FRICTION STIR WELDING OF ALUMINIUM ALLOY WITH A DISTINCT MATERIAL SANDWICHED IN BETWEEN

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ABSTRACT

The friction stir multi-lap welded joint has been created between the sheets of two aluminium Al5052-H32 alloys and the pure copper foil. The values of the shear strengths in the multi-lap weld of dissimilar materials, has been evaluated consisting of a sandwich structure. The sheets used are very thin in terms of thicknesses. The tool material is M2 HSS (High Speed Steel). The design of experiments has been done by following Taguchi method's L_9 approach. The ultimate shear strength is determined for all the samples. Microstructure has been evaluated with the scanning electron microscope (SEM) and the optical microscope for the AlA-Cu-AlA sample found to have the highest ultimate shear strength. Also, micro-hardness has been found out for the same. The AlA-Cu-AlA weld having the highest ultimate shear strength was made with the friction stir weld parameters: 800 RPM of tool rotation speed, 5 mm/min of traverse speed & 0.2 mm of the plunge depth. It was also found that the AlA-AlA weld had higher strength than the AlA-Cu-AlA weld for the same set of varying parameters. While dealing with the thin sheets, clamping plays a significant role. The discussed process could be utilised to create the copper cladding over the tubes of aluminium alloys which would make them light weight and excellent heat sinks.

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CERTIFICATE

I hereby certify that the work being presented in the dissertation entitled "Friction Stir Welding Of Aluminium Alloy With A Distinct Material Sandwiched In Between" in partial fulfilment of the requirement of the award of the Degree of master of technology and submitted to the Department of Mechanical Engineering of Lovely Professional University, Phagwara, is an authentic record of my own work carried out under the supervision of Mr. Prashant Kumar Pandey, C.O.D., Department of Mechanical Engineering, Lovely Professional University. The matter embodied in this dissertation has not been submitted in part or full to any other University or Institute for the award of any degree.

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CHAPTER 1: INTRODUCTION

1.0 OVERVIEW

The friction stir welding process comes under the domain of solid state welding process. Heat is required only to bring the material in the plastic state without any need to further supply heat to melt the base metal. The material that is brought in the plastic state is then deformed using the application of force. The deformation of plasticised material is pointed at mixing it with the other material or another work-piece of same material. This, in turn, joins the two or more work-pieces. The heat that is required for plasticising is generated by the frictional force when the tool surface rubs against the work-piece in a rotational motion. Then, in order to accomplish the intermixing, the tool traverses. Hence, an effective joint is achieved. The energy gets saved in the process because the joining occurred at a temperature lesser than that required to melt the base material. Moreover, since less heat was generated, the heat affected zone is also minimum, hence keeping the properties of the joint consistent.

1.1 HISTORY

Before the advent of friction stir welding, when arc fusion welding was in fashion, the defects to welding ratio was considerably higher. The culprit behind that unfavourable event was the low energy-density fusion welding process which causes the formation of a large pool molten metal and a large heat affected zone. This led to the formation of defects that were developed during the weld pool solidification. In return, these defects led to the distortion of work piece and the welded joint while reducing the strength of the joint as well. Up until 1990s, fusion arc welding and gas welding had been the prevalent players in the welding industry.[1]

Not long before the invention of FSW, certain other non-fusion welding processes such as friction welding, had already been developed. However, the former non-fusion welding processes could only find a very limited use in the industrial applications. In the case of friction welding, the two work pieces are made to come in contact with each other and with the help of linear motion or rotations, relative motion is achieved between them. Along with the relative motion, there is also simultaneous application of the compressive force along the two work-pieces. The reason why the geometry of the parts joined by the friction welding is restricted is due to the availability of only two movements: linear and rotational, which can be utilized to create the relative motion between the work-pieces. The principle governing the joining process in friction welding is that due to the relative motion between the two parts that are to be joined, frictional heat is generated. This frictional heat in turn, causes the softening of the metal at ends of parts in contact. At this semi-plastic softened state, when pressure is also applied, the two parts make up a strong joint at the surface of contact. Friction welding is very much similar to the forming process. Even though there had been geometrical restrictions for the use of friction welding and difficulties in clamping varying sections, it proved to be an efficient way for creating a firm joint between metals, plastics and many other polymers as the area of heat affected zone created in friction welding is very minimal just as in most of other solid state welding processes. This new technology involving the frictional heat and the pressure also unleashed the possibilities of dissimilar material joining.

Another invention that took place during the same period in 1950s when friction welding was prevailing was the laser welding. Since then and until now the laser welding is considered to be a very convenient and efficient mode of creating a joint between the multiples.[2] However, laser beam welding also has a few cost based restrictions and the restrictions cause due the size of parts that are to be joined. In laser beam welding, a high concentration welding source with high degree of penetration heats up the region in the material to be joined very precisely. It is a high density joining process and along with accuracy, offers the minimal affected zone while creating a very thing section of the heat affected zone which is, in some cases, negligible.

1.2 FRICTION STIR WELDING - THE INVENTION

With the advancement in technology and with the need of more sophisticated joints, the welding industry could be seen drifting into the pool of the high density joining processes, which favour less effect on the area in the vicinity of the weld, thus reducing the defects to welds ratio and thereby giving the joint more strength along with the cross-sections having trivial unwanted deformations. The research and the development team in "The Welding Institute (TWI)", situated in United Kingdom, had been carrying out extensive researches in the field of friction welding. Apart from studying the effect of varying rotation speed and torque parameters in friction welding, the researchers also showed interest in the properties of various materials in the plastic state. The need of eliminating the geometric restrictions was already being felt by the team. It was not long after when in 1991 on a very fine day, Wayne Thomas struck an idea of using a probe of a harder material than those materials to be joined and with the correct rotational speed and torque, using it to fuse the specimens together. This led to the invention of process named as Friction Stir Welding. In 1991, Wayne Thomas and his colleagues at TWI patented this technology.[3]

Friction stir welding (FSW) is very similar to the friction welding not just by the name but also by the working principle. Both of them are solid state thermo-mechanical joining processes. The significance of the word "stir" in friction stir welding is that the probe of a harder material than the specimens to be joined causes a stirring action in the material at the joint and thus highly plasticising the material to a point at which the complete joint is created. With FSW, the need of clamping the heavy parts to be joined, as per the 'parts in motion' regulations, could be avoided as the parts now need to the clamped in stationary architecture while only the small probe needs to be clamped as per the 'part in motion' guidelines. Another advantage of FSW over friction welding is that the geometrical restrictions are majorly eliminated. The efficiency of the FSW join depends upon how well the parts have been clamped and how rigidly the tool has been mounted. Although the friction stir welding faces a strong competition from the laser welding, it has its own specialised uses in the industry. In comparison to laser beam welding, the FSW costs less and its equipment accommodates part variety much better than that accommodated by the laser beam welding setup.[4]

1.3 FRICTION STIR WELDING - THE TYPE OF JOINTS

One of the most beneficial factors that can be noticed in FSW is that it doesn't add any mass to the joint since there is no involvement of the filler material in the general use. For the very same reason, it has found industrial applications in the space equipment industry and the automobile industry where the volume to weight ratio matters a lot.

Another advantage that the concerned process carries is that it can effectively join the sum up thickness of up-to 5 mm, depending upon the properties of material and the temperature conditions. Also, high accuracy can be achieved while welding the sum up thickness of plates of 0.2 mm

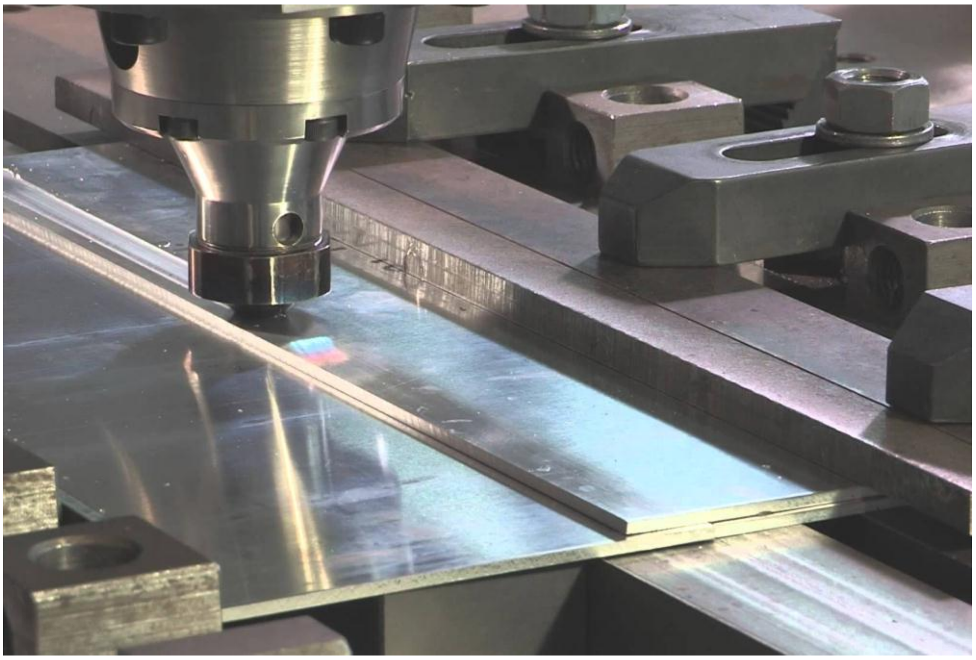


Figure 1 Lap Joint In Friction Stir Welding

The types of joints that can be formed by friction stir welding are the lap join and the butt joint. For a fixed setup it is not convenient to make any other kind of joints in the specimens, however, with the advancement in the technical field where robotic arms are being employed to achieve various tasks in space with higher degrees of freedom, there is no limit in possibilities.

1.4 MOTIVATION

As it has already been discussed that the process of friction stir welding has a wide range of scope in the near future, consider it to be the airplane building industry, the space industry, making of seam welds in boilers or the supercars. Moreover, it is a well-established process to join the dissimilar materials too, say plastics such as polythene, abundant metals such as copper, aluminium and steel, high strength metal such as titanium and innumerable alloys of the listed metals. However, still the standards are being set in this industry and in this phase of research, holistic contribution is necessary.

By the repetitive experimentation and the analysis of results, the standards for this type of solid state welding: Friction Stir Welding Process, could be established. This will enable the future enthusiasts or the people indulging in this technology for the business to save their time, material, efforts and hence money, yet get the superior friction stir welds.

CHAPTER 2: TERMINOLOGY

The following are the explanations to the terms that are commonly used in this report:

Shoulder:- The should is a part of the tool that prevents the plasticised material to escape the weld bead. The shoulder penetrates into the work-piece up to some depth.

Plunge Depth:- The maximum depth up to which the tool shoulder penetrates into the panels of the weld material. The plunge depth is measured normal to the surface of the weld panels.

Probe:- The probe or the pin is the part attached to the shoulder that makes the first contact with the work-piece to be welded and penetrates into it. The pin height is slightly lower than the depth of weld to be required to be penetrated.

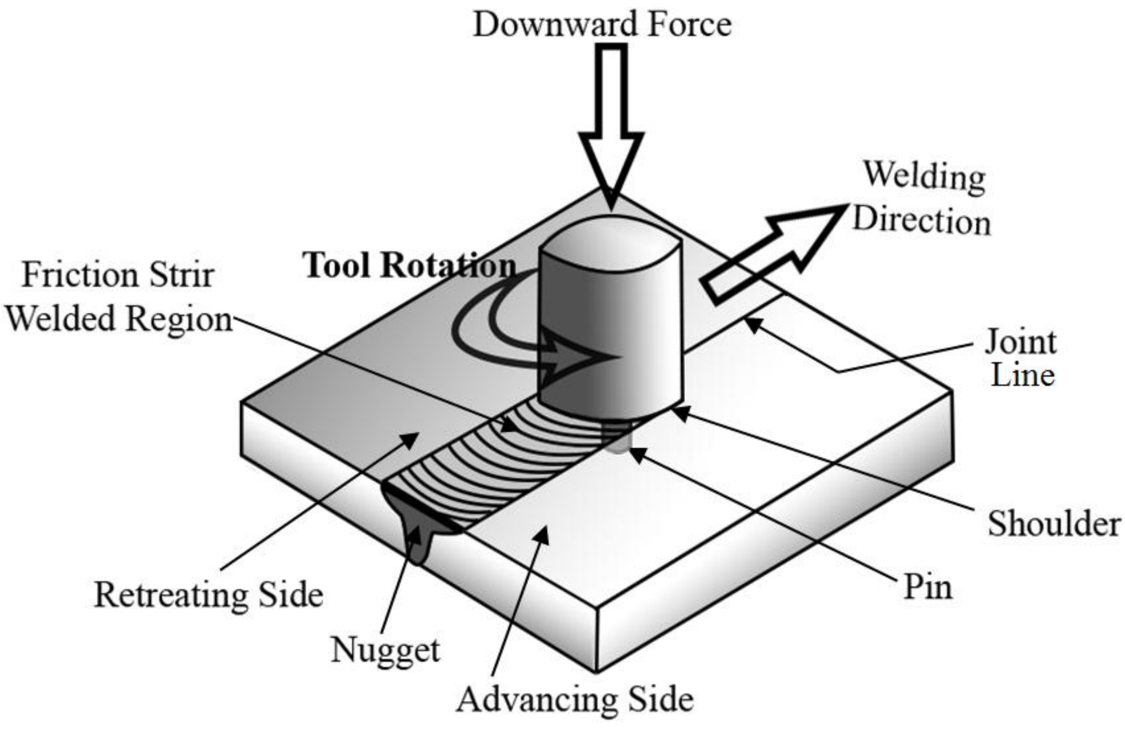


Figure 2 Schematic Diagram Of Friction Stir Welding Process

Joint Line:- The along which the two work-pieces positioned in a butt-joint get welded.

Advancing Side:- The side along which the rotational direction and the tool travel direction has the same sense is known as advancing side in case of friction stir welding.

Retreating Side:- The side along which the rotational direction and the tool travel direction has the opposite sense is known as retreating side in case of friction stir welding.

HAZ:- It stands for the Heat Affected Zone and at this zone the recrystallization takes place.

TMAZ:- It stands for the Thermo-mechanically Affected Zone and only partial recrystallization takes place in this zone.

NZ:- It stands for the Nugget Zone and is the area where the actual welding takes place.

CHAPTER 3: REVIEW OF LITERATURE

Amber Shrivastava et al. [2017][5] worked on developing a method for detecting the formation of discontinuities during FSW. Friction stir welding is fundamentally price effective but the need for noteworthy weld examination can make the process extortionate. A novel method to weld examination is vital in which an in-situ characterization of weld superiority could be attained, lowering the reqirement for post-process examination. For this, friction stir welds with subsurface empty areas and without voids were formed. The subsurface voids were created by lowering the friction stir tool rotation frequency and upsurging the tool traverse speed to make “colder” welds. Process forces were determined during welding, and the void dimensions were determined post-process by electronic tomography: “Three Dimensional X-Ray Imaging”. The 2 parameters, based on frequency field content and time-domain average of the load signals, were found to be linked with void dimension. Standards for subsurface void recognition and size forecast were developed and shown to be in decent agreement with trial observations. With the correct choice of data attainment system and frequency analyser the incidence of subsurface voids can be spotted in real time.

Pankaj Sahlot et al. [2017][6] concluded that the joining of great strength materials by making use of friction stir welding (FSW) is hard because of extreme tool wear and alteration in the form or dimensions of the tool. However, quantifiable understanding of tool wear at the time of FSW of metallic materials with high melting points is very limited. The quantifiable wear examination of H13 steel tool at the time of FSW of Cu-Cr-Zr alloy. More amount of total tool wear is detected for quicker tool rotational speeds, and gentler traverse speeds. Advanced wear rate shows similar connection with these process parameters at the time of initial traverse stage. With more tool traverse the wear rate decreases suggestively and is not much altered by the process parameters. The quantifiable wear study offers insights about tool-wear during friction stir welding process and would be beneficial to better estimate and increase tool life. This would also be beneficial to optimise the process parameters and tool form to reduce tool wear at the time of FSW of materials with high strength.

Bipul Das et al. [2017][7] have made efforts towards the checking of friction stir welding (FSW) process by real-time torque indications in this study work. Signals were studied using separate wavelet transform & arithmetical features namely asymmetry, dispersion and excess are calculated. The calculated features are further treated to develop effective procedure for internal defect recognition in FSW process. A new pointer has been suggested joining the calculated statistical characteristics. The suggested indicator shows considerable deviances for flawed and defect free welds. Other than flaw detection by the computed indication features, they are also offered as inputs to a upkeep vector machine learning based demonstrating tool for the forecast of ultimate tensile strength of the joints. The forecast accuracy of the model with calculated signal characteristics are found to be more than the model established with process parameters. The evaluation of the established support vector regression (SVR) model with artificial neural network (ANN) model & universal regression model produces that forecast performance of SVR is grander to ANN and universal regression model. The suggested work can be altered for its effective use in real-time modelling of FSW process.

Jannik Goebel et al. [2017][8] studied that the aluminium-lithium alloy named AA2198-T851. They friction stir welded the material with bobbin tool using a tool technique with one still and one rotating shoulder. Flaw free welds in three millimetre thick sheet were produced featuring a high excellence surface texture on the still side. The structure at macrolevel forms an asymmetrical shape with microstructural characteristics known from standard FSW. Due to only one revolving side a material flow track near the still shoulder has been observed. A parameter study shows that a WP (weld pitch) of 1 mm/rev coupled with high pressure between the shoulders lead to decent outcomes. Physical performance of 77 per-cent of base metal hardness & 82 per-cent of base metal ultimate tensile strength were achieved. The fracture examination indicates 2 competing fracture styles, one being in the HAZ and the other at the borderline of the SZ (stirred-zone) on the advancing side. The first style is made due to thermal cycle impact, while the second location is affected from weak bonding as an outcome of the thermal cycle and experienced distortion.

Kush P. Mehta et al. [2017][9] analysed the joint of copper to dissimilar material: aluminium using the solid state joining process: friction stir welding. The effect of profile of the tool pin had been researched. The process involved keeping constant all the other parameters but the design of the tool pin. The frequency of fragmental defects was seen to increase while increasing the number of edges in the tool pin profile (considering the surface to be a polygon). A polygonal pin with 4 equal sides all right angles (square) delivered the highest hardness of the weld having HV283. There were a number of intermetallic compounds present in stir zone of Al-Cu. The series of tools used were circular, triangular and hexagonal. Al6061-T651 alloy & electrolytic tough picth (ETP) copper (>99.99% pure cure) were used in the experiment. The defects generated due to polygonal pin due to the scratching its edges implied on the copper surface. However, with the edges of tool probe increasing in number, the tensile strength elevated too. CuAl, $CuAl_2$ as well as Cu_9Al_4 and Cu_3Al were some of the IMCs (intermetallic compounds generated) generated. Although, the pin shape having edges gave better hardness to the weld in comparison to the cylindrical tool, it also made it brittle.

GM Karthik et al [2017][10] have experimented with making an alloy out of copper & aluminium by using friction stir processing. Later, the group performed the friction stir welding on the fabricated specimens. The group very well achieved their task with the alloy of copper and aluminium being created which also responded well to the artificial aging implied upon it. The selective alloying has been discussed including its future scope. A one centimetre thick aluminium plate of AA1050 alloy had been used in the experiment. Along with it, the copper used was in its powder form having particle size of about 60 micrometre. The powder was pushed into the 3 mm deep & 2 mm wide groove via H13 tool of 15 mm shoulder diameter. The end result included alloying of the aluminium with the 2 weight percentage of copper. This was the first time this target was accomplishes and it significantly could be used to enhance the properties.

Noor Zaman Khan et al [2017][11] made efforts towards finding the microstructural and macro-structural conduct by the joints created by FSW between similar and dissimilar materials. The two base materials used in order to accomplish the same were AA2219 & AA7475, both of which are the alloys of aluminium. The process of FSW was employed to join dissimilar and similar 2.5 mm thick sheets of AA 7475-T73 & AA2219-O alloys of aluminium. The alloys AA2219& AA7475 are employed in the machineries of space shuttles and aeroplane, respectively that need competent fabrication process. Friction stir welding is a hygienic welding process skilled of joining tough to weld aerospace alloys of aluminium. The tensile strength, structure at micro-level, micro-hardness as well as fracture surfaces of the friction stir welded joints had been investigated. Grain improvement is observed at the stir zone due to active recrystallization triggered by severe plastic distortion. Least strength for dissimilar joint is detected mostly due to non-homogeneous drive of base materials consequential to variances in mechanical and physical characteristics. The least hardness was seen at TMAZ (Thermo-mechanically

Affected Zone) at the retreating side for every joint because of the thermal softening. Broken surfaces of the similar joints displayed more ductile fracture compared to joint having dissimilar materials which gave rise to lower elongation of the dissimilar joints.

Wei Zhang et al. [2017][12] had carried out an investigation to know the outcome of experimenting with the joining of T2 pure copper and the aluminium alloy Al6061. The special thing in their investigation was the shape of the joint configuration: tooth shaped. Out of this dissimilar bonding, microstructure and the physical properties were to be determined. The process used for joining was the solid state welding: FSW. In the experimentation, dissimilar 6061aluminum alloy and marketable unalloyed copper were friction stir welded: butt weld, while adopting the configuration of joint having tooth shape in order to investigate the influence of Al/Cu composition in welding bead (WB) at the scale of micro-level and mechanical properties of the achieved joint. At initial exams, optimal welding parameters were found to assurance proper heat input. The experiments of welding were performed with the sizes of the tooth as variables, which is a unusual method to tailor Al/Cu composition in weld bead. Macro and the structure at micro-level of the cross section of the joints were branded via Scanning Electron Microscopy (SEM) which was armed with energy dispersive spectroscopy (EDS) & optical microscopy (OM). Special band structure(BS) displaying lamellar-like flow property is worthy of noticing. Moreover, dispersive Cu particles (DP), making composite-like construction, were caught. Large Cu concentration, however, generated a harsh material flow because of its high plasticized temperature & the reduced flowability and could not produce reliable metallurgical bonding. The joint was tested for its micro-hardness and the high hardness was caused mainly by the hard IMCs. Also, tensile tests were done to calculate the joint performance. As per the result analysis, this joint form has special advantage in altering Al/Cu content in the weld bead as well as regulating the microstructure that imposes noteworthy influence on physical properties of the created joints.

Shude Ji et al. [2017][13] worked on eliminating the tear defects by back heating the friction stir weld of the alloy: Ti-6Al-4V. Using varied back heating temperatures, the joint creation and the structure at micro-level were mainly discussed. Results show that the temperature gradient along thickness plays an important part affecting the tearing defect. By increasing the back heating temperature, dimensions of the tearing defect progressively decreases due to lowered temperature-gradient. When using 753K, defect-free BHAFSW joint with complete lamellar structure along thickness and greater hardness could be obtained. Moreover, the BHAFSW could effectually lessen tool wear during welding.

Nan Xu et al. [2017][14] performed an investigation which was based at maintaining a good strength to ductility synergy. The friction welding was done with a stirrer on the Cu, which was the base material. Two copper sheets with 2 mm in thickness were welded by large load friction stir welding with very low speed of welding and rotation rate. Heat-affect zone (HAZ) had been successfully nullified for the enhanced thermal cycle. The grain modification in the stir zone is credited to the combination of continuous active recrystallization, irregular dynamic recrystallization, active recovery and also the twinning-induced active recrystallization. The stir zone displayed ultra-refined grains having low dislocation density & having large fraction of high angle boundaries. Plentiful twin boundaries were presented into the stir zone as well. Deu to this, the stir zone displayed a superior strength & ductility synergy having a strength of 548 MPa and a uniform elongation of thirty six per-cent. Their work also provided an effective technique to improve the strength of FSWed Cu joint without any loss of ductility.

Hui Shi et al. [2017][15] had investigated the IMCs in the banded structure of the joint welded by friction stir welding. The materials involved were dissimilar magnesium and aluminium. Various tool rotational speed (TRS) at a pre-set constant travel speed were used, having the tool offset to Al in order to examine the formation of IMCs in the banded structure (BS) zone & how they affected the physical properties. Large proportions of IMCs, in the form of irregular bands of particles or lamellae, had been found in the banded structure zone, where severe material inter-mixing had taken place during friction stir welding. The BS microstructural properties were varied with TRS in terms of the morphology of the bands and the size and spreading of intermetallic compounds particles. Each weld showed brittle fracture style with their fracture paths spreading mainly in or along the IMCs in the banded structure. It was displayed that these BS microstructural properties had the important effect on the physical properties of the joints. Propositions on modifying the BS microstructure were suggested for optimizing the strength of the BS zone and the final physical properties of the aluminium and magnesium friction stir welded joints.

M.M.Z. Ahmed et al. [2017][16] researched on joining the two dissimilar aluminium alloys: AA7075 and AA5083. The two alloys of aluminium: AA7075-T6 and AA5083-

H111 had been friction stir welded at a pre-set rotation rate of 300 revolutions per minute the and varied traverse speeds of 50 up-till 200mm/min, with a gap of 50mm/min, in dissimilar and similar joints. The structures at micro-level and crystallographic surfaces of base materials (BM) and the welds were inspected by making use of electron backscatter diffraction (EBSD) technique. The physical properties were found using Vicker's hardness testing and tensile testing. The fracture exterior of the tensile tested specimens was inspected with the use of scanning electron microscope (SEM). Microstructural examination of AA5083 and AA7075 base metals showed noteworthy variation in the grain structure of the two alloys having an average grain size of forty micrometre that was not having substructure in case of aluminium alloy: AA7075, while AA5083 BM exposed an typical grain size of twenty five micrometre with the high density of substructure. Apart from it, the type precipitates also are different in these 2 alloys. Even though, the two alloys, which were joined using the same FSW limits the two alloys showed different response in terms of the recrystallized small grains after friction stir welding. Noteworthy grain refining happened in the nugget zone of AA7075 having grain size of six micrometre at welding speed of 50mm/min that was reduced to two micrometre by increasing the speed of welding to 200mm/min. A moderately recrystallized larger grain structure was obtained in AA5083 joints weld nugget zone with grain size of nine micrometre at 50 mm/min that is lowered to three micrometre at 200mm/min. It means that the starting material properties have a noteworthy impact on the ultimate grain structure after friction stir welding. The crystallographic quality in the nugget zone revealed a simple shear consistency without a noteworthy effect of varying the welding speed. The dissimilar joints showed ultimate tensile strength stretched between 245 and 267 MPa and fracture strain stretched between 3 and 5.6 %.A brittle to ductile fracture style was controlling in the examined fracture exterior of the dissimilar joints.

H. Dawson et al. [2017][17] have evaluated the influence of the welding parameters on the oxide dispersion having nano size, and the grain size in the matrix of an Oxide Dispersion Strengthened (ODS) steel upon welding by FSW. Based on collective small angle neutron scattering and SEM, results revealed a decrease in the "volume fraction" of the elements smaller than eighty nanometre in the joints, mainly due to particle accumulation. The upsurge in tool rotation speed or reduction in transverse speed leads to a decrease in nano-sized particle fraction, and moreover to the happening of melting of the particle.

The requirement of the average grain size in the matrix on the element volume fraction shadows a "Zener pinning-type" connection. The result leads to the principal role that the small elements have in pinning grain boundary movement, and thus in controlling the grain size during FSW.

K.H. Kim et al. [2017][18] in their study friction stir welded a butt joint in very thin 430M2 ferritic SS foils with acceptable joint characteristics. The tool used was a pin-less WC-Co fabricated. FSBW had been done at a tool rotational speed of nine hundred revolutions per minute & at a travel speed of ninety six millimetres per minute. The friction stir welded joints were welded totally without any un-welded zone ocuring from smooth material flow, in spite of being chosen pin-less tool. The conclusion came out to be that maximum tensile strength of friction stir welded welds was four hundred and sixty eight mega-pascals, equal to the base metal's tensile strength. Particularly, it was observed that sigma phase creation in FSW welds is repressed associated with that of arc welds, causing improvement of joint strength. The low input process of friction stir welding is an operative substitute for the traditional fusion welding GTAW in very thin ferritic stainless steel foil.

V.C. Sinha et al. [2016][19] made an attempt to compare the microstructure as well as the mechanical characteristics of the friction stir welded joints between the two cases. The first case being the joint created between the two samples of similar metal and the other one being the joint created between the two dissimilar metals. The three pairs of joints created by the combination of Aluminium Alloy (AlA) and the pure copper (Cu) are AlA-AlA, AlA-Cu and Cu-Cu. The rotation speeds were varied between 150 rpm to 900 rpm and in the steps of 150 rpm at 60 mm/min travel speed at a constant angle of 2°, in order to obtain enough experimental results. Through SEM, the microstructure was determined. The following were the intermetallic compounds created at the interface of Aluminium Alloy and pure copper at the friction stir welded joints of these two materials: Al_4Cu_9, AlCu, Al_2Cu & Al_2Cu_3. Also, the corresponding values of grain size were obtained against the different step-values of heat input.

"X-Ray Diffraction" technique was employed in order to measure the residual stresses at the stir zone. At 750 rpm, the ultimate tensile strength of the AlA-AlA joint is about 75 per-cent of that of AlA. Also, at 300 rpm, the tensile strength of Cu-Cu joint was almost equal to that of Cu. As per the experimental results, the ultimate tensile strength of Cu-

AlA joint came out to be about 77 per-cent of that ofAlA. It is to be noted that the tensile strength of Cu-AlA joint at 600 rpm tool rotational speed is higher than that of AlA-AlA joint at 750 rpm.

The reason why there is creation of the poor joint in case of dissimilar metals by using the conventional welding techniques is that due to the difference in chemical, mechanical, thermal properties of the materials and the formation of brittle intermetallic compounds at the weld interface.

Sample Size → 140 mm (long) X 70 mm (wide) X 3 mm (thick)

The tool material used for this purpose was high speed steel with 18 mm shoulder diameter and 2.7 mm pin hight. The bottom diameter of the pin was 2.5 mm

At 150 rpm, in AlA-Cu joint, Cu mixing was only at the shoulder due to low temperature generated while at the tool rotation speed greater than 150 mm, the better mixing of AlA-Cu could be observed. At 900 rpm, compressive residual stresses in Cu-Cu joints were observed.

Qixian Zheng et al. [2016][20] made an attempt to join 6061 Aluminium to a dissimilar metal *i.e.,* 316 stainless steel. The unique thing carried out in this research was that the filler metal was used coupled with friction stir welding. No other such attempt had even been made. The introduction of the filler metal ensured the proper and stronger bonding of the two sheets: 316 stainless steel and 6061 Aluminium. The team of researchers had made use of Zinc to work as the filler metal. The thin foil of zinc was used. It could be observed that stainless steel had some mixing with the zinc at the interface. The work was carried on keeping lap joint in mind. The use of aluminium and steel, both is prominent in the automobile industry and are coupled together for better strength. The reason why introduction of the Zn filler metal increased the strength of the Aluminium-stainless steel join is that zinc has the thermal expansion coefficient value between those values of Al 6061 ans SS 316. Thus, there are lesser gaps generated during the joining process, leading to a stronger joint. The structure formed as before welding was termed as “sandwich structure”.

A. Yazdipour et al. [2016][21] analysed both physical characteristics as well as the microstructure of FSW joint formed between Al 5083-H321 and 316L stainless steel alloys. All the studies were made at 280 rpm. This speed was kept constant throughout the study. The reason why they had opted for friction stir welding was that they needed better ductility and strength balance of the joined which was being obtained the best in case of FSW. This paper dealt with the specified materials due to their high strength and corrosion resistance which made them the best fit for the applications in vehicle industry. The optical microscope and the scanning electron microscope were employed for the testing of the joint. In SEM, X-ray add-on clarified the results a bit further. The tool traverse speeds were varied from 160 to 315 mm/min during the collection of multiple readings. The tensile stress on the material was also carried out to get a reading for the material's tensile strength value.

Shude Ji et al. [2016][22] carried out the friction stir welding on aluminium and magnesium, the two distinct materials in the lap joint configuration. Furthermore, the assistance of a stationary shoulder was taken, which was placed externally to ease the process. There had been the effects of this assistance on the cross-section, microstructure as well as the mechanical properties of the joint. Hence, it was compulsory for this group to analyse all these effects that were caused due to their introduction of the external assistance by the stationary shoulder. There was very minute flash formed on employed on utilizing this technique. Furthermore, not a lot of deformation was observed on the surface making it decently smooth. However, it was a concern that the configuration of the sheets here proved out to be the most important perimeter as it affected both the microstructure and the mechanical strength of the joint.

Toshifumi Kakiuchi et al. [2016][23] carried out their research in order to study how the crack propagates in dissimilar aluminium and steel friction stir welded joint. It is of great significance as it help them judge the weak spots in the friction stir welded joint especially in case of the dissimilar metals. On better understanding of this, various reinforcement steps were performed for the better strengthening of the joints and managing the initiated hair-line cracks. The best way to eliminate the effect of a crack in a joint was to obstruct the path of the crack so that it halts before making further progress and damaging the joint, causing failure. Another reason for the study was to obtain the correct values of temperature, load and time after which the crack fails to maximize safety. The join was created between Al 6061-T6 and SS 304. At 800 rpm rotating speed and 0.2 mm tool offset, the tensile strength of specimen cam out to be 194 MPa. The strength was seed reduced at the aluminium side of the joint due to resolution of precipitates, however, towards the stainless steel side, the strength increased due to work hardening.

Tae-Jin Yoon et al. [2015][24] went forward to analyse the geometric shape and the effect of the onion structure formed during the friction stir welding process. Furthermore, all those effects were also taken into consideration which paved to the formation of this onion structure. The type of FSW joint analysed by them was the lap joint. The materials on which the process was carried out were two dissimilar aluminium alloys. The use of electron backscattered diffraction (EBSD) was made in order to get the reading of micro-texture, strain maps and element maps. Various levels of heat input was provided during the continuous observation process through continuous hole. It was analysed that just when the threaded probe touched the work piece at low heat input, during that time only the onion structure formed. It also resulted in the unwanted void formation on the surface.

Florian A. Besler et al. [2016][25] performed the friction crush welding of sheet -metals with flanged edges. The three materials used for the sheets were copper, steel and aluminium. After bonding the sheets, they were analysed for the yield strength which came out to be of parent material: 90 per-cent for EN AW 5754H22, 95 per-cent for DC01 and 62 per-cent for Cu-DHP. The microstructure testing brought about the revelations that due to the deformation and recrystallization of the extra material of flanges, the grain grain-structure that was formed was finer than the previous one. Thus mostly for welding steel, friction crush welding proved to be a very effective process. The finer microstructure indicated the low heat input at the welded region and also improved the joint properties by reducing the distortion and the residual stresses.

S. No.	Tool Rotation Direction	Tool Rotational Speed (RPM)	Pin Offset (mm)	Tool Traverse Speed (mm/min)
1	Clockwise	280	0.4	160
2	Clockwise	280	0.4	200
3	Clockwise	280	0.4	250
4	Clockwise	280	-0.4	160
5	Clockwise	280	0.4	315
6	Clockwise	280	0	160

7	Counterclockwise	280	0.4	160
8	Clockwise	280	0.8	160
9	Clockwise	280	1	160

Table 1 Welding Parameters[25]

Prakash Kumar Sahu et al. [2016][26] discussed various parameters for the AL/CU FSW such as tool offset position, tool rotational speed and more significantly the influence of the plate position on the microstructure as well as the macrostructure of the joint. The important results obtained by their quest were that the copper must be placed at the advancing side of the tool if finer microstructure is intended. Moreover, the ultimate tensile strength of the joint made with dissimilar metals came out to be 95 per-cent of that of aluminium. The bending angle came out to be 65°. Thus, it also signifies the potential of revolting process: FSW for joining dissimilar material with very fine properties which no other process could achieve. The Vicker's hardness was found out to be higher at the bottom of the nugget than the hardness at the middle portion and the top portion of the nugget. Also, from Al to Cu side, the hardness was observed to increase.

Hui Shi et al. [2015][27] experimented and made report on the friction stir welding of dissimilar Al/Mg joint. The area of significance in this study was the banded structure zone (BSZ). In BSZ, the formation of the intermetallic compounds was specifically analysed. The intermetallic compounds have been known to affect the properties of the joint, say it, microstructural properties or the macro-structural ones. The morphology of the bands as well as the quantity and distribution of IMCs was based upon the TRS (Tool Rotation Speed). Throughout the experimentation, the team made sure that the traverse speed was constant. The end result suggested that the BSZ should be tailored in order to improve the properties of the AL/Mg friction welded joint.

Landry Giraud et al. [2016][28] studied the dissimilar welding of two heat treatable aluminium alloys namely AA6060-T6 and AA7020-T651 by using FSW process. As with all the friction stir welding processes, even here it was observed that the intermixing of the intermetallic compounds had occurred at the interface very prominently. The advance speed was kept between 300 mm/min and 1100 mm/min while the tool rotation speed was kept between 1000 rpm and 2000 rpm. It was nowhere observed that the dissimilar FSW process induced hotter side but the efforts that were made throughout the practical research were very much dependant on the process parameters. The end result of the experimentation left the researchers with the quasi-static tensile values of the specimens.

MATERIAL	TYPE	YS (MPa)	UTS (MPa)	UNIFORM ELONGATION (%)	ELONGATION (%)
AA2098-T3 (RD)	Standard Deviation	0.3	1.3	0.1	1.5
	Average	393	500	15.0	16.3
AA2024-T3 (TD)	Standard Deviation	2.4	3.0	0.7	1.5
	Average	383	515	17.6	21.3
F.S.W. JOINT	Standard Deviation	0.1	0.7	0.1	0.1
	Average	353	455	8.9	9.6

Table 2 Stanard Deviation & Average For Alloys and the F.S.W Joint[28]

Y. Gao et al. [2015][29] were engaged in the study of FSLW (Friction Stir Lap Welding) of the dissimilar Brass/Steel sheets. The motto of their research was targeted to analyse the microstructural properties and their impact on the mechanical properties of the joint. The sheets used for the purpose of research were: Cu-40Zn and S25Z. The SEM and energy dispersive X-Ray spectrometry were employed to analyse the microstructure and it was found out that it varies along the various limits for the various values of welding speed. Hence, the target of the further research would be to formulate an optimum value of the welding speed for the most favourable properties of the joint.

Venkateshkanan M et al. [2014][30] AA2024 and AA5052, the two dissimilar aluminium alloys were friction stir welded and the joint was analysed for the microstructural and macro-structural properties. The main parameter considered in their experimentation was the tool geometry. As discussed in the paper, newly developed steeped tool pin profile makes better joint than the other commonly used tool profiles for friction stir welding.

Minute discontinuities could be observed in the cylindrical and tapered tool profiles while in the other tool profiles, there was no such thing.

CHAPTER 4: RATIONALE AND SCOPE OF THE STUDY

There has been a lot of research carried on in the field of Friction Stir Welding process. However, a very few attempts have been made on:

1.) Friction Stir Lap Welding (FSLW) of more than two sheets, i.e., multiple lap welding.

2.) Friction Stir Welding of very thin plates.

Since very little research has been done on the above two branches of friction stir welding, there is a research gap which needs to be filled by acquiring analysing data to set the standards. Besides, there has not been much study done on the effect of the plunge depth and the pin height even though both of them play a very crucial role especially when we are dealing with the very thin plates as discussed further in this research.

The scope of the study is oriented at making the leak proof joint between the copper and Al5052-H32 aluminium alloy sheets while the copper foil is placed in the middle of two alloyed sheets of aluminium. This would eventually be helpful in making copper cladded aluminium alloy tubes that have better heat sinking capabilities than the aluminium alloy tubes without copper cladding. Not only this, the optimum parameters are found in the study for the thin sheets in a multi-lap joint. It would help the future researchers and industrialists to refine their parameters for production further. This would eventually save their precious time as well as the resources which would otherwise be wasted in the failed samples.

CHAPTER 5: OBJECTIVES OF THE STUDY

1.) To find the optimum parameters: tool rotation speed, traverse speed and plunge depth for the defect free joint.

2.) To determine the process parameters for the defect free joint having the highest ultimate shear strength.

3.) To investigate the microstructure of the defect-free welded sample, having highest ultimate shear strength using optical microscope and scanning electron microscope.

4.) To analyse the micro-hardness (Vicker's hardness) of the sample that had the highest ultimate shear strength.

5.) To propose better clamping mechanism in case of the thin sheets which bend easily under the heavy loads applied during the friction stir welding.

CHAPTER 6: MATERIALS AND RESEARCH METHODOLOGY

6.1 MATERIAL SPECIFICATIONS

There were a total of three different types of materials involved in the experimentation work. One of the materials made up the tool. Other two materials constituted the sheets to be joined and the foil to be inserted.

6.1.1 MATERIAL OF THE TOOL

The material of the friction stir welding tool was M2 (Molybdenum) HSS (High Speed Steel), also known as the tool steel and is a standard to be used for the tools, in industry.

The M2 HSS tool used for friction stir welding in this experimentation was used without heat treatment due to the following reasons:

1.) The M2 HSS tool already has a hardness of 60 HRC (Rockwell C Hardness) without the heat treatment which is much higher than the softer material Al5052-H32, with a Brinell hardness of 60, which is to be welded.

2.) After annealing, the shocks would prove more harmful for the tool and it might break under heavy loads as in case of friction stir welding.

3.) Unnecessary hardening the tool would result in superfluous costs and would also cause wastage of time.

The chemical composition of the FSW tool material: M2 HSS is given below

ELEMENT	MASS
W	6.15%
Mo	5.00%
Cr	4.15%
V	1.85%
C	0.85%
Si	0.30%
Mn	0.28%
Fe	Remaining (81.42%)

Table 3 Chemical Composition Of M2 HSS

The physical properties of M2 HSS are listed below:

Density	8.16 g/cm^3
Melting Point	4680 °C

Table 4 Physical Properties Of M2 HSS

The elastic modulus of tool steel is about 200 MPa.

Figure 3 M2 HSS Tool Used For Friction Stir Welding

The dimensions of the tool were as follows:

Pin Height	1.5 mm
Pin Diameter	5 mm
Shoulder Diameter	18 mm
Collet Size For Tool	18 mm
Total Length Of The Tool	94.5 mm

Table 5 Tool Dimensions

6.1.2 MATERIAL OF THE TWO OUTER SHEETS TO BE JOINED

The aluminium alloys are joined in the experimentation of grade Al5052-H32. It is a comparatively softer alloy than stainless steel.

Figure 4 Al5052 - H32 Sheets

The chemical composition of Al5052-H32 is given as:

Element	Mass
Mg	2.48%
Fe	0.3%
Cr	0.23%
Si	0.09%
Mn	0.03%
Cu	0.02%
Ti	0.02%
Al	Remaining (96.83%)

Table 6 Chemical Composition Of Al5052-H32

The physical properties of Al5052-H32 are mentioned below:

Density	2.68 g/cm^3
Melting Point	607 °C - 649 °C

Table 7 Physical Properties Of Al5052 - H32

The aluminium sheets are of the thicknesses 1 mm each and cross-sectional area 150 mm * 150 mm each.

6.1.3 THE SANDWICHED MATERIAL

Pure copper foil is used as the material that is sandwiched in the two sheets of aluminium alloys.

The physical properties of copper are given below:

Density	8.96 g/cm^3
Melting Point	1085 °C

Table 8 Physical Properties Of Pure Copper

The value of Rockwell Hardness (F scale) for copper, is 54.

The thickness of the copper foil is 0.1 mm and the cross sectional area is 150 mm * 40 mm for each foil.

6.2 RESEARCH METHODOLOGY

6.2.1 TOPIC SELECTION & MATERIAL SELECTION

The topic was selected seeing the wide use of friction stir welding in the futuristic world. Also, another area that was found interesting was copper cladded aluminium tubes.

Figure 5 Copper Cladded Aluminium Tubes

These kinds of tubes have vast applications in cooling the bigger computer systems and are also used in super cars which heat up quite quickly when run at their limits, because of its excellent heat sinking capability. Besides, the inner material is aluminium alloy (Al5052 H32) which is light weight as well as cheap and only a thin layer of copper enhances its thermal properties. The copper cladded aluminium tubes could be used as a radio frequency cable or as the refrigeration tubes. In this thesis work also the fundamentals of joining two aluminium sheets with a copper foil in middle could be used to clad copper to aluminium alloy.

Among the different types of aluminium alloys, Al5052 was found to have good machinability, good weldability, flexibility and also good corrosion resistance. On the other hand, copper was the best choice available to construct a heat sink. Thus, both of them made a very good combination.

6.2.2 SELECTION OF EQUIPMENT

The Vertical Milling Centre (VMC) which a type of vertical milling machine having a CNC (computer numeric control) interface was readily available rather than a dedicated FSW Setup which has not penetrated into the market at a large scale. Moreover, the clamping modifications and tool mounting was very easy on a VMC. So it was the best choice to conduct experiments.

6.2.3 SELECTION OF TOOL PROFILE AND MATERIAL

Upon going through various research papers, it was clear that the cylindrical pin profile was giving out best results in terms of ultimate shear strengths in case of tensile strength for FSWed joints. Also, since the thickness of sheets forming the lap joint was very thin with the total thickness accounting to 2.1 mm, it was quite difficult to form threading on the tool. However, only a single tool was used throughout which was straight cylindrical (not tapered). The tool material was M2 HSS which is a tool standard and a trusted name in industry having Rockwell hardness of 60 HRC without heat-treatment and 65 HRC after the heat treatment. For obvious reasons as discussed in section 6.1.1, tool was used without any heat treatment.

6.2.4 PARAMETERS IN RESEARCH

It is very essential to set restrictions in the boundary of research so as to be able to follow more vertical approach. For the same, the tool material, tool profile and direction of rotation were kept constant while the tool rotational speed, plunge depth and traverse speed were varied.

6.2.5 DESIGN OF EXPERIMENTS - TAGUCHI

A series of experiments were conducted, some of which failed with the tunnelling defects in the friction stir weld zone. With this the, favourable limits for the sampling method: Taguchi were set to obtain samples defect free. Only the shear strengths of defect-free samples were considered.

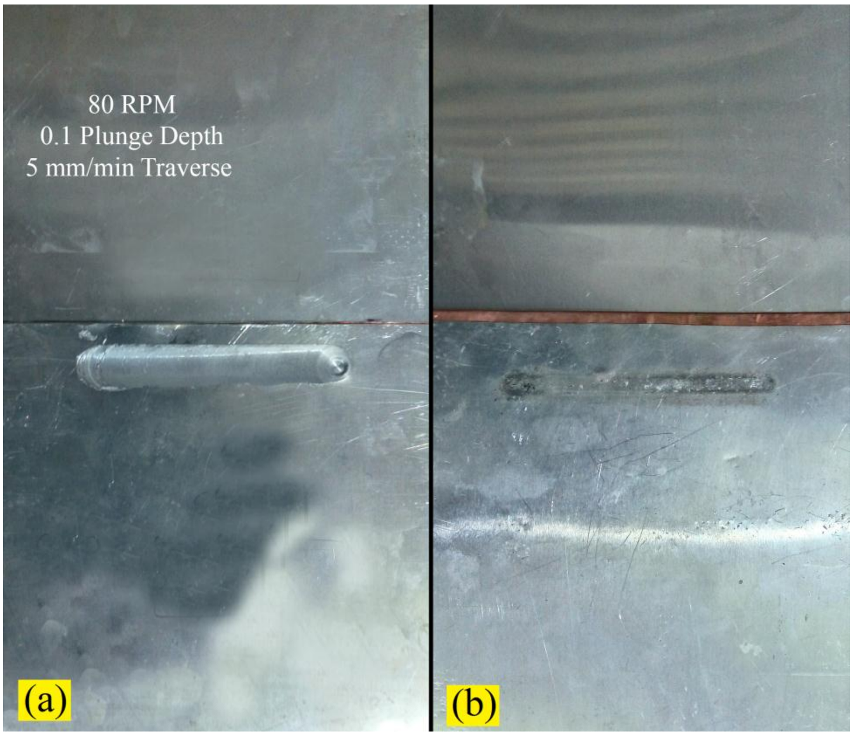


Figure 6 FSW at 800 RPM; 0.1 mm Plunge Depth; 5 mm/min Traverse Speed (a) Front Side Of Weld (b) Back Side Of Weld

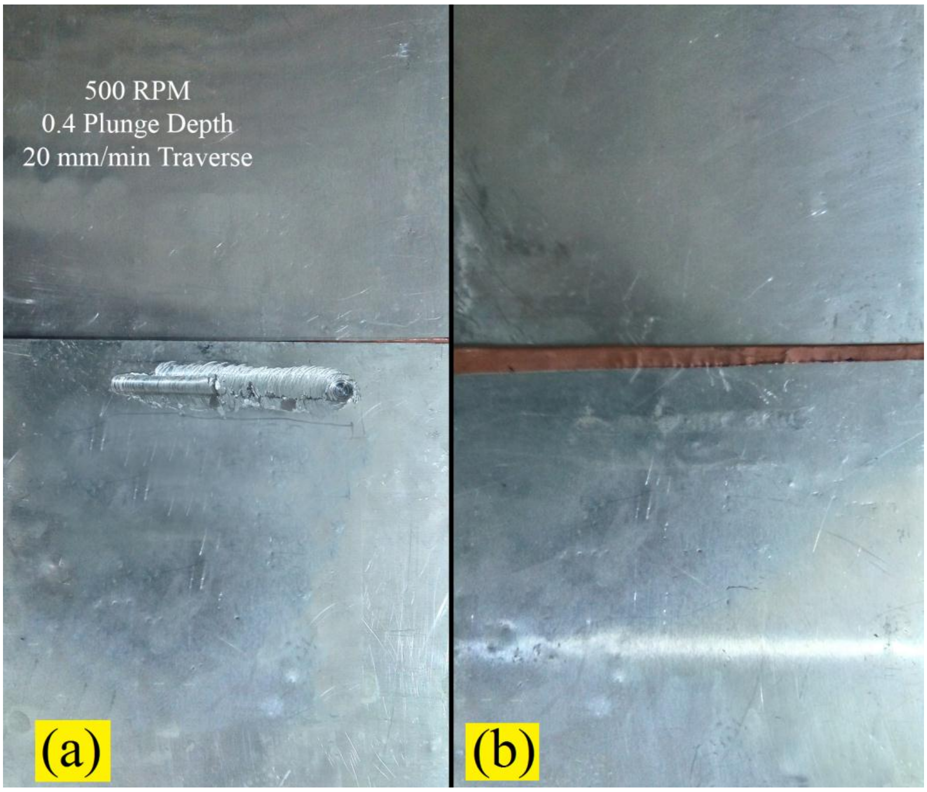


Figure 7 500 RPM; 0.4 mm Plunge Depth; 20 mm/min Traverse Speed (a) Front Side Of Weld (b) Back Side Of Weld

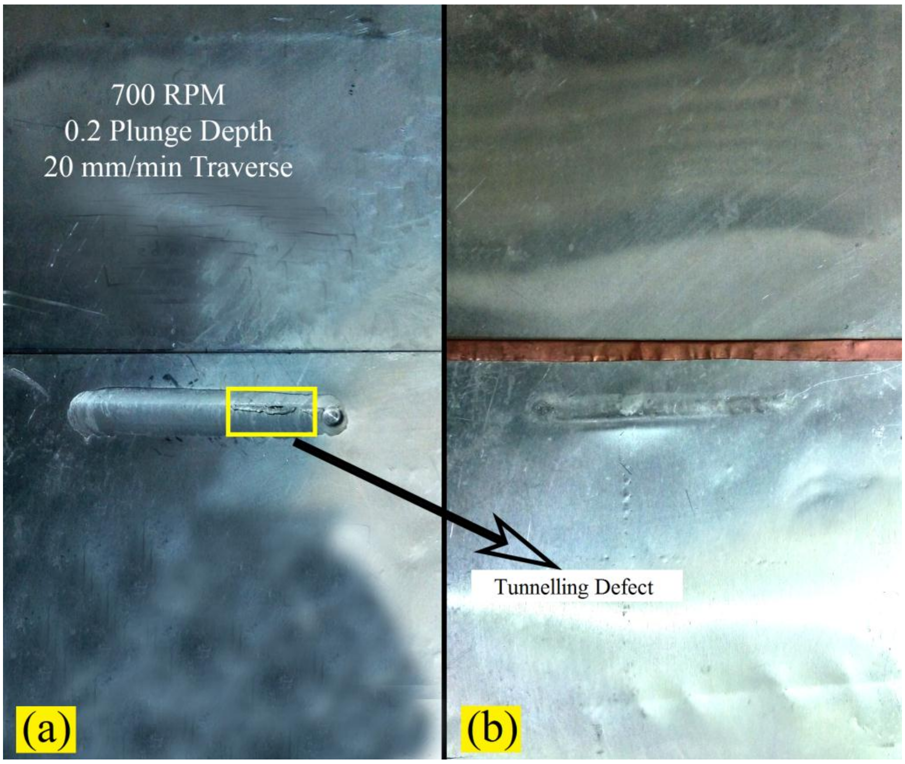


Figure 8 700 RPM; 0.2 mm Plunge Depth; 20 mm/min Traverse Speed (a) Front Side Of Weld (b) Back Side Of Weld

The design of experimentation has been done in accordance with the Taguchi method, with the help of "Minitab" software, and is listed below:

S. No.	Level 1	Level 2	Level 3
1	S	S	S
2	S	U	U
3	S	W	W
4	U	S	U
5	U	U	W
6	U	W	S
7	W	S	W
8	W	U	S
9	W	W	U

Table 9 Design Of Experiments By Taguchi Method

Rotational Speed (RSM)	Traverse (mm/min)	Plunge Depth (mm)
700	5	0.1
700	10	0.2
700	15	0.3
800	5	0.2
800	10	0.3
800	15	0.1
900	5	0.3
900	10	0.1
900	15	0.2

Table 10 Actual Welding Parameters By Taguchi Method

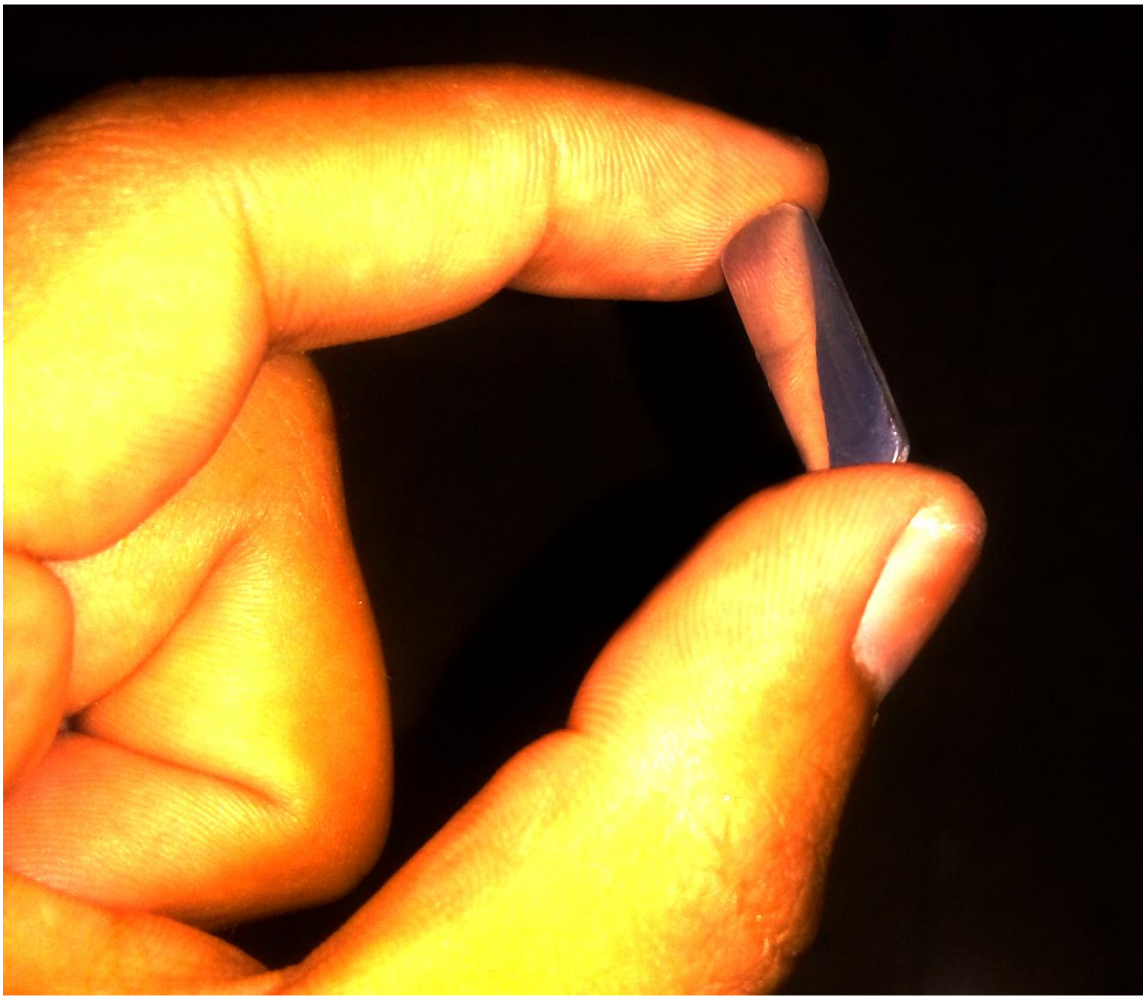


Figure 9 Sample-preparation with Mirror Finish For SEM Image & Optical Microstructure

CHAPTER 7: RESULTS AND DISCUSSIONS

There were a total of nine friction stir welded specimens tested for the shear strengths as per the L_9 orthogonal array of Taguchi sampling method, having a sandwich structure with the two Al5052-H32 aluminium alloy sheets having thickness of 1 mm each on the outer sides and the copper foil of thickness 0.1 mm, place in the middle. Then, as per two parameters where the shear strengths came out to be the highest in case of AlA-Cu-AlA multi-lap friction stir welded joints, two samples of AlA-AlA were friction stir lap welded and their shear strengths were also determined.

The highest ultimate shear strength came out to be 4.413 MPa in the case of AlA-Cu-AlA joint with the parameters: 800 rpm, 5 mm/min traverse and 0.2 mm plunge depth. For the same parameters, the ultimate shear strength came out to be even higher as in the case of AlA-AlA joint having the ultimate shear strength as 5.955 MPa. Moreover, the second highest value of the ultimate shear strength came out to be 3.921 MPa, in case of AlA-Cu-AlA joints at the parameters: 800 rpm, 15 mm/min traverse and 0.1 mm plunge depth. For the same parameters, the ultimate shear strength for the AlA-AlA joint came out to be 4.922 MPa.

The need of proper clamping was felt during experimenting, especially in case of the thin sheets which bend quite easily when the sliding load is applied. Moreover, setting the clamps very tightly over the work-piece material deformed the surface of sheets as Al5052-H32, the work-piece material used, is a soft metal. So, the resolution of the problem could be incorporation of more clamps in the middle or bring some modification in the design of additional clamps such as the use of roller type clamp which is movable as well.

7.1 EXPERIMENTAL WORK

7.1.1 DESIGN OF EXPERIMENTS (D.O.E.)

S. No	Level 1: Rotational Speed (RSM)	Level 2: Traverse (mm/min)	Level 3: Plunge Depth (mm)
1	700 (S)	5 (S)	0.1 (S)
2	700 (S)	10 (U)	0.2 (U)
3	700 (S)	15 (W)	0.3 (W)

4	800 (U)	5 (S)	0.2 (U)
5	800 (U)	10 (U)	0.3 (W)
6	800 (U)	15 (W)	0.1 (S)
7	900 (W)	5 (S)	0.3 (W)
8	900 (W)	10 (U)	0.1 (S)
9	900 (W)	15 (W)	0.2 (U)

Table 11 Actual Design Of Experiments By Taguchi Method

7.2 CALCULATION OF ULTIMATE SHEAR STRENGTH

S. No.	Parameters	Sample For Shear Testing	Shear Fracture Load (N)
1	800 RPM; 5mm/min traverse speed; 0.2 mm plunge depth		3177.459

2	800 RPM; 15 mm/min traverse speed; 0.1 plunge depth		2823.318
3	900 RPM; 10 mm/min traverse speed; 0.1 mm plunge depth		2819.394

4	800 RPM; 10 mm/min traverse speed; 0.3 mm plunge depth		2727.18
5	900 RPM; 15 mm/min traverse speed; 0.2 mm plunge depth		2442.69

6	700 RPM; 5 mm/min traverse speed; 0.1 mm plunge depth		2159.181
7	900 RPM; 5mm/min traverse speed; 0.3 mm plunge depth		1799.154

8	700 RPM; 10 mm/min traverse speed; 0.2 mm plunge depth		1654.947
9	700 RPM; 15 mm/min traverse speed; 0.3 mm plunge depth		1617.669

Table 12 Shear Fracture Load Values

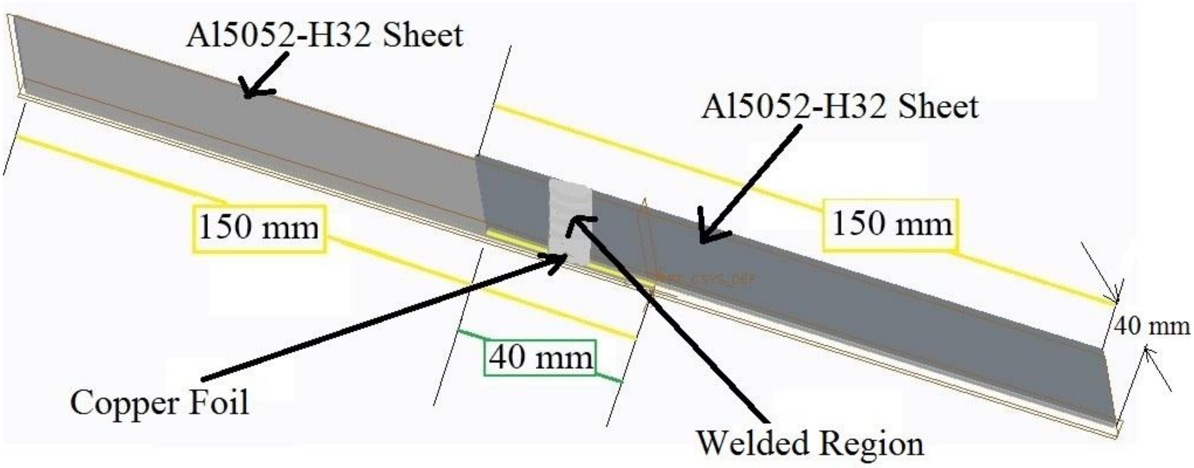


Figure 10 Sample Preparation For Shear Testing

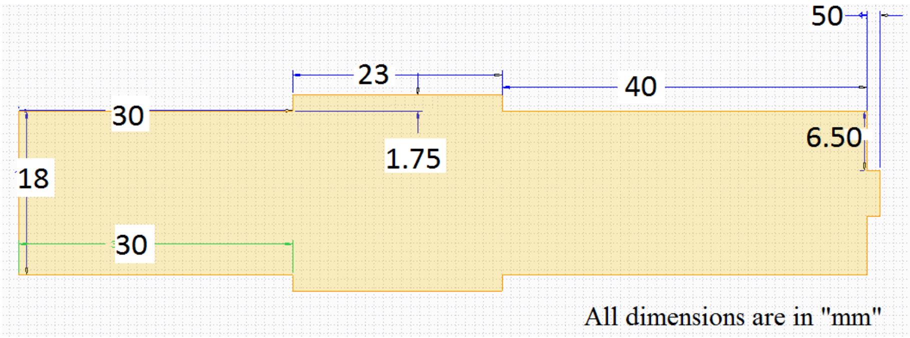


Figure 11 Front View Of The Tool

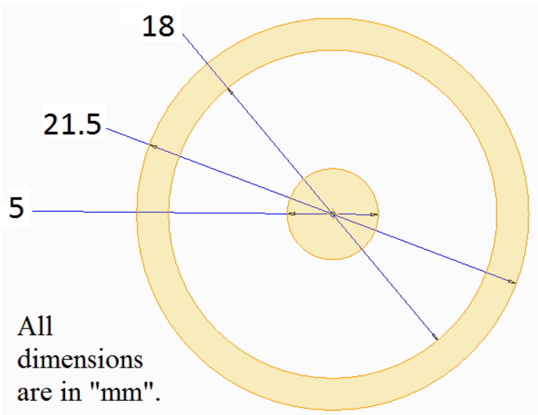


Figure 12 Top View Of The Tool

The area of contact between the plates is same as the welded region in prepared sample for shear strength testing.

Thus, Area = Diameter of tool shoulder * Width of sample = 0.018 m * 0.04 m = 7.2 * 10^{-4}

Also, ultimate shear strength (MPa) = maximum load of fracture (N) / contact area (m^2)

Hence, the values for the ultimate shear strength are given as:

S.No.	**Parameters for AlA-Cu-AlA Joint (Tool Rotation Speed in RPM; Traverse Speed in mm/min; Plunge Depth in mm)**	**Maximum Shear Load (N)**	**Ultimate Shear Strength (MPa)**
1	800;5;0.2	3177.459	4.413
2	800;15;0.1	2823.318	3.921
3	900;10;0.1	2819.394	3.915
4	800;10;0.3	2727.18	3.787
5	900;15;0.2	2442.69	3.392
6	700;5;0.1	2159.18	2.998
7	900;5;0.3	1799.154	2.498
8	700;10;0.2	1654.947	2.298
9	700;15;0.3	1617.669	2.246

Table 13 Ultimate Shear Strength Values

Taguchi Analysis: USS versus S, U, W

Level	**S**	**U**	**W**
1	9.053	11.893	13.003
2	14.548	12.004	12.125
3	11.769	11.472	10.241
Delta	5.495	0.532	2.7622.762
Rank	1	3	2

Table 14 Response Table for Means

Level	**S**	**U**	**W**
1	19.06	21.26	22.21

2	23.24	21.34	21.37
3	21.27	20.96	19.98
Delta	4.18	0.38	2.24
Rank	1	3	2

Table 15 Response Table for Signal to Noise Ratios (Larger is better)

Figure 13 Main Effects Plot For Means

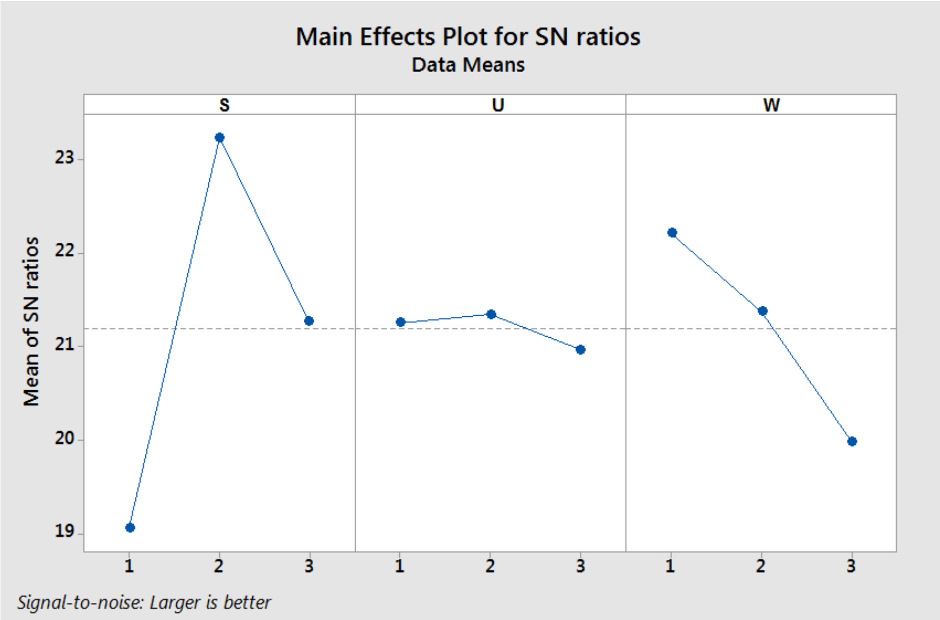
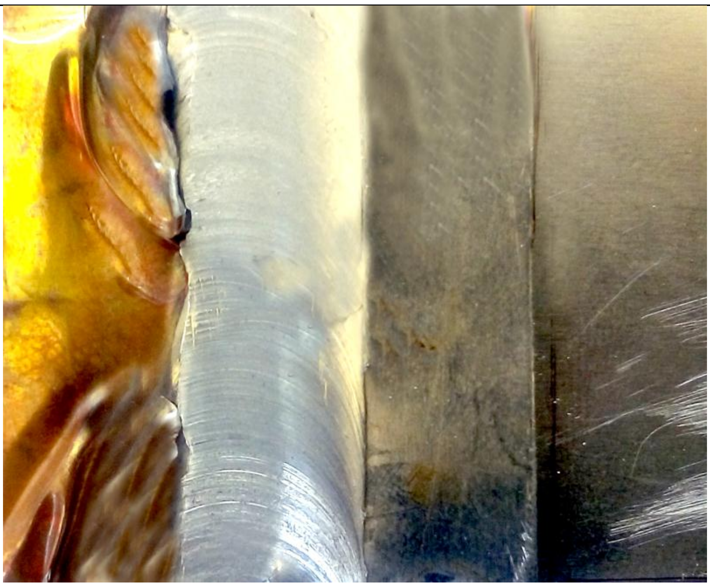
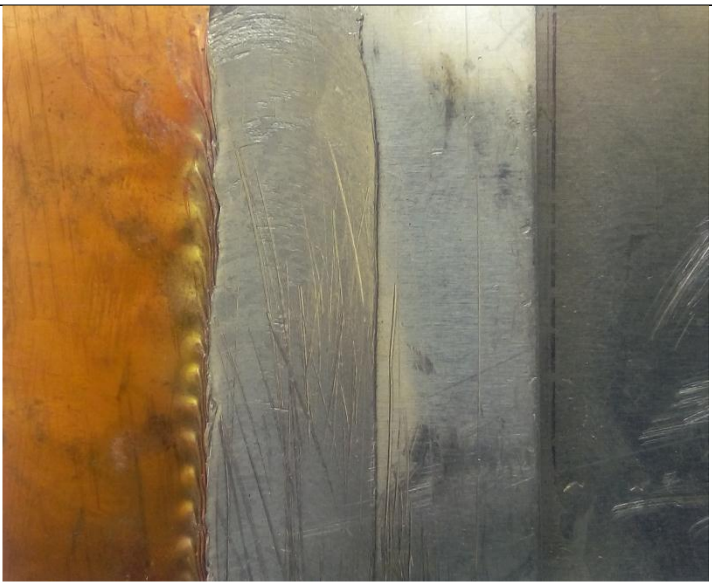
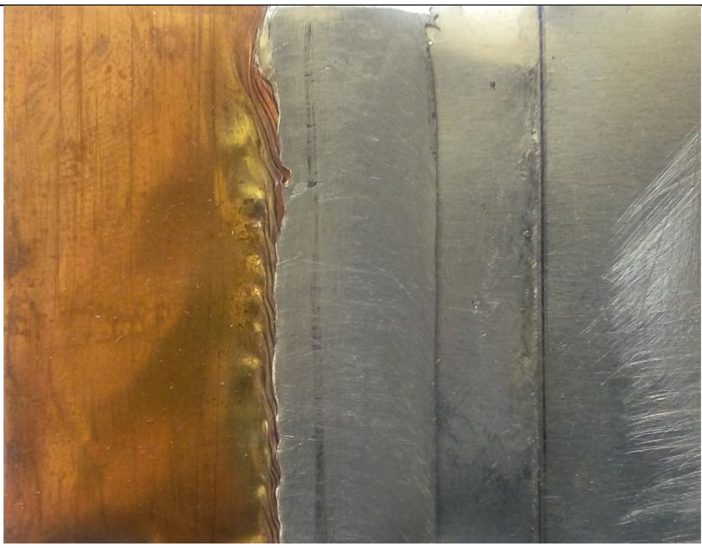
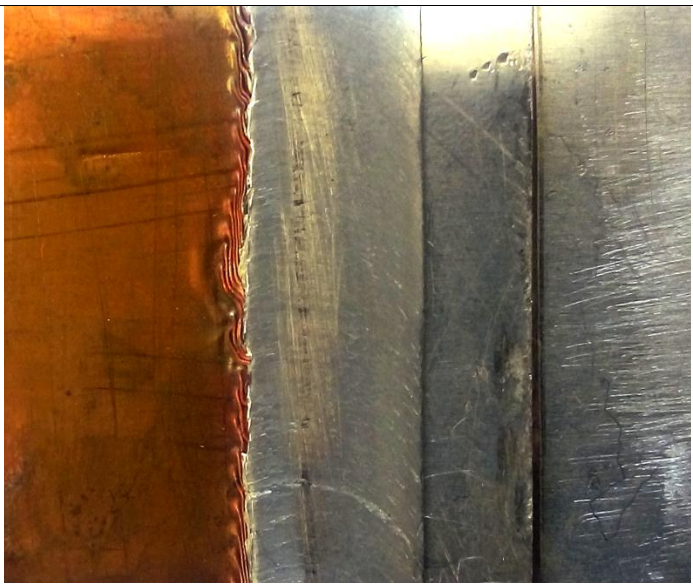
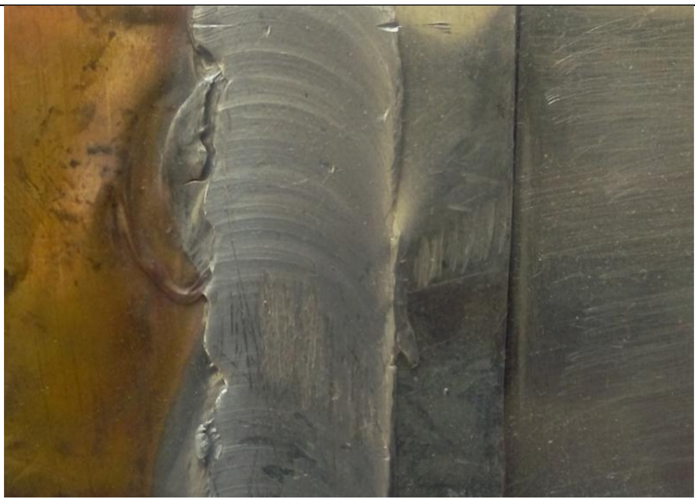


Figure 14 Main Effects Plot For SN Ratio

7.3 MACROSTRUCTURE AND MICROSTRUCTURE AFTER F.S.W.

Visual inspection of the fractured samples

S. No.	Parameters	Bottom Surface After Fracture	Surface Finish
1	800 RPM; 5mm/min traverse speed; 0.2 mm plunge depth		Smooth
2	800 RPM; 15 mm/min traverse speed; 0.1 plunge depth		Smooth with scratches

3	900 RPM; 10 mm/min traverse speed; 0.1 mm plunge depth		Smooth
4	800 RPM; 10 mm/min traverse speed; 0.3 mm plunge depth		Smooth with scratches running through the middle line
5	900 RPM; 15 mm/min traverse speed; 0.2 mm plunge depth		Partially rough

6	700 RPM; 5 mm/min traverse speed; 0.1 mm plunge depth		Smooth with scratches
7	900 RPM; 5mm/min traverse speed; 0.3 mm plunge depth		Rough with onion peel structure
8	700 RPM; 10 mm/min traverse speed; 0.2 mm plunge depth		Rough

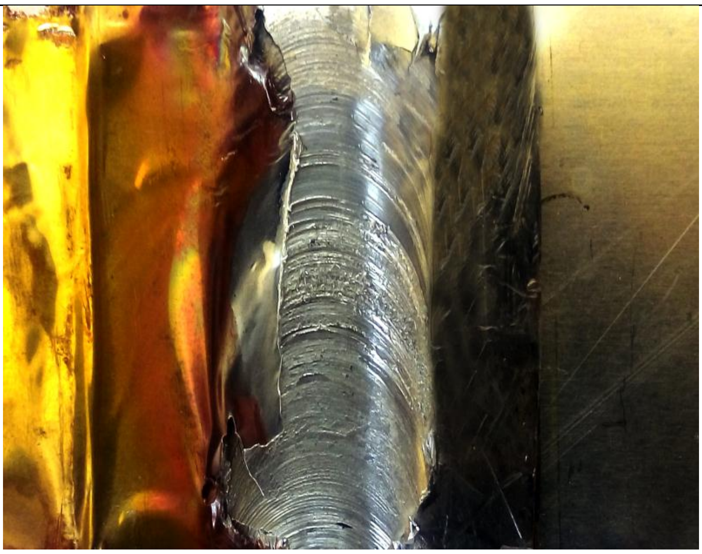
9	700 RPM; 15 mm/min traverse speed; 0.3 mm plunge depth		Rough with flash

Table 16 Surface Finish For Samples

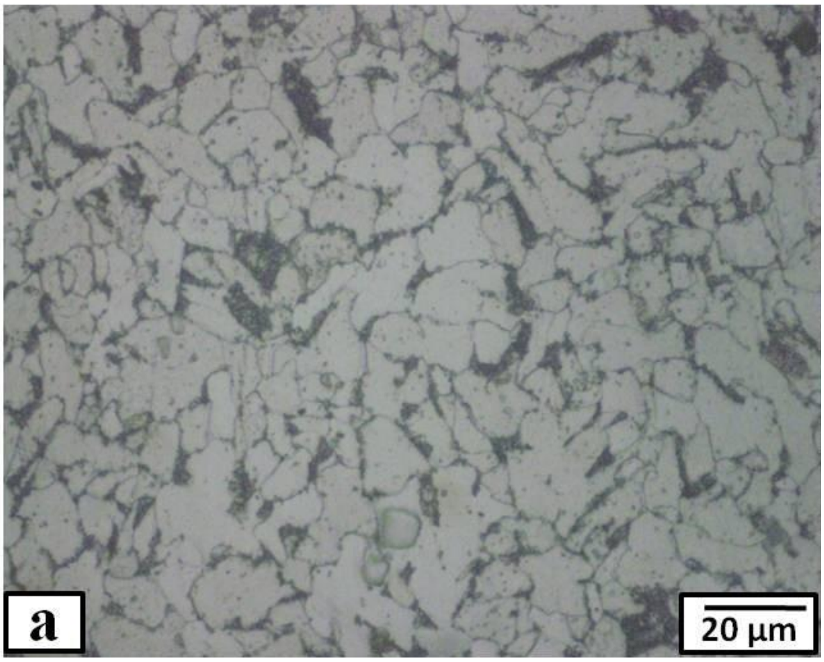


Figure 15 Microstructure Of Welded Sample Having Highest Ultimate Shear Strength

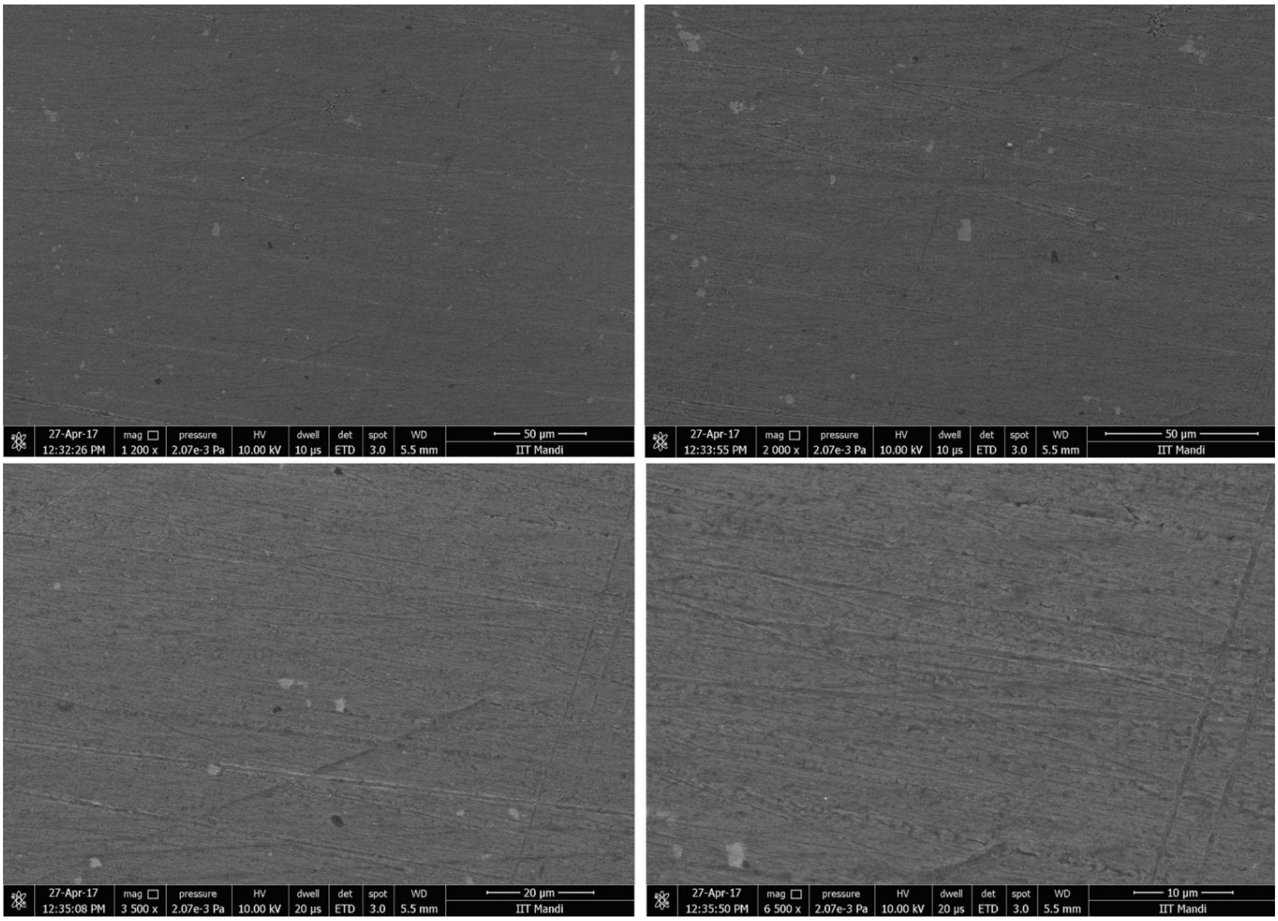


Figure 16 SEM images of the weld surface at 1200X, 2000X, 3500X & 6500X Zoom

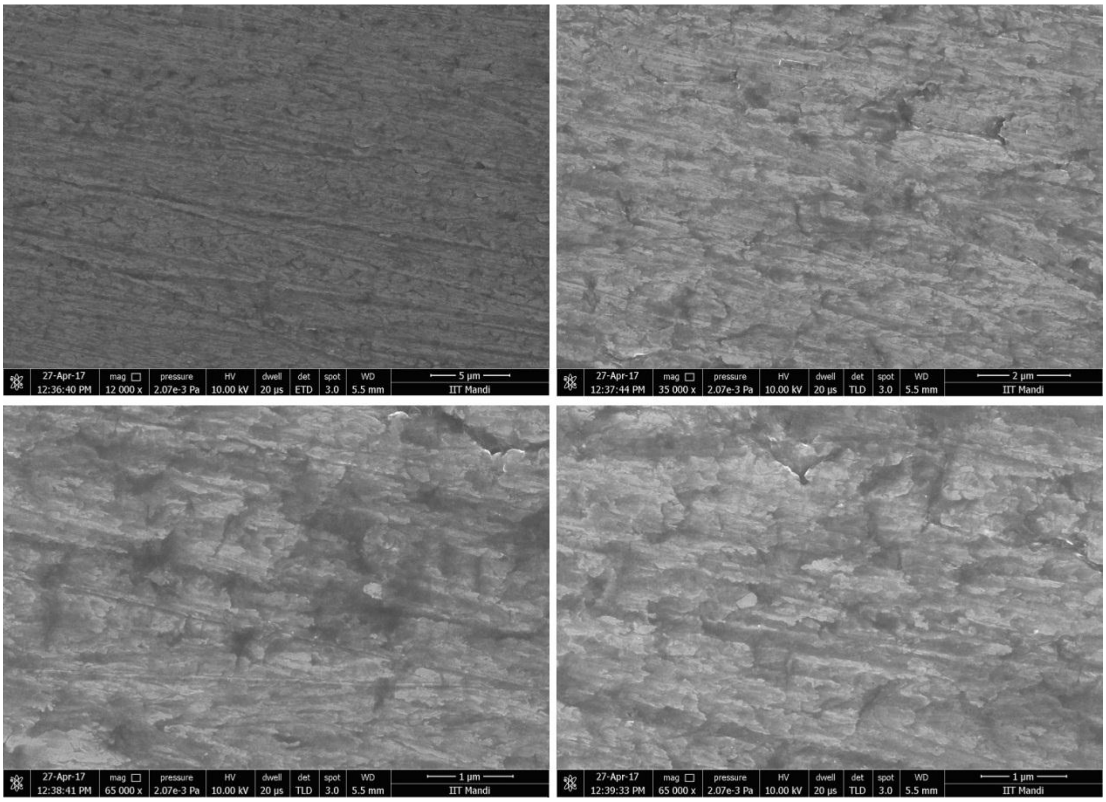


Figure 17 SEM images of the weld surface at 12000X, 35000X & 65000X

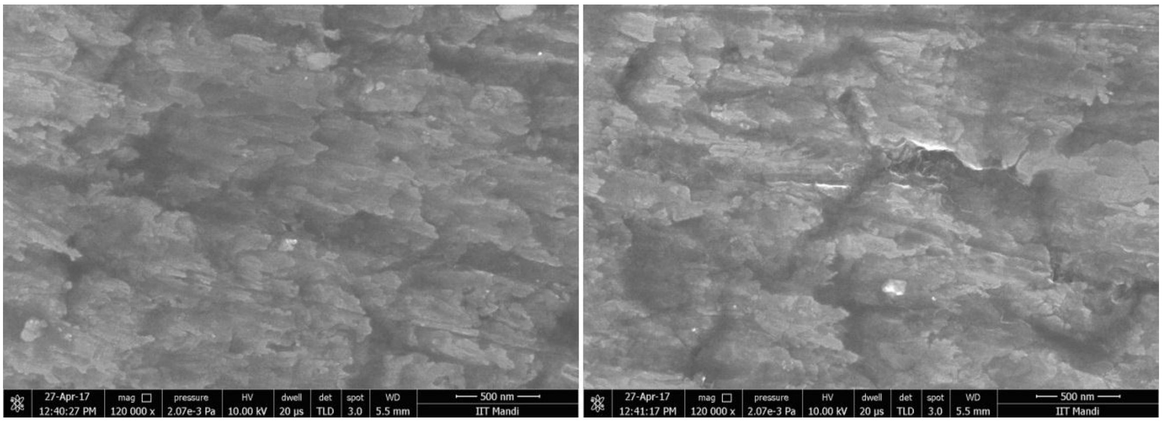


Figure 18 SEM images of the weld surface at 120000X Zoom

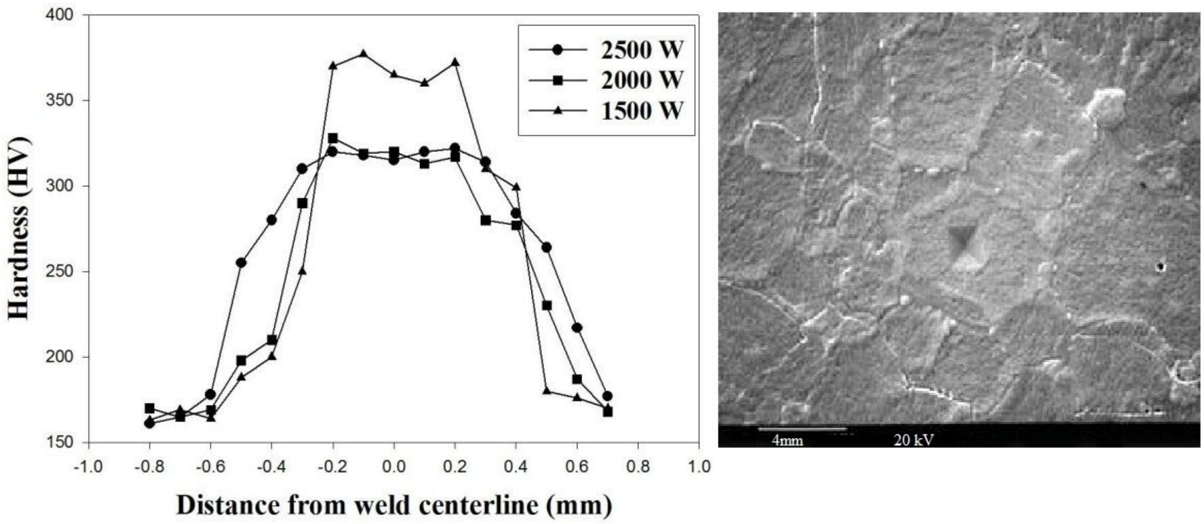


Figure 19 Vicker's Micro-hardness For The Sample With Optimum Parameters

CHAPTER 8: CONCLUSION AND FUTURE SCOPE

After carrying out a series of experiments on the friction stir welded specimens, we come to the following conclusions:

1.) The friction stir lap welded bond of AlA-AlA always has ultimate shear strength higher than the AlA-Cu-AlA FSWed lap joint for the same parameters.

2.) For the thin sheets, clamping is vital because otherwise the sheets may bend under the heavy loads.

3.) All the factors: plunge depth, tool rotational speed and the traverse speed play a very significant role in the surface as well as the strength of the joint.

4.) In case of thin sheets of AL5052, lower values of tool rotational speed cause the material not to plasticise properly and thus making a weak and irregular joint while the higher values of tool rotational speeds burn the work-piece material and cause tunnelling defects.

Friction stir welding, the process discussed in this thesis report has potential to be used in the aerospace industry (since it doesn't add any extra material to the existing mass), in heat exchangers as well as in the radio communication industry. Also, as friction stir welding has the ability to make a leak-proof joint between the dissimilar Al5052-H32 and pure Cu, the process could be utilised for the AlA-Cu structures based near water bodies, even though it is not recommended due to electrolytic reaction and thus corrosion, yet is a better option than other kind of welding processes.

LIST OF REFERENCES

[1] Çam G. Friction stir welded structural materials: beyond Al-alloys. International Materials Reviews. 2011;56:1-48.

[2] Farrokhi H, Heidarzadeh A, Saeid T. Frictions stir welding of copper under different welding parameters and media. Science and Technology of Welding and Joining. 2013;18:697-702.

[3] Motalleb-nejad P, Saeid T, Heidarzadeh A, Darzi K, Ashjari M. Effect of tool pin profile on microstructure and mechanical properties of friction stir welded AZ31B magnesium alloy. Materials & Design. 2014;59:221-6.

[4] Mishra RS, Ma ZY. Friction stir welding and processing. Materials Science and Engineering: R: Reports. 2005;50:1-78.

[5] Amber Shrivastava, Michael Zinn, Neil A. Duffie, Nicola J. Ferrier, Christopher B. Smith, Frank E. Pfefferkorn. Force measurement-based discontinuity detection during friction stir welding. Journal of Manufacturing Processes 26 (2017) 113–121

[6] Pankaj Sahlot, Kaushal Jha, G.K. Dey, Amit Arora. Quantitative wear analysis of H13 steel tool during friction stir welding of Cu-0.8%Cr-0.1%Zr alloy. Wear378-379(2017)82–89.

[7] Bipul Das, Sukhomay Pal, Swarup Bag. Torque based defect detection and weld quality modelling in friction stir welding process. Journal of Manufacturing Processes 27 (2017) 8–17.

[8] Goebel, Jannik, Reimann, Martin, Norman, Andrew, dos Santos, Jorge F., Semi-stationary shoulder bobbin tool friction stir welding of AA2198-T851.Journal of Materials Processing Technology http://dx.doi.org/10.1016/j.jmatprotec.2017.02.011

[9] Kush P. MEHTA, Vishvesh J. BADHEKA. Influence of tool pin design on properties of dissimilar copper to aluminum friction stir welding. Trans. Nonferrous Met. Soc. China 27(2017) 36−54.

[10] G.M. Karthik, G.D. Janaki Ram, Ravi Sankar Kottada. Friction stir selective alloying. Materials Science & Engineering A 684 (2017) 186–190.

[11] N.Z. Khan, A.N. Siddiquee, Z.A. Khan, A.K. Mukhopadhyay, Mechanical and microstructural behavior of friction stir welded similar and dissimilar sheets of AA2219 and AA7475 aluminium alloys, Journal of Alloys and Compounds (2016), doi: 10.1016/j.jallcom.2016.11.389.

[12] Wei Zhang, Yifu Shen, Yinfei Yan and Rui Guo, Dissimilar friction stir welding of 6061 Al to T2 pure Cu adopting tooth-shaped joint configuration: microstructure and mechanical properties, Materials Science & Engineering A, http://dx.doi.org/10.1016/j.msea.2017.02.091

[13] Shude Ji, Zhengwei Li, Liguo Zhang, Yue Wang. Eliminating the tearing defect in Ti-6Al-4V alloy joint by back heating assisted friction stir welding. Materials Letters.

[14] Nan Xu, Qining Song, Yefeng Bao, Yongfeng Jiang and Jun Shen, Achieving good strength-ductility synergy of friction stir welded Cu joint by using large load with extremely low welding speed and rotation rate, Materials Science & Engineering A, http://dx.doi.org/10.1016/j.msea.2017.01.052

[15] Hui Shi, Ke Chen, Zhiyuan Liang, Fengbo Dong, Taiwu Yu, Xianping Dong, Lanting Zhang, Aidang Shan. Intermetallic Compounds in the Banded Structure and Their Effect on Mechanical Properties of Al/Mg Dissimilar Friction StirWelding Joints. Journal of Materials Science & Technology (2016).

[16] Ahmed, M.M.Z., Ataya, Sabbah, El-Sayed Seleman, M.M., Ammar, H.R., Ahmed, Essam, Friction stir welding of similar and dissimilar AA7075 and AA5083.Journal of Materials Processing Technology http://dx.doi.org/10.1016/j.jmatprotec.2016.11.024

[17] H. Dawson, M. Serrano, S. Cater, N. Iqbal, L. Almásy, Q. Tian, E. Jimenez- Melero, Impact of friction stir welding on the microstructure of ODS steel, Journal of Nuclear Materials (2017), doi: 10.1016/j.jnucmat.2016.12.033.

[18] Kim, K.H., Bang, H.S., Bang, H.S., Kaplan, A.F.H., Joint properties of ultra thin 430M2 ferritic stainless steel sheets by friction stir welding using pinless tool.Journal of Materials Processing Technology http://dx.doi.org/10.1016/j.jmatprotec.2016.12.018

[19] V.C. Sinha, S. Kundu, S. Chatterjee. Microstructure and mechanical propertiesof similar and dissimilar joints of aluminiumalloy and pure copper by friction stir welding. Perspectives in Science (2016) 8, 543—546

[20] Q. Zheng, X. Feng, Y. Shen, G. Huang, P. Zhao, Dissimilar friction stir welding of 6061 Al to 316 stainless steel using Zn as a filler metal, Journal of Alloys and Compounds (2016), doi: 10.1016/j.jallcom.2016.06.092.

[21] A. Yazdipour, A. Heidarzadeh, Effect of friction stir welding on microstructure and mechanical properties of dissimilar Al 5083-H321 and 316L stainless steel alloy joints, Journal of Alloys and Compounds (2016), doi: 10.1016/j.jallcom.2016.03.307.

[22] Shude Ji, Zhengwei Li, Liguo Zhang, Zhenlu Zhou, Peng Chai. Effect of lap configuration on magnesium to aluminum friction stir lap welding assisted by external stationary shoulder. Materials and Design 103 (2016) 160–170.

[23] Toshifumi Kakiuchi, Yoshihiko Uemitsu, Kentaro Suzuki. Evaluation of fatigue crack propogation in dissimilar Al/Steel friction stir welds. Procedia Structural Integrity 2 (2016) 1007–1014.

[24] Tae-Jin Yoon, Jung-Gil Yun, Chung-Yun Kang. Formation mechanism of typical onion ring structures and void defects in friction stir lap welded dissimilar aluminum alloys. Materials and Design 90 (2016) 568–578.

[25] Florian A. Besler, Paul Schindele, Richard J. Grant, Michael J.R. Stegmüller. Friction crush welding of aluminium, copper and steel sheet-metals with flanged edges. Journal of Materials Processing Technology 234 (2016) 72–83.

[26] Sahu, Prakash Kumar, Pal, Sukhomay, Pal, Surjya K., Jain, Rahul, Influence of Plate Position, Tool Offset and Tool Rotational Speed on Mechanical Properties and Microstructures of Dissimilar Al/Cu Friction Stir Welding Joints.Journal of Materials Processing Technology http://dx.doi.org/10.1016/j.jmatprotec.2016.04.014.

[27] Hui Shi, Ke Chen, Zhiyuan Liang, Fengbo Dong, Taiwu Yu, Xianping Dong, Lanting Zhang, Aidang Shan. Intermetallic Compounds in the Banded Structure and Their Effect on Mechanical Properties of Al/Mg Dissimilar Friction StirWelding Joints. Journal of Materials Science & Technology (2016).

[28] Landry Giraud, Hugo Robe, Christophe Claudin, Christophe Desrayaud, Philippe Bocher, Eric Feulvarch, Investigation into the dissimilar friction stir welding of AA7020-

T651 and AA6060-T6, <![CDATA[Journal of Materials Processing Tech.]]> (2016), http://dx.doi.org/10.1016/j.jmatprotec.2016.04.020.

[29] Y. Gao, K. Nakata, K. Nagatsuka, T. Matsuyama, Y. Shibata, M. Amano, Microstructures and mechanical properties of friction stir welded brass/steel dissimilar lap joints at various welding speeds, (2015), doi: 10.1016/j.matdes.2015.11.056

[30] Venkateshkanan M, Rajkumar V, Sadeesh P, Arivazhagan N, Narayanan S, Devendranath Ramkumar K. Influences of tool geometry on metallurgical and mechanical properties of friction stir welded dissimilar AA 2024 and AA 5052. Procedia Engineering 75 (2014) 154 - 158.

APPENDIX

FRICTION STIR WELDING OF ALUMINIUM ALLOY WITH A DISTINCT MATERIAL SANDWICHED IN BETWEEN

ORIGINALITY REPORT

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SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

Pashazadeh, Hamed, Jamal Teimournezhad, and Abolfazl Masoumi. "Experimental investigation on material flow and mechanical properties in friction stir welding of copper sheets", The International Journal of Advanced Manufacturing Technology, 2016. Publication	%1
Submitted to Lovely Professional University Student Paper	%1
Friction Stir Welding and Processing, 2014. Publication	%1
S. J. Barnes. "Friction Stir Welding in HSLA-65 Steel: Part I. Influence of Weld Speed and Tool Material on Microstructural Development", Metallurgical and Materials Transactions A, 04/11/2012 Publication	<%1
doaj.org Internet Source	<%1
Submitted to ABV-Indian Institute of	

6	Information Technology and Management Gwalior Student Paper	<%1
7	Submitted to Jawaharlal Nehru University (JNU) Student Paper	<%1
8	Nadammal, Naresh, Satish V. Kailas, and Satyam Suwas. "A bottom-up approach for optimization of friction stir processing parameters; a study on aluminium 2024-T3 alloy", Materials & Design, 2015. Publication	<%1
9	Ouyang, J.. "Microstructural evolution in the friction stir welded 6061 aluminum alloy (T6-temper condition) to copper", Journal of Materials Processing Tech., 20060220 Publication	<%1
10	Martinsen, K., S.J. Hu, and B.E. Carlson. "Joining of dissimilar materials", CIRP Annals - Manufacturing Technology, 2015. Publication	<%1
11	Submitted to University of Northumbria at Newcastle Student Paper	<%1
12	Submitted to Universiti Putra Malaysia Student Paper	<%1
13	Sukumar, Madiri Samuel, Borra Vijay Sudheer Reddy, and P. Venkataramaiah.	<%1

"Analysis on Multi Responses in Face Milling of Ammc Using Fuzzy-Taguchi Method", Journal of Minerals and Materials Characterization and Engineering, 2015.
Publication

14	Cheriaa, Rim, and Ayda Baffoun. "Effects of cross linkers combination, for three dimensional effects, on denim garment properties", Fibers and Polymers, 2015. Publication	<%1
15	dev-www.ess.washington.edu Internet Source	<%1
16	Submitted to VIT University Student Paper	<%1
17	Ahmadnia, Masoud, Saeid Shahraki, and Mojtaba Ahmadi Kamarposhti. "Experimental studies on optimized mechanical properties while dissimilar joining AA6061 and AA5010 in a friction stir welding process", The International Journal of Advanced Manufacturing Technology, 2016. Publication	<%1
18	Pashazadeh, Hamed, and Jamal Teimournezhad. "Numerical investigation on the mechanical, thermal, metallurgical and material flow characteristics in friction stir welding of copper sheets with experimental verification", Materials & Design, 2013. Publication	<%1

19	Mak, K.L.. "The determination of optimal partial fill policy for an inventory system with lumpy demand items", Applied Mathematical Modelling, 199512 Publication	<%1
20	research.ijcaonline.org Internet Source	<%1
21	Jarvis, T.. "The bonding of nickel foam to Ti-6Al-4V using Ti-Cu-Ni braze alloy", Materials Science & Engineering A, 20110315 Publication	<%1
22	International Journal of Structural Integrity, Volume 4, Issue 1 (2013-05-27) Publication	<%1
23	Smith, Christopher, and John Hinrichs. "Friction Stir Welding and Related Processes", Innovations in Materials Manufacturing Fabrication and Environmental Safety, 2010. Publication	<%1
24	Heard, D. W., R. Gauvin, and M. Brochu. "Microstructural investigation of controlled short circuiting gas metal arc welding deposited aluminium–lithium alloy", Canadian Metallurgical Quarterly, 2014. Publication	<%1
25	Reis, P. N. B., J. M. Ferreira, and M. O. W. Richardson. "Effect of the Surface	<%1

Preparation on PP Reinforced Glass Fiber Adhesive Lap Joints Strength", Journal of Thermoplastic Composite Materials, 2012.
Publication

26	Threadgill, P.L.. "The future of friction stir welding", Friction stir welding, 2010. Publication	<%1

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