Experimental Evaluation of Temperature History in Friction Stir Processing of as-cast Magnesium Alloy

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Abstract: Friction stir processing (FSP), based on friction stir welding (FSW), is a thermo mechanical process for modifying the microstructural and mechanical properties of sheet metals and as-cast alloys. FSP also can be used for mechanical alloying and producing metal matrix composites. Having hexagonal close packed (hcp) structure and dendritic Mg12Al17 precipitations in grain boundaries, AZ91 magnesium alloy is a brittle metal. Due to creation of longitudinal cracks and tunneling cavities throughout the processing path, FSP of AZ91 is difficult and also sensitive to processing temperature. In this study, effect of processing parameters such as the rotational and traverse speeds and pin size on the temperature history experienced by material was investigated. Additionally, a minimum temperature required to produce a defect-free specimen is presented.

Keywords: FSP, Surface Treatment, Temperature History, Magnesium Alloy.

I. INTRODUCTION

Friction stir processing (FSP) is based on friction stir welding which is shown that it is now applicable not only on metals but also Polymers. In FSP, a rotating tool travels through a line to modify the microstructure and even to control the cracks and voids, since the material properties of the top surface is different from the bottom one, the welded specimen will act like an functionally graded (FG) material and effect of crack in FG part should be analyzed using semi-analytical and numerical methods[1-4]. Having the quality of good machinability, magnesium alloys present a great potential as structural materials in the aerospace and automobile industries such as thin-walled corrugated tubes or honeycomb Due to hexagonal close-packed (hcp) structure their application is not extended in spite of their exceptional advantage [5-7].

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In the present experiment, the effect of processing parameters such as the rotational and traverse speeds and pin size on the temperature history experienced by material was investigated. Parameters range to produce defect-free specimen is arranged with regard to the tool pin size. Additionally, a minimum temperature required to produce a defect-free, such as cracks and voids, specimen is presented [8-9].

II. EXPERIMENTAL PROCEDURE

The material used in this study was an AZ91 as-cast magnesium alloy with the composition of (in wt %): Fe, 0.0029; Ni, 0.001; Cu, 0.0097; Si, 0.085; Mn, 0.21; Zn, 0.68; Al, 9.1; and Mg, bal. The AZ91 plates was in dimensions of 110×44×5 mm. Two 2344 hot working steel tools were used in this work. The first tool had a square pin with dimensions of 3.5 mm × 3.5 mm and length of 2.5 mm. The second tool had a square pin with dimensions of 4.25 mm × 4.25 mm and length of 4 mm. Both tools shoulders were 15 mm in diameter. The tool rotational speed was varied from 710 to 1400 rpm and the traverse speed from 12.5 to 100 mm/min. The FSP tools were rotated in the clock-wise direction. The tilt angle was 3°.

For the temperature investigations a five sensory thermocouple with 5 ºC accuracy was employed. The sensors diameter was 3.5 mm. So, five holes with 3.5 mm diameter and 16 mm depth drilled on the positions shown in Fig. 1 to insert the sensors. In the present study, the average of temperature profiles detected by five sensors is investigated for each process parameter.

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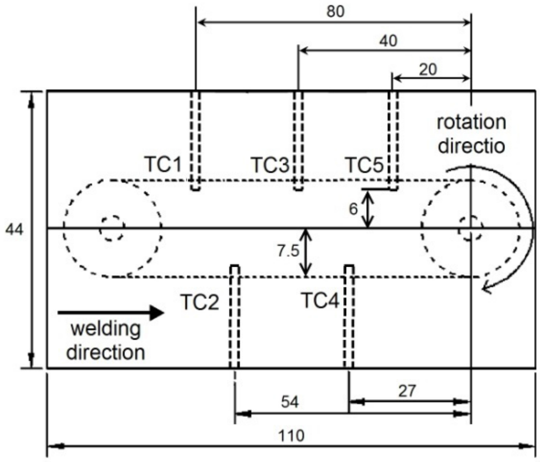


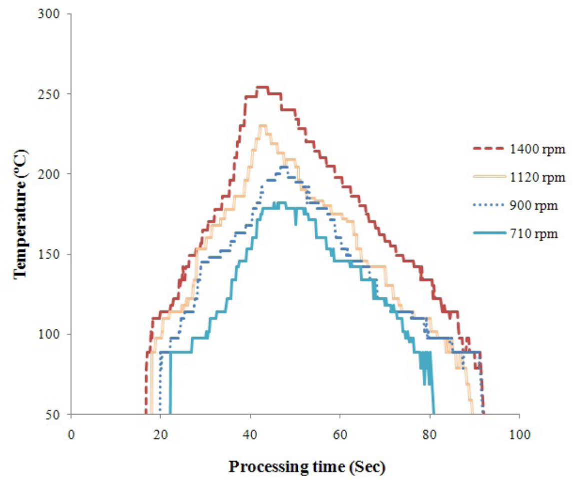
Fig. 1. Layout of the thermocouples inside the work piece.

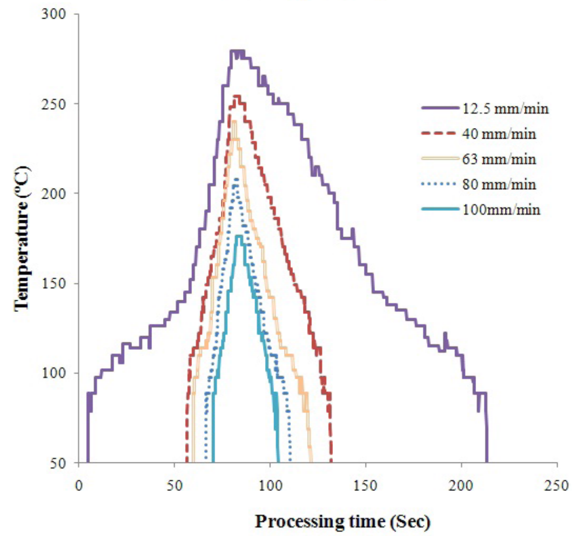
Standard metallographic techniques is used for preparation of the transverse sections of the specimens. 7 ml nitric acid, 5 ml Hydrochloric acid, 5 ml acetic acid, 6 g picric acid, 10 ml water and 100 ml ethanol are mixed to create a solution for etching.

III. RESULTS AND DISCUSSION

Fig. 2a shows the effect of the rotational speed on the temperature history of friction stir processed (FSPed) specimen by the first tool. As can be seen, increase in the rotational speed causes an increase in the peak temperature and a widening in the temperature variation curve. Similarly, Fig. 2b shows the temperature history in the several traverse speeds. Decreasing the traverse speed causes an increase in the peak temperature and a considerable expansion in the temperature history curve. While the specimen is affected by the temperatures up to 100 ºC for about 200 seconds and peak temperature of 280 ºC where the traverse speed is 12.5 mm/min, it is affected by the temperatures up to 100 ºC for just about 35 seconds and a peak temperature of 190 ºC where the traverse speed is 100 mm/min.

It is well-known that the heat sources in the FSP are friction between tool and workpiece and plastic deformation [10]. By increasing the rotational speed or decreasing the traverse speed the rotational speed/traverse speed (ω/v) ratio increases. Consequently, the amount of friction and plastic deformation increases which results in a higher heat input and peak temperature.





(a)
(b)

Fig. 2. (a) The effect of rotational speed on the temperature history. The traverse speed was 40 mm/min. (b) The effect of traverse speed on the temperature history. The rotational speed was 1400 rpm. Specimens are FSPed by the first tool.

From Fig. 2b, the peak temperature at the point with 6 mm distance from centre of the SZ is 181 ºC where the rotational and traverse speeds are 710 rpm and 40 mm/min, respectively. But, increasing the traverse speed to 63 mm/min, in the case of the first tool, causes the peak temperature to drop to 141 ºC which leads to formation of the defects on the processed zone. Fig. 3 shows the formed defects on the specimen processed by the rotational and traverse speeds of 710 rpm and 63 mm/min, respectively. In fact, in the traverse speeds up to 40 mm/min (by the rotational speed of 710 rpm) the amount of heat resulted from plastic deformation and friction is not sufficient for the material to become soft enough. This inadequately soft material cannot flow as well all over the tool pin and merge completely at behind. Thus, cracks and cavities emerge on the processing zone. Therefore, it is not possible to produce a defect-free specimen by the traverse speeds up to 40 mm/min, where the rotational speed is 710 rpm.

Fig. 3. Surface of the specimen FSPed by the first tool at the rotational and traverse speeds of 710 rpm and 63 mm/min, respectively

The surface quality of the FSPed specimen by the rotational and traverse speeds of 1400 rpm and 80 mm/min, respectively, is acceptable and no defects are seen on the cross section. In this specimen the peak temperature was 208 ºC. However, by increasing the traverse speed to 100 mm/min, despite having the acceptable surface quality, a tunnelling cavity formed inside the processed zone which could be seen in the cross section (Figs. 4a and 4b). In this situation the detected peak temperature decreased to 179 ºC. Therefore, producing a defect-free specimen by traverse speeds up to 80 mm/min at the rotational speed of 1400 rpm is not possible.

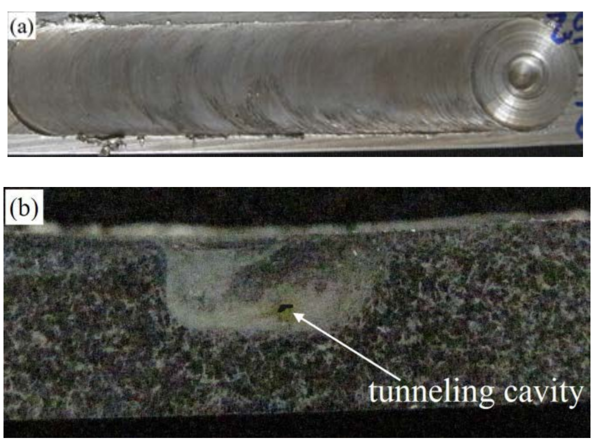


Fig. 4. (a) Surface of the FSPed specimen by the first tool at the rotational and traverse speeds of 1400 rpm and 100 mm/min, respectively and (b) etched cross section of the specimen of Fig. 4a.

Similarly, for the rotational speeds of 900 and 1120 rpm, the maximum traverse speeds which can results in a defect-free FSPed specimen are 50 and 63 mm/min, respectively. At these parameters the peak temperatures were 191 and 196 ºC. Fig. 5 shows the appropriate ranges of traverse speeds versus the rotational speeds to produce defect-free FSPed specimen.

Comparing the peak temperatures of the specimens processed by the rotational and traverse speeds of 710 rpm and 40 mm/min, respectively (181 ºC); and 1400 rpm and 100 mm/min (179 ºC) shows that, despite proximity of the peak temperatures, the second process parameters could not produce a defect-free specimen. Maybe, in spite of equivalent of the peak temperatures, the step time which affects the material is low and do not give an adequate opportunity to the material to become soft enough.

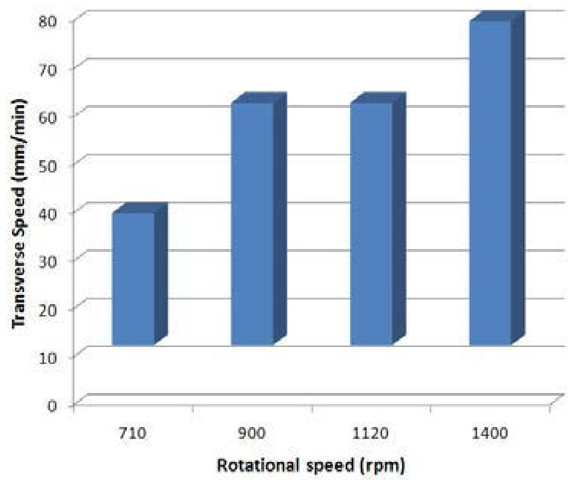


Fig 5- Acceptable traverse speed range versus the rotational speeds in the FSP by the first tool

Fig. 6 shows the temperature history experienced by the workpiece in the 6 mm distance from the center of the SZ during the FSP by the second tool. Comparing to Fig. 2, it is obvious that the peak temperatures are significantly increased in the FSP with the second tool. In the case of the second tool, volume of the materials which undergoes severe plastic deformation increases drastically. Since the volume of material undergoing plastic deformation is $\pi \times 2.5^2 \times 2.5 \approx 49.1\ mm^3$ in the FSP with the first tool, it is $\pi \times 3^2 \times 4 \approx 113\ mm^3$ in the FSP with the second tool. This severe increase in under the processing materials' volume (~ 2.3 times) increases the heat input resulted from the plastic deformation. Also, it should be noticed that the heat input resulted from friction also increases as the surface of the tool pin increases in the case of the second tool.

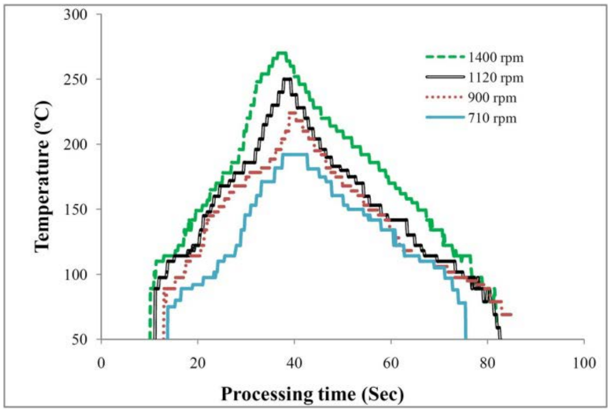


Fig. 6. Effect of the rotational speed on the temperature history experienced by material

Traverse speed: 40 mm/min.

In spite of the significant increase in the heat input in the case of the second tool compared with the first tool, producing a defect-free specimen by the second tool is more difficult. Albeit the peak temperature in FSP with the second tool by the rotational and traverse speeds of 710 rpm and 40 mm/min, respectively, is 192 ºC, a big tunneling cavity is emerged in the cross section of the specimen (Fig. 7). It seems that, regardless of heat input and peak temperature, by increasing the volume of material under process the forging power of the tool shoulder decreases. On the other words, by increasing the volume of material under process the tool shoulder cannot forge and adjoin the material behind the tool pin as well (at the same traverse speeds). Therefore, the traverse speed should be lowered to obtain a defect-free specimen. The appropriate ranges of traverse speed versus the rotational speeds in the FSP by the second tool are shown in Fig. 8.

Fig. 7. Cross section of the FSPed specimen with the second tool at the rotational and traverse speeds of 710 rpm and 40 mm/min, respectively

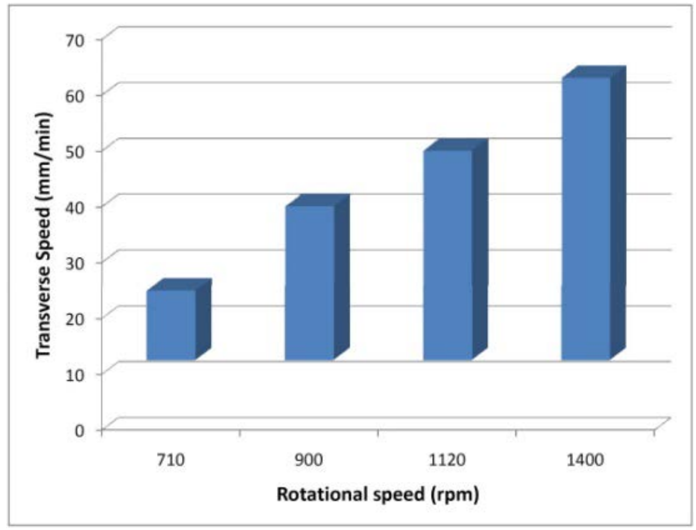
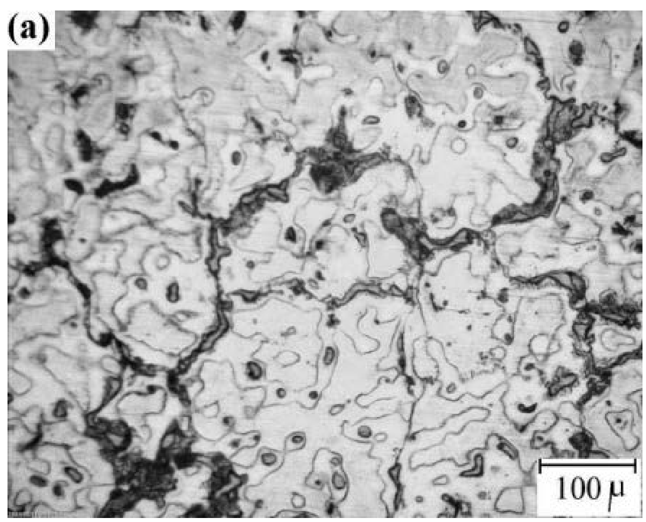
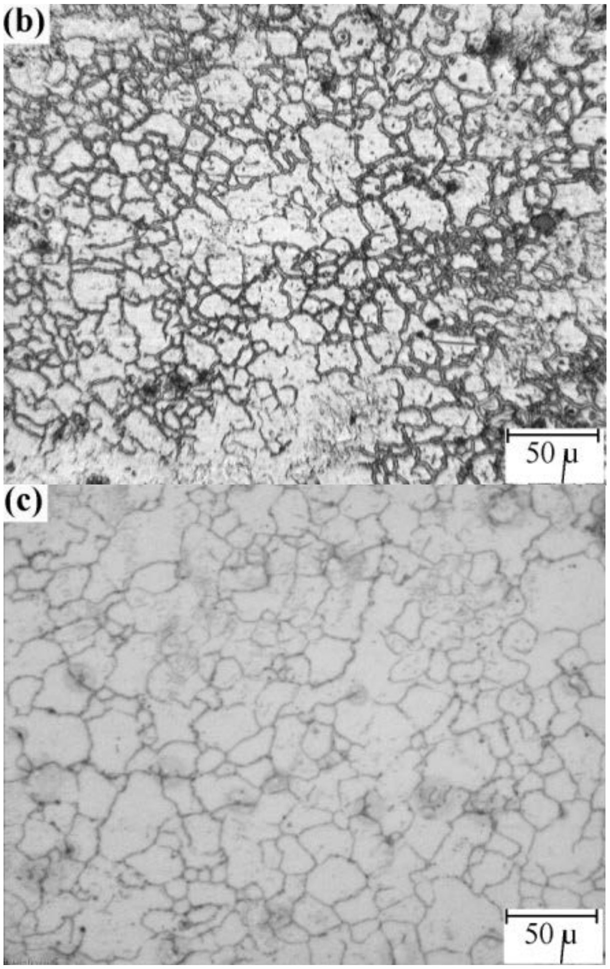


Fig. 8. Acceptable traverse speed range versus the rotational speeds in the FSP by the second tool

Fig. 9 shows the microstructures of the base metal and FSPed specimens with the first and second tools at the same process parameters. As can be seen the grain size in the specimen FSPed with the second tool is a bit larger than that of the specimen with the first tool. Since the heat input in the specimen FSPed by the second tool is higher, the grains grow more during recrystallization.



Grain Size: 150 µm



Grain Size: 15 μm Grain Size: 17.5 μm

Fig. 9. (a) Microstructure of base metal. Microstructure of the SZ of the specimen FSPed by the (b) first tool and (c) second tool. Rotational speed: 1400 rpm, traverse speed: 40 mm/min

IV. CONCLUSIONS

In the present study friction stir processing was successfully done on the surface of AZ91 magnesium alloy. Effects of rotational and traverse speeds and tool pin size on the temperature history curve were investigated. Results show that the peak temperature increases as the rotational speed to traverse speed ratio increases. Increasing the size of tool pin increases the peak temperature significantly due to the increase in amount of materials under plastic deformation. On the other hand, the minimum peak temperature required for producing defect-free specimen increases as the volume of under process material increases.

References

[1]- Seyed Sajad Mirjavadi, Mohammad Alipour, Soheil Emamian, S Kord, AMS Hamouda, Praveennath G Koppad, R Keshavamurthy,Influence of TiO2 nanoparticles incorporation to friction stir welded 5083 aluminum alloy on the microstructure, mechanical properties and wear resistance, Journal of Alloys and Compounds 712, 795–803, 2017.

[2]- Sadegh Hoseinlaghab, Seyed Sajad Mirjavadi, Nasser Sadeghian, Iraj Jalili, M Azarbarmas, Mohammad Kazem Besharati Givi, Influences of welding parameters on the quality and creep properties of friction stir welded polyethylene plates Materials & Design 67, 369-378, 2015.

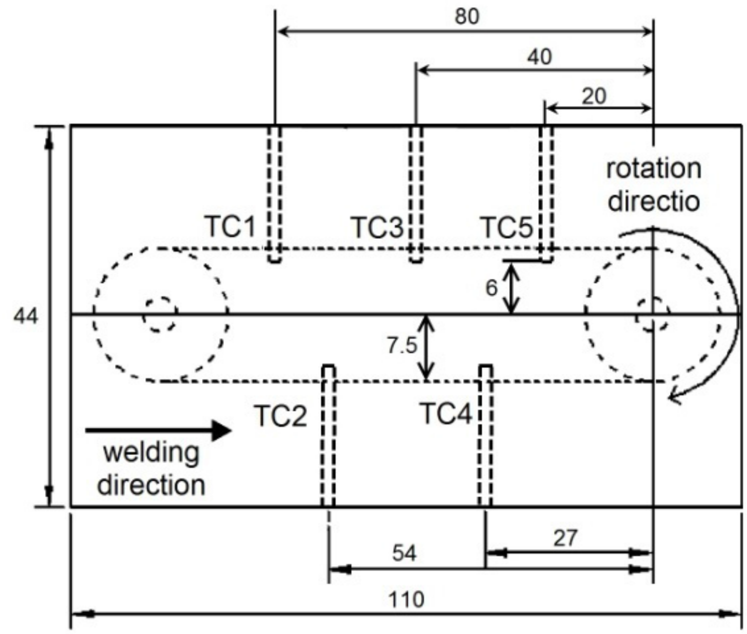
[3]- Majid Azimi, Seyed Sajad Mirjavadi, Seyed Ali Asli, AMS Hamouda,

Fracture Analysis of a Special Cracked Lap Shear (CLS) Specimen with Utilization of Virtual Crack Closure Technique (VCCT) by Finite Element Methods

Journal of Failure Analysis and Prevention 17 (2), 304-314

[4]- Hasan Mirahmadi, Majid Azimi, Seyed Sajad Mirjavadi, Calculation of stress intensity factor for functionally graded cylinders with two radial cracks using the weight function method ,Theoretical and Applied Fracture Mechanics 85, 447-456.

APPENDIX



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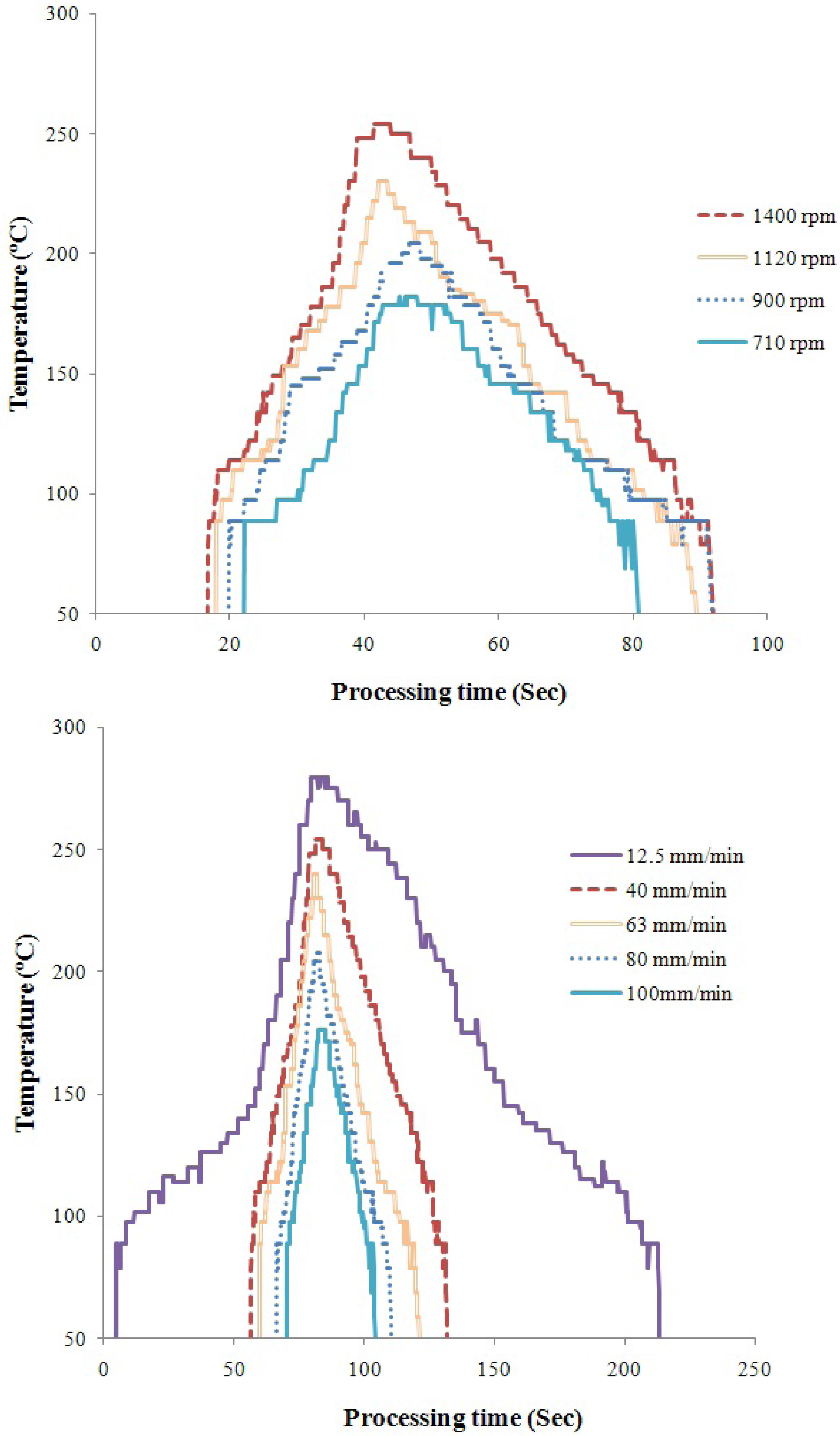

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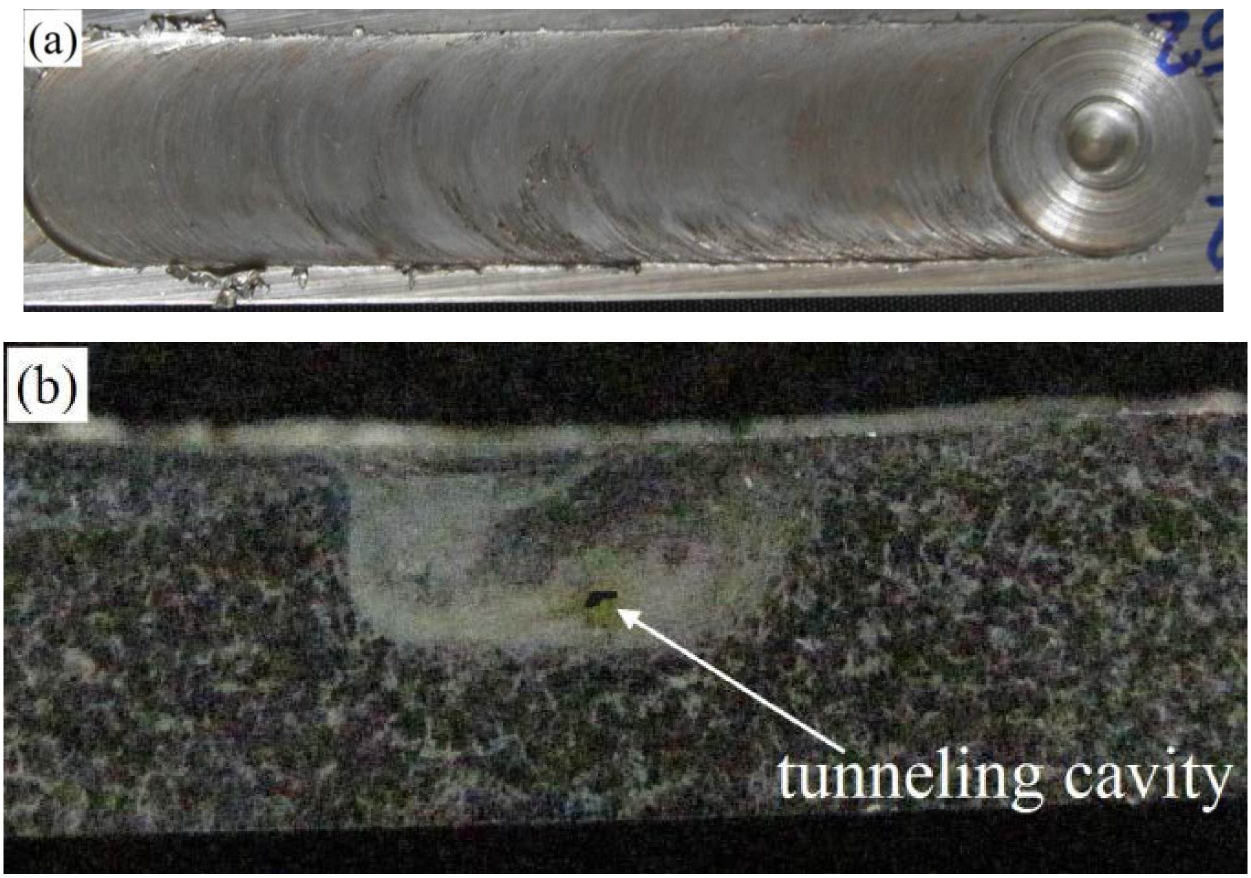

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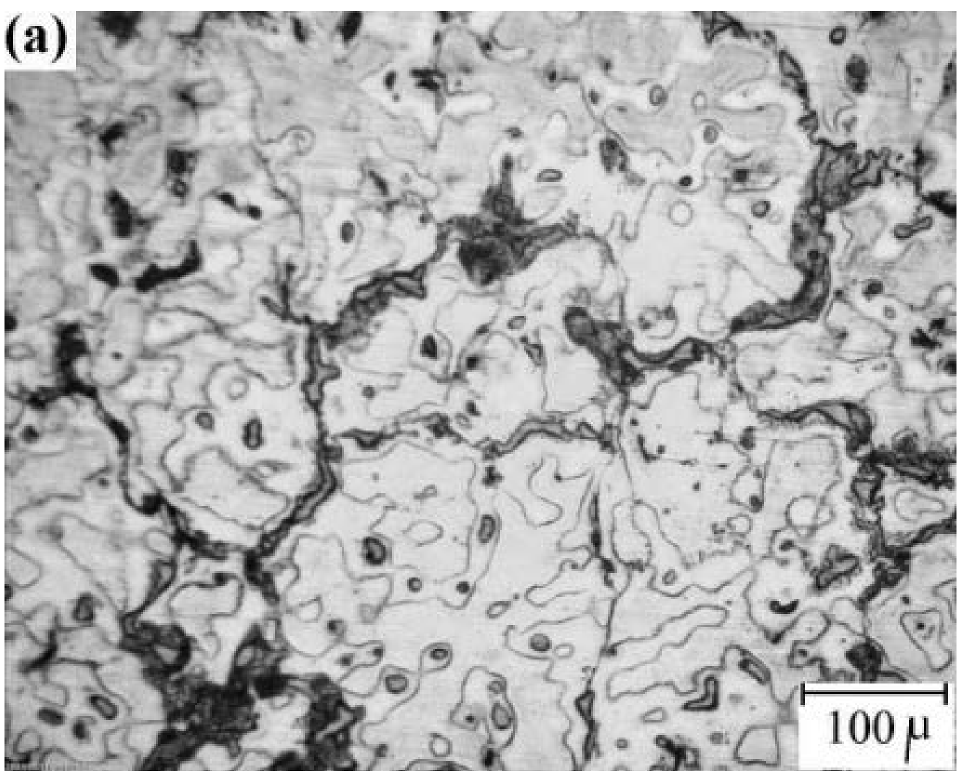
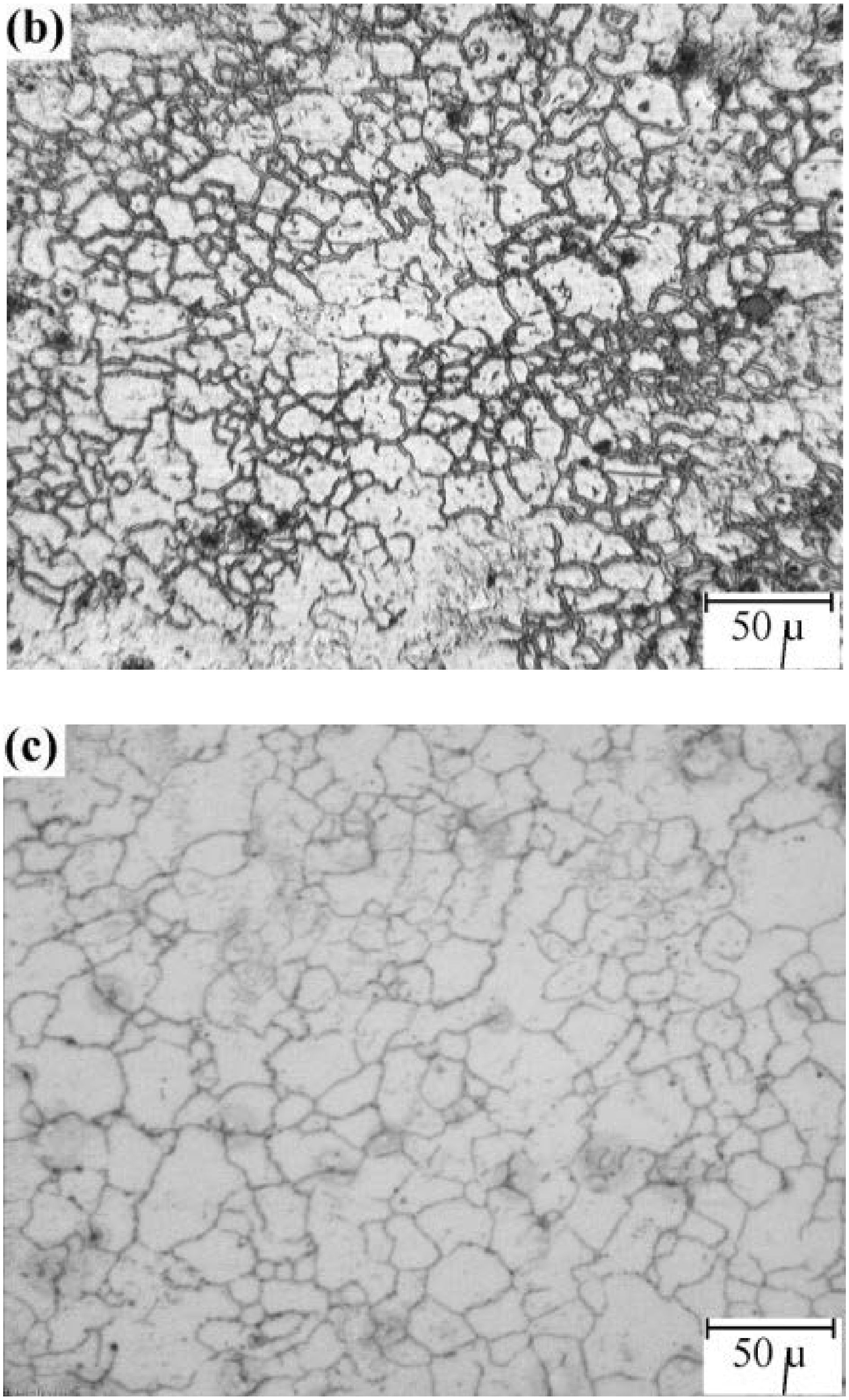
Fig. 7. Cross section of the FSPed specimen with the second tool at the rotational and traverse speeds of 710 rpm and 40 mm/min, respectively



Grain Size: 150 µm



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