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Effect of Dwell Time and Tool Rotational Speed of Friction Stir Spot Welding on the characteristics of AA3105 joints

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Abstract

In the last decades of the twentieth century and the first decade of this century, the issue of rationing energy and the issue of environmental conservation has become the main concern of the company's manufacturing the means of transportation. This can be achieved using Al-alloys and other light alloys as a best alternative for steel in the bodies of the auto industry. Aluminum and light metals alloys have lower melting point and so fusion welding and resistance spot welding processes cause more changes in the properties of these alloys and lead to getting unsound welding. Solid state welding methods such as friction stir spot welding consider the best alternative. In the present work, effect of dwell time and tool rotational speed on microstructural and mechanical properties of friction spot welded joints of AA3105 alloy, was investigated experimentally. The travel speed and plunging depth were kept as constant, whereas, the dwell time and rotational speed parameters were varied with different values and their effect was investigated. Lap shear test, microhardness, and metallographic tests were performed. The results showed that, the shear strength is significantly affected with variation of the input parameters. The main findings of the present work were that high shear strength of the friction stir spot welded joints is achieved at dwell time of 7.5 s and rotational speed of 1400 rpm, as well as the highest microhardness was also achieved with this set of input parameters.

Keywords: Friction Stir Welding, Friction Stir spot Welding, Dwell Time, AA3105 alloy, Shear strength.

1. Introduction

Friction stir spot welding (FSSW) is a new technique of the solid state welding methods, which was developed in order for welding the light weight metals. Because of lower primary cost, high productivity, energy saving and ease of automation, the FSSW is a best alternative choice for resistance spot welding process (RSW). Friction stir spot welding (FSSW) is a derivative of friction stir welding (FSW), which was developed by TWI (Abington,United Kingdom) in 1991**[1].** The FSSW technique includes three stages as shown in Figure 1. Firstly, the tool is located upright on the workpiece surface, and then makes the tool spinning according to the type of application. Next, the tool is pressed to the surface of the top plate. Heat is generating due to the friction between the tool shoulder and workpiece metal. The Input heat softens the metal and facilitates the penetration of a tool's pin. The length of pin is about 50% to 70% of the total thickness of lap joint **[2]**. The length and shape of pin depend on the type of the application. The tool continues in rotating during the penetration process. The plunging continues until the shoulder is attached the surface of the upper sheet. Total plunging depth is limited to the designing forging force. The tool continues to rotate and exert force for a certain time. This time is called the dwell time. The pin stirs the metals around it. Metallurgical combined of the lapped sheets is maintained. At that point the tool is retracted from the weld pieces. The tool geometry and the welding parameter play the main rule for achieving the reliable joints by FSSW. Previous studies showed that the size of the weld zone determines the strength of friction stir spot welded parts. High strength is obtained when the size of weld zone increases with low rotational speed **[3].** Henrichs et al. **[4]** investigated the friction stir welding for the 21st century automotive industry. Joaquin et.al **[5]** studied the effect of pin length on FSSW of dissimilar Aluminum-Steel joints. Baekl et al. **[6]** studied the microstructure and mechanical properties of FSSW for galvanized steel **[6]**. Tuncel et al. **[7]** studied the mechanical performance of friction stir spot welded AA6082-T6 sheets. Sailaja et al. **[8]** investigated the effect of process parameters on mechanical properties of friction stir welding. Pathak et al. **[9]** studied the microstructural and mechanical performance of FSSW of AA5754. Ayad et al. **[10]** investigated the effect of tool shoulder diameter on the mechanical properties of AA1200 friction stir spot welding. Jweeg et al. **[11]** showed how the tool geometry influence on the welding quality and mechanical properties of AA7020-T53 using FSW butt joints. Juncklheere et al. **[12]** investigated the fracture and mechanical properties of friction stir spot welds in 6063-T6 aluminum alloy. The current paper, focused on the investigating of the FSSW process parameters especially, the dwell time and tool rotational speed parameters and their effect on the mechanical properties of the welded joints of AA3105 alloy.

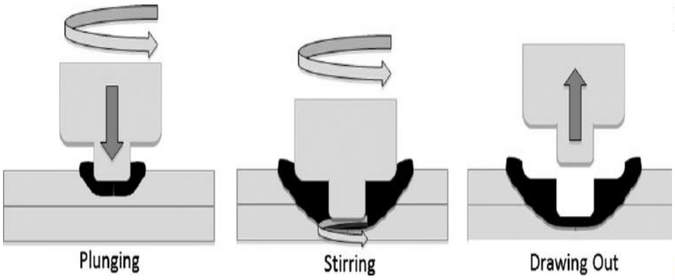


Fig. 1 A schematic illustrating the friction stir spot welding process [3].

2. Experimental procedures:

2.1 Materials

In this study, the AA3105 alloy was selected which consists mainly of aluminum with some alloying addition to increase the strength. Table 1 presents the laboratory chemical composition analysis and mechanical properties of base metal. These tests were conducted in the Specialized Institute for Engineering Industries.

A commercial sheets of AA3105 alloy in a cold-rolled condition with 2 mm thickness was used in the present work. AA3015 sheets with overlap joint specimens were prepared in similar manner to that of the overlap joint in resistance spot welding, which confirm to the specification DIN 50120 as shown in Figure 2. Lap-shear test was conducted using universal tensile machine test using a constant speed of 5 mm/min.

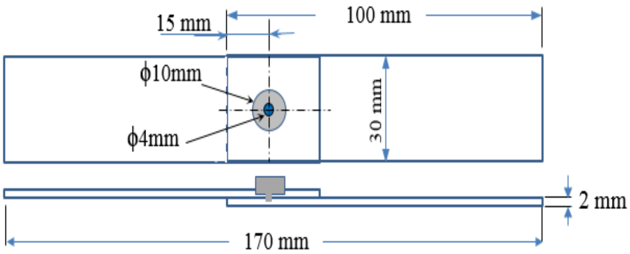


Fig. 2 The lap joint welded parts

2.2 Method

The conventional design of FSW tool was used to manufacture the FSSW tool. Steel grade CK45 was used as a tool material according to DIN17200. The Tool has been produced using turning machine. In order to increase the tool hardness, the tool is heat treated by quenching heat treatment through quenching it in oil from temperature 870 ˚C then tempering at 200 ˚C to obtain the required hardness (49 to 50 HRC). The welding tool geometry is illustrated in the Figure 3.

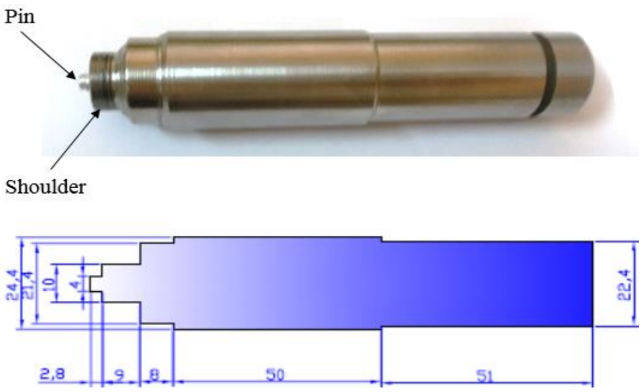


Fig. 3 Welding Tool features (all dimensions in mm).

Whereas, the processing parameters were investigated in the current work are the dwell time and rotational speed with different levels as listed in Table 2. It is important to mention here that, in order to increase the reliability, each experiment was repeated three-replicates and then were averaged. Tensile tests for lap weld joints were carried out using universal tensile Machine (UTM) to measure a shear stress of the weld joint.

Specimens were prepared for microstructural test by cutting the welded joint through the center of the weld as shown in Figure 4. Then they were burnished, polished and etched with (Hf 5% +H2O 95%). Optical microscope with different magnification was used to examine the microstructure of the weld joint. The same specimens of microstructural test can be used for the microhrdness test. Microhardness conducted by using the Vickers hardness tester at 100gf load and 5s dwell time. The process parameters layout and the responses are listed in Table 3.

Fig. 4 Photograph illustrates a section in the welding sample.

3. Results and Discussion

3.1 Effect the Dt and N on lap Shear Force

Table 3 shows all result of lap-shear test of the lap weld joints. Figure 5 presents the main effects of the Dt and N on the shear force. It is clear that shear force increases with increasing the N from 675 N at 426 RPM to about 1025 N at 1400 RPM.

Table 1. The chemical composition analysis and mechanical properties of AA3105

Chemical composition									
Element	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Al
wt %	0.69	0.77	0.18	0.68	0.276	0.018	0.004	0.098	BAL
Mechanical properties									
Property	Tensile strength (MPa)		Proof Stress (MPa)		Elongation (%)		Hardness (HV)		
value	110-145		115		20		51		

Table (2). The process parameters and their levels

Parameter	**Symbol (unit)**	**Levels**				
		1	2	3	4	5
Dwell time	Dt (S)	5	7.5	10	15	
Rotational Speed	N (RPM)	426	640	710	960	1400

Table (3): The input variables layout and responses

		Input Parameters		**Responses**		
StdOrder	**RunOrder**	**Dwell time (s)**	**Rotational speed (RPM)**	**Shear Force (N)**	**Nugget size (mm)**	**Tensile shear strength (MPa)**
12	1	10	640	1550	6	54.85
3	2	5	710	1400	5.2	65.96
4	3	5	960	1575	5.2	74.2
18	4	15	710	590	5.4	25.764
10	5	7.5	1400	2585	5.4	112.882
6	6	7.5	426	1155	5.2	54.41
9	7	7.5	960	1860	5.4	81.22
20	8	15	1400	1170	5.6	47.541
17	9	15	640	510	5.3	23.13
19	10	15	960	900	5.5	37.894
16	11	15	426	400	5.2	18.845
13	12	10	710	1625	6	57.5
7	13	7.5	640	1300	5.2	61.25
5	14	5	1400	1700	5.2	80.09
15	15	10	1400	2700	6.7	76.62
8	16	7.5	710	1695	5.2	79.855
1	17	5	426	450	5	22.94
11	18	10	426	754	5.2	35.52
14	19	10	960	1875	6.5	56.53
2	20	5	640	1060	5	54.03

From other side the maximum force was achieved at Dt of 7.5 s -10 s and then it is decreases with increasing the Dt (Fig. 5). This may be attributed to that the short dwell time (5 s) does not give the joint the sufficient time to properly heating and stirring and so luck of fusion may appear between the mating surfaces. Increasing the Dt to 7.5 s gives the highest shear force attributes to the best welding state due to sufficient heating and stirring the mating surfaces. Increasing the dwell time more than 10 s leads to adverse action on the shear force (see figure 6b). This means that the longer period of dwelling time effects on the microstructural properties of the heated and stirred parts. It is clear from the Figure 5 and Figure 6a that the shear force is mainly affected by the rotational speed (N) of the tool, where, increase in N to be 1400 leads to increase in the shear force from (2600 – 2700 N) within the dwell time of 7.5 – 10 s.

3.2 Effect of Dt and N on lap Shear Strength

The nugget diameter and shear force determine the tensile shear strength of the welded parts. So it is necessary to study the shear strength.

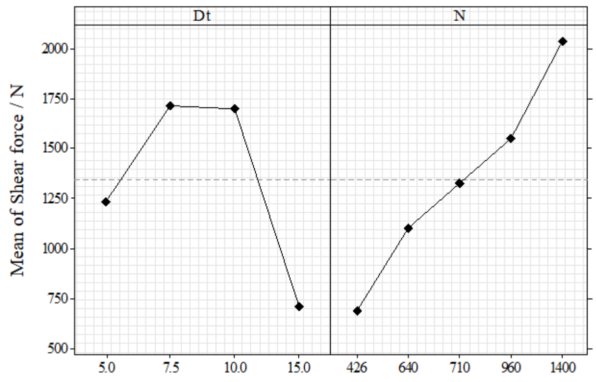
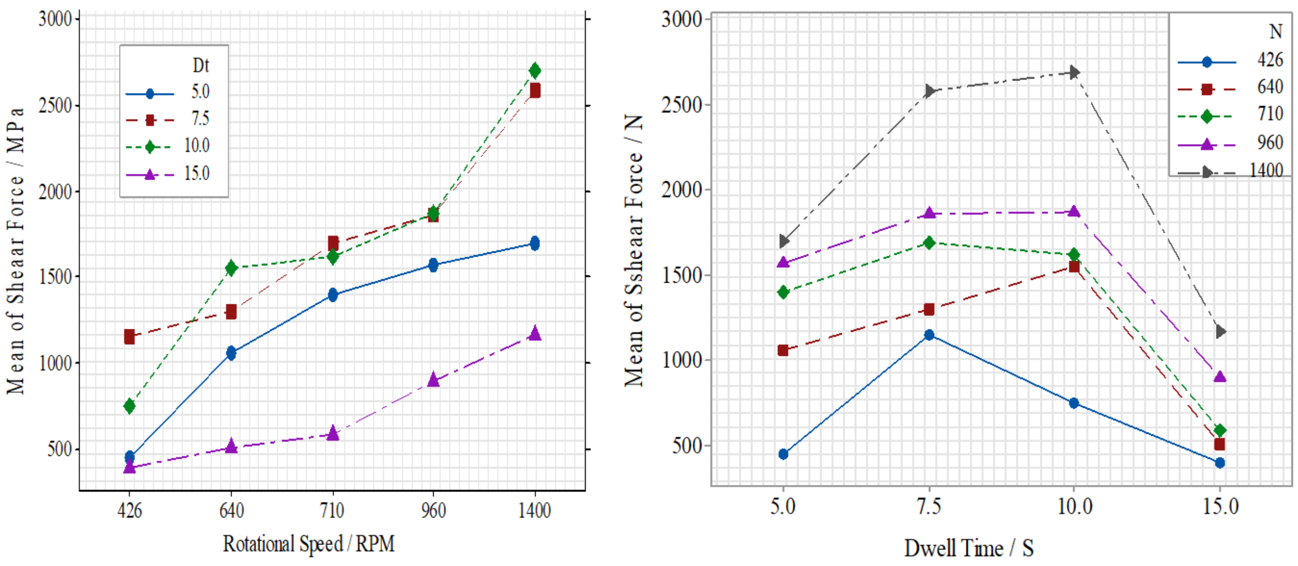


Fig. 5 Main effect of the Dt and N on the shear force.

Figure 7 shows the main effects of the process parameters on the shear strength. It is obvious that the tensile shear strength increases gradually when the dwell time increases from (5 s) to (7.5 s) then it decreases when the dwell time exceeds this range. This can be seen clearly when the dwell time becomes (15 s) the shear tensile strength decreases dramatically (this can be seen clearly in Figure 8a). The reason for this behaviour may be belonged to the microstructure changes due to the effect of the heat input at stirring zone (SZ). Where, more heat input means more the grain size. Long dwell period leads to an increase in the heat generation by the friction. On the otherhand, the increasing in the rotational speed tends to improve the tensile shear strength for all the dwell times since high N causes an increasing in the quantity of dynamic recrystallization. Figure 8b demonstrated that when N increases within the range of (600-700) rpm, there is a gradual increase in the shear strength but the values are closed at all dwell times except (15 s). This behavior can be attributed to equalize the dynamic recrystallization at these condition, which leads to generating fine grain stricture, which in turn increases the hardness and the shear strength. The highest shear strength can be achieved at a set of parameters of 7.5 s and 1400 rpm for Dt and N respectively. Whereas, the worst shear strength for the joint can be achieved with long dwell period (15 s) and lower rotational speed (426 rpm) namely 18.8 MPa. The increasing in rotational speed of the tool from 426 rpm to 1400 rpm at 7.5 s dwell time leads to increase the tensile shear strength from 54.41 MPa to 112.882 MPa (see Figure 8a).



a

b

Fig. 6 Plots illustrate the interactions between the dwell time and rotational speed versus the shear force.

In addition, when dwell time increased from 7.5s to 15s, the tensile shear strength decreased from 112.88 MPa to 47.541 MPa. This reduction in the tensile shear strength is caused by the increase in grain size in the heat affected zone (HAZ) and weld nugget zone (WNZ) because of the increase in the heat input resulted from higher N and excessive Dt, which leads to a longer thermal cycle. In addition, when dwell time increased from 7.5s to 15s, the tensile shear strength decreased from 112.88 MPa to 47.541 MPa. This reduction in the tensile shear strength is caused by the increase in grain size in the heat affected zone (HAZ) and weld nugget zone (WNZ) because of the increase in the heat input resulted from higher N and excessive Dt, which leads to a longer thermal cycle.

3.3 Microstructure

Figure 9 reveals the microstructure of different zones in the cross-sectional area for two FSSW lap joints prepared using tool rotational speed 1400 with total plunge depth of

3mm, and dwell times 7.5 s. There are four zones can be observed: stirring zone (SZ), thermal-mechanical affected zone (TMAZ), heat affected zone (HAZ), and the base metal (BM). There is no change in the grain size of the HAZ due to the absence of any mechanical effect during the plastic deformation, HAZ exposed to heat from the friction only. The grains in HAZ are observed in the samples that were produced at 1400 rpm tool speed as shown in the figure 9 are larger than the grains in a sample of 426 rpm (see Figure 10) . While there is no significant change in grain size of the HAZ which belong to the sample was made at 426 rpm because there is no sufficient heat input.

The heat generation due to friction and strain by plastic deformation caused more changes in the structure of the stirring zone (SZ) and thermal mechanical affected zone (TMAZ). It is obvious that the microstructure of the tested specimens N of 1400 rpm, the metal in the SZ exhibits similar size and fine grains structure as a result to dynamic recrystallization. The heat, which generates due to friction and the strain of plastic deformation, increases, especially in the direction of the keyhole left by the welding tool. Thus, the grain size increases in the thermal-mechanical affected zone (TMAZ). It was clear that grain structure adjacent to the keyhole is fine and the thickness of the stirring zone is larger than that of the specimen of 426 rpm (see figure 10). The microstructure of the TMAZ (at 1400 rpm and 7.5s) reveals great deformation. Besides, they show slightly increasing in the grain size compared to that in SZ. Those grains own almost elongated shape due to extreme plastic deformation and the temperature in this region is not enough for recrystallization. Figure 10 shows that the change in microstructure of the specimen of 426 rpm. The change in the grain size of the TMAZ is less than that of 1400 rpm because of severe plastic deformation due to the lower tool speed. Increasing in the dwell time leads to a long thermal cycle, which means that weld nugget zone (WNZ) and heat affected zone (HAZ) are exposed to high temperature relatively. This leads to noticeable an increasing in grain size and the width of WNZ at 1400 rpm and dwell time 15 s. Figure 11 shows the cross-sectional microstructure for specimen was prepared using 15 s dwell time and 1400 rpm. Figure 12 reveals the microstructure of the specimen taken from the experiment was performed using 426 rpm and 15 s dwell time. SZ region exhibits coarse grains and thickness of the stirring zone is very fine grain region due to low plastic deformation and more heat input. No more change in the TMAZ and HAZ, this can be attributed to lower plastic deformation and decrease in the peak temperature in the HAZ.

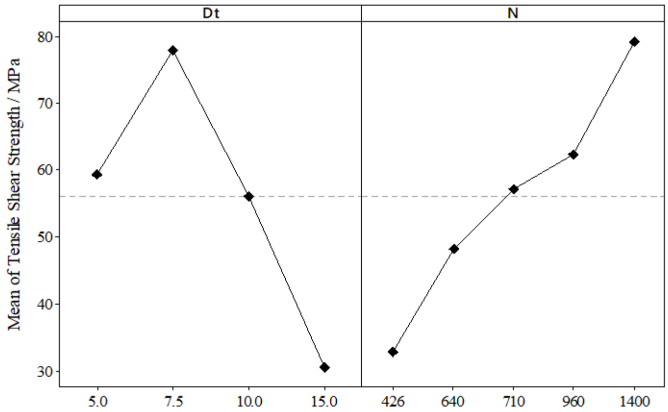
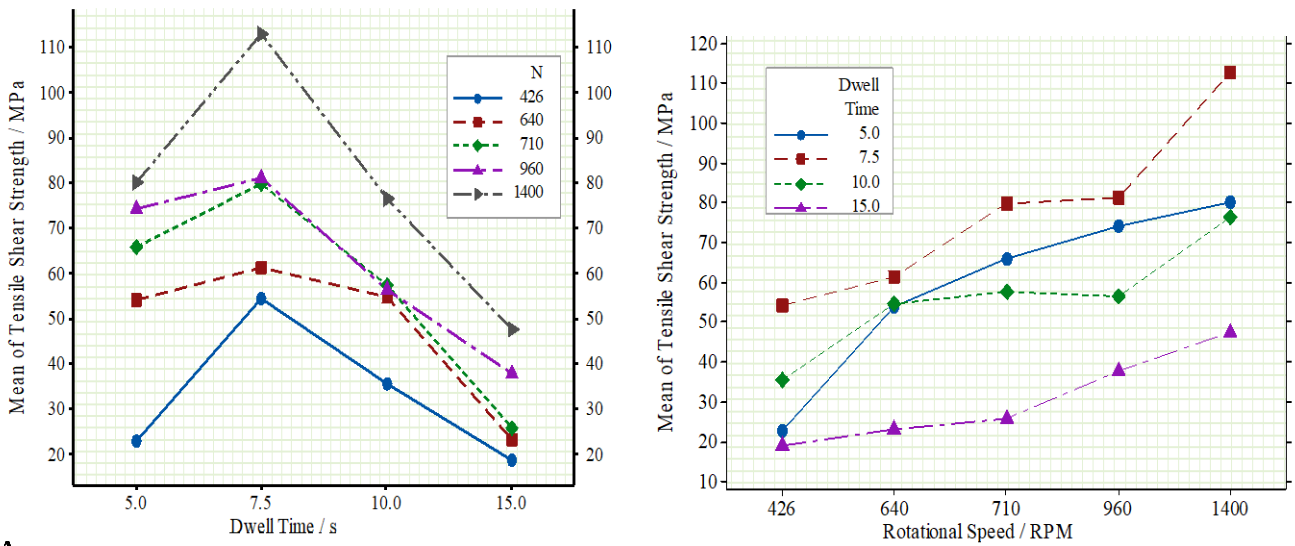
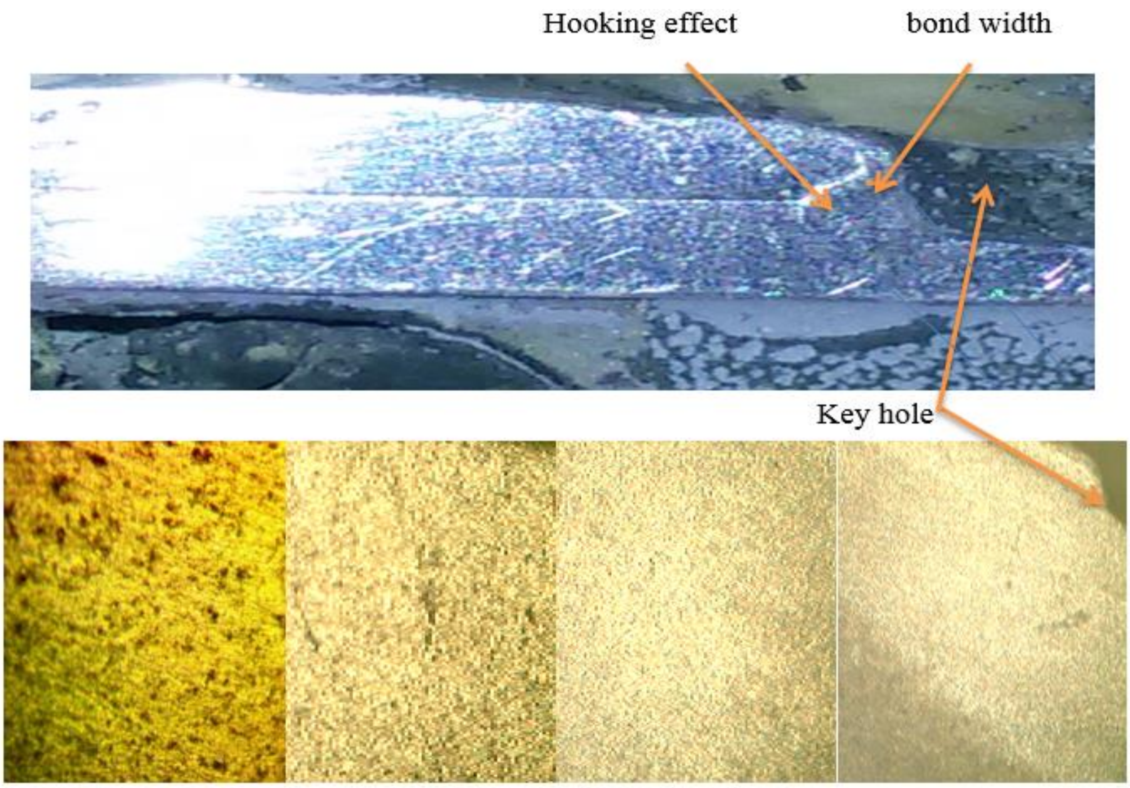


Fig. 7 Main effect of the Dt and N on the shear force.



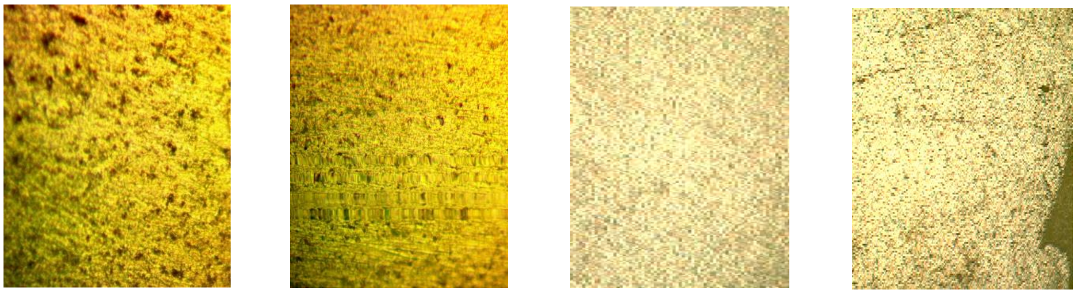
A **B**

Fig. 8 Plots illustrate the interactions between the dwell time and rotational speed versus the shear strength.



BM HAZ TMAZ SZ

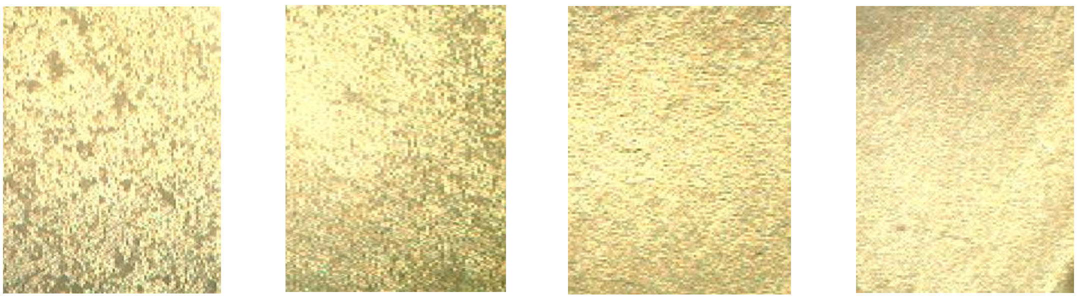
Fig. 9 Micrographs illustrate the cross-sectional micro structure of FSSW BM, HAZ, TMAZ and SZ at 7.5 dwell time and 1400 rpm tool speed, X400



BM

BM HAZ TMAZ SZ

Fig. 10 Micrographs illustrate the cross-sectional micro structure of FSSW BM, HAZ, TMAZ and SZ at 7.5 dwell time and 426 rpm tool speed, X400



BM HAZ TMAZ SZ

Fig. 11 Micrographs illustrate the cross-sectional micro structure of FSSW BM, HAZ, TMAZ and SZ at 15s dwell time and 1400 rpm tool speed, X400

BM HAZ TMAZ SZ

Fig. 12 Micrographs illustrate the cross-sectional micro structure of FSSW BM, HAZ, TMAZ and SZ at 15s dwell time and 426 rpm tool speed, X400.

3.4 Microhardness Test Results

The distribution of hardness along a straight line located about 1.5mm from top surface of the upper sheet of the lap joint is shown in Figure 13. From the profile of hardness, a gradual increasing can be seen in the Vickers micro hardness toward the center of the weld, especially in the (SZ) adjacent to the hole. This raise in hardness can be attributed to the grain refinement at this region, which forms as a result of the considerable plastic deformation. The plastic deformation relates to the rotational tool speed increased and so it increases as the rotational speed increases from 426 rpm to 1400 rpm at the 7.5 s. It is known that one of the strengthening mechanisms is grain boundaries also this boundaries act as a barrier for dislocation movement. Fine grains create high dislocations density and then increase the strength of stirring region and this can be supported by the results obtained in **[6].** The increases in the rotational speed lead to higher heat generation by friction, this heat facilitates softening metal, and increases the rate of recrystallization and more fine grains will be formed which increase in the hardness. The experiments were carried out at 15s dwell time exhibit hardness profile as shown in Figure 13. There is a slight decrease in micro hardness due to the excessive heat input to the weld nugget zone (WNZ) and heat affected zone (HAZ) which increase the grain size in these regions as shown in Figure 11. Increasing in grain size causes a degradation of mechanical properties of weld joints.

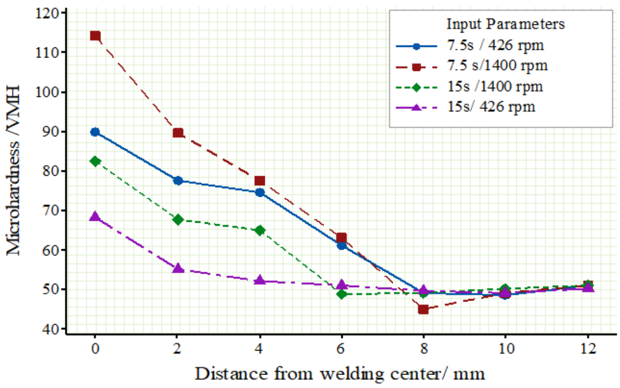


Fig. 13 Plot illustrates the micro hardness variation with minimum and maximum rotational speed at 7.5 s and 15s dwell time.

Figure 13 shows that the highest hardness occurs near the centerline of the weld and gradually decreases toward the heat affected zone. High hardness (114 Kg/mm^2) in SZ as a result of the more plastic deformation in this region and produce more dislocations density (Plastic deformation generated by stirring the metals in this region is considered the main source to generate the dislocations and increases the density of dislocations). Furthermore, the lowest hardness occurs at the center of the SZ is about 68.2 kg/mm^2 as the long dwell period and lowest rotational speed. In addition, low hardness values can be observed in the heat affected zone due to some growth in grains occurred.

4. Conclusions

The present work focused on investigating the effect of Dt and N on characteristics of FSSW Lap–joint of AA3105. Different levels of Dt and N were investigated and tested to show the results. From the current results, the main findings of the present paper can be drawn as follow:

1. The sheer force of the tested specimens significantly affects by the N and Dt, and hence maximum shear force can be achieved was within the range (2600 - 2700 N) at a set of process parameters namely N 1400 rpm and Dt of 7.5 s.
2. The results showed that the Dt has a significant effects on the tensile shear strength of the welded joints. Higher shear strength (110 MPa) can be achieved at dwell tine of 7.5 s and rotational speed of 1400 rpm. This behavior is attributed to dynamic recrystallization and severe plastic deformation which lead to refining the grain structure.
3. Tensile shear strength for all experiments increases in linear relationship with N. Whereas, when Dt increases from 5s to 7.5 s the shear strength also increased and then it decreased with increasing in Dt more than this range due to excessive heat input.
4. The SZ regions exhibit fine granular and equiaxed grains, and the grain size increases away from the keyhole. Coarse grains can be observed when increasing the dwell time and reaches to 15s.
5. Microhardness increases gradually towards the keyhole and the maximum value of hardness has been achieved in the SZ region. Highest microhardness

value was achieved for a Dt of 7.5 s and for N of 1400 rpm.

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