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PROGRESS IN THE WELDING OF AL ALLOY THIN SHEET AND FUTURE PROSPECTUS FOR AUTOMOBILE

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ABSTRACT

Since the early 21st century, the automotive and aluminium industries have rapidly developed a variety of advancements in response to competitive, environmental, and technological problems. Reduction in tare weight of vehicle is one approach for dealing with some of these problems. Al alloys have potential to save mass, which is need for fuel efficiency, environment pollution and emerging electrical vehicle. The estimated consumption of Al alloy in vehicle by 2025 is 250 Kg from current 180 Kg. However, the difficulties in welding Al alloy have hindrance their widespread adoption. Al alloys, which are regarded as being challenging to fuse using a traditional process because of its intrinsic qualities, such as its low melting point, high thermal conductivity, high solubility in hydrogen, formation of oxides, and significant solidification shrinkage. Currently low heat input welding process such as MIGW, TIGW, FSW, LBW and EBW are employed by industries for thin sheet Al alloy. However, each of these techniques' variants suffers from few limitations. Therefore, joining of Al alloy thin sheet is still a difficult and costlier task. Weld beads frequently exhibit many defects which significantly lower the mechanical and fatigue strength of thin Al alloy sheets. This overview aims to provide a concise summary of current advancements in the joining of Al alloys and shows the future prospectus and direction of development in joining of thin sheet Al alloy. The researchers working on joining Al alloys are also intended beneficiaries of this study.

I. INTRODUCTION

The third most prevalent element in the Earth's crust is Al [1]. Al is distinguished by its appearance, lightweight, formability, specific strength, and corrosion resistance. Some Al alloys AA7075 is stronger than structural steel. These remarkable qualities make this metal and its alloys the most cost-effective and appealing option for a wide range of applications, particularly when lightweight is required especially in automobiles, aerospace vehicle etc…

The first time Al alloy sheet was utilized for a hood was on the Japanese Mazda RX-7 in 1985. Al alloy sheets were later used in sports cars and opulent sedans. In automobiles most suitable Al alloys are 5000 and 6000 series. However, 6000 series Al alloys are employed more for automotive sheet metal as their strengths can easily be controlled by heat treatments. Nowadays Al alloy is used in various automobile body sheet metal such as hoods, trunk lids, outer panels, doors and protection covers including heat insulators. Usage of Al alloy in automobiles is increasing exponentially in order to be competitive and satisfy stringent environmental regulations and government norms.

Al alloy has a much wider range of applications because its higher formability due to its face centered cubic crystal structure (FCC), which has an abundance of alternative slip systems. At all temperatures up to the melting point, Al alloys have a FCC structure. As a result, they do not undergo an allotropic phase shift during welding, and their hardness in the heat-affected zone normally remains constant (HAZ). Al may be bonded using a variety of techniques such as fusion and resistance welding, brazing, soldering, adhesive bonding, and mechanical methods such as riveting and bolting. Al alloy has processing qualities that are vastly different from those of the more common material steel, its use in the automotive industry is restricted [2].

Modern automobiles include a variety of body panels made of aluminium alloy, including hoods, bumper, fender, radiator, exterior panels, doors, and protective coverings like heat insulators as shown in Fig. 1. Additionally, in order to remain competitive and adhere to strict environmental rules and governmental standards, the use of aluminium alloy in vehicles is growing tremendously. Moreover, the switch from gasoline engines to electric engine is one of the most significant transformations in the automotive sector. These cars may benefit from aluminum's thermal characteristics and high strength/weight ratio. Automobile manufacturers are dealing with a number of difficulties as they switch to electric vehicle system. According to estimates from Ducker Worldwide Europe on the use of aluminium in vehicles, consumption increased from 120 kg to 180 kg per car over the past ten years, and it is anticipated to reach up to 225 kg per vehicle by 2025 as shown in Fig. 2. [3].

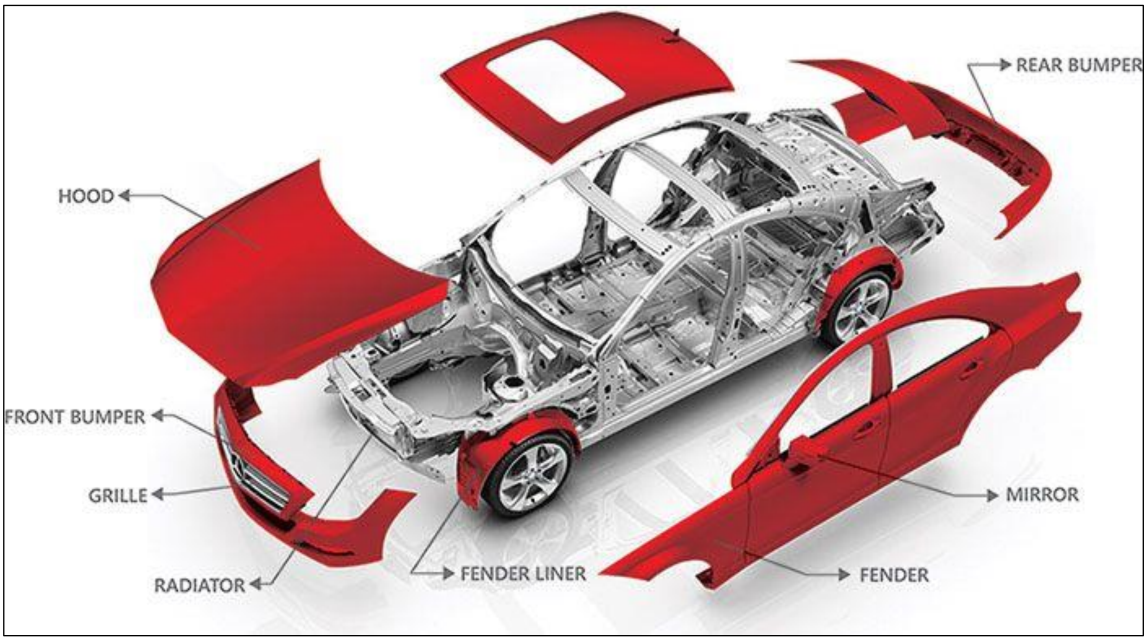

Figure1: Usage of Aluminum alloy in modern car.
Source: Authors, (2024).

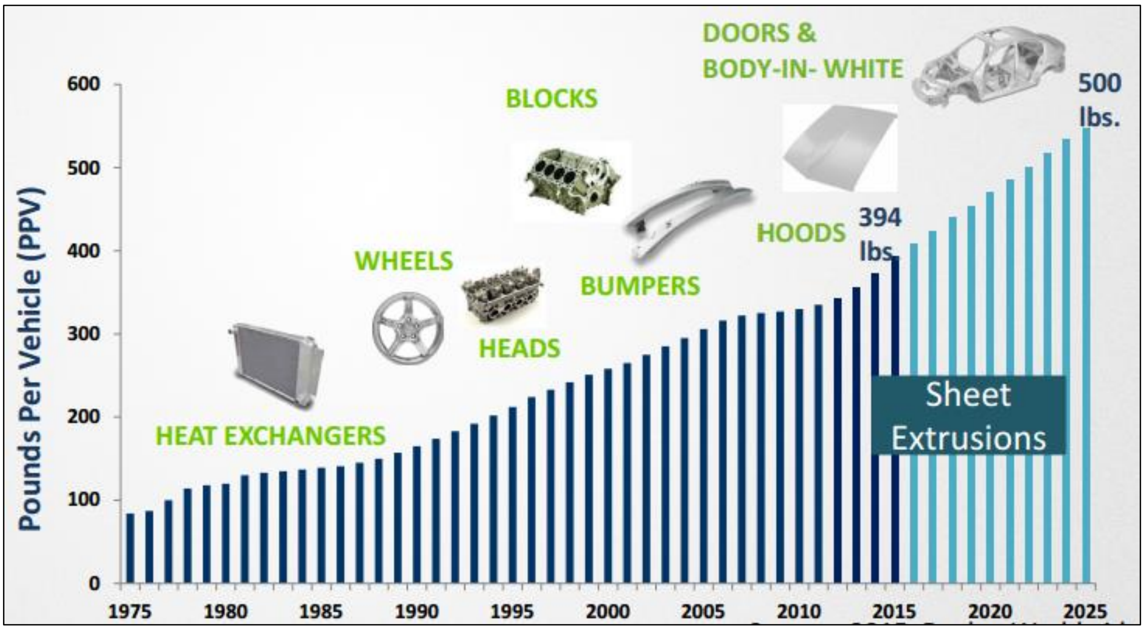

Figure 2: Usage of Aluminum alloy in Vehicles.
Source: [3].

The 5000 and 6000 series of aluminium alloys are best for use in cars. However, since they are heat-treatable and their strengths are easily regulated by heat, 6000 series aluminium alloys are used more for car panels.

5xxx Series Alloys are Al-Mg alloys. They have the highest strength of the thermally non-strengthened alloys. It is also easily welded and has a wide range of uses. They are used in shipbuilding, transportation, pressure vessels, bridges, and construction. The magnesium content, and service circumstances of the welded component, is taken into consideration when choosing the filler alloys. Because of their propensity for sensitization and subsequent susceptibility to stress corrosion cracking, alloys in this series with more than 3.0% magnesium are not advised for elevated temperature service above 66°C.

6xxx series alloys are Al-Mg-Si alloys. They can be found all across the fabrication industry. They are frequently utilized as extrusions and are a part of many structural works. Mg and Si are added to Aluminium to form the compound magnesium-silicide, which gives this material the capacity to undergo solution heat treatment for increased strength. These alloys shouldn't be arc welded without filler material since they are naturally susceptible to solidification cracks. To provide dilution of the base material and avoid the hot cracking issue, sufficient volumes of filler material must be added during the arc welding process.

The automotive manufacturers presently use thin sheet of aluminum alloy of 5000 and 6000 series ranging from 0.6-1.8mm. The thickness of aluminum sheet in various automobiles can vary depending on a number of factors, including the specific part of the car, the desired strength and weight, and the manufacturing process. However, in general hood and trunk use thicker aluminum sheets, around 1.2-1.6mm, for rigidity and dent resistance, whereas doors and fenders are often use slightly thinner sheets, around 0.8-1.2mm, to balance strength with weight and formability. Least thickness is used in roof and quarter panels, which may use even thinnest sheets, around 0.6-0.8mm, for weight savings and easier shaping. Al alloy sheet thickness is maximum in inner structural components like chassis and floor pans, which is around 1.5-2.0mm, for high strength and stiffness.

II. WELDABILITY OF ALUMINUM ALLOY

A weldment is a zone comprising the weld bead, HAZ, and the adjacent base metal. Ideally, a weldment should have the same properties as the base metal. In actuality, When an Al alloy is welded, it can generate a number of faults since aluminium is not a lenient alloy like steel. Weld beads frequently exhibit hot tearing, hardening fissures, porosity, deformation, and melt-through during welding because of adverse welding characteristics of Al alloy as shown in Fig. 3. These flaws significantly lower the mechanical and fatigue strength of Al alloy sheets.

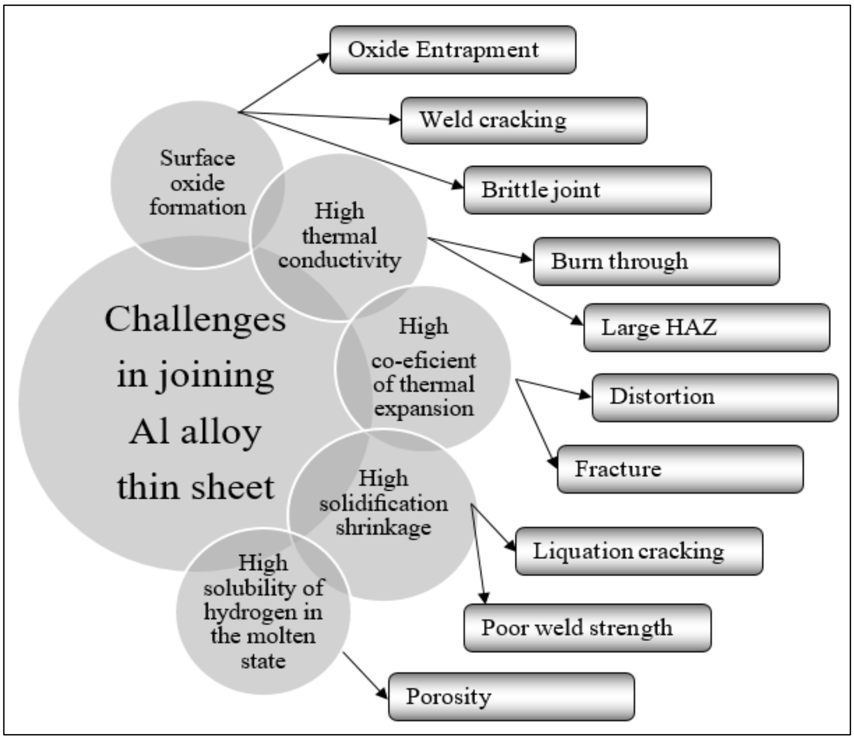

Figure 3: Challenges of joining Al alloy.
Source: Authors, (2024).

The protective oxide coating that exists on Al alloy prevents corrosion but may also hinder welding. The oxide layer over the Aluminium is very strong. When Aluminium surfaces are exposed to air, a thick coating of Al oxide develops rapidly and keeps growing. To create defect-free Al fusion joints, this oxide layer must be removed manually using machining, filing, wire brushing, scraping, or chemical cleaning. Even after chemical cleaning of the sheet surface, within a microsecond, it develops a nano-layer of Al oxide.

Cathodic cleaning during direct current electrode positive (DCEP) MIGW or AC TIGW is an alternate method for eliminating surface oxide. If strong oxides layer is present then oxide pieces may have entrapped in the fusion zone, causing brittle joint, fusion failure, and weld cracking. The oxide must be prevented from re-forming during welding by protecting the joint region with a shield of non-oxidizing gas such as argon, helium, hydrogen or chemically by use of fluxes [4].

Thermal conductivity is the most important physical factor influencing weldability. Al alloys have roughly half the thermal conductivity of copper and four times the thermal conductivity of low-carbon steel. This means that heat delivered four times as quickly to Al alloys as steel for the same amount of heat flux. This resulted in to burn through during joining. Low heat input is key to join Al alloy. However, the strong heat conductivity of Al alloys aids in the solidification of the molten weld pool of Al, allowing for out-of-position welding [4].

High coefficient of thermal expansion, causing distortion is important physical attribute to consider when discussing weldability. As it is the change in length of a material as its temperature changes [5]. Aluminium has a coefficient thermal expansion that is twice of steel. As a result, it may result in to fracture development caused by shrinkage blockage and significant distortion after welding if proper heat source parameter is not chosen. This means that the heat input during joining should be maintained to a minimum [5].

A high coefficient of thermal expansion combined with a high thermal conductivity would result in considerable distortion of Al during welding. Use of thick copper backup plate and tack weld will reduce distortion [4].

For Al alloys, wide solidification temperature range resulted in to poor weld bead strength and liquation or hot cracking. In contrast, melting range is significantly lower than for copper or steel. It demands controlled heat input and higher solidification time [4].

Another challenge for resistant welding of Al alloy is its good electrical conductivity. Al alloy is good electricity conductor and therefore it requires significantly greater current during resistant welding. This demand higher rated machines for welding Al alloy sheet compare to present automotive material steel and increased the cost of joining.

Porosity is common in Al alloys weld bead as Al alloy have high hydrogen solubility when liquid. If the weld pool absorbs hydrogen during fusion joining from ambient humidity and surface contamination, then supersaturated hydrogen form bubbles during cooling. These bubbles cannot escape the weld pool before solidification; they will produce pores in the weld [3].

The question of which welding process is the best and most cost-efficient for joining sheets of Al alloy arises as several welding procedures are available. There is no simple solution to this problem. This is because the selection of a welding method is dependent on several variables, such as the base metal, whether welding is indoor or outdoor, welding rate, filler material utilization, the thickness of metal, etc... Yet, several researchers have made significant contributions by contrasting the effectiveness of various welding methods.

Welding techniques for Al alloys are quite similar to those for replaced structural material steel. However, joining difficulties and defect rate is very high compared to steel owing to discussed adverse properties of Al alloy. Major joining techniques used for Al alloy are mentioned in Fig. 4 apart from mechanical fastening (Riveting) and adhesive bonding. These all techniques suffer from major and trivial problems as mentioned below.

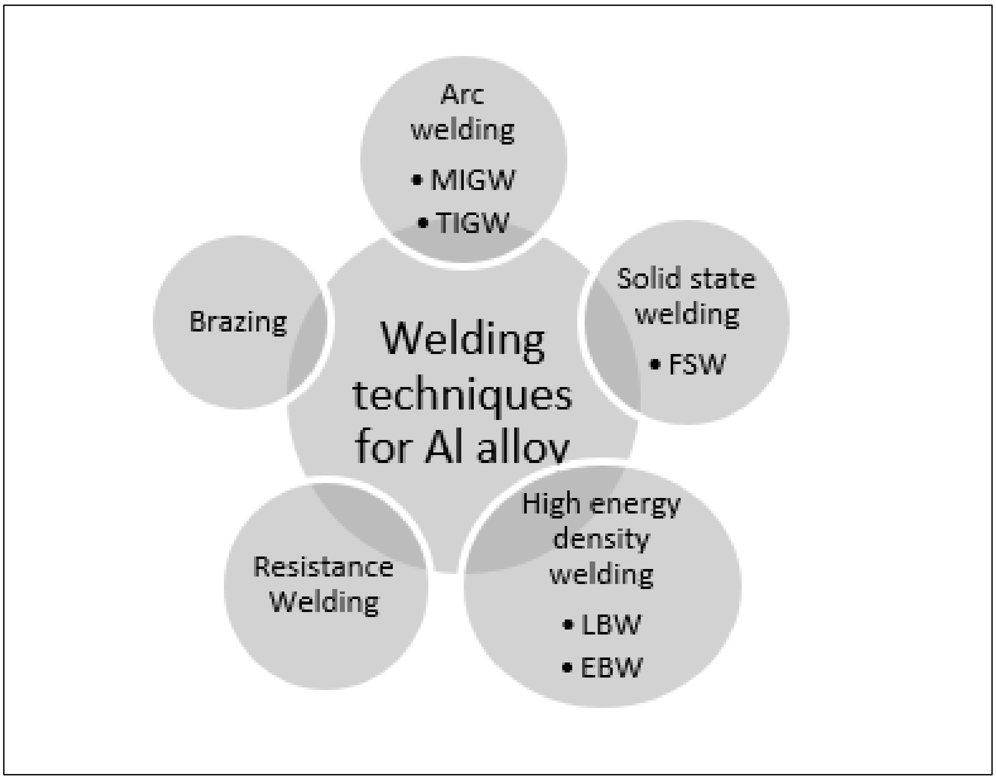

Figure 4: Permeant joining techniques of Al alloy.
Source: Authors, (2024).

Factors that cause weld deficiencies must be carefully addressed if industries are to achieve their quality criteria while meeting a high-volume production demand. However, various welding processes were developed in last two decades for Al alloy because its physical, mechanical, and other qualities differ from those of substituted material steel. Notable developments in Al alloy welding techniques as a result of its commercialization have significantly solved the limitations associated with Al alloy welding like oxide film removal, sound weld bead and HAZ. [8]. Variants of MIGW and TIGW process showed good results through controlled heat input during joining of Al alloy and look promising for economical joining especially for automobile panels [7].

III. WELDING TECHNIQUES FOR AL ALLOY THIN SHEET

III.1 TIG WELDING AND MIG WELDING OF AL ALLOY THIN SHEET

TIGW and MIGW are often used in the industry to connect Al alloys and related alloys; for instance, MIGW is used in the fabrication of automobile bodies. The only Al alloys that may be used for this application are those that cannot be heated. During welding the controlled heat input delivered to the material during joining may cause the evaporation of low melting poin t solute atoms in the fusion zone that causes a loss of strength. The use of suitable filler wires containing alloying additives, the quantity of which decreases owing to evaporation, can reverse this loss of strength in the fusion zone of non-heat-treatable Al alloys [9]. This is especially true for non-heat-treatable alloys like Al alloy, where solid solution strengthening is crucial.

The excellent thermal conductivity caused large HAZ with overaging. It is common in fusion joining of these alloys as a result of excessive heat input leading to loss of strength in this region. The large weakened HAZ in heat-treatable Al alloys is more evident when the heat input is more [10].

Al alloys can be joined using the regulated heat input of the MIGW method, but its use is constrained by challenges with the steady and controlled metal transfer. Although a high welding current offers a consistent spray mode, it also generates more heat, which must be managed by the welding speed. As a result, researchers have created a wide variety of GMAW procedures since the 1980s that make use of the advantages of the MIGW process and do away with its inherent drawbacks. The graphic below in Fig. 5 provides an overview of the MIGW process variations [11].

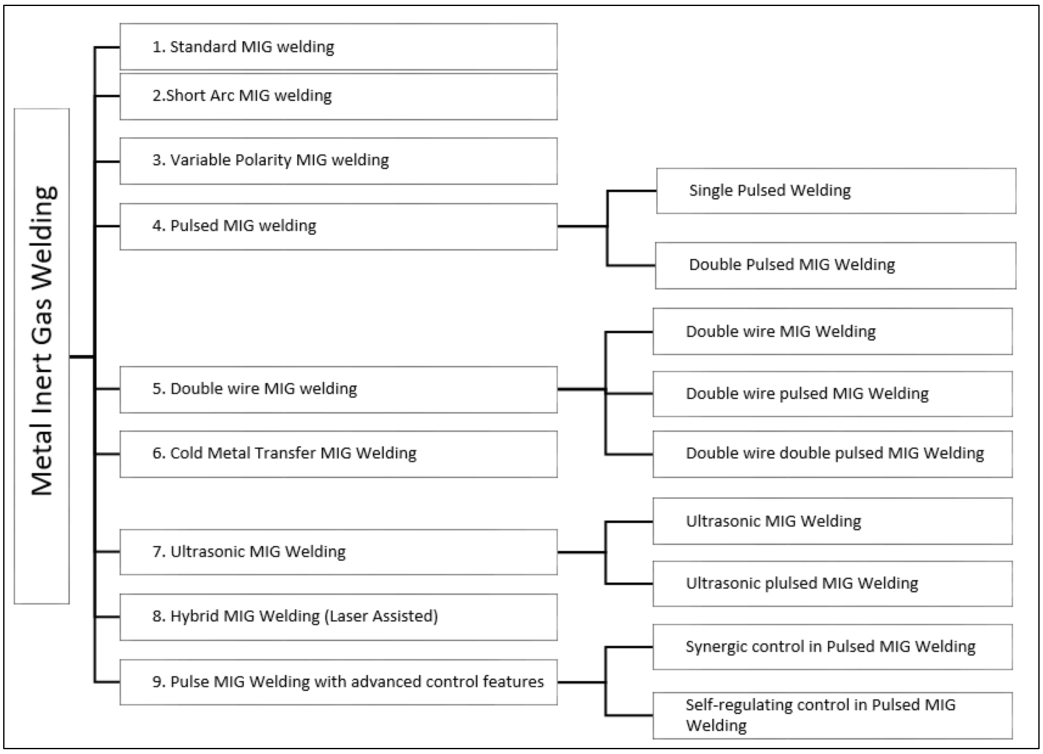

Figure 5: Different types of MIGW process.
Source: [11].

As mentioned above, the weldability of heat-treatable Al alloys has been researched using low heat input techniques through variations of the MIGW process such as pulsed MIGW and cold metal transfer (CMT) MIGW [11-13]. Due to its low heat input, like in FSW, this fusion joining technology provides the opportunity to fusion joint any Al alloys thin sheet of 6xxx and 7xxx series alloys. Comparing this approach to FSW, MIGW is simpler, more adaptable, and quicker [14]. Many studies proved that compared to conventional MIGW and FSW, pulsed MIGW and CMT MIGW offer greater joint tensile strength and ductility [9]. In comparison to conventional MIGW processes, CMT MIGW and pulsed MIGW offer reduced thermal heat input, gap bridging capability, low dilution, quick operation, and little spatter, making it particularly appealing and promising for combining such challenging Al alloys [8].

TIGW and MIGW are often used in industry to fabricate steel automobile bodies. But during the welding of an Al alloy thin sheet, the controlled heat input delivered to the material during joining may cause the evaporation of low melting point solute atoms in the fusion zone that causes a loss of strength. The use of suitable filler wires containing alloying additives, the quantity of which decreases owing to evaporation, can reverse this loss of strength in the fusion zone of non-heat-treatable Al alloys [9]. This is especially true for non-heat treatable alloys like Al alloy, where solid solution strengthening is crucial. The excellent thermal conductivity caused large HAZ with overaging. It is common in the fusion joining of Al alloys as a result of excessive heat input leading to loss of strength in this region. The large weakened HAZ in heat-treatable Al alloys is more evident when the heat input is more [10].

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The weldability of heat-treatable Al alloys has been researched much using low heat input techniques through variations of the MIGW process such as pulsed MIGW (P-MIGW) and cold metal transfer (CMT) MIGW [11-13]. Due to its low heat input, like in FSW, this fusion joining technology provides the opportunity to fusion join any Al alloys thin sheet of 6xxx and 7xxx series. Comparing this approach to FSW, MIGW is simpler, more adaptable, and quicker [14]. Many studies proved that compared to conventional MIGW and FSW, pulsed MIGW and CMT MIGW offer greater joint tensile strength and ductility [9,14,34-35]. In comparison to conventional MIGW processes, CMT MIGW and P-MIGW offer reduced thermal heat input, gap bridging capability, low dilution, quick operation, and little spatter, making it particularly appealing and promising for joining such challenging Al alloys [8].

As the cutthroat competition in the automobile sector keeps manufacturers tight on the production cost. Therefore, in the domestic and economic automobile sector use of Al alloy sheets is hindered, because of its higher investment and production cost compared to steel. The welding of thin Al alloy sheet by conventional arc welding process especially P-MIGW with controlled heat input and correct use of filler wire looks promising

It was reviewed from the literature that P-MIG welding is a complex process and sound weld beads without any defects primarily depends on the selection and control of various welding process parameters. The pulsing creates spray transfer which resulted in low heat input during the welding process, without negotiating welding speed. Especially welding process parameters significantly influence the quality of weld beads compared to electrode parameters. An optimum combination of these pulse parameters only resulted in a defect-free sound weld bead [37-40].

III.2 HIGH ENERGY DENSITY WELDING

Using high-power density fusion joining procedures, such as laser beam welding (LBW) or electron beam welding (EBW), is another approach to reduce the amount of heat supplied during fusion welding [8, 14-16]. LBW and EBW use a highly concentrated heat source. Therefore, there is relatively little total heat input delivered to the workpiece. That is resulted in to very narrow fusion zones and very small HAZ area is formed. It reduced distortion and residual stresses significantly. EBW provides more sound weld bead without oxide formation and porosity as welding carried out in vacuum. Reflectivity of Al alloys demand extra care during LBW. As LBW and EBW process leads very little HAZ, there is not change in hardness in thin sheet around fusion zone. It was also noted, thin sheets welded by EBW and LBW showed no microstructural alteration, and consequent base metal deterioration in the HAZ area compared to MIGW and TIGW, which involves larger heat input during welding. [15] Many variants of EBW and LBW process are developed for sound weld of Al alloy. However extensive research needs to be carried out for reducing high capital cost of such process. As the cut throat competition in automobile sector keeps manufacturer tight on the production cost. Therefore, in the domestic and economical automobile sector use of Al alloy panel is hindered, because of its higher investment and production cost compared to steel.

III.3 FRICTION STIR WELDING

Low heat input during Al alloy joining keeps material deterioration to a smaller level. That is resulted in to greater joint performance. Unlike fusion welding processes, Friction stir welding (FSW)methods often result in joints with higher joint performance because of less heat input during the process. Since development of FSW process in 1991, it showed significant advancement in joining light metal alloys with higher thermal conductivity. [4] Currently, many FSW variants are developed to provide more symmetrical heat input. These are used to butt joints with enhanced joint properties in a shipbuilding, high-speed trains, automobiles and the aviation industry [17-20]. FSW is a contender to take the place of traditional resistance spot welding as well as fusion welding, which is frequently employed in the automobile sector [21]. High electrical conductivity poses challenge in resistance welding of Al alloy thin sheet, is effectively accomplished with FSW. As a result, this will enable the use of lightweight Al alloys in the production of automobiles.

During FSW of Al alloy it was noted by many researchers that the loss of strength brought on by precipitate dissolution and coarsening in these high strength alloys cannot be entirely recovered by grain refining, leading to typically significantly poorer joint efficiencies. [22-23]. AA 6061-T6 and AA 7075-T6 alloys with FSW have been reported to have maximum joint efficiencies of 75 and 80%, respectively. However, following solution heat treatments, these joint efficiency values were recovered to about 90% and 100%. [24-25] FSW variants like external and in-process cooling through compressed air, water, under water FSW or use of liquid nitrogen is researched to limit heat input during joining such highly thermally conductive alloys. Such experiments showed a viable way to increase the strength and hardness of joined sheets. [26-30]

Despite of such advantages, it was mentioned that Al alloy joint prepared by FSW do not offer any advantages over fusion welded joint with respect to the strength of the WZ. FSW process resulted in substantial strength loss in the WZ unless the weld parameters are not properly regulated. [31]

Controlled heat input and correct use of filler wire resulted in significant recovery of strength during MIGW and TIGW. Such recovery is not possible in FSW.

During low heat input welding techniques such pulsed MIGW, pulsed TIGW, CMT MIGW, LBW or EBW the Al alloy deterioration in the WZ and HAZ is not as substantial. [14,16] However, it is important to note that by adopting the ideal weld settings, the amount of strength loss in FSW may be reduced.

FSW has significant shortcomings like automotive thin sheet applications often require joining of curved surfaces and intricate features, which cannot yet be welded with FSW. Moreover, the slow welding speed and lack of process flexibility caused by the need for work piece clamping and access is another major hindrance.

IV. OVERALL THOUGHTS

Despite its many benefits and inherent flexibility of high energy rate welding, the broad application of it's in the automotive industry has been severely limited by the high capital cost of laser equipment.

Good thermal conductivity of Al alloy demand more often dressed tips and costlier, higher rated, larger equipment, which limits resistance spot welding application in spite of significant benefits.

Automotive thin sheet applications often require joining of curved surfaces and intricate features, which cannot yet be welded with friction stir welding.

The weld quality and weld shape in TIGW and MIGW are significantly impacted by the heat input, controlled heat input and stringent control of heat source parameter is essential for sound weld bead [6].

MIGW and TIGW is effectively used in automobile industry to combine Al alloys thin sheet, such as when building automotive panels. However, formation of severe and large HAZ causes strength loss. Recent in-depth studies on the weldability of Al alloys have demonstrated that these alloys may be effectively connected using low heat input arc welding techniques such pulsed MIGW and CMT MIGW.

Furthermore, joints in Al alloys, may be produced using low heat input, high energy density welding techniques like LBW and EBW. High energy density welding process supplied, concentrated low heat input. In such methods loss of strength occurring in the FZ may be reversed to very near base alloy strength by utilizing the proper filler wire. Although the strength loss in the HAZ cannot be prevented, its severity can be reduced by using modest heat input. Al alloy can be joined by pulsed MIGW, CMT MIGW, EBW and LBW provided that the heat input is kept sufficiently low and adequate filler alloys is used.

Additionally, it is widely known that FSW has a lot more promise for connecting Al alloys than fusion welding does because FSW does not always result in a loss of strength in the joint area. Due to the dynamic recrystallization in this instance, FSW only causes the formation of recrystallized grains in the weld area. Heat treatable Al alloys showed considerable decrease in strength in FZ and HAZ is one of the major hindrance in application of FSW. Generation of residual stresses in HAZ degrade material strength. It is common in all welding techniques. However, compared to fusion welding, the degree of residual stress is less severe in FSW. Therefore, overall strength of welded thin sheet is more in FSW compared to fusion welding techniques. Especially, FSW with in process cooling, which kept low heat input provide better joint efficiency with less degradation in base metal. For joining Al alloy thin sheets, currently FSW impressively used by industries. In-depth research is now being done to determine whether FSW can be used to connect curved sheets and intricate shapes with higher speeds.

The use of aluminum in electric vehicles (EVs) is particularly promising, as their heavier battery packs necessitate weight reduction in other areas. Sustainability is another key aspect of aluminum's appeal. It's highly recyclable, with over 70% of all ever-produced aluminum still in use today. Any advancements made in the mass manufacture of light transportation systems and, consequently, a considerable decrease in fuel consumption will be made in the friction stir butt and spot welding of Al and Mg alloys, especially in incompatible combinations.

V. FUTURE OUTLOOK

The aluminum market for the transportation industry has grown significantly during the past few years. Parts made of aluminum have primarily been used in high-end cars. Future trends indicate that aluminum usage will continue to flourish, with applications in the low-cost auto and aviation sectors.

Aluminum can be up to 60% lighter than steel, the traditional king of car bodies. This translates to significant fuel savings, with estimates suggesting a 5-10% reduction in fuel consumption for vehicles with increased aluminum content.

Lighter cars also mean lower emissions, making aluminum a vital player in the fight against climate change. The International Aluminium Institute estimates that widespread aluminum adoption in cars could cut global CO2 emissions by 660 million tonnes by 2050 and will address environmental challenges. Steel will be replaced by lighter materials including aluminium and magnesium, as the most cost-effective way to do this. In the long run Aluminum, magnesium and polymers may replace steel completely in automotive and aviation application [32].

In the high energy density welding processes, LBW looks promising as it provides accurate, effective and concentrated formation of weld bead. But, it is necessary to mitigate major issue of aluminum poor energy absorption capability. In the near future variants of MIGW like pulsed MIGW and CMT MIGW controlled low heat input, process flexibilities, easy automation and use of filler wire provides good quality weld bead with good structural strength of thin sheet joint.

The variant of FSW process like laser assisted FSW may be explored by industries in the near future. Prominent features of FSW with further advancement in process may allowed for the design and production of automobiles using lighter materials like Al alloy and making it a potential replacement for steel bodies of cars made using resistance spot welding.

Traditional arc welds and high energy density joining techniques are expensive in todays' cut throat competition era. Few under develop joining techniques like ultrasonic joining, electromagnetic joining and adhesives will still need to address present issues with long-term performance and productivity disadvantages. The current and potential focus area for welding of Al alloy thin sheet is mentioned in below Figure 6.

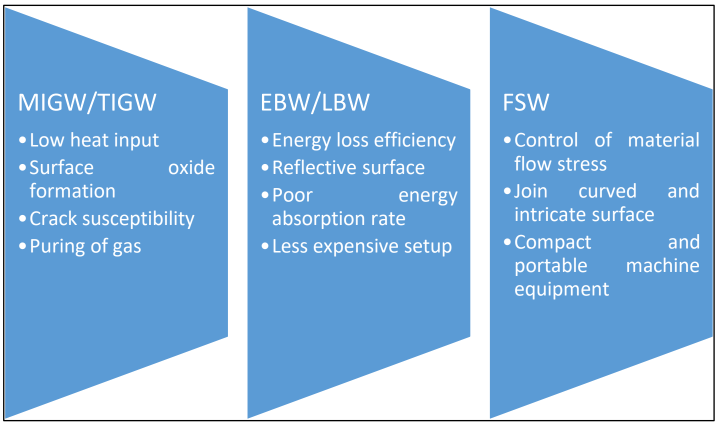

Figure 6: The current and potential focus area for welding methods.
Source: Authors, (2024).

It's equally important to consider further developments in fusion welding technology like cold wire feed LBW, high-brightness fiber lasers, and hybrid laser-arc-friction stir welding, which offer even greater control and efficiency for joining thin aluminum sheets, however its cost effectiveness for domestic low cost automobile need to be explored.

Automotive panels will keep use of Al alloys because of its lightweight and environment friendly. The coming decades will be a prosperous time for aluminium structures as they contribute to society's efforts to address the current and future environmental challenges. Cost remains a hurdle for wider aluminum adoption, as it's generally more expensive than steel. However, advancements in processing and recycling are bringing down costs, and the long-term fuel savings often outweigh the initial investment.

I anticipate that all researchers and technologists will work together in the future to tackle the world's ecological issues by using aluminum structures.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Sachindra Doshia, Vaghosi Ketan and N D Mehta.
Methodology: Sachindra Doshia, Vaghosi Ketan and N D Mehta.
Investigation: Sachindra Doshia, Vaghosi Ketan and N D Mehta.
Discussion of results: Sachindra Doshia, Vaghosi Ketan and N D Mehta.
Writing – Original Draft: Sachindra Doshia, Vaghosi Ketan and N D Mehta.
Writing – Review and Editing: Sachindra Doshia, Vaghosi Ketan and N D Mehta.
Supervision: Sachindra Doshia, Vaghosi Ketan and N D Mehta.
Approval of the final text: Sachindra Doshia, Vaghosi Ketan and N D Mehta.

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