# RECENT ADVANCES IN JOINING TECHNIQUES AND ITS PARAMETERS FOR ALUMINIUM ALLOYS- REVIEW

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## ABSTRACT

*The primary goal of industries is to provide higher-quality products at a lower cost and to increase productivity. Welding is the most important and widely used method of joining two similar or dissimilar materials. Especially automobile and aircraft manufacturers are interested in using innovative processes and advanced materials to reduce weight, cost, and increase part performance. Techniques for joining lightweight dissimilar materials, particularly aluminium, steel, and plastics, are becoming more essential in the fabrication of hybrid structures and components for engineering applications. The most broadly used joining methods for aluminium alloys are TIG, MIT, Variable Polarity Plasma Arc, Laser Beam Welding (LB), Friction Stir Welding, Riveting. However, Aluminium alloys are difficult to weld due to their high conductivity, reflectivity, reactivity, and coefficient of thermal expansion. In this review paper, the research and progress of three main welding techniques for joining Al alloy are reviewed. Which is Friction Stir Welding (FSW), Laser Beam Welding (LB), and Riveting along with its key parameters and applications. The key roles in recent progress in the welding of Aluminium alloys to provide a basis for future research.*

***Keywords:*** *Aluminium alloys, Welding techniques, FSW, LB, Riveting.*

## INTRODUCTION

Aluminium alloys have seen a significant expansion in application areas in recent years, which has prompted considerable research on new generation aluminium alloys. Aluminium alloys are particularly useful in the building of lightweight fortification structures in industries including aerospace, defines, locomotives, automobiles, and energy. Aluminium's remarkable qualities, such as low density, high specific strength, high specific energy absorption capability, good corrosion resistance and thermal conductivity, formability, machinability, non-magnetic nature, and low cost, have led to its widespread use [1]. Welding is one of the most essential production processes utilized in the aluminium alloy sector as part of the fabrication process. Friction Stir Welding (FSW), Laser Beam Welding (LB), Riveting, Tungsten Inert Gas (TIG), Metal Inert Gas (MIG), Variable Polarity Plasma Arc (VPPA), and Electron Beam (EB) welding are the most often utilized joining methods for aluminium alloys. Aluminium alloys, on the other hand, are difficult to weld due to their high conductivity, reflectivity, reactivity, and coefficient of thermal expansion. Due to the high heat input, high thermal conductivity, and high coefficient of expansion, parts may be severely distorted during welding.

The Welding Institute (TWI) created friction stir welding in December 1991. Friction stir welding (FSW) is a relatively recent joining technique that has been employed in high-volume manufacturing since 1996. Because no melting occurs and joining takes place below the melting point of the material, a high-quality weld is created. Friction Stir Welding is a revolutionary solid-state joining process that does not melt or recast the material being welded. As a result, solid-state phase transitions occur during the cooling of the weld when alloys are friction stir welded. In reality, the purpose of this study is to assess the potential benefits of FSW over TIG and MIG, considering the decreased heat input of the solid-state joining method and the high hardening particle stability.

Helmholtz-Zentrum Geesthacht (HZG) in Germany developed and patented the Friction Riveting technology (FricRiveting) in 2007 as a way of attaching hybrid metal–polymer structures. This method uses a cylindrical rivet to unite metallic and/or thermoplastic elements using frictional heat and is based on mechanical fastening and friction welding concepts. A number of applications for laser beam welding of specific aluminium alloys have been approved. The automobile, aerospace, construction, and electronics industries are the most affected. In some situations, laser beam welding is being investigated as a replacement for mechanical fastening and adhesive bonding in the aircraft sector. Because high-powered lasers have just become commercially available, welding can now be considered as a viable alternative to riveting in the assembly of commercial aircraft structures [2].

The rivet first appeared in Egypt around 3000 BC as a connecting element for the manufacture of various tools and items. Because the earth's energy supply is diminishing, car manufacturers would prefer to adopt lightweight structures to save energy. The lightweight structures are made of a difficult to weld aluminium or magnesium alloy. The Self-Piercing Riveting procedure is a cold forming technology that uses a semi-tubular rivet to link two or three sheets. It can link materials that are dissimilar and difficult to weld since the process depends on mechanical interlock rather than fusion. This technique is used by several automobile manufacturers to construct aluminium automotive bodies for space frame and monocoque body assemblies [3]. The mechanical properties of FSW, LB, and Riveting were mostly focused on tensile strength, microstructure, fractography, yield strength, and hardness by most researchers. Tensile strength, microstructure, and hardness tests were evaluated and assessed in this article by using FSW, LB, and Riveting joining methods.

## LITERATURE REVIEW

Shigematsu et al (2003) have reported that Friction stir joining techniques is good for solid state joining especially for aluminum alloys and it’s most suitable for similar materials. A comparative study on microstructure, tensile strength, and elongation for the materials and joint specimens of alloy 5083, 6061 and Joint 5083-5083, 6061-6061, and 6061- 5083.FSW on the similar materials and dissimilar materials are examined and the combination of all materials was joined successfully. So, these results shows that even though it is FSW used for similar materials, it can be used for dissimilar material. But the welding properties like tensile strength and hardness distribution hast to be considered strongly when selecting the material combination.[4]

According to Liu et al (2014). The work in this paper is focusing on friction stir welding of dissimilar aluminium alloy to advanced high strength steel. Aluminium alloy 6061-T6 and type of high strength steel has successfully joined by using friction stir welding technique. The parameters in this paper include tensile test and microstructure analysis. The maximum ultimate tensile strength acquired is 240 MPa which is 85% of the base Aluminium alloy. From the findings, a thin intermetallic compound layer of FeAl or $Fe_3Al$ with thickness of less than 1 micrometer was formed at the interface of Al-Fe because of diffusion and reaction which has created the high joint strength.[5]

Guo et al (2014) focused on the friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys. The parameters in this paper focused on microstructure, micro hardness analysis, and tensile properties. From the finding it is clearly brought out that tensile strength of the dissimilar joint is directly proportional to the heat input. This difference occurred due to the different etching response to the Keller's reagent. Based on this paper all the joints investigated had a good tensile property with ultimate tensile strength more than 215 MPa and the percentage of elongation is more than 6%. At the minimum hardness, all the joints on AA6061 in HAZ regions close to the TMAZ in tensile testing were failed. [6]

Fu et al (2015) made complete study on the Friction stir welding process of dissimilar metals of 6061-T6 aluminium alloy to Az31B magnesium alloy. The parameters of tensile property and microstructure were investigated. The tensile strength achieved under the different position at the rotational speed of 600-800rpm and 30-60mm/min. The maximum tensile strength reached at 175MPa at 700rpm and 50mm/min which was nearly 70% of the Mg base metal. The formation of intermetallic compound layers, the light etching interfacial layer of thickness 3µm was obtained.[7]

Pourali et al (2017) have made a complete study on friction stir welding on Aluminium and steel joints. This paper includes the parameters of microstructure, tensile strength, Al-Fe interface, and fracture surfaces. 93 micrometer of thickness were the intermetallic compound layers formed at the inter joint of FeAl and Fe3Al. The highest tensile strength was founded at low welding speed and high rotation speed. By using overlap shear tests, mechanical properties of the joints were investigated. It has the dimensions of 100mm× 10mm with 400mm2. The highest tensile load obtain was 1925N at the joint welding speed of 50mm/min. During the tensile shear test, specimen failure happened in Al-nugget zones.[8]

Huang et al (2018) have reported that chemical and physical properties have the main impact on joining polymer and metal. The main joining techniques between polymer and metal are adhesive bonding and mechanical joining techniques. Comparatively, FLW and FSLW has the huge potential to the polymer structures. The parameters of 6061-T6 Al alloy have been examined. Such as Tensile strength, elongation, density, and modulus of elasticity. FSW process of Al alloys, the welding peak temperature is between 70-90%. During the examining, the maximum shear bond strength of 20.2 MPa was achieved at the speed of 50mm/min. [9]

Goyal et al (2018) have reported the parameters for joining Al-Mg4.2 alloy. This report includes the parameters of Microstructure, tensile properties, microhardness, and microstructure and fractography. The microhardness of the parent alloy was obtained 88Hv when the load of 500g for 10s. The grains in the nugget zone of the joint increase the hardness. The joint with 15mm shoulder diameter and the pin profile tool more likely to have a better tensile strength.[10]

Borrisutthekul et al (2005) have examined about the dissimilar material laser welding between Mg alloy Az31B and Aluminium alloy A5052-O. This report includes the parameters of tensile shear test and joining strength. From the tensile shear test, the results shown that the failure occurred inside intermetallic compound layer as it decreases the strength of the joint. The maximum strength achieved at 20 MPa and the failure occurred at the load 520N at the welding speed of 2mm/min which is around 37% of yield load of A5052-O alloy. After the experimental results it has concluded that the thin intermetallic and higher joining strength achieved in the edge line welding lap joint. [11]

Mathieu et al (2007) have studied about the dissimilar material joining using laser beam welding technique. Tensile test and microstructure parameters have included in this paper. Based on the microstructure analysis the darkest region near the aluminium alloys is richer in aluminium alloys and the lightest regions are richer in zinc. After the experiment it was observed that the thickness of reaction layer is less than 15 µm. From the tensile tests it is decided that all the joints have a good performance.[12]

Wang et al (2018) have done the experiment on welding parameters on microstructures and mechanical properties of disk laser bean welded 2A14-T6 Aluminium alloy joint. This paper includes the parameters of microstructure, hardness, and tensile properties. The grain size and the porosity ration in the disk laser weld is directly proportional to the heat input. The highest hardness, maximum tensile strength, and the finest microstructure were achieved at the state of laser power of 2500W, welding velocity 2.0m/min and the heat 75kJ/m. The maximum tensile strength obtained at 261.7MPa which is about 62% of the base metal.[13]

Bunaziv et al (2016) have reported about the Fibre laser-MIG hybrid welding of 5mm 5083 Aluminium alloy. The parameters of microstructure and tensile strength were investigated in this paper. The results show that, during the welding process the heat input can be affected the microstructure in the joining zone. Compared to Argon-Helium mixture, pure argon shielding gas has the higher tensile strength due to stable process of hybrid welding in argon.[14]

Pakdil et al (2011) have examined the microstructural and mechanical characterization of laser beam welded AA6056 Aluminium alloy. Microstructural observation, hardness analysis, and tensile properties were investigated in this paper. From the experiment it is decided that, when base material has the yield strength of 347 MPa, yield strength achieved for the all-weld metal micro tensile specimen was 226 MPa. The efficiency of the joint for yield and tensile strength obtained about 65% and 75%. Hardness decreases was observed in the heat affected zone and the fusion zone.[2]

Nahmany et al (2019) have examined the laser beam welding process of AlSi10Mg specimen. The parameters of tensile strength, microstructure, and hardness were examined. The base metal microstructure of AlSi10Mgspeciments after the heat treatment at 3000C for 2 hours are 100 µm, 100 µm, and 1 µm. From the experiment it is very clear that welded samples have higher tensile strength, yield strength, and elongation values compared to cast. The yield strength and the tensile strength of the welded samples are 210-220 MPa, 320-330 MPa respectively. While cast has the yield strength of 180 MPa and tensile strength of 220 MPa.[15]

R Porcaro et al had done the modeling and the analysis of the self-piercing riveting in the software named as the LS-DYANA using inverse modeling. The team have done the analysis part and did the test of static and the dynamic on the double hat sections in conjunction with the aluminium foil sheets slaughtered with the approach of the self-piercing rivets in the vicinity of the flanges to authenticate the pegged rivet model. Here failure is likely to transpire in real crash conditions. And it shows that the behavior of the rivet is likely elastic and have given conclusion that 50% of the shear strength is equal to the tensile strength of the single rivet specimen.[16]

Richard R. et al have come up with the importance of the Aluminium as it is considered as the one of the primary metals in the wide range of the applications and in the present era the Aluminium is customizable and can be use and compete with the composite materials. By using the various joining techniques, the property of the materials is changed which bespeak devaluation in the material management and scraping, improved life expectancy of the material handling.[17]

Dong Hyuck Kam et al had come up with the examination of the quality trait of the Self piercing riveted joints and the issues arise with the various die types like flat die, cone die, and nipple on the geometrical and mechanical achievement of joints. It finally ends the paper with the conclusion of that with the advice / aid of the SPR (self-piercing riveting) case the vibration damping Al panel on the top and die type of nipple spectacle the elite cross-sectional characteristics and the peak tensile shear strength.[18]

J Kang et al had given the result of the parameters like tensile and the fatigue behavior of the SRP (self-piercing riveting) with the CFRP (carbon fiber reinforced plastic) to Aluminium. The fatigue cracks growing in the kinked manner along with the width of the bottom aluminium sheet. It tells that the fatigue crack advance regularly in the cold treated plastically crippled field of the aluminium sheet. And it says that the friction betwixt CFRP and the aluminium sheet commence produces fretting. And the assertive mode of the break down was crack expanded along the width of the aluminium sheet. The nonappearance of the fretting may have subsidized to the upgrade fatigue life.[19]

Jing Zhang et al here it brings about of the reinforcing fibers on the composites bruise behaviour has described. Their result shows that the SPR (self-piercing riveting) is the adequate approach for accompany the fiber reinforced thermoplastic composite panels along with the aluminium alloys sheets. During the testing of the lap shearing the highest strength is observed as a result to the reinforcement of matrix with the fibers. Inclusively the strength of the thermoplastic matrix

FRP composite exfoliate, and the aluminium alloys is much lower that of the Al joint.[20]

Deekshat et al had written the paper which is basically the review paper and they have focused on the application and the usage of the aluminium metal in the past from the period of the 2008-2019. This paper has given a detail information on the evolving of the joining techniques maybe it is a Mechanical processing, or the Welding process and it shown the application of the metal joining in the various avenue maybe it as a similar or the dis-similar metal joining. He has the objective to optimize the strength and welding parameters of the aluminium alloys of the various grades.[21]

Rujira Deekhunthod has come up with a paper which tells the present understanding in Aluminium alloys and how other metals will clout the weld strength and cracking susceptiveness. In his experiment shows that the tensile strength of all the specimens have breakdown in the heat affected zone area (HAZ). Change in the microstructure of the base metal and the weld material after welding. This paper conveys that the porosity doesn’t affect the stability of the welding because the fissure occurs in the HAZ. [22]

Stephanine Timpone has given the information of the Laser welding of the cooling pipes he compared the welding with the arc welding, soldering and brazing as the higher cooling rates that occurs under laser welding conditions changes the way the weld pool and the necessitates a higher ratio to reduce cracking susceptibility, Vickers hardness testing can be useful when welding metal that may form hard phase upon solidification and material composition plays a role in the final microstructure and cracking susceptibility.[23]

N. Bhardwaj et al (2019) have discussed that friction Stir Welding method is mostly used in aerospace industry and it is used for manufacturing high strength aluminium alloy and the application areas are large fuel storage tanks of space shuttles and spaceships and it is accepted as a suitable method to join high strength aluminium alloys in aerospace sector. The success of space vehicle series using FSW such as space shuttles, Ares I launch vehicle, Orion spacecraft proved that FSW is an acceptable welding process.[24]

Guoqing Wanga et al (2017) have reported that the accelerated use of aluminium alloys in automobile industry is due to the high weldability using FSW for similar or dissimilar aluminium alloys. The application areas of FSW are engine parts. car rims, fuel storage and tailor welded blanks for automobile and wings, fuel container, stringer for aircraft. The main reason for using FSW is due to its more strength and low weight of the welds. The other application areas include hull, superstructure, decks for ships and walls, floor areas for trains and frames, pipes, reactors, electronic components housing and connectors for construction, power plant and electrical industry.[25]

Alessio Gullino et al (2019) have reported that the laser welding is used in automobile industry in automobile components such as closures, pillars, and seats, in automobile assembly lines laser welding source can be controlled using remote and focused on the workpiece with higher welding speed and productivity. [26]

Eva Vaamonde Couso et al (2011) have examined that tailored blank in automobile are welded using laser welding process at 6m/min to 15m/min to be profitable. Aluminium alloys of different thickness used in sheets, extrusion and casting will be laser welded and with development of high-power lasers, heavy structures can we welded.[27]

Li Han et al (2010) have reported that the SPR process is used mostly in the joining of the aluminium sheet metals due to no need of the predrilled hole and ability to join two dissimilar metals and there will be no fume emissions.[28]

Dezhi Li et al (2017) have made a study that the main application area for SPR is the automobile industry and which is the main reason for the SPR development. SPR developed in 1960s, however became more efficient in the past 25 years in joining lightweight aluminium alloys.[29]

Yohei Abe et al (2020) have reported that the different types of materials are used in the automobile industry to lower the weight. The steel, aluminium alloy and carbon fibre reinforced plastics are commonly utilised for automobile body parts. Automobile sheet metal components such as steel and aluminium sheets were joined by SPR and clinching processes.[30]

E.Schubert et al (2001) have reported that the aluminium alloys are used in transportation industry due to its less weight capability. The aircraft structures such as skin and stringer which is riveted can be laser welded due to the less cost and weight using AA6013 and also structures made up of titanium could be manufactured by using both laser beam welding in wing and fuselage components.[31]

F Hönsch et al (2018) have reported that in the automobile industry thermal joining of dissimilar metals are difficult and due to that the use of mechanical joining increases constantly. Self-Pierce Riveting has become a most common type of mechanical joining process for lightweight materials in automobile body parts. SPR can be used for joining for both similar and dissimilar materials such as aluminium alloys or aluminium alloy with thermoplastic composite or steel sheets.[32]

Daniel Wallerstein et al (2021) have reported that 5xxx and 6xxx series are the most common aluminium alloy series used in dissimilar aluminium steel joints used in aerospace and automobile applications. Laser welding has become a better decision when it comes to joining of dissimilar materials and the joints used for welding of dissimilar joints are lap and butt joints. The dissimilar aluminium steel joints are used to obtain a very good weight reduction and also for better assemblies.[33]

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## DISCUSSION

### Joining Methods

In this modern and the advancement of the technology the joining is the main factor which has the many advantages for the futuristic purpose, and these will also have some of the constraints for the joining of the various polymer based or the Dis-similar materials like same composition of the metals or the combinations of the alloys. In the manufacturing industries, epically while manufacturing the solid products its very complicated to make such parts directly by casting or any other methods due to its complicated design and having the multifarious geometrical features. To reduce such complexity the complex parts are made and divided into the subparts and joining them in a best possible way to get the replica of the designed solid product. In simple words to explain about the joining means nothing but its assembling of the two or the more products in order to make one single unit with or without the interference of the external elements. The joining is done by the using the some of the fabrication techniques like welding, having the strong bonds between the materials using the Adhesives, riveting and some of the fasteners (like nut-bolt, clip, nail, button, zipper, hook, clutch) etc., In general, the joining can be categorized into the two categories mainly permanent joint and the temporary joints, Basically Welding, Soldering, Brazing and Mechanical fastening will come under the permanent joining. Fasteners, press fit, Cotter joint & knuckle joints are the some of the temporary joints which can be used in the various metal joining process. In the either comparison of the joining process there are many Advantages and limitations for the Joining of the same or the different type of the compositions of the metal and materials. So here, let's get an idea and overview about the some of the joining techniques.[51]

### *Friction Stir Welding*

In today's world the joining has come up with a huge research and development factors for the implementing the joining of the complex solid models. For the joining, the recent developing technology is the Friction Stir Welding (FSW). This project of this technique was carried out in the three modules in which Module-I was proved that the Friction Stir Welding (FSW) is the realistic and the practical welding technique for the Aluminium alloys with the series of 6000, in Module-II the friction stir welding (FSW) was carried out on the Aluminium alloys of 2000 & 5000 series which are generally used in the application of the Aerospace and the Ship industries. They have processed the parameters like the mechanical properties, tolerances, and the metallurgical characteristics. In the last module they have pertinent data for further industrialization of this Friction Stir Welding technique. It has been proven that it can be used for the low melting temperature metals like the brass, copper, Aluminium. The next milestone of this technique is to weld for the materials having the high melting points and can withstand the high temperatures and the pressures to get the perfect weld and have the effective joint. In FSW, the welding metals and a cylindrical shouldered tool with a profile probe are used the weld is produced by the plunging and rotating the profile probe tool into the two welding metals which are fixed and clamped side by side in which solid state is produced by the friction generated during the rotation of the plunged profile probe tool. With the help of this technique there are some of the salient features in the weld quality some of them are having no porosity as it doesn't melt, as this is an extruding and the forging joining method which is controlled by an accurate heat so no lack of fusion, having greater weld strength than the parent metal due to formation of the fine grain structure in the weld nugget, no change in the material as the extra filler material or the any other substance are not used. So, these are the general information about the friction stir welding which would be helpful in getting knowledge about the new trending technology about the joining of the similar or the dis-similar metals.[52]

### *Riveting Process*

In the joining process the welding is not only the solution for getting two materials to make it as single unit but instead of the welding process there is one other method called as the fastening. Generally, this mechanical fastening is having their separate appraisal in the field of the manufacturing industry for the joining of the two materials, the main importance is given to the fastening when we need to join the plastic materials. The mechanical fastening is differentiating into the two categories that are permanent joints and non-permanent joints. The Screws are the main example for the non-permanent joints as then can be removable, replaceable, and reusable. In similar way the working of the rivets is also similar as the only difference is that it is a permanent joint and we cannot use the rivet as reusable. The rivet nomenclature is like it contains the head part and the cylindrical tail later on its other side is also converted into the head of the hemispherical shape. These are mainly used in the lap joint or the butt joint with the large range of the configuration along with the single pin riveting, double pin riveting and the zig-zag form riveting patterns. This riveting can be done by drilling or b placing the rivet on to the place to get join and the tail portion of the rivet is then smashed or deformed into the similar manner of the head shape as this can be made into the movable, fixed, closed and closed-fixed. For the maintenance of the joint the rivet cannot be replaceable as this are needed to destroy to fix the joint again separately. These rivets are made by the process of the cold heading or the cold upsetting from the rollers. These rollers can be used in many areas of application like aerospace, marine, shipping, space industries etc., The one more advantage of this riveting is that it can be mass produced with the accurate and required dimensions. During riveting easy deforming material is required which required the characteristics of lower hardness so, wrought iron or the soft steels metals are used for the making rivets.[53]

### *Laser Welding*

The main source of joining the metal is heat and by using this heat with the maximum concentration at one place with the help of the laser on the metal can be joined or welded this process of joining of the metal using the laser is called as the Laser welding. The weld joint is formed by the laser light intensity which heats the metal material rapidly typically we can say in the milliseconds. Generally, there are various type of lasers into which they are categorized like gas lasers, solid state lasers and diode lasers. This laser beam is coherent and can precisely spot on the area spot without any divergent. This concentrated light beam can be impinged upon the surface to get welded. The lens plays a key role in defining the spot for the joint to be get welded, the larger the spot the high amount of intensity gets generated and used for the heat treatment process and the smaller the spot the more amount of the intensity will get concentrated, and a sharp pot would be helpful in the cutting of the metals. The lasers don't require any vacuum as it can get interact with the any material. In the laser welding the absorption of energy may get effected with some factors like incident power density, the type of the laser used and the condition of the base metal surface that is going to be used. The type of the welding can be done using these three ways with the help of the laser welding there are conduction mode welding, penetration mode welding, keyhole mode of welding. The metals that are used for the laser beam welding are Aluminium, Titanium, Carbon steels, Platinum, nickel, Molybdenum, Kovar, and stainless steels. [54]

## PARAMETERS

### Tensile properties

The tensile test for joining the type of Alumnium alloy Al-Mg4.2 was thoroughly examined. Figures 1 and 2 shows the Tensile properties of Ultimate tensile strength (UTS), yield strength (YS), and joint efficiency of the joints formed with different pin profile and shoulder diameters tools, sequentially. Each joint received three tensile test specimens, with the mean of three measurements used to produce the bar diagram as shown in the fig (1) (2). The ultimate tensile strength and yield strength of the joints were determined using UTM's software interface. The joint efficiency was calculated as the ratio of the joints' UTS to the parent alloy's UTS. Joints made with a 15 mm shoulder diameter tool and a square pin shaped tool have greater tensile properties than those made with other tools. The UTS of all joints was resulted lower values [10]. 2A14-T6 Aluminium alloy welded by laser beam welding process and the tensile results brought out that, when the heat input is 75 kJ/m, maximum tensile strength was obtained at 261.7MPa which is about 62% of the base metal as shown in the figure 3 [13].

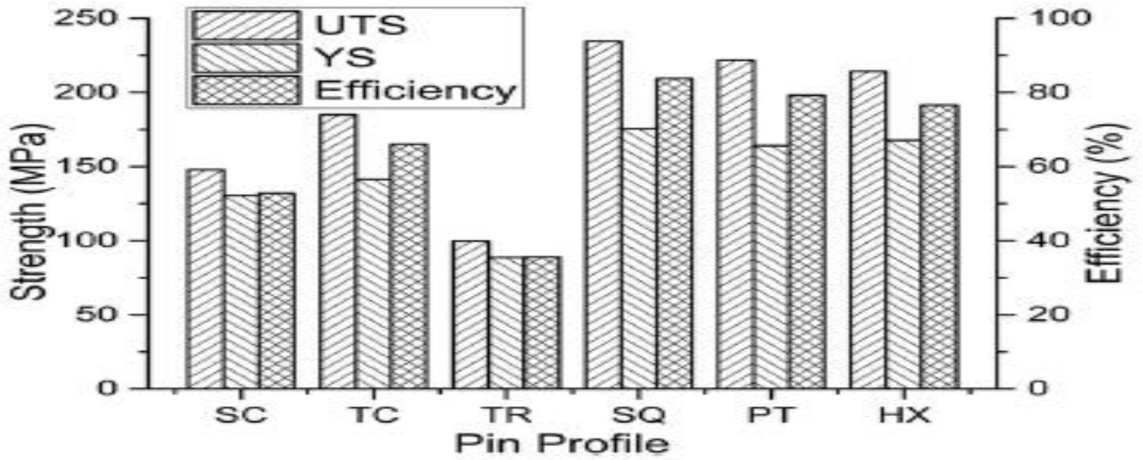

Fig 1. Effect of tool pin profile on strength properties [10]

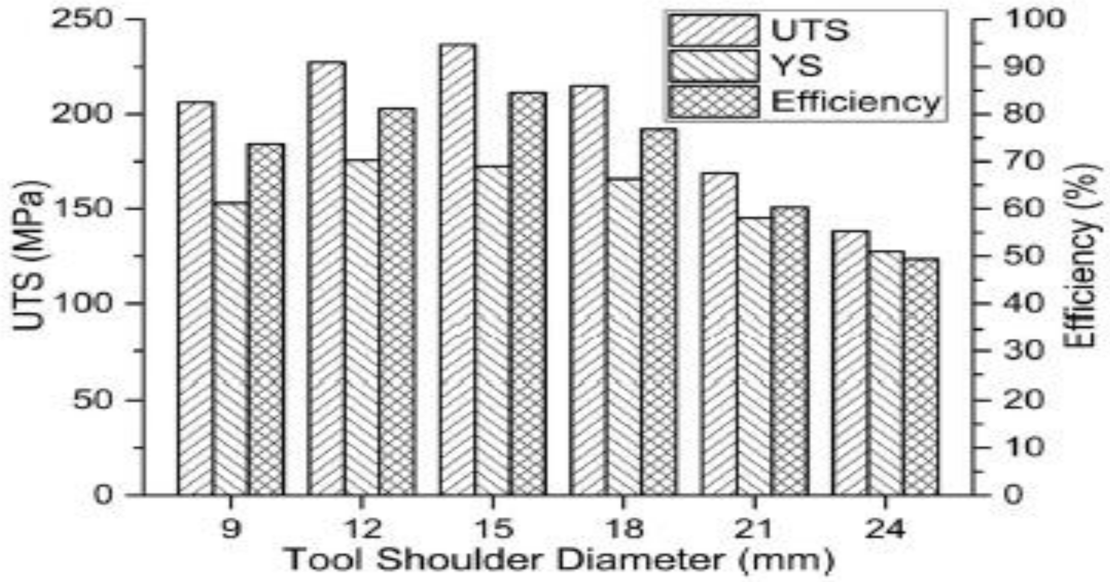

Fig 2: Effect of tool shoulder diameter on strength properties [10]

By using FSW joining technique, dissimilar metal 6061-T6 Aluminium alloy to Az31B Magnesium alloy was examined [7]. With Mg on Advancing Side (AS) and a tool offset of 0.3 mm, the maximum tensile strength of 175 MPa was attained at 700 rpm and 50 mm/min, which was about 70% of that of the Mg base metal. From the result it can be seen that, the low joint strength was caused by the high rotation rate and traverse speed [7]. The maximum joint strength acquired when the speed of the welding process was at the greatest value [7]. The welding property tensile strength has to be considered strongly when selecting the material combination [4].

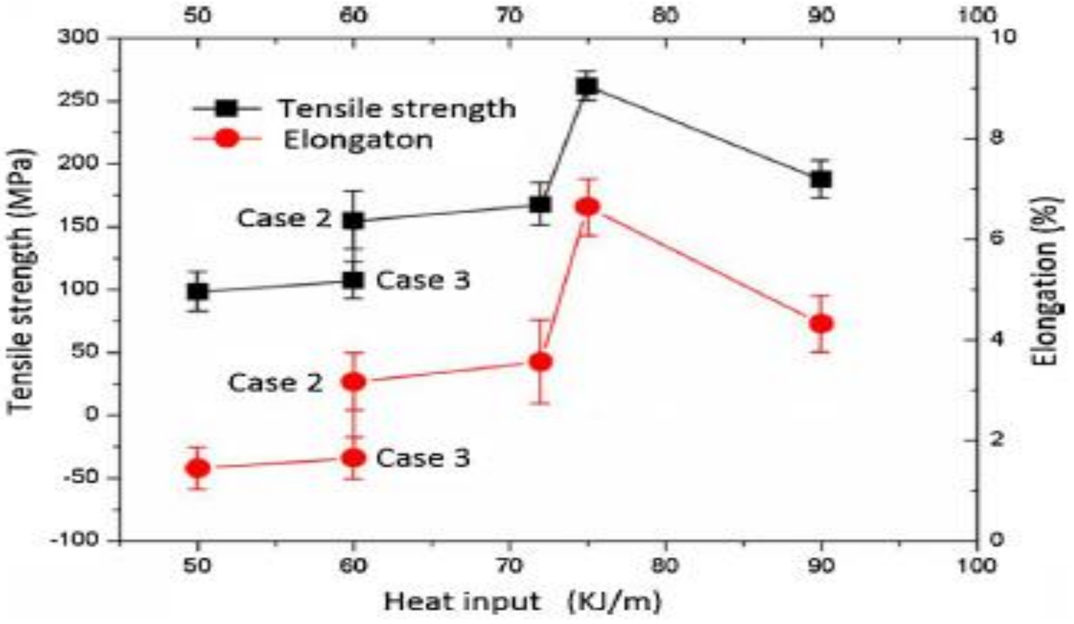

Fig 3: Tensile strength and elongation of the laser beam weld of 2A14-T6 Aluminium [13]

## Microstructure and Metallographic Analysis

Typical cross-sections of Al–Mg dissimilar metal FSW joints welded at 700 rpm and 60 mm/min with Mg on AS and tool offset of +0.3 mm are shown in Fig 4(a). Scanning electron microscope (SEM) investigation was focused on the interface between Al and Mg, as well as the nugget zone on the Mg side, which revealed distinct characteristics from similar metal FSW joints [7]. The microstructure of the formation of defect-free weld nugget depends on the shoulder diameter and the pin profile of the welding tool [10]. A light-etching interfacial layer about 3 m thick existed, representing the production of intermetallic compound (IMCs), as shown in a typical SEM picture of the interface in Fig 4(b).

The existence of Al and Mg elements across the interface was shown by energy dispersive X-ray (EDX) line analysis of the IMCs layer (Fig 4(c)), and the variation in relative concentration of Al and Mg suggested that the IMCs layer was made up of two layers: which are $Al_{12}Mg_{17}$ and $Al_3Mg_2$ respectively. The nugget zone was divided into three zones: the shoulder impacted zone (below the shoulder during welding), the banded zone (upper and middle regions of the joints on AS), and the severe intercalated zone (bottom). Both banded zone Fig 4(d) and severe intercalated zone Fig 4(e–f) revealed Al–Mg intercalated structures induced by severe deformation during the FSW process and varying deformability of Al and Mg. Fig 4(g) (h) illustrate the distributions of Al and Mg elements in the banded zone and severe intercalated zone, respectively. The coexistence of Al and Mg elements in places highlighted by arrows revealed the presence of reaction between Al and Mg elements during FSW. Fig 4(i) shows a typical eutectic structure in the severe intercalated zone, with the bright phase being $Al_3Mg_2$ and the dark phase being a mixture of Al solid solution and $Al_3Mg_2$[7].

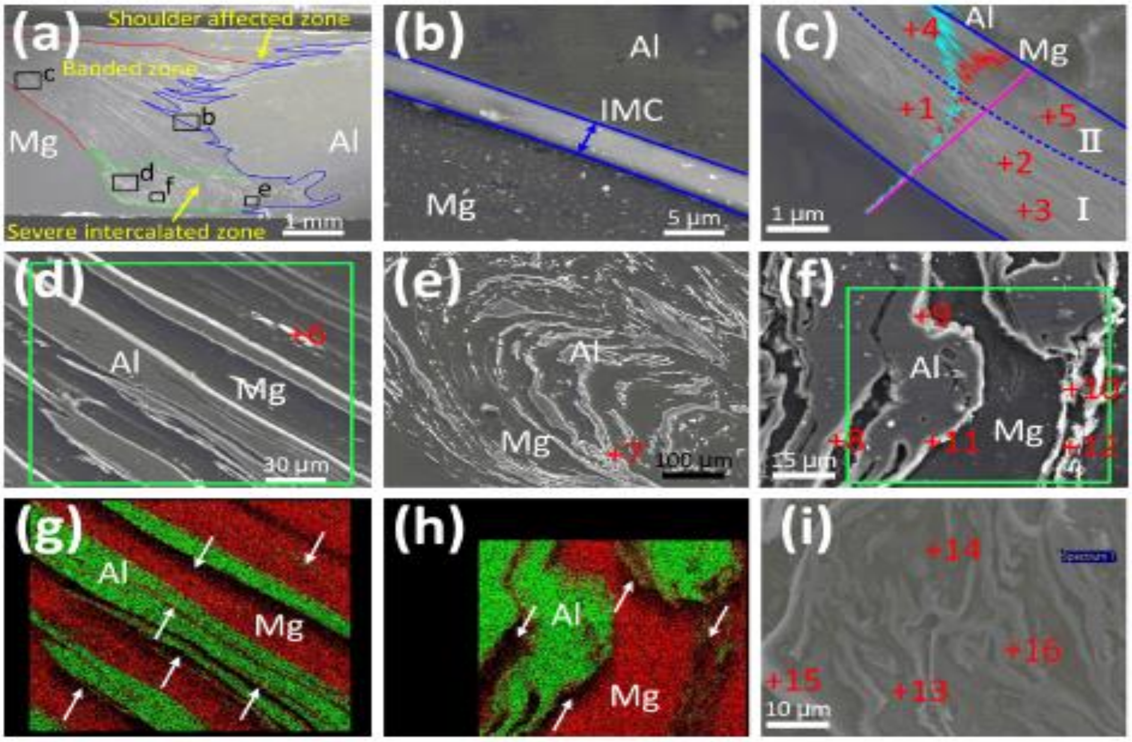

Fig 4. SEM microstructure and EDX analysis of Al-Mg dissimilar metal FSW joint produced at 700 rpm and 60 mm/min with Mg on AS, tool offsetting to AS 0.3 mm [7]

Increases in rotational speed and joining time resulted in greater heat inputs and process temperatures for the PEI-AA 2024-T351 joints. The heat input and temperature of the assessed joining conditions are projected to increase as the rotating speed and joining time at constant joining pressures increase. The increase in the value of the aspect ratio of the anchoring zone with increasing processing temperature is closely related to the heat input and local plasticizing of the metal, as increases in rotational speed and joining time generated higher processing temperatures, according to this analysis of joint manufacturing process parameters. The high heating and deformation rates during the joining process are known to have a major impact on the microstructures of FricRiveted joints [35].

Fig 5 shows the microstructures of disc laser beam welded joints of 2A14-T6 aluminium alloy beneath diverse welding conditions. The welding pool begins to solidify from the fusion line to the welding pool's centre. The major dendrites grow from the fusion line to the weld's centre and in the temperature gradient's direction. With the solidification of the welding pool, constitutional supercooling increases in the fusion zone (FZ), and numerous crystal nuclei form. The crystal nuclei then start to expand and create fine grains. The average values of primary dendritic arm spacing at the fusion line and grain size in FZ are measured along with micro analysis [13]. Heat input can be affected the microstructure in the joining zone [14]. With an increase in heat input, the average grain size drops at first, then increases. When the heat input is 90 kJ/m, the maximum primary dendrite arm spacing at the fusion line and the maximum grain size in the FZ are 12.67 m and 6.67 m, respectively.

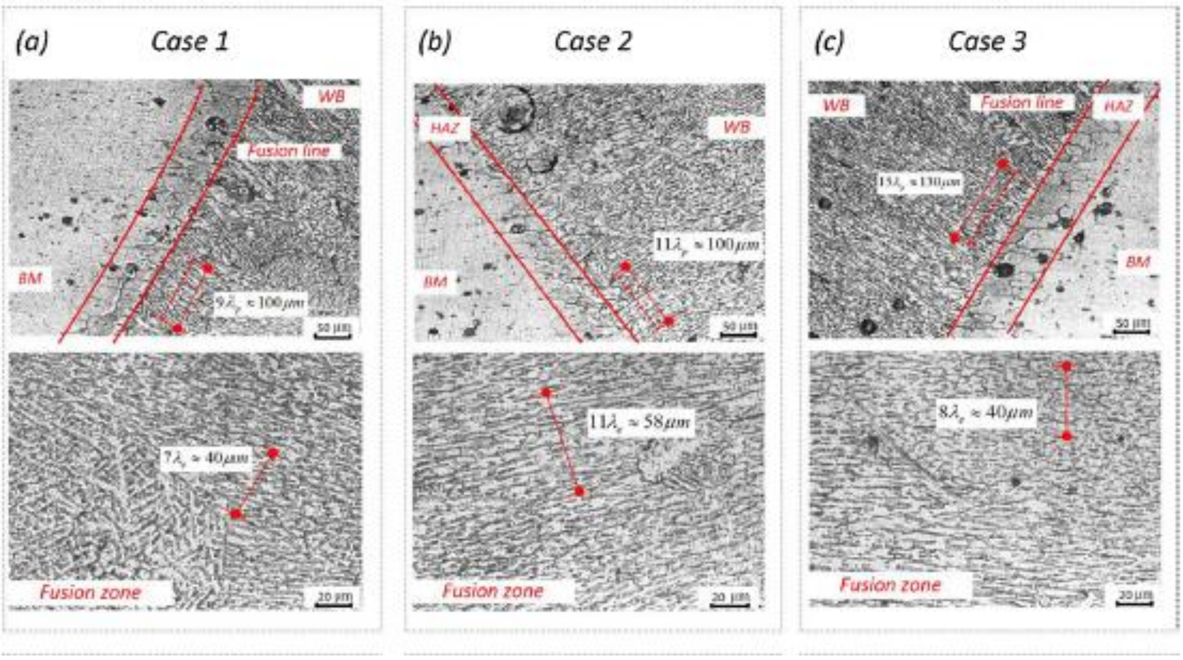

Fig 5. Microstructure of the disk laser beam welded joints under different welding parameter [13]

The microstructure data revealed that laser oscillation influenced the growth of the equiaxed grains in some way [36]. When the heat input is 75 kJ/m, the minimum primary dendrite arm spacing at the fusion line and the minimum grain size in the FZ are 7.69 m and 4.0 m, respectively [13]. The porosity ratio of the disc laser beam weld with 72 kJ/m and 75 kJ/m heat input is substantially lower than that of others. The porosity ratio is higher when the laser power is 2500 W, and the heat input is 50 kJ/m and 60 kJ/m. The reason for this is that due to the low heat input, an incomplete fusion can be seen at the bottom surfaces of the weld, resulting in the production of several significant porosity defects at the bottom of the weld [13].

**Microhardness**

The microhardness of distinct zones of the welded joints was determined using the Vickers microhardness test. With a load of 500 g for 10 seconds, the microhardness of the parent alloy was measured to be 88 HV. As illustrated in Fig (6), the microhardness of the intermediate layer across the joint was measured. Regardless of the pin shape and shoulder diameters of the welding tools, the nugget zone of all joints was found to be harder than the parent material. The hardness of both the heat affected zone (HAZ) and the weld nugget (WN) is lower than that of base metal (BM) [37]. The improvement in hardness is justified by the refining of grains in the nugget zone of the joints. In all joints, the retreating side's hardness was found to be higher than the advancing sides. Among all the joints manufactured with different shoulder diameter tools, the joint produced with 15 mm shoulder diameter tool showed the greatest improvement in stir zone hardness [10].

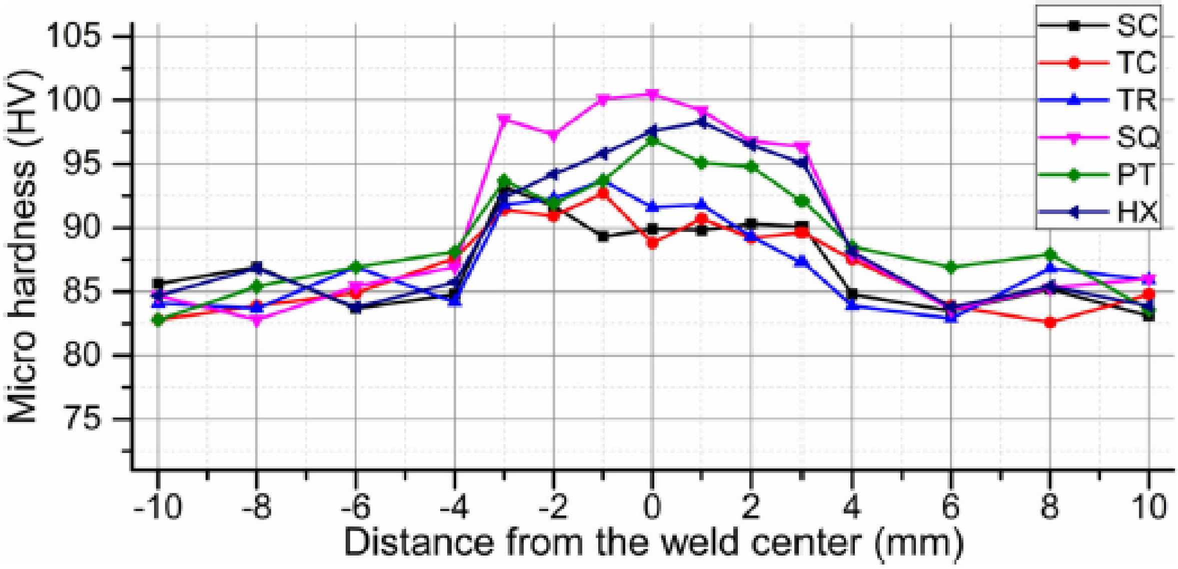

Fig 6. Effect of pin profile on microhardness [10]

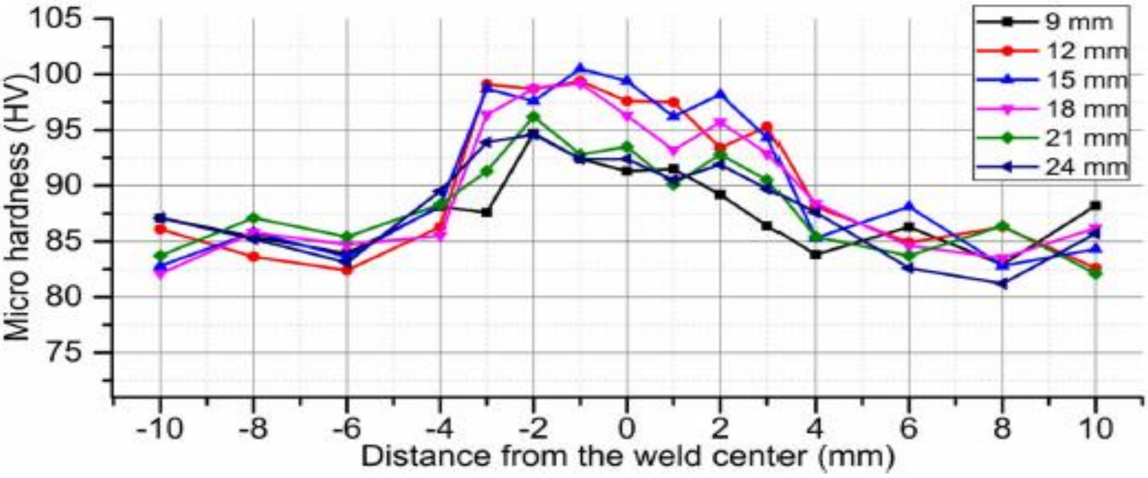

Fig 7. Effect of tool shoulder diameter on microhardness [10]

Furthermore, insufficient heat generation causes coarsening of grains in the nugget zone, which reduces the hardness of the weld nugget. Joints produced with shoulder diameters smaller than 12 mm and bigger than 18 mm suffer from a loss of strength and efficiency due to decreased hardness, coarse grains, and the presence of flaws. The joint fabricated with a 15 mm shoulder diameter tool had a high hardness value and fine grains in the stir zone, as well as a fracture surface with well-distributed fine dimples, which are the reasons for the joint's high strength and efficiency when compared to others. [10].

After examining the 2A14-T6 Aluminium alloy by using disk laser beam joining technique, micro-hardness is reduced at the fusion boundary and gradually increases from the heat-affected zone (HAZ) to the base metal for the same disc laser welded connection (BM). Because gains in FZ are finer, the hardness in the centre of FZ is greater than that at the fusion boundary. The micro-hardness of BM is the maximum, while it is the lowest at the fusion border. The maximum micro-hardness of BM is due to the fact that it is strengthened by solution heat treatment and ageing strengthening treatment, as evidenced in the microstructures in Fig 8 [13]. In contrast to arc welding, where the hardness minimum is in the overaged HAZ region, a hardness drop (strength undermatching) was seen in the HAZ and the FZ, with the hardness minimum located in the FZ. Overaging occurs as a result of heat input during the welding process, which results in a loss in hardness in the HAZ. [2]. The fusion border has the lowest micro-hardness because the strengthening effect is reduced due to the loss of alloying components. The welding thermal cycling coarsens the grains and causes HAZ to age prematurely. As a result, HAZ has a lower micro-hardness than BM. With increasing heat input, micro-hardness near the fusion line and in the FZ increases at first, then declines. The maximum hardness at the fusion line and in FZ is attained when the heat input is 75 kJ/m [13].

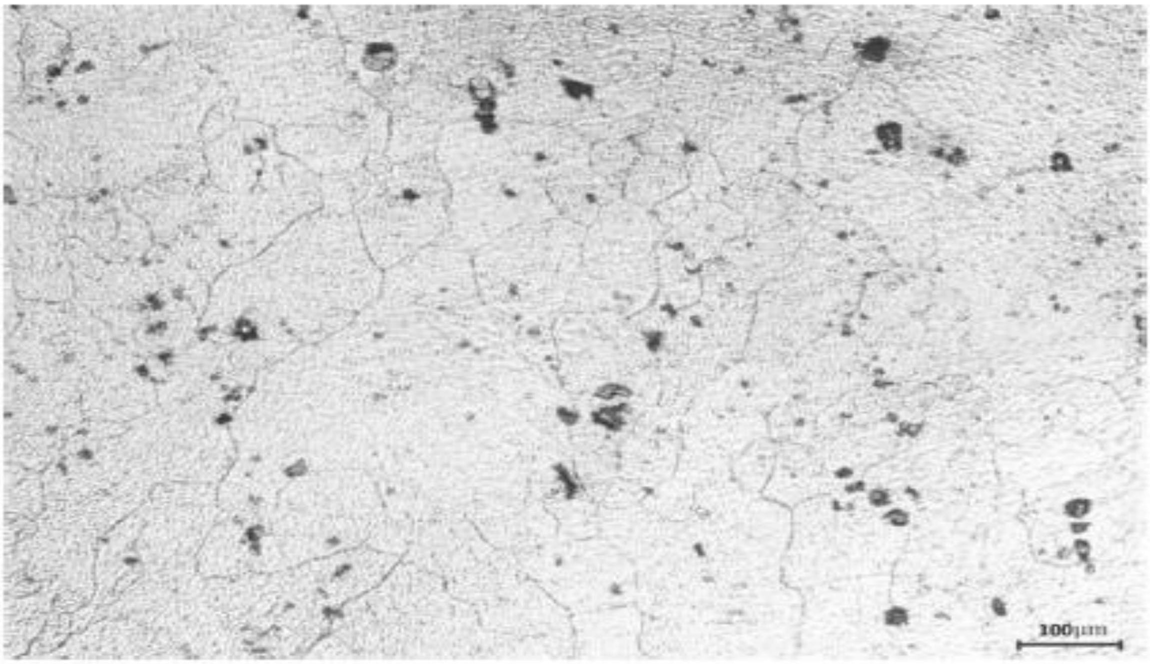

Fig 8. Microstructures of 2A14-T6 Aluminium alloy [13]

The grain shape of the sheet changed from equiaxed, which was far away from the rivet, to streaky, which was close to the rivet. The macro morphology of the joint can be split into five sections. The average hardness at the various location of the joint is observed as 171HV,66.5HV,149HV and 68.9HV [38]. The hardness distribution increases from 72.374.9 [HV] in the base metal to 97.3 [HV] in the B2 transition zone of the upper plate, and 82.285.5 [HV] in the C2 transition zone of the lower plate; the highest value is found in B1 upper plate self-locking area 102104 [HV], and 100 [HV] in the C1 lower plate self-locking area. [3].

Vickers hardness was mapped out on the joints at various process parameters to identify the hardening/softening of aluminium in the F-SPR joint. In comparison to the BM, the aluminium alloys close to the rivet have lower hardness in all three joints. The softened zones were highest in the 3600 rpm-2.0 mm/s junction, measuring 6.2 mm in the upper sheet and 4.8 mm in the lower sheet outside the rivet as shown in Fig 9(a). The minimum hardness was around 130 HV, or 77 percent less than BM's 169 HV. When compared to 3600 rpm-2.0 mm/s, the 1800 rpm-2.0 mm/s joint has a similar overall hardness distribution with a slightly narrower softened zone width as shown in fig 9(b). However, as the feed rate increased from 2.0 mm/s to 8.0 mm/s, the width of the softened zone shrank considerably as shown in fig 9(c). In the 3600 rpm-8.0 mm/s joint, the minimum hardness was around 140 HV, or 83 percent of the base material. TEM images of zones I, II, and III outside the rivet of the 3600 rpm-2.0 mm/s joint. As the materials approach the rivet, the original strengthening precipitates coarsen and show increasing size from zone I to III. Many of the BM's precipitates are coarsened or grow into, resulting in an overaged state [34].

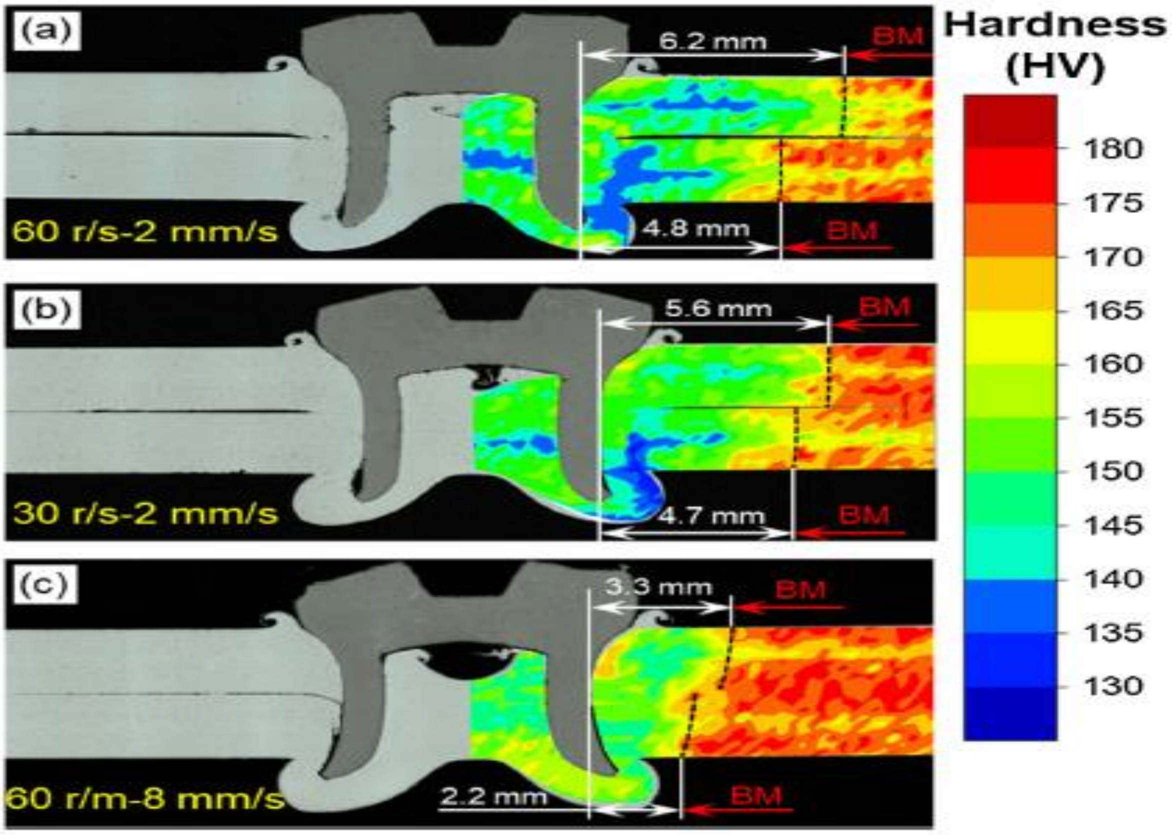

Fig 9. Vickers hardness distribution maps of F-SPR joints under different process parameters. (a) 3600 rpm, 2.0 mm/s, (b) 1800 rpm, 2.0 mm/s, (c) 3600 rpm, 8.0 mm/s [34]

All of the precipitates dissolved in the lower section, where the aluminium was entirely recrystallized, indicating that the temperature is higher than the solution heat-treatment temperature of AA7075-T6 (480$^0$C). As a result, while grain refinement strengthens the materials inside the rivet, the drop in hardness caused by precipitate dissolving and coarsening is difficult to compensate for. Furthermore, due to fine grain strengthening, the lower region of the aluminium inside the rivet cavity was tougher than the remainder of the softened zones. Furthermore, the upper sheet had a wider softened zone than the lower sheet due to the up-to-down heat generating direction when the rivet fed from the upper sheet to the lower sheet during the F-SPR process [34]

## APPLICATIONS

There are various methods to join the aluminium alloys and based on the cost involved in the process and required strength by the joint, the selection of joining process is done. By comparing the application areas of the friction stir welding, laser welding and self-pierce riveting, the friction stir welding has a wide range of applications in areas of automobile, aviation, railway, marine, electrical and construction industry. In automobile industry FSW has its role in manufacturing of vehicle rims, vehicle frames and chassis, engine parts, fuel tanks[39][40] and in the aerospace industry FSW process is used in the manufacturing of fuel tanks of space shuttle and space ships and also in the manufacturing of stringer and wings in the aircraft.[41] In the marine industry the FSW technique is used in the manufacturing of ship main structures such as hull, decks and offshore accommodations and in the railway industry the FSW is used in the container bodies and railway tankers.[39] Laser welding and self-pierce riveting also has its application in automobile and aerospace but its usage is limited to the few areas. Self-pierce riveting is mostly used in the joining of sheet metals in the automobile industry [42] and the sheet metal is made up of materials such as aluminium alloys with composite or steel [43].SPR requires no predrilled hole and emits no fume emission and light weight structures can be joined[44][43].Laser welding is used in manufacturing of tailor blanks in the pillars, seats, closures [45] and used to weld the heavy structures in the automobile[46]Laser welding is used instead of riveting in the wings and fuselage components due to its less cost[47].

## CONCLUSION

In this paper we have compared the joining techniques of the Aluminium by Friction Stir Welding (FSW) with the Laser welding along with the Riveting.

- As in this method of joining done on the Dp 590 sheet steel. Dissimilar gauge tension tests (1.6/1.0 mm) showed that transverse tensile ductility in the laser welded specimens could reach the same level of performance as the friction stir welded specimens. As this Friction Stir Welding (FSW) has a greater formability than the Laser welding.[50]
- The methods like Friction Stir Welding and Laser welding will have the higher strength of the joint while compared to all other techniques, Main advantage of this technique is that it has the capability to reduce the weight of the whole body.
- For the Industrial application of this techniques the fatigue crack propagation and residual strength tests on centre-crack tension specimens, C(T)-specimens, or middle-crack tension specimens, M(T)-specimens), are needed to be get certified for the best quality of the welding for both Friction Stir Welding & Laser Welding.
- In many of the cases found that for maintaining the surface quality the only method found seems to be feasible that is Friction Stir Welding when compared to the others joining techniques.
- While the microstructure part, grains in the FSW are fine and equiaxed, which would help in the having the stronger bonds in welded part than the other techniques for the joining.
- In many of the cases of joining of the metals they have found that FSW process modifies the microstructure of the metal by refining the grain structure.
- In some other cases it is found that Friction stir welding could not produce the higher

productivity (Welding speed) So, instead of that Laser Welding is used.

- During the fatigue test of the material which was gone through the Laser welding & Friction Stir Welding the failure mostly occurs in the welded part and on the base material due to Geometric notches respectively.

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