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Effect of Friction Stir Welding Process Parameters on Tensile strength of Dissimilar Welded Joint

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Abstract: ***In the present work, the effect friction stir welding (FSW) process parameters on the mechanical properties of dissimilar friction stir butt welded aluminium (Al) alloy, AA6061-T6 and stainless steel, 304L were investigated. FSW tools having fixed shoulder diameter, pin tip diameter and pin length with tapered cylindrical (TC) pin profile was used for experimental work. The FSW parameters used were; tool rotational speed (rpm), welding speed (mm/min), plunge depth (mm) and tool offset (mm). The ultimate tensile strength (UTS) of the joint is considered as the main criterion of the joint performance. Taguchi method of optimization was used to determine optimum level of parameter and Analysis of Variance (ANOVA) is done in order to determine significance of each parameter. The results showed that the rotational speed has more contribution among all other parameter followed by welding speed.***

Keywords: Friction Stir Welding, Dissimilar Metals, Tensile Strength, Analysis of Variance

1. Introduction

Fast depletion of primary fossil fuel reserves, hike and fluctuation in fuel prices and environmental degradation and its after effects as a result of burning of fossil fuel are looming problems the world is facing today. In automotive and marine sectors, enhancing fuel efficiency by weight reduction is one among many alternatives available to address these problems. But, significant weight reduction is hardly possible with the use of high strength or slim steel structures alone and the concept of multi-material vehicle structures envisage weight reduction up to 30% [1]. Multi-material design concept combines several different materials such as high strength steels, lightweight alloys and polymers in one unit and one of the most desired material pair is aluminium (Al) alloys and high strength steels. But, efficient joining of Al alloys and steels is hardly possible using fusion welding techniques and it is a major hurdle in this respect. The difficulty in thermal joining of Al alloys with steels is mainly due to the extremely low dilution between the major constituents, iron (Fe) and Al. The strong affinity of Fe and Al to form brittle intermetallic compound (IMC) phases which results reduction in both static and dynamic strength of the joint is also an issue.

Friction Stir Welding (FSW) is invented by The Welding Institute (TWI), England, U. K. for joining of light metals in 1991. It allows considerable weight savings in lightweight construction compared to conventional joining technologies along with high strength. The process of friction stir welding has numerous advantages over the conventional welding technologies. FSW process is carried out in the solid phase below the melting point of the metals and is able to weld numerous materials including aluminium, bronze, copper, titanium, steel, magnesium, and plastic. It also yields significantly less distortion than the fusion welding processes, allowing for high cost reductions in many applications. Thus, the problems related to the solidification of a fused material are avoided. Materials classified as difficult to fusion weld like the high strength aluminium alloys used in the aerospace industry could be joined with a minor loss in strength [2].

1.1 Friction Stir welding process

The process is schematically represented in figure 1. The plates are abutted along the edges to be welded and the rotating pin is plunged into the plates until the tool shoulder is in full contact with the plate's surface. Once the pin is completely inserted, it is moved with a small tilting angle in the welding direction. Due to the advancing and rotating effect of the pin and shoulder of the tool along the seam, an advancing side and a retreating side are formed and the softened and heated material flows around the pin to its backside where the material is consolidated to create a high-quality, solid-state [2,3].

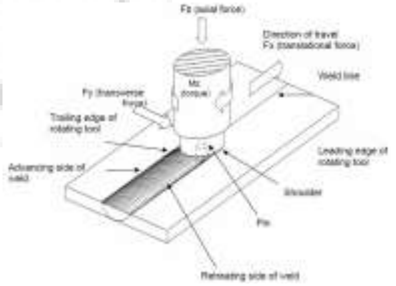

Figure 1: Schematic Diagram of FSW Process

2. Literature Survey

Yazdipour and Heidarzadeh [3] studied the effect of tool traverse speed, offset and rotation direction during dissimilar butt friction stir welding of Al 5083-H321 and 316L stainless steel plates at a constant rotational speed of 280 rpm. The tensile and hardness tests were conducted to evaluate the mechanical properties of the joints. The results showed that defect free joint with the maximum tensile strength of 238 MPa was produced at a traverse speed of 160 mm/min, pin offset of 0.4 mm, and clockwise rotation condition. The reduction in tensile strength of the other joints was due to

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their surface and cross-sectional defects such as tunnel defect, voids, non-uniform distribution and large particles of the steel and microcracks developed in the interface of the dissimilar parts.

Siddiquee et al. [4] performed friction stir welding on austenitic stainless steel plates on an indigenously retrofitted vertical milling machine. AISI-304 equivalent grade stainless steel was welded by FSW using tungsten carbide tools with tapered cylindrical (conical) pin. The results of ANOVA showed the order of importance in which the parameters have affected the UTS in terms of percent contributions i.e. welding speed with (56.83% contribution), shoulder diameter (27.44% contribution) and tool rpm(15.73% contribution).

Ramachandran et al. [5] studied the effect of tool axis offset from the joint interface and geometry of the FSW tool pin on the mechanical and metallographic characteristics of dissimilar FSW welded aluminium alloy and HSLA steel. The constant FSW parameters used were; tool rotational speed of 500rpm, welding speed of 45 mm/min, and an axial load of 7 KN and tool tilt angle of 1.50^{o}. The effect of tool axis offset was investigated by continuously changing the tool axis offset by keeping the tool traverse direction at an angle to the joint interface. FSW tool having TC pin with 100^{o} taper angle has produced the best joint at a tool axis offset of 2 mm towards the Al alloy.

Uzun et al. [6] worked on joining of Al 6013-T4 alloy and 304L stainless steel using friction stir welding. The microstructure, hardness and fatigue properties of friction stir welded 6013 aluminium alloy to stainless steel have been investigated. The weld nugget, the heat affected zone (HAZ), thermo-mechanical affected zone (TMAZ) were observed under optical microscope. Fatigue properties of Al 6013-T4 and 304L stainless steel joints were found to be 30% lower than that of the Al 6013-T4 alloy base metal.

Chen and Kovacevic [7] performed experiments on Al 6061 and AISI 1018 steel having 6-mm thickness. Metallographic studies by optical microscopy, electron probe microscopy, and the utilization of the X-ray diffraction technique have been conducted. It was found that the intermetallic phases Al_3Fe_4 and Al_5Fe_2 exist in the weld zone. The tool was significantly worn during welding and is broken after traveling 100 mm at a rotational speed of 917 rpm. The wear of the tool significantly affects the structure of the weld, and the tool breakage was detected by the incorporated acoustic emission sensors.

Kakiuchi et al. [8] used aluminium 6061 and 304 stainless steel for the experimental work. They found that the tensile strength of 194 MPa was obtained in the condition of the rotating speed of 800 rpm and the tool offset of 0.2 mm. Near the welded boundary, the hardness decreased in the Al side due to the resolution of precipitates during the FSW process while the hardness increased in the steel side due to the work hardening.

Liu et al. [9] worked on Thin sheets of aluminum alloy 6061-T6 and one type of Advanced high strength steel, They observed that the maximum ultimate tensile strength can reach 85% of the base aluminum alloy. Intermetallic compound (IMC) layer of FeAl or Fe3Al with thickness of less than 1 lm was formed at the Al–Fe interface in the advancing side, which can actually contribute to the joint strength. Watanabe et al. [10] tried to butt-weld an aluminum alloy plate to a mild steel plate by friction stir welding, and investigated the effects of a pin rotation speed, the position for the pin axis to be inserted on the tensile strength and the microstructure of the joint. The behavior of the oxide film on the faying surface of the steel during welding also was examined. The main results obtained are as follows. Butt-welding of an aluminum alloy plate to a steel plate was easily and successfully achieved by friction stir welding. The maximum tensile strength of the joint was about 86% of that of the aluminum alloy base metal. A small amount of intermetallic compounds was formed at the upper part of the steel/aluminum interface, while no intermetallic compounds were observed in the middle and bottom parts of the interface.

3. Materials and Methods

The base materials used in the present study were 4 mm thick sheets of stainless steel, 304L and Al alloy, AA6061-T6. The chemical composition of the base stainless steel and Al alloy are given in table 1. The as rolled condition sheets were cut to 125 mm×50 mm× 4 mm size and the 50 mm faying surfaces were mechanically polished. A compound FSW tool having oil hardened EN31 steel shank and tungsten carbide pin and shoulder with tapered cylindrical (TC) pin profile was used for experimental work. The FSW tool used was having 18 mm shoulder diameter, 4 mm tool pin tip diameter, 6 mm diameter at pin root and 3.7 mm pin length. The welding is performed on conventional milling machine with retrofitted friction stir welding setup. The machine is controlled by two motors only, namely, spindle motor and feed motor. The spindle motor is rated at 22 kW and the feed bed motor is rated at 2.2 kW. The main spindle motor provides the spindle rotation while the feed motor supplies power to all the three axis movements of the bed. The spindle speed is available from 30 to 675 rpm and feed rate is available from 12 to 430 mm/min. The FSW trials were carried out by varying the process parameters between the available ranges. The final levels selected for main experimentation are show in table 2. The DoE is used to design the main experimentation. The mixed approach of the Taguchi DoE design is used L_{18} array was selected for main experimentations. The DoE for main experimentation work is shown in table 3.

Table 1: Chemical Composition of 304L SS and 6061-T6 Al

Contents	Wt (%)
C	0.023
Cr	18.52
Ni	8.62
Mn	12.7
Si	0.34
P	0.023
S	0.01
Fe	71.55

Contents	*Wt (%)*
Si	0.47
Fe	0.28
Cu	0.21
Mn	0.018
Mg	0.92
Cr	0.058
Zn	0.013
Ti	0.017
Al	97.77

Table 2: Process Parameters and Their Levels

Process Parameter	*Levels*		
	I	*II*	*III*
Plunge Depth (mm)	0	0.3	-
Rotational speed (rpm)	380	510	675
Welding Speed (mm/min)	16	22	30
Tool Offset on Al side (mm)	1	1.5	2

Table 3: L18 DoE for Main Experimentation

Sr. No.	*Plunge Depth (mm)*	*Rotational Speed (rpm)*	*Welding Speed (mm/min)*	*Tool Offset (mm)*
1	0	380	16	1.0
2	0	380	22	1.5
3	0	380	30	2.0
4	0	510	16	1.0
5	0	510	22	1.5
6	0	510	30	2.0
7	0	675	16	1.5
8	0	675	22	2.0
9	0	675	30	1.0
10	0.3	380	16	2.0
11	0.3	380	22	1.0
12	0.3	380	30	1.5
13	0.3	510	16	1.5
14	0.3	510	22	2.0
15	0.3	510	30	1.0
16	0.3	675	16	2.0
17	0.3	675	22	1.0
18	0.3	675	30	1.5

4. Results and Discussion

4.1 Measurement of Tensile Strength

The tensile strength of welded joint is measured on Universal Testing Machine. The tensile test specimens are cut as per ASTM-E8 standard. The cut specimens are shown in figure 2.

Figure 2: Tensile Test Specimens

The specimen has width of 25mm and length is 250mm. The minimum length required for the testing is 210mm. The width of reduced cross section is 15mm while the length of reduced section is 70mm. The results of tensile testing are shown in table 3.

The signal to noise (S/N) ratios is also shown in table 3 the S/N ratios are calculated using Taguchi method by selecting larger the better characteristics. The ratios are calculated using equation no. 1. The S/N ratios can be directly obtained through Minitab 17 software.

$$\frac{S}{N} = -10\log\frac{1}{N}\sum_{i=1}^{n}\frac{1}{Y^2} \quad (1)$$

Where,
n is the number of replications conducted for a particular experiment
y_i is the response variable value (i = 1,2,3,-----,n)

4.2 Taguchi Analysis of Tensile Strength

The results obtained after tensile testing is analyzed in Minitab 17 software. The plots for S/N ratios are directly obtained from software. Main effect plots also give the inference of the most important factor and the least important factor.

Main effects plot for S/N ratios delineated in figure 3 gives the best settings for each factor to maximize tensile strength of welded joint. S/N ratio values determined by using larger the better quality characteristic are plotted against the levels of process parameters to identify the optimum level of each process parameter. Mean value line for s/n ratio values is also depicted in the figure 3 to show the variability of response values from the mean value. The maximum values of s/n ratio are observed at 0.3 mm plunge depth, 675 rpm rotational speed, 22 mm/min welding speed and 1.5 mm tool offset. Therefore, these are the optimum levels of process parameters to obtain maximum tensile strength. This optimum level of process parameters are used to reduce the variability and make the system robust.

Figure 3: The Main Effects Plot for S/N Ratios

4.3 Analysis of Variance for Tensile Strength

Main effects plots alone cannot determine the influence of process parameters, but analysis of variance (ANOVA) is required to prove the statistical significance of process parameters on response variables. The significance of each process parameter depends on the rejection of null hypothesis. In this study, null hypothesis is considered as the mean values of response variable at each level of process parameter is considered as equal, whereas the alternative hypothesis considers the mean values of response variable at each level of process parameter is not equal. Also 95 % confidence level is considered for the ANOVA analysis, which denotes the extent of suitability of the considered experimental values to the actual processing conditions of direct extrusion process.

Analysis of variance is performed for tensile strength to check the effectiveness of independent variables. Table 4 shows the ANOVA for tensile strength. Fixed factor effects model is considered for ANOVA analysis, as the levels of each process parameter are defined for performing experiments. F value and P value for each and every process parameters is calculated from the mean sum of squares value. Degrees of freedom plunge depth is 1 as the level is 2 for other parameters is degrees of freedom is 2 due to three levels of each parameter and DOF for error is 10, whereas total degree of freedom is 17 as the total number of experiments performed are 18. Sum of squares value mentioned in the table is determined from the total average value of response variable and average value of response variable at each level of process parameters. Mean sum of squares is calculated as the ratio of sum of squares to that of degree of freedom. F value for each process parameter is obtained from the ratio of mean sum of squares of the factor to that of the mean sum of squares of the error.

The critical F value is obtained for 2 DOF of process parameter and 10 DOF of error at 95% confidence level, for plunge depth and for other three parameters DOF is 2 and the DOF of error is 10, so the F critical is found out accordingly. F critical for plunge depth comes out to as 4.9646 and for other three parameters F critical is 4.1028. The F value for all the process parameters in the ANOVA table for tensile strength is higher than the critical F value from the F distribution table. This indicates that all the process parameters considered for this study are significant for tensile strength. Thus, it statistically confirms that influence of process parameters explained from main effect plots is significant.

Rotational speed has the maximum contribution with 49.04% towards the tensile strength followed by welding speed (25.46), whereas plunge depth and tool offset has comparatively lesser contribution 7.92% and 8.49% respectively. The contribution of error (i.e. 9.09%) is very small as compared to that of process parameters.

Table 4: ANOVA for Tensile Strength

Source	*DF*	*SS*	*MS*	*F*	*P*	*%*
Plunge Depth	1	401.87	401.8	8.71	0.017	7.92
Rotational Speed	2	2487.7	1243.8	26.9	0.001	49.03
Welding Speed	2	1291.6	645.8	14.0	0.002	25.46
Tool Offset	2	430.50	215.2	4.66	0.039	8.48
Error	10	461.15	46.11			9.09
Total	17	5072.8				
R Square = 90.91%			R Square (adj) = 84.55%			

5. Conclusions

Welding of dissimilar metals such as stainless steel and aluminium alloy is effectively done by using FSW process. The optimum levels obtained after Taguchi analysis are; rotational speed (675 rpm), welding speed (22 mm/min), tool offset (1.5 mm) and plunge depth (0.3 mm), The ANOVA showed that rotational speed has highest contribution of 49.03 % after that welding speed has influence with contribution 25.46 %. For successful welding tool should be kept in aluminium side with stainless steel kept at advancing side.

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