ISSN No:-2456-2165

Investigations on Machining Aspects of Two Dissimilar Materials During Friction Stir Welding Experimental and Numerical Analysis

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Abstract:- Friction stir welding (FSW) is a solid-state process, which is based on friction welding. It is an effective solid-state welding process in which similar and dissimilar materials can be joined. In the FSW, the tool is used to join the faces of two materials, by generating friction with the help of the tool shoulder. Due to this friction, there will be a rise in temperature, which softens the material near the tool surface and feasibility to mechanically intermix and join the material. This study mainly focuses on the FSW of two dissimilar metals of AA1100 and MG-AZ31. During this experiment, many defects may arise such as distortion, crack formation, lack of fusion, undercut, and incomplete penetration. These defects can be eradicated by selecting the appropriate tool profile, tool material, and suitable weld parameters (which were determined by the variations in temperature, stress-strain generated during the process). From various literature surveys, it has been observed that the weld parameters will affect the quality of the weld. In this given context the present work highlights the variations in deformation, stress, temperature distribution, and strain were systematically investigated and analyzed.

Keywords:- *Welding; Friction; Tool Material;*

I. INTRODUCTION

Welding is a permanent joining process, where it is used extensively in metal-working industries. This permanent joint is made either by using filler material or without using filler material. The welding process can be classified into two types i) Fusion welding process: Parent material is heated up to a molten state and then materials will solidify together. Example: Arc welding, Gas welding. ii) Solid State welding process: Parent materials to be welded which are not melted, as the welding is to be produced due to pressure and temperature Example: Diffusion welding, Roll welding, Friction welding, Forge welding. solid state welding process, which performed at high pressure, which in turn requires better fixture compared to the fusion welding process. This process produces fewer defects, which makes to use for the applications which require high strength but due to several advantages over conventional welding process such as MIG, laser welding, TIG, etc, Friction stir welding process exhibits better fatigue strength, corrosion resistance, impact strength, tensile strength, residual stresses, etc. The Friction stir welding (FSW) can be performed on different joint configurations such as lap joint, T lap joint, edge butt, Fillet joint, T-butt joint.

A. Workpiece material

In this context, we use two dissimilar materials i.e. AA1100 and MG-AZ31. During welding, these dissimilar metals using filler metal may cause oxides to be collected at the weld on the base of the material which led to discoloration. Instead of selecting the best filler metal, it is easy to go through FSW since it doesn't require filler metal.

AA1100: Aluminum due to its advanced and favorable properties such as high ductility machinability, and malleable it was used in many manufacturing and fabrication industries such as shipbuilding, aerospace, infrastructure development, etc[1]. Aluminum alloy when it comes to contact with oxygen it produces a passive oxide layer, AA110, which restricts further oxidation of the body. AA1100 is mechanically stronger in 1000series and it is the most widely used grade because of its properties like excellent corrosion resistance, reflective finish, and high ductility [2].

Fe	0.750
Si	0.080
Mn	0.003
Cu	0.104
Cr	0.001
Mg	0.001
Ti	0.020
Al	99.00

TABLE I. CHEMICAL COMPOSITION OF AA1100 IN %

UTS(MPa)	142
Shear strength (MPa)	69
Tensile strength (MPa)	110
Yield strength (MPa)	105
Fatigue strength (MPa)	41
Elongation (%)	12
Hardness(HB500)	28
Density (1000 kg/m^3)	2.71
Poisson's ratio	0.33

TABLE II. MECHANICAL PROPERTIES PERFORMED AT ROOM TEMPERATURE 25DEG CELSU

MG-AZ31: Magnesium was 75% lighter than steel and 33 % lighter than aluminum. It has very low density, high corrosion resistance, high-temperature properties that are relevant to be used for designing light-weight aerospace parts. Other metals like zinc, aluminum, copper, and zirconium are mixed to improve physical properties. MG-AZ31 has a high strength-to-weight ratio. It is widely available when compared to other grades this is mostly used in manufacturing the components in aerospace industries.

Si	0.08
Fe	0.003
Cu	0.01
Mn	0.20
Mg	97
Zn	0.60
Al	2.5
Ni	0.01

TABLE III. CHEMICAL COMPOSITION OF MG-AZ31 IN %

Tensile strength (MPa)	259
Yield strength (MPa)	157
Elongation (%)	10
Density (1000 kg/m^3)	1.78
Poisson's ratio	0.35

TABLE IV. MECHANICAL PROPERTIES PERFORMED AT ROOM TEMPERATURE 25DEG CELSU

B. *Tool material*

In this study, we used H-13 tool steel for the manufacturing of the tool. This tool material is selected because of its ability to withstand high temperature, cyclic heating, and cooling operations. H-13 tool steel is hot work steel of chromiummolybdenum that was used mainly for hot and cold tooling applications. FSW experiences temperature during its welding process, up to 70-80 percent of the solidus temperature of the taken material.H-13 tool hardness can withstand and not be affected by this temperature generated. For increasing the hardness of the material heat treatment process can be applied. Some of the H-13 tool steel properties are mentioned below in table 5

UTS(MPa)	1990
Elastic Modulus (GPa)	210
Thermal Conducticity(W/m-k)	24.2
Density (1000 kg/m^3)	7.80
Poisson's ratio	0.30
Specific Heat capacity(J/Kg-K)	460

TABLE V. PROPERTIES OF H-13 TOOL STEEL

C. *Working Principle*

1) Initially, the workpiece materials which are to be welded are fixed rigidly with the help of a backing bar so that during the welding process they can't be moved apart.
2) Rotatory tool, which is non-consumable, preferred shoulder and pin profile were inserted or plunged so that touching edges of the plate must be joined. Note i) the shoulder must touch the base material. ii)length of the pin must be slightly less than the weld depth
3) And then the tool is moved transversely along the weld line
4) Due to its transverse and rotation movement, it generates friction which causes material surrounding the tool will be mixed and in turn produces weld
5) That is the friction is generated between the workpiece material and the tool shoulder which plasticized the material and made its flow circulating near the area of the tool surface and made materials to be weld

Tool Direction and	Welding direction
Same direction	Advancing side
Opposite direction	Retreating side

TABLE VI. TOOL TERMINOLOGY BASED ON ITS DIRECTION

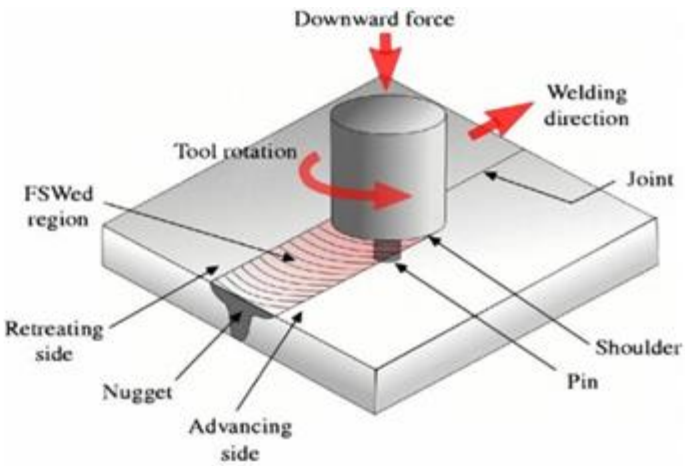


Figure 1: Working Of FSW

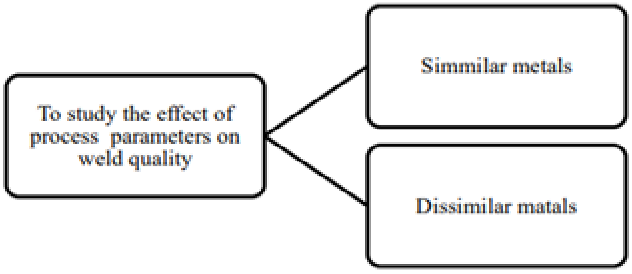
D. *Need for the research*

1) Through the help of various literature surveys collected, it was identified that the strength of the weld is a major concern in any welding process.
2) The weld produces by friction stir welding is mainly dependent on the weld parameter.
3) These parameters decide the quality of weld will increase or decreases.
4) To get sound to weld the best weld parameters should be selected

5) Welding of thin sheets is difficult to weld, but using FSW the complicated process can be turned into easy, where we can weld the sheats of millimeters in size
6) In welding of AA1100 and Mg-AZ31, it exhibits variation in properties
7) Therefore research is needed in welding these dissimilar metals
8) Even though welding of these dissimilar materials are already made, but the rigorous study is required for assessing the proper weld
9) In this study, the investigation has been done on the effect of weld parameter on weld quality in friction stir welding

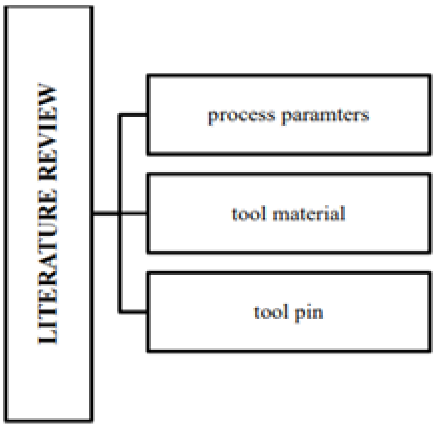
II. RESEARCH OBJECTIVE

The objectives for this research work are as follows:



III. LITERATURE REVIEW

Most of the non-ferrous materials which are used in various applications in industries are difficult to weld because of their low strength, high thermal conductivity, and non-favorable properties. therefore, welding of these non-ferrous materials is avoided using a conventional welding process due to its variation in mechanical properties, where these materials are joined using processes like riveting and brazing, but due to inconvenience in this process like low strength in the weld, hence this made to use the friction stir welding process. The friction stir welding process provides better conditions for welding similar as well as dissimilar metals using friction. the materials which exhibit high variation in their properties can be welded using the FSW process Classification of literature review On an extensive study on various literature, we classified our literature study into 3 departments they are.



A. *Tool material*

- Worked on: Quantitative wear analysis of H13 steel tool during friction stir welding of Cu-0.8%Cr-0.1%Zr alloy Observation: High tool rotational speed and low transverse speed causes tool wear when H13 is the tool material
- Worked on: Wear resistance performance of AlCrN and TiAlN coated H13 tools during friction stir welding of A2124/SiC composite Observation: H-13 steel tool consists of better mechanical properties and excellent adhesion strength
- Woked on: Quantitative wear analysis of H13 steel tool during friction stir welding of Cu-0.8%Cr-0.1%Zr alloy Observation: H-13 steel tool exhibits some wear but does not fail against FSW of CuCrZr alloy

B. *Process parameters*

- Worked on: Numerical studies on controlling of process parameters in friction stir welding Observations:

→ If rotational speed increases, the temperature of friction stir welding also increases

→ If rotational speed and welding speed increases, power consumption also increases

→ Weld quality can be improved by increasing rotational speed and decreasing welding speed

→ If welding speed reaches higher values, simultaneously rotational speed must also increase. This will reduce the defects

→ If both rotational speed and translating speed increases simultaneously will be led to the development of residual stress

- Worked on: Taguchi Optimization of Process Parameters in Friction Stir Welding of 6061 Aluminum Alloy Observations:

→ Tool rotational speed plays an important role when compared to the transverse speed of weld

→ 51 percent impact of heat affected zone are due to rotational speed

- Worked on: Taguchi Optimization of Process Parameters in Friction Stir Welding of 6061 Aluminum Alloy Observations:

→ Tool rotational speed plays an important role when compared to the transverse speed of weld

→ 51 percent impact of heat affected zone are due to rotational speed

- Worked on: Investigation of the effects of critical process parameters of friction stir welding of polyethylene Observations:

→ High welding speed will decrease the tensile strength → The amount of heat dissipated will strongly affect the microstructural properties

→ The strength of the material will decrease due to micro-cracks and voids

➢ Worked on: The influence of process parameters in friction stir welding of Al-Mg alloy and polycarbonate Observations:

→ High rotational speed changes weld zone color into darker

➢ Worked on: Evaluation of parameters of friction stir welding for aluminum AA6351 alloy Observations:

→ Better alignment of tool and weld line will provide better tensile strength

→ Pure Alluminium alloy has a low melting point and thermal conductivity, hence it can be welded using FSW

→ For maximum tensile strength, the welding speed must range to lower values

→ FSW does not require the external heat source

➢ Worked on: Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints Observations:

→ Weld nugget with defect-free and fine-grained structures will provide better tensile strength. This kind of weld nugget will be obtained by selecting suitable parameters

From the study of various literature reviews, we can state that tool rotational speed should be more and welding speed should be less for a better quality of the weld.

C. Tool Pin

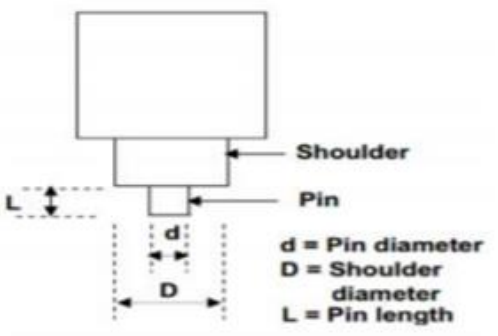


Figure 2: Basic terminology of a tool

From the below table 6 the functions of parts of the tool are listed;

PART OF TOOL	FUNCTION
Shoulder diameter	Gives us plastic flow and generation of heat
Shoulder surface	Allows material movement and plastic deformation
Pin diameter	Pin diameter
Pin length	It stirs the material and forges it
Pin surface	It produces frictional heating and deformational heating around it

TABLE VII. FUNCTONS OF PARTS OF THE TOOL ARE LISTED

IV. FRICTION STIR WELDING PROCESS

Friction stir welding is a process in which both similar and dissimilar materials which have low strength and high conductivity are joined together.

- This process has main advantages such as the materials which are not feasible to join using conventional welding process are joined using friction stir welding process
- The process can be performed using a vertical axis milling machine or a specialized machine that has proper fixtures to perform the experiment
- During this process, a rotational tool that has high strength are inserted or plunged between the workpiece
- The tool is moved along the traverse direction along the weld line
- Due to its transverse and rotation movement, it generates friction which causes material surrounding the tool will be mixed and inturn produces weld.
- That is the friction is generated between the workpiece material and the tool shoulder which plasticized the material and made its flow circulating near the area of the tool surface and made materials to be weld
- Mixing of material will be done in the plastic state because of this even though there is a large difference in material properties weld can be created
- During this process, high stresses are been generated at the area between tools and workpieces hence better fixture and selecting of best weld parameter affect the performance of welding
- Selecting the best parameter gives the better quality of a weld
- After experimenting the results are analyzed by comparing with various tests such as tensile test, flexural test, radiography test, and hardness test, etc which insights the weld performance

A. Weld parameters

We consider these parameters from the various study of literature review they are :

→ Welding speed

→ Axial force

→ Rotational speed

→ Design of welding tool

B. Welding tools

In friction stir welding selection welding tool plays a key role as it shouldn't damage the workpiece material and provide good friction, the welding tool affects the properties of the weld parameters and it should also allow the better flow of materials around the tool

C. Material Flow

The better material flow gives the better weld parameters, the material flow depends upon the tool we choose, so we should choose appropriately the tool as per the workpiece material so that the material flow takes place easily near the tool and workpiece, where the material flow depends upon two conditions :

ISSN No:-2456-2165

- Material flow due to pin
- Material flow due to shoulder

Material flow due to pin : Material flow due to pin takes the major part of mixing the properties of the workpiece material and the flow of material will be layer by layer.

Material flow due to shoulder :

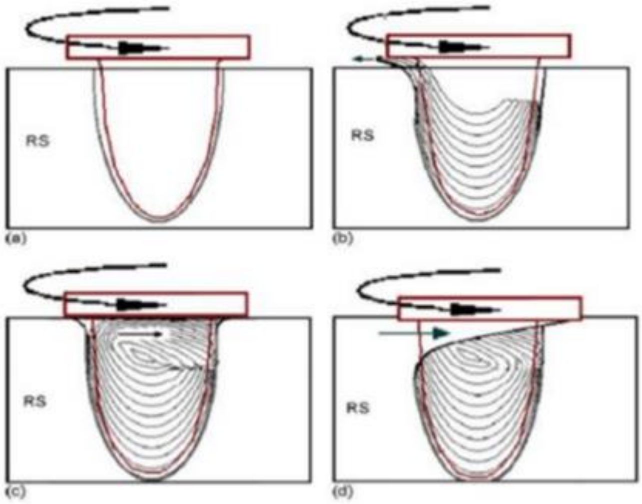


Figure 3: Material flow due to pin

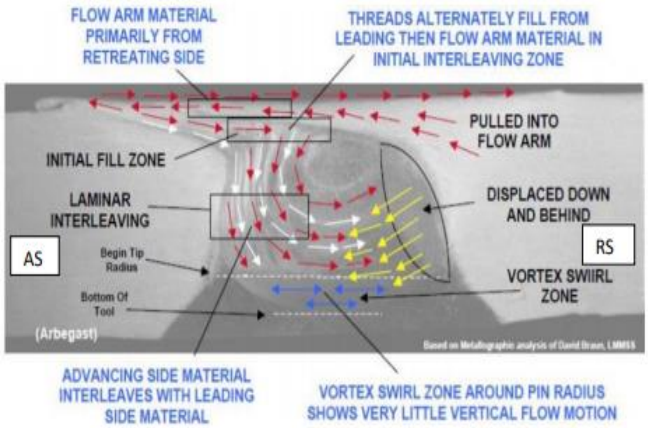


Figure 4: Material flow in advancing side and retracting side

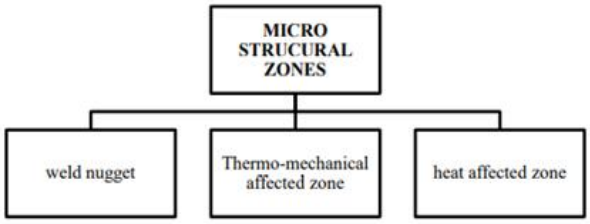
- Red arrows indicate the transfer of material from retracting side to the advancing side
- white arrows indicate the volume of material that flows from the upper part of the advancing side and which deposited on the extrusion zone at the advancing side and middle of the weld nugget
- The yellow arrow indicates a shift of volume of material from extrusion zone to retreating side to downwards
- Blue arrows indicate vertex zone which indicates the weld nugget

D. Microstructural zones

In the friction stir welding process there is any uncertainty in the combination of metal due to the usage of different welding tools which results in characteristics in the microstructure.

The various materials exhibit different microstructural compositions which are based on processing conditions and the material composition

Microstructural Zones are characterized into



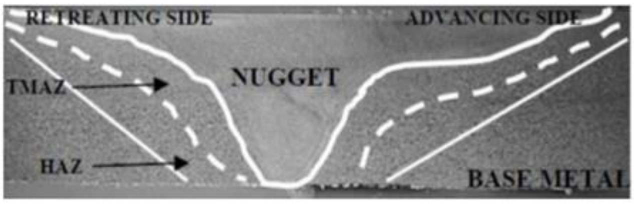


Figure 5: Types of zone

These 3 zones exhibit different mechanical properties where weld nugget and thermomechanical effect zone (TMAZ) are the weakest joints

Weld nugget : It is similar to a thermo-mechanical affected zone where the difference is in the weld nugget the recrystallization of material has happened

Thermo-mechanical affected zone (TMAZ):
- In this region, there was no recrystallization occurs, even though there is plastic deformation. We will observe elongated grains in this region is adjacent to the weld zone.
- It consists of stir zone where tool probe there is a direct interaction has been seen MICRO STRUCURAL ZONES weld nugget

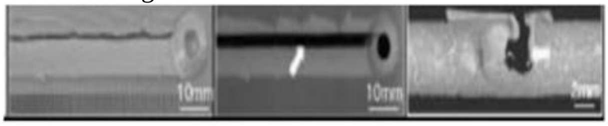
Thermo-mechanical affected zone heat affected zone
- In this region due to strain and temperature, the recrystallization of the material has been observed.
- fine equiaxed grains have been observed in this stir zine region

Heat affected zone (HAZ):
- Due to the heat of the welding very little change in microstructure has been observed
- There is no plastic deformation takes place in this zone
- A coarse-grained microstructure has been observed in this region

Defects Of Friction Stir Welding:

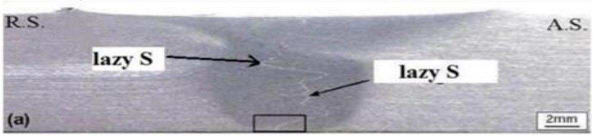
Due to insufficient input heat, we will observe 2 defects :
- Tunnel defect

- Groove light defect



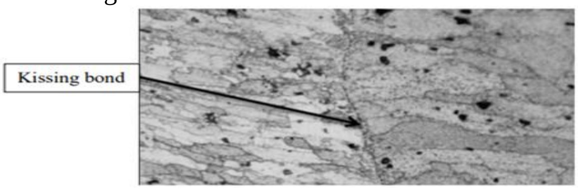
Due to fragmentation and distribution of aluminum alloys :

- Lazy S defect



Due to dissimilar welding and their heterogeneous microstructure

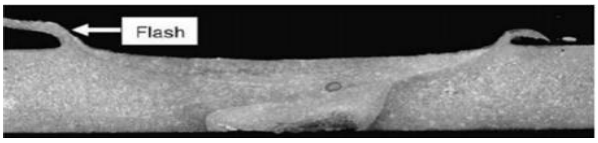
- Kissing bond defect



Due to non-uniform thickness, high rotational and welding speeds causes abnormal stirring which raises defects as shown below;

Due to excess input heat which reduces weld nugget zone area and the thickness causes defect as shown below;

- Flash



E. Workpiece materials

For our experiment, we have chosen aluminum alloy with grade 1100 and magnesium alloy with grade AZ31, because using a conventional welding process to join the materials, may cause the oxides to be formed at the base material, which may lead to discoloration. Therefore instead of choosing to weld with filler material, it is feasible to choose the friction welding process due to its several advantages.

Figure 6: AA1100

Figure7 : AA1100

F. Tool Material

In this joining of dissimilar material, the H-13 steel tool was used because of its ability to withstand high temperature, cyclic heating, and cooling operations. H-13 tool steel is hot work steel of chromium-molybdenum that was used mainly for hot and cold tooling applications. FSW experiences temperature during its welding process, up to 70-80 percent of the solidus temperature of the taken material.H-13 tool hardness can withstand and not be affected by this temperature generated. For increasing the hardness of the material heat treatment process can be applied Square pin profile is selected after extensive literature study because it produces weld joints with higher ultimate tensile strength, better microhardness, and exhibits good mechanical properties/

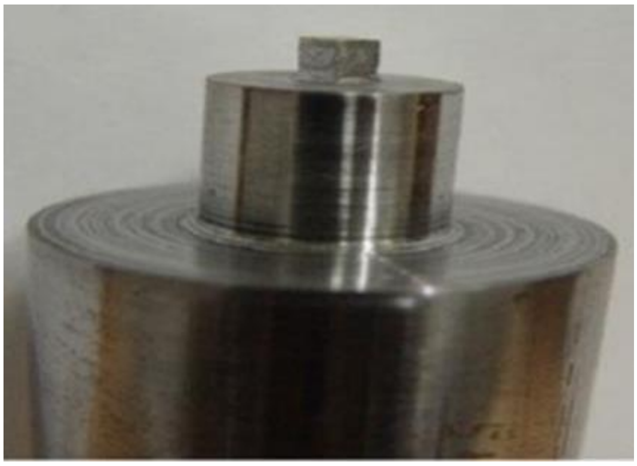


Figure 8: FSW tool

G. Machine used

• In this experiment, we have used CNC vertical axis milling machine

• In this machine, the tool was fixed to the spindle of the machine

• This spindle provides rotation to the tool and downward motion that is z-axis motion

• The workpiece was fixed to the machine table • Machine table provides better fixture and traverse motion that is y-axis motion

Figure 9: CNC vertical axis milling machine

H. Advantages of CNC vertical milling machine

- This machine is user friendly
- It requires a skilled operator
- During the FSW process due to rotation of the tool, the workpiece may lose its position due to improper fixture but this problem is avoided by the vertical CNC milling machine by its better design of black plate
- It also holds that tool in its position so that wear and tear of the tool were minimized and produces better weld quality and helps to maintain its tilt angle
- In CNC vertical milling machine the changing of tool change can be done with ease

I. Joint design

Friction stir welding the best configuration is lap and butt joint because no special preparation is required for these two joints even though other joint configuration can also be welded according to the various engineering applications in this experiment we have chosen butt joint where two plates with equal thickness 6mm have been clamped to black plate firmly. Initially this joint experiences forces from the rotational tool during the time of plug into the workpiece as well as when the shoulder touches the workpiece and the tool's transverse motion.

J. Experimental procedure

- The workpieces are fixed gently to the machine table for the better weld
- Alignment of tool where the weld is needed should be done
- The square pin profile was plunged between two workpiece material where the weld joint is required and this is done by rotational motion of the tool
- Make sure that the shoulder of the tool must touch the surface of the workpiece material and the length of the pin must be slightly less than the weld depth
- And then the tool is moved transversely along the weld line.
- Due to its transverse and rotation movement, it generates friction which causes material surrounding the tool will be mixed and inturn produces weld
- That is the friction is generated between the workpiece material and the tool shoulder which plasticized the material and made its flow circulating near the area of the tool surface and made materials to be weld

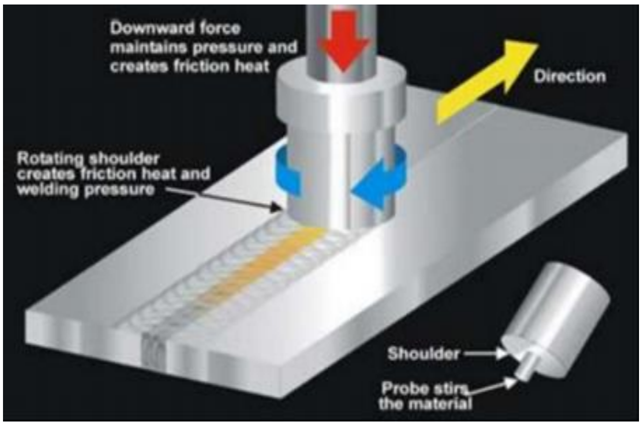


Figure 10: Behavior of tool during FSW process

K. Tensile test

The machine used to perform the tensile test was the Ultimate tensile machine (UTM). By using UTM we can find the values like Ultimate tensile strength, yield strength, strain, poisons ratio, youngs modulus, etc of a material. Initially, that is before experimenting, the values of mechanical properties such as tensile strength, yield strength, etc are known for AA1100 and Mg-AZ31. So to analyze the quality of the weld the results have to be compared. The properties of AA1100 and Mg-AZ31 are given below;

Material	AA1100
UTS (MPa)	142
Shear strength (MPa)	69
Tensile strength (MPa)	110
Yield strength (MPa)	105
Fatigue strength (MPa)	41
Elongation (%)	12
Hardness (HB500)	28
Density (*1000 kg/m^3)	2.71
Poisson’s ratio	0.33

Material	Mg-AZ31
Tensile strength (MPa)	259
Yield strength (MPa)	157
Elongation (%)	10
Density(g/cm^3)	1.78
Poisson’s ratio	0.35

We have observed that an increase in tool rotation (by keeping all the parameters constant)will also increase the ultimate tensile strength and also if high tool rotation speed led to more heat generation between tool and workpiece which intern softens the material near the tool. from this, we can state that higher tool rotation speed will lead to better mixing of material near the tool and also produces more ultimate tensile strength At lower rotation, we observed that there is a decrease in ultimate tensile strength, and at the higher rotation speed This phenomenon is because of tool

ISSN No:-2456-2165

advances the workpiece's material before it mixes the material at higher welding speed and lowers tool rotational speed which led to improper mixing near the material which causes the low strength.

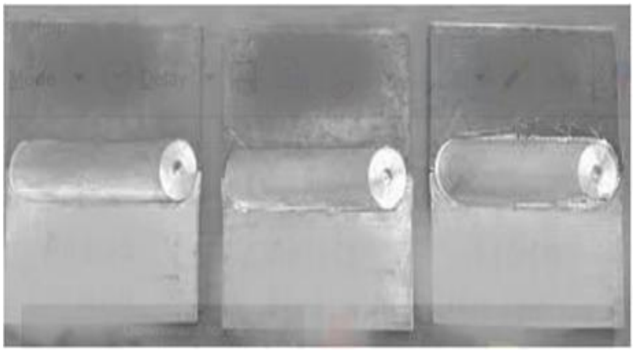
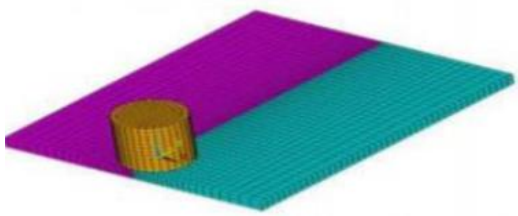


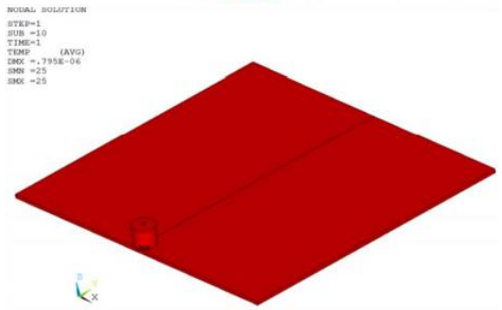
Figure 11: Welded workpiece

V. ANALYSIS USING ANSYS

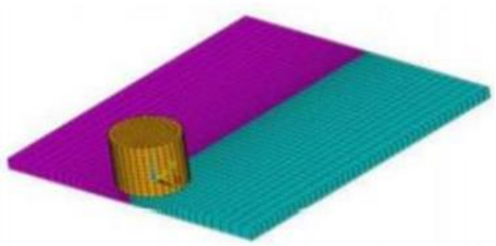
A. Modeling

The modeling has been done for workpiece material, tool material, and modeling for a contact of workpiece and tool i.e contact modeling. The size of workpiece material modeled in 300*100*6 mm. Hexahedral mesh is used to observe the quality of weld around the weld line



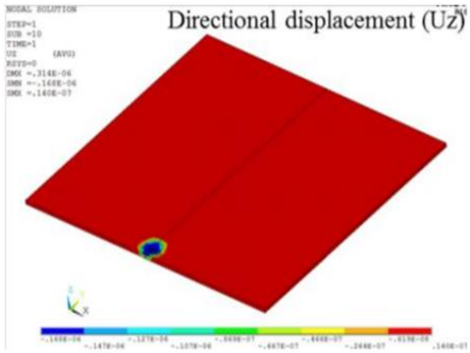


Contact modeling must be done in such a way that the tool shoulder must contact the surface the workpiece. We must also maintain the contact between tool and workpiece

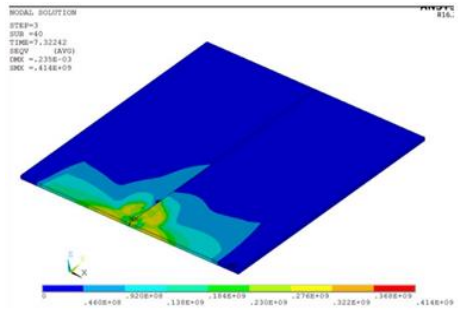


B. Results

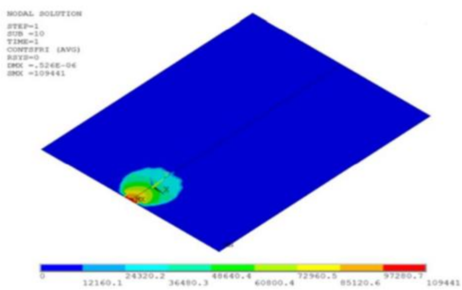
During the plunge of the tool, we will found deformation in the first load step;



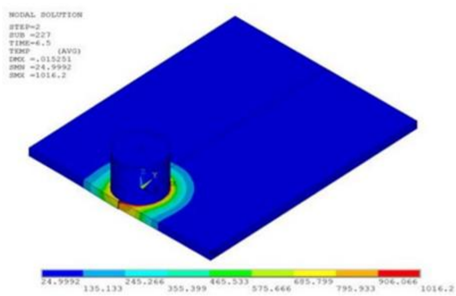
After plunging of the tool, there will be transverse motion along the weld line which causes stresses in the workpiece material



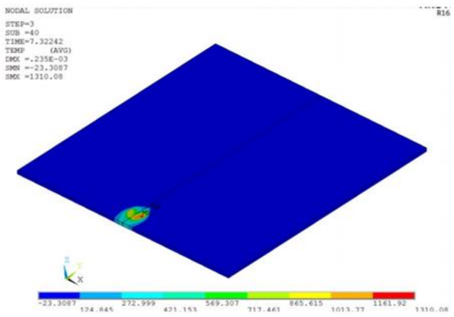
Initially, there was no change in temperature i.e in load step 1



After the tool starts rotating, we will observe the change in temperature from load step 1 to load step 2



As it produces friction and enables a mixture of material it dissipates more heat



VI. ADVANTAGES, DISADVANTAGES & APPLICATIONS

A. Advantages

1) Joining without melting-degreasing solely
2) No Consumables
3) The Rotating Tool is forced against the Workpiece
4) The Plasticized material forms a homogenous
5) Heat input because of friction between the 2 Work Materials
6) FSW doesn't manufacture arc flash, spatter, fumes, and Pollution Free
7) Produces High Mechanical Stress
8) FSW produce defect-free joint
9) It doesn't emit Harmful gases
10) No demand for special edge preparation in most applications
11) When we quote the mechanical properties FSW joints have higher lastingness, small hardness and refined small structure that cannot be achieved by typical fusion attachment and most time fusion attachment provides you the defect on the joint.

B. Disadvantages

1) Non-Forgeable material cannot weld
2) FSW process is less flexible compared to the arc welding process
3) High Initial/Setup cost
4) It cannot make filler Joints
5) Gaps between the parts tube joined needs to be controlled as no filler material is to be added in the process

C. Applications

1) Aerospace- It is used for Fabricating high-strength aluminum alloys, such as large volume fuel tanks(low distortion, High mechanical strength, and fewer Defects)
2) Marine- mostly used in cruise ships welding is used for Extrude aluminum panels which are used in freezing fish on-board fishing ships
3) Automotive- It is used mostly in (aluminum materials for wear resistance) tailor welded blanks (car doors); driveshafts, pistons, turbocharger, U-joints, bumper shocks, and trunk lid. Railway- mostly used in Roof panels, Double skin panels, body joints.
4) Transportation-Automobiles, Ships, Aerospace and Air crafts.
5) Heat Transfer- This joining technique is used for joining aluminum alloys, copper, magnesium, and other low-melting point metallic materials.
6) Nuclear- Used in High-Pressure Vessels.

VII. RESULTS

We considered tool pin profile, tool rotation speed tool shoulder diameter, tool plunge depth, tool tilt angle, welding traverse speed, axial force, etc. as the process parameters during experimentation

Rotational Speed(rpm)	Welding Speed (mm/min)	Axial Force(KN)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
400	15	6.21	71	112	4
400	20	6.21	69	132	6
500	15	6.21	85	120	5
500	20	6.21	92	139	8
600	20	6.21	95	126	8
600	30	6.21	98	149	9

TABLE VIII. EXPERIMENTAL RESULTS AND PROCESS PARAMETERS

A. Discussions

- The tool rotation speed affects the quality of weld with an increase in the tool rotation speed which leads o better mixing of the material
- With the increase in tool rotation speed, there is an increase in ultimate tensile strength
- Square pin profile produces better mechanical properties compared to the other tool pin properties
- A better fixture of the material to the base metal will provide a better quality of the weld
- As a move towards the upper surface of the weld ductility increases and will be high at upper surfaces if the weld and decreases when moved downwards lower surfaces of the weld As we increase the shoulder side of the tool the strength of the weld also increases at the certain point
- The better fixture of material provides better weld quality

B. Conclusions

- Best weld parameters can be obtained through the variations in temperature, stress-strain generated during the FSW process.
- Tool rotation speed is the main parameter that can affect the quality of the weld and can change the mechanical properties of the material
- This is the best welding process for dissimilar metals for improving the mechanical properties than other welding processes like tig etc
- Better mixing of the material gives better ultimate tensile strength
- Square pin profile is the best profile as per other works of literature and gives significant results for the workpiece materials
- Tool pin diameter also plays the key role as if we increase the diameter of the tool pin then the strength of the weld increases and the mechanical properties may vary
- The better fixture of material provides better weld quality
- This process produces fewer defects, which allows use for applications that require high strength.

- High tool rotational speed and low transverse speed causes tool wear

VIII. SCOPE FOR FURTHER RESEARCH

The present study is limited to the analysis of FSW using anysis and tensile tests but it also provides a wider scope for future research such as;

1) FSW of different joints
2) FSW of material in different thickness
3) Better design of fixture of workpiece material
4) Microstructural analysis, hardness test based on which parameters must be selected
5) For minimizing the tool wear selecting the best parameters
6) Using different tool pin profiles and analyzing the best one

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