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Effect of Tool Speed on Axial Force, Mechanical Properties and Weld Morphology of Friction Stir Welded Joints of A7075-T651

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ABSTRACT

The axial force measurement plays an important role in tool designing and identification of its restrictions. Also, it is vital in design of machine mechanism and optimization of welding process parameters. In this study, a friction stir welded butt joint on AA7075-T651 aluminum alloy plate is investigated. With change of some parameters, factors including axial force, mechanical properties, microhardness and weld morphology, are studied. For measuring the axial force, load cell was utilized and a servohydraulic machine was applied to evaluate the mechanical properties. The results show that by increasing the welding speed and in the same rotational rate, the axial force and microhardness increase but the weld appearance quality decreases. However, by increasing the rotational rate in the same welding speed, there is not any certain relationship among the axial force, hardness and weld morphology. Also, by changing the tool tilt angle from zero to 2.5 degrees, the weld morphological feature is enhanced. The results illustrate that the proper change in welding speed and tool rotational rate have great effects on optimizing the welding friction stir process.

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1. INTRODUCTION

Heat-treatable 7xxx-series aluminum alloys are high strength alloys which their strength is even higher than middle strength steels. According to ASTM B209M-14, this alloy is widely used in the fabrication of plates and sheets used in aerospace, military vehicles, marine and rail industries, road construction machinery and bridges. Some heat treatment methods on AA7075 aluminum alloy make it resistant to stress corrosion [1]. The 7xxx series aluminum alloys are not recommended for fusion welding process. The fusion welding method causes a drop in the strength and ductility in the heat affected zone in alloys of this series that may lead to brittle fracture, thermal cracking, porosity and fusion defects [2].

Friction stir welding (FSW) is a solid state metal joining technique which was experimentally invented in 1991 at the Institute of Welding UK [3, 4]. This method may be appropriate for materials which are difficult or impossible to be welded by fusion welding method. The main advantage of this method is its ability to make welds in all of aluminum alloys, especially in 2xxx and 7xxx series [5]. In the FSW technique, the heat generated among the pin, shoulder and workpiece causes softening of the material without reaching the melting point. Then to make joint, the soften region should be mixed/stirred very fast. This process alters the microstructure and flow pattern of the material. As a result, the mechanical properties of the joint depend on the welding parameters and the geometry of pin tool [6].

Hao and colleagues [7] introduced the main variables of control as rotational rate and welding speed of the tool along the joint line, vertical pressure on the tool, tilt angle and the geometry of the tool for the FSW process. However, they believed that the rotational rate and welding speed are the most important parameters affecting the mechanical properties.

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Yang et al. [8] studied the effect of heat input using different diameters of shoulder on the mechanical properties and fracture behavior in friction stir welded magnesium alloy plate. Chowdhury and colleagues [9] investigated the effect of pin tool thread orientation and tool speed on the tensile properties of joints in friction stir welded magnesium alloy. Some of researchers examined the effects of FSW process on the mechanical properties, hardness, microstructure and so on in 2xxx, 5xxx, 6xxx and 7xxx series aluminum alloys [10-15]. Also, in some of researches, the stress-fatigue life as well as the mechanical properties and hardness have been considered as the output parameters. Sharma et al. [16, 17] and Fuller et al. [18] studied the effect of tool tilt angle, rotational rate, welding speed and tool geometry on the plates of 7xxx series alloys.

In the process of FSW, the linear motion of worktable and the tool rotation are provided by means of electric motors. So the electric motors are indirectly responsible for the tool torque and process forces provision. Pew and colleagues [19] measured the tool torque based on the records of motor torque records. Kumar et al. [20, 21] used the load cell to measure force in the FSW of aluminum alloy. On the other hand, Rajakumar and colleagues [22] considered the axial force as an input parameter and Trimble et al. [23] and Su et al. [24] considered the axial force as an output parameter assuming approximate contact between the workpiece surface and shoulder.

The axial force measurement plays important role in tool designing and identification of its restrictions. Also, it is vital in design of machine mechanism and optimization of welding process parameters. The main aim of this study is evaluating the relationship between the axial force and mechanical properties such as tensile strength, elongation, microhardness and weld morphology in butt stir friction welded AA7075-T651 aluminum alloy. This kind of welding process has a great importance in machine design, optimization of welding parameters and overcoming tool limitations. The achieved results from different combinations of welding speed and tool rotational rate are the basis of process optimization.

2. MATERIAL AND TESTING METHODS

The material which is used in this research is AA7075-T651 rolled aluminum alloy in the form of plate. This kind of aluminum is widely used in the aerospace industry. The plates are butt welded by friction stir process. The chemical composition of this alloy is equivalent to E1251-07:2010 in standard ASTM and is given in Table 1. This chemical composition is equivalent to AA7075 alloy in American standard AA which is in the set of Al-Zn-Mg-(Cu) alloy. In Figure 1 a test specimen is shown which has dimensions of 120 × 65 ×3.6 mm.

The tool used for welding the plates was made of hot work tool steel W302 that is equivalent to H13 with Rockwell hardness of 50 (HRC). The tool shoulder was concave and its diameter was 18 mm. The top and bottom diameters of the tapered pin were 8 mm and 6 mm, respectively and the tip length was 6 mm. The tool rotational rate, welding speed and tilt angle perpendicular to the plate surface were considered as the welding parameters. The welding process consisted of three steps: (1) plunging the tool that had the speed of 9 mm/min and a dwelling time of 18 seconds; (2) the welding speed v; and (3) pulling out the tool after 5 seconds of dwelling. To have uniform welding, a distance 0.3 mm was considered between the tip of tool pin and bottom surface of aluminum plates. Concave shoulder was embedded into the plates to make an efficient contact between the shoulder and the workpiece surface.

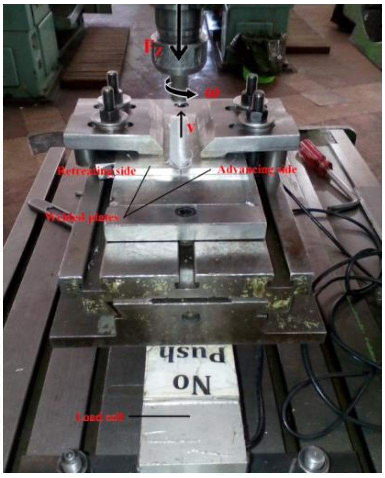

Figure 1. Photograph of FSW that includes conventional nomenclature

TABLE 1. Chemical combinations of current work A7075 and A7075 standard

Element	A7075 current work	A7075 standard
Al	Base	Base
Si	0.04	≤0.4
Fe	0.14	≤0.50
Cu	1.4	1.2-2.0
Mn	0.03	≤0.30
Mg	2.5	2.1-2.9
Cr	0.18	0.18-0.28
Zn	5.8	5.1-6.1
Ti	0.075	≤0.20

TABLE 2. The mechanical properties of aluminum alloy of current work A7075 and A7075 standard

Materials	**A7075 current work**	**A7075 standard**
Yield strength 0.2% (MPa)	526.5	475≥
Ultimate strength (MPa)	570.2	545≥
Percentage of length enlargement (%)	12.53	8≥
Young module (GPa)	70.19	71
Vickers hardness (Hv)	170	-

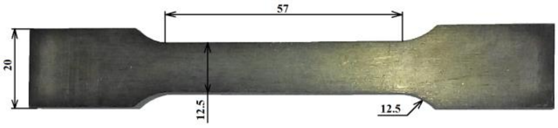

Figure 2. Ggeometric dimensions of sample 12.5 mm

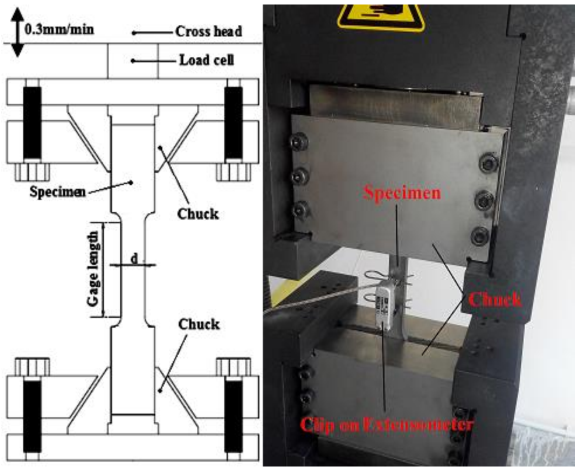

Figure 3. Servohydraulic Zwick/Roell and extensometer

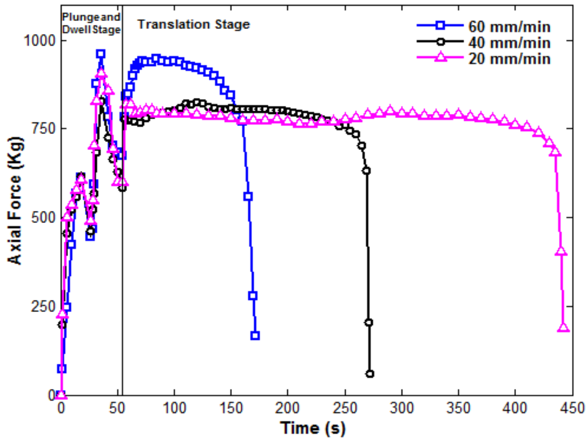

Figure 4. Axial forces versus time for rotation speed of 630 rpm and various welding speeds

The mechanical properties of AA7075 aluminum alloy used in this research are listed in Table 2. To accurately measure the axial force, the compression load cells AB 140 of the capacity of one tone, as in Figure 1, was used.

In this study, the uniaxial tensile tests were used to analyze the mechanical properties of AA7075-T651 aluminum alloy. To do that, some samples provided by wire cut machine from welded plates with the dimensions 120 mm × 130 mm × 6.3 mm were used. To evaluate the mechanical properties, three flat samples with the width of 12.5 mm prepared in accordance with ASTM E8M-97a, were used. This standard determines the tensile test method for metals. A typical sample is shown in Figure 2.

To do the tensile tests, a Zwick/Roell servohydraulic machine, model Amsler AB100 with the capacity of 10 tons was used. This machine is shown in Figure 3. The results were recorded in force-displacement data at a sampling rate of 2 Hz. Tensile tests were carried out using an extensometer and specimen gauge length was considered to be 27.5 mm. To perform the test, the rate of speed was selected to be 0.30 mm per minute. The ultimate strength and elongation can be achieved from the measurements.

ASTM E384-11e1Ev standard test method for Knoop and Vickers hardness of materials was served to evaluate microhardness. First, specimens with length of 40 mm were cut within the joint by wire cutting machine and prepared by hot mounting method. Then surface of the specimens was finished using sandpapers 100-grit to 2000-grit. Polishing the surface of the specimens was carried out by water and Al_2O_3. Finally, the hardness test was conducted on three rows of polished specimens. The hardness was measured with an interval of 1 mm from each other by a force of 200 g during 10 seconds and the diagram for hardness variation was prepared.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3. 1. Axial Force

Figures 4 to 6 show the axial force changes versus the time in the FSW process. During the tool plunging stage in workpiece, namely 0-36 seconds, the axial force increases to its maximum value, which is when the shoulder of tool is completely in contact with the workpiece surface. Over the time, the amount of axial force is reduced due to the increased heat produced by friction in dwelling stage (36-54 seconds). Axial force (axis Z) is measured by a load cell. It is seen in Figures 4 to 6 that for different welding parameters, the axial force is directly related to the welding speed. However, there is no explicit relationship between the axial force and tool rotational rate.

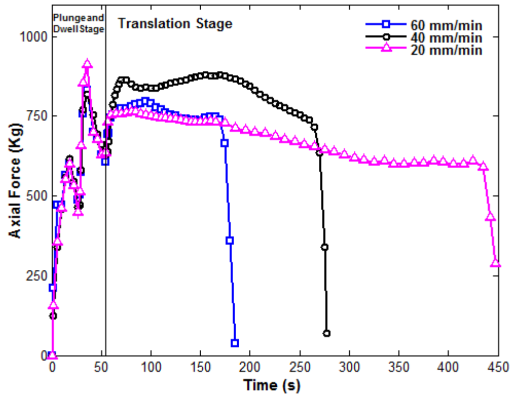

Figure 5. Axial forces versus time for rotational speed of 1000 rpm and various welding speeds

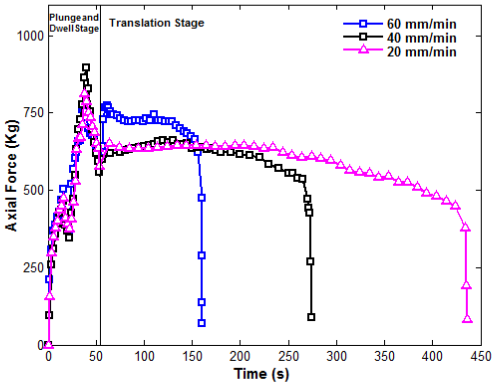

Figure 6. Axial forces versus time for rotational speed of 1250 rpm and various welding speeds

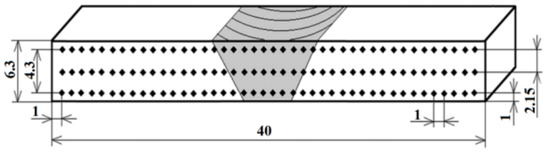

Figure 7. The cross-sectional area of the weld hardness test

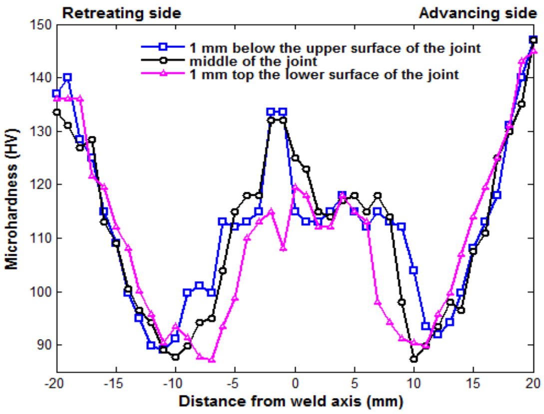

Figure 8. Hardness curves in rotationl rate of 1250 rpm and welding speed of 60 mm/min

3. 2. Microhardness

In this research, the hardness is measured in the heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and stir zone (SZ). Figure 7 schematically shows the areas in which the measurement is done.

Figure 8 illustrates the curves of hardness at 1 mm below of the upper surface, at the middle and at 1mm top of the lower surface of the welded plate. The rotational rate and the welding speed are 1250 rpm and of 60 mm/min, respectively. It can be seen that hardness variation in three rows are negligible. Also, the value of hardness at the middle and at 1mm top of the lower surface of the welded plate are respectively 0.76 % and 2.5 % less than it in 1mm below of the upper surface of welded plate. Also, the base metal hardness is approximately 170 HV which is significantly higher than the SZ hardness value that is 115 HV.

Figure 9 shows the hardness curves in 1 mm below the top surface of the welding joint. This figure is for the rotational rate of 1250 rpm and various welding speeds. It can be seen that as the welding speed increases from 20 mm/min to 60 mm/min, the value of hardness in SZ changes between 60 % up to 70 % of base metal hardness.

The hardness magnitude in SZ is related to the size of recrystallization grains which in turn is affected by heat input. Frigaard et al. [25] introduced the following equation for the heat input q generated by FSW process:

$$q = \frac{4}{3}\pi^2 \mu P_z \omega r^3 \tag{1}$$

where μ is the friction coefficient, P_z is the pressure on the tool, ω is the tool rotational rate and r is the radius of shoulder. Considering the welding speed v, Kim et al. [26] obtained the following equation:

$$Q = \frac{\eta q}{v} = \frac{4}{3}\pi^2 \frac{\eta \mu P_z \omega r^3}{v} \tag{2}$$

In which Q is the heat input per unit length and η is heat input efficiency. Here, the rotational speed ω and the welding speed v are variable parameters and η, μ, P_z and r are constant. Hence, Q may be written as:

$$Q = \beta \frac{\omega}{v} \tag{3}$$

where $\beta = \frac{4}{3}\pi^2 \eta \mu P_z r^3$.

As Equation (3) depicts, the heat input is increased by increasing the rotational rate or decreasing the welding speed. It is well known that high temperatures can lead to the growth of srecrystallization grains. Therefore, the increase in welding speed and/or the decrease in rotational rate lead to the decrease in heat input which in turn causes the reduction of grain sizes and finally increasing the hardness.

Figure 10 shows the curves of hardness values in 1mm below the surface of the welding joint for welding speed of 20 mm/min and various rotational rates.

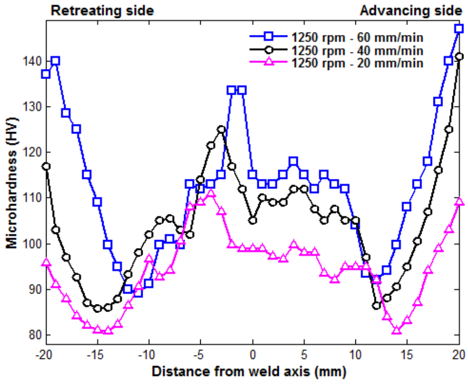

Figure 9. Hardness curves in rotationl rate of 1250 rpm and different welding speeds

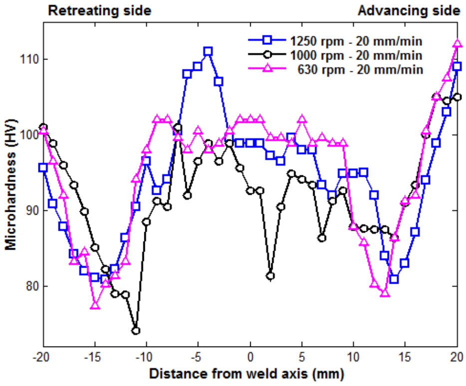

Figure 10. Hardness curves in welding speed of 20 mm/min and different rotation rates

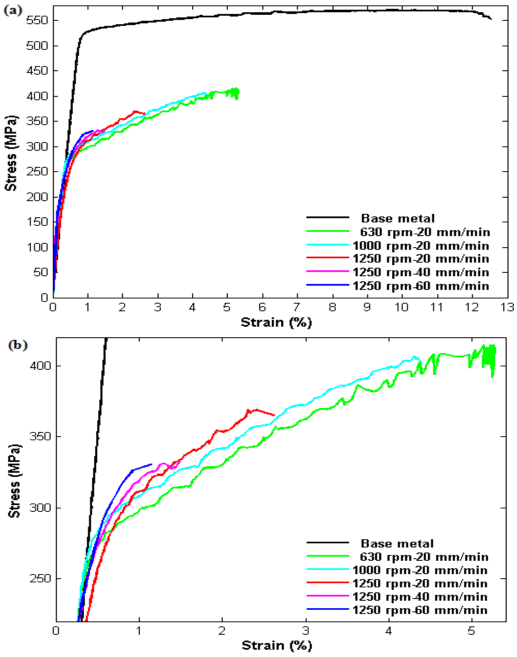

Figure 11. (a) Typical engineering stress-strain curves of the A7075-651 base alloy and FSW welded sample testes, (b) a magnified view of the zone boxed in (a).

It can be seen that as the rotational rate increases, the amount of hardness variation in SZ is almost negligible for all rotational rates from 630 to 1250 rpm, and is nearly 66% of base metal hardness.

3. 3. Tensile Properties

The engineering stress-strain curves for the welding joint and base metal at the room temperature and a strain rate of 0.0053 1/min is illustrated in Figure 11. To better distinguish between the engineering stress-strain curves, a magnified section of Figure 11 is shown in Figure 11b. As it is clear from the Figures 11a and 11b, the ultimate strength reduced after welding. The joint efficiency is defined as the ratio of the ultimate strength of a welding joint to the ultimate strength of the base metal [27]. In current work, the joint efficiency is variable from 58 to 71%. Also, the elongation of the joint is low with respect to the base metal elongation and is almost 1.15 to 5.27% (see Table 3). At a low rotational rate of 630 rpm and welding speed of 20 mm/min a high ultimate tensile strength is obtained. The ultimate tensile strength of the joints decreases as the rotational rate increases from 630 to 1250 rpm. Moreover, the ultimate tensile strength decreases by increasing the welding speed from 20 to 60 mm/min.

Figure 12 shows the location in which the fracture occurs for both the base metal and welding joints. The fracture in all FSW joints except the joint welded with the welding speed of 20 mm/min and rotational rate of 630 rpm occurred in the SZ where the least hardness exists according to Figures 9 and 10. The fracture of FSW joint with the welding speed of 20 mm/min and rotational rate of 630 rpm happened in the HAZ which has the highest hardness compared with other joints, as Figure 9 shows. However, the fracture in both the base metal and FSW joints happened in shear mode, i.e. the angle of 45° with respect to the tensile axis.

TABLE 3. The effect of different rotationl rates and welding speeds on mechanical properties of welded joints by FWS

Base metal/joint conditions	**Ultimate stress (MPa)**	**(Elongation) (%)**
Base metal	570.2	12.53
20 mm/min 630 rpm,	405.7	5.27
20 mm/min 1000 rpm,	401	4.39
20 mm/min 1250 rpm,	364.8	2.62
40 mm/min 1250 rpm,	332.4	1.49
60 mm/min 1250 rpm,	330.4	1.15

Figure 12. Tensile failed samples (rotational rate ω/welding speed v).

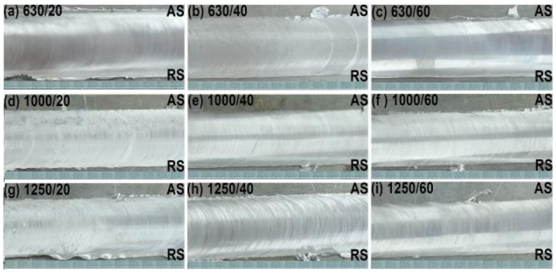

Figure 13. Appearance of welding for various parameters (rotational rate ω/welding speed v). (RS: retreating side and AS: advancing side).

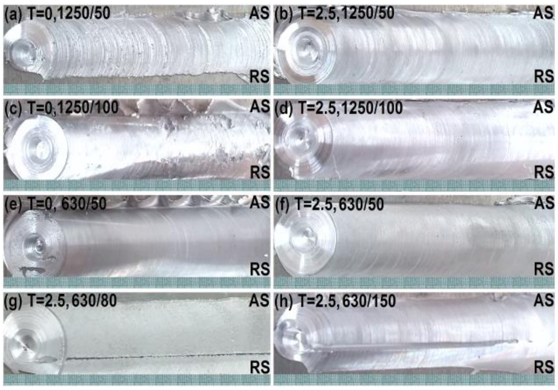

Figure 14. Appearance of welding for various parameters (Tilt angle of tool T in degrees and rotational rate ω/welding speed v).

3. 4. Weld Morphology An appearance of the welding joints which was produced for this study is shown in Figure 13. It is seen that the best quality in weld appearance is achieved at the low welding speed (i.e. 20 mm/min) and high rotational rate. According to Figures 4 and 13 which show, respectively, the axial force and the appearance of weld with mentioned parameters, the resistance to the tool rotation is the lowest and the axial load is minimum. In general, the shear strength decreases significantly in high rotational rate which means that the material around the tool flows easily. On the other hand, as described in Figures 4 to 6, at the low welding speeds, the tool forces are small.

In this relation, one can see the poor-quality welding joints in Figure 14a, 14c and 14e. The defects are related to the tool tilt angle, welding speed and rotational rate. The high welding speed results in the creation of the burr in weld because of inadequate and unsteady flow of material in welded joint in which the material is unable to fill the cavity created by the pin [24, 27]. The lower welding speed and higher rotational rate caused the better weld quality in Figure 14e compared to the one in Figure 14a.

The welding in Figures 14b, 14d and 14f have been performed with the same welding speeds as in Figures 14a, 14c and 14e, respectively, but with the tool tilt angle of 2.5°. As can be seen, the spindle tilt towards trailing direction resulted in high-quality welding joints. A suitable tilt angle ensures that the shoulder holds the stirred material by the pin and move it effectively from the front to the back of the pin. In this manner, a more high-quality welding joint is achievable [27].

Figures 14g and 14h depict poor-quality of the weld appearance which have been performed by the high welding speed, at a constant rotational rate of 630 rpm and with the tilt angle of 2.5°. Here, the mentioned welding parameters are such that the material ahead of the pin is significantly uplifted because of the 2.5° tilt of the tool, which creates a ‘‘plowing action’’ in the weld metal. So, the proper combinations of welding speed, rotational speed and tool tilt angle are essential to obtain a high-quality FSW joint [27].

4. CONCLUSION

In this paper, the axial force, mechanical properties, microhardness and weld morphology of the FSW process on AA7075-T651 aluminum alloy plate have been investigated experimentally. The main results are summarized as follows:

1. The best quality in weld appearance is achieved at high rotational rate and low welding speed. That is because, the tool force is minimum at low welding speed and the shear resistance reduces significantly at high rotational rate.
2. The force increases during the plunging of the tool in workpiece and then decreases to 25% of its maximum value during welding. Also, the axial force is directly proportional to the welding speed.
3. The best mechanical properties are obtainable in the range of 0.016 mm/rev to 0.032 mm/rev (ratio of welding speed to rotational rate).
4. The amount of hardness in SZ increases with increasing the welding speed in a given rotational rate. Also, the hardness in SZ doesn't change significantly with increasing the rotational rate in the same welding speed.

5. The ultimate tensile strength of the joints decreases with increasing of the rotational rate. Also, increasing the welding speed results in decreasing the ultimate tensile strength.
6. By increasing the welding speed and at the same rotational rate, the axial force and hardness increase in SZ and the weld appearance quality reduces, but with increasing the rotational rate in a given welding speed, there is no special relationship between the axial force, hardness and weld morphology.

5. ACKNOWLEDGMENTS

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Effect of Tool Speed on Axial Force, Mechanical Properties and Weld Morphology of Friction Stir Welded Joints of A7075-T651

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چکیده

اندازه‌گیری نیروی محوری در جوشکاری اصطکاکی اغتشاشی دارای اهمیت زیادی در طراحی و محدودیت ابزار، طراحی مکانیزم ماشین و بهینه‌سازی پارامترهای فرآیند جوشکاری می‌باشد. در این تحقیق ورق‌های آلیاژ آلومینیوم A7075-T651 به صورت لب به لب به یکدیگر متصل شدند سپس با تغییر پارامترها، عواملی مانند نیروی محوری، خواص مکانیکی، میکروسختی و کیفیت ظاهری جوش بررسی شد. برای اندازه‌گیری نیروی محوری از لودسل و برای ارزیابی خواص مکانیکی از یک ماشین سروهیدرولیک استفاده شد. نتایج بدست آمده نشان داد که با افزایش سرعت پیشروی و یکسان بودن سرعت دوران، نیروی محوری و سختی افزایش و کیفیت ظاهری جوش کاهش می‌یابد؛ ولی با افزایش سرعت دوران و یکسان بودن سرعت پیشروی، رابطه مشخصی بین نیروی محوری، سختی و کیفیت ظاهری جوش وجود ندارد. همچنین با تغییر زاویه انحراف ابزار از صفر به ۲/۵ درجه، کیفیت ظاهری جوش افزایش پیدا کرد. نتایج حاصل از تغییر در سرعت‌های پیشروی و سرعت‌های دورانی، اهمیت زیادی در بهینه سازی فرآیند جوشکاری دارد.

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