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To cite this article: M Krishna Kishore et al 2019 IOP Conf. Ser.: Mater. Sci. Eng. 474 012012

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Effect of tool/material interface temperature on flow stress and the Zener-Holloman parameter in Al 6082 friction stir butt welds

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Abstract. This paper outlines the temperature around the tool/material interface during friction stir welding (FSW) of Al 6082-T6 alloy. The first section gives a brief overview on temperature measurement around the tool periphery, i.e. trailing edge (TE), leading edge (LE), retreating side (RS), advancing side (AS), and their corners associated with it. The second section was focused on the plasticity behavior of welded material as a function of temperature, governed by flow stress and Zener Holloman (Z)-parameter. Around the tool periphery in a clockwise direction, the critical observations were made from the obtained data. The peak temperature surges with increasing shoulder diameter and it was higher for the weld done with 24mm shoulder diameter tool. It was noted that during every cycle there was asymmetric temperature distribution at tool/material interface, the rate of heat generation was higher in TE to RS-LE zone and lower in RS-LE to TE zone. The calculated flow stress and log Z values were higher on RS and lower in AS to RS-LE zone of the tool shoulder periphery. Flow stress was almost uniform for all the shoulder diameters except on RS of 18mm shoulder tool. The optimum tool shoulder diameter was found to be 21mm, below which the flow stress was high and above which the plasticity at tool shoulder periphery was negligible.

1. Introduction
Al 6082 alloy is a relatively high-strength heat-treatable 6xxx series aluminum alloy and a replacement to conventional Al 6061 alloy. The welding of these alloys leads to coarsening or dissolution of the fine precipitates due to the developed thermal cycles [1]. The use of friction stir welding (FSW) for aluminum alloys, a promising solid-state welding method came into existence since the 1990s. It has numerous advantages over conventional fusion welding techniques [2]. The process occurs in three simple steps, namely: plunging, dwelling, and traversing. The frictional contact heat of shoulder and frictional as well as shear deformation heat of pin is responsible for the formation of bond [3]. The review on the FSW process in the aspects of heat generation was done by Nandan et al. [4]. It was proposed that the temperature, tool force, and torque depend on the process parameters, tool geometry, and workpiece material. The flow of the
material and heat generation were governed by tool geometry, which consists of a pin and shoulder. The profiles of the pin and shoulder were responsible for frictional contact heat generated during the process, and for deforming the material respectively [2]. It was observed that the contribution of the pin is approximately 3% of shoulder heat generation [5].

The shoulder size influence on frictional heat generation and weld formation were studied by many researchers [6-15]. Zhang et al. [6] studied on the effect of the size of the shoulder on temperature distribution, they established a quadratic relation for the efficient power as a function of shoulder diameter and concluded that with increasing shoulder size, the temperature, and effective power increases. In the later attempts by Zhang et al. [7], the effect of shoulder diameter and taper angle on heat generation was analyzed. It was observed that the shoulder-workpiece contact area generates more heat compared to the pin-workpiece contact area. Elangovan and Balasubramanian [8] investigated on the effect of increasing shoulder diameter and concluded that shoulder diameter was proportional to heat generation, the maximum shoulder diameter in their case was 21mm which resulted in the wider thermo-mechanically affected zone (TMAZ). The work carried by Akinlabi and Akinlabi [9] at a constant tool tilt and depth of penetration shows with the increasing shoulder diameter, axial force and torque were increasing.

Kumar and Kailas [10] observed the shoulder interaction with the workpiece and stated that with their increase in interaction, the material outflows from the weld and diverted again towards the weld region. Thomas and Nicholas [11] also reported, increasing the shoulder region leads to the flash generation on sides, which confines to the certainty of critical shoulder diameter. The Zener Holloman (Z-parameter) relation, the influence of shoulder diameter on plastic deformation at peak temperature was reported by Ramanjaneyulu et al. [12]. It was concluded that with an increase in shoulder diameter, temperature and Z-parameter increases up to a certain diameter and beyond that the shoulder contribution is less for the quality of the joint as maximum friction heat was generated in the material. For the selection of optimum shoulder diameter, Arora et al. [13] developed a model based on the utilization of maximum torque. It was understood that the sticking torque signifies the resistance to the flow of plasticized material and it was maximum at critical shoulder diameter. Mehta et al. [14] reported on the influence of shoulder diameter on thermal cycles, forces and torque requirement with a three-dimensional heat transfer and material flow model. Further with the optimum tool shoulder diameter, Zhang et al. [15] observed an asymmetric temperature distribution around the tool shoulder during numerical investigations, and they reported that the temperature gradient was higher in leading edge that in trailing edge. With the existing literature, it was noted that significant research work was published on the effects of shoulder diameter in the FSW process. But for data relating to the temperature flow, material plasticity governed by flow stress and Zener-Holloman parameter was scarce for Al 6082 alloy. In the present study, the work was classified into two categories, i.e., one focusing on the temperature distribution and the other on the flow stress evaluation as well as the Zener-Holloman parameter around the tool shoulder.

2. Experimental procedure

2.1. Methods and materials

A taper cylindrical pin profiled tool made of H13 tool steel (Hardness: 50 HRC) with three different flat shoulder diameters were chosen for welding of Al 6082 alloy sheet of 6mm thickness in T6 heat treated condition. The chemical composition for Al 6082 alloy work material was indicated in table 1.

The experiments were conducted on the Friction Stir welding machine of Make: RV Machine Tools Pvt. Ltd., Coimbatore; Model: FSW-3T-NC. Based on the pilot experiments, the optimum process parameters and tool geometry (as indicated in table 2) were adopted from the previous studies given in references [17-21]. The schematic layout for data acquisition system to measure temperature and force measurements during FSW is shown in figure 1. The K-type (grounded) thermocouples were brought in to contact at various
locations as indicated in figure 2, i.e., at every 45° steps around the tool shoulder outer boundary, Layer 0 (ϕ P mm). Similarly, from Layer 0, the temperatures were also recorded at Layer 1 (ϕ Q mm) and Layer 2 (ϕ R mm) as shown in figure 2, where P = 18, 21 and 24 mm, corresponding to Q = 28, 31 and 34 mm, & R = 38, 41 and 44 mm, respectively. By using the data acquisition system (DAQ) of Model: USB- TC, Make: Measurement Computing Corporation Pvt. Ltd. the temperature readings were recorded.

### Table 1. The chemical composition of Al 6082-T6 work material.

| Element, % wt. | Cu | Mg | Si | Fe | Mn | Zn | Ti | Cr | Al |
|----------------|----|----|----|----|----|----|----|----|----|
|                | 0.03 | 0.96 | 1.16 | 0.27 | 0.05 | 0.01 | 0.02 | Remainder |

### Table 2. The process parameters and tool geometry adopted [20].

| Process Parameter | Value | Process Parameter | Value |
|-------------------|-------|-------------------|-------|
| Tool rotational speed ω, (RPM) | 800 | Pin bottom radius R₀ (mm) | 1.5 |
| Tool traverse speed V₀, (mm/min) | 40 | Pin length h₀, (mm) | 5.5 |
| Plate thickness, t₀ (mm) | 6 | Taper angle, α (degree) | 15.6° |
| Shoulder radius R₁ (mm) | 9, 10.5, 12 | Tilt angle (degree) | 1 |
| Pin top radius R₂ (mm) | 3 | Plunge depth (mm) | 5.7 |

**Figure 1.** Schematic layout of the temperature & force measurements.

**Figure 2.** The arrangement of thermocouples around the shoulder.

### 2.2. Evaluation of the Zener Holloman parameter (Z)

The recorded values of forces and torque acting on the tool during the entire FSW process were adopted for modeling the Z-parameter and flow stresses around the tool shoulder. It is essential to understand the amount of heat generated when different shoulder diameters were adopted. The heat input as a function of torque and process parameters, for the different shoulder diameters according to Akinlabi et al. [9] and Ramanjaneyulu et al. [12] is given in equation (1).

\[
q = \eta \left( \frac{2\pi \omega T₁}{V₀} \right)
\]

where q is heat input (J/mm), η is efficiency factor (equal to 0.9 for aluminum alloys), ω is tool rotational speed, V₀ is tool traverse speed, and T₁ is tool torque (N-m).
According to Perzyna model [4, 18], the viscosity ($\mu$) is a function of effective flow stress ($\sigma_e$) and effective strain rate ($\dot{\varepsilon}$), according to the following equation:

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

(2)

where $\dot{\varepsilon}$ is effective strain rate, which can also be expressed in terms of flow stress and activation energy as per Sellars and Tegart's viscoplastic model [20-22]. This model was used to solve large strain deformation processes it was therefore applicable for FSW also. Equation (3) shows the expression for the effective strain rate as a function of flow stress, activation energy, and temperature. In this model, the flow stress was obtained by performing hot deformation tests of a solid which were equivalent to its recovery or recrystallization steady state of stresses.

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

(3)

where $\sigma_e$ is effective flow stress; $Q$ is activation energy, 153 kJ/mol; $R$ is universal gas constant, 8.314 J/mol/K; $T$ is temperature in °K; while the material constants $n$, $A$, and $\alpha$ have the following values for Al 6082 alloy [20]: $n = 2.976$, $\ln A = 19.29$ s$^{-1}$, $\alpha = 0.045$ MPa$^{-1}$ By rearranging equation (3) we get equation (4):

$$\sigma_e = \frac{1}{\alpha} \sinh^{-1}\left[\left(\frac{Z}{A}\right)^{1/2}\right]$$

(4)

where $Z$ is the Zener-Holloman ($Z$) parameter representing the strain rate, which is given in equation (5).

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)$$

(5)

The rate of strain means the strain w.r.t time ($\dot{\varepsilon} = \varepsilon / t$) where time ($t$) in seconds. The natural strain for the deformed shape of material ($\varepsilon$) can be evaluated using equation (6) [20-22]:

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

(6)

where APR is tool advance per revolution, $l =$ length deformed = $2r \cos^{-1}((d-x)/d)$, $d =$ diameter probe in mm, $x =$ perpendicular distance to the weld direction i.e. from the retreating side (RS) to the streamline in contact to tool pin.

3. Results and Discussion

3.1. Force measurement

For various shoulder diameters, the axial force was measured, and the heat input values were calculated using equation (1), as shown in figure 3. It was noted that with the increase of shoulder diameter the axial force and heat input increased significantly up to 21 mm and later they remained constant. This behavior can be attributed to the material characteristics, where the frictional or shear deformation energy reaches to maximum, and even on the further increase of the size of shoulder the effect is insignificant. The total tool torque ($T_t$) and axial force ($F_z$) was higher for 21 mm shoulder diameter, i.e., 56.49 N-m and 6.28 kN respectively.
3.2. Macrostructural observation

Figure 4 shows the macrostructure of weld zone obtained by different shoulder diameters. The flow of weld line remnant was observed in all the welds. For weld with 24 mm shoulder diameter, the macrostructural observation revealed a crack, which was originated at shoulder tip and extended to the root of the weld. This could be the reason for lower values of axial force and tool torque. However, for welds with 18 and 21 mm shoulder diameters, the weld region was defect free. It was depicted that the weld region is wider with increasing the shoulder diameter. With increasing the shoulder diameter, the size of the weld zone increases as reported in the earlier literature [12].

3.3. The Zener-Holloman parameter and flow stress at shoulder periphery
The Zener-Holloman parameter (Z) used to quantify the plasticity level for a given material. The flow stress at higher temperatures is the function of Z. The asymmetric behavior of temperature flow in the FSW region and their associated effects on material plasticity around the tool shoulder should be apparent. The measured temperature and computed log Z values for different shoulder diameters at different layers were shown in tables 3-5. The values of Z were found to be higher on RS, stable in RS-LE, and higher on LE in case of layer0, layer1, and layer2 respectively. As reported by Ramanjaneyulu et al. [12], with increasing the shoulder diameter, the trend of Z- value at periphery indicated a negligible plasticity.

![Figure 5. Variation of flow stress for Layer0.](image1)

![Figure 6. Variation of log Z for Layer0.](image2)

| Location | Parameter | AS | RS | LE | TE | AS-LE | AS-TE | RS-LE | RS-TE |
|----------|-----------|----|----|----|----|-------|-------|-------|-------|
| Shoulder diameter (mm) | 18 | T (°C) | 366 | 202 | 342 | 367 | 383 | 342 | 335 | 311 |
| | | log Z | 14.8 | 19.1 | 16.3 | 14.8 | 14.7 | 15.3 | 15.4 | 15.9 |
| Shoulder diameter (mm) | 21 | T (°C) | 364 | 322 | 373 | 310 | 374 | 350 | 383 | 339 |
| | | log Z | 14.8 | 15.7 | 14.7 | 16 | 14.7 | 15.1 | 14.5 | 15.4 |
| Shoulder diameter (mm) | 24 | T (°C) | 406 | 328 | 364 | 342 | 379 | 383 | 386 | 352 |
| | | log Z | 14.1 | 15.6 | 14.8 | 15.3 | 14.6 | 14.5 | 14.4 | 15.1 |

| Location | Parameter | AS | RS | LE | TE | AS-LE | AS-TE | RS-LE | RS-TE |
|----------|-----------|----|----|----|----|-------|-------|-------|-------|
| Shoulder diameter (mm) | 18 | T (°C) | 237 | 190 | 197 | 286 | 235 | 272 | 208 | 224 |
| | | log Z | 18.0 | 19.6 | 19.3 | 16.6 | 18.0 | 16.9 | 18.9 | 18.4 |
| Shoulder diameter (mm) | 21 | T (°C) | 260 | 270 | 207 | 270 | 245 | 270 | 231 | 264 |
| | | log Z | 17.3 | 17.0 | 19.0 | 17 | 17.7 | 17.0 | 18.2 | 17.2 |
| Shoulder diameter (mm) | 24 | T (°C) | 252 | 256 | 242 | 288 | 252 | 301 | 223 | 302 |
| | | log Z | 17.5 | 17.4 | 17.8 | 16.5 | 17.5 | 16.22 | 18.4 | 16.2 |

The calculated flow stress was found to be uniform around the tool shoulder for all the shoulder diameters. It is seen in figure 5 that the flow stress is higher for smaller diameters in RS because the material is cooler on RS, as compared to AS, therefore more heat is required to warm and plasticize the material. The similar
trends were observed in log Z plot as shown in figure 6, where the log Z values are higher on RS. Comparatively, the log Z values are lower on AS, the temperature is higher in the zone of AS to RS-LE in the clockwise direction. This shows that the material was plasticized in the zone of AS to RS-LE and transported around the tool pin thereby depositing with forging action in the TE, as reported in the earlier literature [16].

Table 5. The variation of temperature, log Z for layer2 around the shoulder.

| Location | Parameter | AS  | RS  | LE  | AS-LE | AS-TE | RS-LE | RS-TE |
|----------|-----------|-----|-----|-----|-------|-------|-------|-------|
| Shoulder diameter (mm) 21 18 | $T$ (°C) | 193 | 148 | 150 | 251 | 186 | 209 | 161 | 190 |
| | log Z | 19.5 | 21.3 | 21.2 | 17.6 | 19.7 | 18.9 | 20.7 | 19.8 |
| | $T$ (°C) | 215 | 193 | 150 | 212 | 208 | 226 | 194 | 202 |
| | log Z | 18.7 | 19.5 | 21.2 | 18.7 | 18.9 | 18.3 | 19.4 | 19.0 |
| | $T$ (°C) | 240 | 236 | 184 | 274 | 223 | 248 | 180 | 278 |
| | log Z | 17.9 | 18.0 | 19.8 | 16.9 | 18.4 | 17.6 | 19.9 | 16.8 |

4. Conclusions
The following conclusions were drawn from the present research work:

- In the domain of experiments conducted in the present study, the maximum heat input was observed at 21 mm shoulder diameter. The rate of heat generation was higher in TE to RS-LE and lower in RS-LE to TE. At 21 mm shoulder diameter, the higher values of total tool torque ($T_t$) and axial load ($F_z$) were noted, i.e., 56.49 N-m and 6.28 kN, respectively.
- Around the tool shoulder periphery in a clockwise direction, the calculated log Z and flow stress values were higher on RS and lower in the zone of AS to RS-LE. This was because of cool and warm material conditions respectively. With the increasing shoulder diameter, the peak temperature increases and was higher for 24mm shoulder diameter in AS to AS-LE zone, i.e., 406°C.
- The log Z values were lower on AS, and the temperature was higher on the zone of AS to RS-LE clock-wise direction this shows that the material was plasticized in the zone of AS to RS-LE and transported around the tool pin thereby depositing with forging action in the TE.

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