Formability and Grained Structure Refinement of Cold-Rolled Friction Stir Welded AA5754 Sheet

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Abstract. Among different welding techniques currently available in the market, friction stir welding (FSW) is surely considered as an effective and reliable joining technique. Friction stir welds are characterized by lack of voids, cracks and distortions, as the technique does not involve any material fusion. The grained structure of the weld joint is generally finer than the base material. In particular, the nugget zone (NZ) experiences a dynamic recrystallization process during FSW that generally guarantees a stable very-fine grained structure. In the present study, the effect of cold rolling (CR) on the formability limits, the resulted microstructure, and mechanical response of FSW but joint was investigated. To this purpose, an AA5754 aluminium alloy was used. The FSW was performed with rotational and welding speeds equal to 1200 rpm and 100 mm/min, respectively, and an initial tool sinking of 0.1 mm. Strips extracted from the FSWed sheets were CR, with the rolling direction perpendicular to the welding line. Two setups were used in the CR experiments. One, conventional to determine the formability limit of the FSW AA5754 sheet; a second one performed in a CR setup designed to induce an equivalent strain $\varepsilon \approx 1$, in a single passage through the CR gage. This was aimed to make the post-FSW CR able to induce a further grained structure reduction within the NZ.

Keywords: FSW; CR; AA5754; Formability; SPD.

1. Introduction

Compared to other welding techniques, friction stir welding (FSW) has different mechanical and microstructure advantages. The key aspect refers to the welding temperature that is always within the alloy melting point. Hence, all the issues related with solidification from melting, of which the most important are porosity, possible cooling embrittlement, and formation of coarse secondary phase particles are avoided. On the other hand, the formation of residual stresses is usually minimized in FSW joints, were is typically lower than those observed in other welding techniques where alloy or filler melts are used [1]. Setting of proper welding parameters in the FSW process is mandatory to meet quality, soundness, and mechanical and microstructure properties of the joints.

FSW is particularly attractive when lightweight alloys need to be weld, such as Al and Mg alloys, since these are known to be difficult to weld, or are even un weldable through conventional fusion technologies. Typical applications include aerospace, automotive and most of the transportation industries [2, 3].

FSW sheet process is activated by the concurrent action of a rotating pin tool in contact with the sheet top surface, and by the transverse movement of the pin along the welding. The pin is usually inclined to the sheet surface with a set tilt angle. The combined effect of the plunging, the rotation, and the translation of the welding tool generates friction heating between the tool and the sheet width
corresponding to the shoulder area. This pin motion induces the material plastic deformation by stirring, and promotes a complex mixing across and along the joint path. Thus, a plasticized region is created around the tool and beneath the shoulder of the pin, by stirring and shearing action, from a pin retreating side (RS), to a pin advancing side (AS) [2-6]. In addition, during FSW, the material flows around the tool while it is subjected to intense plastic deformation process and local temperature rise. Both the mechanical plastic deformation and the thermal excursion promote the formation of a fine-grained structure in the center of the welded joint, at the so-called nugget zone (NZ). The occurrence of a fine-grained structure in NZ significantly affects the mechanical properties of the welded alloy. It is well agreed that the formation of fine grains within the NZ is a dynamic recrystallization (DRX) phenomena. The NZ DRX is likely to occur continuously by the shearing of the existing grains and subgrains, or by grain formation under the pin action, which eventually are thermally induced to evolve into a high-angle boundary network, that is, into a fine-grained structure [7-9].

A key microstructure FSW issue when used to butt joints is the sheet thickness reduction that is likely to be induced as result of tool and shoulder forging-like effect [1,2,5]. In order to limit, or minimize the welded sheet thickness reduction along the weld joint (namely the NZ), the FSWed joint sheet can be cold rolled (CR). In this case, other than a more uniform sheet thickness throughout the weld joint profile, CR generates a strain hardening coefficient rise that can possibly induce material strengthening and formability improvement [10].

Thus, the present work focuses on the effect of CR on the mechanical properties and formability of friction stir welded sheets in AA5754 aluminium alloy. Strips of the FSWed sheet were CR, with the rolling direction perpendicular to the welding line, to reach a uniform sheet thickness. Formability of the CR FSWed joints was evaluated.

Based on the observed good mechanical and formability response of the FSW and CR AA5754, a second CR set-up was design and used to obtain a very fine grained structure within the NZ, by a single passage into the CR gage. To this purpose, the CR set-up was designed and set to induce an equivalent strain of \( \varepsilon \approx 1 \). In this case a thickness reduction of 10% was induced, and a thickness uniformity was still maintained throughout the FSW + CR joint, from the RS to the AS.

2. Material and Experimental Procedures

2.1. Friction Stir Welding Process

AA5754 sheets were 185 mm long, 80 mm wide, and 2.5 mm thick, for the formability limit studies, and 200 mm long, 60 mm width, 1.5 mm thick, for the NZ grain refinement process obtained by post-FSW CR. The AA5754 alloy had a chemical composition (wt.%) of 3.4Mg, 0.40Mn, 0.20Si, 0.20Fe, 0.10Cr, 0.15(Ti+Zn), and Al bal.. FSW was carried out using a truncated conical-shaped pin with a base of 7.8 mm in diameter, a height of 1.3 mm, and a shoulder diameter of 15 mm. Pin consisted of a tool steel (H = 50HRC). During FSW, the tool was initially forced 0.1 mm down into the aluminum sheet. Welding parameters were set to rotational speed, \( \omega \), and welding translational speed, \( v \), of 1200 rpm and 100 mm/min, respectively. These settings were chosen according to the weldability window of the AA5754 alloy that was determined in two previously published works by some of the present authors [11,12]. The welding line followed a path perpendicular to the alloy sheet rolling direction (RD).

2.2. Post-FSW Cold Rolling

Strips of the FSWed sheets were cut perpendicularly to the welding line, with dimensions suitable for the following CR process.

For the first study of formability, two different rolling passes were used, obtaining a final uniform thickness of the FSW-CR strip of 2.2 mm, that is, a total thickness reduction of \( \approx 10\% \) (mode 1).

For the second study on the grain size reduction potentials at the NZ of the AA5754 sheet, by post-FSW CR, a specifically designed CR set-up able to induce an equivalent strain \( \varepsilon \approx 1 \) in a single passage through the CR gage was carried out (mode 2). This CR set-up is schematically reported in Fig. 1. In this case, after FSW + CR, the sheet thickness reduction on the welding NZ was of \( \approx 20\% \). To study the role of the severe plastic deformation induced by the single passage into the specifically misaligned CR
gage (see Fig.1), the FSW strips were also annealed before CR. The annealing treatment consisted in a 415°C/3h soaking followed by a slow cooling inside the shut-down furnace. This way, the role of post-FSW CR on the MnAl₆ dispersoids formation and on the occurrence of Mg₂Al₃ particle precipitation in the AA5754 Al-Mg-Mn alloy was detected.

Figure 1. Cold Rolling set-up scheme designed to induce an equivalent strain of ε ~ 1 under a single sample passage through the gage.

2.3. Microstructural and Micromechanical Analyses

Metallographic inspections by optical microscopy (OM) were carried out on surfaces mechanically polished and electrochemically etched by a 4% HBF₄ solution at 15V for few tens of seconds. Polarized OM (POM) was used to properly highlight the grained structures.

TEM inspections were carried out by a Philips® CM20 operated at 200 keV. TEM discs were prepared by polishing, dimpling, and ion-milling using a Gatan® PIPS. Microhardness was carried out along middle-height thickness of the FSW section. A Remet® HX-1000 tester was used. Measurements were spaced 250 μm apart.

Tensile tests were carried out on rectangular samples extracted from the base-material (BM), across the weld joint of the FSW, and the FSW + CR. Tensile tests were carried out by a conventional MTS machine equipped with extensimeter, and reported data results from 3 different tensile tests per experimental condition (i.e., BM, FSW and FSW + CR).

3. Results and Discussion

3.1. Post-FSW CR Mechanical Response

Table 1 reports the yield, ultimate strengths, and the maximum elongation obtained in the BM, FSW, and FSW + CR condition, where CR was carried out using the mode 1 (see above).

It resulted that the FSW yield strength is reduced by ~40%, compared to the base metal value. On the other hand, the FSW + CR had yield strength values quite similar to the base metals. This means that the yield strength is fully recovered to the base metal level when the FSW AA5754 sheet is CRed. Yet, the ductility response of the FSW + CR condition (5.5%) reduced 3-fold compared to the BM value of 16.5%, and halved, respect to the FSW value of 12%. The yield strength, σₚ, response corresponds, to some extent, to the ultimate strength, σᵤ, among the three different experimental conditions, i.e. between the FSW and FSW + CR.

Table 1. Yield strength, σₚ, ultimate strength, σᵤ, and maximum elongation, εᵢ, of BM, FSW, and FSW + CR.

|          | BM    | FSW   | FSW + CR |
|----------|-------|-------|----------|
| σₚ, MPa  | 165 ± 5 | 100 ± 5 | 170 ± 5 |
| σᵤ, MPa  | 260 ± 5 | 225 ± 5 | 245 ± 5 |
| εᵢ, %    | 16.5 ± 0.5 | 12.0 ± 0.5 | 5.5 ± 0.3 |
The here reported mechanical responses are in good agreement with previous reported results on same alloy, but different welding parameters [12-15], and on different aluminium alloys [16-22].

The ductility-to ultimate strength relationship here observed, was properly addressed by applying formability tests to the BM, FSW, and FSW + CR conditions. As reported in Fig. 2, it appeared that the limiting dome height (LDH) of the FSW + CR is quite similar to that of the FSW joint. This, in turns, means that the strain hardening effect on the alloy formability (LDH) is much less pronounced than the one on ductility ($\varepsilon_U$). Thence, since formability decreases with the sheet thickness, knowing that the FSW + CR joint is thinner by 10% than the FSW sheet, the CR effect on the formability of FSW sheet can be considered as negligible. It is worth to highlight that the LDH obtained in the BM is only ~5% higher than that of the FSW joint, which in turns, is almost 5% higher than the one of the FSW + CR joint.

**Figure 2.** LDH of the BM, FSW, FSW + CR.

Given the good formability limit obtained by FSW at rotational speed, $\omega = 1200$ rpm, and welding translational speed, $v = 100$ mm/min, a specifically designed shifted roll position to impose a severe shear-like plastic deformation in one single passage through the CR gage was used. The welded sheet integrity, after this specific CR process, was maintained, as shown by the OM montage of Fig. 3, referred to the joint mid-section.

**Figure 3.** OM montage of the FSW + A + CR section, where the annealing (A) was performed at $415^\circ$C/3h, and the CR was performed in one single passage through the CR gage to impose an equivalent $\varepsilon \sim 1$. Weldment integrity is shown from RS HAZ, TMHAZ, the NZ, throughout the AS TMHAZ, HAZ.

The joint integrity is maintained throughout the section from the left-hand side, where the retreating side (RS) is located, to the right-hand side, where is located the advancing side (AS), where no cracking formation is observed.

### 3.2. Grain refinement potentials of FSW + CR

Fig. 4 shows representative POM taken along the NZ section of the FSW, FSW + CR, and FSW + A + CR. It is worth to note that the coarsening of the grained structure observed in the NZ of the FSW + A + CR, was fully reduced by the dynamic recrystallization (DRX) process favored by the following CR [16,17]. No grain size coarsening occurred in the FSW + A + CR, respect to the FSW + CR condition. The mean grain size, $d_g$, was measured by stereological methods (EN-112) in the FSW NZ, and it resulted that $d_g = 65 \pm 4$ $\mu$m, after FSW, $d_g = 4.2 \pm 0.4$ $\mu$m, after FSW + CR, and $d_g = 7.1 \pm 0.4$ $\mu$m, after FSW + A + CR. It was thus shown that the welding parameters here used to carry out the FSW, are suitable to obtain a sound weld joint also upon post-welding severe cold rolling, which greatly reduced the grained structure within the NZ by one-order of magnitude.
On the other hand, Fig. 4, also shows that no cracks were formed in the NZ, after CR. This means that the FSW + A + CR sequence is a sound process that is able to effectively refine the NZ grained structure with no excess of stresses and no cracking formation.

![Figure 4. POM NZ joint section of the FSW, a), FSW + CR, b), and FSW + A + CR, c).](image)

3.3. Role of annealing on the precipitation and intermetallic particles

Fig. 5 reports representative micrographs of FSW, FSW + CR, and FSW + A + CR, where the volume fraction of the different particles and intermetallic phase are shown.

![Figure 5. MnAl₆ dispersoids, Mg₂Al₃ particles, and (Fe, Mn)₃SiAl₁₂ intermetallic particles in the FSW, a), b), FSW + CR, c), d), and FSW + A + CR, e), f). All TEM micrographs refer to the FSW NZ.](image)

One of the major and most interesting aspect of the deformation sequence induced by FSW and following CR, is surely the Fe-rich intermetallic agglomeration process that was promoted by the combination of plastic deformation of, first, stirring (during FSW), and, after, rolling (during CR), type (Fig. 5b, d, f).
On the other hand, the clear effect of the annealing treatment, after FSW, was observed in the mean volume fraction variation of both the MnAl₆ dispersoids and the Mg₂Al₃ particles. The volume fraction of both particle types was higher when the AA5754 FSW sheet is annealing prior CR. As reported in the Table 2, the post-FSW annealing induced an almost 3-fold rise of the Mg₂Al₃ particles volume fraction, respect to the FSW + CR condition, as it passed from \( V_v(Mg_{2}Al_{3}) \approx 7 \, \% \), in FSW + CR, to 19 \( \% \), in FSW + A + CR. Correspondingly, also the MnAl₆ dispersoids increased in volume fraction from the FSW and FSW + CR, to FSW + A + CR, accounting for a 30-35% rise, i.e., \( V_v(MnAl_{6}) \approx 40 \) to \( \approx 55 \, \% \). These particle increments were essentially due to the combined effect of post-FSW annealing thermal energy, and the shear-type plastic deformation, during CR.

|          | \( V_v(MnAl_{6}) \), \( \% \) | \( V_v(Mg_{2}Al_{3}) \); \( \% \) | \( d_p(MnAl_{6}) \), nm | \( d_p(Mg_{2}Al_{3}) \), nm |
|----------|-------------------------------|-----------------------------------|-------------------------|-------------------------|
| FSW      | 40 \pm 10                     | 6 \pm 1                           | 80 \pm 5                | 150 \pm 5               |
| FSW + CR | 45 \pm 10                     | 7 \pm 1                           | 75 \pm 5                | 135 \pm 5               |
| FSW + A + CR | 55 \pm 10                 | 19 \pm 2                          | 70 \pm 5                | 160 \pm 5               |

Another interesting result, is that the mean size of the MnAl₆ dispersoids, and Mg₂Al₃ particles, \( d_p(MnAl_{6}) \) and \( d_p(Mg_{2}Al_{3}) \), seemed not dependent on both CR, and annealing prior-CR. In all the experimental conditions, the \((Fe,Mn)_3SiAl_{12}\) intermetallic particle mean size, \( d_p((Fe,Mn)_3SiAl_{12}) \) ranged \((250\pm50)-(700\pm30)-(900\pm100)\) nm³, the volume fraction \( V_v((Fe,Mn)_3SiAl_{12}) \) ranged \((130\pm30)\) %.

In order to correlate the here observed grain size reduction and particle evolution, both induced by the FSW, post-FSW annealing, and CR, microhardness profiles were measured along the FSW NZ sections, in the FSW, FSW + CR, and FSW + A + CR experimental conditions (Fig. 6).

As reported in Fig. 6, hardness profiles across the FSW joint show a certain degree of uniformity among the different characteristic FSW zones. Across the retreating thermo-mechanical heat-affected zone (R-TMHAZ), and the heat-affected zone (R-HTZ), the FSW-CR and FSW-A-CR showed a hardness profile that was generally lower than the advancing counterparts. The mean hardness in the FSW + CR NZ was the highest, while the two mean values of FSW and FSW + A + CR were quite similar. The higher mean harness in the FSW + CR NZ agrees with the lower mean grain side here obtained, compared to the other conditions.

**Figure 6.** Microhardness profiles across all the meaningful FSW zone, i.e., the parent material (PM), the retreating heat-affected zone (R-HAZ), the thermo-mechanical heat-affected zone (R-TMHAZ), the NZ, and the advancing counterpart, A-TMHAZ, A-HAZ. The hardness were recorded at the mid-height of the FSW section, in the FSW, FSW + CR, and FSW + A + CR experimental conditions. Some authors [13-15,19-22] also studied the role of the FSW parameters and that of the post-FSW thermal treatments on the hardness profiles across the FSW joint section. The here reported results are
in good agreement with similar results obtained in terms of FSW parameters and similar thermal treatments role on the hardness profile along the different meaningful FSW zones.

4. Conclusions
The post-FSW cold rolling (CR) role in terms of mechanical properties and sheet formability of an AA5754 aluminium alloy was investigated. In addition, the soundness of a grain-refined FSW-AA5754 sheet subjected to post-FSW severe deformation by cold-rolling (ε ~1) was tested. The obtained results can be summarized as follows:

- the stress level obtained by deforming FSW sheets followed by CR, is significantly higher than the one obtained in the FSW joint;
- the FSW NZ is characterized by fine equiaxed grains, while after FSW + CR they were slightly deformed and still reasonably fine;
- cold rolling did not significantly affect formability of FSW sheets, as the obtained LDH after FSW + CR was quite similar to that of the FSW;
- By CR at ε ~ 1 the FSW joint in a single passage through the rolling gage, the NZ grained structure reduced by one-order of magnitude, reaching few microns in mean size;
- the annealing treatments affected the hardness profile across the FSW joint, by significantly reduce the hardness, compared to the FSW + CR hardness. On the other hand, the hardness profiles of the FSW and FSW + A + CR had a similar trend;
- the role of annealing on the MnAl$_6$ dispersoids and Mg$_2$Al$_3$ particles was determined in terms of their mean size ($d_p$) and volume fraction ($V_f$). The mean particle sizes of these two types of particles were not affected by the post-FSW annealing. Yet, their volume fraction significantly increased by the combined effect of first, post-FSW annealing, and, after, shear-like deformation on CR at ε ~ 1.

The here obtained results seem to confirm the possibility to scale up a CR process specifically designed to FSW joint aluminum sheets for transportation applications.

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References
[1] Gibson BT, Lammlein DH, Prater TJ, Longhurst WR, Cox CD, Ballun MC, Dharmaraj KJ, Cook GE, Strauss AM 2014 Friction stir welding: process, automation and control, J. Manuf. Process. 16 pp 56–73.
[2] Mishra RS, Ma ZY 2005 Friction stir welding and processing, Mater. Sci. Eng. R: Reports 50 pp 1-78.
[3] Geiger M, Kleiner M, Eckstein R, Tiesler N, Engel U 2001 Microforming, CIRP Annals, Manuf. Technol. 50 pp 445-462.
[4] Rodrigues DM, Loureiro A, Leitao C, Leal RM, Chaparro BM, Vilaça P 2009 Influence of friction stir welding parameters on the microstructural and mechanical properties of AA 6016-T4 thin welds, Mater. Design 30 pp 1913-1921.
[5] Simoncini M, Forcellese A 2012 Effect of the welding parameters and tool configuration on micro- and macro-mechanical properties of similar and dissimilar FSWed joints in AA5754 and AZ31 thin sheets, Mater. Design 41 pp 50-60.
[6] Cabibbo M, Forcellese A, Simoncini M 2016 New approaches to the friction stir welding of aluminum alloys, in Mahadzir Ishak (Eds.), Joining Technologies, InTech pp. 7-26.
[7] Jata KV, Sankaran KK, Ruschau JJ 2000 Friction-stir welding effects on microstructure and fatigue of aluminum alloy 7050-T7451, Metall. Mater. Trans. A 31 pp 2181-2190.
[8] Su J-Q, Nelson TW, Mishra R, Mahoney M 2003 Microstructural investigation of friction stir welded 7050-T651 aluminium, Acta Mater. 51 pp 713-729.
[10] Gehring A, Saal H 2006 Mechanical properties of aluminium in structural sheeting, Thin-Walled Structures 44 pp 1231-1239.

[11] Bevilacqua M, Ciarpica FE, D'Orazio A, Forcellese A, Simoncini M 2017 Sustainability analysis of friction stir welding of AA5754 sheets, Procedia CIRP, 62 pp 529-534.

[12] Casalino G, El Mehtedi M, Forcellese A, Simoncini M 2018 Effect of Cold Rolling on the mechanical Properties and Formability of FSWed Sheets in AA5754-H114 Metals 8 pp 223-240.

[13] Cabibbo M, Forcellese A, Simoncini M, Peralisi M, Ciccarelli D 2016 Effect of welding motion and pre-/post-annealing of friction stir welded AA5754 joints, Mater. Design 93 pp 146-159.

[14] Moshwan R, Yusof F, Hassan MA, Rahmat SM 2015 Effect of tool rotational speed on force generation, microstructure and mechanical properties of friction stir welded Al–Mg–Cr–Mn (AA 5052-O) alloy, Mater. Design 66 pp 118-128.

[15] Bisadi H, Tavakoli A, Sangsaraki MT, Sangsaraki KT 2013. The influences of rotational and welding speeds on microstructures and mechanical properties of friction stir welded Al5083 and commercially pure copper sheets lap joints, Mater. Design 43 pp 80-88.

[16] Fratini L, Buffa G 2005 CDRX modelling in friction stir welding of aluminium alloys, Int. J. Mach. Tools Manuf. 45 pp 1188-1194.

[17] Etter AL, Baudin T, Fredj N, Penelle R 2007 Recrystallization mechanisms in 5251 H14 and 5251O aluminum friction stir welds, Mater. Sci. Eng. A 445-446 pp 94-99.

[18] Sua J-Q, Nelson TW, Sterling CJ 2005 Microstructure evolution during FSW/FSP of high strength aluminum alloys, Mater. Sci. Eng. A 405 pp 277-286.

[19] Olea CAW, Roldo L, dos Santos JF, Strohaecker TR 2007 A sub-structural analysis of friction stir welded joints in an AA6056 Al-alloy in T4 and T6 temper conditions, Mater. Sci. Eng. A 454-455 pp 52-62.

[20] Khorrami MS, Kazeminezhad M, Kokabi AH 2012 Microstructure evolutions after friction stir welding of severely deformed aluminum sheets, Mater. Design 40 pp 364-372.

[21] Jayaraman M, Sivasubramanian R, Balasubramanian V 2010 Establishing relationship between the base metal properties and friction stir welding process parameters of cast aluminium alloys, mater. Design 31 pp 4567-4576.

[22] Zhang HJ, Liu HJ, Yu L 2011 Microstructure and mechanical properties as a function of rotation speed in underwater friction stir welded aluminum alloy joints, mater. Design 32 pp 4402-4407.