Microstructural evaluation of solid state welds obtained by means of flat rolling process

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In extrusion operations based on the use of porthole dies, for the fabrication of tubes and hollow profiles in general, material solid state welding takes place thanks to the very high pressure and temperature at which the material undergoes. Nevertheless, the most important aspect in this process still remains the quality of the welds, also because the testing of extruded tubes is still today an un-regulated matter. A technique based on the flat rolling process is applied in this paper, in combination with micrographic and macrographic analyses, to assess the quality of solid-state welds obtained using different process conditions. Flat rolling experimental tests executed on sandwiches made of two rectangular specimens in AA6060 and AA6082 aluminium alloys were performed. The specimens were characterized by different heights in order to consider different compression ratios that mean different interface pressure and effective stress distributions. All the tests were repeated at different temperature. By verifying if, the material bonding took place or not, it was possible to identify the welding limits conditions in terms of pressure and temperature. Particular attention was paid to the study of both the macrostructure and microstructure of the rolled specimens in order to identify the influence of the process parameters on both the material weldability and the metallurgical weld quality.

Keywords: Extrusion - Flat rolling - Solid state bonding - Aluminum alloys - Metallurgical analysis.

INTRODUCTION

The interest for aluminum extruded profiles is increasing in many industrial fields and the market requests for extruded profiles have radically changed since more and more complex hollow profiles are required by the market. The extrusion of hollow profiles starting from a solid billet is generally based on the use of porthole dies, which are usually obtained assembling two parts: the die cap, which gives the external shape of the extruded part, and the mandrel, whose task is to define the inner profile. In this processes, the material is pushed inside the die, forced to go around the ribs, split into different flows and finally re-welded in the welding chamber, just before to pass through the extrusion hole located in the die cap, where it is deformed to the final profile shape [1-3]. During the process, the material is subjected to high temperature and high hydrostatic pressure at the same time [4, 5].

Many studies have been carried out on extrusion, focusing on the improvement of die durability, the final extruded part quality and the conditions under which the material welds in porthole dies. Saboori et al. [6] conducted important studies on the energy consumption in forward and backward extrusion. Other authors [6-9] studied different aspects concerning friction, temperature and pressure estimation in the different regions of the extrusion dies with experimental, numerical, and analytical approaches. Other important researches were made on the design and optimization of die geometries and products, with analytical, experimental [10] and finite element approaches [11-13].

Nevertheless, the most important aspect in porthole die extrusion processes still remains the quality of the welds. In effect, in the extrusion welding chamber, the material welds only if it is subjected to favorable conditions in terms of pressure at the flows interface, temperature of

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the material and contact duration [14, 15]. This means that a full understanding of material bonding phenomena is strongly desired and also the process parameters affecting the joints quality should be correctly defined and set. The achievement of these suitable conditions is strictly associated to welding chamber geometry, material speed, extrusion ratio and material characteristics. If the pressure applied to the material, the temperature or the time for which the material remains in the welding chamber are too low, the material does not weld or in other cases, the weld quality is poor.
The testing of extrusion tubes is still today an un-regulated matter: tube expansion by means of conical dies is the most frequent industrial quality control procedure also for automotive and railway applications, but such method can be applied only to round shape profiles. In the last years, many researches focused on the analysis of seam welds behavior and several welding criteria were developed and proposed. All these criteria are based on the identification of parameters variously defined that represent the material status. According to all these criteria, the welding phenomena take place when the welding parameter exceeds a limit value.
Amongst the different criteria, one of the most widely used is the one proposed by Piwnik and Plata [16]. Donati et al. [17] also made important studies on this topic, defining a new welding criterion that takes into account not only the interface pressure, but also the relative velocities of the material flows.
Basing on the criteria described above, since it is very difficult to apply testing methods to a reconfigurable extrusion die, some researchers developed and used characterization testing strategies different from the direct test on extruded hollow profiles obtained through the use of port hole dies. For example, some authors [1, 18-20] proposed simplified experimental procedures to analyze the different kinds of welding that can occur in porthole-die extrusion (even though some possible effect of surface oxidation could occur). These different approaches are due to the difficulties that generally occur when tests are executed on the extrusion of original hollow profiles, in which the control and the variation of both the process and the geometrical parameters is often difficult. In other words, the process and the geometrical variation of the parameters in an industrial port hole die extrusion process is a difficult task and the only one possibility is to change the geometry of the die together with their extrusion/welding chambers. Moreover, the common extrusion plants are usually not suitable for the execution of tests controlling chamber temperature and pressure. In particular, some Authors have proposed a new procedure, for the welding limit identification, based on flat rolling experimental tests [21]. In this paper, this procedure was applied on sandwiches made by coupling two rectangular specimens having different thickness and thermal condition, so resulting in different interface pressure and stress distributions.

EXPERIMENTAL CAMPAIGN

Flat rolling tests

Since solid state welding takes place when the material reaches very high pressures and temperatures, an experimental procedure easy to be executed and at the same time able to reproduce this situation with high repeatability can be based on the flat rolling of two sheets coupled together. Based on this assumption, an experimental campaign was set up to execute rolling tests on sandwiches made of two rectangular specimens in different condition of temperature and rolling ratio. Figure 1 shows a scheme of the experimental procedure. Two different aluminum alloys, AA6060 and AA 6082 were taken into account; Table 1 shows the chemical composition of the tested alloys. It is important to remark that all the tested specimens for each alloy came from the same rod and then it is reasonable to assume differences in chemical composition within the limits defined by the standards.

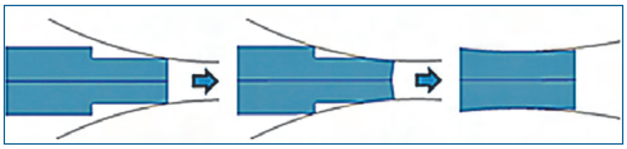


Fig. 1 - Scheme of the experimental procedure.

Type	Element	%Weight	Type	Element	% Weight
AA6082	Si	1.2	AA6060	Si	0.549
	Fe	0.33		Fe	0.176
	Cu	0.08		Cu	0.040
	Mn	0.50		Mn	0.064
	Mg	0.78		Mg	0.405
	Zn	0.05		Zn	0.022
	Ti	0.15		Ti	0.022
	Cr	0.14		Cr	0.007
	Al	Balance		Al	Balance

Table 1 - Chemical composition of the tested specimens in weight % (AA6082 and AA6060).

The specimens had length and width respectively equal to 100 mm and 50 mm. The final thickness of the rolled samples was equal to 10 mm in all cases, while the initial thickness of the specimens was varied to obtain different rolling ratios, as reported in Table 2. A feeding zone 12 mm thick and 20 mm long was machined at the tip of each specimen, independently from its thickness, to ensure an effective dragging in the rolling mill. Moreover, two rivets were placed in that zone to ensure no relative movements between the two strips at the beginning of the rolling. Based on this approach, different interface pressure and consequently different effective stress distributions were reproduced. All the tests were repeated at different temperature in order to investigate the effect of this parameter.

Initial Thickness [mm]	Rolling ratio [%]	Temperatures [°C]
12	17	300, 330, 360, 390, 410, 430, 450, 470, 490, 510, 530
13	23	
14	29	
15	33	
16	38	
18	44	
20	50	

Table 2 - Experimental plan.

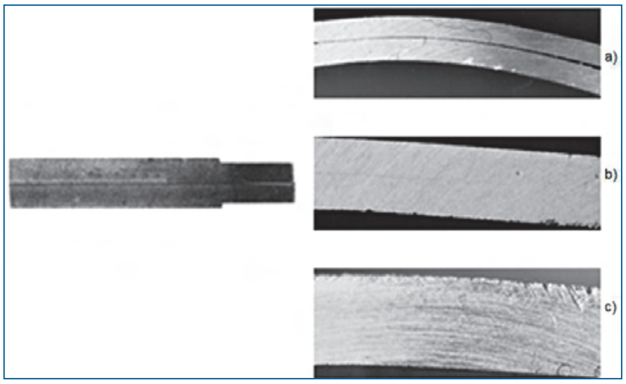


Fig. 2 - Example of a sheet sandwich before rolling (left) and sections of three specimens (right) representing not welded (a), incompletely welded (b) and properly welded (c) samples.

The set up procedure is described in the following steps.

- The coupled specimens were heated into a furnace at a fixed temperature, while the actual rolling temperature of the parts was measured by means of a contact thermocouple. It is important to remark that the inner surfaces of the sandwiches were accurately polished and cleaned just before the coupling.
- The rolling of the sheets sandwiches was carried out for different initial temperatures and rolling ratios, in order to reproduce different pressure and effective stress conditions. All the experimental tests were carried out with the same rolling speed: angular speed equal to 1.05 rad/s, that with a roll radius equal to 95 mm corresponds to a rolling velocity equal to 100 mm/s.
- To evaluate the bonding occurrence, rolled specimens were longitudinally cut and the bonding area was subjected to polishing and to an initial visual inspection with the aim to verify if the material bonding between the sheets took place or not.

As an example of the results, figure 2 shows the sections of three specimens, representing not welded (a), incompletely welded (b) and properly welded (c) conditions.

Macroscopic and microscopic characterization of the bonding surface

Particular attention was paid to the study of the metallurgical structure of the welded material in order to identify the influence of the process parameters on the weld quality. This means that it was possible to identify not only if the weld took place, but also if it was qualitatively adequate. The evaluation of the process parameters effects on the weld quality was performed at both macro and micro scale level.

The welding line quality was investigated by means of a macrographic analysis after having etched the specimens with an alkaline solution (sodium hydroxide at a temperature equal to 70°C) and using polarized light.

A microstructure analysis was performed on the specimens of both alloys for a better assessment of the weld quality. In particular, it was meant to investigate both the trend of non-homogeneous part in the laminate and in the interaction between weld surface and microstructure. Microstructure investigation was performed by means of an optical microscope with polarized light after electrochemical etching; this method assured to highlight the welding line and the grain structure/shape at the same time. Etching was performed, after polishing, with Barker reagent at 20V for a time ranging between 90 and 120 seconds, depending on alloy and specimen size. The base material was also analyzed for a comparison aim.

ANALYSIS OF THE RESULTS

Macroscopic analysis of the joining surface

After having etched the specimens with an alkaline solution, the quality of the weld can be directly related to its visibility: the more visible is the weld, the lower the quality. As an example, figure 3 reports a comparison between two weld lines obtained using a rolling ratio equal to 23% and material temperature respectively equal to 425°C and 488°C. While the specimen rolled at the higher temperature shows a good slim weld, the one obtained at lower temperature shows a much thicker weld line. Even though this last condition can still be considered as a welded condition, it was defined as a borderline result. The visibility of the weld is related to the rolling temperature, with a stronger metal bonding as the temperature raises. For all specimens, at each rolling ratio, the increase in temperature influences not only the occurrence of the weld, but also its quality.

In order to ensure a correct evaluation of the welds, specimens were sectioned longitudinally along the center axis, polished and analyzed with and without etching by means of a microscope. As results of a first inspection, welds were classified into three different quality levels: not welded, minimal weld (borderline condition) and welded. Figure 4 shows the experimental results as a function of temperature and rolling ratio for the two investigated alloys. The results were graphically distinguished between welded and not welded and a limit curve can be drawn for both alloys. The strong role played by temperature in determining the weld quality is clearly evident. This aspect is particularly important especially if we consider that the rolling ratio is strongly related to geometrical and product

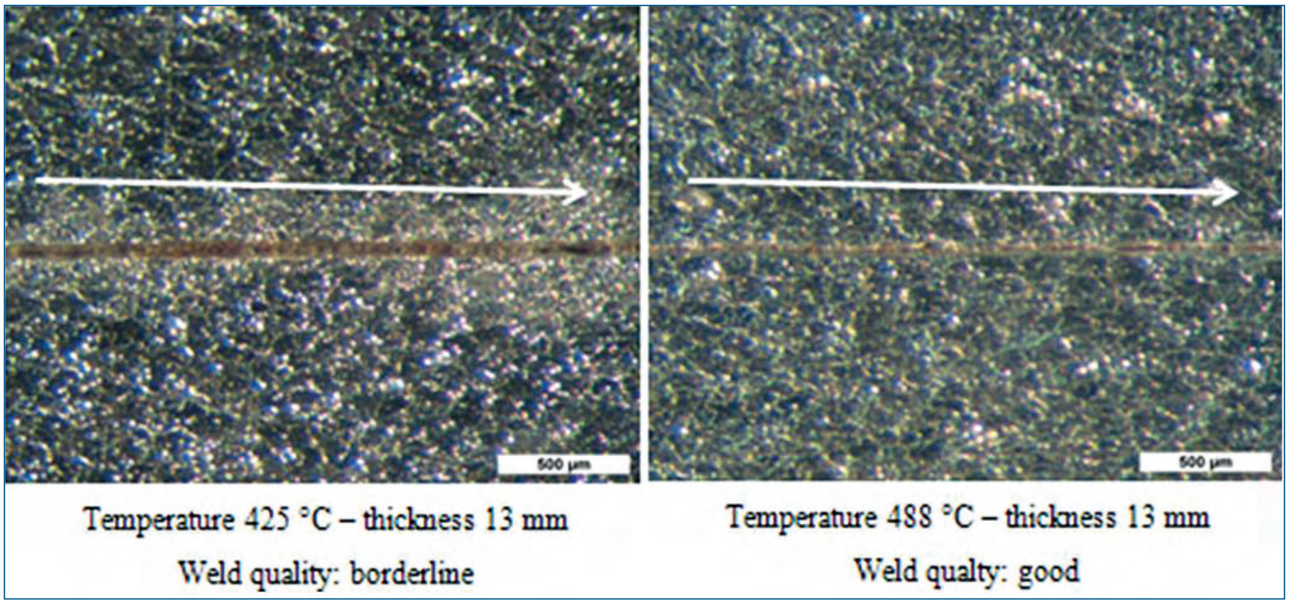


Fig. 3 - Comparison between joint lines obtained at different rolling temperatures.

design requirements and therefore it usually results difficult to be adjusted. An inverse rolling ratio - temperature correlation is observed for both alloys: at low rolling ratio (i.e. low contact pressure), it is possible to obtain good welds only if high material temperatures are reached. On the contrary, when high contact pressure are utilized, a good weld can be also ensured at low temperatures. In a comparison between the two alloys, the AA6060 alloy shows a higher weldability with respect to the AA6082 alloy; in other words, for a fixed contact pressure, good weld can be achieved at lower temperatures. A second-degree polynomial fitting was executed on the data in order to find a relation between rolling ratio and temperature for the borderline conditions. The results are reported in equation 1 and 2 for the AA6060 and AA6082 respectively.

$$RR_{(6060)} = 7 \cdot e^{-06} T^2 - 0.0064T + 1, \quad R^2 = 0.954 \qquad (1)$$

$$RR_{(6082)} = 7 \cdot e^{-06} T^2 - 0.007T + \quad R^2 = 0.996 \qquad (2)$$

where RR is the Rolling Ratio [%] and T is Temperature [C°]. A very good matching was achieved in both cases obtaining a regression index higher than 0.95.

Microscopic analysis of the joining surface

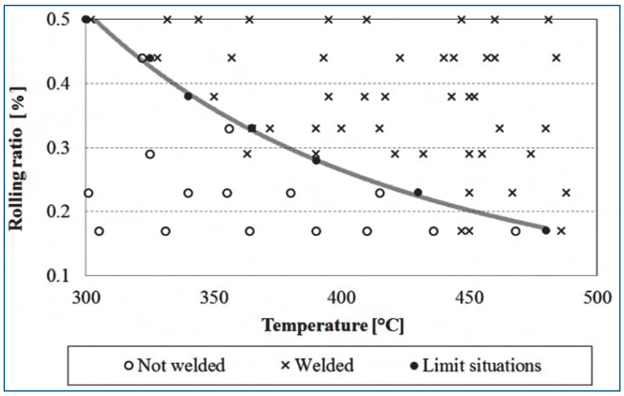
A microstructure analysis was performed on specimens of both alloys for a better understanding of the weld quality. The base material was also analyzed to have a standard reference in the microstructure evolution. Figure 5 shows the base material microstructure for both the considered alloys: in both cases, it appears to be homogeneous and isotropic.

Figure 6a shows the section of a specimen having a 13 mm initial thickness rolled at 425°C. The welding is visible, as a line across the entire section and the grain appears deformed accordingly to the rolling proper strain gradient, as clarified in figure 7. Grain shape changes from almost circular to elongated shape, moving from the surface to the welding region (that is the center axis): this reveals the rolling direction as well (left to right in the figure). Increasing the rolling ratio, figure 6b (thickness of 20 mm), induces higher deformation and therefore the grain distortion appears greater. In this case, also the grains close to the surface show a highly elongated shape.

The microstructure of three AA6082 specimens with borderline quality of the welds is reported in figure 8. It is possible to observe how the specimen number 1 (13 mm and 425°C, see the scheme of figure 8) shows a weld that distinctly divides the microstructure of the two strips: in both magnifications no grain incorporates the weld line, while on both of its sides grains appear severely deformed, small and with different orientation (as inferable to the different grain color). On the contrary, the specimen number 3 (13 mm and 460°C), that has the same rolling ratio and therefore deformation gradient, shows a weld line that is incorporated in the grains. In this case, the grains are formed by the joining of the two strips and the weld is no more a grain boundary line.

A similar behavior is visible in the specimen number 2 (12 mm and 450°C) where in both magnifications the welding line intersects a homogeneous microstructure, which is also characterized by a less severe grain distortion, due to the lower rolling ratio.

Figure 9 shows a comparison between microstructures resulting from tests executed using the same rolling ratio (12 mm) and different temperatures (410°C, 460°C, 481°C) for the AA6082 alloy. For all specimens the weld quality is high, because of the high rolling ratio, even though a a)



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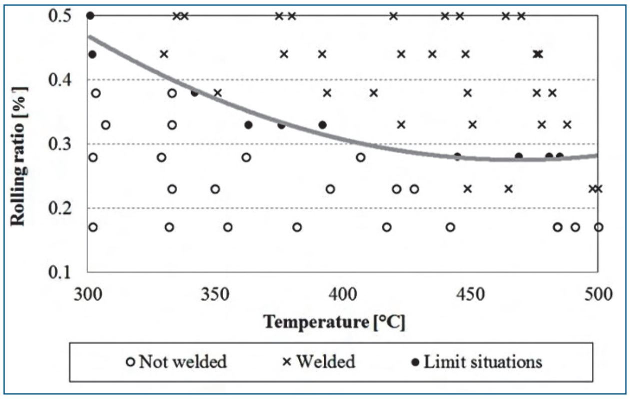
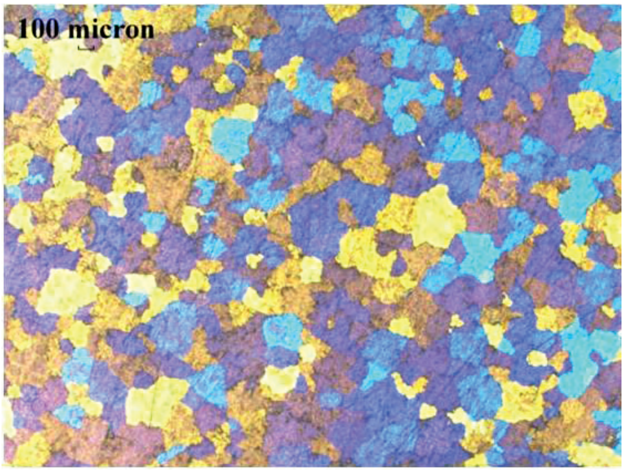


Fig. 4 - Experimental results in terms of weldability as a function of temperature and rolling ratio (i.e. contact pressure) for (a) AA6082 and (b) AA6060.

a)



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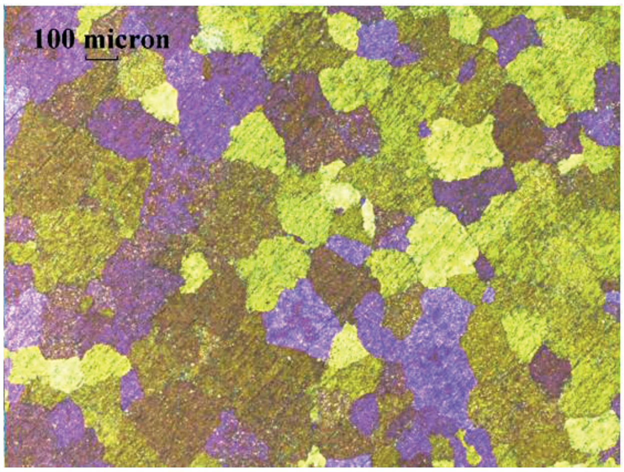
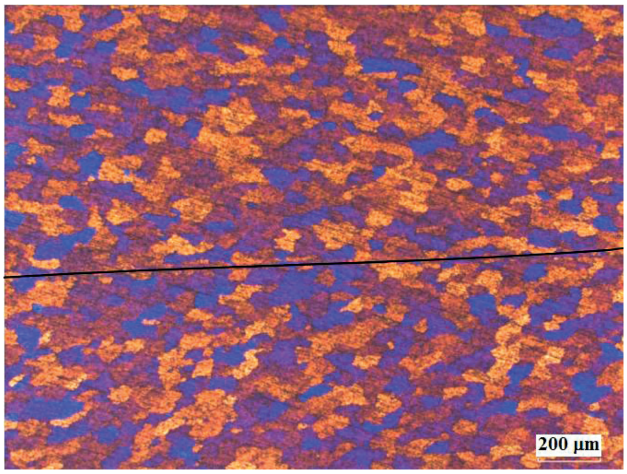


Fig. 5 - Base material microstructure for (a) AA6082 and (b) AA6060.

a)



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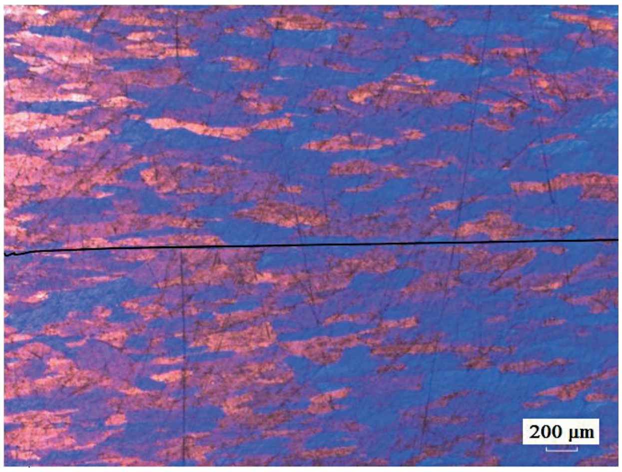

Fig. 6 - Section of specimens rolled at 425°C, having an initial thickness equal to 13 mm (a) and 20 mm (b).

variation and trend in microstructure is visible and can be directly related to a thermal factor. An increase in temperature results in a weld that is more incorporated in the grains.

A similar test has been conducted for the aluminum alloy AA6060. In this case, the results are similar to the aluminum alloy AA6082. As a general remark, it is possible to state that the weld line is less visible for the AA 6060 alloy, with respect to the AA6082 ally; moreover, it is already incorporated in the grains at low temperature. This result can be interpreted as an easier weldability of AA6060 with respect to the AA6082.

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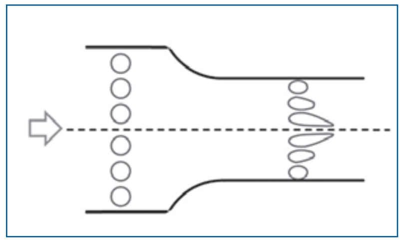

Fig. 7 - Scheme of the grains deformation occurring after flat rolling.

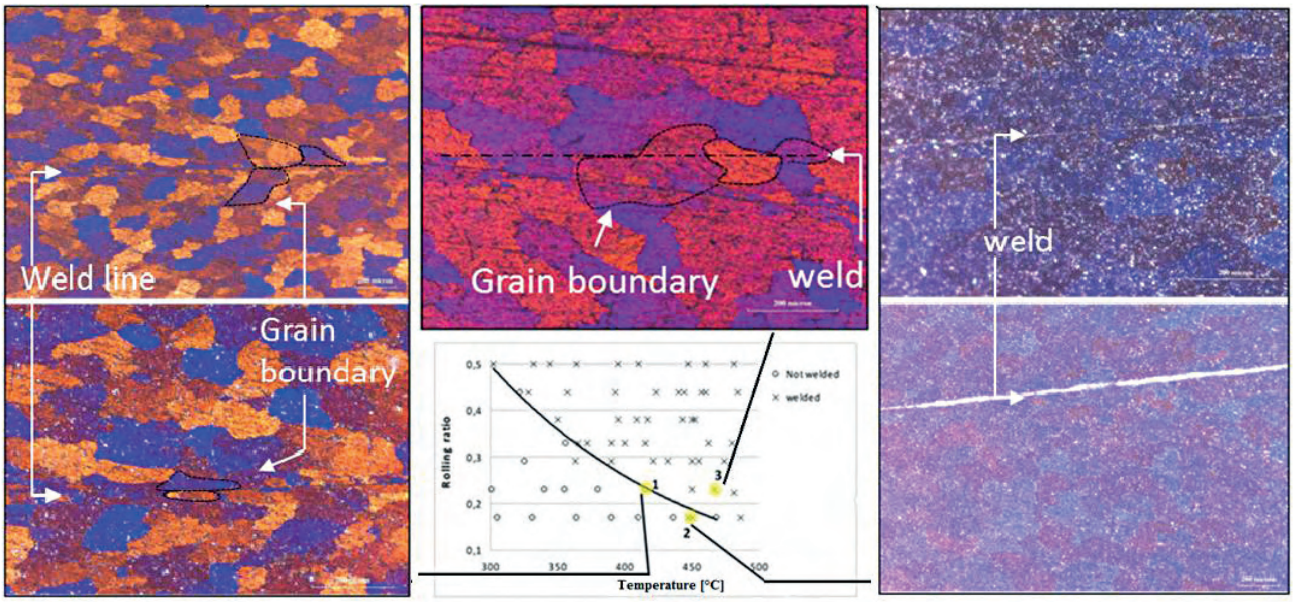

Fig. 8 - Microanalysis of borderline welding conditions for the aluminum alloy AA6082.

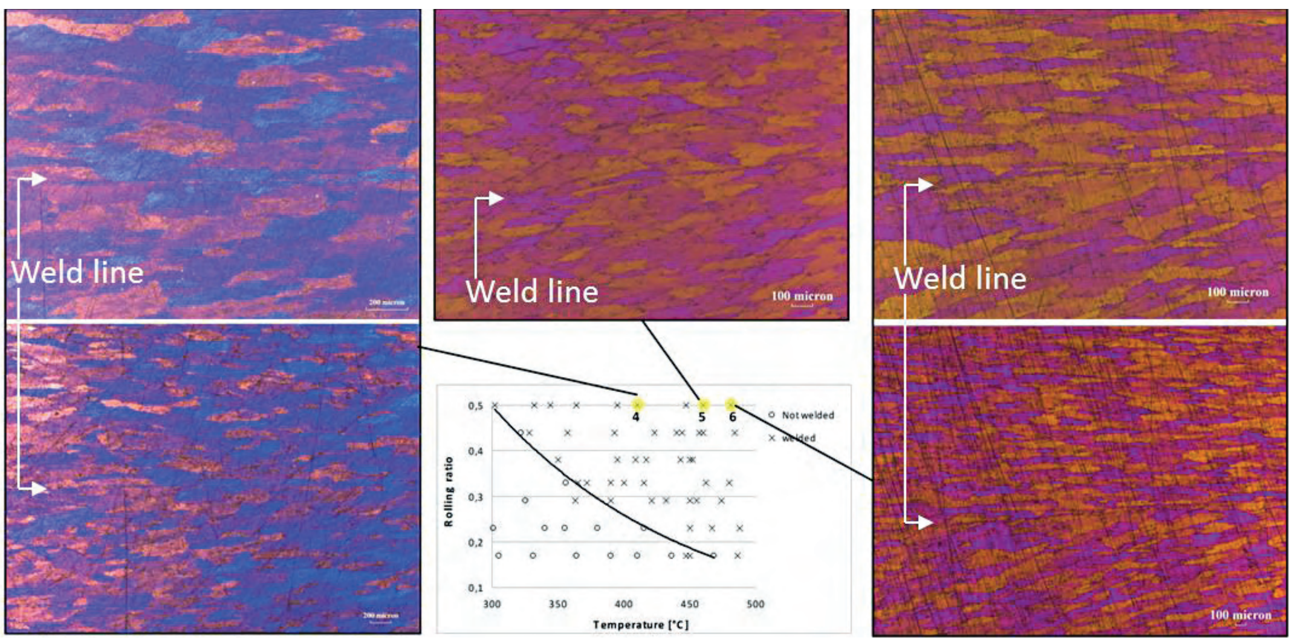

Fig. 9 - Microanalysis of good welding condition for the aluminum alloy AA6082.

CONCLUSION

Experimental tests based on flat rolling of sandwiches made of two rectangular specimens in AA6060 and AA6082 alloys were carried out for the evaluation of the welds quality as a function of the thermo-mechanical condition of the process. At a macroscopic level, the quality of the weld can be directly related to its visibility: the more visible is the weld, the lower the quality. The visibility of the weld is related to the rolling temperature: while the specimens rolled at the higher temperature show a good slim weld, the ones obtained at lower temperature show a much thicker weld line. An inverse rolling ratio - temperature correlation is observed for both alloys: at low rolling ratio (that means low contact pressure), it is possible to obtain good welds only if high material temperatures are reached. Second degree polynomial equations were finally defined for assessing the welding quality limits.
At a microstructure level, as for extruded products, the flat rolled specimens showed a high directionality of the microstructure due to the material flow. Moreover, the level of recrystallization varies significantly for different alloys. The particles result to be elongated and located on lines parallel to the rolling direction. The weld quality is related to the rolling ratio, even though a variation and trend in microstructure is visible and can be directly related to a thermal factor. An increase in temperature results in a weld that is more incorporated in the grains. Finally, the weld line is less visible and already incorporated in the grains at low temperature for the AA6060 alloy, with respect to the AA6082 alloy, so confirming an easier weldability.

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