A COMPREHENSIVE SURVEY ON FRICTION STIR WELDING OF MAGNESIUM ALLOYS

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Abstract— The demand for newer materials having prominent properties is increasing day by day. Automobile & Aerospace fields do play an important role as far as material selection is concerned. The most commonly used material in these fields is Aluminium. Though it possesses all the properties up to some extent constant demand is pushing for alternate materials. Magnesium alloys are a perfect replacement for Aluminium alloys owing to its reliable properties. Friction stir welding is a relatively new technique of solid state welding in which the materials are joined together before reaching their melting point. A combination of Al and Mg alloy is a big leap in Automobile sector. In this paper a detailed review of Friction stir welding of Magnesium alloys has been done. This work will serve as a reference to subsequent researchers.

Keywords— Friction stir welding, Magnesium alloy, Process parameter.

I. INTRODUCTION

Friction stir welding (FSW) is a solid-state process in which a rotating pin tool is inserted into the edges of the sheets to be joined; as the tool shoulder contacts the sheet surfaces, the tool is moved along the welding line. The simultaneous rotation and translation of the tool induce a strong plastic deformation and promote plastic mixing across the joint. FSW allows to avoid the formation of the typical defects caused by the fusion welding processes and to obtain an effective microstructure. Such advantages make FSW very attractive in joining materials difficult to be welded such as magnesium alloys.[33] In FSW a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between two plates. For proper welding the plates must be clamped during the process.[1] Friction Stir welding is a solid state joining process and the heat generated during the rotation of the tool will cause the materials to get joined without reaching melting point. The plasticized material is transferred to the trailing edge of the tool pin, is forged with the tool shoulder and pin.

II. MAGNESIUM ALLOY

Magnesium alloys are promising alternatives for Aluminium, steel etc. due to its outstanding properties. The stiffness to weight ratio, low density, high damping capacity etc are some of them. These properties had enabled them to become a major part of automotive industry. A reduction of 20-70% of total weight of the components can be achieved. Mg alloys are having a hexagonal lattice structure and therefore during plastic deformation there are some complications when compared to Cu etc.[2] Mechanical properties of Mg alloys are improved by adding rare earth elements. Mg alloys are characterized with low melting point, large thermal expansion and therefore welding of Mg alloys using conventional methods will lead to cracks, pores etc. Commercial Mg alloys contain Al (3-13wt %) Mn (0.1-0.4wt %), Zn (0.5-3wt %) and some are hardenable by heat treatment. Mg alloys are often designated by 2 numbers. Letters denote the main alloying elements and numbers represent nominal composition of alloying elements. Addition of zinc and calcium alloys will increase the chance of occurring solidification cracking. Addition of zinc up to 2% is normal but further increase will cause poor weld ability. Some other classifications are based on their strengthening mechanisms as Solid solution strengthened alloy and Precipitation/Dispersion strengthened alloys [34]. Some of the common Mg alloy grades that have been or being friction stir welded are AZ (Mg-Al-Zn) and AM (Mg-Al-Mn) alloys. Among them AZ alloys are producing better welds with good mechanical properties. AZ31 is a wrought Mg alloy with good room temperature strength, corrosion resistance and easy availability which makes it a prime choice for automotive industry.

III. FRICTION STIR WELDING

Friction Stir Welding (FSW) is an innovative solid state welding technique which was first invented by The Welding Institute (TWI), UK in 1991. This technique was developed aiming Aluminium alloys but later it had found profound application in welding of Mg alloys, Cu alloys etc.[3] These alloys once considered unweldable are now possible by FSW. This method utilizes a non-consumable rotating tool to produce frictional heat and thus producing plastic deformation at the location of welding. FSW process consists of a rotating tool with a shoulder and probe arrangement. The heat is developed due to friction between the work piece surface and the tool [3]. The heat thus produced is used to soften the work piece before reaching its melting point. The heat generated during the process
is about 80-90% of the melting temperature. With FSW traditional components current and voltage are not present as the heat input is purely mechanical replaced by force, friction etc. The quality of an FSW joint is always better than other fusion welding processes. In this process the FSW material consists of four distinct microstructural zones namely Nugget zone (NZ), Thermo mechanically affected zone (TMAZ), Heat affected zone (HAZ) and Base material (BM). The process parameters chosen during FSW process have great influence on these zones.[4]

3.1 Process Parameters
The welding parameters are key players during every welding technique and FSW is no exception. Proper selection of welding parameters influences the final weld quality and resulting microstructure. Some of the major process parameters are listed below.

3.1.1 Tool Rotational Speed and Travel speed
This is one of the major process parameters during Friction stir welding and is primarily responsible for the generation of heat. The rotation may be clockwise or counterclockwise accordingly. The motion of the tool generates frictional heat within the work pieces, extruding the softened plasticized material around it and forging the same in place so as to form a solid-state seamless joint. The welding speed depends on several factors, such as alloy type, rotational speed, penetration depth, and joint type. Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. During traversing, softened material from the leading edge moves to the trailing edge due to the tool rotation and the traverse movement of the tool, and this transferred material, are consolidated in the trailing edge of the tool by the application of an axial force [35]. At the other end of the scale excessively high heat input may be detrimental to the final properties of the weld. Theoretically, this could even result in defects due to the liquation of lowmelting-point phases these competing demands lead onto the concept of a processing window: the range of processing parameters that will produce a good quality weld. Within this window the resulting weld will have a sufficiently high heat input to ensure adequate material plasticity but not so high that the weld properties are excessively reduced [36].

3.1.2 Tool Tilt and Plunge Depth
In addition to the tool rotation rate and traverse speed, another important process parameters are tool tilt with respect to the work piece surface and plunged depth. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. The tool is usually characterized by a small tilt angle (θ), and as it is inserted into the sheets, the blanks material undergoes to a local backward extrusion process up to the tool shoulder. Further, the plunge depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders[35]

3.1.3 Effect of Forces
During friction stir welding, there are three types of force act on the tool. Longitudinal force (X - Force), vertical force (Y- force), lateral force (Z-axis). The traverse force acts parallel to the tool motion and is positive in the traverse direction. Since this force arises as a result of the resistance of the material to the motion of the tool it might be expected that this force will decrease as the temperature of the material around the tool is increased. A downwards force is necessary to maintain the position of the tool at or below the material surface. Some friction stir welding machines operate under load control but in many cases the vertical position of the tool is preset and so the load will vary during welding. The lateral force may act perpendicular to the tool traverse direction and is defined here as positive towards the advancing side of the process.[36]

3.1.4 Tool characteristics
Tool design influences heat generation, plastic flow, the power required, and the uniformity of the welded joint. Tool geometry such as probe length, probe shape and shoulder size are the key parameters because it would affect the heat generation and the plastic material. The tool is an important part of this welding process. It consists of a shoulder and a pin. Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process. The shoulder generates most of the heat and prevents the plasticized material from escaping from the work-piece, while both the shoulder and the tool pin affect the material flow. Friction stir welds are characterized by well-defined weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions used.[35]. The commonly used pin profiles, cylindrical, conical, threaded, square, octagonal etc. The commonly used tool materials for FSW are Tool steel, carbide tool, High speed steel etc.

3.2 Weld Quality Parameters and Measurement
There are various quality parameters for a welded joint and these parameters are the judging factor for a good weld. Every welded joint must possess these quality parameters. The weld quality parameters are classified as

3.2.1 Mechanical Properties
The mechanical properties of the weld are playing a crucial role as far as application areas are concerned. The weld joint must possess superior mechanical properties when compared to base material
properties. Some of the common mechanical properties that determine the weld quality are Tensile strength, Strength/weight ratio, Elastic properties, Shear strength, hardness which includes microhardness values, Ductility, Impact strength, percentage elongation, Wear, Corrosive behavior, fracture characteristics, Fatigue etc.

3.2.2 Microstructural Properties

The resultant microstructure after welding will be quite different from parent material. Every process parameter selected during welding has significant impact on final microstructure. All these can be found out by some common metallurgical analysis techniques. In the case of dissimilar alloys welding one of the major problems is the formation of intermetallic compounds. All these can be detected through proper microstructural and metallographic techniques. Some of them are Scanning Electron Microscopy (SEM), Surface topography, Dispersive X-ray analysis techniques which includes EDX & XRD, Optical microscopy etc.

3.2.3 Thermal Properties

Apart from mechanical, microstructural properties on major influential parameter is temperature. The weld temperature varies during FSW owing to change in process parameters, tool pin profile etc. In case of dissimilar alloys the role of temperature is crucial as it determines the formation and thickness of intermetallic compounds. Some of the common thermal analysis methods are Thermo gravimetric analysis, Differential thermal analysis, Differential scanning calorimetry, Thermo mechanical analysis etc. All these analysis procedures are necessary for proper evaluation.

3.3 Review on Friction Stir Welding of Magnesium Alloys

A comprehensive review of Friction stir welding of Mg alloys has been done. Previous researchers were concentrated on the effect of selected process parameters on final weld quality and on mechanical properties. Weideng wang et al. in 2016 [1] found out the influence of tool rotational rates on the temperature profiles and also its influence on mechanical properties of final friction stir welded specimen. Thermocouples were embedded at three representative positions on the advancing side of the FSW joint to record the temperature histories. The friction stir welded joints were trans-sectioned for microstructural and hardness characterization. The mechanical properties of the FSW joints were evaluated by means of uniaxial tensile tests and Charpy V-notch impact tests at room temperature. In addition, based on ABAQUS code, a full 3D finite element (FE) model was developed to simulate the temperature field during the FSW process. The process parameters chosen were tool rotational speed ranging from 800 to 1600 rpm and a constant welding speed of 120 mm/min with a tool tilt angle of 2.5°. He had referred about the effect of process parameters on temperature and joint efficiency. Renlong Xin et al. in 2015 [2] studied the effect of chosen process parameters on texture distribution and plastic deformation behavior of Mg alloys. Detailed microstructure and texture evolutions were examined on Mg welds by electron backscatter diffraction (EBSD) techniques. It was found that the changes of welding parameters can affect texture distribution and the characteristic of texture in the transition region between SZ and thermal-mechanical affected zone (TMAZ). As a consequence, the activation ability of basal slip and extension twinning was changed, which therefore influenced joint strength, inhomogeneous plastic deformation and fracture behaviors. The author found out the effect of welding parameters on final weld microstructure and fracture morphology. A. Forcellese et al. [3] in 2015 studied on vertical forces and temperature during the friction stir welding process. Vertical forces occurring during all stages of FSW were measured using a low-cost dynamometer developed by authors. Furthermore, temperatures in different positions of the welding line were monitored by means of K-type thermocouples. It was shown that during the dwelling stage, the vertical force decreases until a steady-state regime is reached.

Prakash kumar sahu, Sukhomay pal [4] in 2015 used multi response optimization of process parameters during friction stir welding of AM20 Mg alloy with the help of taguchi grey relational analysis. The experiments were carried out by using Taguchi’s L18 factorial design of experiment. The processes parameters were optimized and ranked the parameters based on the GRA. The percentage influence of each process parameter on the weld quality was also quantified. A validation experimental run was conducted using optimal process condition, which was obtained from the analysis, to show the improvement in mechanical properties of the joint. This study also shows the feasibility of the GRA with Taguchi technique for improvement in welding quality of magnesium alloy. Jaiganesh. V., P. Sevvel [5] in 2015 experimented on the effects of process parameters on the microstructure and mechanical properties of Mg alloy. The alloy grade chosen for purpose was AZ80A Mg alloy. The tensile fracture surfaces obtained from successfully fabricated joints are subjected to tensile tests and microstructural investigations were done using scanning electron microscope. From the experimental results, the joints produced under a 5 kN axial force value at 1000 rpm and at a feed rate of 1.5 mm/min were found to exhibit superior mechanical properties and metallurgically defect free weldments when compared with other joints. The chemical compositions of these defect free joints were analyzed using energy dispersive spectrometry. Moreover, ideal level of heat generation, uniform
flow of the plasticized material and formation of fine grain structure with uniform distribution in the FSW zone were found to be the main reasons for these superior mechanical properties and flawless joints. Bhukya srinivasan naik et.al[6] in 2015 experimented on the tensile properties and residual stresses on friction stir welded AZ31B-H24 Mg alloy. The residual stresses in the longitudinal and transverse directions of the weldments were determined using X-ray diffraction. The shear tensile behavior of the lap joints was evaluated at low [233 K (~40 °C)], room [298 K (25 °C)], and elevated [453 K (180 °C)] temperatures. The failure load was highest for the lower heat input condition that was obtained at a tool rotational rate of 1000 rpm and a welding speed of 20 mm/s for all the test temperatures, due to the smaller hooking height, larger effective sheet thickness, and lower tensile residual stresses, as compared to the other two welding conditions that were conducted at a higher tool rotational rate or lower welding speed. The lap joints usually fractured on the advancing side of the top sheet near the interface between the thermo-mechanically affected zone and the stir zone. S.Mironov T.Onuma et.al.[7] in 2015 also concentrated on AZ31 Mg alloy but on varying welding temperatures.AZ31 Mg alloy is having a hexagonal close packed structure was examined. The microstructure evolution of a typical hexagonal close-packed (HCP) material (AZ31 magnesium alloy) during friction stir welding was studied in a wide range of welding temperatures. In all cases, the grain structure development was found to be significantly influenced by the formation of a very strong {0 0 0 1} (uvw) B-fiber texture. Due to limitations imposed by this texture as well as by symmetry of the HCP crystal structure, an extensive lowering of grain-boundary misorientation was found to occur during deformation. Sevvel.P. Jaiganesh V [8] in 2014 experimented on the characterization of mechanical properties and microstructural analysis of Mg alloy during friction stir welding and optimization. AZ31B Mg alloys were friction stir welded by varying several different process parameters and the effects of these parameters on the joint quality, microstructure & mechanical properties were discussed comprehensively. This paper also experimentally proves & suggests the optimized process parameter values to be adopted for effective lap joining of AZ31B Magnesium alloys using FSW technique. B.S.Naik et.al.[9] in 2014 had done a detailed investigation on texture development during Friction stir lap welding of AZ31B –H24 Mg alloy. Friction stir lap welding (FSLW) resulted in the presence of recrystallized grains and an associated hardness drop in the stir zone (SZ). Microstructural investigation showed that both the AZ31B-H24 Mg base metal (BM) and SZ contained b-Mg17Al12 and Al8Mn5 second phase particles. The tool rotational rate and welding speed had a strong effect on the failure load of FS welded joints. A combination of relatively high welding speed (20 mm/s) and low tool rotational rate (1000 rpm) was observed to be capable of achieving a high failure load. Yong Zhao et.al. [10] in 2014 compared the micro hardness values and tensile properties of NZ20K and AZ31 Mg alloy at room temperature and 200°C. The effect of the strengthening phases in NZ20K joint was discussed compared with AZ31 joint. The results indicate that NZ20K shows better property especially at lighttemperature environment. The grain of NZ20K in the nugget zone (NZ) is refined obviously with uniform distribution of strengthening phase particles and it shows clear boundary between NZ and thermomechanically affected zone (TMAZ). The grains of TMAZ are elongated because of the stir action of tool pin. The ultimate tensile strength of NZ20K joint decreases a little from room temperature to 200 C for its main strengthening phase particle- Mg12Nd being stable when the temperature goes up. On the contrast, the ultimate tensile strength of AZ31 joint decreases a lot at 200 C for its strengthening phase soften or dissolve at high temperature. S.Ugender et.al. [11] in 2014 experimented on AZ31B Mg alloy to find out the influences of welding parameters on mechanical properties and microstructure. The friction stir welding had been carried out at 900rpm, 1120rpm,1400rpm and 1800rpm with tool materials High speed steel and stainless steel. The micro hardness values obtained had shown an increase at low rotational speeds. A lowering of tensile strength was obtained at rotational speeds of 1400rpm and 1800 rpm. Inderjeet Singh et.al [12] in 2014 studied the effects of welding parameters on similar friction stir welded joints of AZ31B-O Mg alloy. The effect of weld pitch i.e. ratio of welding speed to tool rotational speed (0.0020 mm/rev to 0.05 mm/rev) was examined on the mechanical and micro structural properties of friction stir welded joints of AZ31B-O Mg alloy. The linear relationship between tensile strength and weld pitch was observed. The maximum value of tensile strength i.e. 187.8 N/mm2 was obtained at weld pitch of 0.05 mm/rev using 20 mm tool 4 shoulder diameter. Most of the tensile test specimens fractured in the area between Stir Zone (SZ) and Thermo Mechanical Affected Zone (TMAZ) towards the advancing side. S.Rajakumar et.al [13] in 2013 showed a relationship between process parameters and tensile strength. Response surface methodology was used for the formation of empirical relationship.AZ61A Mg alloy was used for experimentation .Tool rotational speed, traverse speed, stirrer geometry were considered. Optimization was done with the help of Response surface methodology. S.H.Chowdhury et.al.[14] in 2012 analyzed the influence of process parameters during friction stir welding of AZ31B-H24 Mg alloy. After FSW both the strength and ductility of AZ31B-H24 Mg alloy decreased with a joint efficiency in between about 75 and 82 percentage due to the changes in both grain structure an texture .The
welding speed and rotational rate showed a stronger effect on Yield strength than the Ultimate Tensile strength. A. Razal Rose et al. [15] work in 2011 is focusing on the influences of welding speed on tensile properties of Friction stir welded AZ61A Mg alloy... Five different welding speeds ranging from 30 to 150 mm/min were used to fabricate the joints. Tensile properties of the joints were evaluated and correlated with the stir zone microstructure and hardness. From this investigation, it is found that the joint fabricated with a welding speed of 90 mm/min exhibited the acceptable tensile properties compared to other joints. The formation of fine grains in the stir zone is the main reason for the higher hardness and acceptable tensile properties of these joints. K.L. Harikrishna et al. [16] in 2010 concentrated on Friction stir welding of ZM 21 Mg alloy. Defect free, full-penetration welds were produced after careful process parameter optimization. Microstructural studies, hardness tests, tensile tests, and bend tests were carried out. Welds produced in 5 mm thick (5-mm-welds) and 10 mm thick plates (10-mm-welds) showed relatively finer grains in the weld nugget and in the heat-affected zone compared to the welds produced in 25 mm thick plates (25-mm-welds). When compared to the base material, 25-mm-welds showed coarser grains both in the weld nugget and in the heat-affected zone. No significant hardness differences were observed between the welds and the base material. Tensile tests on 5-mm and 10-mm-welds yielded a joint efficiency of more than 75%. Bend performance of the welds was found to be satisfactory, falling only slightly behind the base material. Overall, the results show that friction stir welding can be successfully utilized for joining magnesium alloy ZM21 in various thicknesses. G. Padmanabhan and V. Balasubramanian [17] in 2009 had done investigations on AZ31B Mg alloy. Fourteen joints were fabricated using different levels of tool rotational speed, welding speed, and axial force. Tensile properties of the welded joints were evaluated and correlated with the weld zone microstructure and hardness. From this investigation, it is found that the joints fabricated using a tool rotational speed of 1,600 rpm, a welding speed of 0.67 mm/s, and an axial force of 3 KN yielded superior tensile properties compared to other joints. Optimum level of heat generation, formation of finer grains, and higher hardness are the main reasons for the superior tensile properties of these joints. Fatigue properties of FSW joints were evaluated, and it was found that fatigue properties of FSW joints were slightly lower than the base metal. Even though the review period is short this paper will be a ready reference for upcoming researchers.

CONCLUSION

In this work Friction stir welding of various types of Mg alloy grades has been considered. The influence of each selected process parameters on final weld quality, microstructural analysis, mechanical properties have been considered in detail. Among various grades of Mg alloy AZ31 grade has been used in major. The process parameters selected were mainly Tool rotational speed, Welding speed, tool tilt angle etc. Though various tool profiles has been used the tool material for almost all the works remains to be H13 Tool steel Thorough literature review related to Friction stir welding of Mg alloys has been done for limited period. The works of various researchers has been highlighted throughout the paper. Remarks of various works are also highlighted.

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