# Effect of SPD and friction stir welding on microstructure and mechanical properties of Al–Cu–Mg–Ag sheets

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A B S T R A C T

Ultrafine grained (UFG) structure with an average grain size of ~0.6 μm was produced in sheets of Al–Cu–Mg–Ag alloy by equal channel angular pressing (ECAP) followed by hot rolling (HR) at 250 °C. These sheets were joined by friction stir welding (FSW) with efficiency of about unity. The effect of severe plastic deformation (SPD), FSW and heat treatment on the microstructure and mechanical properties of the welds and sheets was examined.

*Keywords:*
Al–Cu–Mg–Ag alloy
Equal channel angular pressing
Friction stir welding
Mechanical properties
Ultrafine grained microstructure
Aerospace materials

## 1. Introduction

Silver containing aluminum alloys belonging to the 2XXX-series are currently considered as potential aerospace materials due to acceptable combination of room and high temperature properties. In that respect they are suitable as structural materials for fuselage skin of supersonic aircraft. It is known that increased mechanical properties may be achieved in aluminum alloys through extensive grain refinement by SPD [1]. ECAP is one of the popular methods of SPD, which is capable to produce UFG structure [1,2] and improve mechanical properties of bulk aluminum alloys [3,4]. However, for the fuselage skin the material is required to be in the form of sheets which could be produced by rolling. The authors of [5,6] demonstrate that UFG structure remains in the sheets after rolling. Therefore, the ECAP followed by rolling is a promising technique for the fabrication of UFG aluminum sheets.

Nowadays, integral structures produced by FSW of aluminum sheets/stringers are considered as advanced airframes. FSW has proven its capability to weld aluminum alloys of 2XXX-series, in the naturally aged and peak-aged conditions successfully with no defects [7,8]. Furthermore, FSW retains UFG structure in the joints of non age-hardenable aluminum alloy and IF steel [9,10]. However, there was no information for application of FSW to achieve full-strength joint in the 2XXX-series alloys with UFG structure produced by SPD. In general, FSW and ECAP are both solid-state and hot shear processes based on SPD [1–7]. Therefore, they are promising metal-working and welding processes to produce high-strength integral structures.

The aim of this study is to demonstrate feasibility of FSW to achieve full-strength joint in the UFG Al–Cu–Mg–Ag alloy. We expected that the development of UFG structure in the sheets by SPD and in the weld by FSW gives a synergetic effect on its microstructure and strength.

## 2. Materials and experimental procedures

Experimental aluminum alloy with a chemical composition of Al–5.6%Cu–0.62%Mg–0.56%Ag–0.37%Mn–0.15%Sc–0.09%Zr (in weight%) denoted as Almagest2Sc was manufactured by direct chill casting, homogenized at 520 °C for 24 h and slow cooled in a furnace. A granular structure with an average grain size of ~50 μm was observed in the ingot after homogenization. The ingot was machined into plates with the dimension of 180 mm × 180 mm × 40 mm. An L-shaped isothermal die with a cross-section of 180 mm × 40 mm and a channel angle of 90° was used for ECAP. Deformation through this die produced a strain of ~1 in each passage [11]. The plates were pressed at 250 °C to 8 passes through route A [1]. Next, deformed plates were heated to 250 °C and rolled to a final thickness of ~4 mm. The rolled sheets were butt joined in pairs along rolling direction by a single FSW pass. A tool rotation speed of ~1000 rpm and a traveling speed of ~150 mm/min lying in the range of the speeds typically applied for FSW of 2XXX-series alloys [7] were used.

Tensile specimens with a 25 mm gauge length and a 7 mm × 3 mm cross-section were machined across the former rolling direction and tensioned at ambient temperature. The yield strength (*YS*), ultimate tensile strength (*UTS*) and elongation ($\delta$) were recorded using Instron

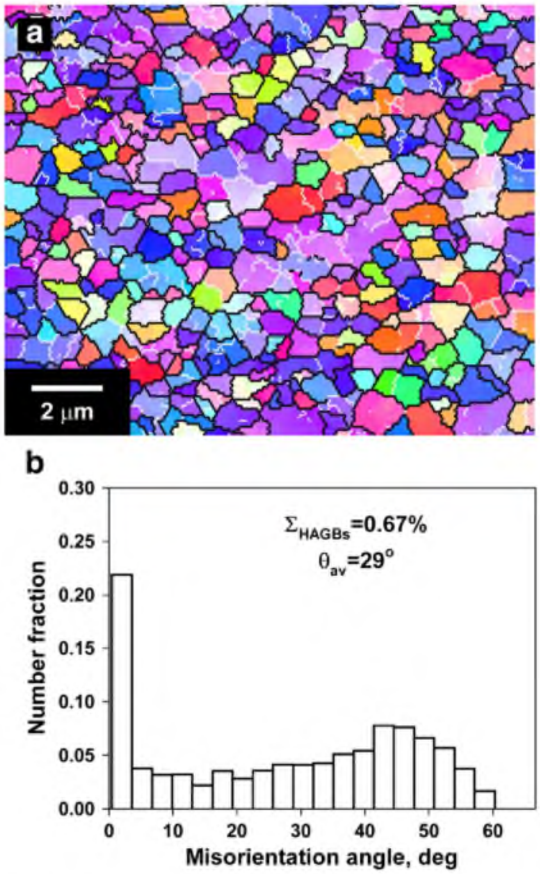


**Fig. 1.** Microstructure of the Almagest2Sc subjected to ECAP followed by HR. (a) Typical EBSD map and (b) misorientation distribution.

5882 universal testing machine. The yield strength efficiency ($E_{YS}$), the ultimate tensile strength efficiency ($E_{UTS}$) and the elongation efficiency ($E_E$) of welds were defined as the ratio of tensile properties of the FSWed joint to that of the parent material.

Microstructural examination was carried out on a section perpendicular to the rolling direction. The methods of microstructure observation and samples preparation including optical metallography and electron backscattering diffraction (EBSD) analysis were described previously in detail [12]. In the data presented, high-angle boundaries (HABs) were defined as $\theta \geq 15°$ in misorientation and low-angle boundaries (LABs) as $2° < \theta < 15°$. HABs and LABs are depicted in EBSD maps as black and white lines, respectively.

## 3. Results and discussion

Typical EBSD map and misorientation distributions of the Almagest2Sc subjected to ECAP followed by HR are shown in Fig. 1a and b, respectively. The deformation structure consists of fine grains delimited by HABs and elongated grains subdivided by LABs on equiaxed subgrains (Fig. 1a). It can be seen that the size of recrystallized grains and subgrains is essentially the same. The average size of these crystallites is ~0.6 μm. The fraction of HABs of ~0.67 and average misorientation ~29° are quite near to 0.7 and 30° achieved in FCC materials processed by SPD [2,13]. Therefore, this deformation structure can be interpreted in terms of UFG structure [2].

The typical cross-section of a weld is shown in Fig. 2a. No welding defects were observed in the joint. The stir zone (SZ) undergoing high temperature and SPD is characterized by the dynamically recrystallized grains with the size higher than those in the UFG sheet (Figs. 1a and 2). The grain sizes decrease from the top to the center of the SZ (Fig. 2b and c) as the center absorbs lower temperature and short thermal cycles [7]. The microstructure with an average grain size of ~2.3 μm, that is ~4 times higher than those of the parent material, is formed in the center of the SZ. Previous studies [14,15] have reported that after the FSW tool has passed, dynamically recrystallized grains may grow statically during cooling of the joints. The

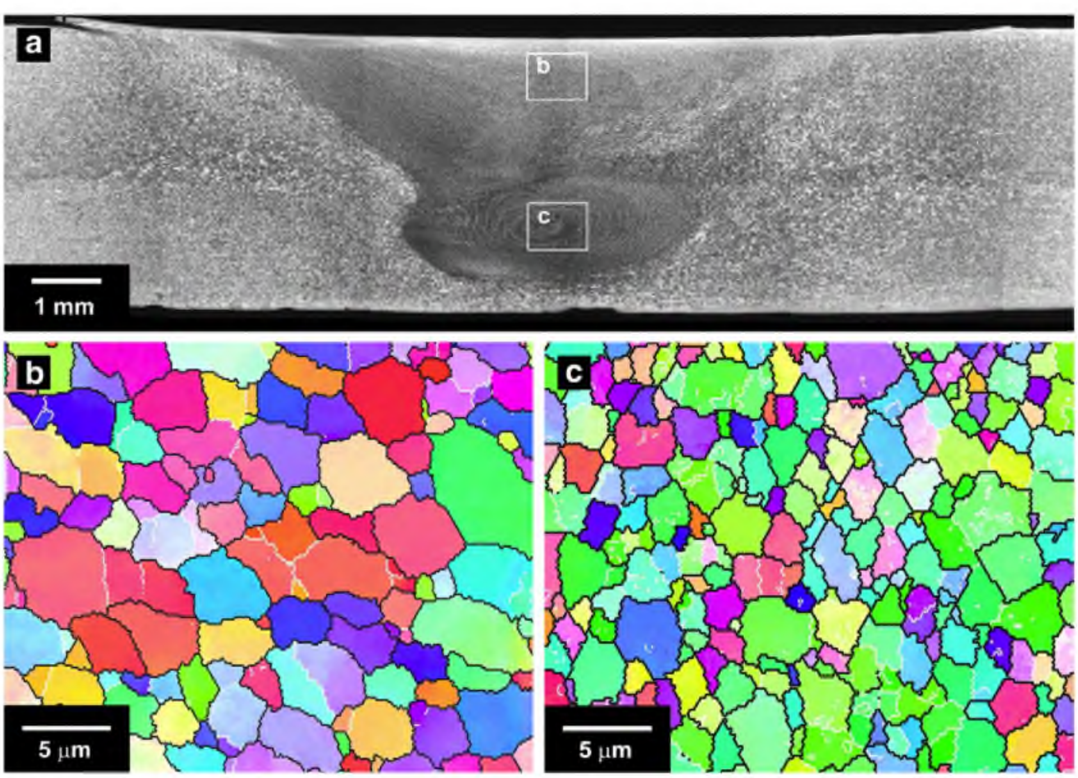


**Fig. 2.** Macrostructure of welded sheets (a). EBSD maps of a top (b) and center zone (c).

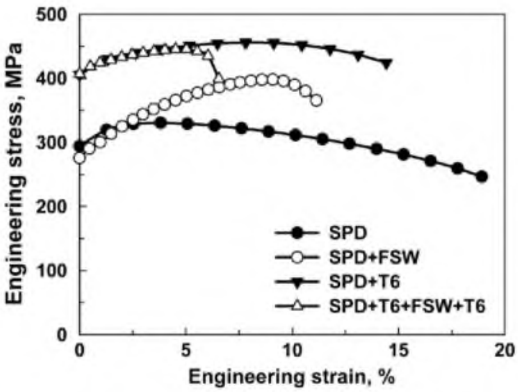


**Fig. 3.** Typical engineering stress–engineering strain curves of the Almagest2Sc subjected to various treatments.

relatively coarse grains of ~15 μm were observed in the thermomechanically affected zone and heat affected zone (Fig. 2a).

The engineering stress–strain curves of the UFG sheets and joints are shown in Fig. 3. Extensive strain hardening over a wide range of strains was observed in the joint weld, whereas continuous softening was found in the UFG sheets (Fig. 3) after short strain hardening. It is known [16] that an increase in grain size provides transition in mechanical behavior of UFG aluminum alloys from strain softening to strain hardening. The transverse tensile properties summarized in Table 1 show that the formation of UFG structure increases strength and ductility of the alloy. In comparison with the UFG sheets, the weld exhibited higher *UTS* and lower *YS*. The joint efficiency of ~0.93 and of ~1.2 is obtained for *YS* and *UTS*, respectively. Typically, such a high joint efficiency is observed in non age-hardening aluminum alloys [7]. At the same time considerable decrease in elongation of the joint associates with hardness distribution due to inhomogeneous microstructure developed across the weld [17,18].

The Almagest2Sc ascribed to be age-hardenable aluminum alloy and artificial aging should be applied to provide dispersion strengthening. Thus, sheets and welds were subjected to conventional heat treatment consisting of solution treatment at 520 °C for 2 h followed by artificial aging for 5 h at 190 °C, i.e. T6-temper was used. It is seen (Table 1) that strength characteristics of the sheets and weld in T6 conditions are essentially the same but the welded material exhibits decreased ductility. An increase in *YS* and *UTS* results from T6-temper (Fig. 3, Table 1). The highest *YS* of 405 MPa, *UTS* of 455 MPa and moderate ductility of 16% were obtained in UFG sheets subjected to T6-temper. The joint efficiency of about unity and of ~0.97 was obtained for *YS* and *UTS*, respectively. Such a high joint efficiency is inherent to non age-hardening aluminum alloys while for age-hardening alloys these values ranged from 0.65 to 0.96 [7].

In spite of increased strength comparing to the non-aged material the strength characteristics obtained in UFG sheets and joints resulted from T6-temper and in the Almagest2Sc alloy after T6-temper [19] are essentially the same. Despite the presence of coherent $Al_3(Sc,Zr)$ particles observed in examined alloy [19], extensive grain coarsening eliminates the UFG structure in the sheets and joints during solution treatment at 520 °C. Thus, significant increase in the strength of the sheets and joints is attributed to the dense precipitations of Ω-phase which are uniformly distributed within the examined alloy [19]. Modification of conventional heat treatment may produce higher strength by

**Table 1**
Room-temperature transverse tensile properties of sheets and joint welds.

| | *YS* (MPa) | *UTS* (MPa) | δ (%) | $E_{YS}$ | $E_{UTS}$ | $E_E$ |
|---|---|---|---|---|---|---|
| Coarse grained | 220 | 290 | 15 | | | |
| SPD | 295 | 330 | 20 | – | – | – |
| SPD + FSW | 275 | 400 | 10 | 0.9 | 1.2 | 0.5 |
| SPD + T6 | 405 | 455 | 16 | – | – | – |
| SPD + T6 + FSW + T6 | 405 | 445 | 7 | 1 | 0.97 | 0.43 |

retention of UFG structure and additional age-hardening. For instance, Kim et al. [3] reported that a low-temperature aging after solution treatment and ECAP can significantly enhance the strength of an AA2024 alloy. Furthermore, application of solution treatment before deformation may shift the formation of UFG structure to lower strains [20]. Therefore, it can be expected that the optimization of the parameters of heat treatment and SPD will retain the UFG structure providing enhanced strength of the Almagest2Sc.

## 4. Conclusions

The present study demonstrates feasibility of the FSW to produce full-strength joint in the UFG sheets of Al–Cu–Mg–Ag alloy. Joint efficiency of about unity was attributed to the UFG structure developed in the sheets and joints. The moderate yield strength of ~285 MPa was obtained in non-aged sheets and joints. T6-temper increases yield strength of the sheets and joints to ~405 MPa. At the same time FSW reduces elongation of the non-aged and aged joints.

## Acknowledgments

This study was supported by the Department of Education and Science, Russian Federation, under grant no. P991. Authors are grateful to the staff of Joint Research Center, Belgorod State University, for their assistance with instrumental analysis.

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