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State-Of-The-Art in Heat Addition during the Friction Stir Welding (FSW) Process by FSW Tool

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Abstract

Friction stir welding (FSW) is widely used to join different grades of aluminium alloy but for steel material it requires high speed rotation of FSW tool which develops high temperature on tool. This review paper is concerned with the effect of temperature in the FSW process and heat generation by the high speed of rotation on the FSW apparatus. The other parameter has also studied to show the effect on FSW tool in stir welding process. In this work different research papers and their work are presented. The variety of work on stir welding process is discussed by hypothetical analysis on past performance.

Research Article

Key Words: Stir welding, FSW, Welding strength, Temperature.

1. Introduction

Friction stir welding gives the high-quality welding and can improve mechanical properties, metallurgical & environmental advantages as compared to conventional fusion welding techniques and joints obtained using FSW is probably free from defects. The Friction stir welding (FSW) process results in the stirring of the plasticized and deformed material as a permanent bond in the solid state, FSW was developed in 1991 by the Welding Institute [1], which still demonstrates the tensile suitability of aluminium materials because high heat input is one of the major disadvantages in fusion welding techniques for welding aluminium alloy [2]. FSW process takes place in the solid-phase, at temperatures below the melting point of the material. It is also energy efficient process which does not require filler material to provide low distortion and good stability of the welding structure [3]. The modern FSW tool consists of the cylindrical piece formed by a pin and shoulder moved along the adjoining surfaces of pieces as illustrated in Fig. 1. Most of the researches apply FSW on steel material by using high grade FSW tool because of their properties steel material possess many challenges in FSW process.

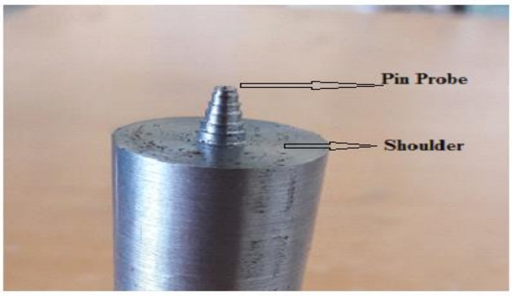

Fig. 1 FSW Tool conical Pin

These tools are high grade steel material which required high speed of rotation above 3000rpm [4]. So, the high speed of rotation causes high temperature on tool which exists above 1000°C [4]. Heat generation depends upon the rotation speed and material of the tool which can affect the quality of the welding. The tool rotation speed and material selected should have good shear strength, wear resistance and oxidation resistance under high temperature. These two problems are pointed in this review work because these two conditions increase the cost of FSW process but showing good result as compared to fusion welding in different type of material that has to join. Also, the high temperature occurs on FSW tool causes the tool wear and reduces the tool life. Many research papers have been reviewed which shows that Friction Welding process shows best result in welding of steel. FSW welding process, one of the innovative fastest growing metal joining processes, the contact pin of FSW tool on work-piece create welded joint by developing friction between two work-pieces but some common areas are still need to improvement.

Four areas are commonly followed in FSW joints, the main one being friction stir processed zone (FSPZ) region produced by pin movement of FSW tool, thermo-mechanical affected zone (TMAZ) which is formed by friction heat and rotation of FSW tool pin to material drift, heat affected zone (HAZ) and unaffected Base metal (UBM) is normally found in all welding zones. Non-consumable tool rotating above fields is formed by material flow behavior under action. It is worth revealing here that tool materials and other parameters along with temperature distribution will be specifically reviewed, as well as the integrity aspects of aluminum alloys during FSW processes. It has been reported by Ouyang et al [5] by the stirring effect of pin threads to supply material for make a sound weld. It was reported by Guerra et al [6] that the contribution of the pin thread may be in a vertical flow trend. In addition, Schmidt et al [7] thought that cyclic flow patterns could be obtained in friction stir welds by threads on pins. The important reason for the difficulty associated with welding in aluminum alloys is its many parameters but especially the temperature distribution is of more concern which depends on the tool material and geometry.

2. Review of Related Studies

Al-Moussawi et al. [8] examined the elemental segregation within DH36 steel [9] by conducting heat input [10] and thermal stress [11] on un-welded specimen incrementally in the range of 1400-1450 °C, also high temperature with high speed reported by another author [44] and at cooling rates similar to that in FSW process. They estimated peak temperature limits at which elemental segregation does not occur and hence prevent their occurrence in practice by applying the findings to the tool’s rotational and traverse speed which inferior the tool geometry. Azevedo et al. [12] presented work on friction Stir Welding had proven its merits for welding of aluminium alloys and was focused in expanding its material database to steel and titanium. Again, the tool geometry has affected by high rotating speed and temperature. Smith et al. [13] proposed CFD modeling that the maximum peak temperature obtained in FSW of 304 stainless steel when tool and work piece contact surface exceeds 400RPM of tool rotation. Avila et al. [14], analysed the fracture toughness of API5LX80 steel in butt joints welded in two passes by FSW till -20 degrees with good results for pipeline applications, for shipbuilding applications. They also used high speed of rotation but due to negative atmospheric condition tool temperature could not exceed and obtained defective welding. Prasanthi et al. [15] present investigation on defect free bonded interface between mild steel (MS) and titanium (Ti) using the rotation friction welding process. The conditions were optimized based on several trials by varying friction welding parameters like frictional force, upset force, burn-off length and rotational speed [16]. It has been established that only fine Fe-Ti particles formed in isolated regions at the interface of as welded MS/Ti joints. The growth kinetics was found to be much slower in friction welded joints as compared to diffusion bonded and explosive clad joints. Azevedo et al. [17] analysed fatigue behaviour in friction stir welded 4mm thick GL-A 36 steel, and studied fatigue growth of mild steel plate welded by friction stir welding and concluded that the growth rate in the welded material was lower than in the base material. Kusuda [18] exposed FSW technology as the world's first to weld dissimilar metals for mass produced vehicles, and made it possible to use standard industrial robots in FSW process but FSW tool had to be changed after welding for quality concern. Ananthapadmanaban et al. [19] studied mechanical property variation under different friction welding conditions for mild steel and stainless-steel joints. Yield strength, ultimate tensile strength, percentage elongation of the welded joints and hardness variations across the weld interface has been reported. The integrity of the joints has been investigated using optical microscopy and scanning electron microscopy. Ramesha et al. [20] suggested that heat input increases the welding speed, even though a lower frictional heat input was preferred to produce fine grains, comparatively a higher friction heat input is required for adequate plasticization of steel to that of low temperature non- ferrous materials. At constant speed the researcher's varied welding speed and heat input, but provided higher amount of heat above 800 J on weld joint which makes harder joint or required very slow rate of cooling. Most of the researchers have suggested the tool has become red hot during welding which damage the tool geometry [21, 22]. In order to understand the depth of this phenomenon it was necessary to understand the effect on tool profile.

Effect on FSW tool

Few researchers analysed the influence of the tool rotation speed which affect the tool profile, and maximum temperature attained by tool at 2000 rpm, the grain size of the stir zone increased exponentially with increasing maximum temperature [23]. Sekhon et. al [24] investigated on three type of tool pin profile along with stirrer rotation speed and welding speed [25-27] in terms of breaking load and percentage elongation effect on FSW tool. Marzbanrad et al. [28] investigated the influence of tool pin profile [29]. The effect of rotation speed on pin and tool shoulder geometries in the weld characteristics were also analysed [30] and pin geometry and shoulder geometry can further cause in weld properties. Shojaeefard et al. [31] studied the effect of pin profile and shoulder diameter on material flow, welding force, temperature, and strain distributions. Deepati et. al [32] studied on tool plunging force and tool shoulder size on heat generation of FSW by using 3–D finite element (FE) transient thermal analysis. Suitable correlations have been made between shoulder diameter vs peak temperature and tool plunging force vs. peak temperature. Rajakumar et al. [33] focused on the rotational speed and tool material has increase the tool temperature which affects the FSW tool, with other parameter welding speed on friction stir welding caused the tool geometry due to high temperature generation during welding process. Elangovan et al. [34] investigated to understand the effect of welding speed and tool pin profile on tensile properties of friction stir welded AA6061 aluminium alloy. They had used five different kinds of tool pin profiles to fabricate the joints at five different welding speeds. From this investigation, they found that the joints fabricated by square pin profiled tool exhibited superior tensile properties compared to other joints. Thimmarajuet al [35] studied on friction stir welding process to evaluate the influence of tool geometry on the material flow characteristics, material flow around the rotating tool was considered as a viscous flow, exhibiting laminar flow characteristics exhibiting non-Newtonian properties. They revealed the tool pin geometry has a considerable effect on the weld nugget zone. Winiczenko [36] depict work on an effect of friction welding parameters on the tensile strength and micro-structural properties of dissimilar AISI 1020-ASTM A536 joints. Friction force and friction time have a positive effect on tensile strength. As friction force and friction time increased, the tensile strength also increases. A maximum tensile strength of 482 MPa could be obtained under the welding conditions of friction force of 15 kN, upset force of 27 kN and friction time of 90 second. Shubhavardhan [37] investigated the effect of interface microstructure on fracture behaviour under static and cyclic loading. FSW parameters affect the interface microstructure and fracture behaviour on dissimilar materials weld by FSW process. Darwins and Satheesh [38] investigated the effects of friction stir welding (FSW) on hot-extruded alloy plates butt welded by FSW at various welding speeds to analyse microstructures and thermo gravimetric on ZE42 magnesium alloy. The obtained results indicated that the alloy was joined without defects. Rashidi and Mostafapour [39] used couple of tools profiles including straight cylindrical pin (SCP) and upward conical pin (UCP) considered for channelling on the linear and nonlinear paths [40]. They discovered that the shear layers displacement along the curve path and the extraction material by tool pin were responsible for the variations of channel properties on curve paths. Few authors investigated the failure of various tungsten-based tools during welding [41]. Asadi et al [42] studied influence of process parameters and tool geometry on material flow [43, 44], welding force, and temperature and strain distributions during friction stir processing. The step imperfection of material flow and channel formation in MFSC technique using the broken tool pin technique. The extruded material [45] from front to the back of tool pin was showed by the cross-section view of the pin that surrounded into the work piece [43]. Previous researches also suggest that work piece temperature condition would give the better result in FSW process [43]. On other side it was necessary to understand the problems of fabricators also.

Fabricators are under increasing pressure to produce stronger and lighter products though using less energy, less environmentally harmful materials with reducible cost and more promptly. The scientific technological significance is to improve the welding joint strength of dissimilar joint. By reviewing literature, the FSW tool is affected by high speed rotation which increases the temperature of FSW tool. If pre-heat treatment has been done on the job piece, it can reduce the speed of rotation of tool. Minimizing the speed of rotation will reduce the temperature of FSW tool. Some parameters are found from the past literatures which raises tool temperature in different condition of Rotation and welding speed. Individually all researches conducted their experiment without any expectation of result, so it is essential to develop some framework which guide the researchers to perform any experiment with some theoretical expectation, for this purpose discussion is proposed.

3. Discussion

From previous literature the factors identified are density of material, speed of welding mm/min, revolution per minute (RPM) and temperature obtained during stir welding. This information is very important for the research in this particular area. In the light of literature review done the study focuses on finding out the relationship among these variables to develop a framework. The following objectives for the study have been made to pursue the research further.

i. To identify the various factor affecting the temperature parameter during stir welding.

ii. To explore the relationship among variables.

iii. To understand the behaviour of temperature by developing a framework of variable under study.

Hypothesis Formulated

In order to achieve above stated objectives, the following hypothesis is formulated.

H1 there is a significant impact of density, speed and RPM on Temperature during stir welding of material.

For realizing the hypothesis, the data of density, speed, RPM and temperature is collected from previous studies. The data is further treated by using statistical tool. The Multiple regression analysis is used to formulate the framework. The data extracted from previous studies are shown in Table 1.

Table 1 Temperature of tool obtained at different parameters

S No.	Material	Temperature	Tool Rotational Speed RPM	Welding Speed mm/min	Density g/cc	Source
1	DH 36	1450	500	400	7.8	[8]
2	AISI 1018	1000	650	100	7.87	[4]
3	6060 T6 AL Alloy	466	500	140	2.71	[10]
4	AISI304	1065	550	400	8	[13]
5	HSLA steel	870	500	57	7.9	[20]
6	Mg-Ze42	648	950	200	1.74	[38]
7	AZ91 Mg Alloy	563	1400	25	1.8	[42]
8	AZ91 Mg Alloy	529	1400	50	1.8	[42]
9	AZ91 Mg Alloy	413	710	50	1.8	[42]
10	AA 6061	195	1000	55	2.7	[47]
11	AA 6061	135	1100	42	2.7	[47]
12	Al 1050	370	1000	56	2.8	[48]

The Table 2 explains the composite impact of all three independent variables on dependent variable i.e. temperature. The R square value of multiple regressions model is 0.8474. The variation is well explained by the three variables understudy in this multiple regression model. The standard error identified to be 177.781. The F-value 12.95 and corresponding p-value of 0.003032 is significant at 5% level of significance as exhibited in Table 3. Hence, we accept alternative hypothesis H1 that all three independent variables together also have significant impact on temperature.

Hypothesis H1: In present study we have a preposition to evaluate temperature during stir welding. The table 3 regression analysis exhibit the formation of model with variables RPM (x_1), Speed of welding (x_2), and density of material (x_3) has impact on temperature. On putting the coefficient values on standard multiple linear regression model, the following framework appear for temperature.

Table 2 Regression Statistics

Multiple R	0.920556
R Square	0.847424
Adjusted R Square	0.782035
Standard Error	177.781
Observations	11

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1228808	409602.7	12.9596	0.003032
Residual	7	221242.7	31606.09		
Total	10	1450051			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-202.754	307.4385	-0.6595	0.530668	-929.731	524.2221	-929.731	524.2221
RPM	0.253018	0.235801	1.073013	0.318857	-0.30456	0.810599	-0.30456	0.810599
Speed mm/min	1.92495	0.599036	3.21341	0.014788	0.508454	3.341446	0.508454	3.341446
Density	99.72802	28.92038	3.448365	0.010715	31.34219	168.1139	31.34219	168.1139

$$T = -202.754 + 0.253x_1 + 1.924x_2 + 99.72x_3$$

where, T is temperature has negative impact and all the 03 variables have positive coefficients, thus it means the independent variables have a direct negative impact on temperature in the model. This model can also be used for identifying the temperature during stir welding where affecting independent variables are RPM (x_1), Speed of welding (x_2), and density of material (x_3). This hypothesis enlightens that tool temperature is affected by tool rotation, welding speed and also the composition of material. High temperature of tool causes the tool wear which have to require the deep study by experimentation in further research. To reduce the effect on FSW tool required heat has to apply on work piece material for plastically deform. Singarapu et al. [49] heated to 300 °C and performed friction stir welding for subsequent passes. The experimental approach consisted in performing welded joints on steel plates of different grades using a thermal FSW procedure to obtain welds. Initially both the dissimilar material is taken close to each other, through clamp these materials are fixed from thickness side. Heat treatment is applied up to 200°C temperature [22] on the edge where welding joint is done by gas welding torch, with this increase in temperature material behaviour is soft and can be easily weld by FSW tool with minimum rotation speed and minimum temperature rise on FSW tool, as suggested by Darwins and Satheesh [38] for hot extruded alloy plate.

Conclusion

In present research different grade of steel material to be welded by friction stir welding on high speed of rotation with high grade tool that is considered. The high-speed rotation of tool requires the heavy motor machine and consumes high power. These tools have to face high temperature approximately1100°C, and have poor tool life due to tool wear. Minimized this rotational speed to minimize the temperature of tool occur during FSW process and tool wear, also tool temperature depends on the density of material. Minimum rotation of tool minimizes the installation cost of machining and tool.

According to general observation by the researchers, FSW tool pin is, closely related to thermal (grain growth) and mechanical deformation of the work piece joint. Since surface anomalies, strain hardening and residual stress are also consequences of these effects, it would be interesting to study the possible inter relationship. In fact, the researchers working on tool tilt angle on machining have primarily attributed reduction in tool wear. Furthermore, influence of temperature developed on plunging including dwell time on aluminium alloy joint needs research attention.

According to general hypothesis, temperature developed during welding change strength and grain structure. Increase in temperature causes weak strength joint and also it gives greater grain structure. Moreover, speed of FSW tool and transverse welding is anisotropic with different variation of temperature which effect on strength. Careful selection of cutting parameters are some of the important considerations for the improvement of strength of joint.

Conflict of interest

The author declares no conflict of interest.

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