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Experimental Investigations and Finite Element Simulation of Friction Stir Welding of Various Aluminium Alloys AA2024 and AA2519

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Abstract: In friction stir welding (FSW), a rotating spherical leg tool is forced to plunge into the plates to be welded and moved along their contact line. The tool penetrates into the work pieces. During this operation, frictional heat that's generated by contact friction between the tool and work piece. The plasticized material is stirred by the tool and forced to "flow'' to the side and the reverse of the tool advantage as the temperature cools down, a solid nonstop joint between the two plates is than formed. In this project work, DEFORM -3D is used to perform the finite element analysis and experimental investigation on the FSW in order to predict residual stresses, temperatures, normal stresses and distortion of the welded structures, that are induced during FSW of the given airframe structures made up of AA 2024 and AA 2519. The weld quality characteristics like hardness, and tensile strength properties of the joints are analyzed.
Keywords: Finite Element Simulation, DEFORM-3D, Friction Stir Welding, AA2024 and AA2519.

I. INTRODUCTION

Friction Stir Welding is a solid state joining technique, invented at "The Welding Institute", United Kingdom, in 1991. The Friction Stir Welding is an effective tool used for Joining Difficult-to-weld metals such as aluminium alloys, magnesium alloys, titanium alloys etc, joining plates with different materials and joining plates with different thickness. In the Friction Stir Welding process, a nonconsumable rotating tool is inserted into the abutting edges of the work-piece. The tool is then transverse along the line of joint. The tool is specially designed with a pin and shoulder. The tool serves two primary functions: firstly heating of work piece, secondly, movement of material to produce the joint.

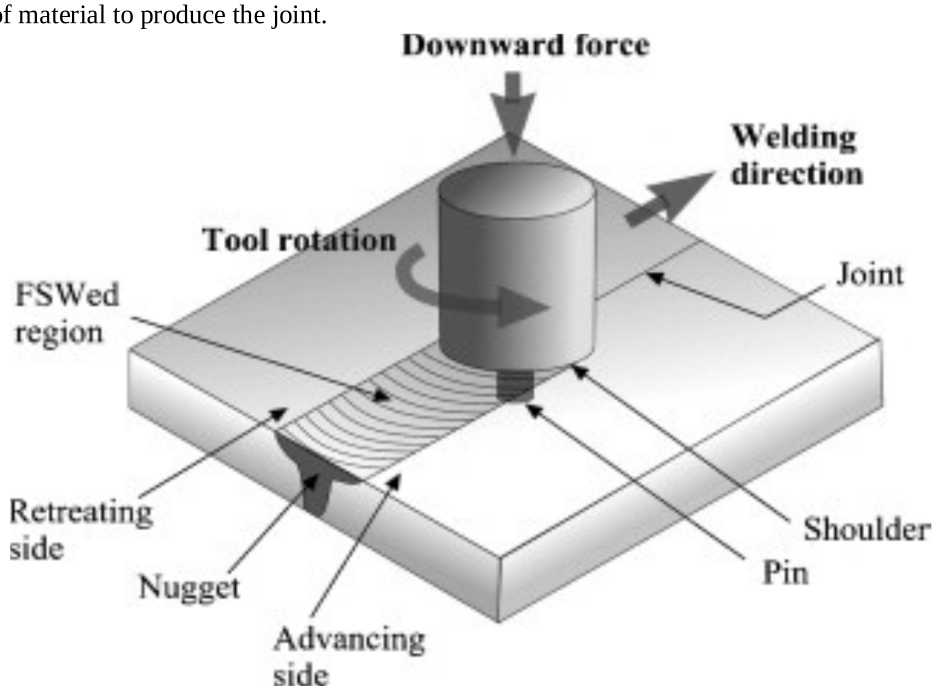


Fig.1.1 Schematic drawing of FSW process

A. *Friction Stir Welding Parameters*

1) *Tool Design:* Tool design is a very important factor in improving the quality of the work piece. To achieve a good finish in job the tool material should be sufficiently strong, tough and hard-wearing at thewelding temperature. The tool should conduct less heat to decrease heat losses and minimizes the damage to the machine's parts caused by the heat produced. The tool should behighly resistive to oxidation so that there are no traces of rust.
2) *Tool Speeds:* As we know the friction stir welding process is a slower welding process, this is because the cylindrical tool turns on the joint to generate heat, and then moving along the length of the joint transmitting that heat. The probe tool with the cylindrical part rotates within the range of 200 to 2000 rotations per minute (rpm). The traverse rate of the tool along the joint line is between 10 to 500 millimeter per minute (mm/min).
3) *Tool Tilt:* Tool tilt is also an important aspect to get a good quality of weld. It welds the joint in a slightly lean position or tilt position which is about 2 to 4 degrees. The forces applied downwards can affect the joint, so to prevent this condition a tilt is given.
4) *Plunge Depth:* The plunge depth is the total depth till which the shoulder of the tool gets inserted into the metal sheet while the pin penetrates further than the shoulder. It is very important factor to determine the quality of job as the plunge depth needs to be correctly set because it ensures the necessary downward pressure is achieved and also ensure that the tool fully penetrates the weld because if the tool is not inserted to correct depth machine may deflect from its position and on giving excessive plunge depth the job may have pin rubbing marks on it.

II. LITERATURE REVIEW

The flow of metal during FSW is investigated using a faying surface tracer and a pin frozen in place during welding. It is shown that the material is transported by two processes [1].

The first is a wiping of material from the advancing front side of the pin onto a zone of material that rotates and advances with the pin. The material undergoes a helical motion within the rotational zone that both rotates, advances, and descends in the wash of the threads on the pin and rises on the outer part of the rotational zone.

After one or more rotations, this material is sloughed off in its wake of the pin, primarily on the advancing side. The second process is an entrainment of material from the front retreating side of the pin that fills in between the sloughed off pieces from the advancing side.

The accurate 3D finite element simulation of the Friction Stir Welding (FSW) process requires a proper knowledge of both material and interface behaviors but friction the key phenomenon of this process, is quite difficult to model and identify. The recent development of more accurate 3D simulation software, which allows modeling the entire complexity of the FSW process, makes it possible to follow a much more rigorous inverse analysis (or calibration) approach. The numerical simulations are based on an Arbitrary Lagrangian Eulerian (ALE) formulation that has been implemented in the Forge-3 F.E. software [2].

The aircraft aluminium alloys generally present low weldability by traditional fusion welding process. The development of the friction stir welding has provided an alternative improved way of satisfactorily producing aluminium joints in a faster and reliable manner.

The influence of process and tool parameters on tensile strength properties of AA7075-T6 joints produced by friction stir welding was analyzed [6].Strength properties of the joints were evaluated and correlated with the micro structure, micro hardness of weld nugget.

III. MATERIAL DESCRIPTION

A. *Input Parameters*

The objective of this thesis is to predict the Temperature distributions, stresses on an Aluminium Alloys – AA2024 and AA 2519 work piece during the friction stir welding process using a specified threaded tool by numerical simulation.

The different welding parameters used in this project are

- Rotational speed of 760,1130 & 1340 rpm at welding speed 11 & 25 mm/min for AA 2024
- Rotational speed of 760,1130 & 1340 rpm at welding speed 11 & 25 mm/min for AA 2519

Element %	AA2519	AA2024
Iron, Fe	0.3	0.5
Copper Cu	6.4	3.8-4.9
Manganese, Mn	0.4	0.30-0.9
Zinc, Zc	0.1	0.25
Chromium, Cr	0.1	0.1
Titanium, Ti	0.15	0.15
Silicon Si	0.25	0.5
Nickel Ni	0.1	0-0.1
Magnesium Mg	0.10	1.2-1.8

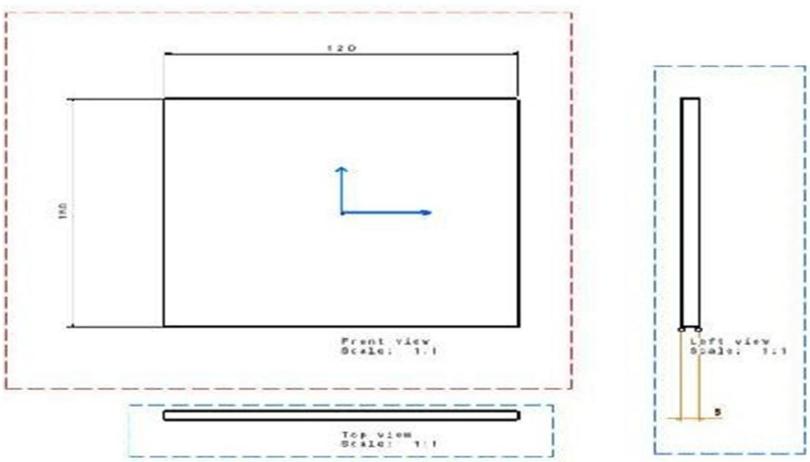
Property of Alloys	AA2519	AA2024
Density (g/cc)	2.84	2.78
Brinell Hardness (BHN)	125	150
Tensile strength (MPa)	310	365
Ultimate Strength (MPa)	360	410
Poisson's Ratio	0.33	0.33
Modulus of Elasticity(GPa)	73.1	73.1
Thermal Conductivity(W/mK)	170	121
Melting Point (^{0}C)	500	520

IV. WORK PIECE GEOMETRY

In this thesis, 6mm thick aluminium 2519 alloy and aluminium 2024 alloy plates are butt welded using Friction Stir welding using the Finite element simulation software DEFORM-3D.

Length of each plate = 150 mm
Width of each plate = 120 mm
Thickness of each plate = 6 mm

For the numerical analysis, as single block approach is used for Friction Stir Welding, the modelling of work piece is done as a single work piece whose configuration is shown in the fig. below



A. FSW Tool

The selection of tool material and tool geometry plays a vital role in the Friction Stir Welding. In this thesis, for Friction Stir Welding of aluminium 2024, 2519 plates, H-13 Steel is used as the tool material. H-13 Steel is chromium, molybdenum, vanadium hot work tool steel which is characterized by high hardenability and excellent toughness. The molybdenum and vanadium act as strengthening agents. The chromium content assists H-13 to resist softening when used at high temperatures. H-13 offers an excellent combination of shock and abrasion resistance, and possesses good red hardness. It is capable of withstanding rapid cooling and resists premature heat checking. H-13 have good machinability, good weldability, good ductility, and can be formed by conventional means.

B. Properties of H-13 Steel

The most commonly used material, easy availability and machinability, thermal fatigue resistance, wear resistance, especially for aluminium and copper.

Element	%
Iron, Fe	90.6
Manganese, Mn	0.40
Carbon, C	0.39
Chromium, Cr	5.20
Silicon Si	1.00
Molybdenum, Mo	1.40

Table 4.6 Composition of H-13 Steel

Property	Value
Density (g/cc)	7.78
Brinell Hardness (BHN)	180
Ultimate Tensile strength (MPa)	1420 – 1810
Yield Tensile strength (MPa)	1280 – 1520
Modulus of Elasticity (GPa)	210
Thermal Conductivity (W/((mm K))	0.0243
Specific Heat (J / kg K)	460

Table 4.5 Properties of H-13 Steel

V. SOLUTION METHODOLOGY

The continuous model proposed assumes the sheets to be welded as a single block. This FE model takes into account the actual interaction between the tool and the work piece allow to get a description of the process closer to reality. In particular asymmetric distributions of temperature, strain and strain rate are calculated by such models. CATIA - V5 is one of the modeling software which is used in this thesis to model the tool and work piece.

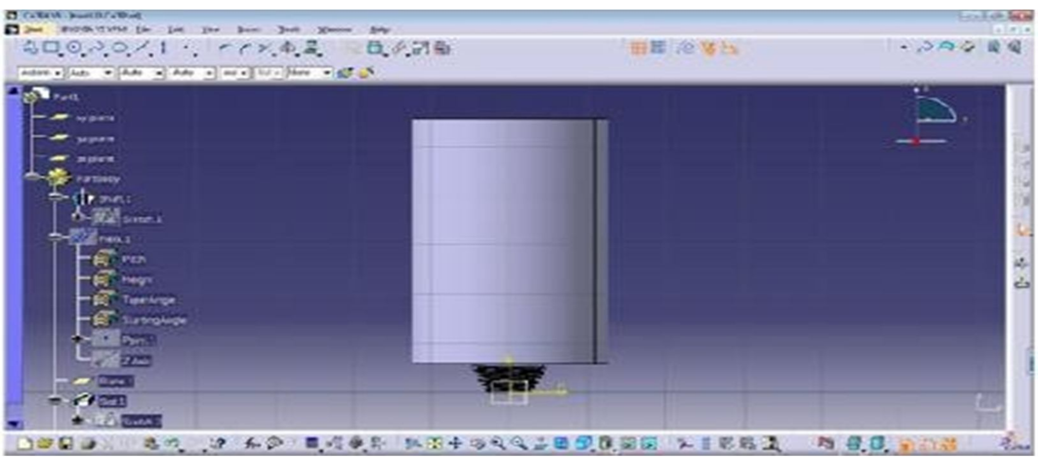


FIG: 5.1 TOOL DESIGN IN CATIA - V5

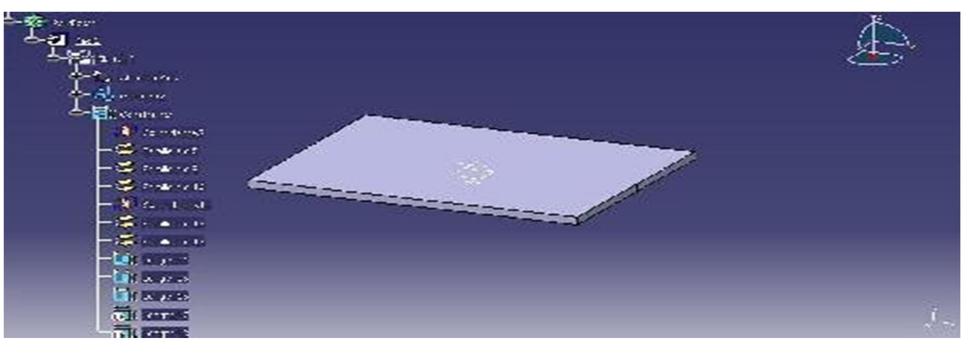


Fig 5.2 Work piece design in CATIA - V5

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A. Introduction To Deform - 3D

DEFORM-3D is a commercial FEA software which uses Lagrangian implicit code designed for metal forming processes, was used to model the FSW process. The use of an implicit code versus an explicit one is a sort of inescapable choice being the latter better suited in order to correctly predict temperature evolutions and stress states.

DEFORM is a finite element method (FEM) based process simulation system designed to analyze various forming and heat treatment processes used by metal forming and related industries. By simulating manufacturing processes on a computer, this advanced tool allows designers and engineers to:

1) Reduce the need for costly shop floor trials and redesign of tooling and processes
2) Improve tool and die design to reduce production and material cost
3) Shorten lead time in bringing a new product to market

B. Simulation OF FSW Using Deform - 3D

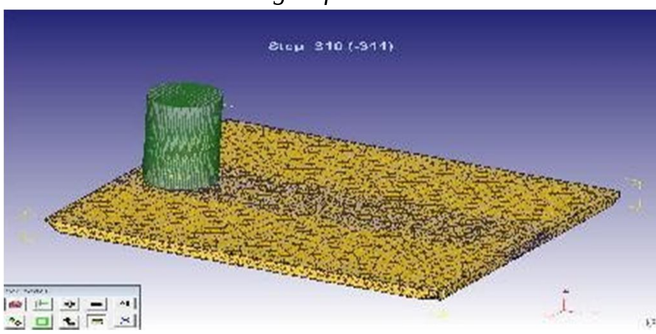

Fig 6.1 Meshed model in DEFORM-3D

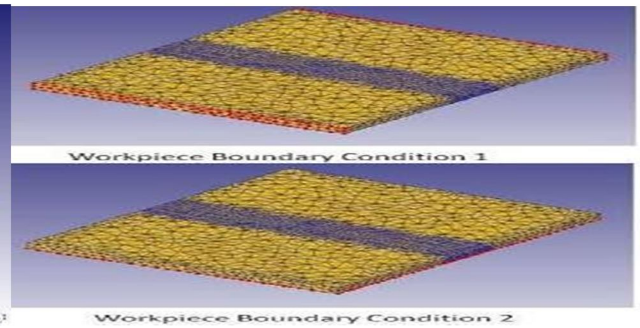

Fig 6.2 Work piece boundary conditions

Assign Plunging Movement to the tool:
Rotational speed= 1130 rpm
Speed = 2 mm / minSimulation Steps Information

Starting Step Number	-1(default for newproblem)
Number of simulation steps	415
Step increment to save	10
Primary die	FSW Tool
Time increment	1 sec

C. Analysis of AA2024 and AA2519

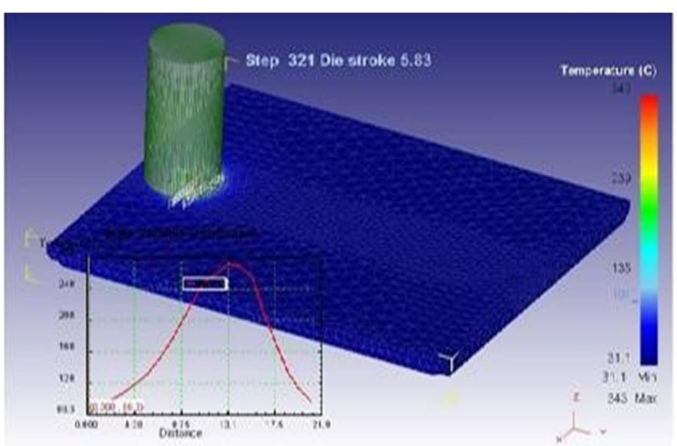

Fig 6.3 Temperature distribution during plunging

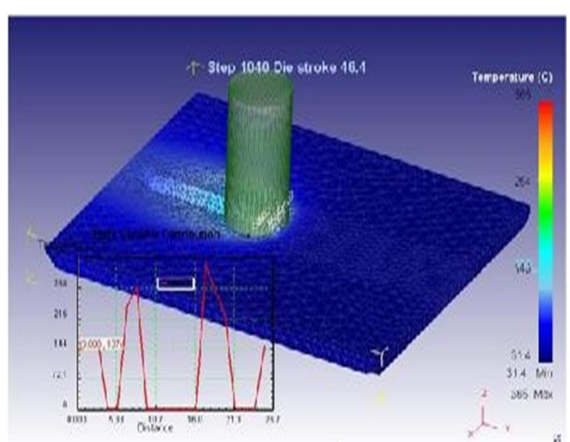

Fig 6.4: Temperature distribution during weldingstep 1040

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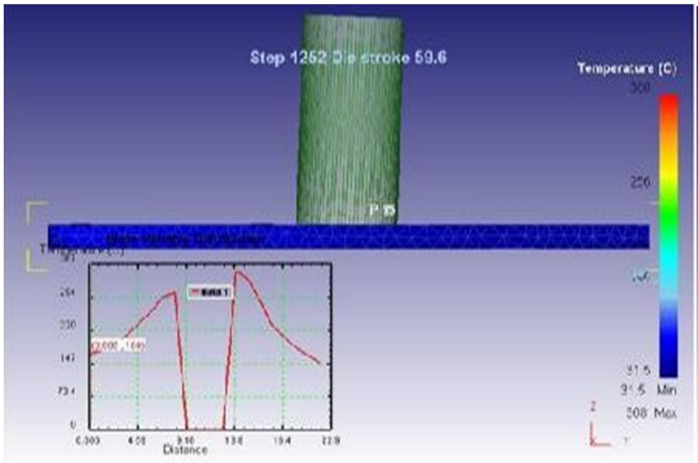

Fig 6.5: X- Direction temperature distribution

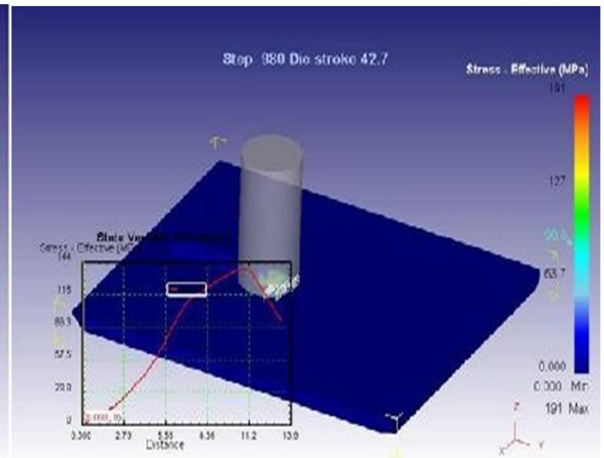

Fig 6.6 Effective stress distribution during weldingphase 1340 rpm

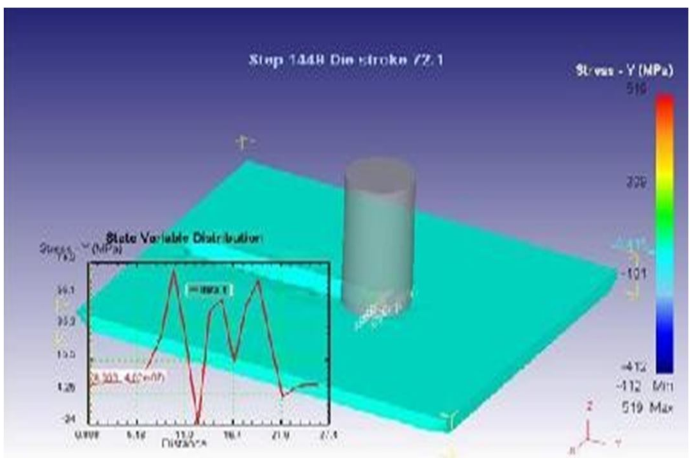

Fig 6.7 Longitudinal stress distribution duringwelding at 1340 rpm

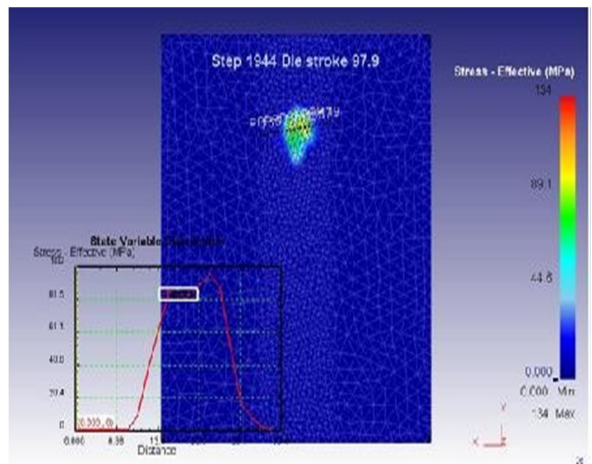

Fig 6.8 Strain distribution during welding step1944

VI. TENSILE TESTING

Tensile bars were made for all eight weld samples. Of these four tensile bars were tested on computerized universal testing machine. All samples were checked by software DELTA-UTM System during testing to ensure that no abnormal failures or sample slippage occurred. A set of properties including Ultimate Tensile Stress (UTS) and elongation at fracture were recorded by the control computer for each test. These values were then used to produce stress-strain curves for the material. Some values recorded by the computer involved slippage and measurement errors in the initial stages of tensile testing.

Sl.No	Thickness of theplate(mm)	Tool rotational speed(rpm)	Tool transverse speed(mm/min)	Quality of weld
1	6	760	11	Poor
2	6	760	25	Poor
3	6	1130	11	Good
4	6	1130	25	Good
5	6	1340	11	Good
6	6	1340	25	Poor

Table 6.1 Welding process parameters for AA 2024

Sl.no	Thickness of the plate(mm)	Tool rotational speed(rpm)	Tool transverse speed(mm/min)	Quality of weld
1	6	760	11	Poor
2	6	760	25	Poor
3	6	1130	11	Good
4	6	1130	25	Good
5	6	1340	11	Good
6	6	1340	25	Poor

Table 6.2 Welding process parameters for AA 2519

In this experiment tensile strength, elongation, percentage elongation and strain from tensile test are determined by using universal testing machine.

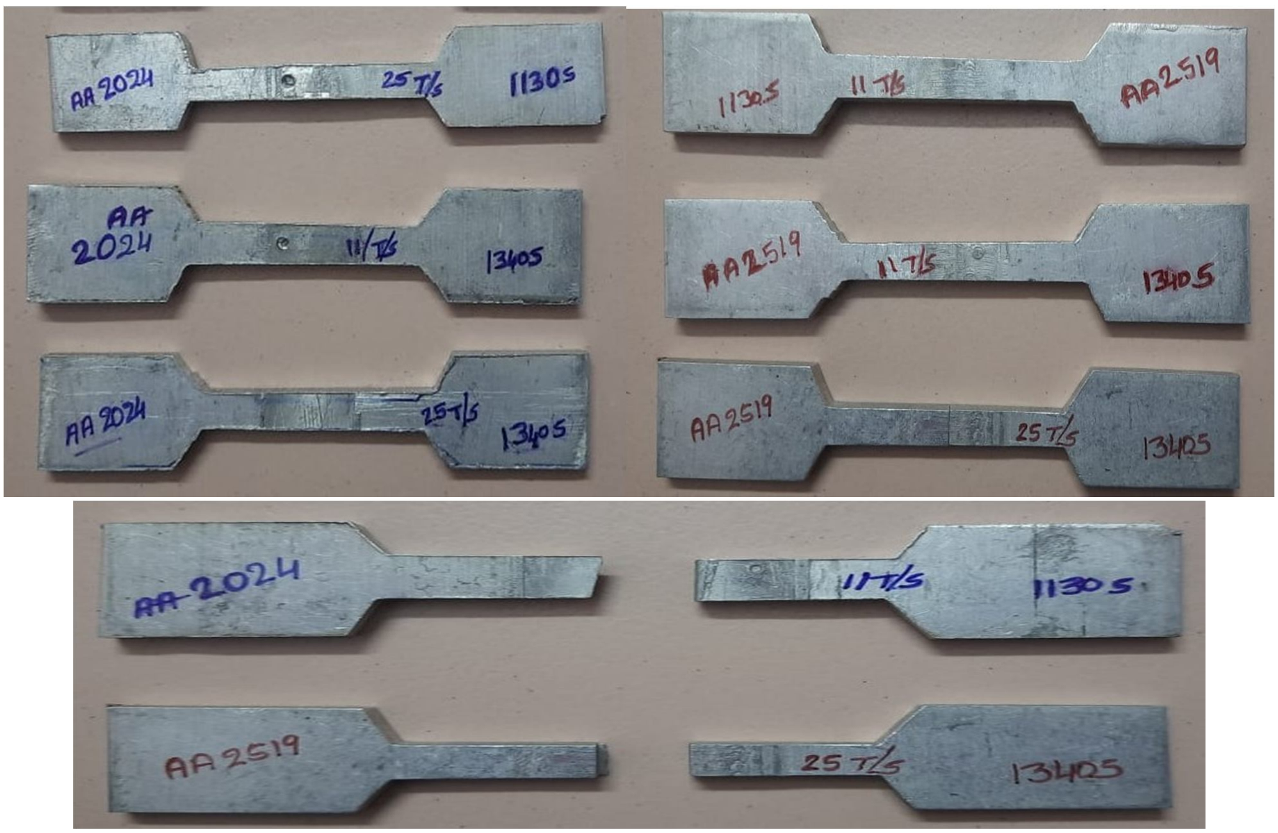

Fig 6.1.Tensile test specimens

The values recorded in this experiment are shown in table are as follows:

S.No	Material	Speed(rpm)	Feed mm/sec	Load (N)	Cross-sectional area mm*mm	Stress = P/A N/mm^2
1	AA2519	1340	11	9230	36	225.8
2	AA2519	1130	11	7610	36	198.7
3	AA2024	1340	11	14500	36	394.4
4	AA2024	1130	11	13600	36	363.8

Table 6.3 The values recorded in the experiment

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S.No	Material	Speed(rpm)	Feed mm/sec	Load (N)	Cross-sectional area mm*mm	Stress = P/A N/mm^2
1	AA2519	1340	25	9230	36	218.6
2	AA2519	1130	25	7610	36	198.7
3	AA2024	1340	25	14500	36	390.4
4	AA2024	1130	25	13600	36	363.8

Table 6.4. The values recorded in the experiment

A. Brinell Hardness Test

The Brinell method applies a predetermined test load (F) to a carbide ball of fixed diameter (D) which is held for a predetermined time period and then removed. The resulting impression is measured across at least two diameters usually at right angles to each other and these result averaged (d). A chart is then used to convert the averaged diameter measurement to a Brinell hardness number. Most typically, a Brinell test will use 3000 kgf load with a 10mm ball. If the sample material is aluminum, the test is most frequently performed with a 500 kgf load and 10mm ball. Brinell test loads can range from 3000 kgf down to 1 kgf. Ball indenter diameters can range from 10mm to 1mm. The test standard specifies a time of 10 to 15 seconds, although shorter times can be used if it is known that the shorter time does not affect the results.

Fig 6.2. Hardness test specimens

S.NO	Material	Speed(rpm)	Weld speed(mm/min)	Load(Kgf)	Impression diameter mm	BHN
1	AA2519	1130	11	2000	5	94
2	AA2519	1340	11	2000	4.7	104
3	AA2024	1130	11	3000	5	139
4	AA2024	1340	11	3000	4.6	128

S.NO	Material	Speed(rpm)	Weld speed(mm/min)	Load(Kgf)	Impression diameter mm	BHN
1	AA2519	1130	25	2000	5	93
2	AA2519	1340	25	2000	4.5	102
3	AA2024	1130	25	3000	5	132
4	AA2024	1340	25	3000	4.8	121

Table 6.5.values for brinell hardness test

VII. CONCLUSION

The process simulation is done for friction stir welding for various welding parameters namely tool rotational and transverse speeds. The temperatures in the work piece are increasing with the increase in tool rotational speed whereas the temperatures are decreasing with increase in tool traverse or welding speed. The maximum temperatures are recorded at the locations close to the stirred zone and the temperatures go on decreasing with increase in distance from the stirred zone

The longitudinal residual stress increased with increasing tool traverse speed, whereas transverse residual stresses did not exhibit evident dependence on the traverse speed.

It is noteworthy that residual stress in FSW is low due to lower heat input and Recrystallisation accommodation of stress. Several test samples were welded with various combinations of tool rpm and welding speed for both the tool geometries. However, it was observed that low tool rpm resulted in consistently poor quality of welding. Whereas, best results were obtained with tool rpm of 1340 in conjunction with 11mm/min low weld speed.

This happened because of high tool rpm with low weld speed caused severe mechanical stirring of the metal causing reduction in grain size leading to higher strength of the welded joints.

VIII. FUTURE SCOPE

Future research will continue to advance the science of FSW, depending the understanding of the complex physical interactions which underlie a process that emerged first as a technology like.

Expanding the applicability of FSW to a wider range of engineering materials, advancing control techniques for continuous welding and spot welding, and developing novel FSW variants. Further investigations on the forces generated during single and multiple passes for different alloys at different conditions and for different process parameters might be very beneficial.

Further studies may be done, considering most of the welding parameters, on a wider range of values. Fatigue analysis, shear tests can be conducted.

Higher thickness aluminium plates can be welded by employing double sided FSW. One can try to use tools made of different materials to improve the quality of the joints.

As the present weld is of butt joint, there is a scope of extending this work to the lap joints and comparison can be done between these two joints.

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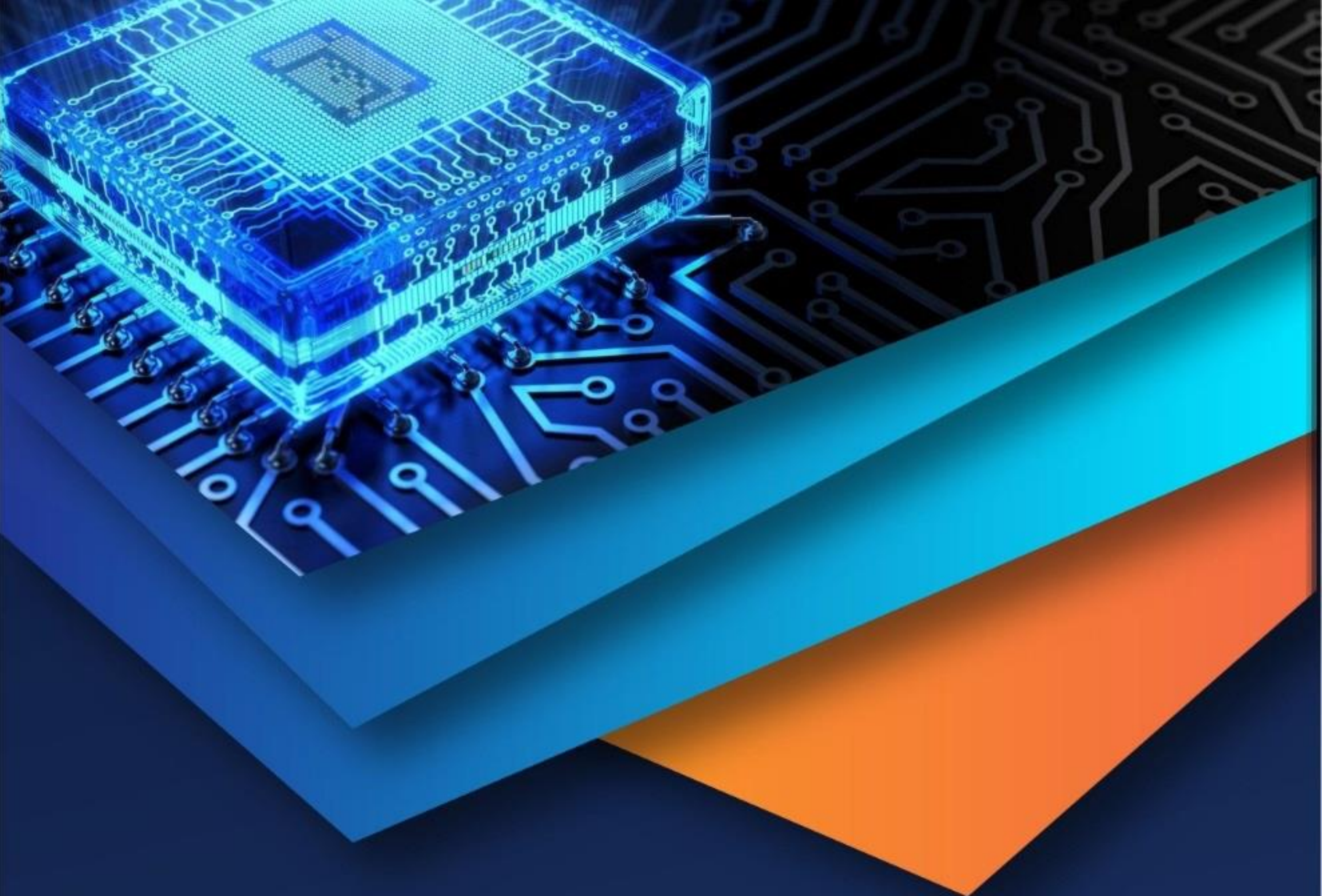

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