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Material flow visualization and determination of strain rate during friction stir welding

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ABSTRACT

Particle image velocimetry (PIV) technique was adopted to understand material flow and measure strain rate around the tool pin during friction stir welding (FSW). The micro-spherical glass tracers in a transparent visco-plastic material, of almost similar densities, were used as experimental materials. The characteristics of material flow, in particular, flow velocity and strain rate were obtained by following the path of the tracer particles. A rotational zone around the tool pin was observed due to large deformation of the material close to the tool pin. The maximum velocity was noted to be 60% (close to the pin surface) of the pin peripheral velocity, and strain-rate was found to be 20 s^{-1} (0.6 mm away from the pin periphery) at FSW parameters of 170 rpm and 50 mm min^{-1}. The strain rate was found to increase from 8 s^{-1} to 44 s^{-1} with increase in rotational speed from 75 rpm to 425 rpm. Predictive correlations were established for variations of velocity and maximum strain-rate as a function of rotational, traverse speeds and distance away from the tool pin surface. Overall, it was established that PIV technique can be utilized for the understanding of material flow and strain-rate behaviour during FSW. Furthermore, this technique enabled in-situ visualization overcoming drawbacks of other techniques reported in the literature.

1. Introduction

Friction stir welding (FSW) is a solid-state joining technique in which a rotating tool is inserted between two metal plates. The metal plates are joined when rotating tool travels along the interface. The plates are joined by material flow caused by stirring action around the tool pin (Mishra and Ma, 2005). Friction stir processing (FSP) is a derivative of FSW technique wherein the process is used for microstructural modification instead of joining. However, both FSW and FSP are similar in terms of material flow behaviour. The technique is very simple and offers enormous potential for joining and processing of low temperature materials. In order to get a sound joint, the understanding of the material flow and strain rate is the key. Significant insight in to the material flow was provided by various researchers using different methods and techniques. One of the techniques used to understand the material flow is by placing marker or tracers of different composition in the form of balls or strips. For instance, Colligan (1999) used small steel shots set at different positions in aluminium sheet to understand the material flow. After welding, the spatial distribution of steel balls was studied using radiography. Guerra et al. (2003) and Schmidt et al. (2006) investigated the material flow in Al alloys using thin copper foil as marker and found the rotational and transitional zones around the tool pin. They found that velocity of marker was higher at retreating side than the average velocity. Liechty and Webb (2008) investigated the flow behaviour by tracking tracers and grid deformation in a plasticine workpiece. The initial and final positions of the tracers have been used for the rough estimation of material flow velocity and strain rate. Use of radiography (Morisada et al., 2015a) has recently enabled tracking of the tracer during the process and showed that tracer rotates multiple times around the pin before leaving the rotational zone. Great deal of understanding has been obtained using these techniques, however, two drawbacks are noticed; a) thermo-physical properties of the tracer and parent materials were quite different, b) information about the intermediate positions of the tracer could not be obtained. The tracer's size and, difference in the densities of the tracer and matrix materials may modify the actual flow pattern due to drag and gravity forces.

In addition to material flow behaviour, numerous efforts were made to determine strain rate during FSW. For instance, Frigaard et al. (2001) estimated the strain rate in the range of 1.6–17.3 s^{-1} at 1500 rpm and traverse speed of 300–720 mm min^{-1} by correlating grain size with Zener-Holloman parameter ($Z = \dot{\varepsilon}\, exp\left({}^{Q}/_{RT}\right)$) where $\dot{\varepsilon}$ is strain rate, T is

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absolute temperature in K, R is universal gas constant and Q is activation energy. Chang et al. (2004) observed that the strain rate varied from 5 to 50 s^{-1} during FSW (180–1800 rpm and 90 mm min^{-1}) based on the assumption that a torsion-type deformation occurs during the process. Arora et al. (2009) reported computed strain rates in the range of ± 9 s^{-1} at 300 rpm and 126 mm min^{-1} during FSW of AA2524 using a three-dimensional coupled viscoplastic flow and heat transfer model. Chen and Cui (2009), reported strain rate of 85 s^{-1} at 740 rpm and 170 mm min^{-1} during FSW of Al–Si cast alloy. Chen et al. (2013) computed the strain rate during FSW of AA6061 in the range of 100–464 s^{-1} near the tool pin surface at 920 rpm, 20 mm min^{-1}. In another work, Chen et al. (2016) computed the velocity of the material flow from pin centre to the outer edge of the shoulder. They have shown linear increase in velocity with radial distance at pin bottom surface, as well as under the shoulder surface, except edges of the pin and shoulder. Morisada et al. (2015b) calculated strain rate of ± 13.4 s^{-1} at 1000 rpm and 400 mm min^{-1} by visualization of material flow using X-ray radiography during FSW of AA1050. Ammouri et al. (2015) estimated the strain rate values of 29–125 s^{-1} at 600–2000 rpm and 75–900 mm min^{-1} in AZ31B Mg alloy. They found that the strain rate was highly influenced by rotational speed rather than traverse speed. It is evident from these studies that wide variation in strain rates were reported. Variation in strain rate values could be due to different techniques, processing parameters, and processing materials used. Hence, well established technique, which can provide in-situ visualization and measurement of strain rates, is required for the better estimation and designing of the processes.

To overcome some of the above mentioned drawbacks of earlier techniques, particle image velocimetry (PIV) technique has been adopted herein to understand material flow during FSW. PIV technique can provide instantaneous velocity field (Bugg and Rezkallah, 1998). This technique provides in-situ visualization of material flow and, estimation of strain rate during process in precise manner (Adrian, 2005). In experimental simulation (Liechty and Webb, 2008) as well as in numerical simulation (Nandan et al., 2006a; Long and Reynolds, 2006) material rheology during FSW was described as non-Newtonian, incompressible and viscoplastic. Also, PIV technique requires transparent material for investigation of flow behaviour. Therefore, a transparent experimental material was selected such that it exhibits non-Newtonian, incompressible and viscoplastic behaviour.

2. Experimental methodology

The material flow was visualized using 10 ± 2 μm spherical glass tracer (density 1100 kg m^{-3}) in a transparent visco-plastic fluid (density 1000 kg m^{-3}) using the PIV technique. A cylindrical flat tip tool pin of 8.2 mm diameter was used for the process. Rotational and traverse speeds of the tool was varied in the ranges of 75–425 rpm and 50–110 mm min^{-1}, respectively. Due to the negligible amount of tracer particles, in comparison to overall processing material, the density of the processing material remained constant. Therefore, the present study can claim that the study was performed without alternating physical properties of the material.

A schematic of experimental set-up with PIV system is shown in Fig. 1. The system consisted of a twin Nd: YAG laser and sheet optics. The sheet optics converted the laser source in to laser sheet. Laser sheet was pulsed through the material. The tracer particles illuminated by laser sheet at each pulse were recorded as an image on a 4 MP high speed CCD camera. The image plane was divided into small interrogation spots and displacement of the particle was measured by cross-correlating the images from the two subsequent time exposures. The spatial displacement that produced statistically maximum cross-correlation approximates the average displacement of the particles in the interrogation cell. This process yielded the displacement verses time data which was used to calculate the velocity and strain rate fields. Velocity associated with each interrogation spot is the displacement divided by the time between the laser pulses (Adrian, 1991). The whole procedure is explained in the following text.

PIV gives the spatial coordinates of two subsequent time frames. These are than used to calculate the velocity profile in x and y direction as expressed in Eqs. (1)–(3).

$$u(x, t) = \frac{x_{i+1} - x_i}{\Delta t} \tag{1}$$

$$v(y, t) = \frac{y_{i+1} - y_i}{\Delta t} \tag{2}$$

$$resultant\ velocity\ V = \sqrt{u^2 + v^2} \tag{3}$$

where x_i, y_i and x_{i+1}, y_{i+1} are spatial coordinates at time exposures of t_o and $t_o + \Delta t$. Δt represents time difference between two captured frames (Fig. 1), u and v are the velocities in x- and y-directions, respectively, and V is the resultant velocity. The velocity field can be used to derive the streamline and strain-rate profiles for detailed understanding of the material flow behaviour.

A streamline is an imaginary line drawn through the flow field in such a way that the tangent to it at any point gives the direction of velocity at that point. Therefore, streamline indicates the direction of motion of particles at each point and mathematically, the equation of streamline in 2-D space can be written as

$$\tan\theta = \frac{v}{u} = \frac{dy}{dx} \tag{4}$$

The strain rate ($\dot{\varepsilon}$) was calculated from two-dimensional velocity field obtained from the post-processing of PIV results. Strain rate, a 2nd order tensor quantity, is expressed in terms of velocity gradients. It is mathematically given by Eq. (5).

$$\dot{\varepsilon} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \tag{5}$$

2.1. Experimental material rheology

Prior to study of the material flow, the rheological study of the material (transparent fluid) was performed. The rheological characteristics, such as shear stress-shear rate, and viscosity-shear rate, of the material were measured using a PP20 rheometer (Anton Paar, MCR102) by keeping the gap between the plates as 0.08 mm. Fig. 2 shows the rheological curves of the experimental material at the room temperature. Over a wide range of shearing, the rheogram shows that minimum yield stress is approximately 35 Pa to initiate the flow. Afterwards, the apparent viscosity ($\mu_{effective}$) of the material decreases with increase in the shear rate (γ). The material, therefore, shows viscoplastic flow behaviour. Chhabra and Richardson (2008) showed that this rheological nature can be represented by the Herschel-Bulkley (H-B) fluid model, as expressed in Eqs. (6) and (7)

$$\tau = \tau_y + m(\gamma)^n\ for\ |\tau| > |\tau_y| \tag{6}$$

$$\gamma = 0\ for\ |\tau| < |\tau_y| \tag{7}$$

where τ is the shear stress and γ is the shear rate, τ_y is the minimum shear stress (yield stress) to initiate material flow, m and n are consistency index and flow behaviour index, respectively.

It should be noted here that experimental model is a qualitative representation of actual FSW process. Similarity between the model and actual process exist in terms of visco-plastic fluid behaviour in the stir zone (Nandan et al., 2006a; Long and Reynolds, 2006; Liechty and Webb, 2008). The notable difference in the present study is that the experimental model had isothermal condition throughout the process zone. Hence, in the experimental model material viscosity was dependent only on the strain-rate.