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Effect of cooling and its lack on hardness and tensile strength in 2024 aluminum alloy FSW welding process

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ABSTRACT

In the field of lightweight metals welding, using traditional welding methods lead to defects such as porosity and pore which cause the loss of mechanical properties. In addition, using shielding gases in the process makes the process complex. So, a new method called Friction Stir Welding (FSW) was invented for these metals. [1] Friction stir welding is a solid state welding process that uses a non-consumable tool to establish the joint between different materials especially aluminum series of 2000 and 7000. Although little heat generated during this process does not melt the base metal, the thermal cycle applied on the sample reduces the mechanical properties of the joint.

In this study, in order to increase the tensile strength and hardness of created joint on 2024-T6 aluminum alloy, Friction stir welding is performed under the water. This process is carried out under water to perform cooling and heating operation simultaneously. And this sample of welding was compared with air welding with the same welding conditions. The research parameters include rotational speed, traverse speed, existence and non-existence of cooling. The material of the tool used in this study is H13 hot work steel. The results showed that the underwater samples have higher mechanical properties than the samples air welded.

***Keywords**: Friction stir welding under water, T6 aluminum alloy, tensile strength, H13 hot work steel*

INTRODUCTION

In the field of lightweight metals welding, using traditional welding methods lead to defects such as porosity and pore which cause the loss of mechanical properties. In addition, using shielding gases in the process makes the process complex. Thus, for this type of metals were known as non-welding metals, a new method called Friction stir welding (FSW) were developed that did not have the defects of previous methods. One of the advantages of this process is that the base metal is not melted. This prevents the penetration of oxygen and eliminates the negative effects caused by the phase change. Moreover, due to the lower heat flux, residual stress and distortion is lower in the part. In this method, welding operation is carried out by tools consisted of two parts of pin and shoulder. The tool with proper rotational speed enters the interface between the two pieces and causes deformation of the material by creating heat generated by the friction between the tool and parts and finally makes a joint between the two parts. Friction stir welding process is shown schematically in Figure 1.

Friction stir welding process creates less heat than traditional welding in the process. However, this amount of heat leads to metallurgical changes. And these metallurgical changes reduces the mechanical properties compared to base metal and eventually leads to residual stresses in the material. So, with thermal cycle control in this type of welding, we can improve its properties. In aluminum alloys, amplifier precipitate is the cause of strength. Dissolution temperature of the precipitates is lower than the temperature during welding. So many of these precipitates will be solved during welding. And this led to a sharp drop of mechanical properties compared to the base metal. Using the coolant during welding prevents reaching the required temperature for dissolution of the precipitates. For this, it leads to strengthening the mechanical properties of the weld.

Friction stir welding of aluminum alloys by thermal cycle control increases the mechanical properties of the weld. This has been studied by various researchers.

Mofid et al. [2] studied the impact of cooling water on binding properties of aluminum to magnesium alloy in friction stir welding. The researchers reported that in the friction welding under water, due to low temperature and less heat input, intermetallic compounds are less than stir air welding. Aidin et al. [3] investigated the effect of temperature of the work piece on the grain size on welding process of 2024 aluminum alloy and reported that reducing the initial temperature of work piece from 30 ° to -30 ° C, recrystallized grain size decreases again. On the other hand, continuous cooling of the lower joint seam by water on 7075 aluminum alloy illustrated that increasing the speed of heat output decreases the dynamic crystallized grain size in the weld zone. Liu et al. [4] examined the tensile properties of 2219 aluminum alloy weld in underwater welding conditions. The results showed that the tensile strength of the weld from 324Mpa in the air welding conditions to 341Mpa in underwater welding conditions is increased. Reviews of fracture surface indicates that the fracture in the underwater welding sample is occurred by the interface between weld metal and TMAZ (Thermal Mechanical Affected Zone). But the air welding sample, the fracture is occurred by the interface between HAZ (Heat Affected Zone) and TAMZ.
Hosseini et al. [5] investigated the underwater friction stir welding on aluminum sheets obtained from the cumulative rolling process. Due to the small grain size of the sheet, friction stir welding under normal conditions increases the grain growth and decreases the quality of the sheet. For this, welding of this sheet was performed under water. Hardness curve was changed compared to conventional friction stir welding mode. Minimum hardness was increased. Tensile strength had a significant increase.
Zhang et al. [6] reported that friction stir welding of 2219 aluminum alloy under water and under 600rpm rotational speed, size of TMAZ is very small, but at speeds greater than 600rpm, TMAZ is detectable and the size increases.

Research Methodology
In this study, the friction stir welding on cooled rolled 2024 aluminum sheets with thickness of 5mm was performed in both air and underwater conditions. Chemical composition of 2024 aluminum alloy is shown in Table 1.

Table 2.1 Chemical composition of 2024 aluminum alloy

Elements	Sn	Pb	Ni	Cr	Si	Fe	Mg	Cu	Zr	AL
AA2024	0.5	0.05	0.05	0.1	0.5	0.5	1.6	4.2	0.2	Bal

Using guillotine, the sheets are cut in 200*100*5 size mm in a way that the rolling direction is place along at the width of the sheet. After cutting, the edge of the sample is machined, and then cleaned by filing. Before testing, samples are washed with acetone to prevent fat on the samples from making change in the heat transfer rate. Then the two sheets are firmly fixed in the fixture that their edges are perfectly in contact and there is no space between them. Welding process was carried out in longitudinal direction with the sample or perpendicular to the cold rolled sheet direction using a FP4M Universal Milling Machine in different rotational and traverse speed. Underwater test is to control the thermal cycle. Smart cooling system works as follows.
Pond was filled in a way that the water level was above the work surface for 40mm. Pool water supply reservoir which has 40 liter volume is filled with water at 20 degrees. To control the temperature of the pool water temperature, a thermometer is used and its sensor is located inside the pool.
This thermometer is set in a way that can adjust the pool temperature between 20 and 30 ° C during welding.
The instruments used in this process include a cylindrical pin and the concave shoulder surface that has an angle of 5 ° inward. This surface leads the material into the chamber made by the angle due to the pin rotation. Also, the tool centers must be carefully regulated with the samples in contact edges. Tools are made by H13 hot work steel and are hardened to 54Rc BY heat treatment. During the welding, tools form was examined carefully to exchange tools when there is any change in the tools forms.
To evaluate the effect of welding parameters on the properties of the joints made, the process was conducted at different rotational and traverse speeds. In this study, welding is done in five rotational speeds: 800-1000-1200-1400-1800 rpm. And the traverse speed was selected as 40-60-80-100 mm/min. Deviation angle of tools in all tests were selected 2 degree.
After the welding operation, the place of sample joints were visually inspected and their appearance and possible imperfections were examined. For the next step, the joint created was examined from a mechanical point of view. In this regard, the tensile test sample with ASTM-E8 standard (Fig.1) were taken

perpendicular to the direction of welding. Tensile test was performed at room temperature at a speed of 1mm/min by computer-controlled INSTRON tensile machine.

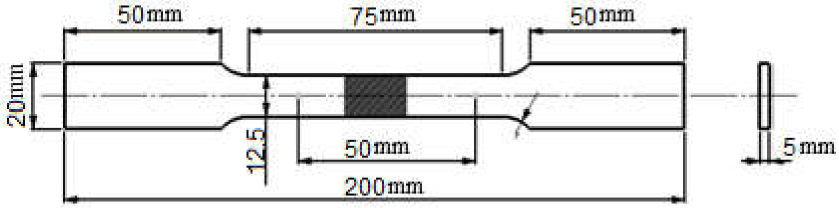

Figure 1. Dimensions of tensile samples conforming to ASTM-E8 standard

Results and Discussion

3.1 Tensile tests results

One of the most important criteria for evaluating the quality of the weld is the weld tensile strength. For this purpose, in this study, all weld samples that had no apparent defect, put under tensile test. To gain a measure to compare the results, tensile test was also performed on samples of aluminum sheet.

The results extracted from stress-strain curves, shows the tensile strength and general form of the tensile curve have non-smooth points in some samples. In addition to information on stress-strain curves, there are information extracted from the samples about the part of the sample in which fracture occurred.

3.1.1 Place of fracture in tensile sample

Fracture in tensile test in butt joints of friction stir welding, usually occurs in places of the least hardness [7]. However, in defective welds, two factors determine the fraction place. The first factor is stress concentration at the defect place and second factor is the distribution of hardness in the weld cross section [8]. The competition of these two factors determines the place of fracture. In defect welds, big of concentration defect brings high stress. Thus, stress concentration on defect overcomes the hardness factor and causes a fracture in the defect zone. But in zones where the defects are very little, it is possible that the stress concentration is not dominant at the defect place and fracture occurs at the place of least hardness. Figure (2) shows the fracture place of all tensile samples.

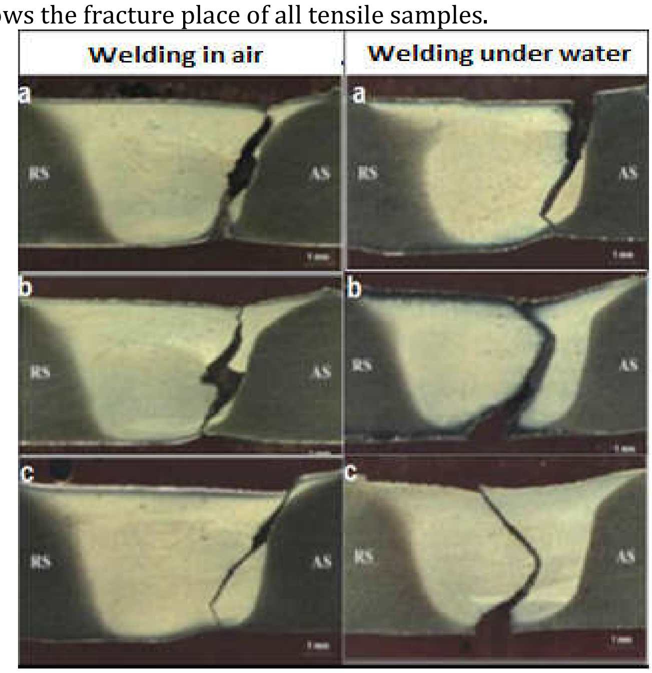

Figure 2. Fracture area of tensile samples at traverse speed of
(a) 60 mm/min (b) 80 mm/min (c) 100 mm/min

In all samples the place of figure is at the weld zone. In justification of this, as noted before, in defective welds, stress concentration at the place of the defect and the place of minimum hardness are in competition with each other. In most of weld samples, due to the large size of the defect formed, stress concentration at the site of the defect overcomes the place of minimum hardness and fracture occurred at the site of the defect.

Cross-section of welding underwater at rotational speed of 1400 rpm after tensile test is shown in Figure 3. This cross-section can be compared with air welded sample cross-section with the same conditions as shown in Fig. 4. As can be seen, in the cross-section of underwater welding sample, due to the heterogeneity and the stress concentration areas, the sudden fracture of the sample in the tensile test has occurred without reducing the amount of stress.

Figure 3. Fracture cross-section of the welded sample underwater

Figure 4. Fracture cross-section of the air welded sample

3.1.2 Effect of traverse speed parameter change on weld strength

In low traverse speed (40mm/min) in underwater and air welding, samples taken from weld joints, all have fracture in HAZ and TMAZ boundary in the AS area (leading tool side). But air welding has a much larger HAZ area than the case of flooding. This area, as stated earlier, has the least hardness (Figure 2).

In underwater welding with two traverse speeds of 60 mm/min and 80 mm/min, the fracture zone is at AS side and the zone between TMAZ and steer. This is due to the narrow width of the soft area. Because the heat input decreases due to increased traverse speed and the use of water as the cooling fluid. But in air welding, the fracture place in these two traverse speeds is different. Since in traverse speed of 60 mm/min heat input is greater than traverse speed of 80 mm/min, fracture occurs at the boundary of HAZ and TAMZ zones. But in traverse speed of 80 mm/min due to reduced heat input, fracture occurs in the zone between TAMZ and the place close to the steer. Since the failure occurs in the area of lowest hardness, minimum hardness increase (increasing traverse speed from 40 mm/min to 80 mm/min) improves the strength. In underwater and air friction stir welding of 2024 aluminum alloy, in flooding state with rotational speed of 1000 rpm, with increasing traverse speed from 60 mm/min to 80 mm/min, the tensile strength of the weld was increased (281-319 MPa) and in traverse speed of 100 mm/min 100 it was decreased significantly (240 MPa). (Due to Lack of proper mixing and creating tunnel defects at this speed). But in the case of air welding with the above rotational speed, and traverse speed from 60 mm/min to 80 mm/min, the tensile strength decreased compared to the underwater welding (281-250 MPa). This is due to the heat created compared to the flooding case. In traverse speed of 100 mm/min, since less heat than in the previous traverse speeds is created in the weld zone, soft area has less width and the tensile strength of the sample is bigger than the flooding case. The results are shown in Figure 5:

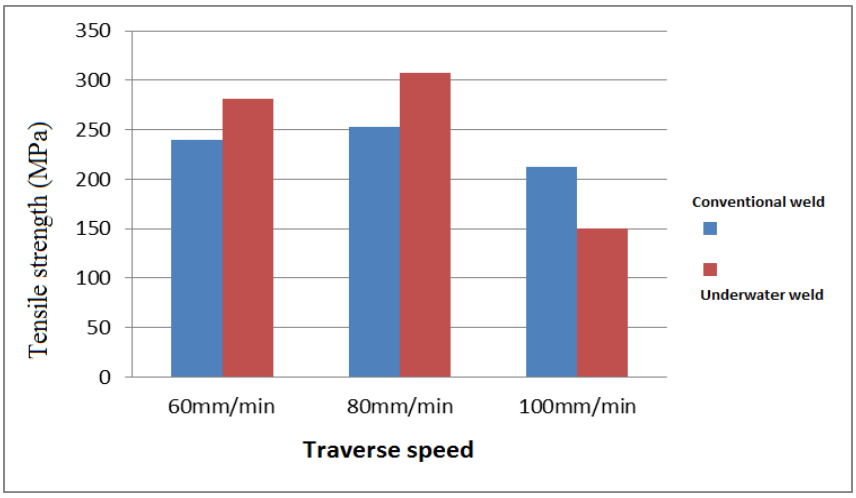

Figure 5. Effect of traverse speed on the tensile strength

3.1.3 Relationship between the tensile strength and fracture zone
We should reduce the input heat to achieve a perfect friction stir welding joint with a strength equivalent to the base material strength in order to remove the softness effect of HAZ completely or to a great extent.
Under stable conditions, with rotational speed of 1000 rpm and traverse speed of 80 mm/min for normal and underwater welding, tensile strength of 2024 aluminum alloy joint in normal friction stir welding is 70% of the tensile strength of the base material (about 275 MPa), while in underwater welding, it is 77% (about 307 MPa). The obtained results show that the tensile strength of the weld joint in underwater welding grows, while the increase percentage of weld length in underwater welding is (about 2%) lower than the normal weld (about 8 percent). (Fig. 7)
As shown in Figure 2, position of fracture in underwater welding joint and conventional welding joint are different. Samples obtained from conventional welding, have fracture in tensile test in the zone of HAZ (or boundary between TMAZ and HAZ) and in AS.
This phenomenon states that HAZ is the weakest weld zone, while the samples obtained from the underwater weld have fracture in the boundary between steer and TMAZ area in AS zone which represents the strength of HAZ in underwater weld.
Fracture surface in conventional friction steer welding have large and deep holes which indicates large plastic deformation in tensile test. While fracture surface concavities in underwater welding is unclear and represents the plastic deformation.
In all FSW joints that were under water cooling, fracture line is a curve or perpendicular to the applied force, and in conventional friction steer welding joint, fracture is a straight line whose surface makes an approximately 45 degree angle with the direction of the applied force. Fracture surface in conventional friction steer welding joint includes secondary cracks and coaxial deep holes with large diameters. Secondary cracks represent the more ultimate tensile strength in conventional friction steer welding joint (compared to weld joint under water cooling). Conventional friction steer welding joint and weld joint under water cooling have soft fracture. (Fig. 2)
3.1.4 Effect of rotational speed parameter on weld strength
Friction steer welding of 2024 aluminum alloys was performed under water and in the air. Rotational speeds of 1000 and 1400 rpm were studied (Fig. 6). At rotational speed of 1000 rpm, the tensile strength of the weld joint reaches a level equivalent to 304 MPa (77 percent of base material tensile strength). At this speed (1000 rpm) underwater weld joint has reached a desirable level, while in conventional friction steer welding joint by 1000 rpm rotational speed, the obtained tensile strength was 251 MPa. At 1000 rpm speed, tensile strength shows a sharp drop (about 214 MPa). In addition, the maximum tensile strength of the weld joint underwater is bigger than the weld joint in conventional welding. And it is clear that cooling by water has a positive effect on weld strength and increases it.
Increasing rotational speed in friction stir welding underwater, elongation percentage is slightly modified (at 1000 rpm is about 5%). This is while in the case of air welding, elongation percentage is 6.5. But at 1400 rpm in underwater welding, elongation percentage is greatly reduced (about 1.5%). This condition occurs because of a cavity defect in the speed.
As we know, in tensile test, plastic deformation occurs in soft area. In hardness distribution, soft area width increases with increasing rotational speed of 1000- 1400 rpm. Thus, plastic deformation of the material becomes bigger in the weld zone. But it should be noted that by increasing the rotational speed

the hardness of perturbation zone increases. Joint effect of these two factors (plastic deformation of material and hardness) causes the elongation percentage get not altered significantly.
In samples performed at the speed of 800 rpm underwater, no weld occurred due to inadequate mixing of materials. For this reason, the tests were skipped in this rotation speed or less than that. Also, at the rotational speed of 1400 rpm, both underwater and in the air, due to the emergence of tunnel track (less is underwater samples and more in air welding samples) occurred in this area.
It is clear that the fracture of all the samples occurs in the weakest area of hardness. At the speed of 1400 rpm, although the minimum harness (compared to other speeds) is lower, the factor that causes sharp drop of mechanical properties of the weld in this speed, is not the sharp reduction of weld hardness but emerging cavity defect in high rotational speed.

Figure 6. Fracture in weld joint at rotational speeds of 1000 and 1400 rpm in air or underwater conditions

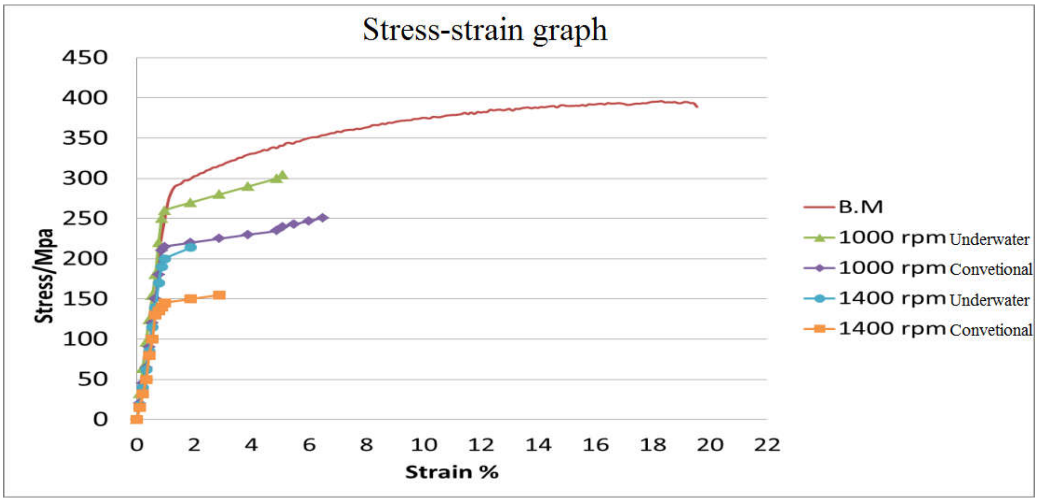

Figure 7. Stress-strain graph

3.2 Results of hardness evaluation
One of the mechanical properties of the weld is microhardness distribution in its cross section and investigating changes of microhardness in weld section by changes of welding parameters such as tools and rotational and traverse speed help to understand better the behavior of the material during the welding process.
During friction stir welding of aluminum alloys both heat treatment and non-heat treatment operations, the nugget zone shows a recrystallized microstructure. In the case of aluminum alloys for heat treatment operation, high working temperatures during the process in nugget zone and slightly in the zone affected by the heat and mechanical work, lead to the dissolution of a part of sedimentary phases.
3.2.1 Effect of rotational speed parameter change on hardness
With increasing rotational speed, width of soft area increases and in welding underwater with the speed of 1200 rpm, hardness of perturbation zone is reduced. So that hardness distribution in cross-section is U-shaped and the lowest hardness is attributed to the steer area. This happens for higher rotational speeds before 1800 rpm rotations, and in rotational speed of 1800 rpm both in underwater and in air welding,

hardness distribution in cross-section by moving from the base material to the weld center, is initially decreased and then increased. And thus the hardness distribution in the cross-section becomes W-shaped. As we can see in the figure, minimum hardness in underwater welding is bigger than minimum hardness of air welding. At the rotational speed of 1200 rpm in underwater welding, since the soft area is reduced, the minimum hardness is in TMAZ and close to perturbation zone. At the speed of 1200-1600 rpm, since the input heat is increased, the soft area in occurred in HAZ and close to TMAZ. (Fig. 8)
In perturbation zone, it's worth noting that with increasing rotational speed, the hardness increases. In this zone, due to the impact of the water used for cooling, after complete dissolution, metastable phases will not be precipitated again. Consequently, it should be noted that, the partial strength of the sediment is small and is not the dominant factor affecting hardness of perturbation zone. With increasing rotational speed, coaxial grains size in perturbation zones is increased and hardness is reduced. On the other hand, with increasing rotational speed, dislocation density is increased and therefore hardness is improved.

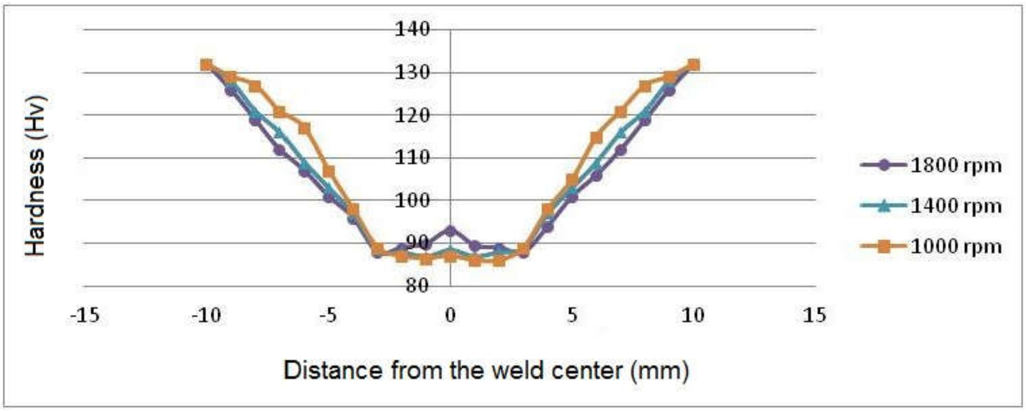

Figure 8. Hardness distribution at different rotational speeds in flooding case

So it can be concluded that when partial strength of the sediments is insignificant, dislocations are the main factors affecting the intensity of the perturbation zone hardness. When the rotational speed is low, dislocations density is less and strain-hardness is not much that can improve the lost strength due to declining sediments, so the perturbation zone will have the minimum hardness. But at high rotational speeds, dislocations density increases, which leads to increase of perturbation zone hardness; and TMAZ and HAZ will have the least hardness. (Fig. 9)

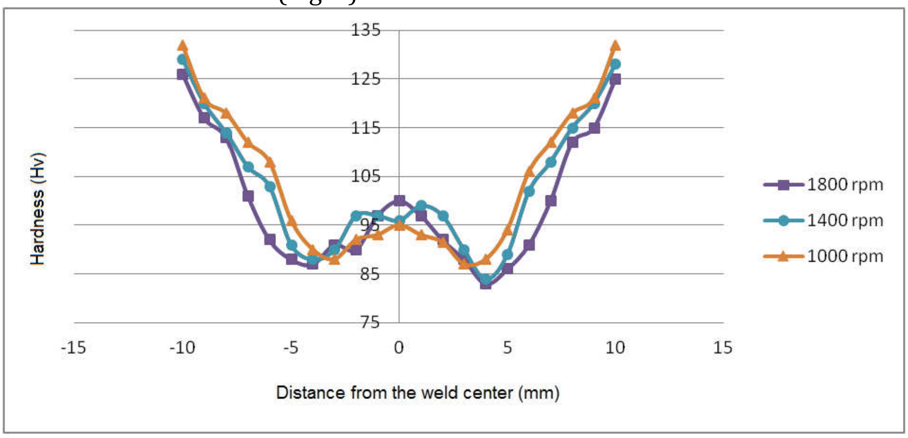

Figure 9. Hardness distribution at different rotational speeds in normal case

3.2.2 Effect of traverse speed parameter on zone with lowest hardness
In underwater and air friction stir welding, with increasing traverse speed, TMAZ and HAZ hardness is increased and the width of the soft area is reduced. And the minimum hardness increases, because with increasing traverse speed, sediments decline in the poorest areas of the weld is reduced. At rotational speed of 1400 rpm in underwater and air welding, the least hardness occurred in the boundary between TMAZ and HAZ in the area of AS when traverse speed was at 40 mm/min. At this rotational speed in underwater and air welding, when traverse speed is 60 mm/min and 80 mm/min, the boundary between

TMAZ and perturbation zone has the least hardness (in AS) and at the traverse speed of 100 mm/min and rotational speed of 1400 rpm, perturbation zone has the least hardness.
At the traverse speed of 40 mm/min, the extent of the sediment decline in TMAZ is more than HAZ. But the zone with lowest hardness is mainly based in HAZ rather TMAZ. This is due to the large number of dissolved sediments in TMAZ which leads to partial bathing and hardness deposition. So we can conclude that hardness in TMAZ is more than HAZ. (Fig. 10)

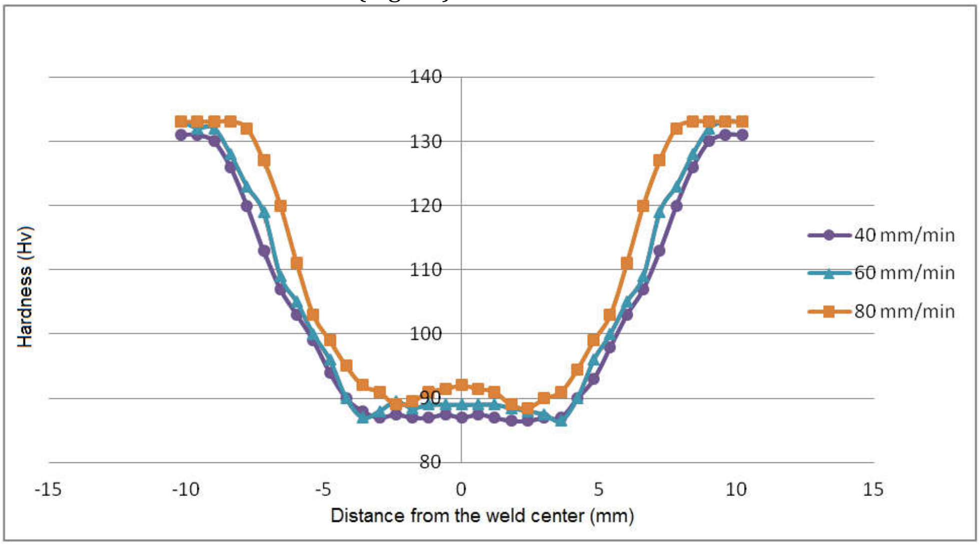

Figure 10. Hardness distribution at different traverse speeds

CONCLUSION

Friction stir welding process was performed under water to improve the mechanical properties of the joint. The effect of process key parameters such as traverse speed and rotational speed on mechanical and microstructure properties of the joint were examined. In this regard, experiments were performed at different rotation and traverse speeds.
In friction stir welding of 2024 aluminum alloys underwater, increase in tools traverse speed, reduces the deformation of the material, heat input and consequently width of soft area during welding and increases the hardness of TMAZ and HAZ. Increasing the hardness will also ultimately lead to improved tensile strength of the weld joint.
Samples of underwater welding in tensile test of HAZ zone, and air welding samples from the zone between the TMAZ and perturbation zone were broken which suggests that tensile properties of the joint welded under water is higher.
In a samples welded underwater at the rotational speed of 1000 rpm and traverse speed of 80 mm/min had the highest tensile strength.
The maximum hardness was obtained under rotational speed of 1000 rpm and traverse speed of 100 mm/min.

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