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Statistical Analysis of Friction-Stir Welding of Al-6063 Alloys

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Abstract

Aluminum 6063 alloys are widely used in various engineering and industrial applications since they are highly corrosion resistant and exhibit superior mechanical properties. They are often used in extrusion projects because of their, weldability, moderate strength and good workability. These properties allow them to excel in architectural applications, piping, tubing, general extrusions for medical, automotive, parts profiling, building and construction, recreational equipment and furniture. Investigations revealed that joining of these alloys by conventional welding techniques has several limitations. Friction Stir Welding (FSW) is a highly efficient manufacturing process with improved safety due to absence of toxic fumes or molten spatters and also end products with reduced weld defects, better retention of mechanical properties, less distortion and less residual stress.

The present work focuses mainly on the characterization of friction stir welded joints of Al 6063 alloys using reconfigured Vertical Milling Machine. Brinell Hardness, Impact strength & Fractography study of the weldments were carried out to analyze the hardness, impact strength and microstructure of the weld zone and heat affected zone. To justify the impact of contribution of input parameters over the process outcome, Minitab -17 statistical modeling analysis was carried out.

Keywords: *Aluminum 6063 alloy, FSW, Hardness, Fractography, Minitab-17 analysis*

1.0 Background

Friction Stir Welding (FSW) is a solid-state joining process, in which two similar or dissimilar work pieces are welded using a wear resistant tool. Various process parameters such as tool rotational speed, feed rate, tool shoulder diameter, pin angle etc. are found to have primary effect on the quality of the weld obtained as well as on the mechanical properties of the weld joint [1]. It has been observed that a sufficient amount of heat is required at the joint during the process to facilitate proper joining of alloys. Insufficient heat may result in powder formation and weld with defects may be obtained which can be assessed visually (e.g. cracks along the weld line). Increasing the dwell time and/or the tool rotational speed can contribute to higher heat generation at the junction. However, increment of tool rotational speed above a certain value may cause the mechanical properties of the joint to deteriorate due to excessive softening of the metal at the weld zone. Feed rate of the worktable also has a considerable effect on the quality and properties of the weld [2-4].

2.0 Literature Review

Researchers carried out dissimilar metal FSW of Al 6063 and AZ91 Mg alloy sheets at 1100 rpm tool

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rotational speed and 25/mm/min tool travel speed. The weldment showed a profound effect of material flow mechanism at the nugget zone for the combination of tool travel speed and rotational speed. The weld interface lacked perfect metallurgical bonding, as revealed during microhardness measurements across the weld joint [5]. Researchers working on friction stir welded Al6063 alloys investigated the effect of weld parameters over yield strength, percentage of elongation and ultimate tensile strength and developed a mathematical model using five level central composite rotatable design approach. Analysis of variance (ANOVA was used to check the precision of the developed mathematical model. Response surface methodology (RSM) was employed for 95% confidence level [6]. Effect of tool on the material flow pattern during FSW and observed two distinct patters namely: “shoulder driven flow” and “pin-driven flow”. These regimes gave rise defect free onion ring pattern in friction stir welds [7]. Yunus et al. investigated the submerged status of AA6063 alloy during FSW to optimize process parameters using Taguchi technique. ANOVA was carried out to assess the percentage contribution of input parameters over process outcome [8]. Mandeep et al. critically reviewed the effect of process parameters on FSW of similar and dissimilar aluminum alloys [9]. The bottom-up approach to optimize major independent parameters of FSW process was developed and tensile properties were co-related with the justification from microstructural studies. The investigation highlighted the significance of bottom up approach over analytical optimization, which was affected by complex thermo-mechanical interactions and precipitation hardening. Fracture location, during the bulk tensile testing, was the HAZ of the advancing/retreating sides of specimen where coarsening of precipitate had occurred [10]. Two level factorial techniques were found to be an effective tool to determine the influence of process parameters on tensile strength and impact toughness of friction stir weldments. Tensile strength decreased with increase in tool rotational speed and increased with increase in welding speed. Impact toughness decreased with increase in rotational speed, welding speed and also pin diameter [11].

In the present work investigation has been carried out to assess the hardness and impact strength of FSWed Al 6063 alloys, followed by fractographic studies to justify the results. A Minitab - 17 analysis was carried out determine the significance of input variables over the process outcome.

3.0 Experimentation

Initially, a 6mm diameter holes were drilled at the four corners of the processing plate and the backing plate using the vertical drilling machine. The aluminum process plate and the backing plates were clamped onto the T-slot of the vertical milling machine using nuts and bolts. Friction stir welding was carried out for three different tool rotation speeds of 250rpm, 500rpm and 1000rpm with feed rates of 0.25 mm/s, 0.5mm/s and 1mm/s at tool diameter 15mm, 20mm and 25mm. As per Taguchi’s full factorial method, 27 experiments were carried out and results were tabulated. Brinell Hardness tests [12] and Charpy Impact tests [13] were conducted as per BIS norms and results were tabulated. Fractography tests were conducted on weld specimen using Scanning Electron Microscope to assess the sub surface damage.

4.0 Results and Discussion

4.1 Friction - Stir Welded Joints

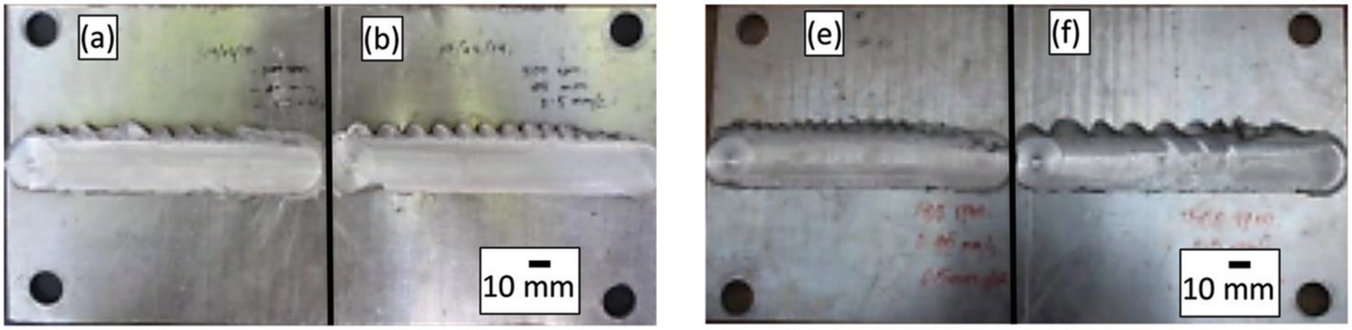
Fig.1 shows the FSW joints of Al 6063 alloys for varied input parameters. Visual inspection of the joints clearly indicates sound welds with increased values of input parameters (rpm) because of better fusion of material.

4.2 Impact Strength

The main effects plot (Fig.2) indicates steeper slope for RPM whose individual impact on the outcome impact strength is around 30.7 % as per ANOVA. Similarly, the next parameter is tool shoulder width having considerable slope and process spread whose effect on the impact strength would be 26.9%. Compared to these two parameters, it was found that feed rate is having very low influence on the impact strength of weldments and the same is reflected in the graph through the plot with very little slope. Its effect on the outcome is also found very low i.e 7.04% as per ANOVA

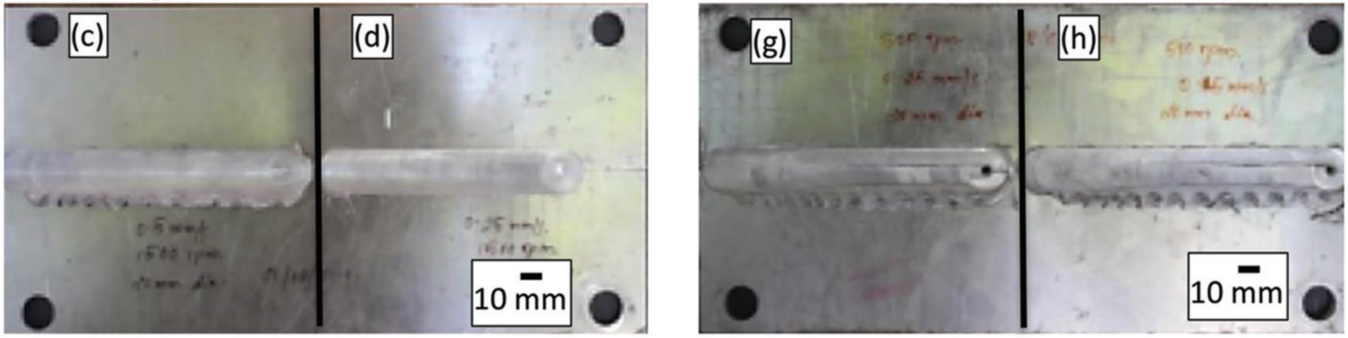
But, through the interaction plot (Fig.3) and also ANOVA calculations for two-way interactions, it was found that the combined effect of RPM and feed rate is very high compared with the combined effect of RPM & tool shoulder width and feed rate and tool shoulder width

Maximum cross-over or intersection of lines were seen in the two-way interaction of RPM and feed rate



Weld Specimen for a combination of, (a) 1000 rpm, dia. 20mm tool shoulder, 0.5mm/s feed rate (b) 500 rpm, dia.25 mm, 0.5mm/s

Weld Specimen for a combination of, (e) 500 rpm, dia.25mm tool shoulder, 0.25mm/s feed rate (f) 0.5mm/s



Weld Specimen for a combination of, (c) 1500 rpm, dia 20mm tool shoulder, 0.5mm/s (d) 0.25mm/s

Weld Specimen for a combination of, (g) 500rpm, dia.20mm tool shoulder, 0.25mm/s feed rate and (h) 0.5mm/s

Figure 1: Weld specimens for various process parameters

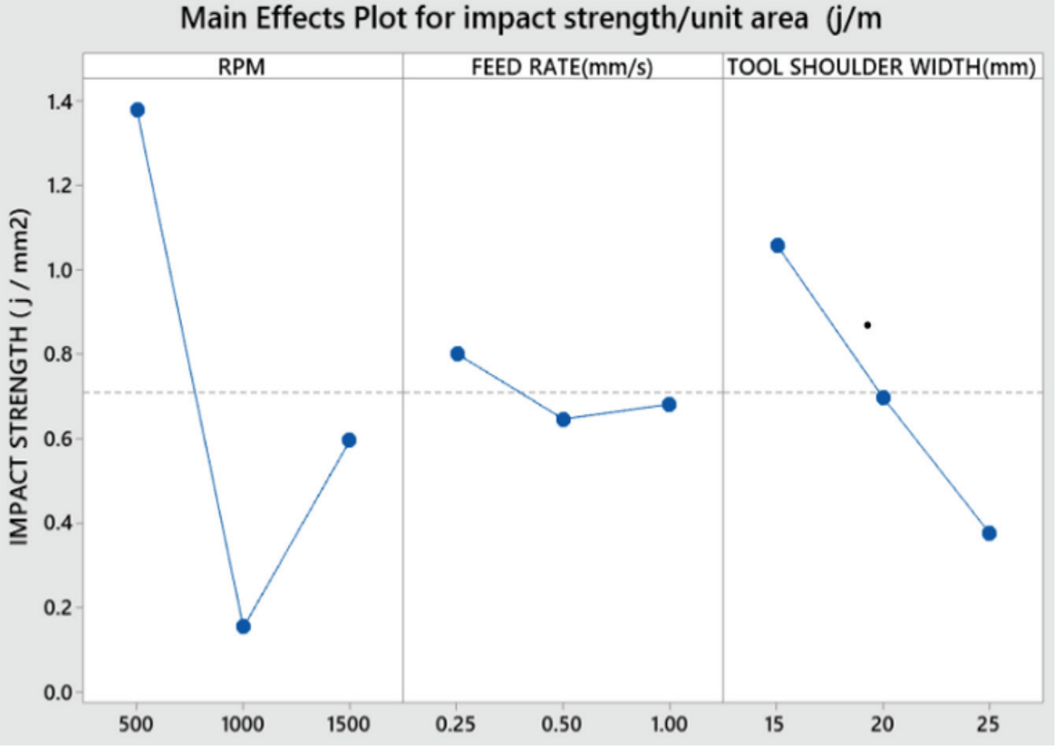


Figure 2: Main effects plots for Impact strength of friction – stir welded joints of Al 6063 alloys

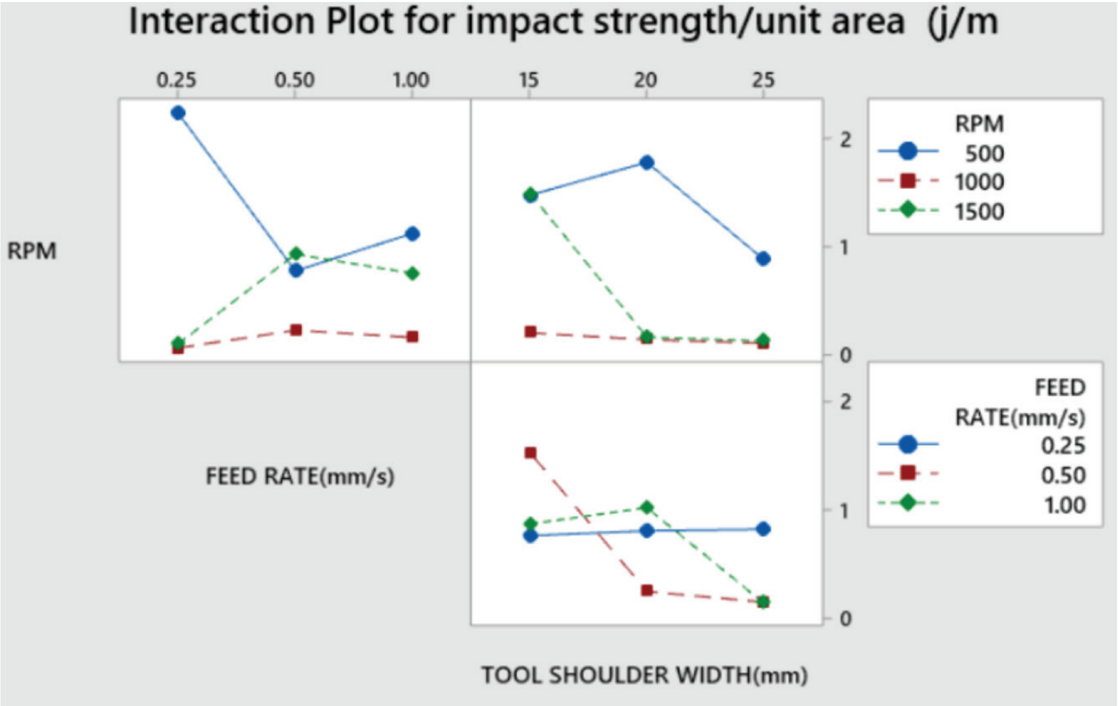


Figure 3: Interaction plots for Impact strength of friction – stir welded joints of Al 6063 alloys

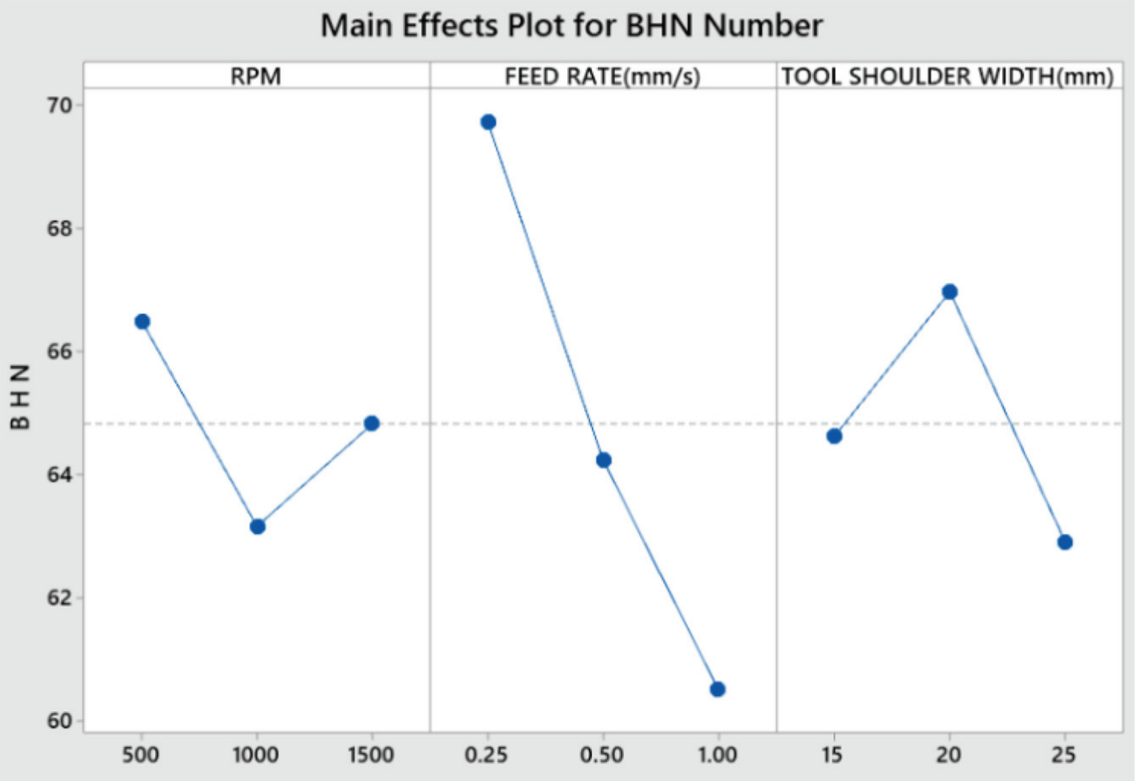


Figure 4: Main effects plots for BHN of friction – stir welded joints of Al 6063 alloys

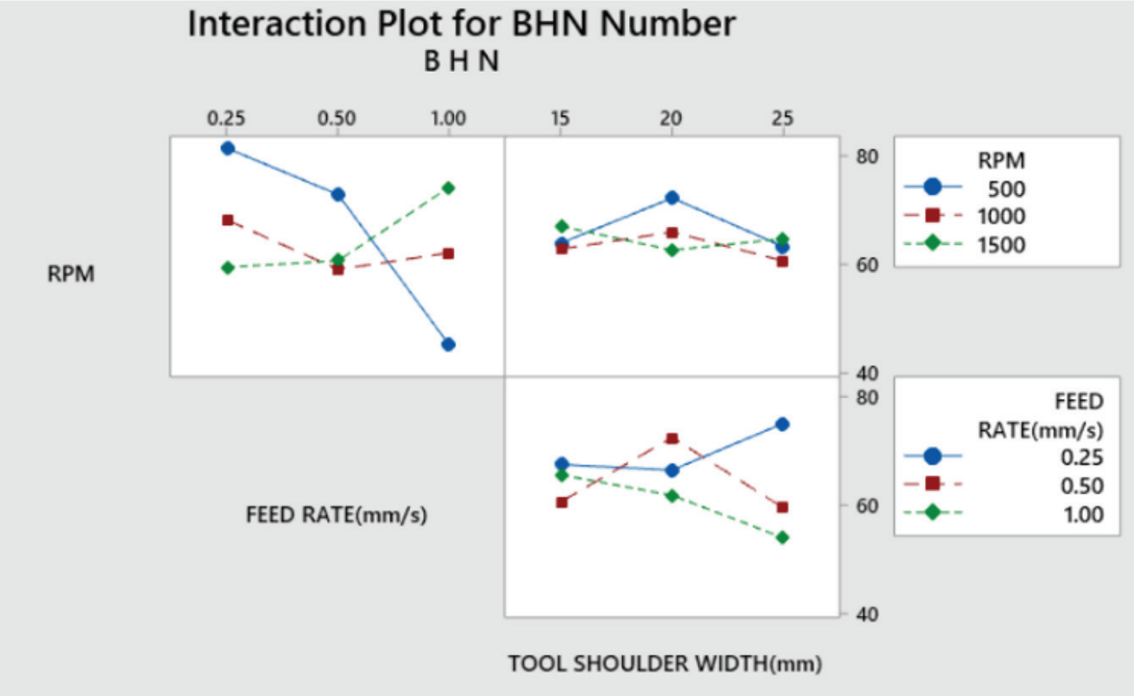


Figure 5: Interaction plots for BHN of friction – stir welded joints of Al 6063 alloys

The main effects plot (Fig.4) indicates steeper slope for Feed Rate whose individual impact on the outcome BHN of weldments is around 10.9 % as per ANOVA. Similarly, the next parameter is tool shoulder width having very less slope and process spread whose effect on the impact strength is almost negligible i.e 2.72%. The slope of RPM also found very low & negligible impact on the outcome i.e 1.81% but through the interaction plot (Fig.5) and also ANOVA calculations for two-way interactions, it was found that the combined effect of RPM & feed rate on BHN is very high (52.12%) compared to the combined effect of feed rate & tool shoulder width (9.39%) and RPM and tool shoulder width (3.93%) but through ANOVA it was found that the interaction effect on the outcome of the process is dominating over individual effect on the BHN. Maximum cross-over or intersection or convergence of lines were seen in the two-way interaction of RPM & feed rate

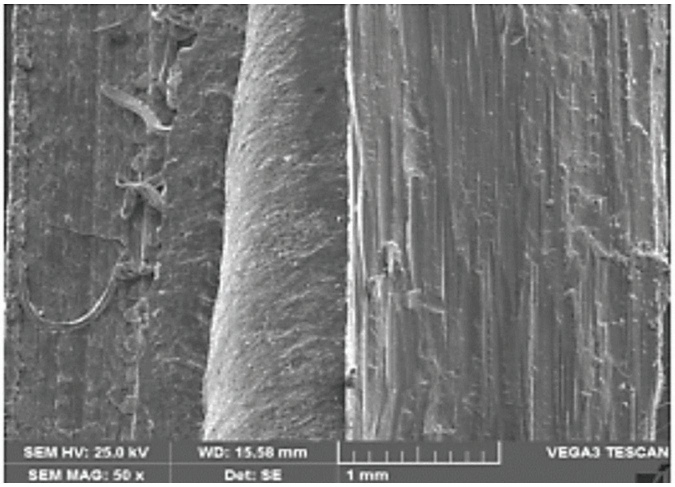


Figure 6a: 1500 rpm, 0.25mm/s feed rate, 15 mm tool diameter with 50 X magnification

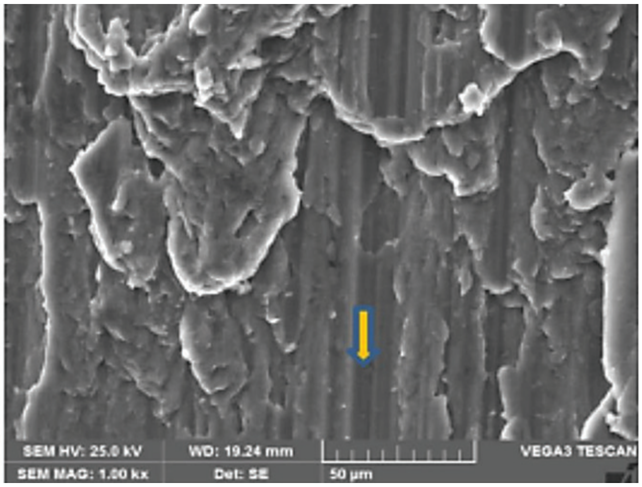


Figure 6b: 1500rpm, 0.25 mm/s feed rate, 15mm tool diameter with 1000 X magnification

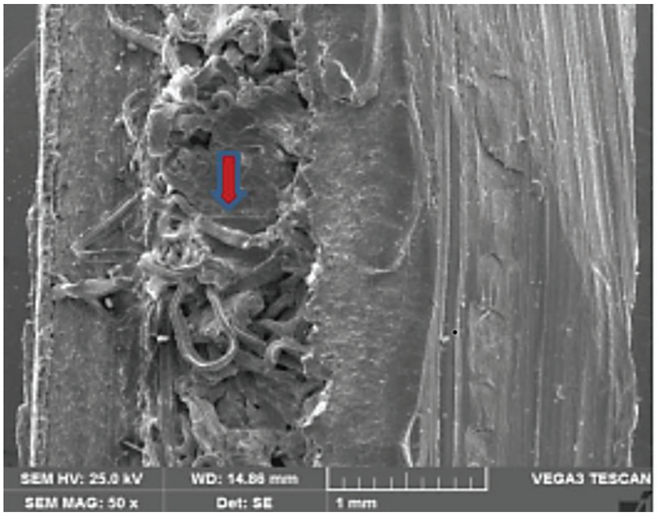


Figure 7a: 1500 rpm, 0.5mm/s feed rate, 15 mm tool diameter with 50 X Magnification

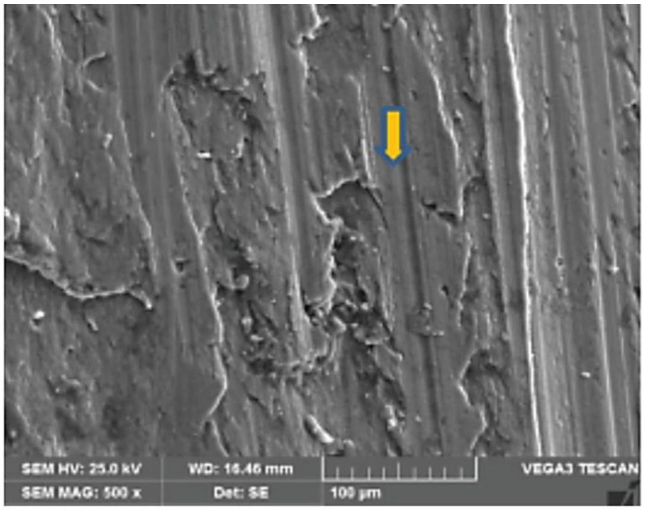


Figure 7b: 1500rpm, 0.5 mm/s feed rate, 15 mm tool diameter with 1000 X Magnification

Table 1: Anova for Impact Strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
RPM	2	10.647	5.3237	10.83	0.005	30.7
Feed Rate (mm/s)	2	2.440	1.2198	2.48	0.145	7.04
Tool Shoulder Width (mm)	2	4.647	2.3233	4.73	0.044	13.4
RPM*Feed Rate	4	9.329	2.3323	4.75	0.029	26.9
RPM*Tool Shoulder Width	4	2.291	0.5727	1.17	0.394	6.61
Feed Rate* Tool Shoulder Width	4	1.362	0.3404	0.69	0.617	3.93
Combined interaction of all three		11.42				
Total	26	34.646				100

Table 2: ANOVA for BHN

Source	DF	Adj SS	Adj MS	F-Value	P-Value	%Contribution
RPM	2	0.000006	0.000003	0.36	0.707	1.81
Feed Rate (mm/s)	2	0.000036	0.000018	2.26	0.166	10.9
Tool Shoulder Width (mm)	2	0.000009	0.000005	0.58	0.580	2.72
RPM*Feed Rate	4	0.000172	0.000043	5.43	0.021	52.12
RPM*Tool Shoulder Width	4	0.000013	0.000003	0.42	0.788	3.93
Feed Rate* Tool Shoulder Width	4	0.000031	0.000008	0.97	0.473	9.39
Combined interaction of all three		19.13				
Total	26	0.000330				100

4.4 Fractography Tests

The welded specimen subjected to Charpy impact tests were observed under SEM to ascertain the nature of fracture surfaces. The pictures from fracture surface of welded specimen is shown in Figures 6 and 7 for transverse specimen taken across weld region, at low and high magnifications for 0.25 and 0.5 mm/s feed rate, respectively. The figures clearly indicate wider track spacing as indicated by yellow arrows in the figures. The track spacing indicate deformation before fracture [14]. Further, web-like pattern seen at lower magnification, in Fig.7a by red solid arrow, indicate extensive local deformation to failure and is in commensurate with the impact test results shown in ANOVA table [15,16].

5.0 Conclusions

- The weld joint obtained for 25mm tool shoulder diameter, 1mm/s feed rate and 500rpm was found free from defects and porosity
- Most of the weld joints obtained from 15mm tool shoulder diameter have porosity and other defects
- Speed of the tool (RPM) has major effect on hardness of the weld obtained through FSW compared to feed rate (mm/s) and Tool Shoulder Width (mm)
- The interaction between the Tool shoulder width (mm) and Feed rate (mm/s) contribute more towards the hardness of the weld obtained through FSW
- SEM (Scanning Electron Microscope) analysis suggests that the fracture is more Ductile in nature

6.0 References

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