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TECHNICAL PAPER

Effect of Friction Stir Welding Parameters on Mechanical Properties and Microstructure of AA2195 Al–Li Alloy Welds

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Abstract In this paper, effect of friction stir welding process parameters on mechanical properties and microstructure of AA2195 welds were studied. Five levels of tool rotation speed from 400 to 1000 rpm and three levels of travel speed from 100 to 300 mm/min were considered. These parameters affected heat input generation in the welds, thereby influencing stir zone geometry, grain size evolution in stir zone, tensile properties and hardness of the weld. Low tool rotation speed and high travel speed resulted in finer grain size. Travel speed significantly affected the tensile properties compared to rotation speed. Processing window to achieve defect-free welds was identified, and maximum weld efficiency was obtained at 400 rpm rotation speed and 300 mm/min travel speed.

Keywords AA2195 · Friction stir welding · Tool rotation speed · Travel speed · Mechanical properties

1 Introduction

AA2195 is a third-generation Al–Cu–Li alloy used in propellant tanks of satellite launch vehicle owing to high specific strength and excellent properties at cryogenic temperature. Because the alloy is prone to fusion welding defects such as porosity and hot cracking, friction stir welding (FSW) is a potential manufacturing process to realize the aerospace structures [1, 2]. In FSW, weld properties and quality are controlled by various process parameters such as tool rotation speed, tool travel speed, tool profile, tool tilt angle and axial force [3]. Among these parameters, tool rotation speed and travel speed are critical parameters to be controlled. Previous studies on the effect of these two parameters on weld geometry, tensile properties and microstructure of AA2195 alloys are limited. In this study, influence of tool rotation speed and travel speed on AA2195 FSW welds is reported.

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2 Experimental Details

To achieve T87 temper condition, AA2195 alloy plates were solution treated (ST) at 505 °C for 60 min. Subsequently, plates were subjected to 7% cold working and aging treatment was carried out at 146 °C for 30 h. Sheets of 150 mm length × 65 mm width × 5 mm thickness were prepared to produce square butt FSW joints. FSW machine manufactured by ETA Technologies, Bangalore, was used in this study. Effect of tool rotation speed (rpm) and tool travel speed (mm/min) studied at various levels is shown in Table 1, and all other FSW parameters were kept constant. FSW tool was made of H13 tool steel having taper threaded pin with scrolled shoulder. Shoulder diameter was 20 mm, and the pin diameter was 6 mm at the top and 4 mm at the bottom with 4.8 mm pin length. The weld coupons were held in the fixture, and tool moved in horizontal position to produce the welds. Tool travel was across the rolling direction, i.e., welds were oriented normal to rolling direction.

Optical micrographs were taken using Carl Zeiss, Axio Lab A1 inverted microscope. Base material and weld cross section were cut, mounted, polished and chemically etched

Table 1 Process parameter's variation and nomenclature in this study

Nomenclature	Tool rotation speed				
	1000 rpm	800 rpm	600 rpm	400 rpm	200 rpm
Travel speed					
100 mm/min	100/1000	100/800	100/600	100/400	100/200
200 mm/min	200/1000	200/800	200/600	200/400	200/200
300 mm/min	300/1000	300/800	300/600	300/400	300/200

using Keller's reagent to reveal the microstructure. Microhardness measurements were made on base material and weld cross section using Q-ness universal hardness testing machine with 500-g load. Base metal and transverse weld tensile specimens were fabricated with 25 mm gage length and 6.25 mm gage width. Tensile testing was conducted on a 2000-kN Instron servo-hydraulic universal testing machine with constant crosshead speed of 0.1 mm/min.

3 Results and Discussion

Microstructure of AA2195 alloy depicts typical rolled structure of elongated grains as shown in Fig. 1. Average tensile properties of AA2195 are 573 MPa ultimate tensile strength (UTS), 535 MPa yield strength (YS) and 12.1% elongation. High strength in AA2195 alloy is achieved by T1 (Al_2CuLi) precipitates formed during aging treatment. Hardness values of AA2195 alloy in T87 temper condition are 182 to 186 HV.

Heat input in FSW process is governed by various parameters such as tool rotation speed, tool travel speed, tool shoulder diameter, pin diameter and pin length. The empirical relation between FSW parameters and heat input index is given below [4]; the same relation is used to calculate the heat input index.

$$\mathrm{HI} = 7.2\,V^{-0.80}N^{0.10}D^{0.55}d^{0.45}h^{0.30}\lambda^{0.40}$$

where HI heat input index, V travel speed (mm/s), N rotational speed (rad/s), D shoulder diameter (mm), d pin diameter (mm), h pin length (mm), λ thermal conductivity of work piece (W/mK).

Five levels of tool rotation speed and three levels of tool travel speed have been considered, and corresponding heat input has been calculated. Heat input index is given in Table 2.

Tool rotation speed and heat input are directly proportional. As the tool rotation speed increases, heat input increases. Higher tool rotation speed generates higher temperature due to friction heating. Conversely, tool travel speed and heat input are inversely proportional and heat input decreases with increase in tool travel speed. Highest heat input index of 966 is obtained at 100 mm/min and 1000 rpm, and lowest heat input index of 342 is obtained at 300 mm/min and 200 rpm. It is observed that role of travel speed is dominant in heat input generation compared to tool rotation speed.

It is observed that higher tool rotation speed (1000 rpm) produces flash defect. High heat input results in material softening and expulsion from weld zone in the form of flash. Lower tool rotation speed (200 rpm) creates tunnel defect due to low heat input. At low rpm, heat input is not enough for proper stirring and complete mixing of material in the stir zone. No defects are observed in welds produced at tool rotation speeds of 400 rpm, 600 rpm and 800 rpm with all three levels of travel speeds. Therefore, further microstructural analysis and evaluation of mechanical

Fig. 1 Optical microstructure of base metal AA2195-T87

Table 2 Effect of process parameters on heat input index

Heat input index	Tool rotation speed				
	1000 rpm	800 rpm	600 rpm	400 rpm	200 rpm
Travel speed					
100 mm/min	966	944	918	881	822
200 mm/min	555	542	527	506	472
300 mm/min	402	392	381	366	342

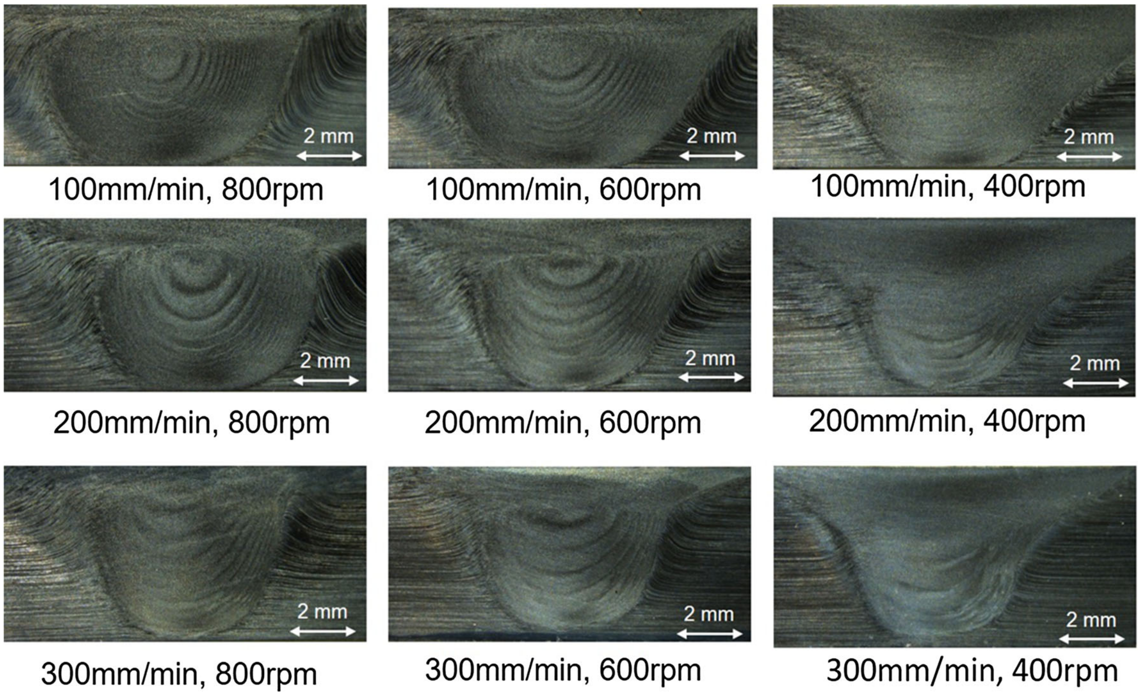

Fig. 2 Effect of process parameters on macrostructure of welds

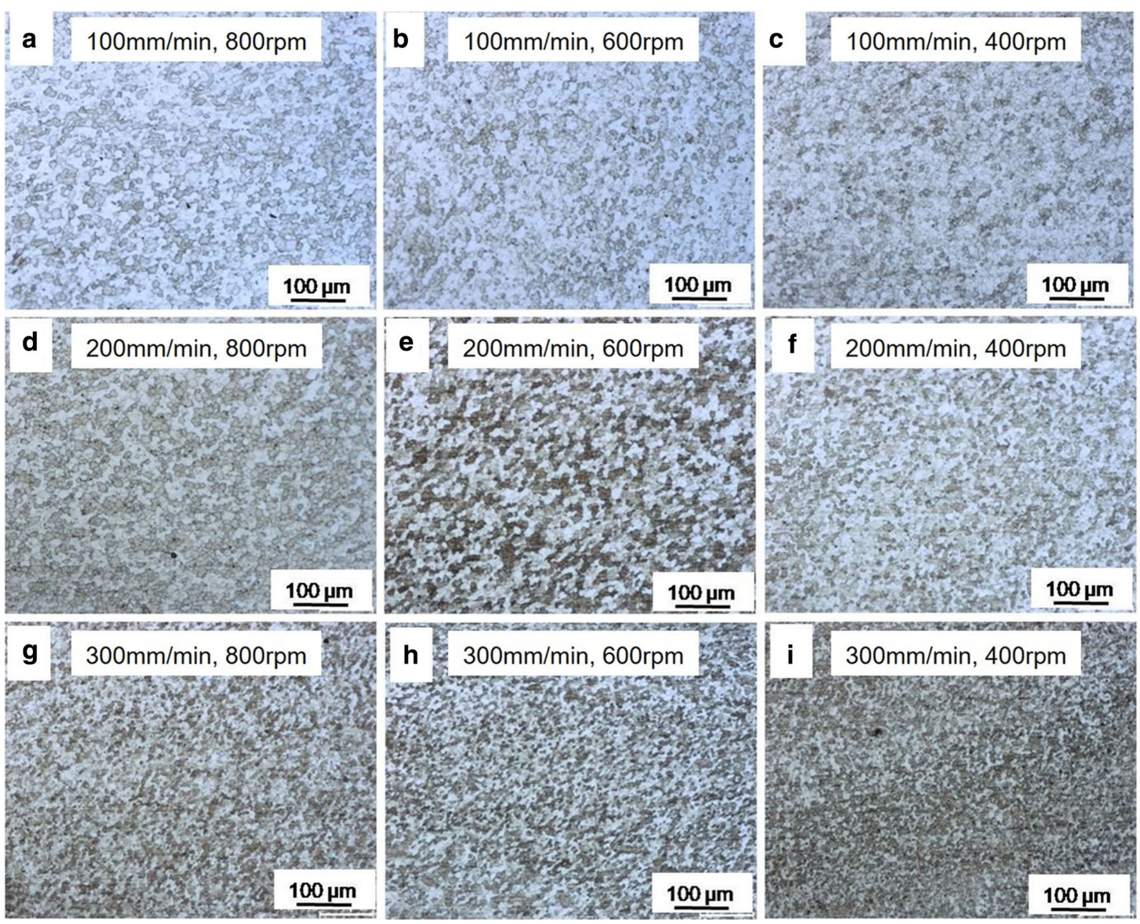

Fig. 3 Effect of process parameters on evolution of grains in nugget zone

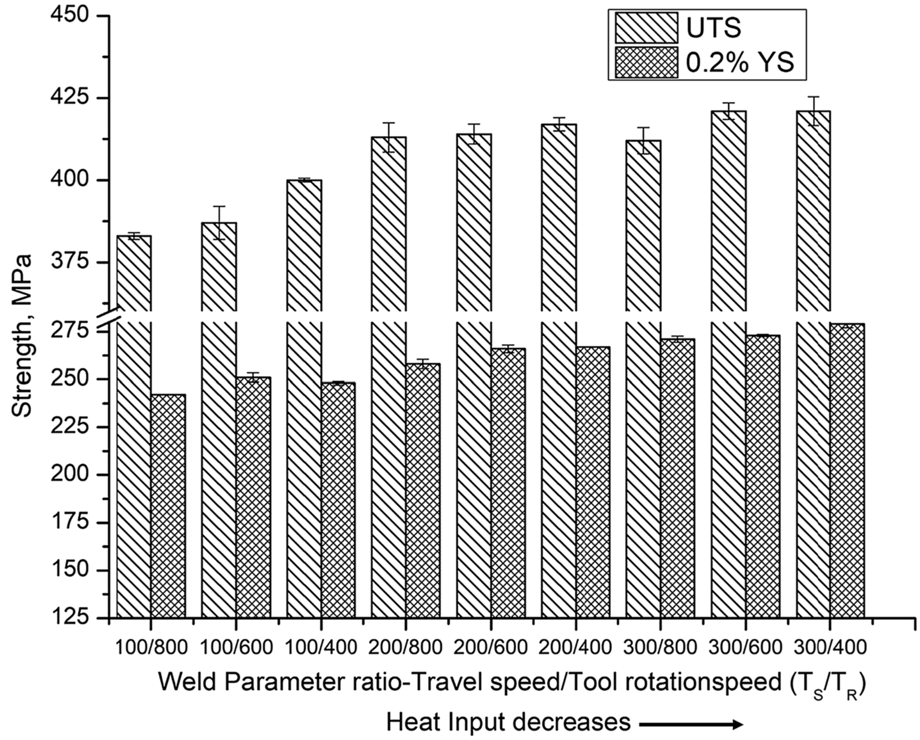

Fig. 4 Effect of welding parameters on tensile properties of welds

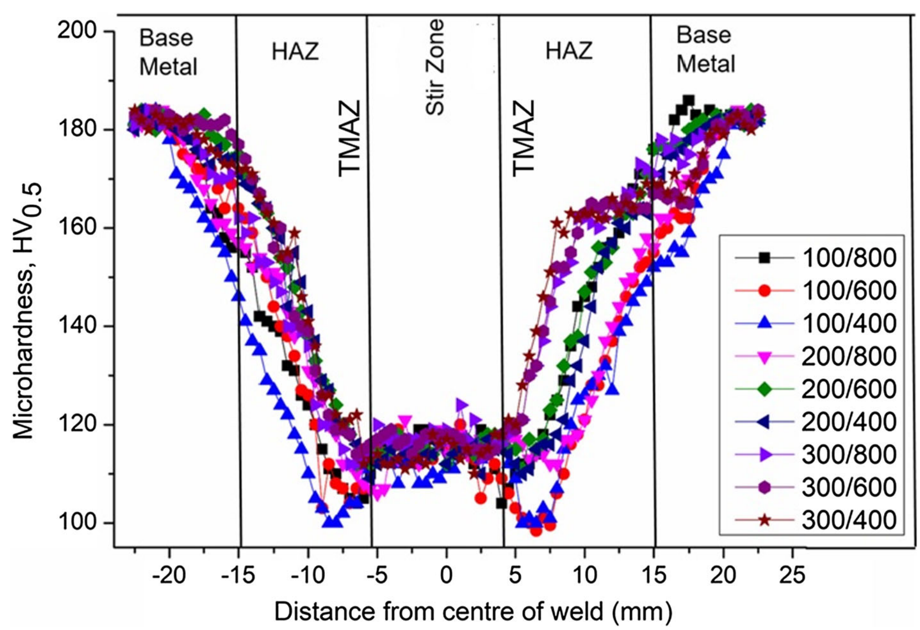

Fig. 5 Effect of welding parameters on hardness across the welds

properties become restricted to these nine welds. Figures 2 and 3 show macrostructure and microstructure of welds, respectively, processed with optimum process parameters.

In as-welded condition, dissolution and coarsening of precipitates occur in weld and T8 temper history is lost. However, strengthening in weld is achieved by solid solution strengthening and grain refinement. FSW parameters control the grain evolution significantly. Higher heat input produces coarser grains in the weld which reduces the grain size strengthening contribution. In this study, low travel speed and high tool rotation speed (high heat input) is characterized with low tensile properties and vice versa. At highest heat input (100 mm/min, 800 rpm), ultimate tensile strength (UTS) and 0.2% yield strength (YS) are 383 MPa and 243 MPa, respectively. Likewise, at lowest heat input, UTS and YS are 421 MPa and 279 MPa, respectively. In as-weld condition, maximum weld efficiency of 73% with respect to UTS is obtained at 400 rpm tool rotation speed and 300 mm/min travel speed.

It is observed that influence of tool travel speed is much stronger than that of tool rotation speed in improving the tensile properties of weld. Decrease in tool rotation speed from 800 to 400 rpm did not increase the properties significantly, whereas increase in travel speed from 100 to 200 mm/min and then to 300 mm/min has increased the properties notably. Ratio of travel speed to tool rotation speed is related to heat input of joint. Figure 4 shows a plot of this ratio versus UTS and YS. As this ratio increases, tensile properties increase. Tensile specimens fail at the thermo-mechanically affected zone (TMAZ) in all the welds. It is evident that weakest region in AA2195 welds is TMAZ, irrespective of processing parameters. However, properties of TMAZ are dependent on heat input. Elongation of welds is comparable with base metal; no significant change in elongation is observed.

Micro-hardness traverse across the welds is performed to understand the hardness variation in the weldment. Hardness profile of all the welds show similar "W" shaped pattern with small dip adjacent to stir zone. As shown in Fig. 5, lowest hardness is observed at thermo-mechanically affected zone (TMAZ) of all the welds. Also, it is confirmed from the broken tensile test specimens that the location of failure is at TMAZ. In the stir zone, hardness of high heat input welds (low travel speed and high tool rotation speed) is relatively lower than the low heat input welds. This trend is due to grain size variation in the welds.

4 Conclusions

1. Both tool rotation speed and tool travel speed influenced the tensile properties and defect formation in FSW welds. At high rotation speed (1000 rpm), flash defects were observed. At low tool rotation speed (200 rpm), tunnel defects were observed.
2. Window for achieving defect-free welds was obtained as 400–800 rpm tool rotation speed and 100–300 mm/min travel speed.
3. Weld stir zone was characterized by fine recrystallized grains. Decrease in tool rotation speed and increase in travel speed resulted in finer grain size.
4. Travel speed had a significant effect on tensile properties, while tool rotation speed had only marginal effect. Tensile properties increased with increase in the ratio of travel speed to tool rotation speed. Failure location was always in TMAZ.
5. Highest weld efficiency in as-welded condition was 73% with respect to UTS, and it was obtained at travel speed of 300 mm/min and rotation speed of 400 rpm.

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