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Review paper

REVIEW OF POLYMER-MATRIX COMPOSITES WELDED TO ALUMINIUM ALLOYS

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This review covers previous work by different scholars on welding polymer-matrix composites to aluminium alloys between 2015 and 2021. The highest tensile shear stress measured for the joint between polymer-matrix composite and aluminium (AA7075) alloy was 59.9 MPa. Welding using top-thermic friction stir was the method that produced the desired outcome. Additionally, the aluminium (AA2024) alloy and fibre-reinforced polymer composite were joined using an ultrasonic metal welding procedure, which produced a weld with a high tensile shear strength of roughly 58 MPa. The friction-aided joining of carbon fibre-reinforced polyphenylene sulphide composites and aluminium (AA7075) alloy has been studied by researchers. A laser treatment was applied to the aluminium surface to enhance the interlocking between the two materials being combined. This development was reported to cause inadequate bonding between the polymer-matrix composite and the metal. Despite this, the joints demonstrated significant load-bearing capacities of up to 10.7 kN.

Keywords: polymer-matrix composites, mechanical properties, reinforcements, welding, aluminium alloys.

INTRODUCTION

Composites are joined to metals to exploit their distinctive characteristics and considerably improve the metal's isotropic behaviour (1). Several welding methods have been employed in the joining of composites to metals (2). When welding thermoplastic composites to metals, the interface at the joint is heated above the melting point (for semicrystalline polymers) or beyond the glass transition temperature (for amorphous polymers) and is then compressed to consolidate (3). Thermosetting and thermoplastic polymers are often used as matrices for polymer matrix composites for various technical applications due to their low melting points (4), lightness in weight, and ease of processing amongst others. Nonetheless, thermoplastic-based composites are mostly utilized because they can be recycled, have shorter times of processing, have high resistance to impact (3, 5), and can be applied from microelectronics to large wind turbine blades (6).

Two or more components (phases) are combined to form a composite material (7, 8, 9). The overall composite will have qualities that are distinct from those of its constituent parts while maintaining the characteristics of each. Rice and Sparks (8) reported that the matrix and one or more scattered phases are the two distinct and separate phases that must be present in a composite material. When compared to any of the components, its bulk characteristics are different. The scattered phase is held in place by and shares a load with the

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matrix, the principal continuous phase. Typically, it is a softer phase and is more ductile. The secondary phases that are incorporated into the matrix are called dispersed phases. The reinforcing phase is frequently used to describe this phase since it is often stronger (8).

Numerous metallic components have been replaced with composite materials, particularly in the sectors of aircraft, avionics, civil structures, automobiles, and sports equipment (8). Future use of these materials is anticipated to see a patronage increase of roughly 5% on average annually. Their high strength and stiffness-to-weight ratio are factors contributing to this increase. Some advanced composite materials can be as strong and rigid as some structural metal alloys while having a much lower density and total component weight (10). Advanced composites are very appealing in circumstances where the component's weight is important because of these features. The fundamental drawback of most composite materials, similar to ceramic materials, is their fragility and low fracture toughness. By carefully choosing the matrix material, some of these flaws may be remedied in specific circumstances (7, 8).

Polymer-matrix composites (PMCs) have lower strength and heat resistance compared to the metal matrix and ceramic matrix composites (8). The maximum service temperature is typically determined by the polymer matrix since it frequently softens, melts, or degrades at a much lower temperature than the fibre (7). The least expensive polymer resins are polyesters and vinyl esters. Glass fibre-reinforced composites are the primary end-uses for these matrix materials (11). Several resin compositions offer a variety of properties for these polymers. Epoxies are widely used in PMCs for aerospace applications because they are more moisture-resistant and have better mechanical qualities than polyester and vinyl resins. The highest temperature for continuous use of polyimide resins, which are employed in high-temperature applications, is about 230 °C. Lastly, high-temperature thermoplastic resins with promise for use in aerospace applications include polyether-ether-ketone (PEEK), poly (phenylene sulphide), and polyetherimide (7).

The joining of thermoplastic composites is a crucial step in the construction of thermoplastic composite aeroplane structures. Researchers have studied and developed a few joining methods for thermoplastic composite components. The main types of attachment for thermoplastic composites are mechanical fastening, welding, or fusion bonding, solvent bonding, and adhesive bonding. Welding offers a lot of potential for joining, assembling, and repairing thermoplastic composite components and has several advantages over other joining techniques. Fusion-bonding includes melting the polymer on the component bond surfaces, forcing those surfaces together, and then allowing the polymer to solidify and consolidate (12).

COMPOSITES MADE OF POLYMER-MATRIX THAT CAN BE WELDED TO ALUMINIUM ALLOYS

POLYMER-MATRIX COMPOSITES (PMCS)

In polymer-matrix composites (PMCs), which feature a polymer resin matrix, fibres act as the reinforcing medium. These materials are used in the biggest variety of composite applications and in, the highest quantities because of their room-temperature properties, ease of manufacture, and low cost (7). Future developments are required to boost mechanical characteristics even more and create quick and affordable processing techniques. Fin-

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ding reinforcements and processing settings that can meet these demands are therefore heavily prioritized (6, 13).

COMPOSITES MADE OF GLASS FIBRE-REINFORCED POLYMERS

Fibres enclosed in a polymer matrix make up the composite material known as fibreglass (7). Typically, fibre diameters fall between 3 and 20 μm. Several factors make glass an attractive material for fibre reinforcement. When combined with other polymers, it produces a composite with a very high specific strength, which makes the composite useful in a variety of hostile environments (14). It can be produced into an affordable glass-reinforced plastic using a wide range of composite production processes, and it is widely available.

Numerous manufacturing processes are used to produce glass fibre-reinforced polymer composites, which are extensively used in a wide range of industries. Glass fibre-reinforced composites have received a great deal of investigation in recent years (15) because of their exceptional mechanical properties. They have been used often in advanced technical applications. But because composites are anisotropic, it can be very difficult to detect damage and failure when they are subjected to real-time loads (16).

COMPOSITES MADE OF CARBON FIBRE-REINFORCED POLYMER

Composites made of carbon fibre-reinforced polymer (CFRP) are incredibly strong and light fibre-reinforced polymers. They are widely employed in an expanding variety of consumer and technical applications that call for materials with a high strength-to-weight ratio and stiffness (rigidity) (7, 17). Although other thermoset or thermoplastic polymers, such as polyester, vinyl ester, or nylon, are sometimes utilised, the binding polymer is often a thermoset resin like epoxy. However, it is occasionally necessary to manually process CFRP composites to get the desired design (18).

ARAMID FIBRE–REINFORCED POLYMER COMPOSITES

A long-chain synthetic polyamide fibre with at least 85% of the amide linkages directly connected to two aromatic rings is known as an "aramid fibre" (41). Because they beat metals in terms of strength-to-weight ratios, aramid fibres are frequently used. Since the fibres are ductile and relatively flexible, they may be processed using the most common textile methods. The most important trade names for aramid textiles include Nomex and Kevlar (7). These aramid composites are often employed in ballistic products (bulletproof jackets and armour), sports equipment, tires, ropes, missile casings, and pressure vessels, and as an asbestos substitute in brake and clutch linings and gaskets for vehicles (7).

WELDING POLYMER-MATRIX COMPOSITES TO ALUMINIUM ALLOYS

In the production process of welding, components are melted together and then cooled to create fusion, thereby joining the materials. Welding can take place between a thermoplastic and a metal. The parent metal (base metal) is melted during welding, unlike lower-temperature processes like brazing and soldering (20, 21). When the polymer chains on the

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surface of one component are sufficiently mobile to entangle with chains on the surface of the other component, polymer welding occurs (22).

Not all welding techniques are appropriate for connecting composites made of polymer-matrix materials with aluminium alloys. Abrasive stir welding, according to Huang et al. (23), is a potential production technique for combining aluminium and polymer-matrix materials because it joins the materials below their melting temperatures (23, 24). The two components may be fused - a technique known as fusion welding - or they may be joined together under pressure and maybe with the addition of heat to form a metallic connection across the interface.

STIR-WELDING USING FRICTION FOR POLYMER-MATRIX COMPOSITES AND ALUMINIUM ALLOYS JOINTS

Since its invention in 1991, friction stir welding has been utilised to combine thermoplastics as well as aluminium alloys (25).

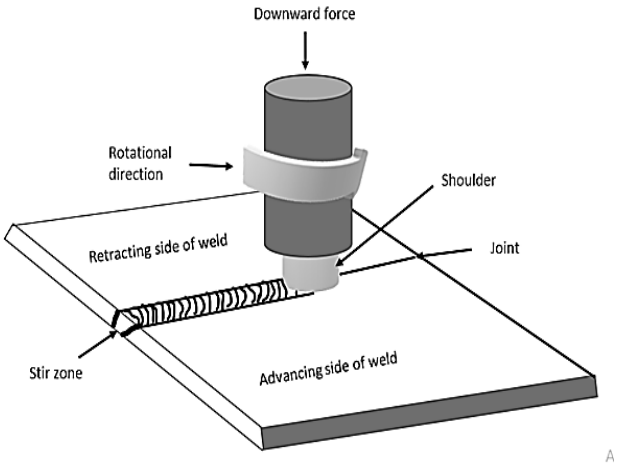

Figure 1. The friction stir welding method (26, 27)

Contrary to conventional friction welding techniques, which rely on relative motion between the two elements to be fused, friction stir welding involves driving a rotating or reciprocating tool down the joint line between two stationary components. As a result of frictional contact between the material and the moving tool, the polymer at the junction melts (25), and when the tool has passed, the material solidifies to form a weld (25), as seen in Figure 1 (26, 27).

ULTRASONIC WELDING OF POLYMER-MATRIX COMPOSITES TO METALS

High-frequency mechanical sound energy is used in ultrasonic welding to soften or melt the thermoplastic at the connecting line. Under pressure, ultrasonic vibrations at a frequency of 20 or 40 kHz are then applied to the pieces that need to be joined through the welding horn (25). Figure 2 (28, 29) depicts the ultrasonic welding setup.

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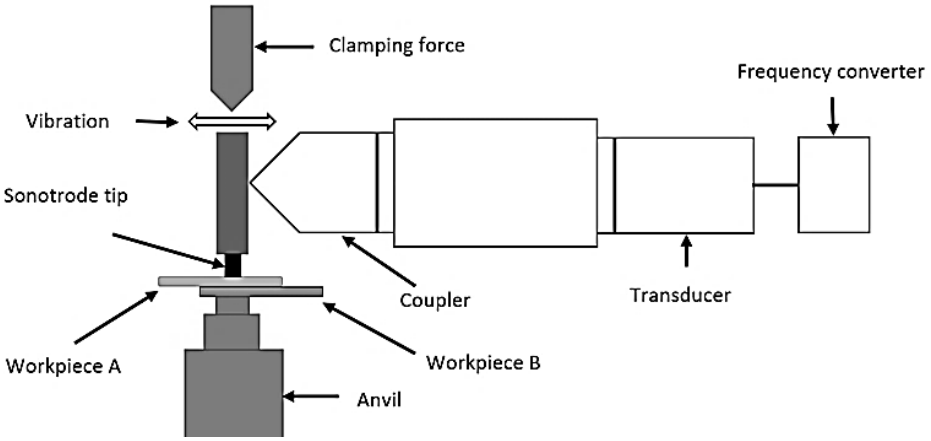

Figure 2. Set-up for the ultrasonic welding (28, 29)

The ultrasonic welding method has a varying heating effect depending on the type of material being welded. The mechanical properties of the material to be welded, the component design, and the welding equipment design all have an impact on how successfully a component can be welded (25). The thermoplastic composite structures may be joined quickly and with high bonding strength using the ultrasonic welding (UW) process (30).

Due to the significant difference in the thermal expansion coefficients of metal and composite, ultrasonic welding is currently only possible at very small polymer matrix composite-metal junctions (31). This variation in coefficients of thermal expansion, according to Melentiev et al. (31), might lead to thermal cycling wear.

LASER WELDING OF METALS TO POLYMER-MATRIX COMPOSITES

During laser welding, a strong beam of light, frequently in the infrared portion of the electromagnetic spectrum, is directed towards the material to be connected (32). This causes a resonance frequency in the molecule to be excited, which heats the substance in the vicinity.

The use of laser welding in the industry has just recently emerged after being originally tested on thermoplastics in the 1970s (25). The two types of laser welding that are frequently used are transmission, and carbon dioxide laser welding techniques. Plastics easily absorb CO_2 laser radiation, but they also restrict the depth to which the beam may penetrate, making film applications the only feasible use for the method. The Nd: YAG and diode lasers have less of a tendency to absorb their radiation than other types of lasers and are appropriate for transmission laser welding. To guarantee that the laser beam concentrates on the joint region during welding, one of the polymers must transmit laser light while the other must absorb laser energy (25).

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OVERVIEW OF CURRENT LITERATURE RELATED TO THE JOINING OF POLYMER-MATRIX COMPOSITES (PMC) TO METALS

TRENDS IN ACADEMIC RESEARCH ON COMPOSITES WITH POLYMER-MATRIX WELDED TO METALS (2015 – 2021)

Discussions in the previous sections have mentioned the various techniques which have been used successfully to join polymer-matrix composites (PMCs) to metals. PMCs – metal joints have recently attracted several research interests from various authors across the globe. For instance, up to 9,083 papers have been published on PMCs welded to metal between 2015 to 2021 as presented in Table 1.

Table 1. Polymer-matrix composites that are welded to metals: trends in academic publications (2015 – 2021)

Year	Publications on polymer-matrix composites welded to metals	Ref.
2015	796	(33)
2016	927	[34)
2017	1,090	(35)
2018	1,220	(36)
2019	1,400	(37)
2020	1,630	(38)
2021	2,020	(39)
Total	9,083	

As can be seen from Table 1, there is a progressive growth in research about joining PMCs to metals. This can be attributed to the recent demand for metal-composite structures in several engineering applications, especially in aircraft industries (40). The overview of the findings of some of these studies on the welding of PMC to metals is presented in Table 2.

PREVIOUS STUDIES ON POLYMER-MATRIX COMPOSITES WELDED TO METALS

Table 2 provides a summary of several studies that have looked at the welding of polymer-matrix composites to metals.

Meng et al. (41) studied joints composed of PMCs and metals using the friction self-riveting welding method. The PMCs were softened and squeezed into the pre-fabricated holes and porous oxide structures under the frictional heat and forging force, mimicking the squeezing behaviour of the joining process to cause mechanical interlocking. The resulting joints were evaluated to ascertain their strength. It was observed that the joint attained maximum tensile shear strength of 27 MPa. In another study conducted by Li et al. (42), in which a PMC was joined to AA7075 aluminium alloy using a top-thermic friction stir lap welding technique. The tensile shear strength of the joint was found to be 59.9 MPa. Al-Obaidi (61) investigated the influence of prominent bonding factors (metal thickness, vibration amplitude, and bonding forces) on the ultrasonic joining of an amorphous thermoplas-

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tic polymer (ABS 750 SW) to an aluminium alloy (Al 6082-T6). He concluded that increasing bonding pressures, oscillation amplitude, and bonding duration resulted in increased lap shear strength (> 2.31 MPa), and pre-treatment of Al alloy resulted in improved mechanical interlocking between the polymer and metal alloy surfaces.

Table 2. A summary of prior research on metal-welded polymer-matrix composites

Welded materials	Welding technique	The strongest possible tensile shear (load) attained	Ref.
Metal + polymer-matrix composite	Friction self-riveting welding	27 MPa	(41)
7075 aluminium alloy + polymer-matrix composite	Welding using top-thermic friction stir	59.9 MPa	(42)
Aluminium alloy 6014 with carbon fibre-reinforced polymer composite	Spot welding with regenerated friction	(1.6 kN)	(43)
Short carbon fibre reinforced polyether-ether ketone composite with aluminium alloy AA2060-T8	Friction stir welding with joint performance and shape control	33 MPa	(44)
Composite made of carbon fibre-reinforced polymer and aluminium alloy	An innovative static shoulder design for friction stir spot welding	(0.26 kN)	(45)
Aluminium alloy + polymer composite	Electromagnetic pulse welding	-	(46)
AA5754 aluminium alloy + poly methyl methacrylate composite	Stir-welding using friction	50 MPa	(47)
Metal + thermoplastic composite	Welding using resistance elements	-	(48)
Composite made of polyether ether ketone reinforced with carbon fibre and aluminium alloy	Spot weld using the friction-stir process	(2.69 kN)	(49)
Composite material reinforced with extra carbon fibre and aluminium alloy (AA5052)	Spot weld using the friction-stir process	(1.78 kN)	(50)
Aluminium alloy AA7075 with carbon-reinforced polyphenylene sulphide	Joining with friction.	(10.7 kN)	(51)
SS304 stainless steel + glass fibre reinforced plastic composite	YAG Continuous wave laser welding	(4 kN)	(52)
Composite material made of carbon fibre and 6061 aluminium alloy	Hybrid laser-arc welding	(4.65 kN)	(53)
Aluminium alloy (AA5754) + composite made of carbon fibre-reinforced epoxy	Spot welding with ultrasound	34.8 MPa	(54)
Aluminium alloy (AA2024) + composite of fibre reinforced polymer	Spot welding with ultrasound	58 MPa	(55)
Composite made of carbon fibre reinforced polymer + aluminium sheet	Spot welding with ultrasound	30 MPa	(56)
aluminium (AA5052) alloy and Composite made of polypropylene and short carbon fibres (PP-SCF)	A new refill friction spot welding	28 MPa	(57)
Composite made of carbon fibre-reinforced poly (phenylene sulphide) and aluminium AA2024-T3 (alclad and bare)	Friction Spot welding	43 MPa and 27 MPa	(58)
Carbon fibre reinforced polymer composite [CFRPC] with metal (steel DC01 and aluminium AlMg3) (CF-PEEK and organic sheets CF-PA66)	Induction Spot Welding	$AlMg_3$/CF-PA66 is 14.5 MPa, while DC01/CF-PEEK is 20 MPa.	(59)
Stainless steel + polymer-matrix composite	Dynamic joining	(4.99 kN)	(60)
Amorphous thermoplastic polymer (ABS 750 SW) + aluminum alloy (Al 6082-T6)	ultrasonic welding	> 2.31 MPa	(61)

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Ashong et al. (43), studied the refill friction stir spot welding of dissimilar AA6014 Al alloy and carbon-fibre-reinforced polymer composite. The joint was found to support a maximum load of 1.6 kN. Huang et al. (44) investigated the use of friction stir welding to link AA2060 aluminium alloy to short fibre-reinforced poly-ether-ether ketone while simultaneously managing shape and performance. It was observed that the joint provided high-quality surface integrity and maximum tensile shear strength of 33 MPa. In addition, it was found that reducing the heat input made it easier to get rid of welding flaws while also enhancing the joint's capacity to bear weight. Bolouri et al. (45) designed a unique static method for friction stir spot joining of Al alloys and carbon fibre-reinforced composites. To examine their impacts on the joining temperature, the interaction of the materials, and the strength of joints, the primary joining parameters, including pin rotational speed, pin feed rate, and pin plunge depth, were modified. It was found that the pin rotational speed had the greatest impact on the joining temperature, and a lap shear force of 230 to 260 N was observed. In a related study, Derazkola et al. (47) joined AA5754 aluminium alloy with poly methyl methacrylate via friction stir spot welding. It was observed that fewer flaws emerged as the interaction layer's thickness increased when the heat input into the stir zone was controlled by speeding up the rotation. Joint strength of 50 MPa was attained. Dong et al. (49) improved the welding parameters of the friction stir spot welding technique. With a plunge speed of 10 mm/min and an 8sec dwell period, it was found that the ultimate tensile shear force was 2690 N. Khalil et al. (46) studied the magnetic pulse hybrid joining of polymer composites to AA5052 aluminium alloy. The joint was found to support a maximum tensile shear load of 1779.6 N. The study noted two ways of establishing the joint namely: the employment of a metallic insert in a polymer composite and the use of an exterior patch. The mechanical tests indicated a negligible reduction in tensile strength when using magnetic pulse welding on the insert whenever the juxtaposition of the hole weld was avoided.

Troschitz et al. (48) carried out a study on the joining of thermoplastic composites with metals using resistance element welding. Metal (weld) inserts were employed to interact with the composite material, thereby giving rise to a top-notch joint. Lambiase et al. (51) studied the mechanism of bonding of AA7075 aluminium alloy and carbon fibre-reinforced polyphenylene sulphide (CFRP) during friction-assisted joining. The aluminium surface was given a laser texture to encourage interlocking between the two materials being put together. However, it was observed that there was poor contact between the metal and reinforced plastic substrates. Despite this, the joints had significant load-carrying capacities of up to 10.7 kN. In a related study, Kuzu et al. (52) used continuous wave laser welding technology to combine SS304 stainless steel and glass fibre-reinforced plastic composite. The results of the mechanical strength test (53) showed that the strongest joint could withstand a force of roughly 4000 N before breaking. On the other hand, the joint created by fusing AA6061 aluminium alloy and carbon fibre plastic composite with the help of a laser-arc hybrid welding technique yielded a maximum tensile shear load of 4650 N with a welding current of 90 Amperes (53).

The use of ultrasonic spot welding to join AA5754 aluminium sheet and carbon fibre-reinforced epoxy composite has been successfully carried out (54). The carbon fibre epoxy stack was coated with a thermoplastic polyamide film before curing, generating a functional surface on the thermoset matrix that made welding go more quickly. Average adhesive joint strength of 34.8 MPa was realized (54). Aluminium sheet and carbon-reinforced polymer

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composite were joined using an ultrasonic spot-welding procedure (56), resulting in a joint with a tensile strength of about 30MPa. When aluminium alloy and fibre-reinforced polymer composite were joined by ultrasonic metal welding, a greater tensile strength of 58MPa was obtained (55). Threaded Hole Friction Spot Welding (THFSW) which is a novel infill friction spot welding procedure, was developed by Pabandi et al. (57) to weld sheets of composite material made of short carbon fibre-reinforced polypropylene (PP-SCF) and AA5052 aluminium alloy. The method involved adding melted and then resolidified polymer to the pre-threaded hole. The findings showed that THFSW was effective in joining aluminium to polymer sheets, and the hole was filled with melted polymer. The joint's maximum shear strength was 28 MPa. Alclad and bare aluminium AA2024-T3 were joined together with carbon fibre-reinforced poly using the THFSW welding procedure. By employing aluminium bare specimens, lap-shear tensile strength as high as 27 MPa was reportedly attained. On aluminium surfaces, sandblasting was also used as an efficient mechanical surface pre-treatment. This increased surface roughness, which in turn enhanced the mechanical interlock and performance of the joint. The alclad specimens also had lap shear strengths of 43 MPa.

Mitschang et al. (59) studied induction spot welding of metal/CFRPC hybrid joints. Metal (steel DC01 and aluminium $AlMg_3$) and carbon fibre-reinforced polymer composite [CFRPC] (organic sheets CF-PA66 and CF-PEEK) were joined using induction spot welding (59). $AlMg_3$/CF-PA66 and DC01/CF-PEEK joints were observed to have shear tensile strengths of 14.5 MPa and 20 MPa, respectively. The study noted that for structural loading, joining polymer matrix composites to metal (like stainless steel) requires resolving intrinsic variations in the joining properties of each material. A substance that would act as a bridge between the metal and the composite is therefore required. A weldable, hard steel intermediate material that can also pick up the composite fibre stress would be suitable. It was explained that expanded mesh or shear studs that interact with and press on the crossovers of the composite's woven-reinforcement design serve as the intermediary in the "dynamic joining" idea. An ideal PMC-metal joint is one with the ability to absorb energy from the joint’s plastic behaviour. Strong structural stress transfer, scalable joint stiffness (based on the number of studs and their material properties), fabrication accuracy and use of commercial off-the-shelf processes to build the metallic portion of the joint are among the potential benefits of the dissimilar material joining concept. The greatest shear load of the dynamic joint between polymer matrix composites and metals according to Whitney & Bettinger (60), was around 4.99 kN. However, further study to investigate the mechanical behaviour of the welded joint using the diametral compression strength test (62) is advised.

CONCLUSIONS

In the present study that reviewed the welding of polymer-matrix composites and aluminium alloys, the following conclusions can be made:

(1) The maximum tensile shear stress obtained for the joint between 7075 aluminium alloy and polymer-matrix composite was 59.9 MPa (42), using top-thermic friction stir lap welding.
(2) Researchers have explored the friction-aided joining of AA7075 aluminium alloy and carbon fibre-reinforced polyphenylene sulphide composites (51). It was observed

that despite the processing circumstances involving the use of a laser to texturize the surface of the aluminium alloy, there was inadequate contact between the metal and reinforced plastic substrates. The joints did, however, possess excellent 10.7 kN load-bearing capacity.

(3) The ultrasonic metal welding process used in joining AA2024 aluminium alloy and fibre-reinforced polymer composite gave a high tensile shear strength joint of about 58 MPa.

The results above provide invaluable information that welding polymer-matrix composites to aluminium alloys utilizing friction stir welding and ultrasonic welding methods can result in a robust joint.

RECOMMENDATIONS TO FILL UP THE KNOWLEDGE GAPS FOUND AFTER REVIEWING EARLIER RESEARCH ON POLYMER-MATRIX COMPOSITES JOINED WITH ALUMINIUM ALLOYS.

After reviewing past studies on polymer-matrix composites welded to aluminium alloys, the following suggestions have been made to fill up the knowledge gaps found:

(i) There is limited knowledge about the optimum methods to prepare the interfaces (between the polymer-matrix composite and aluminium alloy) for welding. Future research into the appropriateness of the surface textures for welding from a metallurgical standpoint is advised.

(ii) The majority of the reviewed study focused on tensile and shear strengths. Investigations should be conducted into other crucial mechanical qualities such as ductility, impact resistance, compressive strength, and flexural strength.

(iii) Prior research largely concentrated on joints between aluminium alloys and polymer-matrix. It is recommended that research be done into the possibility of joining various metals and alloys to polymer-matrix composites.

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