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Optimizing the effect of rotational rate and transverse velocity on residual stresses and UTS in friction stir welded as cast A356-SiC composites

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Abstract: In the last few years the friction stir welding process (FSW) was applied in order to get desirable mechanical and technological performances of the joints. The prediction and optimization of residual stresses is a critical point of view for a proper welding process design. In this research the effect of transverse velocity and rotational rate interaction on maximum ultra tensile strength (UTS) and minimum residual stresses is investigated by RSM. Finally the great agreement between tensile strength and maximum residual stress was achieved by modeling the effect of rotational rate and transverse velocity on residual stresses and UTS.

Keywords: Friction Stir Welding, residual stress, tensile strength, modeling, RSM

1. Introduction

Particle-reinforced aluminum alloy matrix composites are recognized to have more improved elastic modulus, tensile and fatigue strength over monolithic alloys [1–3]. Cast A356 aluminum alloy, which is commonly used as cylinder head and engine block material [4], has widespread applications for structural components in the automotive, aerospace, and general engineering industries because of its excellent castability, corrosion resistance and particularly high strength-to-weight ratio in the heat-treated condition [5–9].

Mechanical properties of the components made of cast A356 aluminum alloy are strongly dependent on stress state, defect distribution, and microstructures of the materials. Therefore, it is important to understand the detailed microstructures and defect population of the cast aluminum components. A number of technical articles have been published in the literature about the microstructure and tensile properties

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of cast A356 aluminum alloy with and without eutectic modification and grain refinement [10–16].

Microstructural parameters such as grain size, dendrite arm spacing (DAS) and the morphology of silicon and intermetallics also play an important role in determining the mechanical properties of Al–Si alloys. Modification of the eutectic Si crystals in Al–Si alloys is achieved by rapid solidification, chemical modification and thermal modification. Several works have shown that the coarse and large Si needles can be changed into a fine well-rounded phase after T6 heat treatment [17–19].

In this research the T6 heat treated A356-SiC composite plates were joined by friction stir welding process, Friction stir welding (FSW) is a solid-state process invented by The Welding Institute (TWI) in 1991 [20]. One of the beneficial aspects of friction stir welding aluminum alloys is that it introduces low residual stresses [21-23], which helps retain dimensional stability of the joined elements. However, even such low residual stresses can significantly influence the near-threshold crack growth in Al alloys [24,25].

2. Methods

2.1 Material preparation

In this work A356- 20% SiC as cast composites were used. The chemical composition of A356 as matrix alloy is shown in table 1. The as cast ingots were chopped by wire cut and prepared for the friction stir welding process.

Table 1. Chemical composition of A356 alloy

%Si	%Mg	%Fe	%Mn	%Cu	%Zn	%Al
7.1	0.40	0.21	<0.1	<0.1	0.1	Rem.

2.2 Heat treatment and FSW

In this step the samples were subjected to a T6 heat treatment as follows, first the prepared sheets were solutionized at 540°C for 4 hours and immediately were quenched in 80 °C water. Subsequently the sheets were aged at 180°C for 4 hours. Afterwards the prepared sheets were subjected to friction stir welding. The dimensions of Pin length, Pin Diameter and Shoulder Diameters are 2.75 ± .05 mm, 5.85 and 16.5 respectively. A H13 steel with 60 HRC hardness were utilized as the tool for joining the sheets in FSW process.

2.3 Design of Experiment using Response Surface Method

In order to modeling of the transverse speed (V) and rotational rate (W) effects on UTS and residual stresses, the response surface method was applied to design the experimental procedure. Thus, three V and three W values were selected for FSW of different sheets. Table 2, shows the RSM design of experiment values [26,27].

Table 2. RSM design of experiment for FSW of A356 SiC as cast composites

	C1	C2	C3	C4	C5	C6
	StdOrder	RunOrder	PtTypes	Blocks	V(mm/min)	W (rpm)
1	1	1	1	1	20	800
2	2	2	1	1	80	800
3	3	3	1	1	20	1600
4	4	4	1	1	80	1600
5	5	5	-1	1	20	1200
6	6	6	-1	1	80	1200
7	7	7	-1	1	50	800
8	8	8	-1	1	50	1600
9	9	9	0	1	50	1200
10	10	10	0	1	50	1200
11	11	11	0	1	50	1200

2.4 Tensile test

In order to prevent applying any excess stress on welded sheets, tensile tests were produced via wire cut, according to ASTM E 8M–00b standard and Fig. 1 [28].

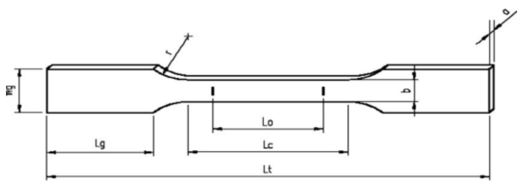


Fig. 1. Tensile test sample dimensions; a= 3mm, w_g =10mm, L_g =30mm, L_c =32mm, r =6mm, b =6mm, L_o = 25mm and L_t =100mm.

2.5 Residual strain measurement by using Williamson-Hall equation

In this research, the XRD results of all friction stir welded composites were used to calculate the residual strain through the Williamson-Hall method. [29]

$$B\cos\theta = \frac{K\lambda}{D} + \varepsilon\sin\theta \quad (1)$$

While B is peak width; D is grain size, λ is wavelength of the X-ray, K is a constant whose value is approximately 0.9, θ is the Bragg angle and ε is strain [30-32].

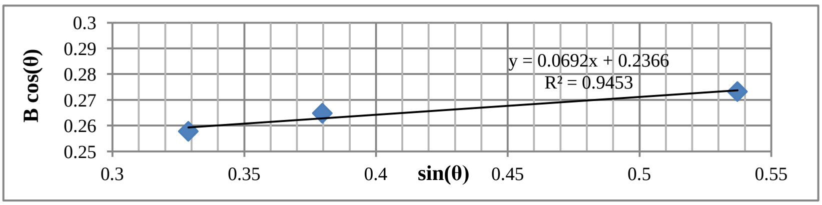


Fig. 2. An example of calculating ε from the XRD results via Williamson-Hall equation

For each component, three peaks were used to determine the linear equation between Bcosθ and sinθ. Then, by knowing K and λ, the slope of the line would be ε. Fig. 2 is an example of the procedure. For each specimen, residual stresses of 6 points in a transverse path at top surface of the weld were measured by finding the equivalent stress value for the calculated ε.

3. Results and Discussion

3.1 Effect of transverse speed and rotational rate on Ultra Tensile Strength

As it is shown in the Fig. 3, when transverse speed increases and rotational speed decreases, the ultra tensile strength of the welded components improves. This happens because while the rotational speed reduces, the local heat generated due to friction between the shoulder and work piece, decreases. Also, by elevating the transverse speed, the time of local friction between the rotating shoulder and workpiece declines, which causes a reduction in local heat generation and consequently, an improvement in weld strength. Therefore, the maximum UTS of welded composites are obtained when 80 mm/min transverse speed (the highest value in the experimental procedure) and 800 rpm rotational rate (the least value) is implemented. [29,33,34]

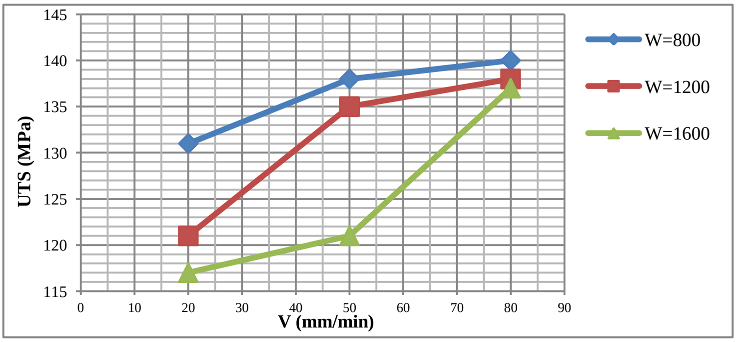


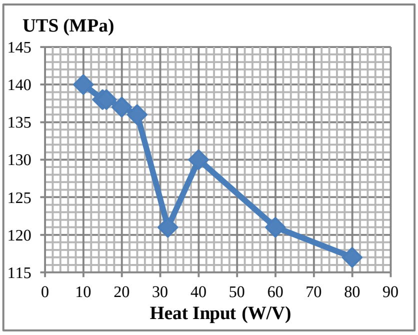
Fig. 3. Effect of V (transverse speed) and W (rotational rate) on Ultra Tensile Strength of the as welded A356-SiC composites

The heat input in FSW procedure is contributed with the W/V ratio. As shown in the Fig. 4, by increasing the ratio (heat input), the UTS of welded composites decreases generally. Again, the main reason is associated with heat generation. By increasing the W/V ratio, the local heat generation enhances, thus the more grain coarsening of the weld nugget occurs and the UTS decreases. [29,35,36]

Eq. 2 is the RSM model which best interprets the effect of V and W on UTS of welded components.

$$UTS\,(MPa) = 135 + 7.83V - 5.5W - 2.7V^2 - 2.7W^2 + 2.5VW \quad (2)$$

The initial value of UTS is 135 MPa that is approximately equal to UTS of T6 composites before welding. This equation and Fig. 5, verifies the information



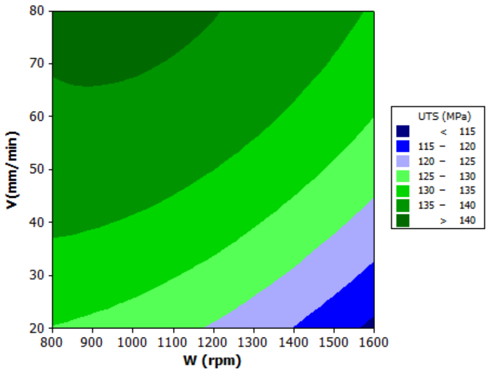


Fig. 4. Interacting Effect of V and W on Ultra Tensile Strength of the as welded A356-SiC composites

Fig. 5. The UTS contour result of RSM

obtained from Fig. 3, that means by increasing V and decreasing W, UTS of welded sheets improves. However, the coefficient of V is greater than W that means V is more effective on UTS. Also, the equations contains the terms of V^2 and W^2, with negative coefficients and an interacting term of VW. Therefore, the highest UTS values are gained in the brown region when V is greater than 68mm/min and W is lower than 1200 rpm [26,27,29].

3.2 Effect of transverse speed and rotational rate on residual stresses

Fig. 6 shows the transverse speed and rotational rate effects on the maximum residual stresses which are calculated through Stress-Strain schemes obtained from tensile tests and XRD results. At lower rotational rates (800rpm), the increment of transverse speed results a reduction in the maximum of residual stresses, while in higher rotational rates it is vice versa.

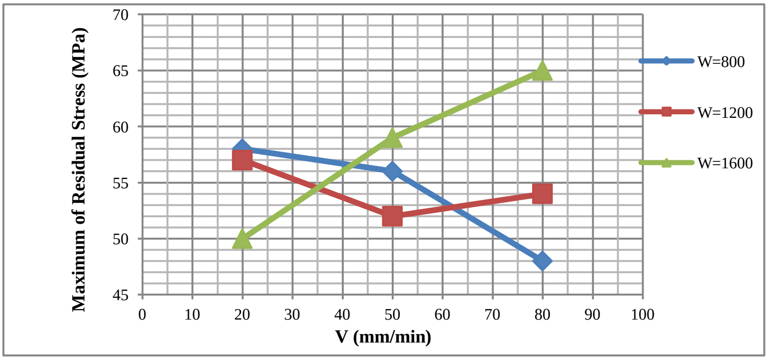


Fig. 6. Effect of V (transverse speed) and W (rotational rate) on Residual Stresses of the as welded A356-SiC composites

Fig. 7 shows that the W/V ratio (heat input) effect on the residual stresses has an optimum condition that means in order to achieve lower residual stresses, one of the V and W should be low. In most MMC systems, the matrix material has a higher coefficient of thermal expansion (CTE) than does the reinforcement, which leads to a tensile stress in the matrix and a compressive stress in the reinforcement when the material is cooled from a process temperature: either following initial fabrication or after a thermomechanical forming process. Also, residual stresses are affected by temperature gradient, welding constraint and heat transfer in the procedure. While the increment of the rotational rate causes more friction between shoulder and workpiece, the higher transverse speed also results in reduction in contact time, which means the lower heat transfers from the pin to machine, and the higher process temperature and temperature gradient will be produced. Thus, both high V and W produce more residual stresses. [29,33,37]

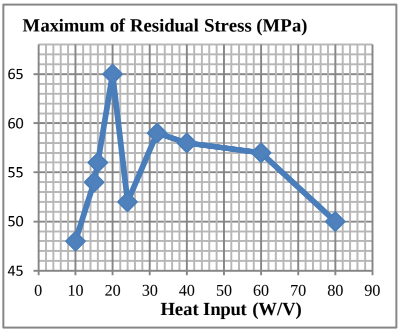


Fig. 7. Effect of W/V ratio on Residual Stresses of the as welded A356-SiC composites

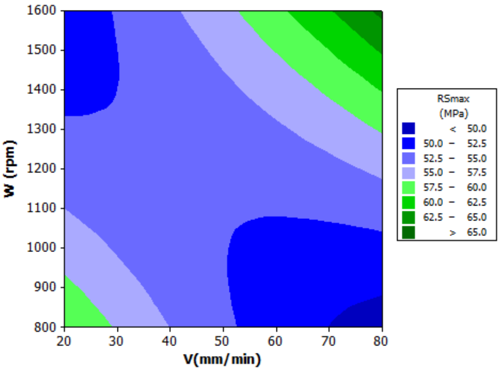


Fig. 8. The maximum of residual stresses contour result of RSM

Eq. 3 is the RSM model which best interprets the effect of V and W on maximum residual stresses of welded components.

$$RS\max(MPa) = 53.09 + 0.87V + 1.95W + 1.53V^2 + 1.78W^2 + 6.32VW \quad (3)$$

It can be inferred from Eq. 3 that the initial residual stresses at lowest heat input would be at least 53 MPa. This equation also shows that since all coefficients of V and W are positive, increasing in both V and W cause an increment of maximum residual stresses. Fig. 7 verifies this information too. The minimum residual stresses can be obtained in the case at least one of the V and W values is low (the blue region). Furthermore, applying middle values of V with average W, also results in minor residual stresses. However, when V and W are high concurrently, the residual stresses would be much higher [26,33,37].

4. Conclusions

- It was illustrated that the ultra tensile strength of the welded components will be modified when transverse speed increases and rotational speed decreases.
- As shown in the Fig. 4, by increasing the W/V ratio (heat input), the UTS of welded composites decreases.
- It can be inferred from Eq. 2 and Fig. 5 that the most UTS would be achieve when applying transverse speeds higher than 68 mm/min and rotational rates lower than 1200 rpm.
- It was concluded that the W/V ratio (heat input) effect on the residual stresses has an optimum value that means in order to achieve lower residual stresses, one of the V and W should be kept low.
- It can be inferred from Eq. 3 and Fig. 8 that the most minimum residual stresses would be achieve when applying average transverse speeds and rotational rates. The best parameters would be these two couples: V lower than 30 mm/min while W is higher than 1340 rpm, and W lower than 1100 rpm when V is higher than 53mm/min.

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