# The Effect of Travel and Rotational Speeds on the Mechanical Properties of Al2024 in Underwater Friction Stir Welding

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**Abstract**

In this research, the friction stir welding was performed underwater in order to evaluate and improve the mechanical properties of aluminum 2024 alloy. Welding samples were compared with the samples in the air welding. The results showed that samples of the underwater welding in case the rotational speed is 1000 RPM and feed rate is in 80 mm/min, has the highest tensile strength, also they obtain the highest hardness at a rotational speed of 1000 RPM and forward speed of 100 mm/min. Also, an increase of travel speed reduces deformation of the material, heat input and soft area width during the welding process and increases hardness of TMAZ and HAZ. With increasing rotational speed, heat input and soft area width increased. This will, on the one hand, decrease the hardness of TMAZ and HAZ and, on the other hand, increase the stiffness of the disturbance area. Increasing hardness also ultimately improves the tensile strength of the welding joint.

*Keywords:* Underwater Friction-Stir Welding, Al2024, Travel Speed, Rotational Speed.

## 1. Introduction

Aluminum alloys are classified into heat-treatable and non-heat treatable. Heat-treatable alloys (such as 2000 and 7000 series) get their strength through hardening precipitation mechanism. In many melting methods, the operating temperatures are above their melting points, which destroy all of alloys' basic properties. Therefore, the emergence of new methods of solid state welding with possible low operating temperatures is highly considered.

The welding process cycle may lead to precipitate solving or coarsening in the metal structure, so that deposition continues during and after the welding process [1]. Friction-stir welding process is a solid-state welding to increase the strength of aluminum alloys at low operating temperature. Specific tools with a pin and shoulder rotate with a proper speed at the interface of two pieces and the created heat, due to friction between the tool and the parts, deform the materials and connect two pieces [2]. Depending on maximum temperature, two factors of plastic deformation and the friction between the tools and workpiece lead to increasing the temperature in stir zone and the surround [3].

Underwater friction stir welding is one of the friction welding methods to improve the quality of welding by controlling the input heat and holding down the temperature of the tools during the process.

In general this process is done in two ways.

In the first method, the whole tools and pieces are underwater and in the second method, certain amount and speed of water flows on the surface of the workpiece.

Two important variables in the process, the rotational speed of the tool (ω) and the speed of tool's movement along the welding line (v), play a significant role in the input heat to the piece and the material [4]. In general, the higher the speed of rotation and the lower the speed of moving forward, the more the welding input heat will increase.

Even though, friction stir welding process creates less input heat than the traditional methods, this amount of heat still causes metallurgical changes in the substance and subsequently effects on microstructures such as grain size, granularity boundary, precipitate solving and thus the mechanical properties of welding for mentioned reasons, it is important to be aware of temperature distribution during the process. It should be noted that temperature measurement in the stir zone is too difficult due to plastic deformation. However, successful welding requires enough heat so that the material gets hot enough to cause plastic deformation and reduce the applied force to the tool.

Higher speed than the limit will cause the material to stay cold and, subsequently, to break the pins and to create cavities in the welding site. On the other hand, the higher input heat will expand the welding spot and the adjacent areas to the tool, which ultimately leads to an increase in residual stress and lower hardness and strength in these areas.

Therefore, thermal cycle control can improve the properties of this type of welding [5]. Various

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researchers have studied about the effect of thermal cycle control on the mechanical properties of the welding site in the friction stir welding of aluminum alloys.

A number of researchers studied the friction stir welding underwater on aluminum sheets, obtained from the rolling process. Due to the very small size of the grains in these sheets, friction stir welding in common conditions causes grain growth and loss of quality of the sheet. So the welding of the sheets was done underwater. In previous researches, maximum temperature of this zone had been predicted by welding microstructure [6]. In some cases, a thermocouple, embedded in a pin is used to measure the temperature in this zone [7].

The curve of hardness compared to the usual friction stir welding was changed. Minimum hardness and tensile strength were increased significantly. Ren and colleagues examined the tensile properties of aluminum alloy 2219 in underwater welding. The results showed that the tensile strength of the welding site increased from 324 MPa in the welding conditions in the air to 341 MPa underwater. Reviews of broken sections in three samples indicate that the broken spots in underwater welding are located between metal and TMAZ (thermo-mechanical affected zone) [3,8]. In the case of welding in the air, it's located between HAZ (Heat Affected Zone) and TMAZ [9]. Tang et al. [10] reported that high pressure and rotational speed increase the temperature of the welding zone in the friction stir welding. Rajamanycham [11] stated that the peak temperature of the weld zone is more affected by tool rotational speed. However [12], the moving speed mostly affected the mechanical properties of welding.

Hirata et al. [13] reported increasing the travel speed and decreasing the rotational speed lead to decreasing the heat input and increasing the hardness of welding metal. In this report, it is also explained that the hardness of welding metal is less than base metal and more than the HAZ, and the main factor of high strength and hardness is fine grain.

Rhodes et al. [14] estimated the maximum temperature of the welding process between 400 to 480°C for Al7075-T65.Murr and co-workers [15] showed that all precipitates do not solve during process and temperature reaches at maximum 400°C for Al6061 welding. Fig. 1. shows the result of temperature distribution in different distance and different rotational speeds [16]. Considering the presented graph, increasing the rotational speed from 300-650 RPM increases the temperature up to 40°C, while the increasing from 650 to 1000 RPM increases the maximum temperature just up to 20°C. Also, in the HAZ, metal affected by heat and deformation simultaneously [3,11,17]. Because of being exposed by elevated temperature, we see the structural changes and precipitate distribution. Since the plastic deformation of the material is too much and exposures to elevated temperatures, micro-structural changes such as recrystallization, precipitate coarsening in the joint zone is predictable. In the welding nugget region, too much deformation resulted from the heating leads to dynamic recrystallization and forming the fine grains in this zone [10]. The size of the forming grain in this zone affects by welding parameters and tools shape and thus, 1 micrometer grains can be achieved under the special conditions [3,13].

The aim of this study was to evaluate and compare the improvement of mechanical properties of aluminum alloy, welded in the water and air, under the same welding conditions.

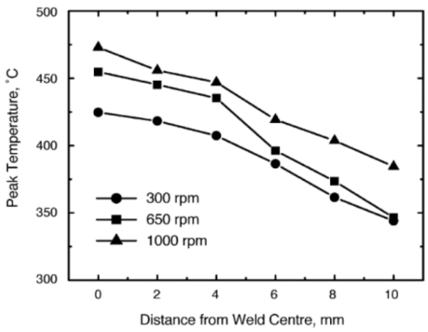



**Fig. 1. The effect of the rotational speed on the maximum temperature [16].**

## 2. Materials and Methods

Sheets of 2024aluminum alloy, made under the annealed condition and with dimensions of 100×200×5 mm, were selected for this study.

Two pieces were kept together for friction welding operations. Due to the low temperature of the piece in the vicinity of the tool, the material flow is difficult and an operation is similar to drilling in which a transverse force on the tool is high. Therefore, measures must be taken to prevent the separation of parts.

A steel sheet with 10 mm thickness, was used to control the position of the pieces in the force pressure and to prevent a possible distortion of the tool during the process. A number of pegs and screws were used to contain two components and stop the moving of the parts in the horizontal direction (Fig. 2.).

A universal milling machine FP4M, with the ability to provide a rotational speed of 250, 500, 1000, 1200, 1400, 1500, 2000, 2200 RPM and moving forward speed of 12, 40, 60, 80, 100, 150, 200, 300, and 600 millimeters per minute was used to create the required rotation of pin within the piece. For higher welding quality, the maximum applicable load of 1800 N was applied to the lever of the piece to create enough vertical force to maintain instruments on the welding sheets.

Applicable force at the time of stopping the machine, was approximately considered as applicable force on the workpiece during the welding process.

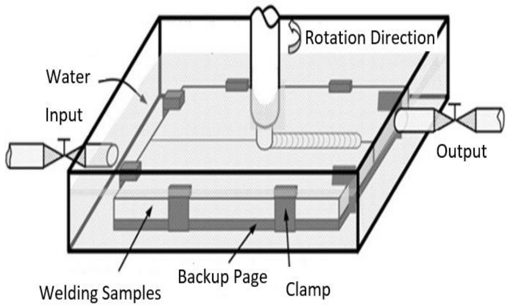



**Fig. 2. Schematic picture of underwater friction stir welding process.**

The length of the pin was considered due to the deflection angle as its corrosion and shortening was observed when the moving speed was very low and the tip of the pin was in frictional contact with the surface of the workpiece. Consequently, the tools need to lathe and heat treatment.

Pre-heating of the workpiece was done by rotating the shoulder on its surface to start the process. If the pre-heating time is short, the metal paste operation does not perform well and consequently tool's movement is interrupted. If pre-heating is too much, the materials will circulate around the pin and consequently driven from the seam toward the free space on the back of the pin.

### 2.1. Welding process

Cylindrical tool with 8.4 mm pin, which is 2.0 mm shorter in length than the thickness of the sheet, was used for the welding. The welding tool is made of chrome (H13 AISI). A vertical milling machine was used to provide the rotational and moving speeds for welding. The workpieces were tied up in the clamps on the table. The deviation optimum angle of 5.3 degrees was considered for the device [5].

The rotating welding tools get into the seam between the two sheets, pause for a short time to preheat the piece, move forward along the connection, and then leave the piece with the upward movement before they reach the bottom sheet to complete the welding process.

The advance of the welding process was controlled by timers. Pin diameter was selected according to the recommended values in the selected sources [4]. It must be considered that if the selected pin diameter is not suitable, either the pin breaks over the process due to the lateral applied pressure or higher rotating speed is needed to transfer the material from the leading to the back area. Also, the surface of all welding tools must be smooth.

### 2.2. Temperature measurement

Four different thermometers (BM; NAGEET; TMAZ; HAZ) were used to measure the temperature of the welding regions. Depending on the diameter of the shoulder, the selected locations to measure the temperature were 1, 5, and 10 mm from the edge of the tool (Fig. 3.). The sensor of the multi-meter thermometer (GWINSTEK GDM394), with the ability of measuring in the range of 1°C to 40°C and accuracy of 1/1000°C was used to control the temperature history over the process. The error of the tool is %1 in the range of 0-400 degrees according to the manufacturer. Only the temperature of the external surface at a specific distance from the pin was measured by direct connection of the sensor to the piece. The temperature of each spot was recorded every 10 seconds to avoid the error of thermometer timing feedback.

The test parameters were rotational speed of 1000 RPM, speed of moving forward of 60 mm/min., deviation angle of 5.3 degrees, and the tool with the shoulder of 20 mm in diameter.

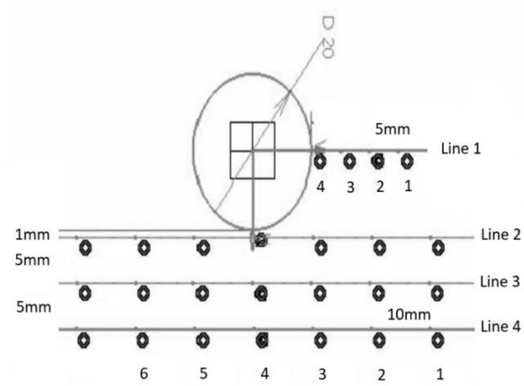



**Fig. 3. The temperature measurement sites on the piece and shoulder position of the tool.**

### 2.3. Tests of mechanical properties

Change in hardness and elastic properties of the samples were examined after the welding process. According to the standard method ASTM B557M (2010), the test samples were prepared and drawn with the bending rate of 1 mm/min. at room temperature. The results were analyzed. Based on the standard method of ASTM E10 and by using the hardness tester of Dension Every, Microhardness of the samples were measured by load of 200 gr, dwelling time of 10 s and the average of the obtained data was recorded.

## 3. Results and discussion

### 3.1. Temperature distribution

Due to the water capacity to absorb the heat, a high thermal difference was observed between friction stir welding of Aluminum 2024 in the water and in the air. (Fig. 4. & Fig. 5.). Also, plastic deformation and the friction between the tool and the work-piece increase the temperature in and around the stir area. The increase of temperature affects the micro-structure of the material such as grain size, grain boundary formation, dissolution of deposits, and consequently, mechanical properties of welding [5]. Therefore, it is important to know about the temperature distribution during the process.

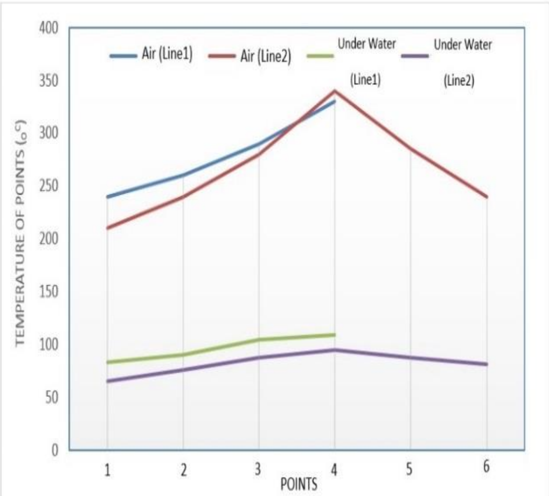



**Fig. 4. The temperature charts of lines 1 and 2.**

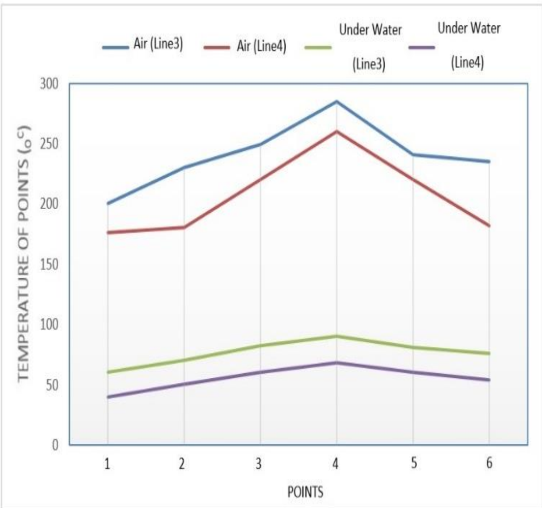



**Fig. 5. The temperature charts of lines 3 and 4.**

The measurement of the temperature is very difficult in the stir area due to plastic deformation. The temperatures of the welding zone in the air and in the water are 350°C and 100°C, respectively (Fig. 4.). Also, the period that the temperature is higher than 100°C in HAZ is much less than one, which is in welding in the air that consequently increases the tensile strength and hardness and decreases the percentage of relative elongation. Water cooling operation decreases the maximum temperature and the period of placement in the high temperatures.

**3.2. The effect of travel speed on weld strength**

In accordance with Fig. 6. , comparing the welding in the air under travel speed of 60 and 80 mm/min with underwater welding, tensile strength has been reduced. The reason is that the resulted heat is higher than underwater welding. Since a lower heat is produced through the travel speed of 100 mm/min in welding point in comparison with previous travels, the soft zone width is shorter and the tensile strength of the type of underwater welding is much more because of improper mixing and also the tunnel failures in underwater welding.

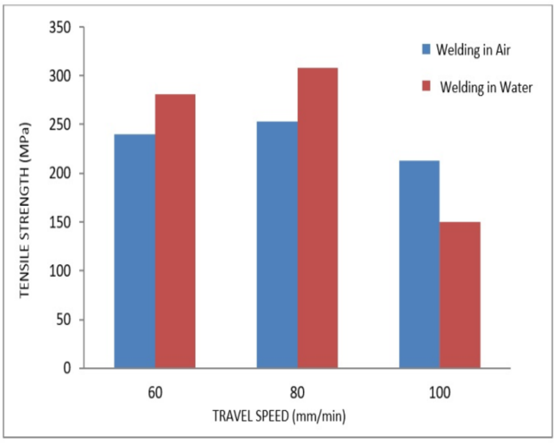



**Fig. 6. The effect of forward speed on the tensile strength at rotational speed of 1000 RPM**.

In accordance with Fig. 7. , in underwater welding and through two travel speeds of 60 up to 80 mm/min a fracture has been resulted in AS side and in the zone between TMAZ and stir because of narrowing the soft zone. The reason is that the input heating and using the water as a coolant is decreased. But in air welding, the fracture zones are different through these two travel speeds. In travel speed of 60 mm/min, the input heating is more than a travel speed of 80 mm/min, therefore the fraction is happened between HAZ and TMAZ zones. But in travel speed of 80 mm/min, the fraction is happened between TMAZ zone and near to stir zone, because the input heating is decreased. Since fraction is happened in the zone with the least hardness, increasing the minimum hardness resulted from travel speed of 60 up to 80 mm/min improves the strength. Similarly, in underwater welding, a slight heating is transferred around the nugget zone due to the higher level of heat absorption by water, and it causes HAZ and TMAZ zones to be in exposure of the lower heating, so that they have higher hardness and most of the fractions are in the nugget zone. Therefore, one can conclude that the more hardness a zone has, the fewer fractions happen in it.

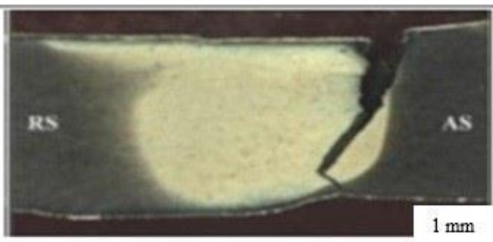
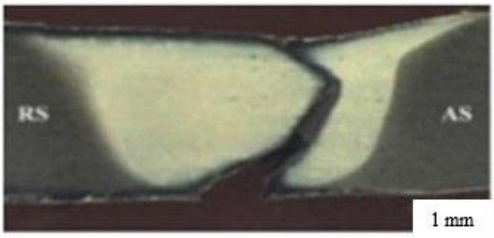
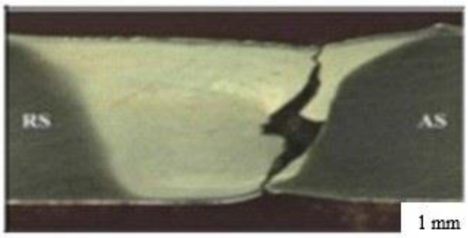
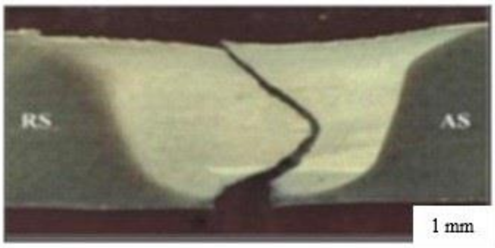
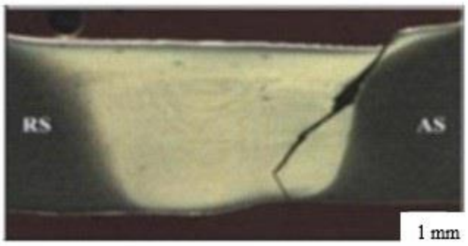
| Travel Speed (mm/min) | Underwater | Air |
|---|---|---|
| 60 |  |  |
| 80 |  |  |
| 100 |  |  |

**Fig. 7. The fracture zone of tensile samples in the different travel speeds at rotation speed of 1000 RPM**.

**3.3. The effect of travel speed on hardness**

By increasing the travel speed, TMAZ and HAZ hardness increases and width of the soft zone decreases, because by increasing the travel speed, deposits decay decreased in the weakest points of the weld. In accordance with Fig. 8. , in the travel speed of 40 mm/min, deposits decay is more extended in TMAZ than HAZ. But the zone with the least hardness is more in TMAZ than HAZ .The reason is that too much deposits has solved in TMAZ which results in hard increasing and hardness deposits [2]. Therefore, one can conclude that hardness in TMAZ is more than HAZ. But in other air welding samples, since the heating distributes on the surface and it cannot concentrate in the weld center, hardness in weld center is more than TMAZ zone which causes the most breaking to happen in TMAZ zone and the hardness graph, achieved by such test, would be W shape [6].

**3.4. The effect of rotational speed on weld strength**

Attempts for welding with speeds of 250 and 500 RPM failed, because the piece did not receive enough heating to be the pasty form. The reason may be the lack of an imposed stress and the smoothness of the pin surface as well. In accordance with Fig. 9. , in speed of 500 RPM, welding tools traveled into the piece, but it was with swarf which is not desired. Because two pieces were not jointed behind the tool and the process was not completed. Generally, increasing the rotational speed increased the resulted heating in the process [4]. As the rotational speed reached up to 1000 and 1400 RPM and other parameters were considered as constants, the piece received the enough heating for getting paste. Finally, regarding the fact that the more heating is produced during the faster speeds the rotational of 1000 and 1400 RPM were studied in the present research. In accordance with Fig. 10. , through rotational speed of 1000 RPM, the tensile strength of underwater weld joint reaches to 304 MPa (77 of %100 of the base material tensile strength), while the resulted tensile strength was 251 MPa during a normal friction-stir welding through the rotational speed of 1000 RPM.

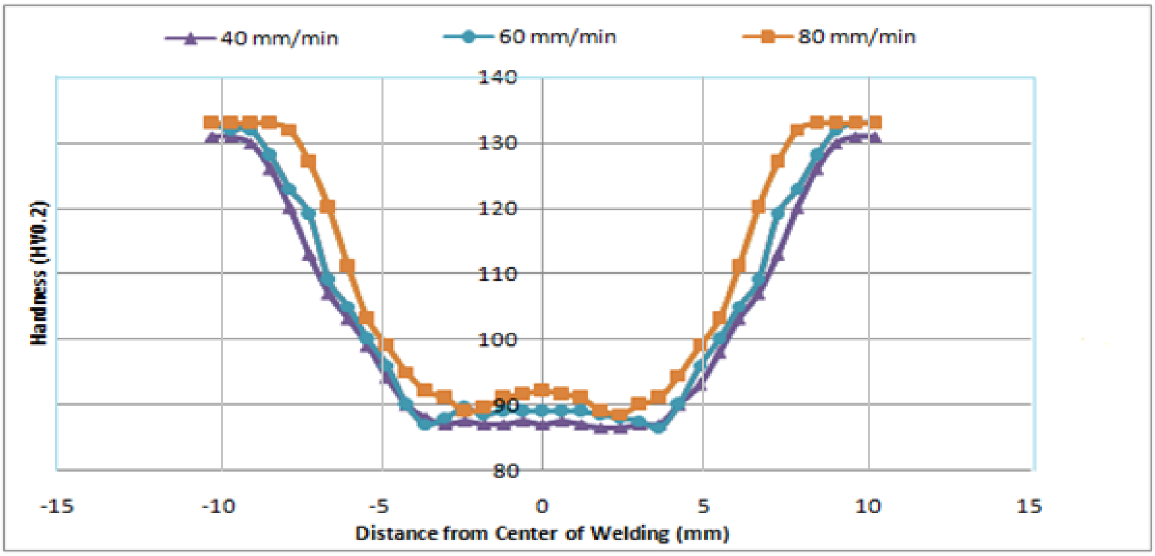



**Fig. 8. The hardness distribution in the different travel speeds in underwater under 1000 RPM.**

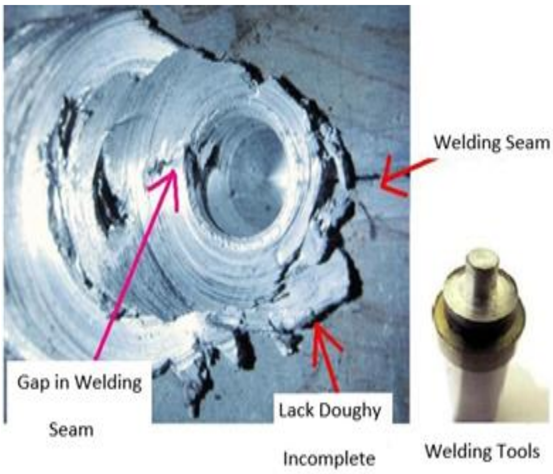



**Fig. 9. Filings in the low rotational speed at flooding mode, welding by 500 RPM at air mode.**

Through the speed of 1400 RPM the tensile strength of the underwater weld sample dropped too much (down to 214 MPa). Furthermore, the maximum tensile strength of the underwater weld joint is more than of the normal weld joint and clearly, cooling with water affects the tensile strength positively and increases it [9]. As the rotational speed increased the percentage of the length increasing has slightly changed (in 1000 RPM it is around %5) in underwater welding; while in air welding it is around %6.5. However, the length increasing percent has decreased too much (around %1.5) and the reason is the pitting failure developed through this speed.

### 3.5. The effect of rotational speed on hardness

In accordance with Fig. 11. , when rotational speed increases, the soft zone is wider and the hardness of the stir zone decreases through the underwater welding with 1200 RPM. So, the hardness distribution at cross section is U shape and it is considered that stir zone has the least hardness. The same is true for faster rotational speed up to 1800 RPM, and for 1800 RPM by moving the hardness distribution at the cross section, from base material toward the weld center, it decreases at first and then increases, so that hardness distribution at cross section becomes a W shape. As shown in Fig. 11., the minimum hardness distribution in underwater welding is more than that of air welding. In an underwater rotational speed of 1200 RPM, since the soft zone has decreased so the minimum hardness distribution happens at TMAZ and near the stir zone, and in 1200 and 1600 RPM, it happens more in the HAZ and near TMAZ.

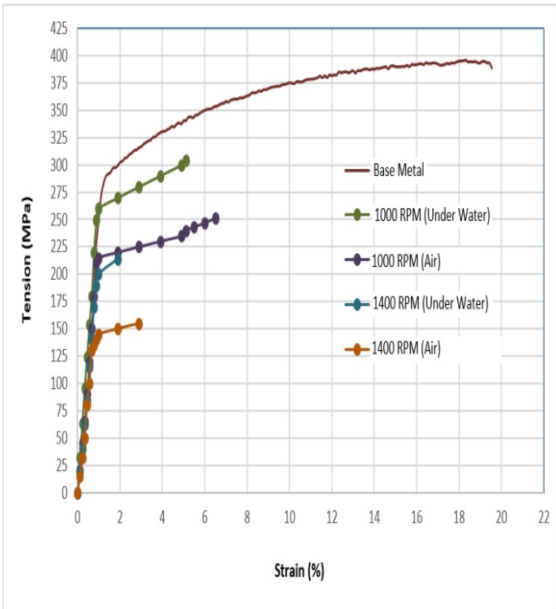



**Fig. 10. The stress-strain curve at two different rotational speeds with travel speed of 80 mm per minute.**

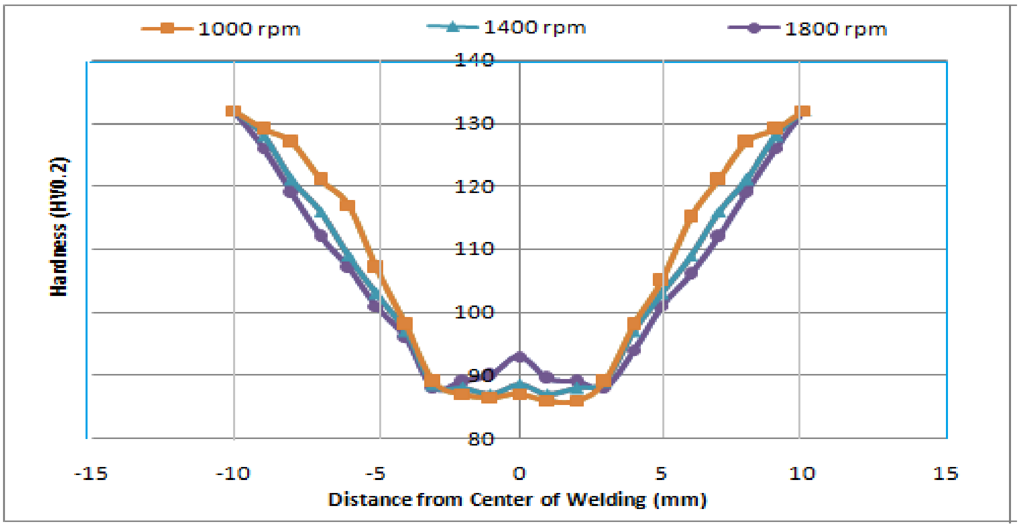



**Fig. 11. The hardness distribution in various rotational speeds at flooding mode with travel speed of 80 RPM.**

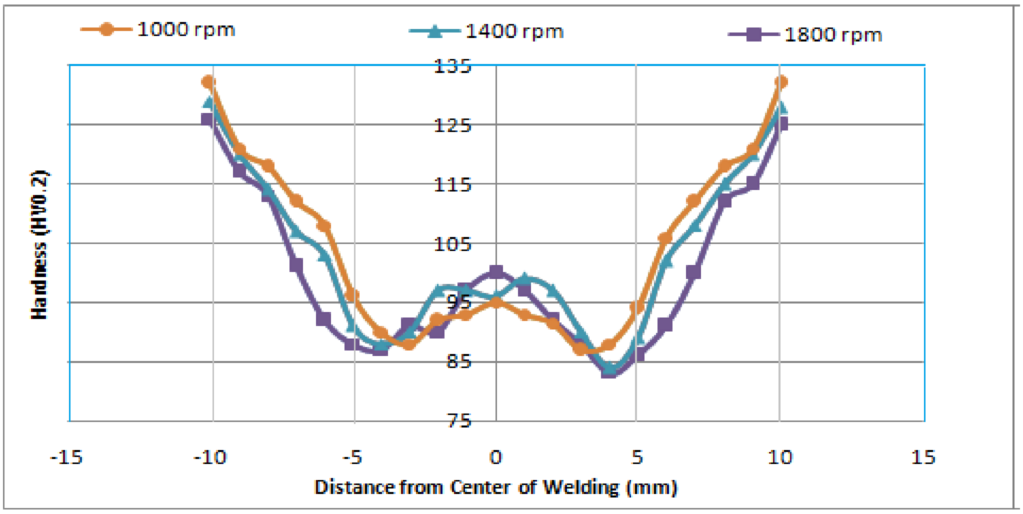



**Fig. 12. The hardness distribution in various rotational speeds at normal mode with travel speed of 80 RPM.**

In stir zone, increasing the rotational speed hardness increases the hardness. In this zone, due to the effect of water used as the coolant, meta-stable phases are not deposit more after dissolution. Therefore, it should be said that a little strength is achieved by deposits and the stir zone is not the main element affecting the hardness.

When the rotational speed increases, the size of coaxial grains in stir zone increases and the hardness decreases. On the other hand, however, by increasing the rotational speed, dislocation density increases as well thus the hardness improves [14]. So, one can conclude that in condition that a little strength is achieved by deposits, dislocations are the main factor affecting the hardness level in stir zone. During the slower rotational speed, dislocation density is less and the resulted “strain hardening” is not enough to improve the missed strength resulted from deposit decay and thus the stir zone has the least hardness. But in fast rotational speeds, dislocation density increases that results in much more hardness in the stir zone and TMAZ or HAZ have the least hardness [14]. Although in air welding increasing the rotational speed makes the soft zone wider, water as coolant decreases the harmful effects of the thermal circles on the joint properties, so the soft zone would not be wider [10]. In the rotational speeds of 1000 and 1800 RPM, because of the more input heating, this effect makes the soft zone wider and increases the grains growth which results in hardness decrease (Fig. 12.).

## 4. Conclusions

1. Increasing the travel speed decreases material deformation, input heating and thus the soft zone width during the underwater welding and increases the hardness of TMAZ and HAZ. Increasing the hardness, at last, improves the tensile strength of the weld joint.

2. Increasing the rotational speed increases input heating and thus the soft zone width. This results in decreasing the TMAZ and HAZ on one hand, and increasing the stir zone hardness on the other hand.
3. The underwater welded sample in tensile test broke from HAZ zone and air welded sample broke from TMAZ zone which shows that the joint tensile properties of the underwater welded sample is much more.
4. In the rotational speed of 1000 RPM and the travel speed of 80 mm/min, the underwater welded sample had the maximum tensile strength and the maximum hardness achieved by the rotational speed of 1000 RPM and the travel speed of 100 mm/min. But in air welding, the maximum change of length achieved by the rotational speed of 1000 RPM with the travel speed.
5. By increasing the rotational speed, size of coaxial grains increases in the central zone and hardness decreases. On the other hand, however, by increasing the rotational speed, dislocation density increases and hardness improves.

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