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INFLUENCE OF SHOULDER DIAMETER ON MECHANICAL RESPONSE AND MICROSTRUCTURE OF FSW WELDED 1050 AL-ALLOY

WPŁYW ŚREDNICY RAMIENIA NA MECHANICZNĄ REAKCJĘ I MIKROSTRUKTURĘ ZGRZEWANEGO TARCIOWO STOPU ALUMINIUM 1050

In this study, commercially pure (CP) aluminum specimens were welded using Friction Stir Welding technique (FSW). Welding process was carried out by rotating 1500 rpm and by moving 200 mm/min. Under constant friction force, four different shoulder diameter (20, 25, 30 and 40 mm) were used. During welding, temperature measurements were performed using non-contact laser thermometer at various parts of the plates from the welding center to outwards. Microscopic and mechanical tests were used to characterize the samples. It has been observed that HAZ limited the dimensions of stirrer shoulders. Hardness values of welding zone were slightly high but they were quite close to the hardness of base metal. Tensile strength of the samples was significantly affected by the shoulder diameter.

Keywords: Shoulder diameter, mechanical properties, Aluminum, FSW

Próbki z technicznie czystego aluminium 1050 spawane były przy użyciu techniki zgrzewania tarciowego (Friction Stir Welding). Proces spawania przeprowadzono przy prędkości obrotowej 1500 obr/min i prędkości liniowej 200 mm/min. W warunkach stałej siły tarcia, zastosowano cztery różne średnice ramienia (20, 25, 30 i 40 mm). Podczas spawania, pomiary temperatury przeprowadzono przy użyciu bezkontaktowego termometru laserowego na różnych częściach płyty, od centrum spawania na zewnątrz. W celu scharakteryzowania próbek wykonano badania mechaniczne i mikrostruktury. Zaobserwowano, że strefa wpływu ciepła ogranicza wymiary ramienia. Twardość materiału w strefie spawania była nieznacznie wyższa od twardości poza nią. Średnica ramienia znacząco wpływa na wytrzymałość próbek.

1. Introduction

Recently, solid state joining processes have been popular, because of easy processing and various advantages; such as, consumables and high energy are not needed, fume does not occur, less heat affected zone (HAZ) is formed and welding of dissimilar materials is possible such as 2xxx and 7xxx series Al-alloys. Several industrial companies and researchers are focusing on investigating FSW technique. This technique was invented at The Welding Institute (TWI) of UK in 1991 [1]. Defect free welds with good mechanical properties have been made in variety of aluminum alloys, even those previously thought to be not weldable. The basic concept of FSW is simple. A cylindrical, shouldered tool with a profiled pin is rotated into the joint line between two pieces of materials. Frictional heat occurred between the tool and work pieces. The localized heating softens the material around the pin and the combination of tool rotation and translation leads to the movement of the material from the front of the pin to the back of the pin. As a result joining process occurred in the solid state. The welding zone includes four distinct regions as follows: Parent metal (Unaffected region), Heat affected zone (HAZ; closer to the weld centre), thermo-mechanically affected zone (TMAZ; significant plastic strained region without recrystallisation) and weld nugget (recrystallisation region) [1].

FSW involves complex material movement and plastic deformation. Welding parameters, tool geometry and joint design play an important role for the microstructural evaluation of the material. Tool geometry is the most influential aspect of process development. The friction between the shoulder and work pieces result in the biggest component of heating. The shape and size of the pin and the shoulder is important for the aspect of heating. The shoulder also limits for the heated volume of the material. The second function of the tool is to stir and

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move the material. The uniformity of microstructure and properties as well as process loads are governed by the tool design. Generally a concave shoulder and threaded cylindrical pins are used [2, 3]. The effect of stirrer geometry [4, 5], powder metallurgy production techniques and porosity size and content [6] on the bonding, microstructure and mechanical properties were studied. Dawes [7] explained the tool development and outlined some of the recent tool designs currently under investigation and analyzed the advantages and disadvantages of the scroll shoulder concept. Although considerable studies have been reported in published literature about pin geometry effects, tool rotation and weld speed, the effect of shoulder diameter on microstructural evaluation and mechanical properties of CP aluminum has been not studied so far. Therefore, the present study performs heat distribution of the weld material during welding process as well as carrying out hardness and tensile response of the material and observing the microstructural features of CP aluminum. Also, a finite element model was used to predict the transient temperature distribution using ANSYS.

2. Experimental procedures

The base material was a rolled CP Al (1050) sheet of 5 mm thickness having the nominal composition (wt%) 0.19% Si, 0.045% Fe, 0.006% Cr, 0.006% Mg, 0.006% Mn, 0.004% Cu, balance-Al. To carry out FSW process, 5×65×120 mm aluminum plates were welded for a length of 120 mm parallel to the rolling direction. Single pass welding procedure has been followed to fabricate the joints. The test pieces were first ground using steel brush and sandpaper to remove the oxide film, and then cleaned with acetone to remove dirt such as oil. From each welded plate, three tensile specimens and one hardness specimen were cut out. Room temperature tensile testing was carried out using Instron MFL type device with 30 kN load cell using a constant-crosshead speed of 0.5 mm/min. Tensile specimens were machined to position the weld nugget in the middle of the sub-size specimen; gage length was 72 mm and width was 25 mm. The FSW tool has a columnar shape with a screw probe and manufactured H13 tool steel with the tilt angle 2°. The diameter and length of probe were M4 and 5 mm height, respectively for the various shoulder diameters. The shoulder diameters were 20, 25, 30, 40 mm. The flat smooth surface was chosen under the shoulders because it can reduce stress concentration due to cutting effect and increase the effective contact surface. The tool plunge down force was 15 KN. The tool rotation speed was in the clockwise direction and the welding speed was 1500 rpm and travelling speed was 200 mm/min. The temperatures reached during welding were measured using non-contact laser thermometer. Measurements were taken at 0, 10, 20, 25, 30, 35, 40, and 45 mm from the shoulder diameter. In this investigation linear three dimensional thermal model to estimate the thermal history of the butt-welded joint was developed using the finite element code ANSYS. This model employed three dimensional eight nodded 20000 thermal solid elements. Temperature dependent thermal properties of Aluminum 1050 were used in this model ($T=218\ W/m_*K$, $\rho = 2.7\ kg/m^3$). Following FSW, Vickers hardness profiles were measured on a cross-section parallel to the welding direction. All the joints were cross-sectioned perpendicularly to the welding direction for metallographic analysis. After the metallographic processes such as grinding (200-1200), polishing (with alumina), and etching (Keller's reagent), microstructure photographs have been taken from the parts.

3. Results and discussions

3.1. Temperature distribution

The difference in energy input due to the shoulder diameter changed dramatically. The resulting temperatures were measured during welding as shown in Figure 1. It was observed that the increase in shoulder diameter increase the peak weld temperature. The highest temperature change is observed next to the pin shoulder in all conditions. This is related with the stirrer size. The highest temperature is obtained weld tool/workpiece interface where the maximum friction is appeared. An increase in contact surface area significantly altered the temperature distribution due to the frictional coefficient of the material and the size of the shoulder diameters, temperatures dramatically decreased while the distance increased. Typical isotherms on the whole workpieces surfaces are shown in Figure2. It can be seen from these figures that the HAZ expands and temperatures arise as the pin shoulder increases. As expected, maximum predicted temperatures are located under the rim of the shoulder, where maximum tangential velocities are found. Comparisons of ANSYS predictions with experimental data are illustrated in Figure 3. In general for 15 to 30 mm distances, temperature predictions tend to be high when compared to experimental data. One explanation may be related to the microstructural changes in HAZ and TMAZ during FSW. As it is known, an increase in temperature leads to an increase in grain size and, on the contrary, an increase in strain rate leads to a decrease in grain size. It may also be due to an inadequate representation of the materials flow stress for the ranges of strain rates. An impact of varying weld parameters on the temperature distributions have been reported for 7050 Al alloy [8]. A thermal model of the FSW of Al alloys was also presented that incorporates heat generation due to plastic formation and heat flux between friction and plastic deformation based on the ratio of the plastic energy to the total effective(mainly frictional) energy generated in the welding [9]. This energy depends on the friction coefficient and frictions are between shoulder and workpiece surface. The average heat input per unit area is given as [10]:

$$Q = 4/3\ \pi^2 .\ \mu .\ P.\ \omega .\ R^2 \qquad (1)$$

Where Q is net power heat input (W), μ the friction coefficient, P the pressure (Pa), ω rotational speed (revelution/s), and R is the tool radius (m). Frigaad et al. [10] suggested that the tool rotation speed and shoulder radius are the main process variables in FSW. Their process

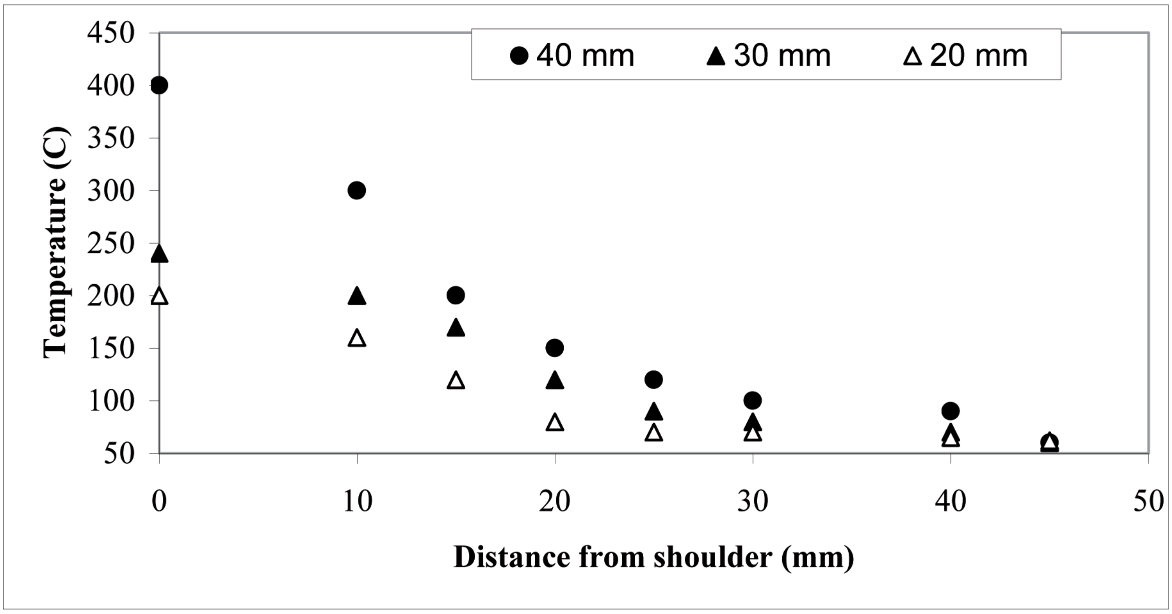

Fig. 1. Temperature distribution of the tested materials for various diameter of shoulder (20,30 and 40mm)

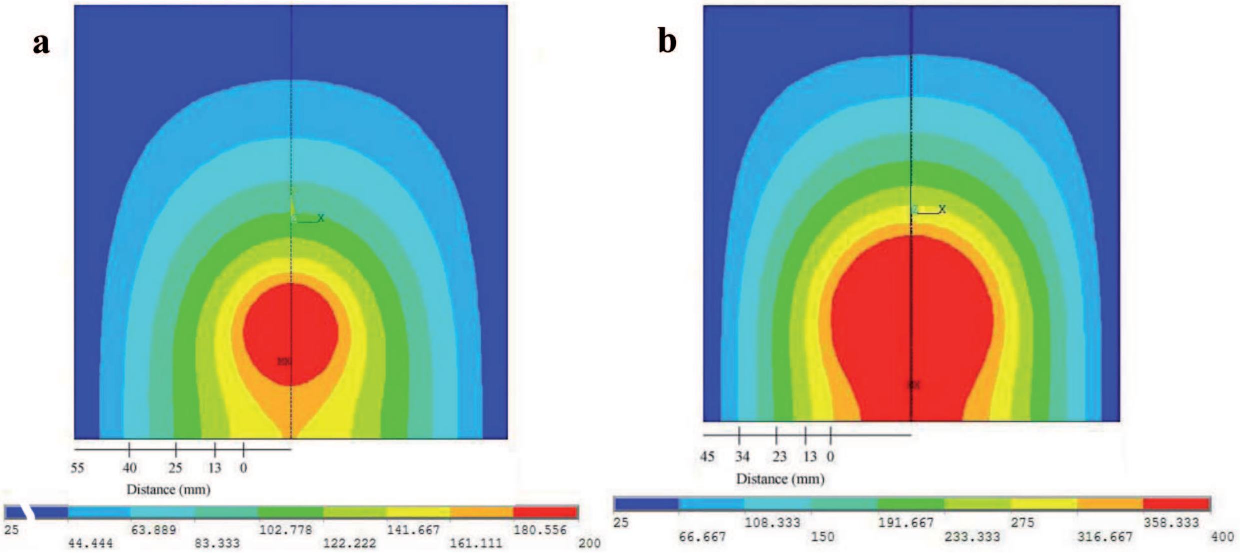

Fig. 2. Temperature counters (in °C) on the workpiece surfaces a) 20 mm shoulder b) 40 mm shoulder

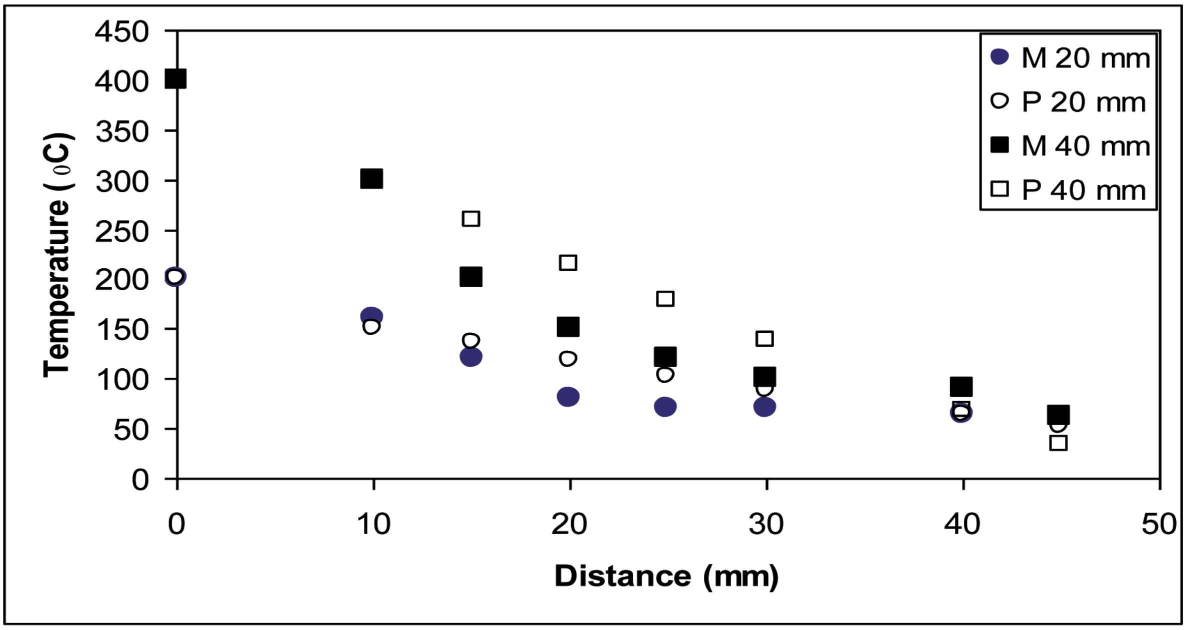

Fig. 3. Comparison of the Measured(M) and Predicted(P) temperature along the transverse direction for the 20mm and 40 mm shoulders

model was compared with in situ thermocouple measurements in and around the FSW zone. They measured peak temperature of above ≅ 500°C was recorded in the FSW zone for Al alloys. In the present case 400°C was predicted and measured for the largest shoulder diameter for the commercially pure aluminum. As expected above formula decrease in shoulder diameter significantly reduced the heat input and hence decreased the peak and following temperatures for the other constant welding parameters.

3.2. Hardness test results

The effect of the shoulder diameter in the hardness values are shown in Fig. 4. As it can be seen from the figure that, 30 HV in base material, 27 HV in HAZ, 34 HV in nugget have been measured for 20 mm welds. These values have; 30HV, 22HV, and 24 HV respectively for 40 mm welds. It is seen that welding process slightly hardens the material at nugget with the hardness increasing by nearly 12% around the weld line to about 34 HV compared with the base metal 30 HV for the 20 mm shoulder diameter. Similar trend was also observed for the other shoulder diameters too. However, 70% hardness value (22 HV) decreased at the nugget with the biggest shoulder diameter specimen compared with the base metal (30 HV). Hardness values seem to be affected by the size of the shoulder diameter and its decrease caused slight increase in hardness. Also Fig. 4 clearly shows three main regions in the hardness profiles, the hardened region around the weld line (nugget), the unaffected base material and transition between them. These results show that strain stored in the base material affects evolution of the grain structure in the stir zone during FSW, because the mechanical properties of commercially pure Aluminum is mainly affected by the grain size [11]. Grain size of nugget is much finer than that of base metal; grain refinement plays an important role in material strengthening. According to the Hall-Petch equation, hardness increases as the grain size decreases. Such a trend was previously observed in the welding of the steel [12]. Also, rapid local plastic deformation during FSW process may cause cold working strain hardening and increased amount of dislocation density in Al. It was shown in Fig.1 that increased shoulder diameter increase the peak temperature on the welding line. Higher temperatures may accelerate the grain growth of the recrystallized grains in the TMAZ and HAZ region, thus increase in shoulder diameter caused the reduction in hardness values. Furthermore, it can be said that relatively high input under the large shoulder can be caused more pressure and more densification in powder metallurgy processed material compared with others. Moreover, Svensson [13] showed that the precipitates mainly responsible for hardening may dissolved in the large contact surface welding due to the high heat input.

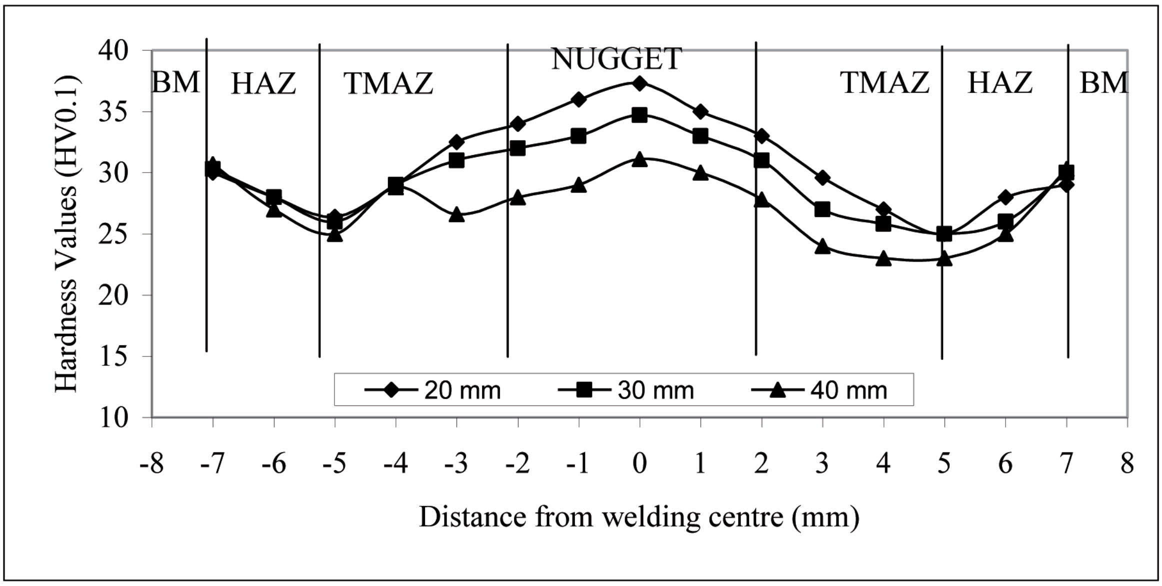

Fig. 4. The effect of shoulder diameter on hardness values of the tested specimens

3.3. Tensile properties

Tension test were carried out on these specimens and the results are given in Table 1. It can be seen that the tensile properties of joints welded by diameter of shoulder 20 mm and diameter of shoulder 25 mm tools are higher than the other two. No damage was observed in the welding zone. Most of specimens failed at heat affected zone. This result indicates that; the weld metal left by the stirrers exhibit higher strength than the base metal. Tensile strength of the base metal has 110 MPa and elongation has %10 [14]. It was shown that the variation in both the strength and ductility was also function of the welding parameters [15], however, in this study all of the experiments, the welding parameters were held the same, the only difference in the experiment was the pin geometry. The higher strength of the weld metal can be attributed to heat generation, ultra finer grain formation and dislocation distributions during welding process. Also, it is obvious that slight increase in ductility was visible in almost all welded samples. It can be concluded from Table 1 that the smaller shoulder diameter caused, the higher tensile strength and higher ductility of the joint compared with base metal. But, the joints fabricated by 40 mm shoulder tool exhibited inferior tensile properties compared to their counterparts in the base metal. In this investigation it has been observed that a larger tool shoulder (40 mm) lead to wider contact area and resulted in wider HAZ and TMAZ region and subsequently the tensile properties of the joints are deteriorated. Because, the tool shoulder diameter is having directly proportional relationship with the heat generation due to friction [16]. Hence, the shoulder diameter must be optimized to get friction stir processed region with good consolidation of metal and narrow region of HAZ and TMAZ. For comparison purpose, the microhardness values at different tool shoulder diameters are presented in Fig. 4. Nugget zone hardness is higher in the joints fabricated using the tool with shoulder diameter of 20 and 30 mm compared to other. The joint fabricated using the tool with shoulder diameter of 40 mm, consist of coarse grains. This may be reason for lower tensile and hardness values compared to their counterparts.

TABLE 1
Mechanical properties of tested specimens

Shoulder diameter (mm)	Ultimate Tensile Strength (MPa)	Elongation (%)
20	113	13
25	111	12
30	100	10
40	91	8

3.4. Microstructure

It is generally known that the fusion welding of aluminum alloys is accompanied by the defects like porosity, slag inclusions, solidification cracks, etc., and these defects deteriorate the weld quality and joint properties. However, FSW joints are known to be defect free since there is no melting takes place during welding and the metals are joined in the solid state itself due to the heat generated by the friction and flow of metal by the string action. But FSW joints are prone to other defects like pin hole, tunnel defect, pinning defect, kissing bond, cracks, etc. due to improper plastic flow and insufficient consolidation of metal in the friction stir processing region [17]. Figure 5 shows the pictures of the tested materials. The appearance of the welds was clean and no obvious defects can be found. However, there are severe plastic deformations due to the shoulder diameter. An increase in shoulder diameter caused more increment of materials accumulation on the advancing side of the specimens as seen in the same figure from right to the left. An onion ring types of circles were deformed by the tool shoulders. The outlook of this material provides information about the weld quality. With a good weld the continuous rings are 100% complete. All the tools produced perfect circular rings on the material surfaces as shown in Figure 5. Recent TEM observation for these line patterns confirmed the existence of high density of amorphous Al_2O_3 oxides [18]. However, the 40 mm diameter tool produced more and rough flash compared with others. Typical microstructures of the nuggets are shown in Figure 6. A significant influence of shoulder geometry was observed on the nugget grains (Fig.6.c), this is due to the extensive plastic deformation, and the different heat power generated by the shoulders. By decreasing the temperature in the nugget zone the force acting on the material is not able to produce a plastic flow proper of a dynamic recrystallisation process. The increase in the temperature of the material for shoulder diameter is larger for welding parameters. The material is extremely softened and can be subjected to grain growth after deformation (Fig.6.b). The deformation extent of the plastic material and the flow of the material connect with the microstructures and the properties of the nugget [3]. The highest heat input causes more plastic flow and plastic formation and additional grain growth in the 40 mm diameter tool compared with others. All fixed rotational speed and travelling speed the heat power depends on contact surface between tool and sheets. FSW give rise to noticeable microstructural changes, especially deformation in the TMAZ results in severe bending of grain structure. This zone corresponds approximately to the edge of welding tool's pin, this zone no recrystallisation was observed because the temperature derived from FSW process is not high enough and deformation was not so severe to cause recrystallisation [19]. Also, The contact surfaces 314, 706, and 1256 mm^2 for the 20, 30, 40 mm diameter tools respectively.

Fig. 5. Macroscopic pictures of the tested materials (Right to the left: 20 mm, 25 mm, 30 mm and 40 mm shoulder diameter)

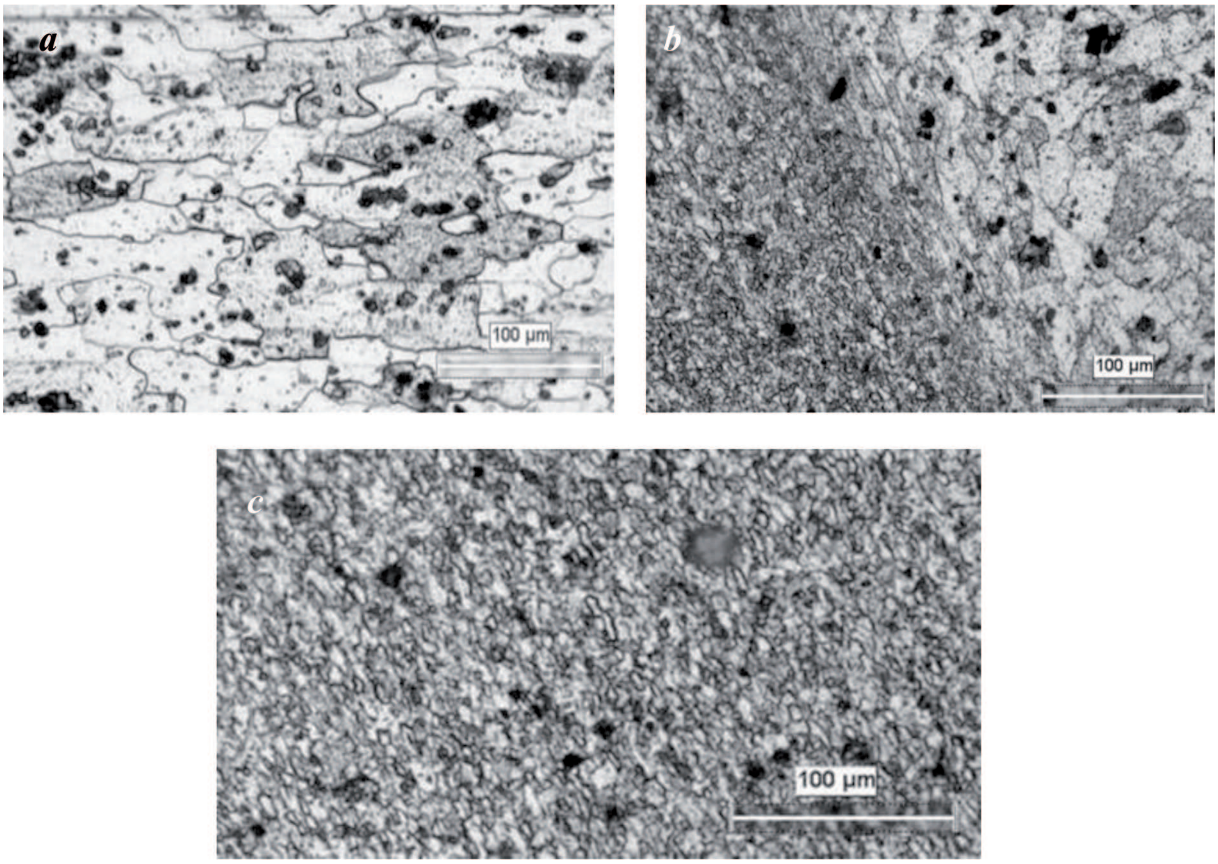

Fig. 6. Typical microstructure of the friction stir welded specimens a) base metal b) transition zone c) nugget

4. Conclusions

In this paper 1015 Al-alloy was bonded using FSW process. Four different pin tool diameters were designed to study the influence of the shoulder diameter on the weld shape and mechanical properties. The results indicate that the diameter of the shoulder have a significant effect on the joint structure and mechanical response. Defect free weld zone was formed with the various shoulder diameters. No distortion was observed in all tested conditions. The heat distribution of the specimens changed due to the distance and the size of the shoulder diameter. The hardness values of the 20 and 30 mm shoulder specimens were slightly higher than the base metal due to the fine grain formation in the nugget, but HAZ was seriously affected from the large heat input related to the shoulder diameters. Increasing grain size in this region seriously decreases the hardness values. Parallel to these changes tensile properties of the Aluminum also changed. As the size of shoulder diameter was increased the UTS and ductility seriously decreased. Microstructural examination of the weld zone and the mechanical property tests results showed that the best bonding was obtained with the 20 mm shoulder diameter tool.

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