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Mechanical properties and formability of cold rolled friction stir welded sheets in AA5754 for automotive applications

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Abstract

The effect of cold rolling on mechanical properties and formability of friction stir welded blanks in AA5754 aluminium alloy was investigated. To this purpose, FSW experiments were performed on 2.5 mm thick sheets with rotational and welding speeds equal to 1200 rpm and 100 mm/min, respectively, and tool sinking of 0.1 mm. Part of the FSWed sheets was cold rolled, with the rolling direction perpendicular to the welding line, until the obtaining of a constant sheet thickness equal to 2.2 mm. Finally, the mechanical properties and formability of joints, both before and after cold rolling, were evaluated by means of uniaxial tensile and hemispherical punch tests; the experimental results, in terms of stress vs. strain curve, microstructure, and limiting dome height, were analysed and discussed.

Keywords: Aluminium alloy; Friction stir welding; Cold rolling; Formability, Mechanical properties.

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1. Introduction

Friction stir welding (FSW) is a solid state green technology developed for the obtaining of joints with mechanical properties higher than the ones given by fusion welding. Such process is very attractive in joining lightweight materials, such as Al and Mg alloys, difficult to be welded or unweldable through fusion technologies. Furthermore, FSW is suitable in the manufacturing of multi-sheet lightweight structures obtained by assembling two or more blanks, also in different materials and/or thicknesses, typically used in the automotive and transportation

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industries [1-3]. In friction stir welding sheet blanks are joined by the action of a rotating pin tool getting in contact with the top surface of the sheets and then moving along the welding line with a proper tilt angle. The combined effect of the plunging, rotation and translation of the tool involves heat generation by friction between tool and sheets and by stirring of the deforming material and induces a strong plastic deformation of the workpiece by promoting its complex mixing across the joint. As a consequence, a plasticized region is created around the tool so that material is extruded from the advancing to the retreating side [1, 4].

One of the aspects usually referred as a limitation in friction stir welding of butt joints is the thickness reduction in the weld resulting from the forging effect of the tool shoulder [5]. It leads to a decrease in both mechanical properties and formability of the FSWed blanks with an effect that becomes ever more pronounced with decreasing the initial sheet thickness. Furthermore, the thickness reduction causes the worsening of the aesthetic appearance of the welded blank assembly and this drawback can further contribute to reduce the field of application of FSW. In order to ensure a constant sheet thickness, the FSWed blank can be subjected to cold rolling (CR) process. As a matter of fact, CR leads to an increase in the strain hardening coefficient that, in turn, allows an improvement in both material strength and formability, besides to a more uniform sheet thickness in the FSW [6]. However, the effect of the degree of strain hardening and the positioning of the welding line with respect to the rolling direction on the mechanical properties and formability of the welded blank assembly has to be accurately investigated.

In this framework, the present work aims at studying the effect of cold rolling on the mechanical properties and formability of friction stir welded sheets in AA5754 aluminium alloy. To this purpose, FSW experiments were performed on 2.5 mm thick sheets, using a pin tool with constant values of rotation and welding speeds. Then, part of the FSWed blanks was cold rolled, with the rolling direction perpendicular to the welding line, until the desired constant sheet thickness of 2.2 mm was reached. Finally, mechanical properties and formability of joints were evaluated by means of uniaxial tensile and hemispherical punch tests; the stress vs. strain curves and the limiting dome height values, both before and after cold rolling, were analysed in detail.

2. Material and experimental procedures

2.1. Friction stir welding experiments

Butt joints in AA5754 aluminum alloy, in the H114 temper state, were obtained by performing FSW experiments with a machining center. The sheet blanks were 185 mm in length, 80 mm in width and 2.5 mm in thickness. The pin tool, in H13 tool steel, was characterised by a shoulder diameter of 15 mm, a truncated cone pin with base diameter and a height of 3.9 and 2.3 mm, respectively. FSW was carried out with the tool sinking of 0.1 mm, and constant values of rotational speed (ω) and welding speed (v) equal to 1200 rpm and 100 mm/min, respectively, chosen within the weldability window of AA5754 alloy [7]. All the welding experiments were carried out with a nuting angle equal to 2° and welding line perpendicular to the rolling direction (RD) of the sheets in the as-received condition.

2.2. Cold rolling of FSWed blanks

Part of the assembled blanks was subjected to cold rolling (CR) after friction stir welding in order to make uniform the blank thickness. In particular, the CR was performed on friction stir welded strips, obtained by cutting the blank perpendicularly to the welding line, 90 mm in width and 170 mm in length. The strips were rolled with the RD perpendicular to the welding line. Two different rolling passes, with a thickness reduction equal to 0.2 and 0.1 mm, respectively, were carried out. The final uniform thickness of the welded blank assembly was 2.2 mm.

2.3. Uniaxial tensile tests

The effect of the cold rolling on the mechanical properties of the welded blanks was investigated by means of room temperature tensile tests carried out using the servo-hydraulic universal testing machine MTS 810. To this purpose, tensile samples were machined from FSWed blanks both before and after cold rolling. The loading direction was perpendicular to the welding line, and the gauge length was equal to the shoulder mark. The tests were carried out according to ASTM E8/E8M and BS EN 895. At least three repetitions for each condition were performed. The results were plotted in terms of nominal stress (s) - nominal strain (e) curves and the yield strength (YS), ultimate tensile strength (UTS) and strain at the onset of necking (e_u) were derived before and after cold rolling. Finally, the true stress - true strain data in the region of uniform plastic deformation were used to calculate the work hardening coefficient (n).

2.4. Formability of FSWed joints

Formability of the FSWed joints, before and after cold rolling, was investigated at room temperature using the hemispherical punch-based method [8]. To this end, square shape samples, with a side of 90 mm, were deformed until the onset of necking. Formability was quantified by means of the limiting dome height (LDH) obtained as the punch stroke at the peak of the punch force vs. punch stroke curve recorded during test. At least three repetitions for each process condition were carried out.

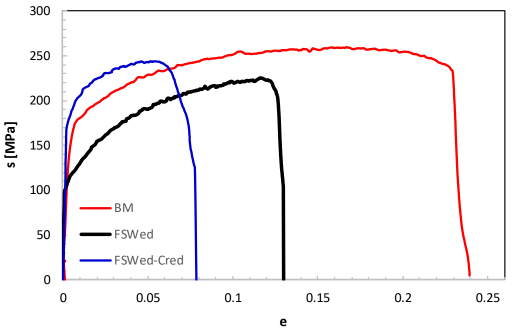
2.5. Microstructural and micromechanical analyses

For the microstructural analysis, samples were cut from the FSWed sheet before and after cold rolling operations to show the welding section. Then, the surfaces were mechanically polished and electrochemically etched by a 4% HBF4 solution at 15 V for 2 min. Finally, detailed views of the microstructure and panoramic surveys were obtained by micrograph montage using polarized optical microscopy (POM).

Microhardness measurements were carried out along the FSWed section at the middle-height thickness. Measurements were spaced 2 mm apart. Each data point is the average of 7 individual measurements.

3. Results and discussion

Fig. 1a shows the typical s-e curves of FSWed blanks in AA5754 alloy. It clearly appears that, for a given strain level, the s value obtained by deforming samples subjected to friction stir welding followed by cold rolling is significantly higher than that provided by FSWed ones. Furthermore, the s-e curves show that the ductility of the FSWed-CRed samples is about half compared to that of FSWed samples indicating that the strain hardening caused by cold rolling leads to the decrease in the strain to failure of the AA5754. Fig. 1a also shows, as a reference, the flow behavior of the base material (BM). As expected, the BM exhibits the highest level of ductility; as far as the nominal stress is concerned, the BM is characterized by s values between those given by the FSWed and the FSWed-CRed blanks. Such behaviour is consistent with that observed in previous papers both on the same alloy, but with different thickness values, welding parameters, tool geometry and sizes [9], and on different aluminium and magnesium alloys [5, 10-13]. Fig. 1b summarises the values of the yield strength, ultimate tensile strength, strain at the onset of necking and strain hardening coefficient obtained in the different conditions investigated.



(a)

Properties	BM	FSWed	FSWed-CRed
YS [MPa]	164	101	168
UTS [MPa]	258.8	224.5	243.6
e_u	0.166	0.119	0.057
n	0.199	0.272	0.136

(b)

Fig. 1. (a) Typical nominal stress vs. nominal strain curves and (b) mechanical properties of base material and welded samples in AA5754 alloy before and after cold rolling passes.

The discrepancy between the nominal stress of the FSWed-CRed samples and that of the FSWed one decreases with increasing strain (Fig. 1a). Such behavior can be attributed to the different strain hardening coefficients obtained on the welded samples before and after cold rolling, as shown in Fig 1b. As a matter of fact, owing to the strain hardening imposed by cold rolling to the welded blanks, the n value of the FSWed-CRed samples is lower than that of FSWed ones and, consequently, leads to a slower increase in stress with strain.

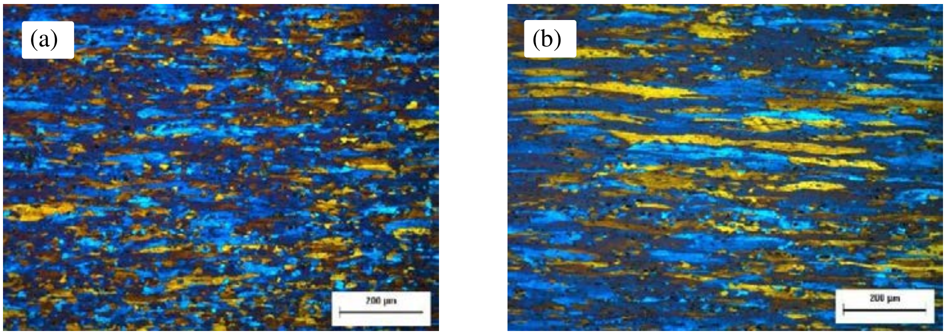


Fig. 2. Microstructure of the parent material (a) before and (b) after cold rolling of AA5754 alloy.

Such evidence is confirmed by the microhardness test results reported in Table 1. It can be seen that, in the stirred zone, the hardening effect produced by cold rolling causes an increase in HV_{200} equal to about 10%. A similar increase was also observed in the parent material after cold rolling due to the change in microstructure as shown in Fig. 2; it clearly appears that the parent material microstructure is composed of elongated grains oriented towards the rolling direction.

Fig.s 3 and 4 report the overviews of the FSWed and FSWed-CRed sheets, respectively. It is apparent that the grain size of the stirred zone is lower than those of the thermo-mechanically affected zone and parent material. This was observed in both conditions; moreover, larger magnifications revealed that the nugget was characterized by fine equiaxed grains in the FSWed sample (Fig. 3c) and slightly deformed grains in the FSWed-CRed one (Fig. 4c), whereas the thermo-mechanically affected zone has apparently larger and elongated grains (Fig.s 3b and 4b).

Fig. 5 shows the effect of cold rolling on formability of the friction stir welded blanks. Contrarily to the behavior experienced by ductility (Fig. 1), the limiting dome height of the FSWed-CRed blanks is very similar to that of the FSWed blanks. It means that the strain hardening effect on formability is much less pronounced than the one on ductility. Such behaviour can be attributed to the stress state occurring during the hemispherical punch test that is much closer to the balanced biaxial tension than to uniaxial tension and, therefore, necking is less severe. Furthermore, by considering that formability decreases with the sheet thickness and that the FSWed-CRed blanks are thinner of about 10% than those FSWed, the influence of cold rolling on LDH of FSWed sheets is negligible. Finally, it is noteworthy that the LDH value of parent material is only 4.5% higher than that of the FSWed blank and 10.4% higher than the one of the FSWed-CRed blank.

Table 1. Microhardness (HV_{200}) of friction stir welded AA5754 alloy before and after cold rolling.

Region	**FSWed**	**FSWed – Cred**
Stirred zone	81±2	90±1
Parent material	73±2	80±1

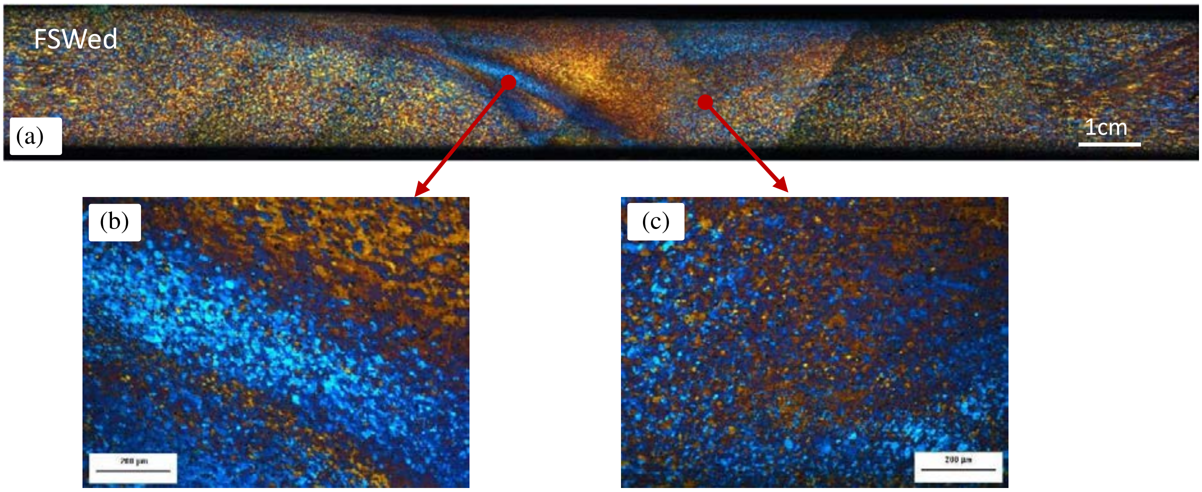


Fig. 3. (a) Panoramic surveys with details of FSWed blanks in AA5754 alloy, (b) thermo-mechanically affected zone and (c) stirred zone.

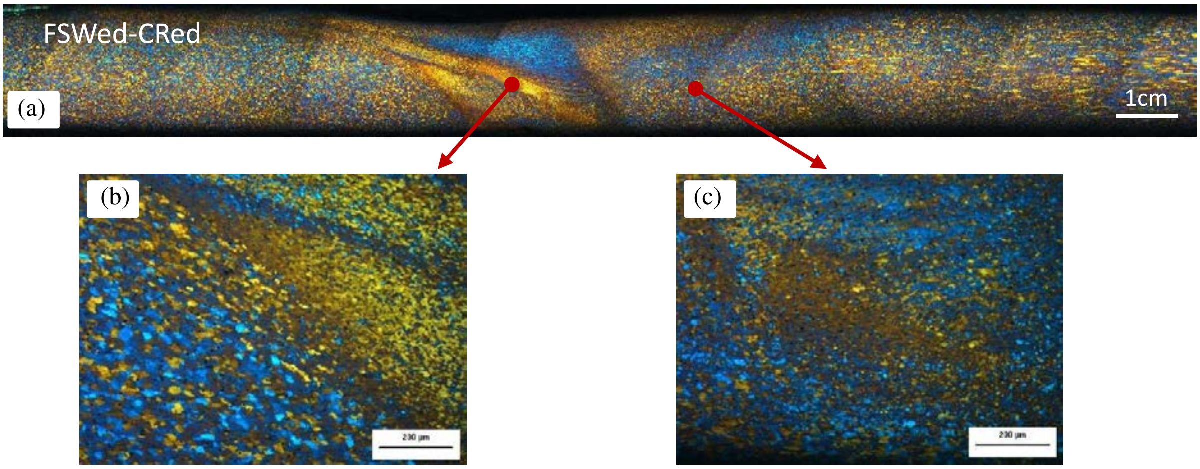
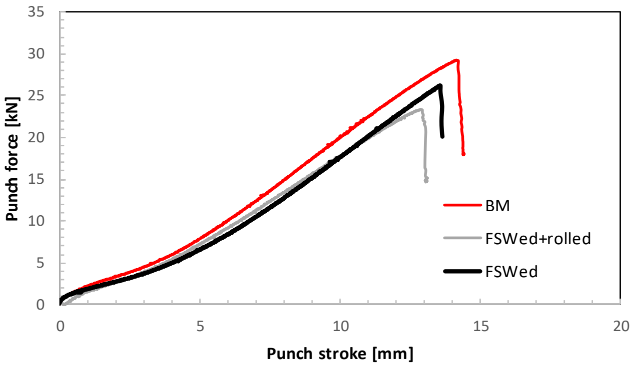


Fig. 4. (a) Panoramic surveys with details of FSWed-CRed blanks in AA5754 alloy, (b) thermo-mechanically affected zone and (c) stirred zone.

4. Conclusions

In the present work, the influence of cold rolling on the mechanical properties and formability of friction stir welded sheets in AA5754 aluminium alloy was investigated. To this purpose, FSW was carried out on 2.5 mm thick sheets, using a pin tool with constant values of rotation and welding speeds. Then, part of the FSWed blanks was cold rolled, with the rolling direction perpendicular to the welding line, until reaching the uniform sheet thickness of 2.2 mm. The main results obtained are summarized as follows:

- for a given strain, the stress level obtained by deforming samples subjected to friction stir welding followed by cold rolling is significantly higher than the one provided by FSWed samples;
- ductility of the FSWed-CRed samples is about half compared to that of the FSWed samples;



	LDH [mm]
FSWed+CRed	12.54
FSWed	13.57
BM	14.15

Fig. 5. Limiting dome heights of base material and FSWed joints, before and after cold rolling.

- the discrepancy between the nominal stress of the FSWed-CRed samples and that of the FSWed one decreases with increasing strain due to the different strain hardening coefficients obtained on the welded blanks before and after cold rolling;
- the grain size in the stirred zone is smaller than those of the thermo-mechanically affected zone and parent material;
- the stirred zone is characterized by fine equiaxed grains in the FSWed sample and slightly deformed grains in the FSWed-CRed;
- cold rolling does not significantly affect formability of FSWed blanks since the limiting dome height of the FSWed-CRed blanks is very similar to that of the friction stir welded ones.

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