Experimental Study on the Effects of Friction Stir Welding Parameters on the Quality and the Mechanical Properties of the AZ91 Joints

Sajjad Rouhi [a,*], Mehrdad Ashjari [b], Amir Mostafapour [a]
[a] Faculty of mechanical engineering, University Of Tabriz, Tabriz, Iran
[b] SAIPA Engineering and Manufacturing of Equipment and Tools Co. (SEMET CO.), Tabriz, Iran

***Abstract* - The objective of the study was to characterize the properties of a magnesium alloy welded by friction stir welding. The results led to a better understanding of the relationship between this process and the microstructure and anisotropic properties of alloy materials. Welding principally leads to a large reduction in grain size in welded zones due to the phenomenon of dynamic recrystallization. The most remarkable observation was that crystallographic textures appeared from a base metal without texture in two zones: the thermo-mechanically affected and stir welded zones. The latter zone has the peculiarity of possessing a marked texture with two components on the basal plane and the pyramidal plane. These characteristics disappeared in the thermo-mechanically affected zone (TMAZ), which had only one component following the basal plane. These modifications have been explained by the nature of the plastic deformation in these zones, which occurs at a moderate temperature in the TMAZ and high temperature in the SWZ.**

I. INTRODUCTION

As the lightest materials among constructional alloys, Magnesium alloy are expected to be widely used in transportation and aerospace industries [1-3]. However, one of the main limitations for the application of magnesium alloy is its poor formability due to its intrinsic HCP crystal structure. To improve the ductility of magnesium alloys, there are extensive works on the development of fine grained magnesium alloys, which are produced through techniques such as spray forming, powder metallurgy, and severe plastic deformation techniques [4-5].FSWwhich was invented by the welding institute (TWI) of the UK in 1991 [6] is a welding process in which a non-consumable welding tool is used to generate both the frictional heat and mechanical deformation simultaneously in order to make a solid state joint. Although FSW has been investigated extensively in the case of aluminum and magnesium alloys [7], but there are A few texture studies regarding FSW aluminum and magnesium alloys have been reported. Sato et al.[8, 9] have reported a detailed texture analysis of FSW welds. The study of the texture evolution is required to understand the anisotropic characteristics of welds and their influence on mechanical properties. In our work, we chose to work with the magnesium alloy AZ91. The main interest in magnesium alloys lies in the fact that they are the lightest metallic materials currently available (magnesium density is about 1.74 g/cm^3). The use of magnesium alloy as a structural material is beneficial in reducing the weight of a vehicle. Thus, magnesium alloys possess excellent specific properties and are being designed to replace steel and aluminum in many structural applications. In general, they have about the same corrosion resistance as mild steel in similar environments but are less corrosion resistant than aluminum alloys. [10] Moreover, magnesium alloys have limited strength, fatigue, and creep resistance at elevated temperatures as well as low stiffness and limited ductility.However, the formability of magnesium alloys is inferior to that of other metallic materials such as steel and aluminum alloys because of their hexagonal close-packed (HCP) structure, but it can be improved by grain refinement. [11,12] For these reasons, magnesium alloys are still under development to improve their properties. With the increasing number of applications of magnesium alloys, a reliable joining process is required, but there are still a number of challenges associated with welding magnesium alloys.Indeed, magnesium alloys have been welded to repair structures because of the generation of many defects such as oxide films, cracks, and cavities. Therefore, the development of a suitable welding method for magnesium is an essential technology to make this material more widely applicable. However, conventional fusion techniques are difficult to use when joining thick sections of magnesium alloys.These techniques lead to poor surface properties, including low hardness, wear, and corrosion resistance, and they produce large shrinkage during solidification. [13]Magnesium alloys can be joined using a wide variety of processes, but conventional processes have exhibited several disadvantages, such as a large HAZ, porosity, evaporative loss of the alloying elements, and high residual stresses.[23] Thus, laser-beam welding and FSW are alternative methods that could overcome the abovementioned disadvantages.[13, 14] The objective of this study was to characterize the mechanical and microstructural property evolution in every zone of a welded sheet. This work characterized the microstructural modification (characterization of the grain size, chemical properties and phase analysis), the mechanical properties [yield strength (YS), ultimate tensile strength (UTS), elongation, and micro hardness) and the crystallographic texture occurring during FSW. The studied material was a magnesium alloy (AZ91) welded by FSW.

II. EXPERIMENTAL

The alloy used in the study of FSW welding was a ternary magnesium-aluminum-zinc alloy with the designation AZ91 according ASTM standards. The chemical composition of the BM is presented in the Table 1.

Table1Chemical Composition of AZ91 Alloy

Al	Zn	Mn	Si
9.1 %	0.68%	0.21%	0.085%
Cu	**Fe**	**Ni**	**Mg**
0.0097%	0.0029%	0.001%	balance

Sheets of AZ91 alloy presented in Figure 1 were obtained from an industrial source.They were obtained by high-pressure die casting under neutral gas and did not undergo heat treatment to maintain the as-cast condition, which is generally used in automobile applications. The plates obtained were sheared to recover the areas measuring 8 mm in thickness. Their edges were machined by milling. For the experimental study performed within the framework of our research, we machined samples into parallelepipedic shapes with dimensions of 150 *50 * 8 mm^3. The tensile strength of the BM was 141MPa.

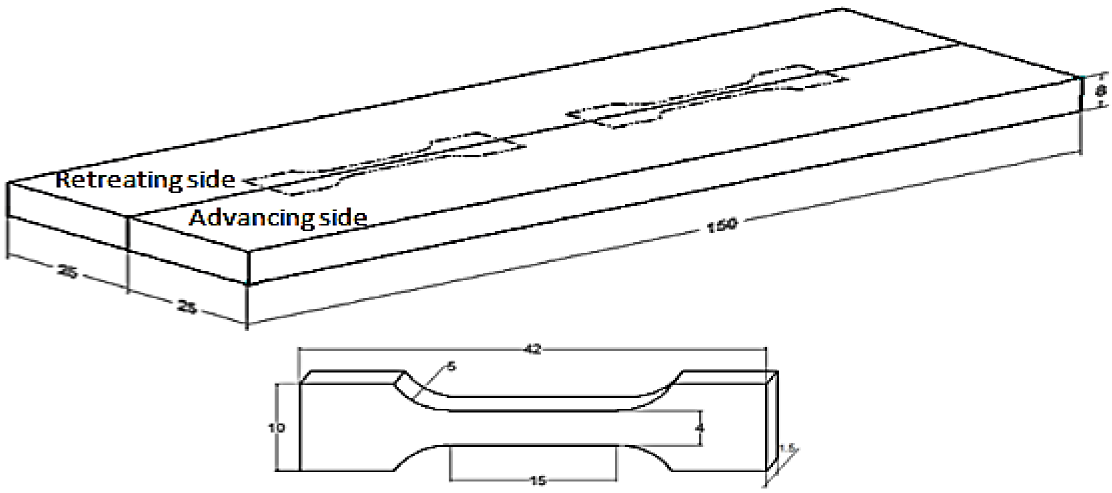

Fig1. Sheets of AZ91 alloy presentedand tensile sample

Two plates were welded together side by side using a FSW process. A pin diameter of 6(4.25*4.25) mm and shoulder of 18 mm have been used. The process parameters that were varied were the welding speed (V) and tool rotation rate (W). The optimized domains are summarized in Table 2.

Table 2 Selected Parameters

Weldingspeed V(mm/min)	63	40
Tool rotation(Rpm)	1250 and 1500	1250
observation	Voids+craks	Sound weld

Experiments performed showed that increasing welding speed (V) at a constant tool rotation rate (W) was resulting in inside voids and lack of bonding caused by the insufficient material flow. For a constant welding speed, a low tool rotation rate was leading to the formation of inner voids because the frictional heat was not sufficient to promote material flow show in figure 2.

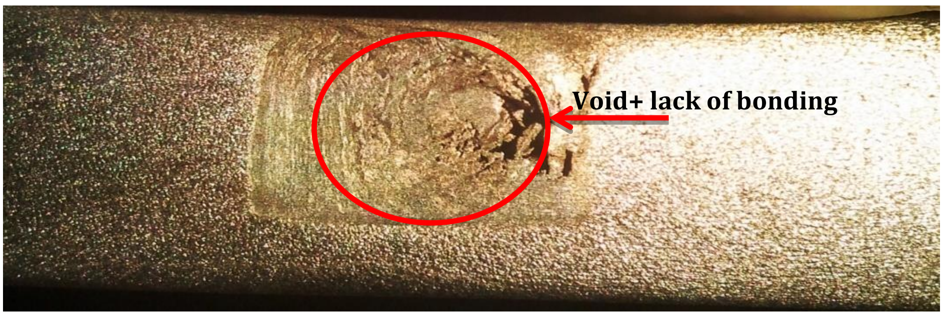

Fig2. Material flow(traverse speeds 63 mm/min; rotational speed was 1250 rpm.)

These defects disappeared with increasing W, but with a further increase, inner voids, lack of bonding, and surface crack due to excess expelling of the material are created.

From microstructure variation point of view, results showed that a low welding speed could provide a controlled dynamic recrystallization leading to a fine grains structure. We observed that increasing of this ratio was leading to an increase in the heat input, an improved material flow and then, a wider and deeper weld nugget. From mechanical properties point of view, results showed that the increasing welding speeds over a critical value lead to decrease the UTS while the YS was kept constant. With a further increase in welding speed, the weld tensile strength dropped, that was attributed to the appearance of many defects: porosity, cracks, and lack of clash between the two plates. These observations are consistent with all the studies carried out previously in the literature.[15,16] In conclusion, many parameters can be considered in FSW.

III. RESULT AND DISCUSSION

Metallurgical Analysis

Grains size measurement by microscopy optical. The aim of this part is to have a detailed description of the microstructural properties (distribution of the grains size) in every studied zone. The microsections for the structure examination were first polished with sandpaper of 100 to 2000 grits and then mechanically polished with 3 and 1 µm diamond oil-suspension. After mechanical polishing to a mirror finish, the welds were examined by optical microscope. The microstructure of the magnesium alloy was exposed by Nital Etchant (20 pct HNO3, C2H5OH) and by the reaction of Keller Etchant (2.5 mL of HNO3, 1.5 mL of HCl, 1.0 ml of HF, and 95 mL of water).[17]

The welded zone is composed of two parts: the transition region (TMAZ) and the SWZ. These zones underwent grain refinement, which produced grains that were significantly smaller than those in theBMand the HAZ regions. Two different grain sizes were observed in the following zones (Figure 3): in the hole corresponding to the pin location (i.e., in the SWZ) and the fine-grained area observed under the shoulder (i.e., in the TMAZ). However, these two zones are also characterized by significant differences.

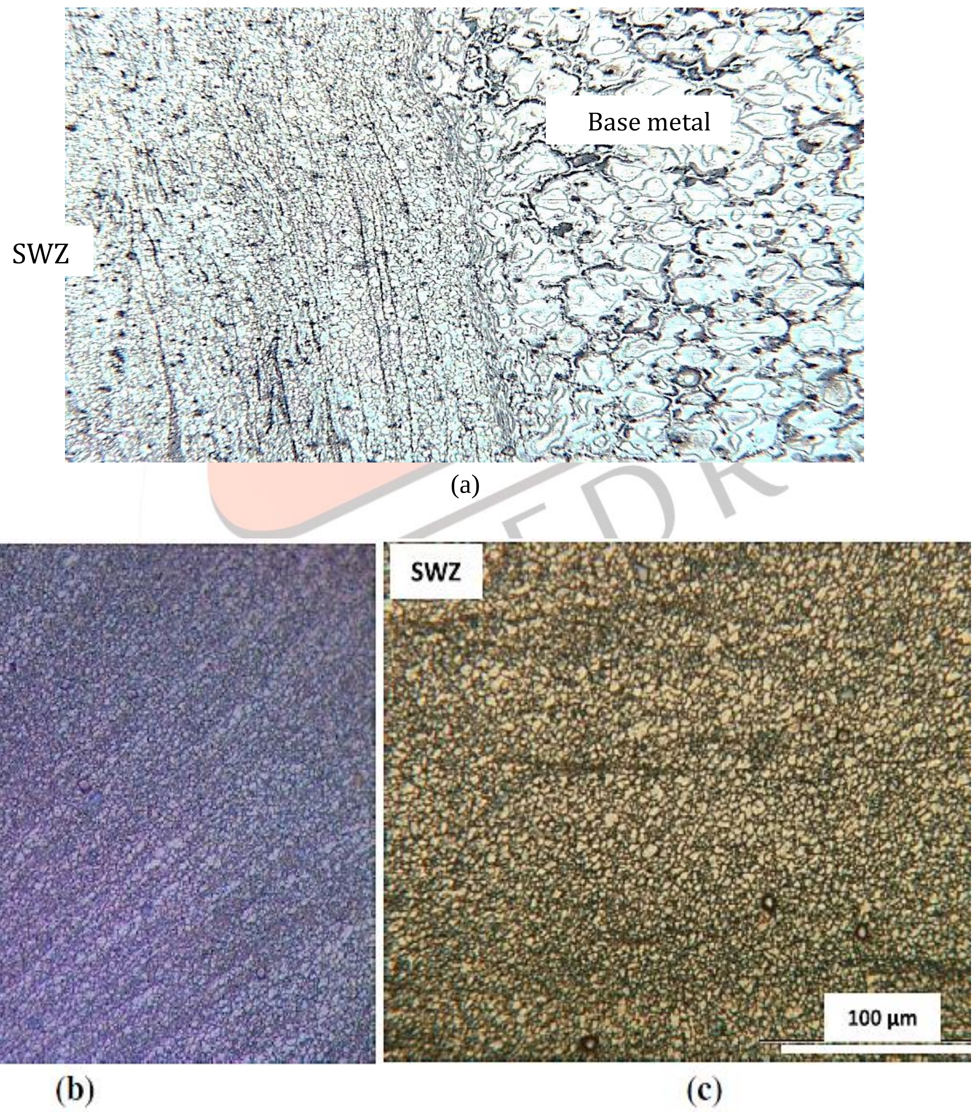

Fig3.(a) Microstructure of the welded zone. (b) Microstructure in the thermo-mechanical affected zone (TMAZ). (c) Microstructure in the stir-welded zone (SWZ) or nuggets.

The TMAZ and interface TMAZ/FSW. In the TMAZ (Figures 3(a) and (b)), magnesium grains presented an elongated shape due to plastic deformation during FSW. We observed that a deformed grain structure consisting of subgrains is formed just outside the stir zone in the TMAZ. The deformation of the grains increased with decreasing distance from the SWZ. Under the shoulder, some very fine-grained lines following the tool rotation were observed (Figure 3(a)).

These were formed of several lines following the tool rotation and alternating small and large grains. The microstructure consists of partially recrystallized grains. The result is that the grain size in the TMAZ is coarser than that in the nugget region, following a grain size gradient, because of insufficient deformation and thermal exposure These observations are confirmed by the distribution of grains size. Moreover, our results show that there is a little variation in grain size in the RS (14 µm) compared to that in the AS (16 µm), which is caused by the greater straining expected in the latter location. These results have been explained by the fact that this zone undergoes only plastic deformation in the retreating and in the AS of the nugget at relatively low temperature. This phenomenon is caused by an insufficient heating temperature and a strong inhomogeneity in strain deformation, which leads to partial dynamic recrystallization during FSW. Similar observations were made by several authors during the FSW of AZ31B magnesium alloy.[18, 19]

Microhardness Characterization

From the mechanical properties standpoint, the study of microhardness demonstrates that FSW welding induces particular profiles in the studied zones. Figure 4shows the microhardness results, measured close to the surface on both sides of the linear weld in a profile including the BM passing through the HAZ and the welded zones. The same measurement has been realized along the same profile and at a depth around 1mm. On the surface, the AZ91 friction stir-welded joint exhibits a significant microhardness evolution through the weld. The microhardness profile is symmetrical considering the center of the nugget. Significant variations (increase or decrease) of microhardness are measured in each transition region: BM and HAZ, HAZ and TMAZ, TMAZ and nugget. The higher microhardness values are measured in the SZW and in the center of the HAZ (100 ± 5 Hv0.2). The lower values (65 ± 2 Hv0.2) and the BMmicrohardnessis intermediate (80 ± 4 Hv0.2). The results have enabled us to demonstrate that for microhardness that there are particular distributions in the different zones studied and that can be related to the modifications of microstructure, in particularly with the crystallographic texture. In the HAZ, near to the TMAZ zone, the microhardness is the same compared to the BM and sometimes it is slightly higher. This one can be explained by the presence of precipitates which are formed in this zone considered to be a zone of diffusion which contributes toward augmenting the microhardness.[20] The microhardness in the TMAZ and in the nuggets is higher than in the BM. As can be seen from this diagram,the average microhardness of the stir zone rises as traverse speed increases from20mm/min up to 63 mm/min. As we know the cooling rate increases as the traverse speed rises and the grain growthbecomeslimitedduringthe dynamic re-crystallizationandthereforeafinegrainedstructure is achieved. Thewell-knownHall–Petchrelationship states that strength andhardnessincreaseastheaveragegrain size decreases.Darrasetal. [21] also reportedthatanincreasein traverse speed or decrease in the rotational speed leads to a rise in the hardness.

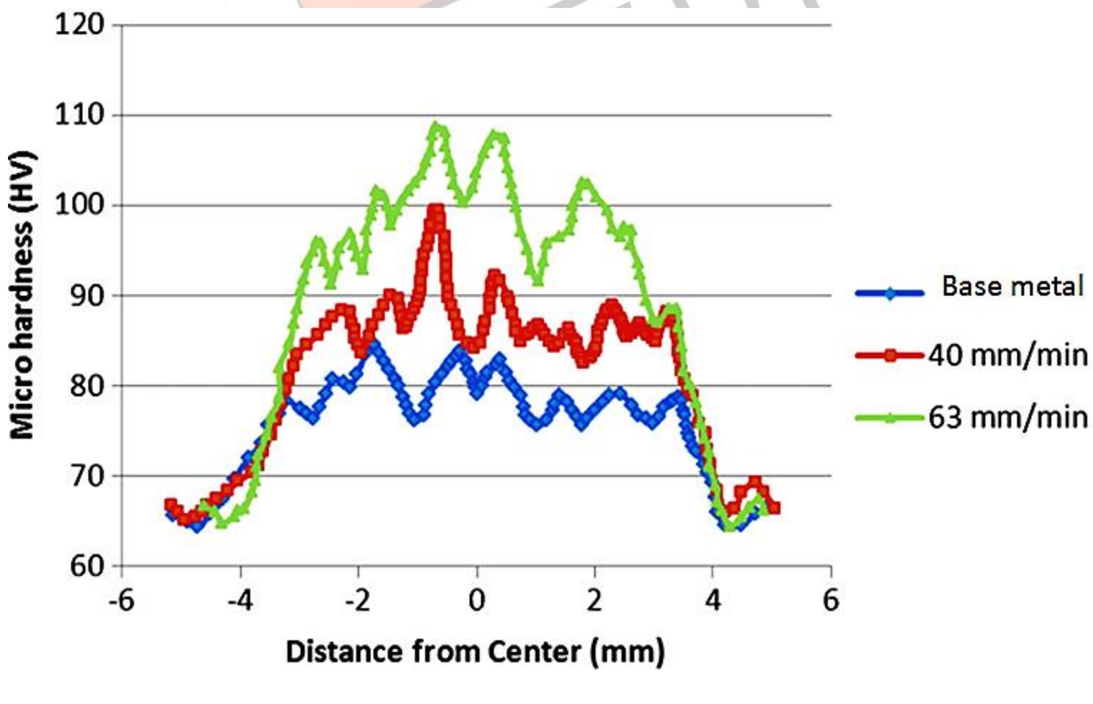

Fig4. Hardness profileofthespecimensproducedwith BM and traversespeedsof40 and 63mm/min;rotationalspeedwas1250rpm.

Tensile test

Fig. 5 shows the stress strain curve for specimens produced with traverse speeds of 40 and 63mm/min. As is clear from the diagram, the mechanical properties of the specimens improve by increase in the traverse speed. In fact, increasing the traverse speed leads to a limitation in grain growth while dynamic recrystallization and according to the Hall–Petch relation- ship the ultimate tensile strength improves. As we see, the UTS and elongation in the specimen with traverse speed of 40 mm/min are about 192 MPa and 12.5% respectively which show an improvement of almost 38% in UTS and 85% in elongation compared to the base metal. The as-cast AZ91 magnesium alloy has a completely brittle fracture with low yield strength and UTS. We can see that the UTS and elongation of the FSWed specimen produced in 40 mm/min traverse speed and rotation speed 1250 rpm increased from 139 to 193 MPa and 6.74 to 12.56 Mpa respectively in comparison with the base metal. The main reasons of the improvement in UTS and elongation are as follows:

- hard precipitates of Mg17Al12 in the grain boundaries which are the favorable sites for starting the cracks are dissolved by FSW;
- porosities and voids of the cast alloys disappear because of the FSW [22], so one of the main factors which decrease the UTS and elongation is dropped by FSW.

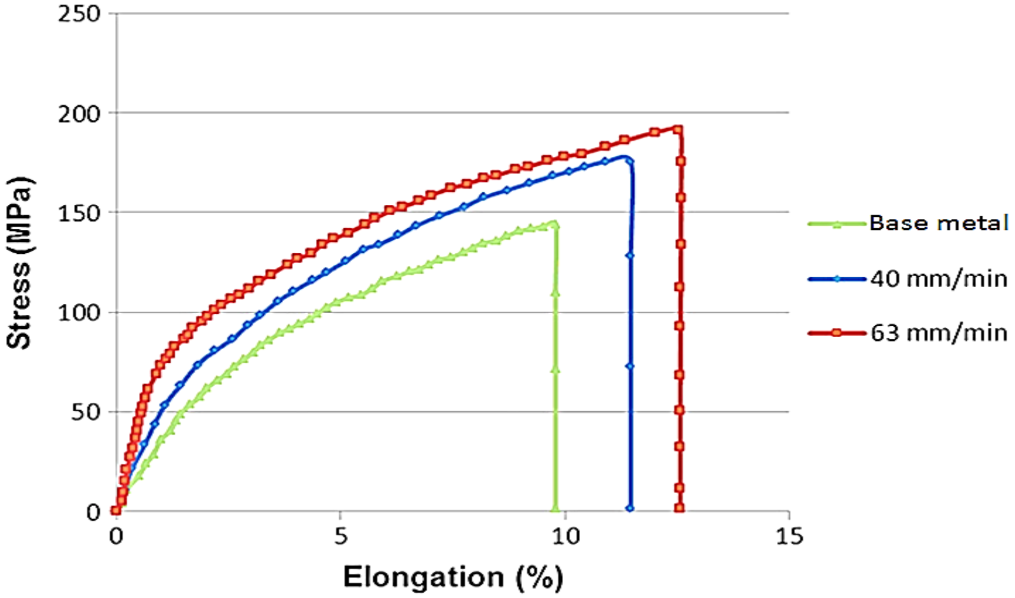

Fig 5.Stress straincurvesforspecimensFSWedwithtraversespeedsof40and 63 mm/min;rotationalspeedwas1250rpm.

IV. Conclusions

The results of this study demonstrated the microstructural and anisotropic modifications induced by FSW in a thin sheet of magnesium alloy (AZ91). The characterization of FSW AZ91 optimized joints resulted in the following conclusions. The results of this study reveal that FSW induces the generation of several distinct zones with different microstructural, anisotropic, and mechanical properties. The following conclusions are drawn from this research.

- Increase in the traverse speed has a similar effect on the mechanical behavior of the composite; it limits the grain growth during solidification and therefore tensile strength improves according to the Hall–Petch relationship.
- By decreasing the traverse speed, the grain size in the SZ decreased and hardness increased significantly because of the reduction in the time while metal was exposed to heat;
- The welded zones feature fine grain sizes that are significantly smaller than those in the BM and the HAZ regions. In the TMAZ and in the SWZ, the grain size decreases significantly and reaches an average size between 2 µm in the nuggets and 16 to 14 µm, respectively, in the advancing and RS. These zones are principally composed of an α −Mg phase with β-$Mg_{17}Al_{12}$precipitates localized around the grain boundaries.
- By performing friction stir welding on the AZ91 base metal, UTS and elongation of the parent metal increased and by performing FSW in more than base metal, distribution of the reinforcement became more uniform and UTS rose consequently.

V. References

[1] K. U. Kainer."Magnesium alloys and their applications". Deutsche Gesell schaftfürMaterialkundee.V, (2000).

[2] Horst E. Friedrich. Barry L. Mordike. "Magnesium technology, metallurgy, design data, applications". Springer Berlin Heidelberg, New York, (2006).

[3] B.L. Mordike, T. Ebert."Magnesium properties — applications — potential". Materials Science & Engineering A, vol. 302

(2001), pp. 37–46.

[4] H. Watanabe, T. Mukai, M. Mabuchi, K. Higashi. "Deformation mechanism of fine-grained superplasticity in metallic materials expected from the phenomenological constitutive equation". ActaMaterialia, vol. 49 (2001), pp. 2027–2037.

[5] C.Y. Chen, Y.A. Tsao, Mater. "On the hardening of friction stir processed Mg-AZ31 based composites with 5–20% nano-ZrO2 and nano-SiO2 particles". Materials Science & Engineering A, vol. 383(2004), pp. 21–29.

[6] Thomas WM, Nicholas ED, Needham JC, Murch MG, Temple SP, Dawes CJ. "Improvements relating to friction welding". G. B. Patent No. 9125978. 8; 1991.

[7] Franchi AS, FernandeFF, Travessa DN. "Microstructural aspects and mechanical properties of friction stir welded AA2024-T3 aluminum alloy sheet". Materials & Design, vol. 32(2011), pp. 4684–4688.

[8] Y.S. Sato, H. Kokawa, M. Enmoto, and S. Jogan: Metall. Mater. Trans. A, 1999, vol. 30A, pp. 2429–37.

[9] U.F.H.R. Suhuddin, S. Mironov, Y.S. Sato, and H. Kokawa: Mater. Sci. Eng. A, 2010, vol. 527, pp. 1962–69.

[10] B.L. Mordike and T. Ebert: Mater. Sci. Eng. A, 2001, vol. 302, pp. 37–45.

[11] H. Watanabe, H. Tsutsui, T. Mukai, H. Ishikawa, Y. Okanda, M. Kohzu, andK.Higashi: Mater. Trans., 2001, vol. 42, pp. 1200–1205.

[12] A. Luo: Can. Metall. Q., 1996, vol. 35, pp. 375–83.

[13] S.W. Kalee, W.M. Thomas, and E.D. Nicholas: Magnesium Alloys and Their Applications, Wiley-VCH, New York, NY, 2000, pp.175–190.

[14] X. Cao, M. Jahazi, J.P. Immarigeon, and W. Wallace: J. Mater. Process. Technol., 2006, vol. 171, pp. 188–204.

[15] J.A. del Valle, M.T. Perez-Prado, and O.A. Ruano: Mater. Sci. Eng. A, 2003, vol. 355, pp. 68–78.

[16] K. Nakata, Y.G. Kim, and M. Ushio: Trans. Join. Weld Res. Inst., 2002, vol. 31, pp. 141–46.

[17] A. Kouadri and L. Barrallier: Mater. Sci. Eng. A, 2006, vol. 429A, pp. 11–17.

[18] J.A. Esparza, W.C. Davis, E.A. Trillo, and L.E. Murr: J. Mater. Sci. Lett., 2002, vol. 21, pp. 917–20.

[19] Y. Sirong, C. Xianjun, H. Zhiqiu, and L. Yaohui: J. Rare Earths, 2010, vol. 28, pp. 316–20.

[20] C. Shaw and H. Jones: Mater. Sci. Eng. A, 1997, vols. 226–228, pp. 856–60.

[21] B.M. Darras, M.K. Khraisheh, F.K. Abu-Farha, M.A. Omar, Mater. Process. Tech. 191 (2007) 77–81.

[22] P. Cavaliere, P.P. De Marco, J. Mater. Process. Tech. 184 (2007) 77–83.