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A New Surface Modification Technique and Their Characterisation: Friction Stir Processing of Al-Zn-Mg Alloy

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ABSTRACT
Since aluminium alloy is a well-known light alloys to use in aerospace and automotive industries. Therefore, a new method, so far little known in metal forming industries, is the friction stir processing of surface layers. Friction stir processing (FSP) is an emerging surface engineering solid-state technology which provides the ability to thermomechnically process selective locations on the materials surface and to enhance specific properties to some considerable depth. However, from a practical point of view it is important to determine the impact of FSP conditions, therefore, a tool rotation speed, travel rate, pressure force as well as the shape and type of tool on the moment acting to heat generated in the stirring area. The heat generated in the area being processed and the level of plastic strain are factors having a decisive effect on microstructural changes, and, consequently, on the mechanical and functional properties of newly formed areas. In this phenomena that the main FSP features have been investigated through OM (optical microscopy), SEM (scanning electron microscopy), FESEM (field emission scanning electron microscopy), TEM (transmission electron microscopy) and mechanical properties. Moreover, aluminium alloy being an age-hardening response to evaluated through Vicker's hardness measurement a typical characterisation at present task. The research of the FSP of surface layers, so far has been focused mainly on the metallurgical analysis of microstructural changes in modified aluminium alloys.
Key words: light alloy, FSP features, solid-state technology, mechanical properties, TEM.

I. INTRODUCTION

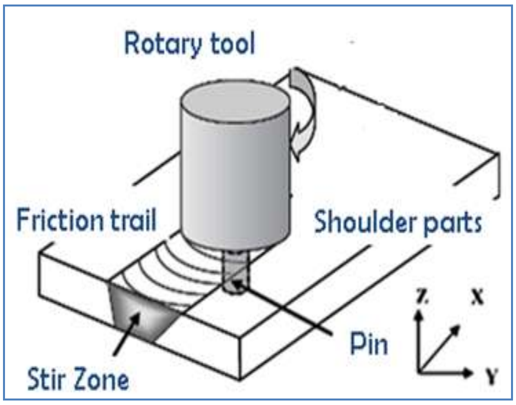


Fig.-1: Concept of FSP method.

Over the years, aluminium alloys have been used extensively in many engineering fields due to their high strength-to-density ratio, strong age-hardening ability, and competitive weight savings and energy savings materials. Typically, aluminium castings contain porosity, segregated impurities, and inhomogeneous microstructures. In this case, FSP has been applied to Al alloys with resulting property improvements. Since, FSP is a metal working technology adapted from FSW (friction stir welding) using the same basic principles, produces the recrystallized grains in the stir zone due to the dynamic recrystallization from severe plastic deformation, and further affects the mechanical properties [**1-4**]. A schematic illustration of FSP is shown in Fig.-1. The rotating tool provides a continuing hot working action, plasticizing the metal within a narrow zone, while transporting material from the leading face of the pin to its trailing edge. According to plastic deformation degree and the heat input during FSP at different microstructural zones have been indentified: the stir zone (SZ) experiencing intense plastic deformation and high temperature exposure being characterized by fine and equiaxed recrystallized grains, the thermo-mechanically affected zone (TMAZ) experiencing medium temperature and deformation having deformed and unrecrystallized grains, and the heat affected zone (HAZ) experiencing only temperature, characterised by precipitation coarsening. The process is carried out in solid state at low temperature (typically below $0.4T_m$), for aluminium alloys. The processed zone is deformed and under the thermal effect recovers or recrystallizes, forming a defect free recrystallized fine grain microstructure [**5**]. The aim of this paper to insight examination for using FSP to refine microstructural modification and their properties enhancements of present alloy has selected.

II. EXPERIMENTAL PROCEDURE

The experiment was conducted on one light-weight aluminium alloy having following chemical composition (in wt.%): Zn-5.3, Mg-3.0, Sc-0.25, Si-0.11, Fe-0.10 with the rest Al. The plate (dimensions:150×90×8 mm^3) was longitudinally friction stir processed. The following parameters were adjusted during processing run in an indigenously designed and developed milling machine with fixture plates firmly fixed with base plate. In Fig.-2 represents, on FSP plate double-pass was made with width of plasticized zone (4.1 mm) exhibiting, with predetermined tool. Tool has 3 mm, 5 mm pin diameter and pin height, respectively. The main processing parameters have been tabulated in Table-1. Several characterizations have been done likely OM, FESEM, and TEM examinations. The age-hardening characteristics have been identified through Vicker's hardness measurements (e.g. at as-cast sample first solution treated from 465 ^{o}C/1h then immediately water quenching, then maintained artificial ageing at 120 ^{o}C, 140 ^{o}C, 180 ^{o}C at various ageing time intervals). Similarly, the tensile samples [flat shape sample dimensions (mm): full length 58, gauge length 26, width 4] have been collected from FSP zone, and tested with cross head speed 1 mm/min at UTM (25 KN, H25 K-S, UK) at room temperature.

Table-1: Processing parameters of FSP.

FSP parameters (experiment performed through double passes)			
Tool rotation speed (rpm)	Work piece travel speed (mm/min)	Friction pressure (up-setting force)(KN)	Pin angle (^{o})
1025	75	15	2.5

III. RESULTS AND DISCUSSION

Grain refinement is easily achieved by FSP through the large plastic deformation with intensifying heat which induces the generation of severe crystal lattice rotations and simultaneously an extremely high number of dislocations rearranging into new low and high-angle grain boundaries and deformation twins and twinned boundaries [**6**]. Here, the two main process parameters for FSP are the tool rotational speed (rpm) and work piece travel speed (mm/min). For given tool geometry and depth of penetration, it has been observed that the peak temperature generated within the SZ is a strong function of the rotational speed, and travel speed (heat input per unit length) [**7**]. Around the SZ several parameters have affected including grain size, texture, as well as the coarsening and dissolution of precipitates and their re-precipitation in heat treatable Al alloy, which control the

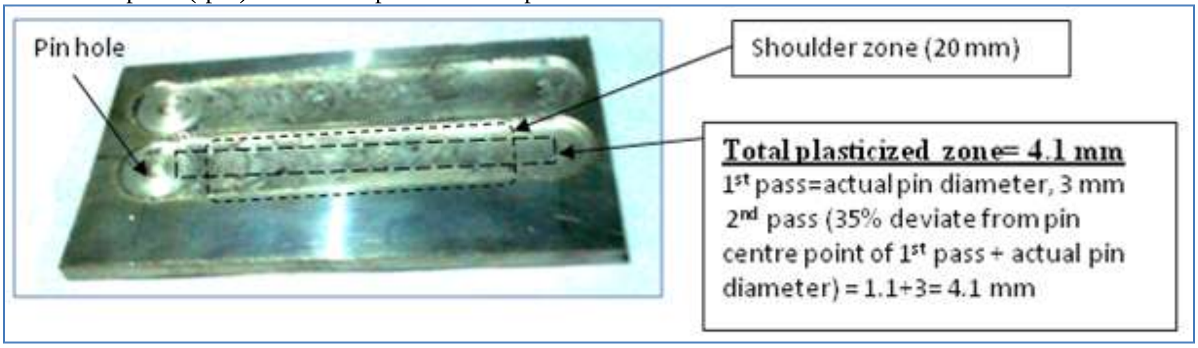
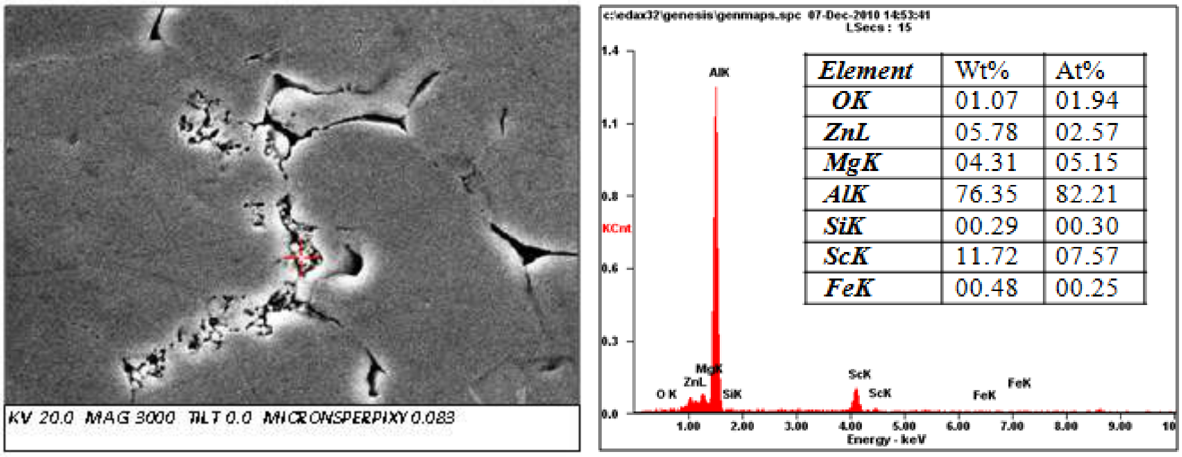


Fig.-2: Macrostructure of FSP sample (as-cast) through double passes.



Element	Wt%	At%
OK	01.07	01.94
ZnL	05.78	02.57
MgK	04.31	05.15
AlK	76.35	82.21
SiK	00.29	00.30
ScK	11.72	07.57
FeK	00.48	00.25

Fig.-3: FESEM analysis (as-cast) of studied alloy.

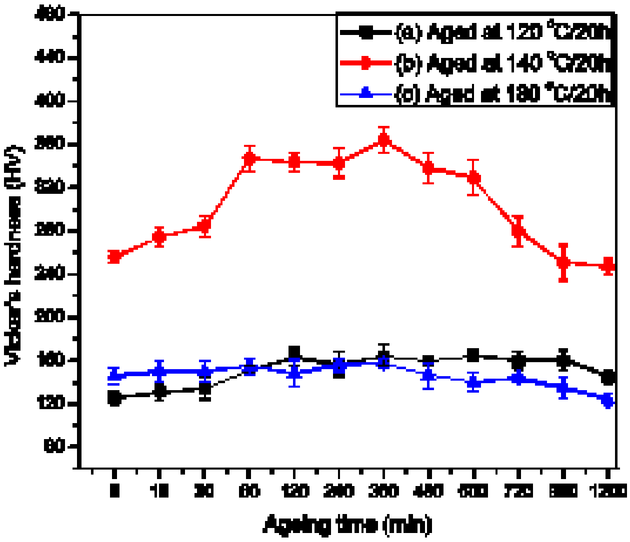


Fig.-4: The illustration of ageing curves.

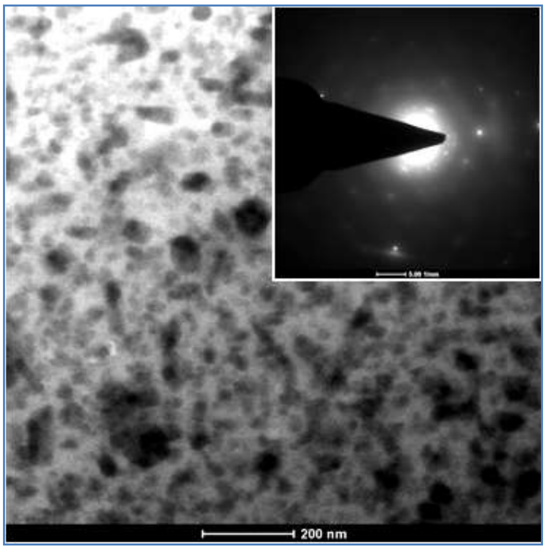


Fig.-5: The TEM micrograph of studied alloy.

mechanical properties of SZ. In Fig.-2, typically macrostructure shows, how to performed FSP and created of different regions. Similarly, in Fig.-3 shows FESEM analyzed grain boundary segregation (very high 11.72%Sc) of impurities elements of as-cast studied alloy. Being, an age-hardenable Al-Zn-Mg alloy with Sc (as cast grain refiner) addition evaluated through Vicker's hardness testing (10 kg. load) which has shown in Fig.-4. Among the three ageing temperatures at 140 ^{o}C shows highest ageing effect due to formation coherent GP zones and ή-phase formation (as peak-aged and hardest phase) are main causes. In Fig.-5, shows TEM micrograph (aged at 140 ^{o}C/6h) to exhibited fine aged particles and $L1_2$-Al_3Sc phases. On the other hand, inset diffraction pattern indicated fine precipitates spotted in around the circles. It is very significant to evaluated surface modification by FSP of present studied alloy. In Fig.-6(a-b), shows cast structure with segregated elements, rather, after T_4 heat treatment cast structure got refine and equiaxed grains. In Fig.-6(c), shows different regions created during FSP and it has distinctly shown grain refinement effects with unprocessed zone called base metal (BM). In red square indicated at SZ ultrafine grains (400-500 nm) refinement. Then, next adjacent region in black square at TMAZ has indicated very fine grains (>10 μm) refinement [**8**]. The next adjacent region in blue square at HAZ has indicated some elongated grains nearer to BM. In Table-2, the tensile results have been tabulated as per FSP test. After AC and T_4 conditions, at (T_4+FSP) state all the properties increased many fold. The proof stress ($\sigma_{0.2}$) and ultimate tensile stress (σ_u) increased 201.9%, 231.0%, respectively. The ductility increased 152.8% in line.

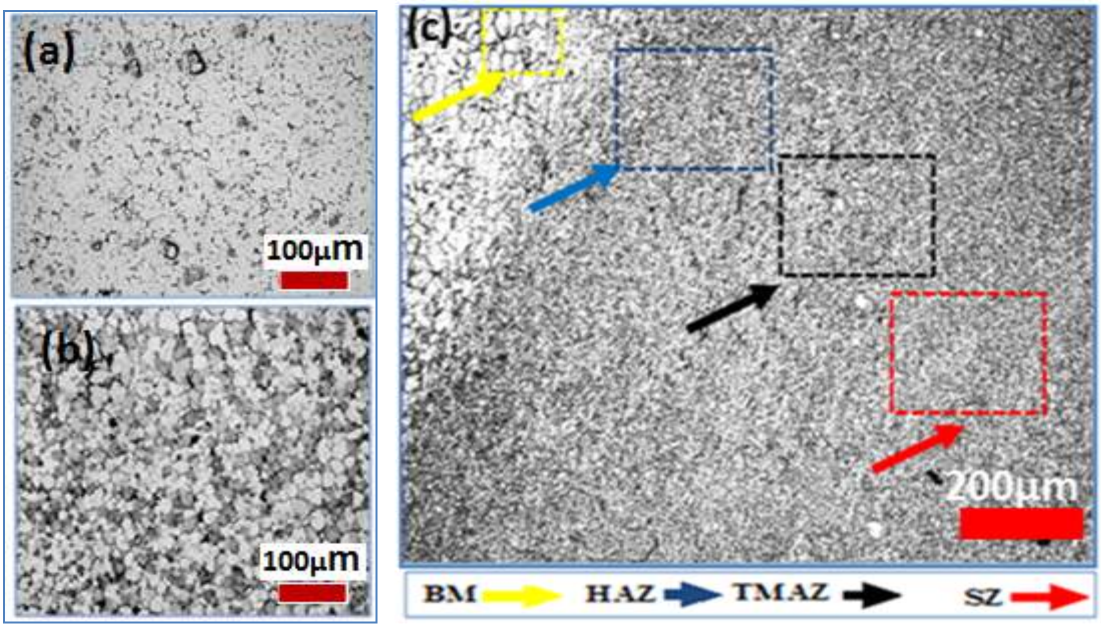


Fig.-6(a-c): The optical micrographs illustration of studied alloy (a) as-cast, (b) T_4 , (c) during (T_4+FSP) condition at different processing zones (arrows indicated as different regions).

Table-2: Results of tensile properties are tabulated through FSP direction of studied alloy.

Comparison with FSP through double passes	Tensile properties		
	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	δ (%)
As-cast	51.4	82.0	1.8
T_4 condition	53.7	83.9	3.6
T_4 + FSP	162.1	278.1	9.1

(*Note:T_4 = Solutionized at 465 ^oC/1 h then WQ; YS denoted at 0.2% offset from stress-strain curve.)

IV. CONCLUSIONS

(1) FSP is a solid-state novel technique to modify cast surface layer.
(2) During FSP at several zones have been created but SZ is the most refine zone.
(3) The FSP set up and process parameters all affects on material properties.
(4) Lowest grain size achieved through FSP around 400-500 nm in SZ region.
(5) Dispersoids like Al_3Sc are effective means of inhibiting the grain growth during FSP.
(6) The increased ductility and strength observed is a result decreasing porosity, refinement of second phases and the grain size of the studied alloy.
(7) Therefore, the combined effects of FSP and the age-hardening properties to Al alloy have concurrently strengthened by ultrafine-grained and precipitation hardenings.
(8) The formation of a fine grain structure suggests a very high nucleation rate during dynamic recrystallization.

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