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Research Paper

THE EFFECT OF VARIATION OF TOOL GEOMETRY ON FRICTION STIR WELDED ALUMINUM ALLOYS—AN EXPERIMENTAL INVESTIGATION

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In the recent past, the scope for welding of aluminum alloys using FSW has increased. A non-consumable tool is used to generate frictional heat in the abutting surfaces in which the shoulder and the pin are the important parts of the tool. Tool design is one of the most important and critical parameters that influence the FSW process as it determines the joint properties and microstructures. Tool pin profile, axial force, tool rotational speed, and welding speed are a few of the other important parameters that decide the weld quality. Physical FSW tools are manufactured using H13 (Chromium hot worked steel). Using each tool, friction stir welding process is carried out on two base materials AA6351 and AA6061 separately. The various process parameters are optimized by using the Design of Experiments (DOE) approach. As the stirring is the important phenomenon in the FSW, the quality of weld depends on how optimally the material is melted at the joint. A modified tool is designed and fabricated, which resulted in obtaining a better weld joint for the same combinations of parameters. The results obtained with the actual tool and modified tool are compared, and it is found that the results obtained by using the modified tool are much better.

Keywords: Friction stir welding, 6061 & 6351 aluminum alloy, Tool rotational speed, Welding speed, Axial force, Mechanical properties, Tensile strength, Modified tool

INTRODUCTION

Friction Stir Welding (FSW), a solid state process which is particularly suitable for welding aluminum can overcome the difficulties in conventional welding of aluminum alloys. Because friction stir welding is performed below the melting temperature, protection requirements are greatly reduced

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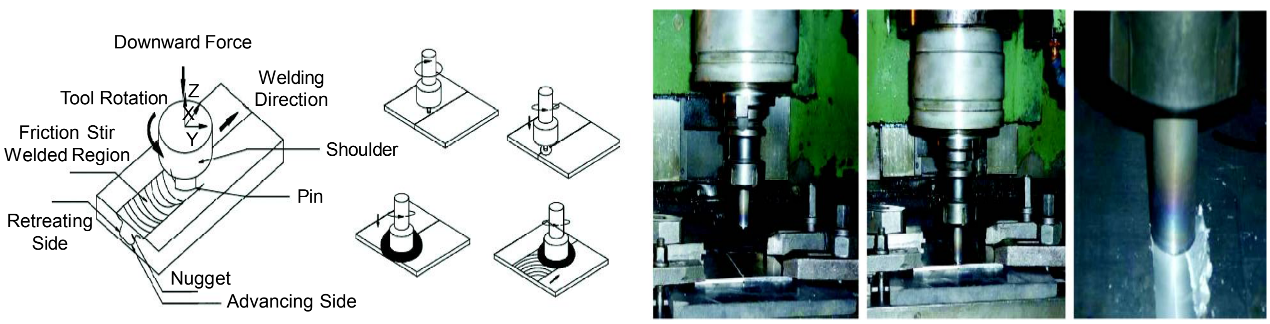
and hence, this welding process is suitable for many applications in aerospace industries joining AA6XXX. The critical process parameters are identified as Axial Force (F), Tool Profile (T), Weld Speed (WS) and Tool Rotational Speed (TRS). Tools are fabricated to weld aluminum alloys. The various process parameters are optimized by using the Design of Experiments (DOE) approach.

Figure 1: FSW Process and Stages of Friction Stir Welding Process



The FSW is conducted with varied weld speeds and the fatigue strength of FS welds influences the welding speed (Ericsson and Scandstrom, 2003). The effect of the tool shape on the mechanical and micro structural properties of friction stir welded aluminum plates by using three different tools and weldability is found to be effected by the tool shape at high rotational speed significantly (Hidetoshi *et al.*, 2006). Elangovan and Balasubramanian (2008) used tools made with three different shoulder diameters and five different profiles of tool pin to fabricate the joints. They found that the tool with square profile pin with 18 mm shoulder diameter produced mechanically sound and metallurgically defect free welds when compared to other tools with different tool pin profiles. The effect of different shoulder geometries on the mechanical and micro structural properties of a friction stir welded 6082 aluminum alloy were analyzed by Scialpi *et al.* (2007). Elangovan *et al.* (2008) worked on AA6061 and mentioned that AA 6XXX is used widely in the fabrication of light weight structures.

EXPERIMENTAL PROCEDURE

The most common defect found in FSW known as void or worm hole is due to lack of consolidation of the material inside the weld nugget. The insufficient refilling of the advancing side of the nugget is due to the two conditions. Porosity tends to form very close to the pin and on the advancing side. Other defects like pinhole, piping defect, kissing bond cracks etc, due to improper flow of metal and insufficient consolidation of metals in FSW region is observed. In the present study an attempt is made to minimize the defects observed by conducting experiments with a modified tool which has a cavity at the end of the shoulder and also by identifying the optimal axial force in addition to the optimal values of tool rotational speed and weld speed. The base plate chosen for this investigation is AA6061 and AA6351. The profiles of the tool pin shown below in Figure 2 are used for the experimental work.

Figure 2: Tapered Profiled Tool, Threaded Cylindrical Profiled Tool and Square Profiled Tool

The design of pin and shoulder are important as it is required to retain in the weld cavity the maximum amount of material that is transferred. The heat generated by the rotating tool softens the material in the vicinity of the tool. The tool pin shears the material to its backside during FSW process to plastic state. The material undergoes intense plastic deformation around the tool.

During the time of tool plunge, a cavity is created in the base material and the pin profile decides the shape of the cavity. Excessive flash is formed and other defects like groove, tunnel and cavity were observed and the formation of these defects are due to either excessive or less heat input, or abnormal stirring (Colegrove and Shercliff, 2005). The material which gets ejected from the weld cavity has to be retained in the cavity, so that a strong bond is formed. For this purpose, a groove is provided as shown in Figures 3a and 3b at the tip-tool interface in the modified tool to facilitate the retention of the plasticized material in the weld cavity.

RESULTS AND DISCUSSION

The results obtained by using the existing tool are compared to the results obtained by using modified tool. Experiments for joining the

Figure 3: Existing Tool and Modified Tool

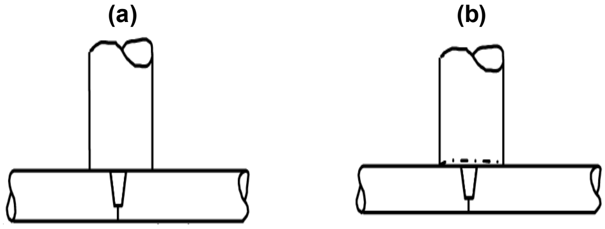


Table 1: ANOVA for UTS (Means) AA6351

Source	DOF	Existing Tool				Modified Tool			
		Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe	Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe
F	2	160.83	80.42	1.17	1.22	139.69	69.85	1.75	3.27
T	2	170.70	85.35	1.25	1.73	130.78	65.39	1.64	2.78
WS	2	253.38	126.69	1.85	5.96	526.24	263.12	6.61	24.30
TRS	2	750.62	375.31	5.48	31.43	683.40	341.70	8.59	32.85
Error	9	616.52	68.50			358.21	39.80		
Total	**17**	**1,952.05**				**1,838.32**			

Table 2: ANOVA for YS (Means) AA6351

Source	DOF	Existing Tool				Modified Tool			
		Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe	Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe
F	2	50.02	25.01	3.24	8.75	74.72	37.36	1.75	5.37
T	2	42.34	21.17	2.74	6.81	58.84	29.42	1.38	2.70
WS	2	74.91	37.46	4.86	15.05	76.13	38.07	1.78	5.61
TRS	2	158.53	79.27	10.28	36.21	193.08	96.54	4.52	25.26
Error	9	69.41	7.71			192.39	21.38		
Total	**17**	**395.21**				**595.16**			

Table 3: ANOVA for %E (Means) AA6351

Source	DOF	Existing Tool				Modified Tool			
		Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe	Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe
F	2	0.88	0.44	1.28	2.00	1.08	0.54	1.70	4.63
T	2	1.33	0.67	1.94	6.67	1.29	0.65	2.03	6.82
WS	2	1.63	0.82	2.37	9.78	1.80	0.90	2.83	12.13
TRS	2	2.72	1.36	3.96	21.07	2.57	1.29	4.04	20.15
Error	9	3.09	0.34			2.86	0.32		
Total	**17**	**9.65**				**9.60**			

Table 4: ANOVA for Hardness (Means) AA6351

Source	DOF	Existing Tool				Modified Tool			
		Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe	Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe
F	2	37.44	18.72	1.39	2.56	33.78	16.89	2.49	5.50
T	2	55.44	27.72	2.05	6.98	48.44	24.22	3.57	9.48
WS	2	61.78	30.89	2.29	8.53	72.44	36.22	5.34	16.01
TRS	2	131.44	65.72	4.87	25.62	152.11	76.06	11.22	37.67
Error	9	121.51	13.50			61.01	6.78		
Total	**17**	**407.61**				**367.78**			

aluminum alloys using friction stir welding were performed using DOE. The values of the output parameters are considered to evaluate the S/N ratio and to obtain ANOVA values. Main effects based on ANOVA results for the responses of the joints are presented.

Figure 4: Comparison of S/N Ratios Obtained by Using Existing and Modified Tool for AA6351 for UTS, YS, % E and Hardness

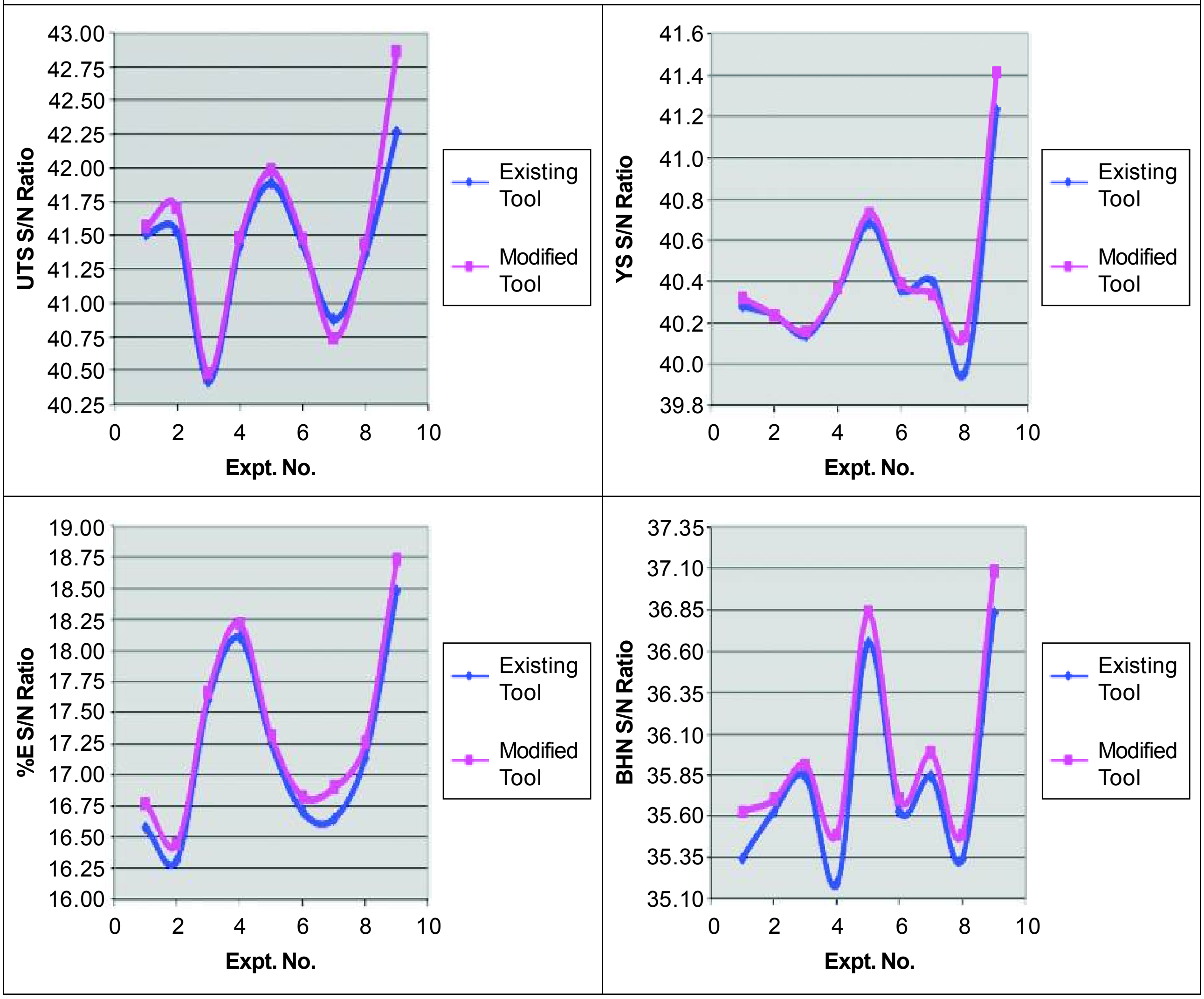


Table 5: ANOVA for UTS (Means) AA6061

Source	DOF	Existing Tool				Modified Tool			
		Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe	Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe
F	2	189.46	94.73	2.46	6.39	156.51	78.26	1.74	3.32
T	2	221.53	110.77	2.87	8.21	285.92	142.96	3.19	9.76
WS	2	336.59	168.30	4.36	14.75	308.18	154.09	3.43	10.87
TRS	2	664.14	332.07	8.61	33.38	856.10	428.05	9.54	38.12
Error	9	347.08	38.56			403.80	44.87		
Total	**17**	**1,758.80**				**2,010.51**			

Table 6: ANOVA for YS (Means) AA6061

Source	DOF	Existing Tool				Modified Tool			
		Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe	Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe
F	2	112.84	56.42	1.45	3.54	114.45	57.23	1.20	1.76
T	2	131.54	65.77	1.69	5.45	145.67	72.84	1.53	4.62
WS	2	177.71	88.86	2.28	10.15	164.23	82.12	1.72	6.32
TRS	2	209.23	104.62	2.68	13.35	238.42	119.21	2.50	13.12
Error	9	351.16	39.02			428.48	47.61		
Total	**17**	**982.48**				**1,091.25**			

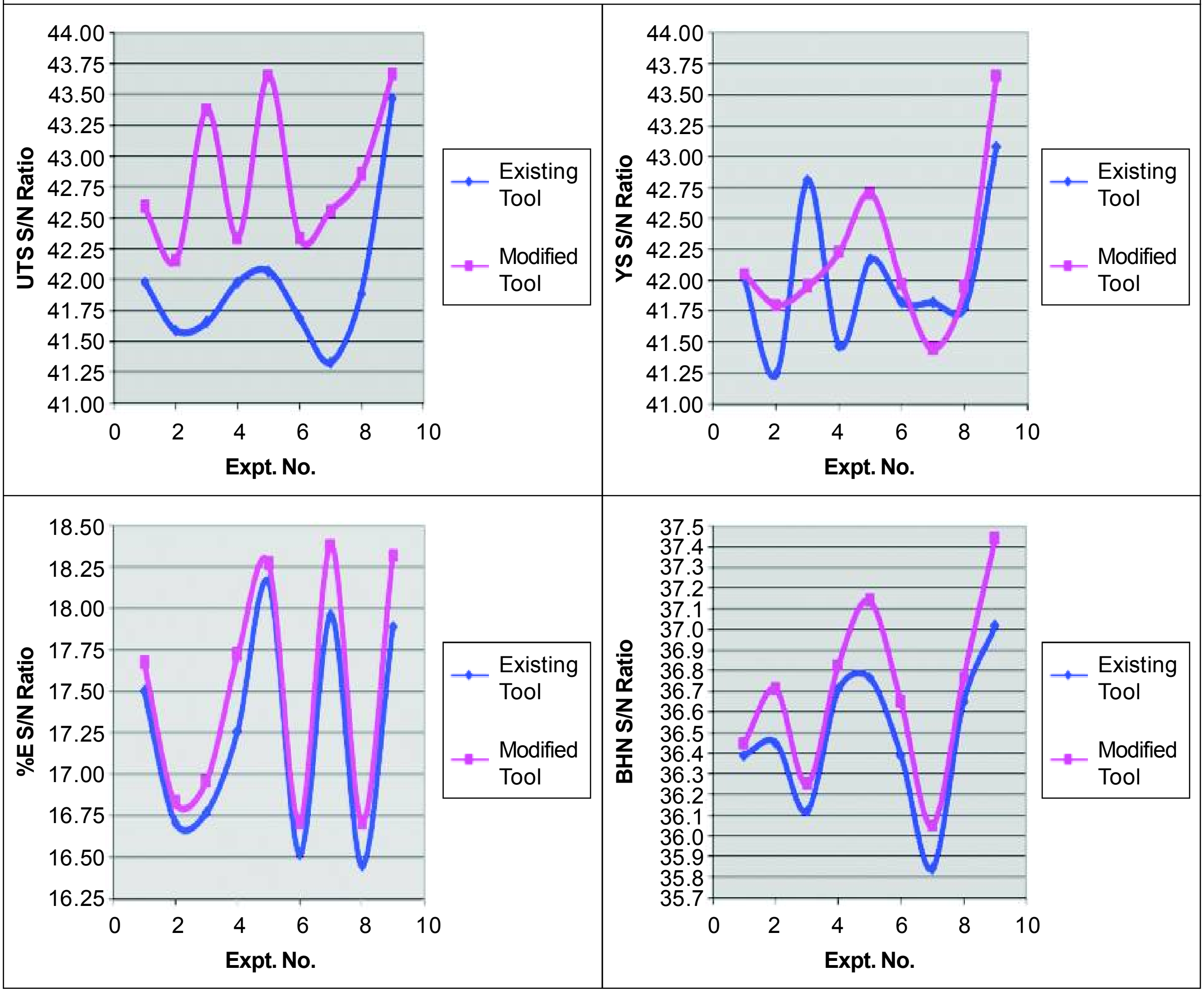
Table 7: ANOVA for %E (Means) AA6061

Source	DOF	Existing Tool				Modified Tool			
		Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe	Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe
F	2	0.47	0.24	2.30	4.51	1.04	0.52	1.21	1.77
T	2	0.62	0.31	3.03	7.06	1.11	0.56	1.29	2.46
WS	2	1.41	0.71	6.90	20.47	1.70	0.85	1.97	8.33
TRS	2	2.47	1.24	12.08	38.46	2.33	1.17	2.70	14.59
Error	9	0.92	0.10			3.88	0.43		
Total	**17**	**5.89**				**10.06**			

Table 8: ANOVA for Hardness (Means) AA6061

Source	DOF	Existing Tool				Modified Tool			
		Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe	Sum of Squares (SS)	Mean Squares = SS/DOF	Fisher Ratio = MS/MSe	% of Contribution = MS/MSe
F	2	16.78	8.39	1.54	3.53	32.33	16.17	1.32	2.66
T	2	16.78	8.39	1.54	3.53	37.33	18.67	1.52	4.37
WS	2	40.44	20.22	3.71	17.68	52.00	26.00	2.12	9.38
TRS	2	44.11	22.06	4.05	19.88	60.33	30.17	2.46	12.23
Error	9	49.00	5.44			110.51	12.28		
Total	**17**	**167.11**				**292.50**			

Figure 5: Comparison of S/N Ratios Obtained by Using Existing and Modified Tool for AA6061 for UTS, YS, % E and Hardness



CONCLUSION

Among the two base materials considered, AA6061 was found to exhibit better mechanical properties and this alloy is found to be amenable for friction stir welding by different tool profiles (Tables 1, 2, 3 and 4) than AA6351 (Tables 5, 6, 7 and 8) H13 tool material is found to withstand for AA6061 without breakage of tip at the time of welding process. From ANOVA it can be concluded that the TRS and WS are the dominant parameters that have influence on the mechanical properties than the axial force acting on the joints (Tables 1 to 8). The Square profiled tool facilitates the stirring action from tip to the collar, and due to this the turbulence is avoided, when compared with the use of other tool profiles. The defect-free welds were possible with the square profiled tool for the same reason. The tool rotational speed of 1000 rpm, weld speed of 60mm/min and axial force of 6kN generated good welded joints (with maximum values of mechanical properties that were obtained) when square profiled tool is used. By modifying the tool shape, joints with improved mechanical properties are obtained in the FSW process. The same pattern is observed for all combinations of parameters. It is observed that the results obtained by using modified tool are comparatively better than those for the existing tool. Due to the provision made at the end of the shoulder for flow of the material removed during the FSW process (in the modified tool), the heat generated is uniform and this resulted in avoidance of the tool getting stuck at the line of joint (Figures 4 and 5). From the results obtained it can be concluded that the shape of the tool pin and shoulder play a very important role in obtaining better mechanical properties for the weld joints. This is evident from the results obtained for the square pin profile due to flat faces produces a pulsating stirring action in the flowing material.

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