Tensile Properties of Friction Stir Welded Joints of AA 2024-T6 Alloy at Different Welding Speeds

Dhananjayulu Avula1, Venkateswarlu Devuri2*, Muralimohan Cheepu3, Dheerendra Kumar Dwivedi4

1Department of Mechanical Engineering, Government Polytechnic Rajampet, Andhra Pradesh 516126, India
2Department of Mechanical Engineering, Marri Laxman Reddy Institute of Technology and Management, Telangana 500043, India
3Department of Mechatronics Engineering, Kyungsung University, Busan 48434, Republic of Korea
4Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Uttarakhand 247667, India.

*Corresponding author E-mail: devuri.venky@gmail.com

Abstract. The influence of welding speed on the friction stir welded joint properties of hardness, tensile properties, defects and microstructure characterization are studied in the present study. The friction stir welding was conducted on AA2014-T6 heat treated alloy with 5 mm thickness plate in butt joint configuration. The welding speed was varied from 8 mm/min to 120 mm/min at the fixed travel speed and load conditions. It is observed that the welding speeds at higher rate with wide range can be possible to weld this alloy at higher rates of tool revolution suggesting that the inherent capability of friction stir welding technique for aluminum 2014 alloys. The strength of the joints gradually increases with enhancing of welding speed. The micro structural observations exhibited the formation of equiaxed grains in the stir zone and slightly in the thermo-mechanically affected zone. In addition, the size of the grains decreases with increase in welding speed owing to the presence of low heat input. Hence the hardness of the joints slightly increased in the stir zones over the other zones of the weld nugget. The joint strength initially increases with the welding speed and starts to decreases after reaching to the maximum value. The relationship between the welding conditions and friction stir welded joint properties has been discussed.

1. Introduction
The solid state welding processes have significant role on joining of incompatible materials, similar and dissimilar materials combinations. Friction stir process (FSW) is one the solid state welding process, which is suitable to for joining of similar and any other combination of materials successfully. The Welding Institute (TWI) of United Kingdom in 1991 was developed the FSW process and applied this process for initially for joining of aluminum alloys [1-3]. The output of the FSW weldments with higher strength with the presence of less defects lead the FSW process prominent process in aluminum industries. The continuous and rapid development on this technique has been became familiar to weld many other alloys, such as nickel, titanium, steel, magnesium and copper alloys [4-11]. In the past decades, the demand for aluminum increasing for various applications of structural, automotive, nuclear
and chemical industries, due to this the demand for joining of aluminum alloys increasing tremendously. Although aluminum and aluminum alloys can be fabricated by using most of the conventional welding processes such as resistance welding, gas metal arc welding, different brazing processes, gas tungsten arc welding, and soldering, the joining of aluminum is in general very difficult by fusion welding processes due to the aluminum has a low melting temperature and high thermal diffusivity value. During welding of aluminum and its alloys, much higher heat input is needed due to the highest heat dissipation into the substrates and the welding speed are need to maintain at low speeds. Moreover, the oxidation of the melting surfaces of the work piece and thermally induced cracks in the joints are often occur which are caused to deteriorate the mechanical properties of the joints [12-19]. The similar problems of oxidation formation during welding also can be seen for titanium and its alloys. The welding of titanium and its alloys always ready to form the inter metallic compounds as like aluminum alloys [20-25]. To overcome these issues, solid-state welding methods of friction stir welding, friction welding and explosive welding processes are contemplated. In case of dissimilar joining, solid state welding methods exhibits the satisfactory results with the highest joint strength [26-29]. The oxidation issues are also observed in the arc welding of steels, where the oxides forms with the alloying elements as a solid slags over the weld bead [30, 31]. Friction stir welding process has been regarded as an anticipating welding method for the welding of aluminum and its alloys.

In the friction stir welding process, welding conditions are most effective on producing of high quality joints. The main FSW welding conditions are welding speed, tool rotation, which enhance the joint properties and mechanical strength of the welds [32]. Sakthivel et al. [33], reported that the effect of welding FSW welding speed on the commercially pure aluminum grade material. The strength of the joints is gradually decreasing with the increasing of welding speed. Whereas, the weld strength are increased when the decrease in transverse speeds The similar observation are found for the FSW of copper material and the stir zone of the welds exhibits a lower hardness even though the grain size of the stir zone is finer that the base metal at higher welding speed [34]. The effect of combination of welding conditions are welding speed, rotational speed and applying load on the copper material are studied by Sun et al. [7]. The strength of the joints is increasing with the combination of increasing load and decreasing welding speed. Whereas, the other reports revealed that even though the strength of the joints increasing with decreasing of rotational speed, the possibility of increasing of defects formation in the stir zone due to the insufficient heat generation during welding [35, 36].

The effect of welding parameters of rotation speed, tool geometry, transverse speed are also studied for dissimilar combination of aluminum alloys and steel materials which exhibits the significant changes in the joint strength [37]. Some of the previous studies reported that the influence of welding conditions on the joints strength and especially the transverse and rotating speed on the A1100-H24 and steel lap joints. For this combination, the fracture strength increases with the transverse speed decreased and the rotation speed increases [38]. Kimapong et al. [39] studied the dissimilar lap joint of A5083 to SS400 by FSW process and reported that the strength of the joints increased with lowering of rotation speed and tool pin depth into the work piece, and increase in transverse speed. Watanabe et al. [40] studied the FSW process parameters effect on tensile strength of 5083 aluminum alloy and medium carbon steel plates. The strength of the joints achieved the 86% of the 5082 aluminum alloy base metal tensile strength. Tanaka et al. [41] reported that the influence of rotation speed on the temperature increase in the joint and strength of the 7075 aluminum alloy and mild steel in the fixed welding parameters of welding speed and pin position. The heat generation in the weld zone during welding caused to form the intermetallic compounds thus the resulted joint strength was evaluated.

In FSW, the welding conditions have to be determined individually for evaluating the join properties of each and every new material and alloys. In general, the welding speed in FSW process depends on several factors such as type of material alloy, tool rotational speed, depth of penetration, applying load and joint configuration [42]. Moreover, FSW can be able to join the substrates in any configuration of the joint types. The welding conditions are also effect on the microstructural features of the weld nugget zones with the formation of various regions [43]. In the present study, the effect of welding speed on
strength of the joints, characterization of the microstructural features and hardness variation across the different zones of the weld nugget have been investigated for the heat treated 2024 aluminum alloy.

2. Experimental Procedure

In the present work, the AA2024-T6 alloy with 5 mm thickness were used as base metals and the samples were machined in the dimensions width – 50 mm and length – 150 mm for the FSW joint. The edges of the samples were machined to flatten the uneven surfaces to achieve the perfect butt joint configuration. The chemical compositions of the base metal are provided in Table 1. The samples were polished using rough emery paper and followed by cleaned with steel wire brush to remove the oxide layer over the plate surface. The alloys were thoroughly cleaned with alcohol and dried to remove grease, oil and dirt, etc. before welding. The specimens are rigidly clamped in the fixture using mechanical clamps in the butt joint configuration with the close fitting. Friction stir welding tool of tempered die steel tool was used with the cylindrical threaded pin profile for FSW welding. The FSW process was conducted on the vertical milling machine of model of HMT, with a power capacity of 7 HP and rotation speed of 635 rpm. The welding conditions are optimized based on the trial and error method to find the suitable welding conditions. The welding speed was varied from 8 mm/min to 120 mm/min at a constant rotary speed of 635 rpm for producing the FSW joints. The welding parameters and FSW tool details are presented in the Table 2.

After welding, the FSW samples were inspected using destructive techniques and visually to identify the weld defects in the weld metal. It was observed that the weld produced at the conditions of 19, 30, 48 and 75 mm/min welding speed are defect free and showed highest strength. After completion of welding, the weldments were cut in transverse direction to prepare the metallographic samples for microstructural evolution and defects analysis. The weldments were etched with Keller’s etchant solution of HCl 1.5 ml + HF1 ml + HNO3 2.5 ml + H2O 95 ml. The microstructures of the welds were examined under optical microscope, and fracture surfaces were analysed through scanning electron microscope (SEM). Microhardness was conducted across the weld joint and 0.1kg load with the dwell time of 20 seconds. The mechanical tensile properties of the welds were tested using universal tensile machine, at a 1 mm/min cross head speed. The tensile strength tests were conducted at room temperature to maintain the accuracy for all the joints. The tensile samples were prepared as per the ASTM E8 standard [44], and maximum values of the tensile strength were taken from the average of three samples.

Table 1 Chemical composition of the base metals used for the present study

| Elements | Mg  | Si  | Mn  | Cu  | Al    |
|----------|-----|-----|-----|-----|-------|
| AA2024   | 1.95| 0.28| 0.56| 4.12| Balance |

Table 2 FSW welding conditions used in this study

| Process parameters | Values |
|--------------------|--------|
| Rotational speed (rpm) | 635    |
| Welding speed (mm/min) | 19,30,48,75 |
| D/d Ratio of tool      | 3      |
| Pin length (mm)        | 4.7    |
| Diameter of Tool shoulder (D) (mm) | 15    |
| Diameter of pin (d) (mm ) | 5     |
3. Results and Discussions

The effect of welding conditions in FSW behaves differently for different components or materials. In the present study, to understand the 2024-T6 aluminum alloy behaviour with the change in welding speed extensively investigated on its microstructural and mechanical properties of the joints. In general, for FSW the important parameters of transverse speed and tool rotation both have substantial effect on the mechanical properties and thermal input. Moreover, the weld zone peak temperature increases with the ratio of tool rotation rate and transverse speed, especially for the alloy of AA2024-T6, AA7075-T6 and AA5083-O [45-47]. The microstructural observations of the welds exhibits the three distinct regions of thermo-mechanically affected zone (TMAZ), stir zone (SZ) and heat affected zone (HAZ) with the variation in grain size and formation of precipitates. These are apparently parameter dependant and SZ size varies with the welding speed. There are no defects observed for the joints under the investigated parameters. Figure 1 illustrates the microstructures of the cross section of the joints. The formation of three regions in the weld nugget macrograph can be seen from the Figure 1(a). It is observed that the nugget has formed with two distinct morphologies of upper and lower parts. The microstructural features are characterised on advancing side and retreating side of the weld nugget. The enlarged view of the stir zone exhibits the fine equiaxed grains formation compared to the other zones. The grain size in the HAZ and TMAZ is quite larger than the SZ owing to the temperature variation during welding. Although HAZ experiences a thermal cycle, there is no evidence of formation of plastic deformed regions. In general HAZ has experiencing a temperature distribution of more than 250 °C for a heat treated alloys [48]. The sizes of HAZ grains are almost similar to the base metal and the lower hardness has been observed for this region. The interface between the SZ and base metal has very clear view at advancing side compared to the retreating side due to the intermixing of the weld metal during welding.
The microstructural features varied with the increase in welding speed and it is observed that the grain size varies significantly in the SZ. The microhardness measurements have been performed across the weld zone. The hardness distributions of the welds produced at different welding conditions are depicted in Figure 2. It is observed that the hardness of the base metal varies from 132 HV to 137 HV. During welding due to the thermal cycle and strain hardening effect by dynamic recrystallization, thus considerable softening occurs in the weld zone over the base metal. Therefore, the hardness lowers in the TMAZ towards the SZ as compared to the base metal hardness. The hardness of the weld metal gradually increases with the increasing of welding speed. The highest hardness values are found at the welding speed of 48 mm/min. The increase in hardness owing to the formation of fine grain size in the nugget zone at higher welding speeds for the 2024-T6 aluminum alloys. The hardness was welds at 78 mm/min shows decreasing trend of the hardness. It is well known that the higher welding speeds subjected to a decrease in both the peak temperature and deformation in the weld zone. On the contrary, decrease in the deformation zones during FSW caused for the enhancing of grain size as per the recrystallization principle. Whereas, it is known fact that the lower in peak temperature of the weld zone thermal cycle contributes to formation of small sized fine recrystallized grains. Thus the disparity of the recrystallized grain size with welding speed during FSW completely relies on which factor is highest contribution.

The tensile properties of the FSW joints welded at different welding speeds are depicted in Figure 3. It is found that the elongation and tensile strength of the welds shows the similar variation of both the variations. The strength of the joints gradually increases initially and decreases finally with the further increasing of welding speed after reaching the highest strength. It is observed that the elongation and the strength of the joints obtained at the welding speeds of 19 mm/min to 75 mm/min, the results within this range have little variation and their highest strength values are accompanying to the 48 mm/min and its starts to reducing at 75 mm/min. The strength of the joints out of this range of welding speeds found the larger variations and joints fails within the weld zone. However, some of the joints at various conditions shows the elongation of the joints differently unlike strength of the joints. It is noticed that the elongation of the joints decreasing with increasing welding speed. The elongation of the 19 mm/min welding speed joints is almost 20%, whereas the elongation of 14% has been recorded for the 48 mm/min welding speed joints. It is observed that the strength of the joints are related to the microstructural changes of grain size difference with the welding speed. The hardness and the strength of the joints significantly improved with the increase in welding speed. Figure 4 shows the fractographs of the tensile
failure samples welded at various welding speeds. After tensile test, the samples exhibited the significant neck formation around the failure location when the welding speeds reached to 48 mm/min. It shows a significant of the occurrence of micro plastic deformation in the SZ of the weld joints during tensile test.

![Fractographs of the FSW welded joints at the different welding speed of (a) 19 mm/min, (b) 30 mm/min, (c) 48 mm/min and (d) 75 mm/min.](image)

At lower welding speed, the fractographs clearly showed the absence of occurrence of micro plastic regions. These micro plastic regions are higher at the 48 mm/min welds fractographs and are elongated and broken under tensile loads. The ductile nature of the fracture regions are more in the 48 mm/min welds compared to the other joints produced at different conditions.

4. Conclusions

The FSW joining of 2024-T6 aluminum alloys were butt welded at different welding speeds ranging from 8 mm/min to 120 mm/min to investigate the effect of welding speed on welding defects, strength and microstructural features of the joints. Some conclusions can be drawn as follows:

- The gains in the SZ and TMAZ are dynamically recrystallized and the equiaxed fine grains are formed in the SZ. The heat affected zone grains are slightly affected by thermal cycle heat input and coarse grains are formed.
The hardness and tensile strength of the joints increased with the increasing of welding speed initially and decreased finally after reaching the maximum strength of the joints.
The fracture surfaces revealed the occurrence of micro plastic regions in highest strength joints.
The welding speed is one of the dominant parameter to achieve the maximum joint strength.

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