J. Adv. Manuf. Eng. 1(1) (2020) 9-15

JOURNAL OF ADVANCES IN
MANUFACTURING ENGINEERING

Experimental, Mechanical Characterizations of Friction Welding of Steel and Aluminium Joints

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Abstract

Rotary friction welding (RFW) is a solid-state joining process which works by rotating one workpiece relative to another while under a compressive axial force, which produces coalescence of materials workpieces. It is considered most viable alternative to overcome the difficulties faced in conventional joining techniques. As it is a solid state welding process, the process does not form molten pool thereby eliminating the solidification errors. It offers many advantages for some manufacturing sectors for a wide range of applications. In this research, we investigated the mechanical and metallurgical characteristics of RFW welded joints for homogenous and heterogeneous assemblies. We have studied A60 steels and 2017A series aluminum alloys. The obtained welds are similar in appearance in that they have several Microstructural distinct zones. So, the results show that by increasing the rotating speed employing 1000 and 1600 rpm, the mechanical properties during the RFW process is lightly improved, favored by the increase in heat flow. In the same specimen, the micro hardness distribution is generally viewed lightly changed between center line throw weld of welded tube and close to their boundary line. This is due to the no-uniform of temperature distribution in cross section. Thus, plastic deformation of heated portion of the metal plays an important role in friction welding process and their quality. Microstructural analysis reveals that grain growth in the joint WCZ and in heat affected zone HAZ because of the no-uniform of thermal flux distribution in both directions (transvers and longitudinal of tube). Finally using RFW, the fabricators allow to perform and maintenance the mechanical components with low cost and which it conserves their welding quality compared to the classical fusion welding.

Keywords: *Rotary Friction Welding (RFW), Plasticized Material, Heat Flux, Characterization, Microhardness*

1. Introduction

Rotational Friction Welding (RFW) is known as a solid-state joining process [1-2] that involves rotating one workpiece relative to another one under an axial force, which coalesces the workpiece materials and plastically displace material from the faying surfaces. It is considered the most viable alternative to overcome the difficulties encountered in conventional assembly techniques. Since this is a solid situation welding process; the process does not form a melted pool, thus eliminating solidification defects. In this process kinetic energy is converted into heat energy to obtain large amount of localised intense heat generation and high deformation there by producing high quality weld and unusually high efficiency coefficient [1, 3]. So we have less energy consumption and highly strong weld, compared to other welding processes.

RFW process offers many advantages for the same manufacturing sectors for a wide range of applications such as combinations of materials that can be welded, while they are not with traditional welding techniques. The obtained welds generally have a similar appearance in that they have several distinct microstructural zones: a weld center zone (WCZ) or nugget zone; a thermo-mechanically affected zone (TMAZ) and a heat affected zone (HAZ) [3-5].

RFW can join two different materials having different mechanical and thermal properties. Examples: aluminum-steel or titanium-copper assembly... This possibility can save the economies by having a judicious design of such parts. An example is the design of a combustion engine valve. The head of refractory material is welded to the rod of wear-resistant material and so.

In this work, we studied the mechanical and metallurgical characteristics of RFW welded joints for homogeneous and heterogeneous assemblies. We studied A60 steels and 2017A series aluminum alloys. In characterization steps we have used some specific apparatus and instruments. We used tensile tests and Micro-hardness measurements to obtain mechanical properties, as well as microscopic observations for metallographic analyzes. Comparisons of these features for some welds are made at the end.

2. Experimental Procedure

A drill press (BX-833V) was used for rotary friction welding, as shown in Figure 1, of our different samples. Two rotating speeds ω are employed 1000 and 1600 rpm.

The infrared thermometer IR-730 is used which allow us to measure the temperature that reigns on rotating workpiece during process. The infrared thermometer is specifically designed for industrial maintenance, automotive, quality control and fire prevention applications etc. Its temperature range is from -32 °C to 1250 °C.

The AFG dynamometer (Advanced Force Gauge), see figure 1, is the most complete and versatile force measuring instrument currently available on the market, it can be used independently or fixed on a manual or motorized test bench for greater flexibility, the AFG dynamometer is able to recognize torque data with this system. The AFG then becomes a universal display whatever the application.

The Tachometer used combines the optical and mechanical measurement of the rotation speed. A connection to an adapter, a cone or a wheel makes it possible to switch to mechanical measurement mode. This allows measurement of speed as well as distance. Reflective strips (Optional) allow optical measurements to be made by attaching them to the object to be measured. All that remains is to place the light spot on the tape to make the measurement.

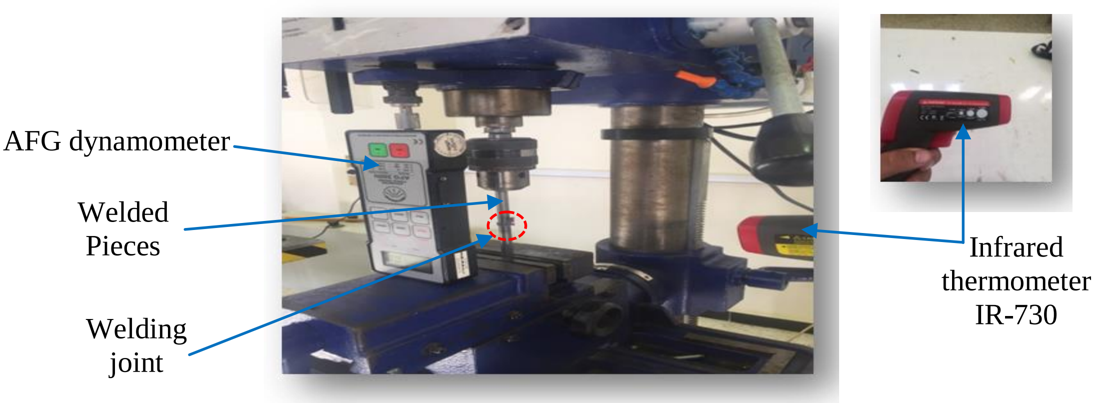


Figure 1. Experimental setup for welding on drill press and some instruments

We have studied the welding process RFW for rods with 10 mm in diameter of two materials, the aluminum alloy 2017A and the steel A60; their chemical compositions are presented in tables 1 and 3 respectively.

Table 1. Chemical composition of 2017A alloy in percent by weight [6].

Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr+ti
0.20-0.80	≤ 0.70	3.5-4.5	0.4-1.0	0.4-1.0	≤ 1.0	≤ 0.25	< 0.25

The conventional mechanical properties of aluminum alloys 2017A (Yield strength at 0.2% **$Rp_{0.2}$**, Breaking strength **Rm**, and Elongation at rupture **A**) currently used are given in Table 2.

Table 2. Mechanical Properties of 2017A Alloy.

Ø (mm)	Rm (MPa)	$Rp_{0.2}$ (MPa)	A (% mini)
Ø ≤ 55	≥400	≥250	10

The steel used in our study is a non-alloy steel of common use (European designation : Fe590-2 + E335 or 1.0060, German designation: St 60-2, French designation: A60-2 or A60) of chemical composition represented in Table 3, the dimensions of the pieces are 150 mm in length and Ø10 mm in diameter.

Table 3. Chemical composition of A60 steel in percent by weight [7]

Elements	P	S	N	Fe
Mass percentage	0.055	0.055	0.014	Rest

The steel is for general use in general mechanics. It is untreated, it offers good mechanical resistance. General purpose of non-alloy structural steel. Chemical analysis is not defined by the standard and does not guarantee any heat treatment. Used in parts subjected to high surface pressures, worm gear, pinions, keys, shafts, rings ... etc.

Table 4. Mechanical Properties of A60 Steel.

Nuance	Re (N/mm²)	Rm (N/mm²)	A%	Hardness
A60	335	590-710	14	Hv=171-204

The cutting was carried out in the workshop "mechanical preparation" at the C.R.T.I. research center (in Algiers) using a cutting machine (Steel disc) with the cold continuous lubrication to avoid any heating that could change the properties and characteristics of the material. Tensile samples welded and no welded are immediately passed through the Traction machining (INSTRON); assisted by the bluehill3 software. According to the AFNOR standard which recommends round specimens whose shapes are illustrated in Figure 2a and Figure 2b. The tests were conducted and at ambient temperature.

Coating: The purpose of the coating is to be able to handle small irregularly shaped samples as well as to protect fragile materials with thin layers of coating to ensure sharp edges. There are two methods of coating: hot coating and that for A60 steel and cold coating for aluminum. For the hot coating, the means to use is a wrapper, plus the resin, a hardener and apply a temperature of 180 °C for a period of 20min for steel. For the cold coating, it was made using a hardener plus a resin to avoid any reaction with the substrate.

Polishing: The surface condition obtained after the cuts in the chainsaw, although smooth to the touch, is clearly insufficient for a microscopic observation. The image obtained on these raw samples is too fuzzy to be exploitable, hence the need for sanding. The latter is carried out with the aid of a variable speed manual polishing machine from 0 to 500 tr/min using abrasive papers of varied granulometry from N° 80 to N° 4000 for a good finish (Mirror condition) with felt paper plus suspended alumina, (Figure 2c).

Chemical attack: Chemical etching for steel is by a solution containing a mixture of 100 ml of C_2H_5OH ethanol plus 1% HNO_3. The reaction is done quickly, however a special precaution must be taken to the appearance of small bubbles on the surface: It is necessary to homogenize the solution on the surface to avoid a burn at the places of their appearance and for the aluminum one uses an attack by a solution containing Keller's mixture: 95 mL H_2O, 2.5 mL HNO_3, 1.5 mL HCl and 1.0 mL HF. The objective is to see the effect of the welding parameters on the microstructure thanks to a metallographic study. Thus, we used an optical microscope of the brand *Nikon Eclipes LV 100 ND*, supplied with the software (Nikon) for its servocontrol on PC. The device having a magnification power of x2000, we were able to go down to 5.

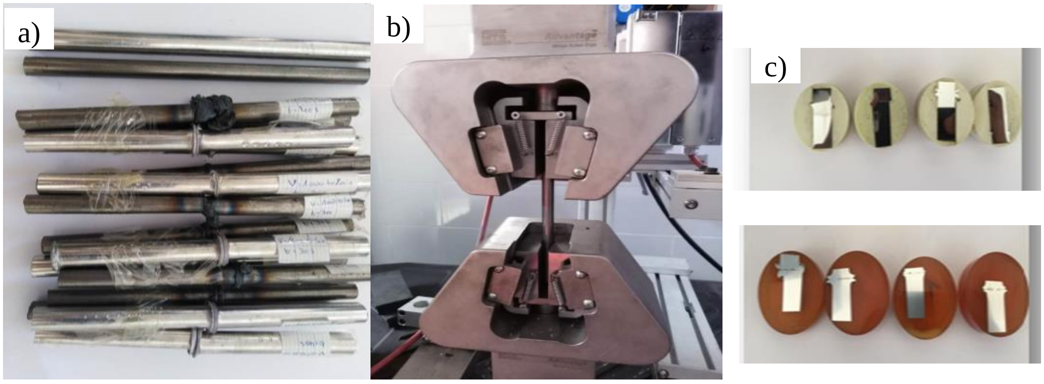


Figure 2 a,b,c. Some steps of preparations and characterizations

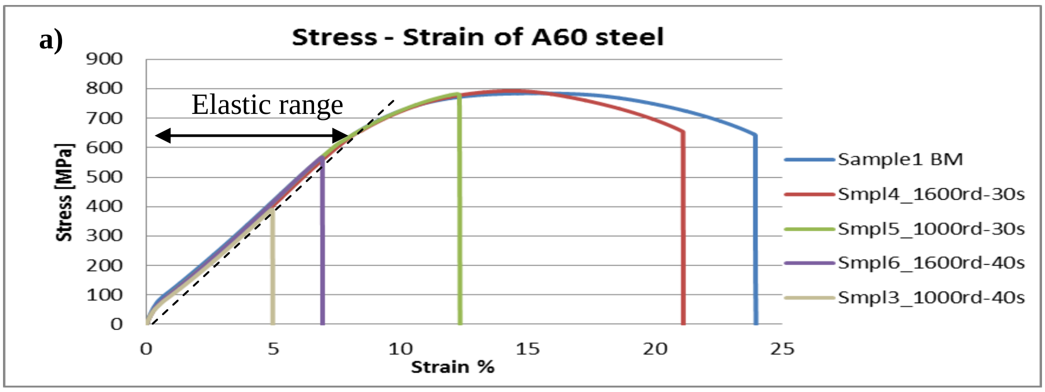
Vickers microhardness: After tensile tests for determining the mechanical properties of the weld seam, we opted also for the Vickers micro-hardness tests (WILSON 3300). We worked on 2 lines with parallel points (Measures were made at C.R.T.I-Algiers). The greatest number of measuring points is made on the weld zone of each sample, a regular step separating the points of each line from the center going towards the two HAZ respectively, so as to have symmetry with respect to the center of the welding. The HAZ is very small compared to the WZ, because it does not exceed 3 mm. Constrained by this factor, we cannot exceed the 3 measurement points for each of them. In order to get around this problem and have measurement points relative to the same place for each sample, we move away from the 0.3 mm joining line for each sample, then we resume the step to 0.5 mm, which allows us to be able to compare the different samples correctly. For the base metal (BM), we move away from the edge of the HAZ by 0.5 mm and proceed to the measurement of 3 points taking as not 1 mm. At the end of all the measurements, we calculate for each point of the curve an average between 3 parallel points. The used load is 300g.

3. Results and Discussions

3.1 Mechanical Analysis

For our work, we have performed tensile tests on rotary friction welded specimens to study the strength of the weld seams. These tests are carried out on several groups of specimens whose difference is characterized by the difference of the welding parameters (welding speed, welding time, etc.). Also, each group is composed of four test tubes (see Figures 2a and 2b).

The tensile tests show that the welds have a large stress range until 637.13 MPa (Elastic range) for A60 steel; and until 115.78 MPa for 2017A aluminum (Figure 3a and Figure 3b).



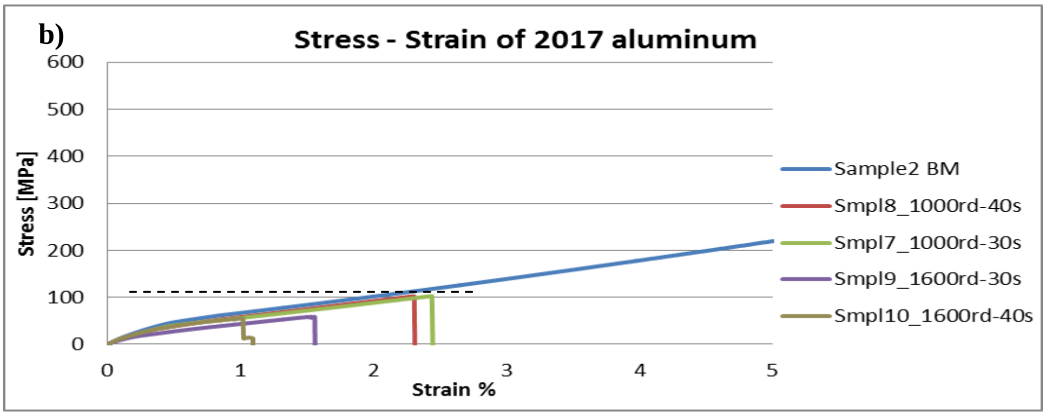


Figure 3. Tensile test curves of welded specimens and compared to the base metal BM of: a) Steel A60, b) Aluminum 2017A.

It is important to note that the break during the tensile tests for the majority of the tensile test pieces occurred outside the weld seam, which reflects the weld quality achieved, and the plastic domain starts from 570 MPa.

The tensile tests carried out on the Aluminum 2017A test pieces, have a good mechanical resistance and their mechanical characteristics (Re and Rm) are close to the characteristics given by the standard, thus the certificates of conformity.

Overall, it was found that the test pieces have the shortest welding time (t=30 s) have better traction curves, whatever it is metal. While the test pieces with higher rotation speeds (1600 rd/mn) have the best tensile limit for steel.

3.2 Metallographic and Hardness Characterizations

The chemical attacks used allowed us to highlight the microstructures of the different couples analyzed and related to Alu-Alu, steel-steel and Alu-steel welded materials. This examination allowed us to highlight that welding has no defects and we can distinguish between the structures in the welding zone [3]. And the difference of the layers is legible see the grain structure in the welding zone. The microhardness measurements clearly show this layer difference.

The optical micrograph of steel A60 (Figure 4) shows a ferritic-pearlitic classical microstructure with polyhedral grains of α-ferrite in white and perlite colony (α + Fe_3C iron carbide) in black, as shown in Figure 4a Base Metal.

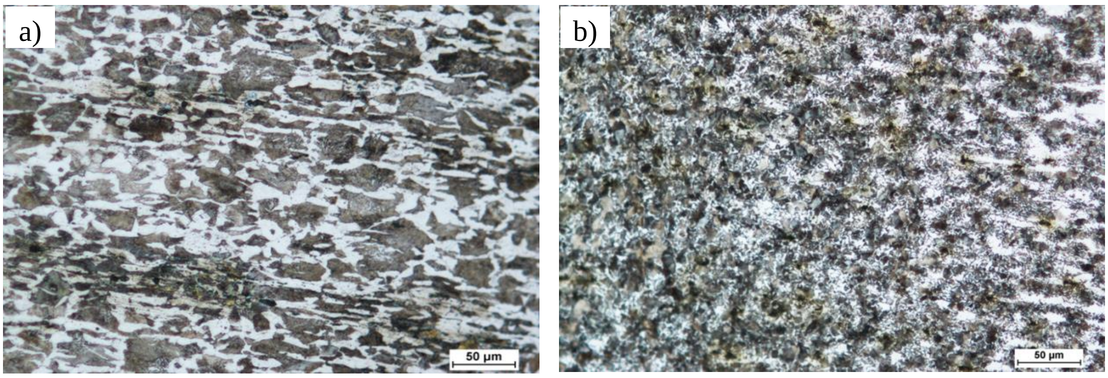


Figure 4. A60 steel optical micrograph of: a) The BM, b) the HAZ.

The microstructure of the base metal that underwent structural transformation (Heat-Affected Zone) (Figure 4b) shows a dominant Martensitic structure for the A60 metal with appearance of small grains in Bainite, due to the high carbon content of the latter.

The Heat affected zone (HAZ) experienced a rise in temperature. It is limited towards the center by the thermomechanically affected area (TMAZ). The thermal cycle undergone by the HAZ affects the size of the grains; there is a slight enlargement of the grain size in this zone. The temperature gradient obtained during assembly can also affect the hardness characteristics. There is a drop in hardness in this area (Figure 5). Regardless of the welding conditions, there is a decrease in the hardness in the HAZ that comes from the restoration. The slight increase in hardness in the core comes from refinement of the crystalline structure.

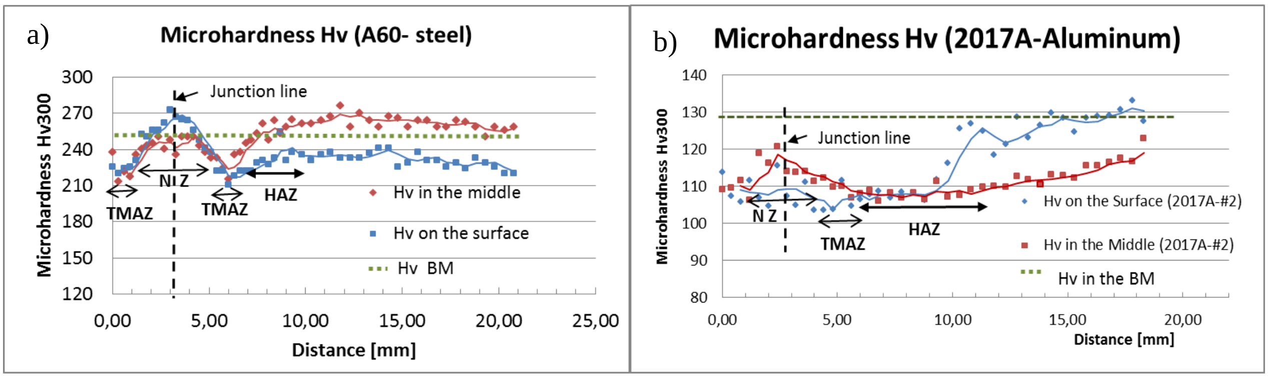


Figure 5. Microhardness evolution of: a) A60 steel, b) 2017A Aluminum.

The thermomechanically affected area (TMAZ) is around the core (Weld Zone WZ) and it is bounded by the boundary of the thermally affected zone. It undergoes large deformations which cause a change of orientation of the grains with respect to the initial direction of the deformation. A difference in grain orientation in this area can be distinguished in relation to the flow of material. The core undergoes a large deformation and a very high temperature gradient which brings it back to a viscous semi-solid situation. In this zone, the material is subjected to an intense gradient of deformation. The grains of the base metal are totally crushed by the process and undergo dynamic recrystallization [4, 9]. Microscopic observations in this area reveal fine, equiaxed grains (Figure 6).

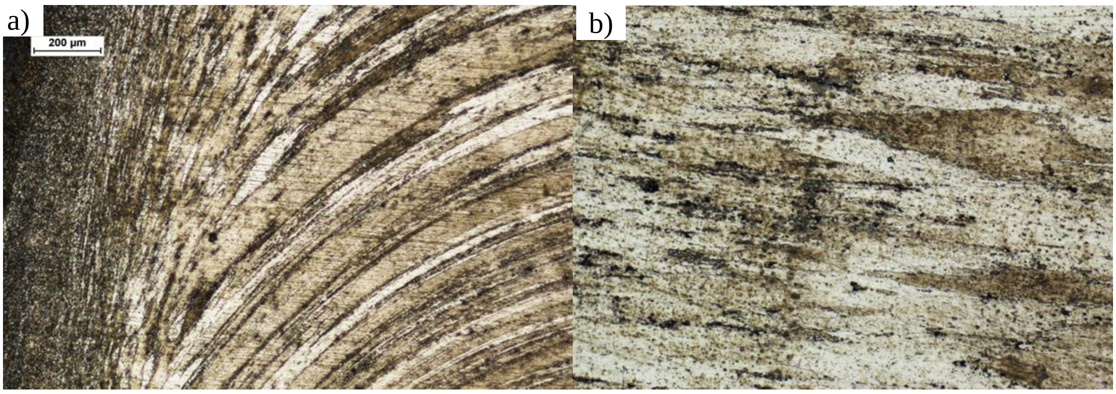


Figure 6. 2017A Alloy optical micrograph of: a) The Weld Zone and TMAZ, b) The BM.

The chemical composition of an alloy and its metallurgical situation obtained by heat treatment and/or cold deformation gives it its mechanical properties. The shape of the grains observed is independent of the nature of the alloy, but depends mainly on the shaping and whether or not there has been annealing. This metallurgical state is altered by the rise in the temperature in the welded zone. In the case of the aluminum alloy, this results in a local decrease in the properties of the base metal in the welded zone (thermally affected zone, the HAZ), (Figure 6a).

In this case too, the hardness is more or less high in the zone of the core and in the base material characterized by the presence of precipitates responsible for the hardening.

4. Conclusion

The results of the parametric study, although they enabled us to identify the influence of certain operating parameters as increasing welding speed in a defined weldability domain, but show also the difficulty of identifying the impact of each parameter on the mechanical characteristics of the cords. This difficulty can be explained by the coupling of the physical phenomena resulting from these operating parameters. Microscopic observations of the bead have identified the different areas of the FSW weld joint. They have led to the identification of the boundaries between these different areas through the change of microstructure and grain orientation. At the end of the uniaxial tensile tests, the friction welded joints showed acceptable mechanical properties of our welds.

Nomenclature

RFW	Rotational Friction Welding
BM	Base Metal
WCZ	Weld center area
TMAZ	Thermo-mechanically affected zone
HAZ	Heat affected zone
Hv	Microhardness (Vickers)
t	Time, sec
T	Temperature, ^{o}C
F	Welding Force, *N*
ω	Rotation speed, rpm

References

[1] Shete, N., & Deokar, S.U. (2017). A Review Paper on Rotary Friction Welding, International Conference on Ideas, Impact and Innovation in Mechanical Engineering *(ICIIIME 2017)*, 5(6), 1557 – 1560.

[2] Imani, Y., Guillot, M., & Tremblay, A. (2014). Optimization of FSW tool design and operating parameters for buttwelding of AA6061-T6 at right angle. Proceedings of the Canadian Society for Mechanical Engineering International Congress.

[3] Liu, H. J., Fujii, H., & Nogi, K. (2004). Microstructure and mechanical properties of friction stir welded joints of AC4A cast aluminium alloy. Materials Science and Technology, 20(3), 399-402.

[4] Genevois, C. (2004). Genèse des microstructures lors du soudage par friction malaxage d’alliages d’aluminium de la série 2000 et 5000 et comportement mécanique résultant. PhD thesis, INPG.

[5] Aissani, M., Gachi, S., Boubenider, F., & Benkedda, Y. (2010). Design and Optimization of Friction Stir Welding Tool. Materials and Manufacturing Processes, 25(11), 1199-1205.

[6] Barralis, J., & Maeder, G. (2005). Les précis AFNOR/Nathan. Métallurgie, élaboration, structures-propriétés, normalisation, collection. (ISBN 978-2-09-179582-9).

[7] Hantcherli, M. (2010). Influence d’éléments d’addition sur les transformations de la martensite revenue dans les aciers faiblement alliés. Thèse Doctorat de l’École Nationale Supérieure des Mines de Saint-Étienne. France.

[8] Adel, M. (2008). Effet des additifs sur la microstructure et les propriétés mécaniques des alliages d'aluminium-silicium. Thèse de doctorat, Université du Québec à Chicoutimi.

[9] Philibert, J., Vignes, A., Bréchet, Y., & Combrade, P. (2013). Métallurgie. Du minerai au matériau, Technique et ingénierie / Mécanique et matériaux. Paris, Dunod, coll. 2ndéd.