# FRICTION STIR WELDING OF ALUMINUM LIGHT-ALLOYS: NEW APPROACHES

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## Abstract:

**Friction stir welding (FSW) is the most widely used solid-state joining technique for lightweightplate and sheet products. This new joining technique is considered an energy-saving,environment friendly, and relatively versatile technology. FSW has been found to be a reliablejoining technique in high-demand technology fields, such as high-strength aerospace aluminum andtitanium alloys, and for other metallic alloys that are hard to weld by conventional fusion welding. A first new FSW configuration was defined as double-side friction stir welding (DS-FSW). In the DS-FSW, the welding is performed on both sheet surfaces, that is, the first welding is followed by a second one performed on the opposite sheet surface. In this present contribution focuses on two modified-FSW techniques and approaches applied to aluminum alloysplates.**

**Keywords: FSW, aluminum alloys, mechanical properties, microstructure, DS-FSW**

## Introduction:

FSW produces a high-quality joint, compared to other conventional fusion welding processes. It is also a welding process particularly suited for joining nonmetal materials to metals, especially in those cases where it is not possible by using conventional fusion methods [1-2]. Its key factors and main properties consist of the welding nature of the FSW metals. The weld zone undergoes a solid-state process promoted by the frictional heat between a rotating tool and the welding metal. The plasticized zone, induced in the material by the rotating tool, is further extruded from the leading side (advancing side, AS) to the trailing side (retreating side, RS) of the tool during its steady translation along the joint line. Neither filler material nor shielding gas is required. The temperature involved is typically some 50–100°C below the metal melting point, and thus there is no volume change during joining. Moreover, it is generally agreed that FSW, compared to the fusion welding techniques, induces rather low residual stresses after welding. This also implies process-reduced manufacturing costs [3-4]

In these works ([5-7] to cite but few) the reader can find allthe technological information concerning the major fields of application; typical components that arelikely to be joined by using FSW; and the most used and appropriate alloy systems.

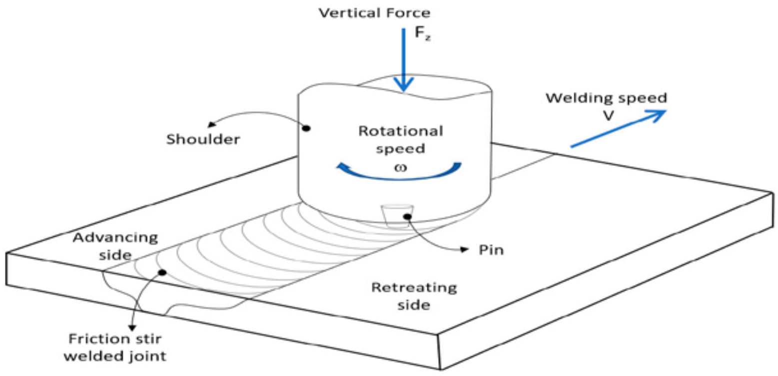


Figure 1: Scheme of FSW process.

One of the major advantages of using the FSW process is to overcome possible void formationpossibly caused during several other fusing techniques, such as arc welding, or other cleantechniques. From a technological viewpoint, FSW requires a shoulder which is protruded with a pin,also called the probe. The shoulder arrangement creates the frictional heating, and a pin probe ischiefly responsible for the generation of the material stirring throughout the joint interface volume
[8].

A new FSW approach is here presented. This was developed to promote a better joint formability and it consists of carrying out the FSW process on both the sheet surfaces. In this process, the first welding operation is followed by a second welding performed at the plate opposite surface. Such an innovative methodology has been defined by these authors as double-side friction stir welding (DS-FSW) [9]. This new FSW methodology has proven to be able to seal the geometric discontinuities, possibly produced by the first welding process, by means of the second welding operation performed at the opposite surface at the same experimental conditions. In addition, this new approach allows more uniform hardness values across the NZ. Moreover, the recrystallized grain size across the NZ is more homogeneous with respect to the surrounding FSW zones, compared to the conventional FSW, as shown by Cabibbo et al. [10]. Such improvement in the joint quality is very attractive, especially in those cases where the joint materials are meant to be subjected to post-welding forming operations. The hardness and local Young's modulus, determined by nanoindentation, were used to probe the overall weld joint strength. Nanoindentation profiles are also used to correlate the sub-micrometer hardness values to the corresponding FSW microstructure, and finally to properly correlate the welded plate formability with the welded sheet microstructure and micromechanical response.

As for the resulting plate microstructure modification at the welding zone and along the adjacentzones, three different metallurgical zones are usually recognized to which peculiar grained structure,secondary phase precipitation sequences and mechanical properties correspond.

These are (Figure 2):Nugget zone (NZ): This is where the metal is in direct contact with the pin being continuouslystirred during the passage of the rotating pin.b. Thermomechanically affected zone (TMAZ): Where the microstructure is highly plasticallydeformed. c. Heat affected zone (HAZ): Where the material undergoes thermal cycles with no plasticdeformation. [11]

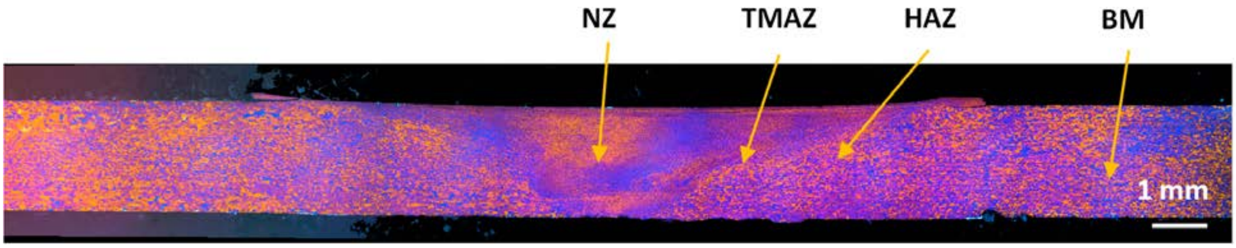
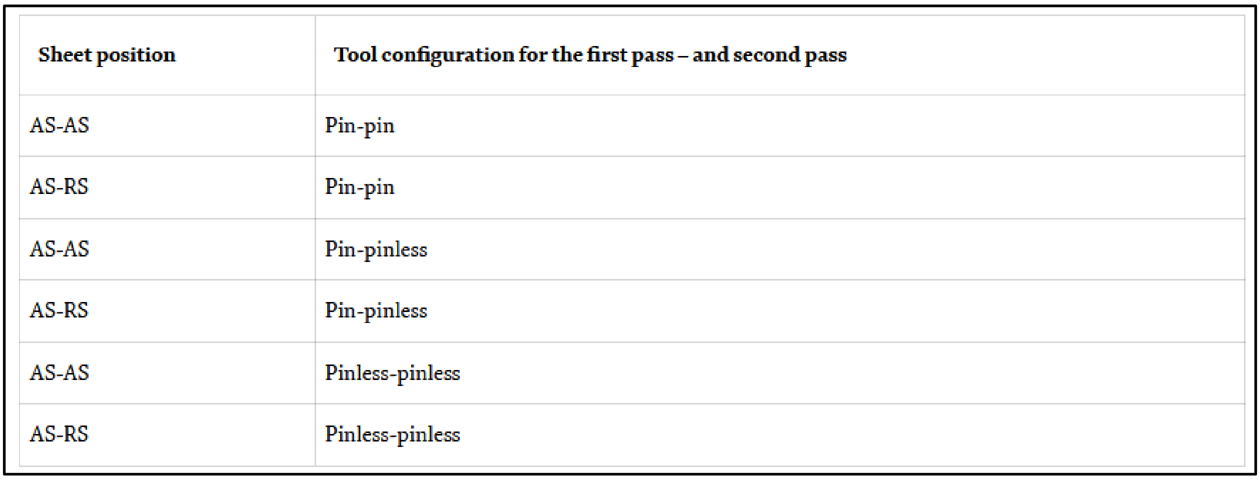


**Figure 2.** Typical optical microscopy macrograph showing various microstructural zones in a FSWjoint in AA6082-T6 aluminum alloy (blanks thickness = 2 mm, truncated cone pin tool with shoulderdiameter = 12 mm, ω = 1200 rpm and v = 100 mm/min).

## DS-FSW method

As for the DS-FSW method, a conical pin tool geometry (H13 steel of HRC = 52), with a shoulder diameter equal to 12 mm and cone base diameter and height of the pin of 3.5 and 1.7 mm, respectively, with a pin angle of 30°. A 19-mm-diameter rotating tool was used. All the welding experiments were carried out with a nutting angle equal to 2°. [12]

In Table 1 are reported the different tool configurations and sheet positions used in the DS-FSW. The used blanks were 180 mm in length, 85 mm in width, and 2 mm in thickness. The FSW was performed by fixing the welding line perpendicular to the rolling direction.



| **Sheet position** | **Tool configuration for the first pass – and second pass** |
|---|---|
| AS-AS | Pin-pin |
| AS-RS | Pin-pin |
| AS-AS | Pin-pinless |
| AS-RS | Pin-pinless |
| AS-AS | Pinless-pinless |
| AS-RS | Pinless-pinless |

DS-FSW configurations (in terms of tool used and sheet arrangement).

The third and fourth configuration differs from the first two only in the absence of the pin during the second welding process. In the last two (AS-AS, and AS-RS pinless-pinless), the welding process was performed with no pin in both processes. Figure 3 shows a schematic representation of the three DS-FSW configurations used here. [13]

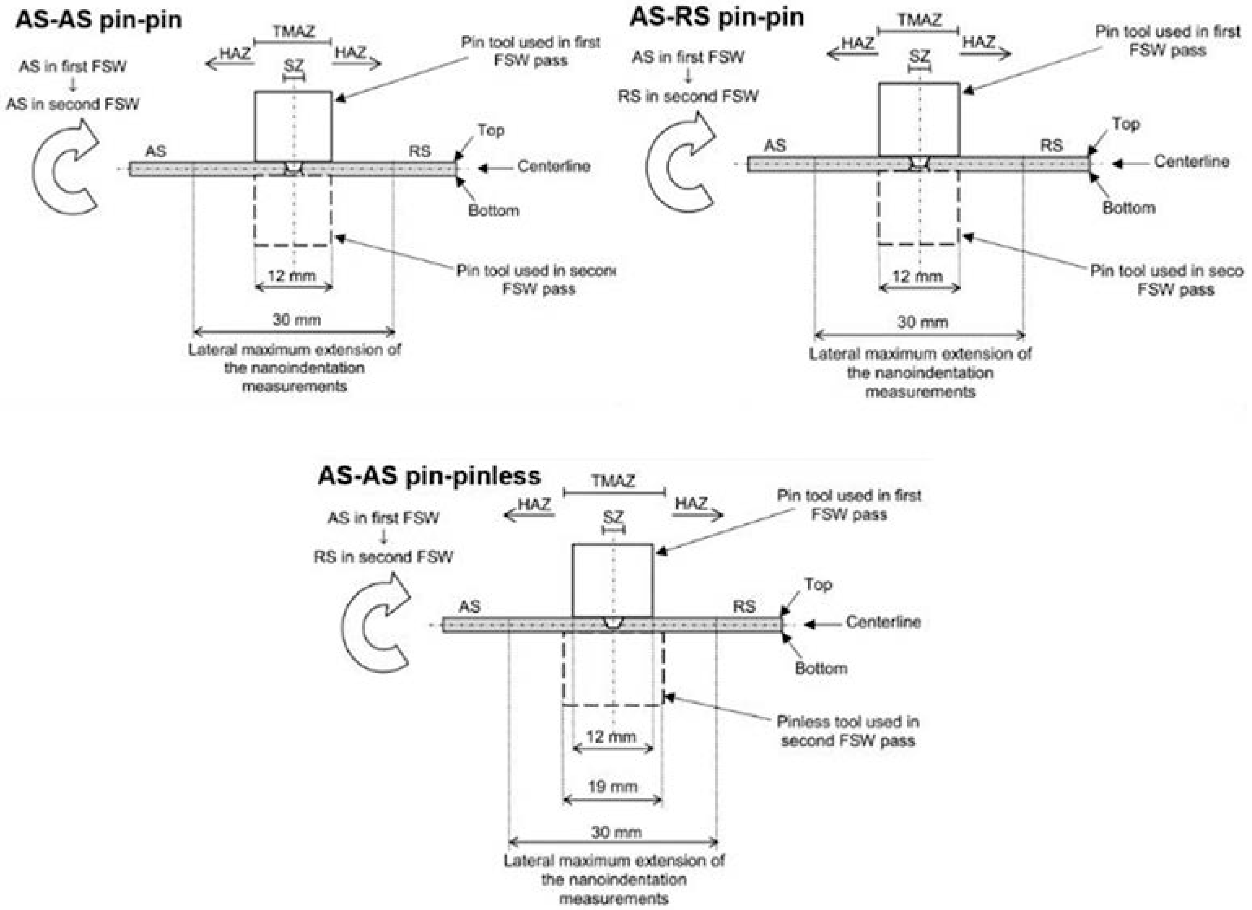


Figure 3: Representation of the three DS-FSW configurations: AS-AS pin-pin (left side); AS-RS pin-pin (center); AS-AS pin-pinless (right side).

In order to evaluate the advantages offered by the new welding methodology, the experimentalresults obtained using the DS-FSW were compared with those given by the conventional FSW, carried out, under the same process conditions, both in the pin and pinless tool configurations. [14]

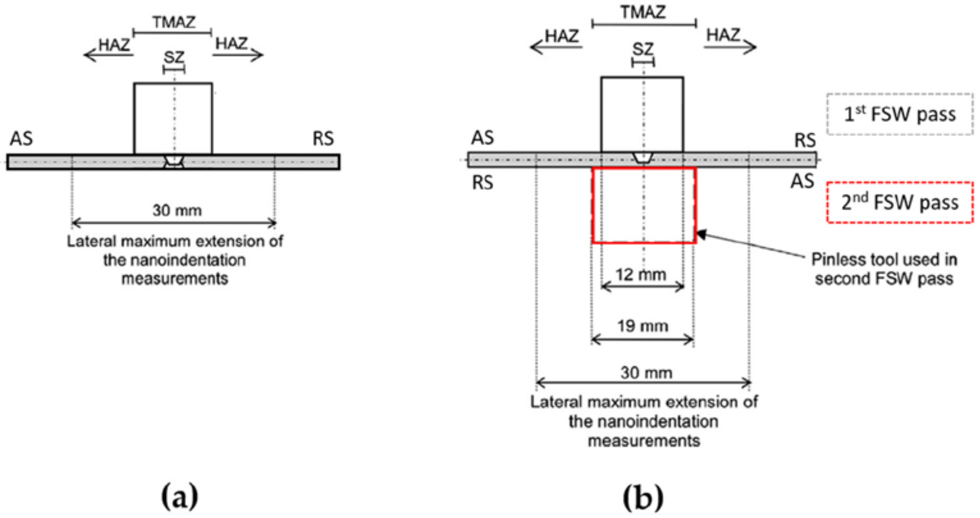


**Figure 4:** Comparison between (**a**) conventional FSW and (**b**) DS-FSW processes.

## Research Methodology:

In both the cases, aluminum alloys were tested. In the first methodology, a heat-treatable AA6000-series alloy (AA6082) was used; whereas in the second methodology, a nonheat-treatable AA5000-series alloy (AA5754) was welded.

## Result and Discussion:

Table 2 reports the limiting dome height values of the welded joints, both for the conventionalFSW and DS-FSW processes. Irrespective of the welding methodology used, LDH values of joints are lower than those measured for the base material, due to the presence of the welding line that leads to a reduction in formability [60,61,74–78]. By focusing on the DS-FSW, it can be observed that the joints are characterized by LDH values higher than those measured on conventional FSW joints, leading to a reduction of LDH, as compared to the base metal, of 10.9%; compare that to 27.7% between the conventional joint FSW and the BM [15].

**Table 2.** Limiting dome height (LDH) values obtained by hemispherical punch tests on base materialand joints obtained by conventional FSW and DS-FSW methodologies.

| Plate Condition | LDH (mm) | Reduction in LDH with Respect BM (%) |
|---|---|---|
| BM | 11.9 | - |
| FSW | 8.6 | 27.73 |
| DS-FSW | 10.6 | 10.92 |

The improvement given by DS-FSW can be attributed to the positive effect of the second passthat allows both the closure of the geometric discontinuity and the decrease in the height of the stepgenerated by the first welding pass. Such results can be attributed to the different microstructuresobtained by the two welding methodologies [16].

Microstructure of the joints at the different pin rotation radii

Figure 5 shows an overview of the FSW plate microstructure, in which the occurrence of a grain dynamic recrystallization process in the NZ is evident. [17]

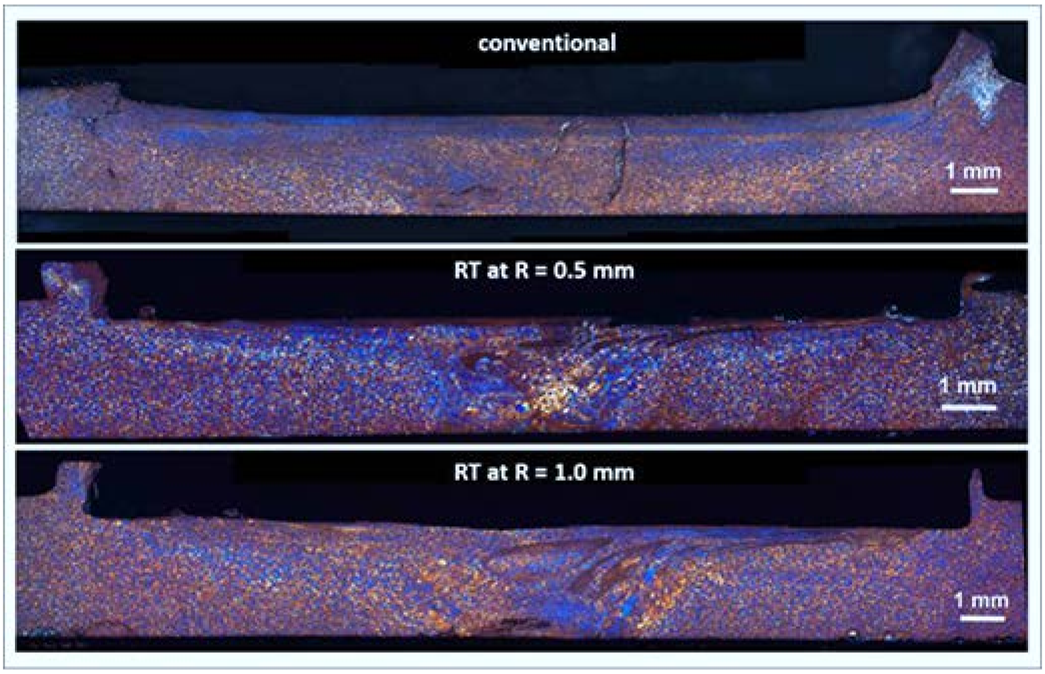
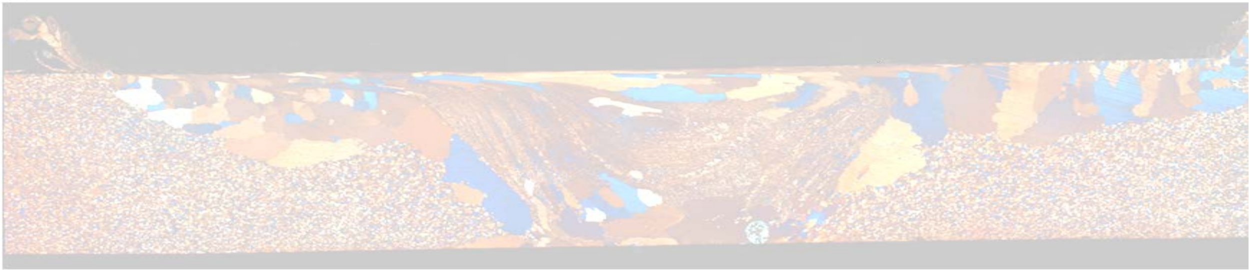


Figure 5 Montage of polarized optical micrographs (POM) RT-FSW at R = 0 (conventional FSW), 0.5, and 1 mm.On the basis of the microstructure and nanoindentation results herein reported, the soundnessand improved mechanical and technological properties of the DS-FSW joints are inferred by the farmore uniform hardness, *H*, and reduced Young’s modulus, *Er*, values across the FSW joint.

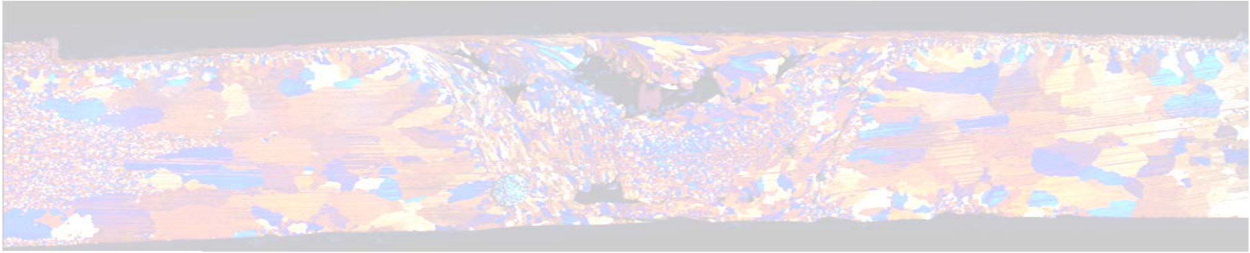
As for the microstructural modification induced by the pin deviation from centreline in the nonagehardening AA5754, the R = 0mm equiaxed grains characterize the whole extension of the FSWsheet. Under that experimental condition, the mean grain size throughout the welded zone (HAZ,TMAZ of the AS and RS) was essentially same as was observed at the BM. On the other hand, at R = 0.5 mm, fine equiaxed recrystallized grains were induced to form throughout the HAZ, and TMAZ,in both the AS and the RS. Anyhow, in this case, the NZ was characterized by a diffuse presence ofvery coarse irregular grains; i.e., mixed fine recrystallized grains and coarser abnormal grain growth.

The very coarse grains were flattened and pinched off in the central region of the top surface of theFSW section. This flattened grain region coincided with the shoulder diameter, also considering theentire pin deviation excursion of 2R = 1mm. In the surrounding zones, coarse grains appeared due tothe effect of the PWA (Figure 6). [18]

(a)



(b)



(c)

**Figure 6.** Montage of POM images of joints in AA5754 alloy obtained by performing FSW and postweldingannealing treatment (PWA at 415 °C/3 h, followed by furnace cooling). The effect of pindeviation from welding line on microstructure of joints: (**a**) R = 0 mm, (**b**) R = 0.5 mm and (**c**) R = 1mm.

## Conclusion:

In this study two different evolutions of FSW were introduced and discussed. These were foundto improve, significantly, the mechanical responses of the welded sheets compared to conventionalFSW techniques. One FSW improvement consisted in the practice of a double side welding, and thiswas successfully applied to an age-hardenable AA6082 alloy.The first approach consists of a double-side FSW (DS-FSW). The second approach is represented by a radial deviation of the rotating pin from its centerline, during FSW (RT-FSW). Both new methods were tested in a conventional pin and nonconventional pinless configuration. Several interesting achievements, from a technological point of view, were obtained and are here summarized.

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