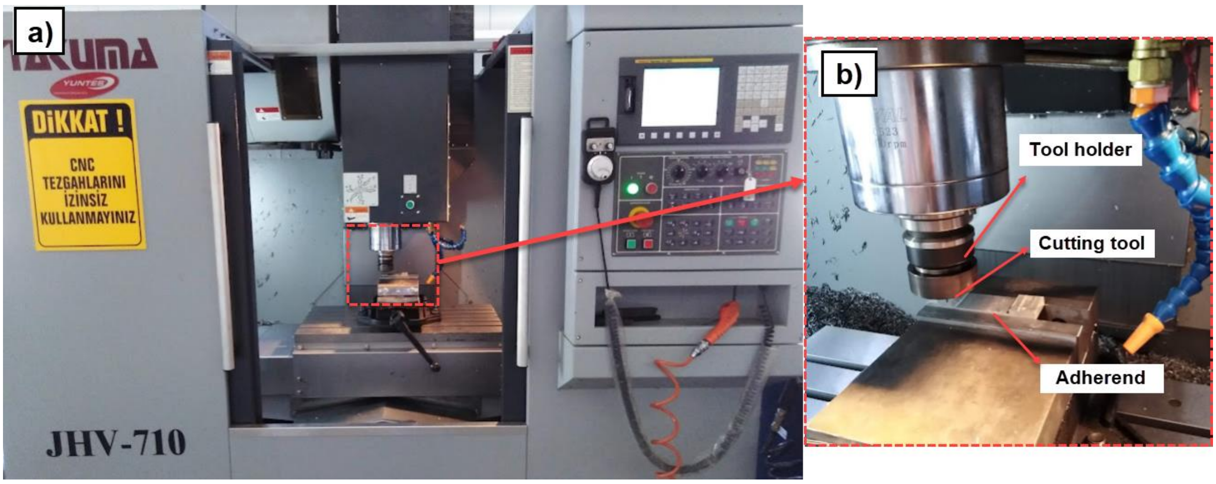

Figure 2. Machining of samples on CNC machine, a) the CNC vertical machining center utilized for the surface patterns, b) the image of the machining adherend

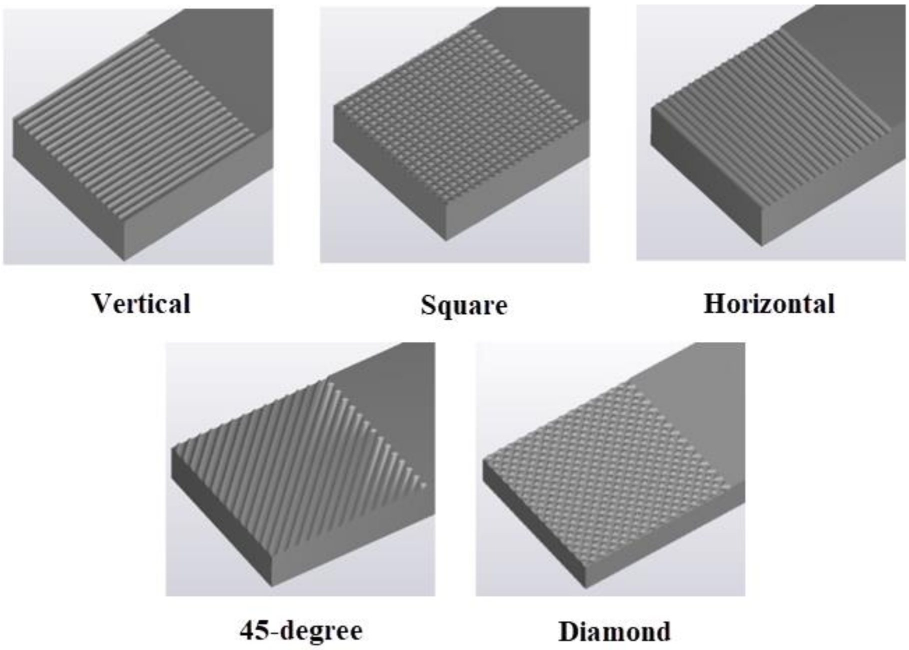

Figure 3. The sketches of the surface patterns

2.3. Shear Strength Test

The shear strength tests were conducted via the Alşa test machine (Fig. 4) with a displacement rate of 2 mm min^{-1}.

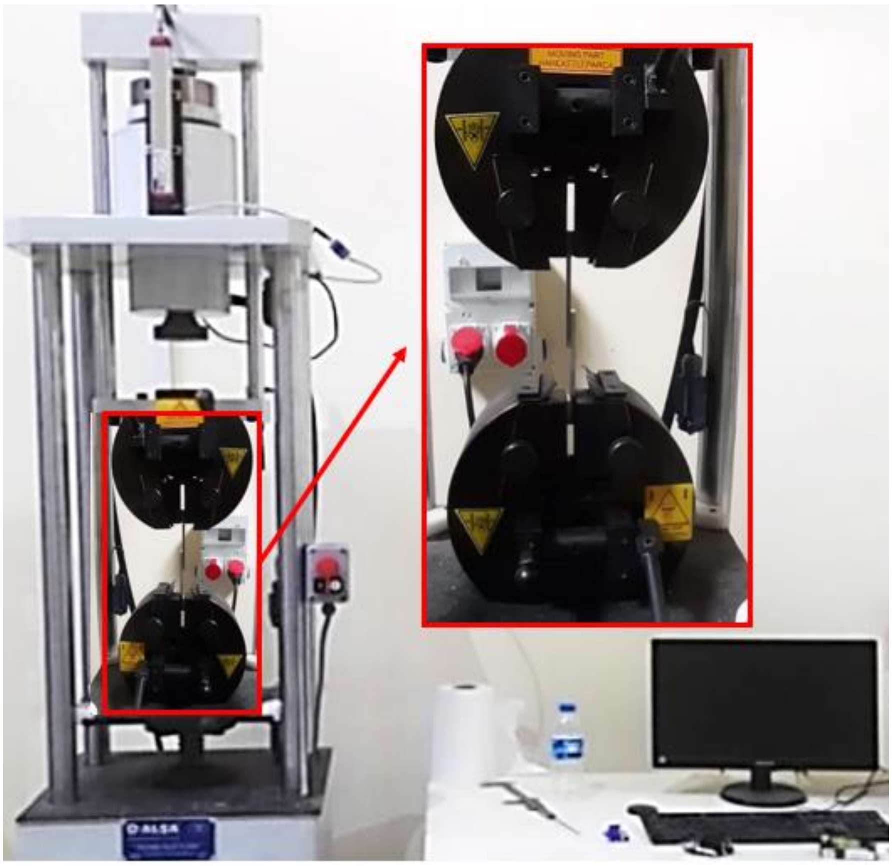

Figure 4. The shear strength test machine

3. Results and Discussion

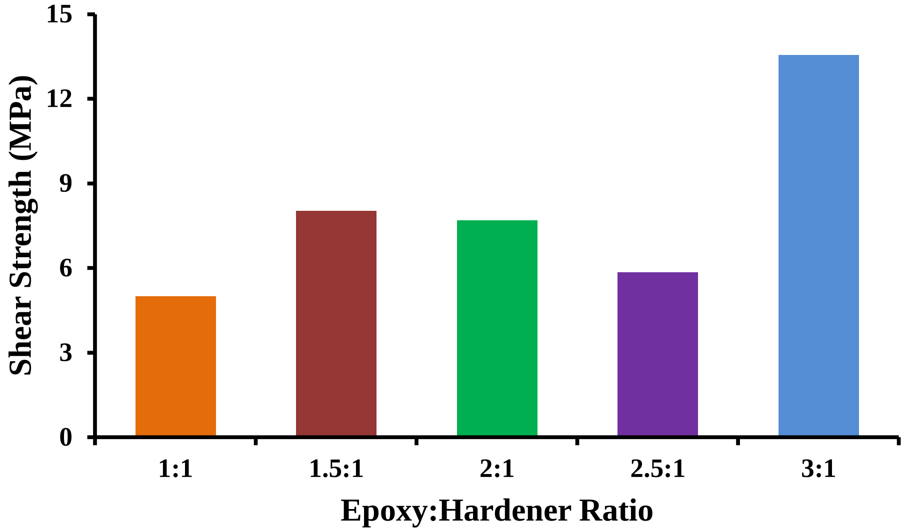

Figure 5. The effect of epoxy/hardener ratio on the shear strength

It is well known that surface characteristics have an important role in the adhesion of epoxy to the adherent surface. The mechanical interlocking between epoxy and an adherent surface interface can enhance adhesion strength. Thus, improving the mechanical interlocking can play an important role in the enhancement of joint strength. The improvement in mechanical interlocking can be obtained by surface treatment (Baburaj et al., 2007). Thus, for this purpose, various patterns were processed onto the aluminum surface to achieve higher adhesion strength between the epoxy and the aluminum surface for the enhancement of lap joint shear strength (Fig. 6). The shape and direction of the patterns were differentiated to find the best pattern that could demonstrate highest shear strength in the lap shear tests. Surface roughnesses against the shear stress direction increase the peel strength (Van Dam et al., 2020). Different shapes engraved on the surfaces change the surface roughness and shape of the roughness. The effects of pattern shape and direction could be easily seen in Fig. 7. The lowest shear strength was observed for the horizontal pattern and found as 16.9 MPa. Moreover, the shear strength increased as the pattern shape was changed to square, vertical, and diamond patterns, and it was calculated as 19.9, 21.9, and 23.0 MPa, respectively. The highest value was observed for 45-degree patterns and it was measured as 24.6 MPa. The results showed that surface patterning affected the shear strength of epoxy-bonded lap joints and the values depended on the pattern shape. With this result, the adhesion strength of sandpaper polished substrate was increased by 81% after being processed with 45-degree patterns.

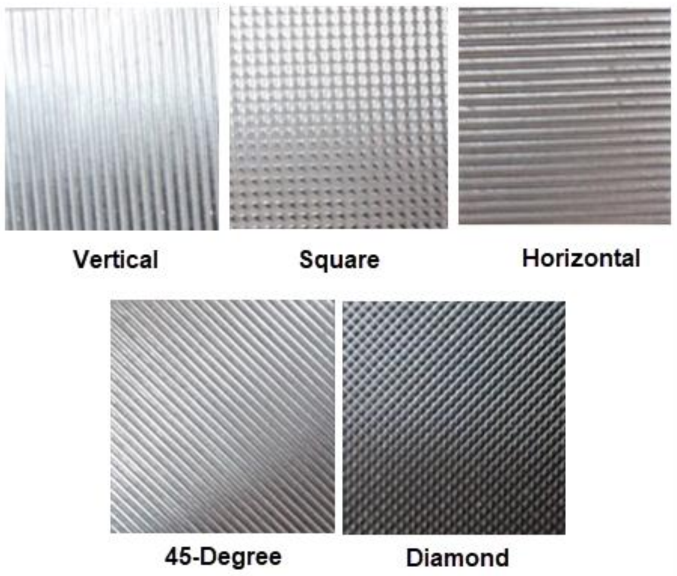

Figure 6. The surface patterns of the lap joints

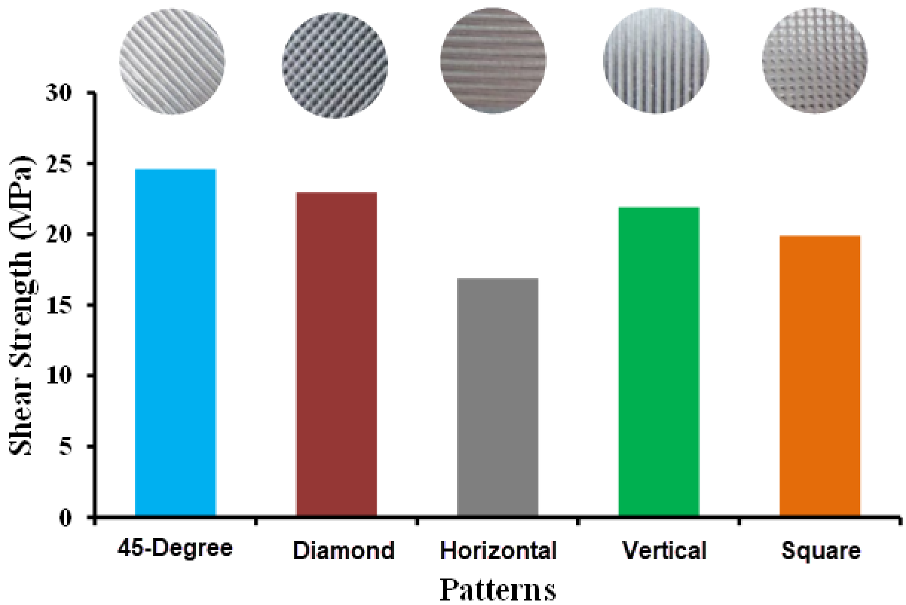

Figure 7. Shear strength test results of various surface-shaped specimens

Besides the surface pattern shape, the pattern dimensions could also affect the adhesion strength of the epoxy onto the aluminum surface. To examine the dimension effect, the pattern of 45 degrees that provided the highest shear strength was utilized with lower and higher widths and depths. It can be seen from Fig. 8 that, an increase in the depth provided slight enhancement whereas a decrease in the depth led to slightly lower shear strength. From this result, it could be concluded that the depth of the pattern affected the shear strength slightly and 300 μm could be regarded as the optimum depth for the epoxy application with a shear strength of 25.5 MPa. On the other hand, the width length demonstrated more effect on the shear strength. As the width length decreased, the roughness and area of the metal surface increased. Thus, the epoxy had more surface area to interact and the adhesion between epoxy and metal surface was enhanced (Kanani et al., 2020). This increase provided a positive impact on the shear strength. When width lengths were 2.5, 2.0, 1.5, and 1.0 mm, the shear strengths were found as 20.3, 24.6, 27.1, and 28.0 MPa, respectively. Moreover, the increment became smaller as the width length increased. Also, after a point, the trend reversed and the shear strength decreased slightly. This may be due to the epoxy penetration problem into the channels having lower dimensions. When the dimensions decreased, the viscous epoxy could not effectively fill the channels and voids and air bubbles occurred. The epoxy-metal surface interaction suffered from this condition and the shear strength decreased (Rudawska et al., 2019). Moreover, the increase in the width length led to a decrease in the shear strength. Since fewer channels with higher dimensions provided lower roughness and surface area for the epoxy adhesion, the adhesion strength decreased and the shear strength value also showed decrement.

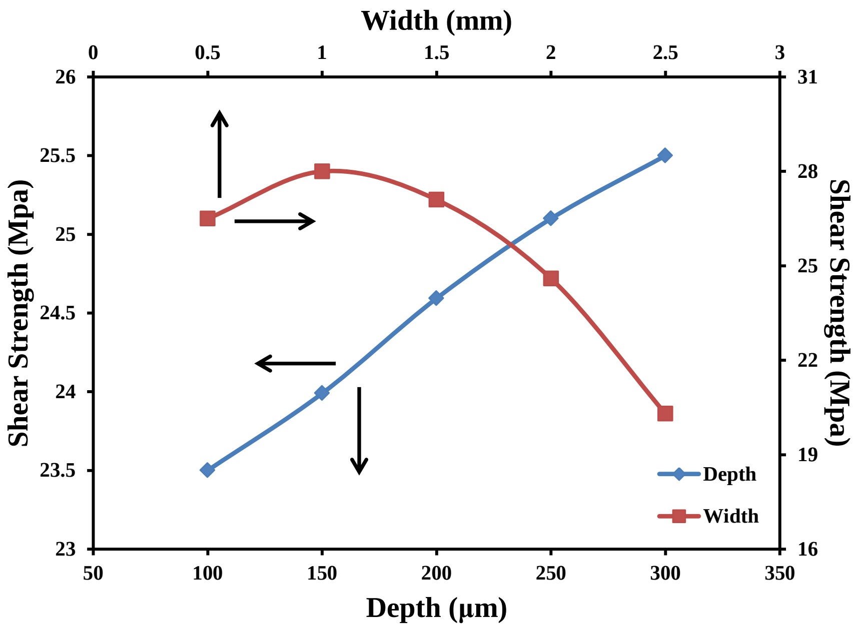

Figure 8. Best shape with different channel widths and depth

4. Conclusion

Various surface patterns were processed with CNC vertical machining center on an aluminum surface to increase the shear strength of the lap joints bonded with epoxy adhesives. It was found that the shear strength was pattern-shape dependent. Among the patterns vertical, square, horizontal, 45 degrees and diamond patterns, 45 degrees were utilized, and 45 degrees demonstrated the highest enhancement. The shear strength increased from 13.6 to 24.6 MPa after the application of 45-degree patterns. Moreover, it was found that the pattern features also affect the shear strength. A decrease in the depth led to slightly lower shear strength, whereas an increase in the depth provided slight enhancement.

The optimum depth was found as 300 μm and the obtained shear strength was calculated as 25.5 MPa. Furthermore, an increase in the width length led to a decrease in the shear strength. On the other hand, a decrease in the width length provided higher shear strength. The increment became smaller as the width length increased. Also, after a point, the trend reversed and the shear strength decrease slightly. The optimum width length and the corresponding shear strength were found as 1.0 mm and 28.0 MPa, respectively. These results showed that patterning can enhance the shear strength of the lap joints bonded with epoxy adhesives.

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Statement of Conflict of Interest

The authors have declared no conflict of interest.

Author's Contributions

The authors contributed equally.

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