Section A -Research paper
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Experimentally Investigation The FSW Of Dissimilar AL Alloys Using The Taguchi L-27 Approach

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***Abstract*—Friction stir welding (FSW) has become a favourite choice in the joining process of light weight metals. In FSW the material joining is taken place at the solid state. The process is carried out by inserting a rotating tool traversing along the faying surfaces of the material to be joined. It offers nearly defect free welds with minimized distortion and fine grain structure. However, the mechanism of welding and the process parametric combination for welds with consistent and reliable results are not clearly established. Even though FSW offers many advantages over the conventional welding processes, it is considered to be a slow process from a commercial point of view. Efforts to gather a suitable combination of parameters to produce good welds were mostly confined to lower linear speeds. There exists an ambiguity in the determination of the process parameters to produce reliable welds at higher welding speeds. Efforts to increase the welding speed resulted in defect generation because of insufficient heating during welding. .Considering the above requirements, AA2024 (Al-Mg alloy) and AA6061-T6(Al-Mg-Si) alloys appear to be highlysuitable for the deep- sea mining structures. Both these classes of alloys have a proven history of successful use in deep sea mining and other and marine applications.**

***Index Terms*—AA2024 (AlMg alloy), AA6061T6(AlMgSi), Welding, FSW OVERVIEW AND BACKGROUND Welding**

I. OVERVIEW AND BACKGROUND

Welding

Welding is the metal joining process or fabrication process in which heat and pressure are involved in the making of a permanent joint between two materials involved in the joining process. The materials are heated to a high temperature at the edges and after reaching softening point or melting; the edges of two materials are brought together and joined by applying pressure or without that. Welding is different from the brazing and soldering processes that involve low temperature heating and are suitable to join very thin materials.

Welding originated in Europe and Middle East during the Bronze and Iron ages. In ancient Greece, people used the welding technology for making iron pillars. Blacksmiths contributed thus most of the part in forge welding where they heated the material for softening and joined them together to form a new joint. The arc welding practiced during the eighteenth century was popular among the materials scientists and industrialists.

During the nineteenth century, resistance welding and thermit welding were developed and used by people for joining materials through creation of electrical resistance and for producing heat at the edges of the materials and making perfect permanent weld joints. The growth of welding reached a huge milestone during the World War I when the arc welding method was used in the fabrication of ships and aircrafts. The British used the arc welding technique in the fabrication of most of their military weapons, tanks, marine equipments and aero applications. During the 1920s, major improvements were made in the arc welding process through introduction of flux and automatic movement of electrode with respect to a work piece that prevented the formation of porosity in the weld region and the brittleness of the weld materials.

During the mid-twentieth century, stud welding, submerged arc welding, under water welding and Tungsten arc welding were developed. They were found suitable for construction work in marine fields. After 1960, shielded gas metal arc welding was developed and used in joining non-ferrous materials and subsequently, plasma arc welding and electro slag welding were practiced for industrial applications. The recent developments in welding have made large contributions to industrial growth and reduced economic crunch. The advent of Electron beam welding facilitated the welding process in high depth at a narrow space by generating a narrow beam of electrons and the advent of laser beam welding improved the speed of the welding by introducing the automatic welding process. In 1991, friction stir welding was invented by The Welding Institute, UK. It is practiced all over the world for many industrial applications.

A. CLASSIFICATION OF WELDING PROCESS

Generally, materials are joined by three methods, namely, the mechanical fastening method, the adhesive bonding method and the welding method. The mechanism of joining is different in each method and the joining method is selected based on the application requirement of the materials.

In welding,the two materials that aret obejoinedare melted to liquid state and a filler material is used and melted along with the base materials.Finally, the solidified metals make a permanent joint which is the welded joint.

The Welding process as shown in Figure 1 has been evolved since it’s invention during the fifth century and welding processes are classified based on the method by which the

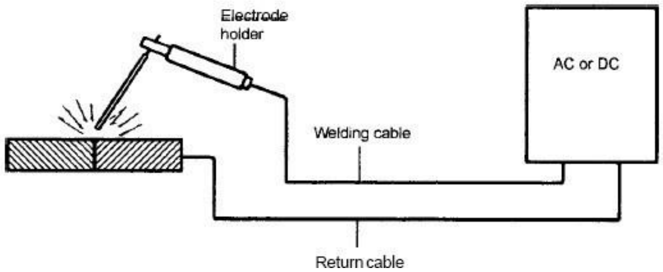

Fig. 1. Welding process**(Source: KlasWeman 2003)**

base metal is melted. Details of the classification of various welding methods are given in the Figure 2.

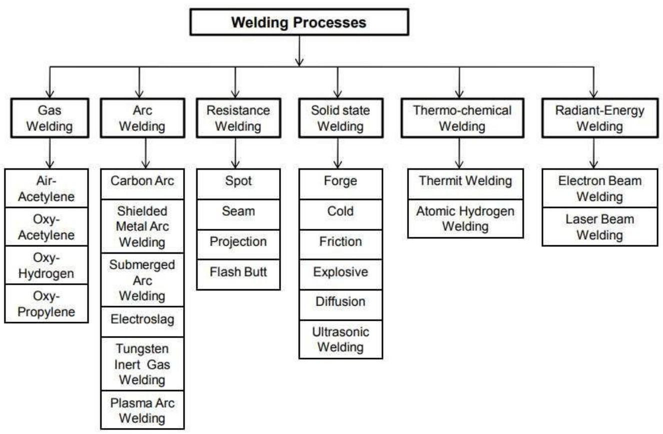

Fig. 2. Classification of welding process**(Source: Welding Handbook: Volume Two, American Welding Society 1978)**

When the metal is heated and melted by the arc generated by the electrical methods, it is known as arc welding. Well known arc welding methods include submerged arc welding, metal inert gas welding and tungsten inert gas welding. When pressure is used for performance of the welding process, it is resistance welding. The commonly used pressure welding processes are friction stir welding and spot welding. When gas is used for welding, then it is called gas welding where oxy-acetylene gases are used. When some chemical reactions are used for the production of heat then, it is thermit welding. The major and important welding processes are discussed in the following sections.

1) Gas welding: Gas welding, one of the oldest and cheapest ofthe welding processes, uses oxy-acetylene gas for producing heat. Three types of flames are used in this welding method, namely neutral flame, carburizing flame and oxidizing flame and filler material is used while joining in some applications. The heat produced by the gas welding attains the maximum temperature of 3100 $^{\circ}$C which is lower compared to the temperature of thearc welding process. Gas welding is performed by mixing oxygen with gases such as acetylene, hydrogen, propylene, gasoline, butane etc. Selection of gases for the gas welding is made according to the applications. Oxy-acetylene gases are used in most of the applications and the process is called oxy-acetylene welding. The welding system comprises gas cylinders, mixing chamber, welding torch and control valves as shown in Figure 3. Gas cylinders hold the gases to burn. Oxygen and acetylene gases are kept in separate tanks and each one is fixed with control valves to regulate the gases individually. The mixing chamber mixes the gases in the correct ratio set by the operator and a nozzle is provided at the end for the release of the mixed gas and flame is produced by igniting the gas. The welding torch comprised of the mixing chamber and the weld nozzle.

The advantages of gas welding are as follows: Gas welding is suitable for welding both ferrous and non-ferrous materials, the cost of the equipment is low, equipments are portable, no electricity is needed for the welding and less skilled operator can handle the gas welding operations without any risk.

As against these many advantages, gas welding has a fewdisadvantages like: the temperature of the material can't reach as high as arc welding, thick sections cannot be joined using gas welding, shield is not available during welding leading to weakening of the joint, slow rate of heating and high strength steels can't be welded using gas welding.Gas welding finds application in automobile and air craft industries for joining sheet metals and most of the time; gas welding is applicable for repair works.

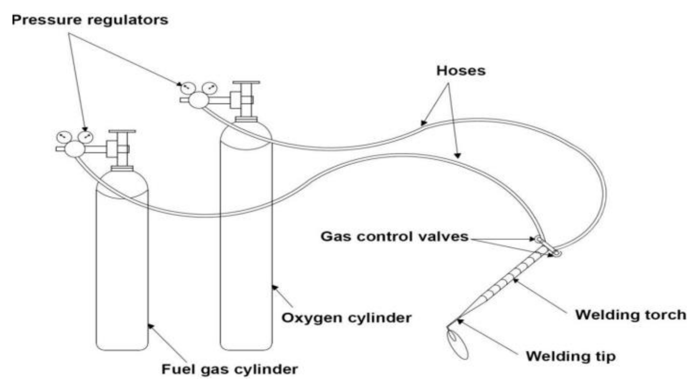

Fig. 3. Gas welding system **(Source: Samir Hajili 2017)**

2) Arc welding: In arc welding, heat is produced between the consumable or non- consumable electrode and the work piece by an electric arc generated using an electric power source. The power may be DC or AC and the voltage and current are varied according to the type of materials to be welded and thickness of the work pieces. Arc welding is a fusion welding process that creates a temperature of about 6500 $^{\circ}$C while performing the joining using the heat produced by the electric arc. The electric arc can be handled either manually or guided by a machine along the weld line for automatic welding. While performing the welding operation, the heated material reacts with the oxygen and nitrogen available in the air. This leads to the formation of oxides on the weld surface and this decreases the strength of the weld. Shielding or slag is coated on the electrode itself for eliminating the chemical reaction between the work zone and the atmosphere or in some type of arc welding; the shielding gas is supplied separately as illustrated in Figure 4. Arc welding processes can be classified into several categories on the basis of the consumable electrode and non-consumable electrode.

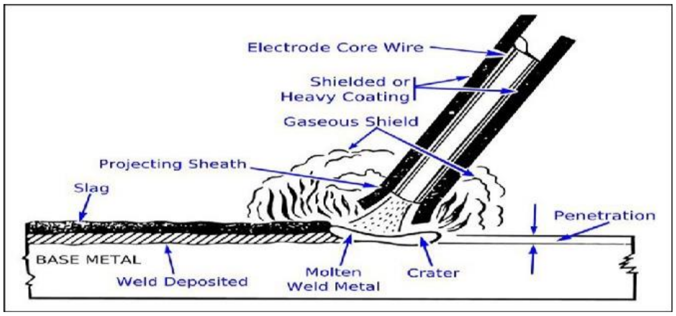

Fig. 4. Shielded metal arc welding process**(Source: Hitesh Arora et al. 2019)**

a) Consumable electrode arc welding method: In this method, a consumable electrode is used to perform the welding operation. The consumable electrode and the work piece are connected in the electric circuit. While the electrode is brought closely to the work piece, an electric arc is produced in the space between the consumable electrode and the work piece,melting the work piece edges as well as the electrode, which is consumed along with the melting of the work piece. After solidification, a rigid joint is formed.Consumable electrode arc welding is further classified into many categories. The important welding processes are discussed in the following sections.

Submerged arc welding: Submerged arc welding shown in Figure 5 uses a continuously fed consumable electrode and a blanket of flux to perform the welding operation in the work piece. While performing welding, the arc is submerged beneath the gases produced due to the flux that can be visually seen. The Flux consists of chemicals used in the production of gases and alloying elements as addition to the molten pool for improvement in the strength of the weld.

II. RELATED WORK

FRICTION STIR WELDING OF ALUMINUM ALLOY AA2024 Friction stir welding is the solid-state welding where the materials to be joined are heated by the friction developed due to the rotation of tool pin against the work pieces. The work pieces are not melted into liquid but are in the form of viscous liquid and hence convective heat transfer is not found affecting its properties. The properties depend on the amount of heat produced,

cooling rate after welding and the strain rate. The Aluminum alloy AA5083- H111 is an armour grade material containing

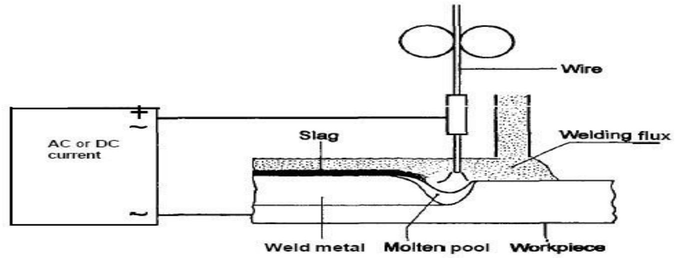

Fig. 5. Submerged arc welding process**(Source: KlasWeman 2003)**

Al as the chief element and the elements like magnesium and manganese are present in a moderate level. The aluminum alloy AA2024 is used mainly in marine applications due to its better resistance to the chemical and corrosion attack. Several investigations have been performed by earlier researchers on the aluminum alloy AA2024 to understand the physical properties of the material under various environments. In this section, a detailed literature survey is done on friction stir welding of aluminum alloy AA2024 for various applications and the influencing factors are discussed elaborately.

Rahmatian et al. (2020) conducted research on AA2024material by adding SiC nanoparticles using double sided friction stir welding and studiedon the influence of SiC nanoparticles on the weld joint. Further, factors like rotational speed, transverse speed, tool pin length and number of passes were analyzed to understand the influence of aforementioned factors on the properties of the weld joint. The results showed the achievements of the defect free nanocomposite joint by changing the rotational and transverse speed, and tool pin length. The inclusion of SiC improved the hardness at the stir zone and formed the fine grains. The optimum process parameters, namely, rotational speed of 80 rpm, transverse speed of 1000 mm/min and tool pin length of 6 mm were found to produce a defect free welding. Further, the tensile strength and fracture toughness were improved by 84% and 89% respectively compared to the those of the parent materials.

Ismail et al. (2020) did the experimental study of the AA2024T joint in 1F position and investigated on the jig fixture and tool pin design on the macrostructure of the weld joint. The authors have reported the influence of tool pin profile and jig fixture on the grain size and macrostructure changesat stir zone and the tool pin rotational speed involved the major part in the macrostructure changes.

Dewangan et al. (2020) studied the effect of welding speed on the friction stir welding of AA2024and AA7075 performed using a cylindrical pin profile and found the entire grain size in weld zone affected by temperature distribution. The study also showed the dissimilar joint exhibiting good strength at the welding speed of 20 mm/min and the similar joint displayed better strength at the welding speed of 45 mm /min also. In addition, the dissimilar joint required more heat input while compared to the similar joint.Bagheriet al. (2020) worked on the effects of water cooling and vibration on the friction stir welded aluminum alloy AA2024joints and reported that the grain size at the weld zone was reduced with simultaneous application of vibration and water cooling. Mechanical properties such as tensile strength, hardness value and formability index value were enhanced while applying water cooling due to the formation of small grains, a high strain rate and low heat input.

Duong et al. (2020) investigated the effects of tool offset and reversed metal flow on the mechanical properties of the friction stir welded AA5083-H116 – AA7075 T-joints. The results showed improvement in the mechanical properties due to the enhancement of bonding strength in the interface while offsetting the tool towards the advancing side. Further, the maximum joint efficiency of 90% was achieved while performing double pass welding and the reversed metal flow influenced the weld interface.

Dada (2020) studied on the friction stir welded joint made with AA2024 material and found the microstructure changes, location and types of defects causing reduction in weld strength. The authors found that the

defects at the sharp edges initiated the crack propagation and reported that the understanding of microstructure and defects determined the optimized parameter to be considered in the friction stir welding to obtain better weld strength.

Hao et al. (2020) made experimental studies onthe effects of microstructure and welding parameters on the friction stir welding of AA2024joints and found that the ratio of rotational speed to welding speed (n/v), and the microstructure affected the mechanical properties of the friction stir welded aluminum alloy AA2024 joints. The results showed that the tensile strength of the joint was decreased while performing the welding using a very large or very small n/v ratio. The hardness study exhibited the advancing side of heat affected zone witha minimum hardness value.

Sajuri et al. (2020) studied the strain hardening effects on the microstructure and dislocation density of the friction stir welded AA2024aluminum alloy joints. The results showed a 20%reduction in the tensile strength after post weld cold rolling and further, the grain size was reduced at the nugget zone due to the plastic deformation of material. Post welded cold rolling improved the dislocation density due to the interaction between dislocation stress fields. In addition, the post welding cold rolling enhanced the tensile strength and showed the maximum tensile strength value of 403 MPa.

Msomi et al. (2020) took up the mechanical properties of friction stir welded AA1050 – AA2024 joints and optimized welding parameters for similar and dissimilar joints for their investigation. The main focus was on the determination of the mechanical properties at different locations of the weld. The results showed a lower tensile strength at the beginning of the weld while compared to the middle and end of the weld. The bending test showed no trend in the location of the weld and the fracture morphology displayed the dimpled failure and confirmed that the failure is ductile in nature.

Kumar et al. (2020) studiedthe effects of tool parameters on the tensile properties of friction stir welded AA2024 – AA6082-T6 joints and have reported the achievement of the highest value of tensile strength while using the tool shoulder diameter of 18 mm, tool offset of 0 mm and tool tilt angle of 1 ° without any defect in the weld joint. Further, the microstructure study showed no tunnel defect and formation of intermetallic compound in the samples.

Derazkola et al. (2019) performed underwater submerged friction stir welding using AA2024and A441 AISI steel. They have reported a reduction in the peak temperature of the welding to 400 ° C while the weld environment was surrounded by the low temperature submerged water. The low temperature submersion medium reduced the inter metallic layer thickness formed while welding and subsequently affected the hardness and tensile properties of the weld joint. In addition, all the materials failed at the inter metallic layer while being cooled at room temperature.

Niu et al. (2019) studied on the cyclic deformation behavior of the friction stir welded AA5083-H112 and AA2024-T351 dissimilar weld joint and analyzed the effect of microstructure and loading history on the characteristics of the weld. The results showed the top portion of the joint, exhibited AA2024 at the stir zone which was placed at the retreating side while performing the weld. The lowest dislocation density was observed at the stir zone of AA2024 material whereas the lowest dislocation density was observed at the heat affected zone of the AA2024 material. Recrystallized grain fractions of 73% and 34% were observed in the AA5083- H111 and AA2024 material respectively. Further failure and strain hardening were also observed in the lowest hardness zone of the AA2024 material. The value of cyclic hardening improved as the value of stress amplitude increased.

Fattah-alhosseini et al. (2019) examinedthe microstructure and corrosion characteristics of the nugget region of the friction stir welded AA2024and AA1050 aluminum alloy joints. Display of the equiaxed flowing shape by the grains at the nugget zone was seen. The spectroscopy study showed the nugget zone placed in on the advancing side. The ultimate tensile and yield strength displayed were of superior value compared to that of AA1050 and exhibited lower value while compared with that of AA5083.

Zayed et al. (2019) investigated the development and characterization of AA2024aluminum alloy joint reinforced with SiC and Al2O3 using friction stir welding. They have reported the achievement of the ultimate tensile strength of 120 MPa at 600 rpm. A 30% increase in the hardness value was seen while increasing the reinforcing particles and the maximum hardness value was achieved for 50% SiC and 50% Al2O3 in reinforcing content. The inclusion of SiC reinforcing powder in AA2024improved the wear resistance value of AA2024by 40% and the hybrid composite showed the maximum wear resistance while adding 50% SiC and 50% Al2O3while reinforcing content.

Ramalingam et al. (2019) examined the microstructure, hardness and corrosion behavior of friction stir welded AA2024aluminum alloy joints.They have reported that the friction stir welding refined the grains, improved the hardness and the corrosion resistance at three testing temperatures. However, there was a decrease in hardness value in some specimens due the dissolution of phases. Further, the SEM image analysis showed a large pit formation in the base material that showed a higher corrosion rate compared to friction stir welded specimens that displayed smaller pit on the surface.

Tsarkov et al. (2019) examinedthe influence of gaps in the friction stir welded aluminum alloy AA2024and saw a decrease in the joint efficiency while performing the weld by maintaining a gap of above 1.5 mm without filler material and suggested the usage of filler material to improve weld quality.

Jain et al. (2019) worked on the influence of SiC content on the microstructure and tribological properties of the friction stir welded AA5083/SiC joints. The results showed the distribution of the SiC particle was to be homogeneous in the weld centre irrespective of the particles volume fraction. The grain at the stir zone seen was fine, recrystallized and equiaxed and the bonding strength of the joint showed an improved value. The hardness and wear study showed improvement in the hardness and wear rate of the material with increase in the volume fractions of the SiC content. The analysis of wear debris of surface composite of the AA5083/SiC showed fine flake compared to the wear debris profile of the AA2024alloy material confirming the AA5083/SiC composite experienced a lesser wear.

Maji et al. (2019) studiedthe effects of incremental forming in friction stir welding on the formability of aluminum alloy AA2024sheets. They found that the formability using the single incremental forming method was better compared to that observed in the conventional forming method. A decrement in the formability of the welded joint was observed compared to the formability of parent materials due to severe plastic deformation and the strain hardening effect.

Yadav et al. (2019) analyzed the effects of fatigue life of AA2024and AA6062 joint made by friction stir welding. The fatigue life measured at a load of 2.5 kN was 30,000 cycles, 20,000 cycles and 10,000 cycles for AA2024–AA6062, AA2024and AA6062 materials respectively. Hence, the friction stir welded dissimilar material displayed a higher fatigue life while compared to that of parent materials.

Gupta et al. (2018) performed multi objective optimization on friction stir welding parameters of AA2024– AA6063 aluminum alloy joints and found that the optimized parameters producing defect free weld joints were, a tool rotational speed of 900 rpm, welding speed of 60 mm/min, tool shoulder diameter of 18 mm and tool pin diameter of 5 mm.

Kundu et al. (2018) studied the modeling of multi-objective parameters of friction stir welding of AA2024– H321 using response surface methodology and selected four process parameters namely traverse speed, tool tilting angle, rotational speed and dwell time to perform the analysis. The authors concluded that the rotational speed and tool titling angle dominated the process while compared with other process parameters.

Zhou et al. (2018) made a study of the influence of kissing bond on the mechanical and fracture behavior of the friction stir welded AA2024– H112 aluminum alloy joint and reported the welding parameters showing a substantial effect on the length of the kissing bond. There was a decrease in the length of the kissing bond with increase in the welding heat input, rotational speed and welding speed. The length of the kissing bond and morphology of the kissing bond displayed a remarkable effect on the tensile strength and fracture morphology of the welded joint.

Donatus et al. (2018) investigated the variations in the stir zone and thermo-mechanically affected zone of the friction stir welded AA2024– AA6082 aluminum alloy joints and concluded that the Mg alloy element was affected mainly in the stir zone and heat affected zone in both the alloy materials i. e. AA5083-O and AA6082. The mass fraction analysis displayed the 60% of Mg element in the stir zone of the retreating side affected More when compared to other elements while performing the welding process. Changes in the hardness profile were observed as the result of the influence of grain size on the heat affected zone of the retreating side.

Palani et al. (2018) investigatedthe effects of process parameters of friction stir welding of aluminum alloys AA5083-H321 – AA8011 joints on the mechanical properties of the welded joint material. The authors included the reinforcing ceramic particles Al2O3 and SiC in the weld joint while performing the friction stir welding. The results showed the similar aluminum alloy joint AA8011/Al2O3 displaying the maximum tensile and hardness values while compared to that of other similar and dissimilar joints.

Raweni et al. (2018) optimized the process parameters of friction stir welding of AA2024aluminum alloy joints using the Taguchi L-27 method and concluded that, the order of influencing factor based on their impact on strength of the welding were the welding speed, tool tilting angle and tool rotational speed. Further, the optimum parameters for the total energy and energy for crack initiation was concluded as the rotational speed of 600 rpm, welding speed of 125 mm/min and tilting angle of 3 ˚.

Hao et al. (2018) studied the defects in the morphology of friction stir welded T-joint of AA2024and AA7075 aluminum alloy material, They found four defects in morphology namely tunnel, bonding line, hook and kissing bond. They saw an increase in welding speed creating a tunnel defect and bonding line defect whereas the hook defect was minimized while advancing the welding speed. In addition, the kissing bond defect was not related to the welding process parameters and found it hard to be eliminated.

Jain et al. (2018) examinedthe microstructure, mechanical and sliding wear behavior of AA5083/B4C/SiC/TiC surface composite fabricated by friction stir processing. The Mi-

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crostructure study revealed the fine feature of the grain reinforcement. Dense distribution of reinforcing particles was seen in the retreating side and the advancing side of the stir zone. Friction stirs processing improved the plastic deformation and mixed the reinforcing particles well with the parent material and improved the bonding strength. The authors have reported the inclusion of reinforcing particles making an improvement in the tensile, hardness and wear behavior of the welded material. The pin-on-disc wear analysis showed changes in the wear mode from abrasive wear to delamination wear.

Papantoniou et al. (2018) fabricated the AA5083/Al2O3 surface composite using friction stir processing and studied the microstructure changes in the weld zone. The microstructure study showed a porosity percentage of 60% in the weld zone and the pore diameter varied from 0.2 –.

1) Further, the effect of microstructure reflected on the micro-hardness of the material: El-Sayedet al. (2018) studied the effects of friction stir welding parameters on the peak temperature and the mechanical properties of the AA5083-O aluminum alloy. The authors reported the display of very little effect on the peak temperature of the welding process by the welding speed and tool pin profile. The defect free welded joint was achieved while using the welding speeds of 50, 100 and 160 mm/min and threaded pin profile. The threaded pin profile showed the better tensile properties at the welding speed of 50 mm/min compared to the tensile strength of tapered pin profile at the same welding speed.

2) SUMMARY OF LITERATURE SURVEY AND IDENTIFICATION OF RESEARCH GAP: Literature review on the topics of friction stir welding of aluminum alloys AA2024 , AA6061-T6 and AA2024 - AA6061-T6 show

that many investigators have performed the research on the friction stir welding of Aluminum alloy joints made by AA2024 and AA6061. Several investigators have concentrated on the microstructure change and mechanical properties of the friction stir welded aluminum alloy joints and few investigators have used nano particles extracted from the metals as a reinforcing agent in the weld zone and achieved the improvement in the physical properties. The focus of many works is on the effects of process parameters like tool rotational speed, welding speed, tool tilting angle and bead width on the weld joint and compared the experimental works with the theoretical work by using the finite element analysis. Some works have been performed using the finite element analysis method to determine optimum process parameters. Very few works have been done on the combinations of friction stir welding of aluminum alloy joints using AA2024 and AA6061.

Based on the literature review, there exists a research gap in the performance of in-depth analysis of parameters like erosion-corrosion, stress corrosion cracking, fatigue and wear behavior of the dissimilar joint of aluminum alloys AA2024 and AA6061, to understand the suitability for marine and deep ocean applications.

3) NEED FOR THE PRESENT WORK: Marine and deepsea exploration and exploitation require reliable deep-sea machineries which can withstand the harsh environment of the deep- sea. The deep-sea environmental conditions include the effects of highpressure conditions, erosion corrosion due to waves and current, stress corrosion, wear due to abrasive sediments and bio-fouling, high fatigue due to cyclic loads etc. (Makogon et al.2007).

Lightweight aluminium alloy super structures and enclosures are being proposed for the deep-sea machineries to make them lighter for handling in high seas and also to avoid sinkage problems in the sea bed. This has led to present research work of joining the aluminium alloys erosion corrosion, stress corrosion cracking, fatigue and wear tests which are very common effects in deep-sea environment. In addition, tmechanical behavior of the joints is examined by conducting tensile and microhardness tests.

4) SCOPE OF THE PRESENT STUDY: In this research work, aluminium alloys AA2024 and AA6061 were joined together by friction stir welding using different tool pin profiles. The process parameters were also varied and welds were produced with variations in the rotational speed from 800 rpm to 1200rpm, traverse speed from 44 mm/min to 100 mm/min. The welds were produced for the combination of parameters arrived with Orthogonal Array (OA) of the Taguchi L-27 technique. The micro hardness and tensile tests were carried out at the weld center of specimen fabricated using the above combination of parameters. The optimal parameters which result in a sound weld joint were arrived for further research work.

Various tests which are very common effects in deep-sea environment like erosion corrosion, stress corrosion cracking, fatigue and wear tests were conducted on the friction stir welded samples with optimal parameters. These studies will result in better understanding the suitability of dissimilar joint of aluminum alloys AA2024 and AA6061 for marine and deep ocean applications like deep sea-bed mining.

III. TAGUCHI L-27 TECHNIQUE

Design of Experiments (DoE) is the common procedure used for a reduction in the time and cost of the experimental work. Taguchi L-27 technique is one of the DoE procedures for finding the optimal parameters that influence the output of the experimental work. It is the statistical tool applied for many problems in industrial applications. Taguchi L-27 procedure finds the most influencing parameter with less expenditure and time consumption. The selection of parameters is optimal in the design of experiments and the forecasting of the output is quite simple and economical to use in the real applications (Rao *et al.* 2008). Taguchi L-27 procedure illustrated in Figure 3.19 involves designing of the experiment using the orthogonal array approach. The experiments are further conducted for a set of experiments with the combination of the parameter levels as arrived in the orthogonal array. The optimal levels of the parameters arrived at were based on the criteria specified and verified with the confirmation experiment. Once the outcome of the confirmation experiment is comparable with the expected outcome, the parameter levels are declared as optimum levels. Otherwise, the orthogonal array is further refined to get more reliable results .

IV. CONCLUSION

It has been observed that FSW at higher welding speeds was feasible for the given parameters; however the tilted tool produced defective welds. Taguchi analysis of the experimental results proved that the tool tilt was the most influential parameter deciding the weld strength. The weld pressure at higher welding speed was possibly low and the tool tilt caused further depletion in welding pressure. In these cases, the pressure was reduced below a limiting value which was required to avoid volumetric defects. The macrostructure vindicated this fact as it showed that weld material flow for the welds with a tool tilt was not synchronised and periodic. Microhardness of the welds was found to be lower for welds produced with a tool tilt. Hence it can be concluded that tool tilt is detrimental at higher welding speeds or causing a reverse effect at higher welding speeds. An analytical model was suggested for the FSW of aluminium alloys based on the slip factor with simple tool having cylindrical pin. An expression for slip factor is suggested which represented slip as a partition of frictional work and work of plastic deformation. The slip factor is expressed in terms of the tool torque. It is noticeable that tool torque increases at higher welding speeds. The model enabled computation of maximum temperature in the FSW process. The proposed model has taken partial slipping and partial sticking tool contact conditions in to consideration. That could be the reason that the model displayed errors in the computation of maximum temperature for lower welding speeds. At lower welding speeds slipping contact conditions dominated during welding process.

REFERENCES

[1] P. Colegrove, M. Painter, D. Graham, and T. Miller, "-dimensional flow and thermal modelling of the friction stir welding process proceedings of second international symposium on friction stir welding," 2000, pp. 3–3.

[2] K. Surekha, B. S. Murthy, and K. R. Prasad, "Microstructural characterization and corrosion behaviour of multipass friction stir processed AA 2219 aluminium alloy," *Surface & Coating Technology*, vol. 202, pp. 4057–4068, 2008.

[3] M. Russell and H. R. Shercliff, *Analytical modelling of microstructure development in friction stir welding First International Symposium on Friction Stir Welding*, Thousand Oaks, 1999.

[4] Z. Zhang, B. L. Xiao, and Z. Y. Ma, "Effect of welding parameters on microstructure and mechanical properties of friction stir welded 2219 Al- T6 joints," *Journal of Material science*, vol. 47, pp. 4075–4086, 2012.

[5] 2011.

[6] R. Palanivel and P. K. Mathews, "Prediction and optimization of process parameter of friction stir welded AA5083-H111 aluminum alloy using response surface methodology," *Journal of central south university*, 2012.

[7] H. Schmidt, J. Hattel, and J. Wert, "An analytical model for the heat generation in friction stir welding. Modelling and Simulation of," *Materials Science and Engineering*, vol. 12, pp. 143–157, 2004.

[8] S. Rajakumar, C. Muralidharan, and V. Balasubramanian, "Optimization of the friction stir welding process and tool parameters to attain a maximum tensile strength of AA7075-T6 aluminium alloy," *Proceedings of the Institution of Mechanical Engineers*, vol. 224, no. 8, pp. 1175–1191, 2010.

[9] P. Cavaliere, G. Campanile, F. Panella, and A. Squillace, "Effect of welding parameters on mechanical and microstructural properties of AA6056 joints produced by friction stir welding," *Journal of Materials Processing Technology*, vol. 180, pp. 263–270, 2006.

[10] W. Xu, J. Liu, G. Luan, and C. Dong, "Temperature evolution, microstructure and mechanical properties of friction stir welded thick 2219-O aluminium alloy joints," *Materials and Design*, vol. 30, pp. 3460–3467, 2008.

[11] Y. Chao and X. Qi, "Thermal and thermo-mechanical modelling of friction stir welding of aluminium alloy 6061 - T6," *Journal of Material Processing and Manufacturing Science*, vol. 7, pp. 215–233, 1998.

[12] V. Thomas and E. D. Nicholas, "Friction Stir Welding for the Transportation Industries," *Materials and Design*, vol. 18, pp. 269–273, 1997.

[13] V. Firouzdor and S. Kou, "Al-to-Mg friction stir welding: effect of material position, travel speed and rotation speed," *Metallurgical and Materials Transactions A*, vol. 41, pp. 2914–2935, 2010.

[14] "An analytical model of heat generation for eccentric cylindrical pin in friction stir welding," *Journal of Materials Research and Technology*, vol. 5, no. 3, pp. 234–240, 2016.

[15] A. P. Reynolds, "Flow visualization and simulation in FSW," *Scripta Materealia*, vol. 58, pp. 338–342, 2008.

[16] M. Z. H. Khandkar, J. A. Khan, and A. P. Reynolds, "Prediction of temperature distribution and thermal history during friction stir welding: input torque model," *Science and Technology of Welding and Joining*, vol. 8, pp. 165–174, 2003.

[17] M. Jayaraman and V. Balasubramanian, pp. 605–615, 2013.

[18] G. Oertelt, S. S. Babu, S. A. David, and E. A. Kenik, pp. 71–79, 2001.

[19] Muruganandan and Das, "Friction stir welding process parameters for joining dissimilar aluminium alloys," *International Journal of Mechanical engineering and Technology*, vol. 2, no. 2, pp. 25–38, 2011.

[20] T. Seidel and A. P. Reynolds, "Visualization of the material flow in AA2195 friction-stir welds using a marker insert technique," *Metallurgical and Materials Transactions A*, vol. 32, pp. 2879–2884, 2001.

[21] M. Attallah, G. Hanadi, and Salem, "Friction stir welding parameters: a tool for controlling abnormal grain growth during subsequent heat treatment," *Materials Science and Engineering: A*, vol. 391, pp. 51–59, 2004.

[22] V. Gadakh and K. K. Adepu, "Heat generation model for taper cylindrical pin profile in FSW," *Journal of Materials Research and Technology*, vol. 2, no. 4, pp. 370–375, 2013.

[23] S. W. Kallee, J. Davenport, and E. D. Nicholas, "Railway Manufacturers implement friction Stir Welding," *Welding Journal*, vol. 81, pp. 47–50, 2002.

[24] S. Kanwar, S. Arora, M. Pandey, R. Schaper, and Kumar, pp. 941–952, 2010.

[25] C. Dawes and W. M. Thomas, "Friction Stir Process Welds Aluminium Alloys," *Welding Journal*, vol. 75, pp. 41–45, 1996.

[26] H. N. B. Schmidt, T. L. Dickerson, and J. H. Hattel, "Material flow in butt friction stir welds in AA2024-T3," *Acta Materialia*, vol. 54, pp. 1199–1209, 2006.

[27] . J. Yuh, X. Chao, W. Qi, and Tang, "Heat Transfer in Friction Stir Welding- Experimental and Numerical Studies," *Transactions of the ASME*, vol. 125, pp. 138–145, 2003.

[28] C. Devanathan, A. Murugan, and A. Sureshbabu, "Optimization of process parameters in friction stir welding of Al 6063," *International Journal of Design and Manufacturing Technology*, vol. 4, no. 2, pp. 42–48, 2013.

[29] W. Tang, X. Guo, J. C. Mcclure, L. E. Murr, and Nunes, "Heat Input and Temperature Distribution in Friction Stir Welding," *Journal of Materials Processing and Manufacturing Science*, vol. 7, no. 2, pp. 163–172, 1988.

[30] H. Aydin, A. Bayram, and I. Durgun, "The effect of post- weld heat treatment on the mechanical properties of 2024- T4 friction stir- welded joints," *Materials and design*, vol. 31, pp. 2568–2577, 2010.

[31] W. M. Thomas, E. D. Nicholas, J. C. Needham, M. G. Murch, P. Temple-Smith, and C. J. Dawes, 1991.

[32] R. Mishra and Z. Ma, 2005.

[33] M. Yu, E, and Z. Zhenqiang, "Structure response in the riveted and friction stir welded stringer panel under the tensile loading 13th international conference on fracture," 2013, pp. 16–21.

[34] O. Hatamleh and A. Dewald, "An investigation of peening effects on the residual stresses in friction stir welded 2195 and 7075 aluminum alloy joints," *Journal of Materials Processing Technology*, vol. 209, pp. 4822–4829, 2009.
[35] R. M. Mishra and M. W.
[36] J. C. Mcclure, T. Tang, L. E. Murr, X. Guo, and Z. Feng, *A Thermal Model for Friction Stir Welding*, J. M. Vitek, S. A. David, and J., Eds.
[37] J. Q. Su, T. W. Nelson, R. Mishra, and M. Mahoney, "Microstructural investigation of friction stir welded 7050- T651 aluminium," *Acta Materialia*, vol. 51, no. 3, pp. 713–729, 2003.
[38] 2007.
[39] P. Podrzaj, P. Jerman, and D. Klobcar, "Welding defects at friction stir welding," *Metalurgija*, vol. 54, no. 2, pp. 387–389, 2015.
[40] R. Rai, A. De, H. K. D. H. Bhadeshia, and T. Debroy, pp. 325–342, 2011.
[41] H. Fujii, L. Cui, M. Maeda, and K. Nogi, "Effect of tool shape on mechanical properties and microstructure of friction stir welded aluminium alloys," *Journal of Materials Science and Engineering A*, vol. 419, pp. 25–31, 2006.
[42] P. Cavaliere, D. A. Santis, F. Panella, and A. Squillace, "Effect of anisotropy on fatigue properties of 2198 Al - Li plates joined by friction stir welding," *Engineering Failure Analysis*, vol. 6, pp. 1856–1865, 2008.
[43] S. Malarvizhi and V. Balasubramanian, "Effect of welding processes on AA2219 aluminium alloy joint properties," *Transactions of Nonferrous Metals Society of China*, vol. 21, pp. 962–973, 2011.
[44] H. Aydin, A. Bayram, A. Uguz, and S. K. Akay, "Tensile properties of friction stir welded joints of 2024 aluminum alloys in different heat treated- state," *Materials and Design*, vol. 30, pp. 2211–2221, 2009.
[45] G. Singh, S. Saini, and A. Rana.