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Influence of shoulder diameter on Temperature and Z-parameter during friction stir welding of Al 6082 alloy

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Abstract. In this research article, the effect of increasing shoulder diameter on temperature and Zener Holloman (Z)-parameter for friction stir butt welded AA6082-T6 was studied. The temperature at the Advancing side (AS) of weld was measured using the K-Type thermocouple at four different equidistant locations. The developed analytical model is utilized to predict the maximum temperature (T_{peak}) during the welding. The strain, strain rate, Z- Parameter for all the shoulders at four distinct locations were evaluated. The temperature increases with increase in shoulder diameter and the maximum temperature was recorded for 24mm shoulder diameter. The computed log Z values are compared with the available process map and results shows that the values are in stable flow region and near to stir zone the values are in Dynamic recrystallization region (DRX). The axial load (F_z) and total tool torque (N-m) are found to be higher for shoulder diameter of 21 mm i.e., 6.3 kN and 56.5 N-m respectively.

1. Introduction

Friction Stir welding (FSW), a solid state welding process is also termed as continuous hot shear autogenous process [1, 2]. The working principle of FSW is a three stage process namely (a) *plunging and dwelling, (b) traversing or welding* and *(c) retreating*. In the first stage the plunging and dwelling where a specially designed consumable/non-consumable pin/probe of nearly one-third of the shoulder diameter is rotated at desired speed (rpm) and simultaneously inserted in to the joining edges of the two plates to be welded either by force control mode or position controlled mode and dwell for certain period (seconds) so that because of the friction at the tool/workpiece interface the material is heated and plasticizes there by reducing the applied force. The second stage, the traversing or welding where the rotating non-consumable tool is linearly traversed along the weld/joint line with desired velocity therefore the joint is formed. In the final stage, i.e., retreating where the rotating tool is extracted out of the material leaving a keyhole of almost equal to dynamic volume of the pin [3, 4, 10, 17, 18].

The essential variables of the process are tool rotational speed (rpm), tool traverse speed (mm/min) and axial force (kN), the secondary parameters which influence the quality of the joint include tool geometry, tool tilt angle (degrees), plunge depth, and many other depending on the application. Nandan et al. [3] reviewed the FSW process in the aspects of plastic flow, heat generation and transfer during welding, parameters of tool design, formation of defect, structure and properties of the welded materials. They concluded that depending on various process parameters, temperature filed, force, torque and power are varying. The use of friction stir welding in transportation industries is summarized and discussed in brief by Thomas et al. [2] and also on the increase of the shoulder diameter region, concluding to the side flash generation and limits to certain critical diameter. In friction stir, the mechanism of weld formation generally involves two kinds of material flow regimes i.e., pin-driven flow and shoulder driven flow as discussed by Kumar et al. [4] that as the interaction of the shoulder with workpiece increases, the material that escapes from the weld interacts more with shoulder and reverted back to the weld.

Employing the Z-parameter the shoulder diameter influence on plastic deformation was studied by Reddy et al.[10] to explain the large plastic deformation. In an attempt to select the optimum shoulder diameter DebRoy et al. [20] proposed a model based on maximum torque utilization. Significant research has been done on influence of shoulder diameter, however, in particular for 6082-T6 material, the data is inadequate and very few researchers calculated the Z value, which is most important factor to describe the plastic behavior of material and to understand the underlying science of property variations.

2. Experimental

2.1 Materials and Methods

The 6 mm thick AA6082-T6 sheet of 150x70mm dimensions and H13 tool steel of 70 mm length was chosen as the base and tool material respectively and the experiments were carried out on FSW machine (RV Machine tools make, Coimbatore).The process parameters used during the process are listed in the Table 1. The tool was designed as plane shoulder with taper cylindrical pin profile. The selected process parameters 900 rpm, 20 mm/min were resulted from the best condition from the trial experiments [17]. During the welding process, the K-type thermocouples were inserted up to 4mm from the bottom and transient temperatures were recorded at four locations on the advancing side (AS) as shown in the Fig. 1 and 2. These thermocouples were connected to the USB based Data Acquisition module (USB-TC, MCC make) for recording the data as displayed in the Fig. 1.

Table 1: Materials and Conditions used during Welding.

Process Parameter	**Value**	**Process Parameter**	**Value**
Tool rotational speed ω, (rpm)	900	Tilt angle (degrees)	1
Tool Traverse speed υ_f, (mm/min)	20	Pin Length h_P, (mm)	5.5
Shoulder diameter D_s (mm)	18, 21, 24	Plunge Depth (mm)	5.7
Pin top diameter D_{P_1} (mm)	6	Pin bottom radius D_{P_2} (mm)	3

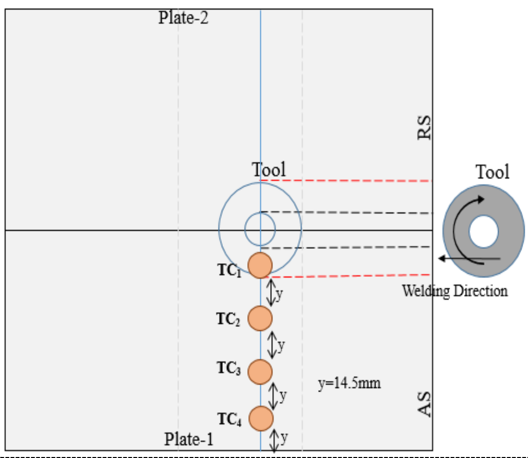

Figure 1. Arrangement of Thermocouples.

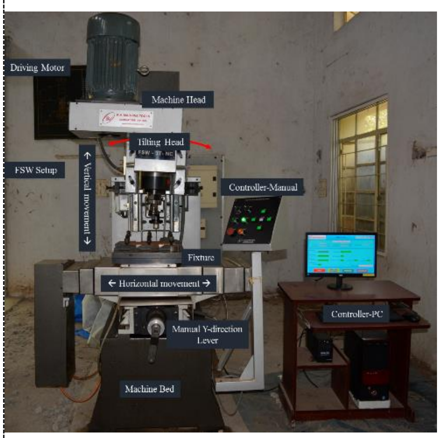

Figure 2. Experimental setup

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2.2 Constitutive Modeling

The tool torque, T_{tool} (N-m), axial force, F_Z (kN) acts on the tool were recorded from inbuilt online data-acquisition (DAQ) facility of the FSW machine during the entire friction stir welding process and these data is used for modeling the temperature, strain, rate of strain and Zener-Holloman parameter for the four locations of the temperature readings (TC_1 to TC_4).

2.2.1 Temperature for Taper cylindrical (TC) pin profile

During the FSW, the tool torque is expressed sum of the torques generated by shoulder, pin bottom and pin side surface [5-7] as shown in eq. 1, which was the input, from the online monitored tool torque from the Table 2. The tool torque for a taper cylindrical (TC) pin profile with flat shoulder is given in the eq. 2.

$$T_{Total} = T_{Shoulder} + T_{Pin\ bottom} + T_{Pin\ Surface} \quad (1)$$

$$\left[T_{Total}\right]_{TC} = 2\times\mu\times F_Z \times\left(\frac{R_S}{3} + \frac{\left(R_{P_2}^3 - R_{P_1}^3\right)}{3R_S^2} + \frac{\left(R_{P_1} + R_{P_2}\right)^2}{2R_S^2}\times L\times h_P\right) \quad (2)$$

Where Slant Height, $L = \sqrt{h_P^2 + \left(R_{P_1} - R_{P_2}\right)^2}$ & μ =Co-efficient of friction (=0.5, in general) [5, 18]

The E_L, energy generated per unit length of weld, can be obtained by multiplying the T_{Total} with the APR (tool advance per revolution) as shown in eq. 3.

$$E_L = T_{Total}\times APR \quad (3)$$

For a given material and the thickness, with the increase of pin length, the heat transfer efficiency increases, therefore there was need to consider the transfer efficiency (β) which is well-defined by the ratio of height of the pin (h_P) to the plate thickness (t). The effective energy generated per unit length of weld $\left(E_L\right)_{eff}$ is obtained by multiplying the energy to unit length with transfer efficiency as depicted in eq. 4.

$$\left(E_L\right)_{eff} = \beta\times E_L \quad (4)$$

The empirical relation given in eq. 5 is between the ratio of temperature and the effective energy generated to AA6082-T6 aluminum alloy [5-6]

$$\frac{T_{\max}}{T_s} = 1.56\times10^{-4}\left(E_L\right)_{eff} + 0.54 \quad (5)$$

2.2.2 Heat input

The heat input (J/mm) was determined for all the shoulder diameter using the eq.6 [9-10] and the calculated values were tabulated in Table 3. and shown in the Fig. 5

$$\mathrm{E} = \eta\frac{\left(2\pi\omega T\right)}{\upsilon_f} \quad (6)$$

Where, E = Heat Input in (J/mm), η =Efficiency Factor = 0.9 [10] (for aluminum alloys)

2.2.3 Flow stress model & Zener Holloman Parameter

FSW is regarded as a large strain deformation process, where the selection of constitutive flow stress model is critical. Out of several constitutive flow models, the Sellar's and Tegart (perfectly visco-plastic) model [11-14] is considered. The model relates the flow stress of a solid during hot

deformation which is equal to its recovery or recrystallization steady state of stress, independent of the plastic strain.
As per the Perzyna model, μ is function of the effective flow stress σ_e and effective strain rate $\dot{\varepsilon}$ as shown in eq. 7 [8]

$$\mu = \frac{\sigma_e}{3\dot{\varepsilon}}, \ where\ \dot{\varepsilon} = \left(\frac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}\right)^{1/2} \ and\ \dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad (7)$$

The rate of strain expressed in eq. 8 is a function of flow stress and temperature

$$\dot{\varepsilon} = A(\sinh \alpha\sigma_e)^n \exp\left(-\frac{Q}{RT}\right) \qquad (8)$$

Where constants, ln A, S^{-1} =19.29, n = 2.976, α, Mpa^{-1} =0.045, Q is activation energy, 153 kJ/mol for AA6082-T6 and R is universal gas constant, 8.314 J/mol/K were obtained by fitting the eq. 8 to hot deformation data [12], and all are dependent on temperature. By rearranging the above relation

$$\sigma_e = \frac{1}{\alpha}\sinh^{-1}\left[\left(\frac{Z}{A}\right)^{\frac{1}{n}}\right] \qquad (9)$$

Where Z, in eq. 9 is known as the Zener-Holloman (Z) parameter which is a strain rate compensated by temperature and is expressed as

$$Z = \dot{\varepsilon}\exp(Q/RT) \qquad (10)$$

Eq. 10 is used for the evaluation of 'Z', the temperature and rate of strain are the critical inputs from the experiments. Natural/true strain of the deformed material (ε) was calculated by using the eq. 11 [15-16]

$$\varepsilon = \ln\left(\frac{l}{APR}\right) + \left|\ln\left(\frac{APR}{l}\right)\right| \qquad (11)$$

l = deformed length= $2r\cos^{-1}\left(\frac{r-x}{r}\right)$, r=average probe diameter in mm, x =distance perpendicular to the welding direction, from the retreating side (RS) to the streamline in contact to tool pin. The strain rate is estimated from, $\dot{\varepsilon} = \varepsilon/t$, where t, time in seconds per revolutions.

3. Results and Discussion

3.1 Evaluation of Peak Temperature and Forces

The temperature, total heat input, axial force and tool torque data for all the shoulder diameters was evaluated and shown in the Table 2, Measured peak values are around the tool shoulder and are different from those measured at four distinct locations.

Table 2: Axial force, Tool torque and Total Heat input for different cases

Shoulder diameter (mm)	Axial Force, F_Z (N)	Tool Torque, T, (N-m)	Heat Input, E (J/mm)	Measured* Temperature, T_{Peak} (^{0}K)	Calculated Temperature, T_{Peak} (^{0}K)
18	3814.79	34.33	2780.98	656	641.45
21	6276.26	56.49	4575.39	647	795.67
24	6129.16	55.16	4468.15	679	787.70

The Fz and T and also max. temperature are identified to increase with shoulder diameter as revealed in Fig. 3(a) and Table 2, because of the frictional heating and at the point of maximum frictional heat of the material with further increasing in the shoulder diameter decreases the force and tool torque decreases since the material is already plasticized [9-10] there is no much effort because of the size of the shoulder after critical value of diameter. Heat input values were plotted for all the shoulder diameters for the process parameters selected, as presented in Fig. 3(b). The increase in the diameter of shoulder increases the heat input as well, but up to the critical diameter of 21 mm which may be attributed to the increase in the frictional area and after that it starts stabilizing**.**

3.2 Zener-Holloman Parameter

The flow stress at high temperature levels is the function of 'Z' (strain-rate compensated by temperature), it is termed as the index of the level of material plasticity. It determines the joint effect of temperature and rate of strain on the material plasticity.

Further, the value of 'log Z' at specified locations in the FSW region can be selected as the index of material flowability, with significant effect towards the quality of the weld. The computed log Z values as shown in Table 3 and 4 are compared with the available process map [19] and results shows that the values are in stable flow region and near to stir zone the values are in Dynamic recrystallization region (DRX).

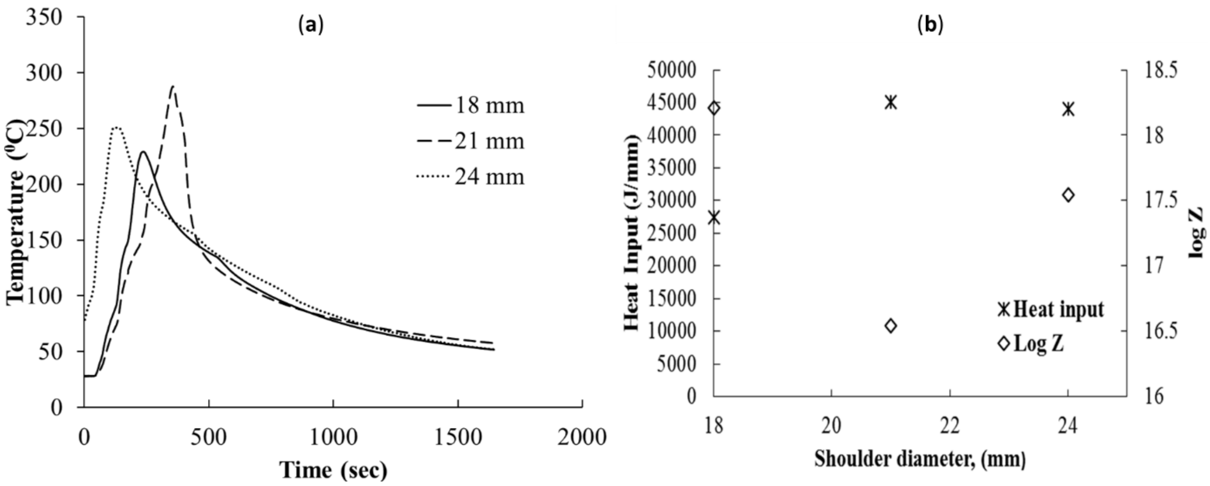

Figure 3. (a) Temperature profiles (b) Heat input and Log Z for diferent Shoulder diamaters

Table 3: Variation of Temperature, Log Z for different cases at Location TC_1 and TC_2

	At Location TC_1		**At Location TC_2**	
Shoulder diameter (mm)	**Temperature (^{0}K)**	**Log Z**	**Temperature (^{0}K)**	**Log Z**
18	502.23	18.21	423.08	21.19
21	560.92	16.54	473.11	19.19
24	524.09	17.55	455.58	19.84

Table 4: Variation of Temperature, Log Z for different cases at Location TC_3 and TC_4

	At Location TC_3		**At Location TC_4**	
Shoulder diameter (mm)	**Temperature (^{0}K)**	**Log Z**	**Temperature (^{0}K)**	**Log Z**
18	402.33	22.16	381.53	23.24
21	417.91	21.42	404.84	22.04
24	417.97	21.42	410.87	21.75

4. Conclusions

The work carried out has resulted the following

1. The axial load (Fz) and total tool torque (N-m) was found to be higher for shoulder diameter of 21 mm i.e., 6.276 kN and 56.486 N-m respectively this is because of the critical diameter beyond this size of shoulder, induced plasticity cannot increase significantly.
2. The analytical model for temperature generation, is found to be suitable for shoulder diameters less than or equal to 18mm (approximately 2.5% error for shoulder diameter 18mm) because of the lack of temperature dependent material properties in the developed relation. As a noted fact, the peak temperature 679^{0}K is obtained for the shoulder diameter of 24mm, there by the thermocouples measurement is justified.
3. The computed log Z values for different regions on AS results in stable flow region under the process map of the 6082 aluminium alloy

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References

[1] Thomas WM, Nicholas ED, Needham JC, Murch MG, Templesmith P, Dawes CJ, et al. Patent Application No. 9125978.8; December 1991.

[2] W.M.U. Thomas, E.D. Nicholas, A. Hall, C. Cb, Friction stir welding for the transportation industries, 18 (1998) 269–273

[3] R. Nandan, T. Debroy, H. Bhadeshia, Recent advances in friction-stir welding – Process, weldment structure and properties, Prog. Mater. Sci. 53 (2008) 980–1023. doi:10.1016/j.pmatsci.2008.05.001.

[4] K. Kumar, S. V. Kailas, The role of friction stir welding tool on material flow and weld formation, Mater. Sci. Eng. A. 485 (2008) 367–374. doi:10.1016/j.msea.2007.08.013.

[5]C. Hamilton, S. Dymek, a. Sommers, A thermal model of friction stir welding in aluminum alloys, Int. J. Mach. Tools Manuf. 48 (2008) 1120–1130. doi:10.1016/j.ijmachtools.2008.02.001.

[6] V.S. Gadakh, K. Adepu, Heat generation model for taper cylindrical pin profile in FSW, J. Mater. Res. Technol. 2 (2013) 370–375. doi:10.1016/j.jmrt.2013.10.003.

[7] A. Ramadan, S. Essa, M. Mohamed, Z. Ahmed, A.Y. Ahmed, A.E. El-nikhaily, An analytical model of heat generation for eccentric cylindrical pin in friction stir welding, Integr. Med. Res. (2016) 1–7. doi:10.1016/j.jmrt.2015.11.009.

[8] Zienkiewicz OC, Cormeau IC. Visco-plasticity solution by finite-element process. Arch Mech 1972; 24:872–89.

[9] E. Akinlabi, S. Akinlabi, Effect of Shoulder Diameter on the Resulting Interfacial Regions of Friction Stir Welds between Aluminium and Copper, Amr. 299–300 (2011) 1146–1150. doi:10.4028/www.scientific.net/amr.299-300.1146

[10] K. Ramanjaneyulu, G.M. Reddy, A.V. Rao, Role of Tool Shoulder Diameter in Friction Stir Welding : An Analysis of the Temperature and Plastic Deformation of AA 2014 Aluminium Alloy, (2014). doi:10.1007/s12666-014-0401-z.

[11] T. Sheppard, D.S. Wright, Determination of flow stress: part1 constitutive equation for aluminum alloys at elevated temperatures, Met. Technol. June (1979) 215–223

[12] T. Sheppard, A. Jackson, Constitutive equations for use in prediction of flow stress during extrusion of alurninium alloys, Mat. Sci. Tech. 13 (1997) 203-209.

[13] T. Sheppard, D.S. Wright, Determination of flow stress: part1 constitutive equation for aluminum alloys at elevated temperatures, Met. Technol. June (1979) 215–223.

[14] I. Flitta, T. Sheppard, Nature of friction in extrusion process and its effect on material flow, Mater. Sci. Technol. 19 (2003) 837–846. doi:10.1179/026708303225004422.

[15] A.P. Reynolds, Flow visualization and simulation in FSW, Scr. Mater. 58 (2008) 338–342. doi:10.1016/j.scriptamat.2007.10.048

[16] T. Long, W. Tang, A. P. Reynolds, Process response parameter relationships in aluminium alloy friction stir welds, Sci. Technol. Weld. Join. 12 (2007) 311–317. doi:10.1179/174329307X197566.

[17] M. Krishna Kishore, A. Kumar, Effect of shoulder profile on the friction stir welding of 6082-T6 aluminum alloys, IIW 6th WRCC, 7th –9th April 2016, IIW Hyderabad.

[18] M. Krishna Kishore, A.Kumar, Experimental & Simulation Studies of Temperature distribution in Friction Stir Welded AA6061-T651 alloy using Deform-3D, ICTACEM- 14, Dec 29- 31st 2014, IIT Kharagpur

[19] Prasad Y V R K, and Sasidhara S. Hot Working Guide: A Compendium of Processing Maps, ASM International (1997).

[20] A. Arora, A. De, T. Debroy, Toward optimum friction stir welding tool shoulder diameter, Scr. Mater. 64 (2011) 9–12. doi:10.1016/j.scriptamat.2010.08.052.