Optimization of Process Parameters for Friction Stir Lap Welding of AA6061-T6 and AA7075-T6 Aluminum Alloys Using Taguchi Technique

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Abstract—*In the present study, the effect of process parameters such as tool rotation speed, welding speed and plunge depth in Friction Stir Welding (FSW) of AA6061 and AA7075 lap joint alloys are investigated. Experiments are conducted with different levels of process parameters using Taguchi orthogonal array. Properties of welded joints are analysed by conducting suitable tests such as ultimate tensile strength, hardness and microstructural analyses. Optimum levels of process parameters are determined based on shear strength values. Confirmation runs are conducted to validate optimum values. Microstructural investigations revealed three distinct zones namely Stir zone (SZ), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) in welded specimen. Further, the microstructural analysis revealed fine grained distribution in SZ and TMAZ while coarse grained structure in HAZ. Hardness studies conducted supports microstructural analysis i.e low hardness values are seen in HAZ of the welds. ANOVA tests revealed the effects of process parameters on the shear strength of welds. It is concluded that shear strength increases with increase in tool rotation speed and welding speed..*

Keywords—FSW, AA6061, AA7075, lap joint, orthogonal array, HAZ, TMAZ, SZ

I. INTRODUCTION

In recent years, Friction stir welding (FSW) is a widely used technique for welding especially Aluminium alloys. FSW technique can be applied for welding of similar or dissimilar aluminium alloys and with other metals such as stainless steel, copper etc., Aluminium alloy series like 7xxx and 2xxx which were considered non-weldable by any other welding technique can be easily welded using FSW. Hence FSW is a solid state welding process in which the materials to be welded are not melted, instead it is welded by traversing a specially designed rotating non-consumable tool over the weld line. Specially designed tool for FSW consists of tool pin of specific profile and tool shoulder with a specific diameter. Rotation of tool pin causes the stirring action of the material during welding process. Once the tool shoulder touches the material surface, it generates frictional heat between the shoulder and the material upper surface. After sufficient dwell time, the tool is traversed along the weld line so that a continuous joint is created due to the combined stirring action of the pin and frictional heat.

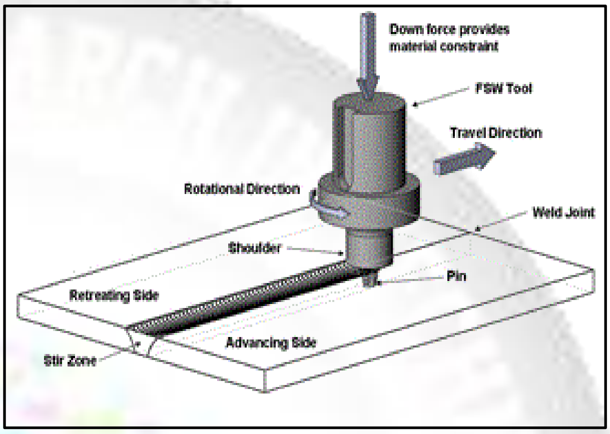

Fig.1: Friction Stir Welding schematic

The main advantage of FSW is the reduced number of defects when compared to other welding processes. However, improper levels of FSW process parameters can lead to defective welds. Defects such as voids, surface galling, tunneling, insufficient penetration occur due to improper level of process parameters in FSW [1]. FSW process parameters such as tool rotation speed, tool traverse speed, plunge depth, tool tilt angle, axial force, tool shoulder diameter influence the properties of welding. Ana et al. [2] revealed that tool rotation speed, tool traverse speed and plunge depth are the parameters of greater significance in lap joining of aluminium alloys. However, the analysis of parameter interactions with their levels in the FSW technique is to be carefully studied for the efficient joint mechanical strength.

Several studies have been conducted on FSW of aluminium alloys. Different tests have been conducted to analyse the influence of tool rotation and traverse speed over the microstructure and tensile properties of aluminium alloys 2024 and 6061 by Sadeesh et al [3]. Author investigated the effect of welding speed on microstructures, hardness distribution and tensile properties of welded joints and the analysis revealed that hardness in HAZ of 6061 was minimum where all the welded joints failed at this region during the shear tests. Various optimisation techniques were followed for the process parameter optimisation by Koilraj.M et al, YahyaBozkurt et al, Benyounis K.Y et al and Edwin Raja Das J et al [4-7]. YahyaBozkurt et al in his investigation revealed that the positioning of the plates played an important role on the strength of the welded joints. Optimisation of process parameters for FSW of 6062 and 8011 aluminium alloys were done using Taguchi approach by Elanchezhian C et al [8]. Feasible working ranges for various aluminium alloy series are determined by Rajkumar.S and Balasubramanian. V [9]. They determined the optimum welding condition to attain maximum strength for each alloy series by using Response Surface Methodology. Effect of material positions (6061 and 7075 alloys) on tensile strength are evaluated and It was revealed that the material mixing is much more effective when AA6061 alloy was located on the advancing side [10]. Author also inferred that micro hardness value on HAZ is very low and all the tensile specimens were found to be fractured at this region during tensile testing. Avinash P et al investigated the feasibility of friction stir welding of AA7075 T6 and AA2024 T3 [11], fatigue crack growth behaviour of friction stir welded AA7075-T651 aluminium alloy joints are investigated and it was found that the fatigue life of AA7075-T651 is very low as compared to the parent metal before welding [12].

Among these works of literature, it was found that researchers are more focused on FSW of dissimilar aluminium alloys, especially in butt joints. And the research works on FSW of lap joints are very scarce. However, certain authors have conducted experiments regarding the lap joints of aluminium alloys, still there is a lack of studies concerning the proper determination of parameters and their levels for the joints. Authors have analysed the influence of tool rotational speed on mechanical properties of friction stir lap welded 6061-T6 Al alloys and concluded that hardness distribution in the upper and lower plates at the lowest rotational speed are much closer[13], R.M Leal et al. [14] investigated the effect of overlapping FSW on mechanical properties and microstructure of 5083-O and 6063-T6 alloys by giving four welding passes over the material. Author analysed that the subsequent overlapping passes produces a modest increase in hardness and strength in both alloys as well the elimination of tunnel defects in welds. FSW lap joining of aluminium and magnesium alloys are conducted Y.C Chen and found no welding defects at lower welding speed and higher tensile strength was attained at the same [15]. Buffa G. et al found that the use of cylindrical–conical pin tools and the correct choice of the relative sheet positioning increase the welded nugget extension and mechanical performances of FSW lap joints of AA2198-T4 alloys [16], Babu.S et al investigated the microstructure and mechanical properties of FSW AA2014 lap joints [17]. L. Dubourg et al. [18] investigated process optimization and mechanical properties of friction stir lap welds of 7075-T6 stringers on 2024-T3 skin.

FSW lap joints can replace riveted joints in aircraft structures, as they offer light weighting and cost savings and was verified in Papadopoulos et.al[19]. As systematic study on the analysis of FSW of AA6061 and AA7075 lap joints has not been reported in the literature, the present study investigates the FSW lap joining of AA6061 and AA7075 using varying process parameters and levels by employing Taguchi Orthogonal Array (OA). AA6061 and AA7075 are two aluminium alloys belongs to the series 6xxx and 7xxx which are having wide applications in the fields of aerospace, automobile and rail transportation industries.

II. EXPERIMENTAL PROCEDURE

Rolled sheets of AA6061 and AA7075 alloys with 3 mm thickness is used as base material for the present study. The sheets are obtained in T6 temper condition. Chemical compositions of the selected alloys are presented in Table 1.

Alloy	Cr	Cu	Fe	Mg	Mn	Si	Zn	Ti	Al
AA6061	0.04-0.35	0.15-.04	Max 0.7	0.8-1.2	Max 0.15	0.4-0.8	Max 0.25	Max 0.15	Bal
AA7075	0.18-0.28	1.2-2.0	Max 0.5	2.1-2.9	Max 0.3	Max 0.4	5.1-6.1	Max 0.2	Bal

Table 1. Chemical Composition of AA6061 and AA7075 Alloys (Weight %)

As the weld nugget is predominantly occupied by the retreating side of the welding, the experiments must be conducted by keeping high strength alloy AA7075 on the retreating side, and AA6061 on the advancing side [20]. Highest tensile strength during FSW of AA6061 and AA7075 was obtained when 6061 material was placed at the advancing side[10]. High-speed steel (HSS) material with hexagonal profiled pin machined on both sides is used as a tool in the FSW process. The tool has a pin diameter of 5.5mm, pin length 4.5mm and shoulder diameter of 20mm as shown in Figure 2. The ultimate tensile strength and tensile elongation with respect to rotation speed and welding speed is higher for hexagonal profiled tool [20]. It is inferred that, due to continuous friction and heat generation in the FSW, the tool material will undergo wear and tear which can cause improper stirring action of the tool and thereby causing deterioration in the strength and other mechanical properties of the welded specimen. For this reason, a double sided tool pin configuration is used to overcome the disadvantage mentioned above. Parameters and their levels are obtained by conducting number of trial runs which is presented in Table 2.

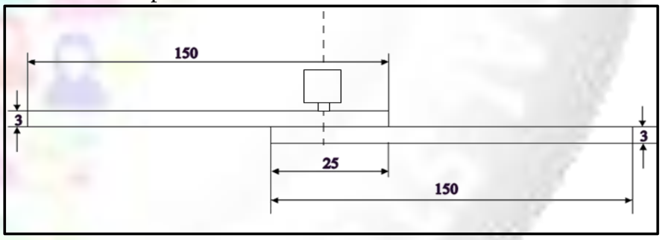

Fig.2: Joint configuration used for experimental run

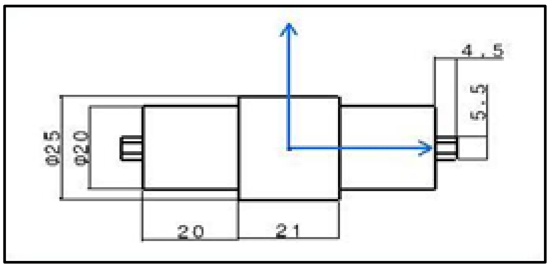

Fig.3: Design of tool (HSS) used for the research work

Level	Parameters		
	A Tool Rotation Speed (rpm)	B Welding Speed (mm/sec)	C Plunge Depth (mm)
1	700	2	0.05
2	900	3	0.10
3	1000	4	0.15

Table 2: Process Parameters and Their Levels

A number of trials are conducted to determine the weldability and working range of parameters for the welding process while Ana. C. F et al [2] reported that the most influential process parameters for FSW of lap joints are rotation speed, traverse speed and plunge depth. Hence these process parameters and their levels are chosen for conducting experiments. ShanmugaSundaram et.al [20] and Rajkumar S et al. [21] revealed that the increase in tool rotational speed or welding speed leads to the increase in the tensile strength and it reaches a maximum value and then decreases. Several tools such as Response Surface Methodology (RSM), Taguchi Analysis, Analysis of variance (ANOVA), Finite Element Analysis (FEA) can be used for studies on FSW [22]. Application of design of experiment (DOE) can save the cost and time by reducing the total number of experiments. Taguchi is a DOE technique used for optimisation of parameters and the method is based on orthogonal arrays (OA's).

Table 2 shows the factors and their levels for conducting experiments. L9 Taguchi Orthogonal Array (TOA) is chosen to select combination of factors and their levels as shown in Table 3.

Square plates of dimensions 150mm x 150mm are cut and are welded in lap joint configuration using FSW technique. The joints are welded normal to the rolling direction. Experimental trials are conducted with AA7075 sheet overlapped above AA6061 and the tool is rotated in clockwise direction. AA6061 alloy is kept in advancing side and AA7075 on retreating side of the weld. The weld joint configuration for the experiments is shown in Figure 2. The side where the tool rotation and welding direction are same is referred as the advancing side of the weld whereas the side where tool rotation and welding motion are opposite is referred as retreating side of the weld [20]. Required samples are cut from the welded specimens for carrying out various analysis before and after welding. Microstructural analysis of parent metal and welded specimens are analysed using an optical microscope. Tests are conducted to determine the shear strength and hardness values of the welded specimen.

III. Results and Discussions

A. *Signal to noise ratio (SN ratio)*

Signal to noise ratio (SN) in a Taguchi design is used to identify the control factors that reduce variability in a product or process by minimizing the effects of uncontrollable factors (noise factors). Control factors are those design and process parameters that can be controlled. Noise factors cannot be controlled during production or product use, but can be controlled during experimentation. In the present investigation SN ratio is calculated based on the quality characteristics intended. The main objective function of the investigation is to maximize the lap shear strength. Thus larger the better SN ratio is preferred for the present study.

Experiment	A Tool Rotation (rpm)	B Welding Speed (mm/sec)	C Plunge Depth (mm)	Mean Shear Strength (MPa)	SN ratio
1	1	1	1	115	41.2140
2	1	2	2	119	41.5109
3	1	3	3	123	41.7981
4	2	1	2	117	41.3637
5	2	2	3	116	41.2892
6	2	3	1	128	42.1442
7	3	1	3	129	42.2118
8	3	2	1	133	42.4770
9	3	3	2	134	42.5421

Table 3: Orthogonal Array for Experiments

B. Larger the better

The formula used to calculate the SN ratio is shown below.

$$\text{S/N ratio} = -10log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}$$

The larger SN ratio is selected as it corresponds to the best quality characteristic [23,24]. From the table 4 and 5 the optimum level combination was found out to be $\boldsymbol{A_3B_3C_1}$.

Level	A	B	C
1	119.0	122.0	**125.3**
2	120.3	122.7	121.7
3	**132.0**	**126.7**	124.3
Delta	13.0	4.7	3.7
Rank	1	2	3

Table 4: Response Table for Means

The optimum parameter combination based on the mean is $\boldsymbol{A_3B_3C_1}$.

Level	A	B	C
1	41.51	41.71	**41.95**
2	41.60	41.76	41.70
3	**42.41**	**42.05**	41.88
Delta	0.90	0.34	0.25
Rank	1	2	3

Table 5: Response Table for Signal to Noise Ratios.

The optimum parameter combination based on SN ratio is $A_3B_3C_1$.

Tensile strength predicted

$= A_3 + B_3 + C_1 - 2T$

$= 132.0+126.7+125.3 - 2(124)$

$=$ **136 MPa.**

Where A_3 is the average mean value of tool rotation speed at third level, B_3 is the average mean value of welding speed at third level, C_1 is the average mean value of plunge depth at first level and T is overall mean.

C. Analysis of Variance (ANOVA)

Analysis of variance, or ANOVA is a powerful statistical technique that involves partitioning the observed variance into different components to conduct various significance tests. ANOVA helps indetermining the significant factors and how far the responses are affected by the process parameters. Table 6 shows the anova results for means. F test was also carried out to analyse the significance of process parameters. Higher value of F indicates that the factor is highly significant in affecting the response variable. The tool rotation speed plays a vital role in welding and it contributes 69.5 % to the overall contribution. The main effects plot and interaction plots for both means and signal to noise ratios are shown in figure 4 -7 respectively.

Source	Dof	Adj SS	Adj MS	F Value	%Contribution
A	2	306.89	153.44	14.24	69.50
B	2	101.56	50.78	4.71	23.0
C	2	11.56	5.78	0.54	2.62
Residual error	2	21.56	10.78		4.88
Total	8	441.57			100

Table 6: Analysis of Variance for Means

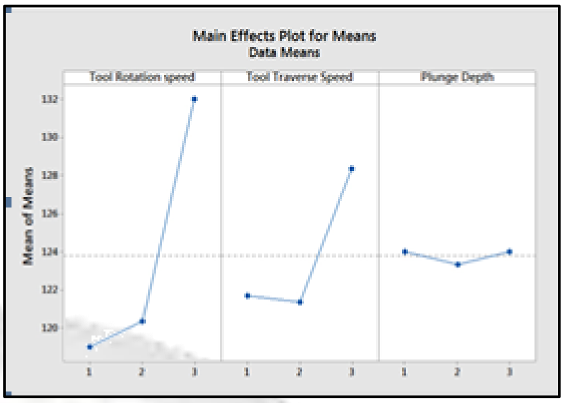

Fig.4: Main Effects Plot for Means

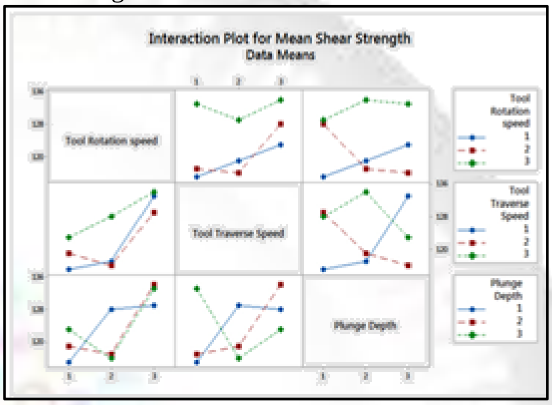

Fig.5: Interaction Plot for Means

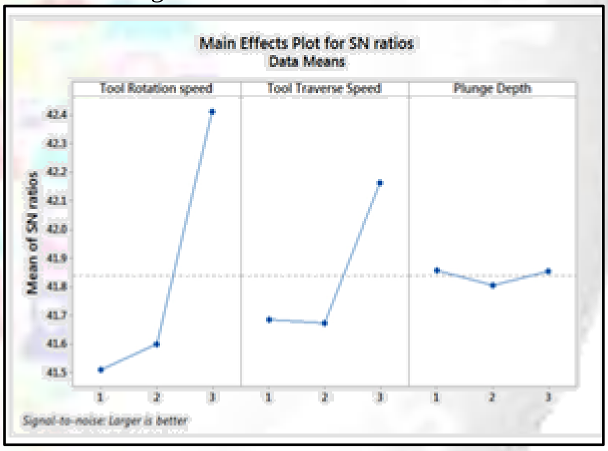

Fig.6: Main Effects Plot for SN Ratios

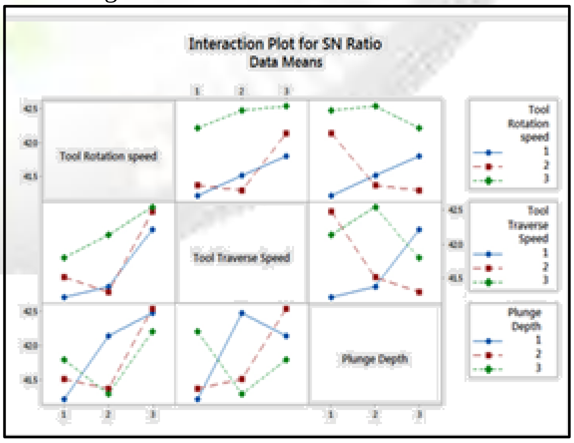

Fig.7: Interaction Plot for SN Ratios

D. Confirmatory tests

Optimum level of process parameters obtained from Table 4 and Table 5 (is used for conducting confirmatory tests to validate the experiment.ie., Tool rotation speed 1000 rpm, Welding Speed 4mm/sec and Plunge depth 0.05mm. In order to obtain reliable results, three shear test samples were cut from welded specimens and are subjected to tensile shear test. The average shear value obtained was 127 Mpa which is 94% in accordance with the predicted results.

IV. MECHANICAL PROPERTIES

A. Lap shear test

The results of lap shear tensile tests for the experimental runs are tabulated in Table 3. The dimensions of the lap shear test specimen are shown in Figure 8.

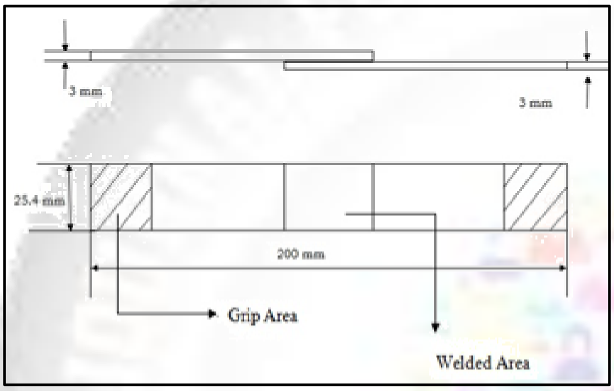

Fig.8: Dimension of Shear Test Specimen

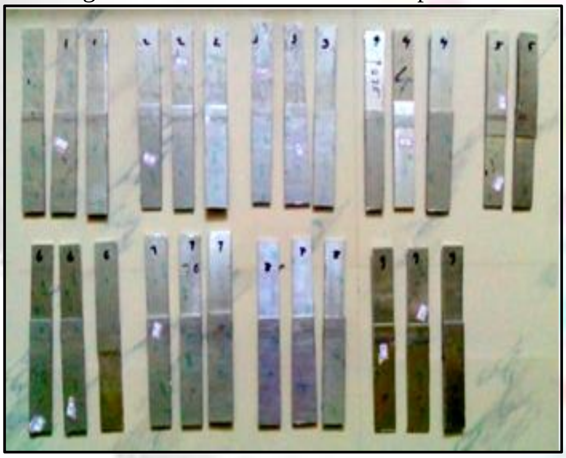

Fig.9: Shear Test Specimens

Three test specimens were cut from each welded materials to validate the results. From the shear tests, it is found that all the specimens failed at Heat Affected Zone (HAZ) of AA6061 side which is the weaker metal. Dissimilar FSW of aluminium alloys were fractured at the HAZ sections of weaker material side [4, 10,]. It can be understood from Table 3, that the shear strength of FSW lap joints increase with increase in tool rotation speed and welding speed. The highest shear strength value is obtained at a rotation speed of 1000 rpm and welding speed of 4mm/sec. Results of shear tests is plotted in the graph as shown in Figure 10.

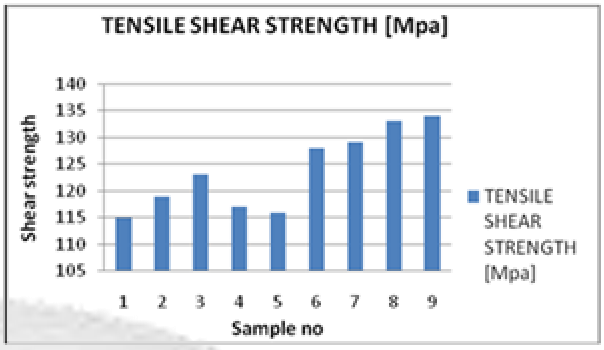

Fig.10: Tensile Shear Strength Variation

B. Microstructural Analysis

Microstructure analysis of the welded specimen is carried out using an optical microscope to understand the granular changes after welding. A test sample is cut and then polished and then etched using a standard Keller's reagent for analysis. Figure 11 shows a microstructural image of the lap welded specimen at 100μm magnification level.

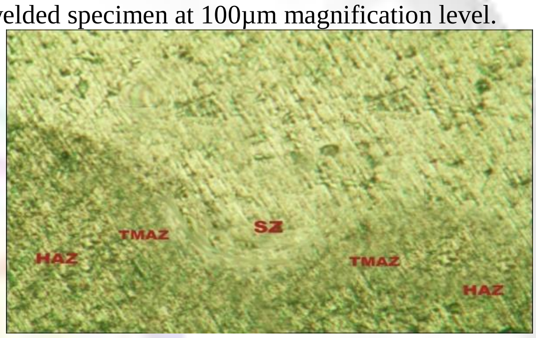

Fig.11: Microstructural Analysis

Three distinct regions such as Stir Zone (SZ) or Weld Nugget, Thermo-Mechanically Affected Zone (TMAZ) and Heat Affected Zone (HAZ) are clearly seen during the microstructural analysis. Nugget region can be defined as the region in which the original grains and sub grains appears to be replaced with fine grains. Weld nugget in the microstructure reveal that the materials is fully welded together so that the top material AA7075 is completely fused with the bottom material AA6061. Further, grains in the nugget regions are found to be finer and hence it improves mechanical properties in the weldment. Onion rings can be seen at the bottom of this region. The next zone, TMAZ is the region in which the material gets plastically deformed due to frictional heat generated by the tool. In this region, the grains are found to be in unrecrystallised state. Finally in the HAZ, it can be seen that the crystal structure is almost same as the parent metal. It can be understood that HAZ has undergone little change during thermal cycles as compared to other zones which can modify the properties of the welds to a significant level.

C. Hardness Test

Vicker's Microhardness tests are conducted across the welds to evaluate the variation of properties and microstructures of the weldment. The hardness values are tested at a spacing of 1 mm each. The results are plotted graphically in Figure 12.

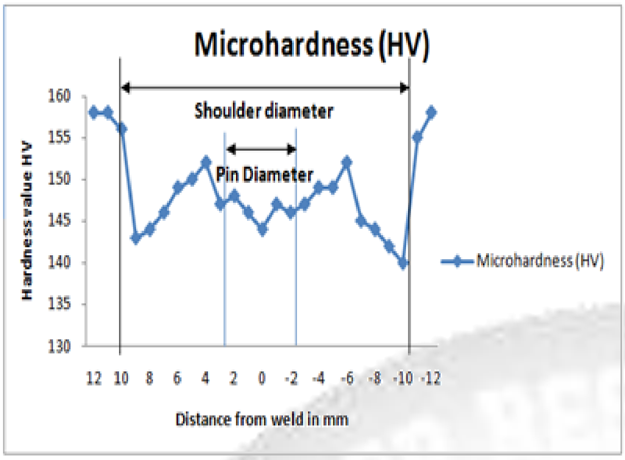

Fig.12: Micro hardness Profile Across the Weld

Hardness values of AA6061 and AA7075 show a lower value at the weld than the parent metal. It reveals that the hardness value at the centre of weld nugget is comparatively lesser within the nugget region. Hardness values are found to be in an increasing trend towards the TMAZ region and decrease on reaching the TMAZ boundary. It can be said that the increase in the value of hardness is due to the refined grain structures. Beyond TMAZ region, the hardness values starts to increase and becomes parent metal hardness value. It can be understood that this is due to lesser effect of thermal cycles at the HAZ region. Therefore minimum value of hardness is found in the HAZ regions close to TMAZ. This seems to be a reason for fracture at HAZ during shear tests.

V. Conclusion

AA6061 and AA7075 alloys are successfully lap joined by FSW technique by varying process parameters and their levels. Process parameters are optimised to maximize the shear strength of welded joints. The following conclusions are made from the present work.

1) Tool rotation speed of 1000rpm, welding speed of 4mm/sec and plunge depth of 0.05 are found to be optimum level of combinations for FSW of AA6061 and AA7075 alloys.
2) Microstructural analysis reveals that the weld nugget consists of onion rings and the grain structure becomes fine during FSW.
3) Lap shear strength of the joint shows an increasing trend with increase in tool rotation and welding speed. The maximum Shear Strength value of the joint is found to be 134 MPa with a tool rotation sped 1000rpm, welding speed 4mm/sec and plunge depth 0.10mm respectively.
4) The tool rotation speed plays a vital role in welding and it contributes 69.5 % to the overall contribution.

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