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Continuous casting and rolling for the manufacturing of thin Al sheets

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ABSTRACT

Purpose: Purpose of this paper is presenting the state-of-the-art and the mechanism of Al continuous casting process and to improve the microstructure of the Al sheets reducing the morphological differences between the surface layer and the core of the considered alloy.

Design/methodology/approach: After a short illustration of some techniques which are presently employed for the production of Al alloy sheets for packaging applications, the development of the grain structure and the effect of the homegenization treatment and rolling on the microstructurural evolution has been presented and discussed.

Findings: The positive effect of the homogenization treatment and rolling on the microstructure has been demonstrated. The homogenized alloy presents improved workability and machinability.

Research limitations/implications: Based on the up to date achieved outcomes, it appears that homogeneous, fine microstructure and quite uniform distribution of the particles allow obtaining higher mechanical properties. The future research work will be oriented to get additional and detailed data on the performance of the alloy.

Practical implications: The continuous increase of Al-based alloys in different applications involves manufacturing high integrity and superior performance components using cost-effective and safely processes. In this direction the research communities together with manufacturing industries are focusing their attention to develop new and enhanced products using innovative procedures. The central issue is the technological transfer to industry for affordable mass production.

Originality/value: Obtaining a fine and homogenous microstructure for Al sheets by reducing the morphological differences between the surface layer and the core of the alloy improved mechanical performances and enhanced workability and machinability has been obtained. High performance end-product make this type of alloy very attractive for packaging material production.

Keywords: Continuous casting; sheet rolling; Al sheets, microstructure; Homogenization

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1. Introduction

Casting aluminium alloys have currently received special attention and there are an amplified tendency to employ them in the near future in many industrial applications. In many situations, the use of aluminum represents a very attractive choice, since it can contribute to gain fuel efficiency with high impact on the clean-up of the environment. However, the inferiority of some of the characteristics of the Al alloys with respect to other potential metals or alloys use for the same purpose can represent some limitations. The quality of the casting depends on many factors, e.g. sample morphology, presence of porosity, segregation or non-metallic inclusions, etc. which originate from the conditions of the solidification phase and/or from the homogenization treatment. The presence of such defects has a negative effect and consequently can limit the material performances in different commercial exploitations. The capacity to manage the microstructure as it evolves through solidification and thermal and deformation processing has usually enabled the products to be cost-effectively manufactured with the quality and consistency demanded by the marketplace [1-9].

In addition to their fluidity and castability features aluminum alloys are characterized by specific microstructural, mechanical and physical/ chemical properties,. The choice of the alloy is limited by the adopted casting technology [10-13] and commonly, components of complex shapes are prepared by casting or forging processes. Moreover, Al has an exclusive barrier properties and results to be an ideal packaging material [1,2,14].

This paper describes the state-of-the-art and the mechanism of Al continuous casting process followed by some considerations on the effects of cold rolling and on the homogenization cycle on the microstructural transformation of the alloy.

Fundamentally Al foil is produced by rolling sheet ingots cast from molten Al; this is followed by re-rolling on sheet and foil rolling mills to the desired thickness, or by continuously casting and cold rolling. The control of the constant thickness of the Al foil during the production process is of fundamental importance. Different techniques have been developed. One of the most commonly used approach consists of employing beta radiation; the rays are passed through the foil to a sensor on the other side which in turn control the distance between the rolls by a reaction-loop type system. If the intensity becomes too high, i.e. corresponding a thinner foil, the distance between the rollers is increased. Vice-versa, if the intensities become too low indicating that the foil has become too thick, the rollers apply more pressure, causing the foil to be made thinner.

The continuous casting method (CC) is much less energy intensive and has become the preferred process [15]. For thicknesses below 0.025 mm, two layers are usually put together for the final pass and afterwards separated which produces foil with one bright side and one matte side. The two sides in contact with each other are matte and the exterior sides become bright, this is completed to reduce tearing, to increase the production rates, to control the thickness, and to get around the need for a smaller diameter roller [16].

Al foil has a shiny side and a matte side. The shiny side is produced when the Al is rolled during the final pass. It is difficult to produce rollers with a gap fine enough to cope with the foil gauge, therefore, for the final pass, two sheets are rolled at the same time, doubling the thickness of the gauge at entry to the rollers. When the sheets are later separated, the inside surface is dull, and the outside surface is shiny. This difference in the finish has lead to the perception that favoring a side has an effect when cooking. While many believe that the different properties keep heat out when wrapped with the shiny finish facing out, and keep heat in with the shiny finish facing inwards, the actual difference is imperceptible without instrumentation [17]. The reflectivity of bright Al foil is 88% while dull embossed foil is about 80% [18].

Al is widely used for such purpose thanks to some properties:

1. It is flexible and strong also durable and does not make the food rust if there is water.
2. Aluminium can be converted into thin sheets (because it is malleable) which can be folded into any shape.
3. Then it is readily available in affordable cost.
4. It is a metal thus it is a good conductor of heat, so it keep the food hotter for a longer time.
5. It prevents germs to enter the food.

During the rolling stages some lubrication is needed, since otherwise the foil surface can become marked with a herringbone pattern. These lubricants are sprayed on the foil surface before passing through the mill rolls. Kerosene based lubricants are commonly used, although oils approved for food contact have to be employed for foil intended for food packaging.

Al becomes work hardened during the cold rolling process and is annealed for most purposes. The rolls of foil are heated until the level of softness is reached, which may be up to 340 °C (644 °F) for 12 hours. During this heating, the lubricating oils are burned off leaving a dry surface. Lubricant oils may not be completely burnt off for hard temper rolls, which can make subsequent coating or printing more difficult. The rolls of Al foil are then slit on slitter rewinding machines into smaller rolls. Roll slitting and rewinding is an essential part of the finishing process.

Al foils thicker than 25 μm are impermeable to oxygen and water. Foils thinner than this become slightly permeable due to minute pinholes caused by the production process. Due to its many economic advantages the continuous casting of Al has become more and more important during the last 40 years. This process is mostly used for the production of semi-fabricated strip, for cold rolling to foil stock building sheet and can stock. They are also used to cast endless wire bar stock.

CC process converts molten Al alloys directly into an endless coiled strip suitable for cold rolling or wire-bars for wire-drawing. They effectively eliminate the operations associated with traditional mould casting (discontinuous process) or a semi-continuous process and subsequent hot mill deformation. Therefore the capital investment and operational costs are significantly lower than in a conventional production process. Continuous casting is the preferred casting method in many modern plants because it offers higher productivity. CC has been employed with increasing commercial success for Al as well as for other metals.

Among the continuous casting technologies the strip casting processes now account for a remarkable share of the world's output of rolled Al semi-fabricated coil stock (approximately 30%).

Continuous strip casting has proved itself for the production of foil stock, of strip for painting and - in some cases - of strip for deep drawing processes. The various strip casting technologies are suitable for the casting of wrought alloys and allow the production of strip from 3 mm to 20 mm thickness and up to 2150 mm width.

Fig. 1 illustrates the main feature of all continuous casting process.

The molten metal goes into the casting mould (in Fig. 1, the space between the two rolls), solidifies there and leaves the mould as a continuous strip.

After casting, the strip can be directly coiled - or it can be immediately (without down cooling) rolled into a coilable gauge. For the mass production of collapsible tubes and rigid cans the machines for the blanking of slugs or for extruding can be placed directly after the casting machines. In this way a continuous production is achieved.

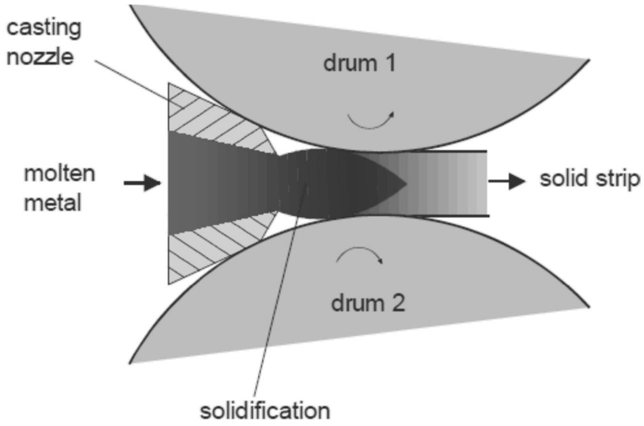

Fig. 1. Schematic representation of the continuous casting process

The conventional way of producing rolling slabs is Direct Chill (DC) semi-continuous casting process, although some slabs are produced by pouring molten metal into a permanent mould. After DC casting, the rolling slabs are re-heated to about 500°C and hot rolled to a coilable thickness between 4 mm and 6 mm.

The principal benefit of the continuous technologies consists of the saving of several production steps in the production of strip or foil compared to conventional technologies.

This saving of production stages includes several other advantages: compared with the conventional way, processing costs are only a third to a half as high, operating and investment costs are only a quarter to a third as high and there are smaller space and labor requirements. Less energy is required because it is no longer necessary to preheat the ingot before hot rolling. The productivity is 15-20% higher; the material consumption is about 1.5-2% lower. Newer developments, such as those made by Pechiney and FATA Hunter, enable very thin strip to be produced. This leads to even less rolling stages, e.g. when producing thin foil or beverage cans stock.

When continuous casting was first introduced it appeared to have many advantages which result to production economies. However it soon became obvious that the technology introduced some features in the finished product that limits its use compared with conventionally produced material. Foil stock however in particular lends itself to the continuous strip route.

The most serious of these disadvantages are related to the difficulties which is present in casting alloys with high alloy content. Due to the wide freezing range of these alloys there is a risk of cracks in the strip. If not all the metal is solidified at the narrowest point of the casting machine, the liquid or the semisolid metal can leave the casting mould. It is possible to avoid this inconvenience with a lower casting rate, but even this solution is limited because, if the casting rate is too low, it is possible to have solidification in the direction of the casting nozzle. Consequently, the casting rate of alloys is lower than that of commercially pure Al.

Therefore only alloys with a low alloy content can be cast, such as:

- commercially pure aluminium Al99.2 to Al 99.6 (series 1000);
- AlMn (max. 2% Mn, Series 3000);
- AlMg (max. 2 to 3% Mg, exception Alusuisse Caster II with max. 5% Mg, Series 5000),
- AlFe (max. 2% Fe) or
- AlMnFe (max. 1% Fe, max 1% Mn).

It is important to note that in any comparison of the output rate of different continuous casting processes, it is necessary to compare the production of the same alloys.

Usually the various strip casting technologies are divided according to the dimensions of the finished product into processes:

- for wide strip casting (width up to 2150 mm);
- for narrow strip casting (maximum width 800 mm);
- for strip, that can be coiled immediately after casting (gauge max. 10 mm);
- for strip to be hot rolled after leaving the casting machine (gauge between 20 mm and 40 mm);
- for thin gauge casting (gauge under 3 mm).

The continuous casting of wire bars is also of great economic importance. As is the case for strip casting some production steps are saved. For the alloy content the same limitations has been obtain. That is why mainly commercial pure aluminium is cast. The same production process can be used also for other alloys, i.e. AlMn and AlMgSi (Aldrey) are produced. All these materials are although used in electrical engineering.

Aluminum foils (Al sheets with a thickness below 200 µm) found their use many applications like thermal insulations, fin stocks, honeycombs, electrical coils, capacitors, transformers, cable foils, semi-rigid containers, caps, closures, pouches, bags, wraps, peel-off lids, household foils, lithographic plates, decorative products, etc.

Various processes are presently employed for the manufacture of Al alloy band for packaging applications. The direct chill (DC) caster, with conventional hot mill, is the most extensively used and it produces high-quality slip. DC casting has been the most important casting technique for producing large rolling slabs and extrusion billets of Al alloys. At the same time, CC techniques for Al alloy products have been available for 50 years.

On the other hand, the investment and operating costs of DC casting are relatively high. CC process are increasingly used to produce aluminium strip for packaging applications, principally due to its economically advantages. Several CC processes have been used for the manufacture of Al packaging alloys, including twin-roll, twin-belt, block, and wheel belt configurations. Al foils are commonly produced on twin-roll casters because their comparatively low production rate is not an inconvenience in the smaller foil market. Twin-belt casters are important sources of foil stock both in North America and Europe [10,19]. Currently, twin-roll casting or strip casting is the preferred method for fabricating thin-gauge Al sheets and foils. The strip casting process combines two processes of continuous casting and hot rolling. The molten liquid metal is directly transferred into the space prepared by two rotating rolls and side walls. Compared to the conventional continuous casting, the preliminary forming process using a mould has been eliminated and the production line from molten liquid metal to the final products is evidently shortened. Furthermore, due to high cooling rates, it can increase the mechanical properties of the metal [12].

Besides the economic benefits, strip casting is also able to reduce segregation, to improve inclusion size distribution and to refine microstructural and textural homogeneity [13].

The alloys belonging to the series 1xxx, 3xxx, 8xxx alloys are typically used for foil productions. Achieving a fine and a homogeneous as-cast microstructure, as well as fine eutectic phase, represents the central parameter to get good quality end-product for any purpose.

CC is the preferred casting method in modern plants because it offers high productivity, but there are some limitations in its use since not all alloys can be cast.

CC processes converts molten Al alloys directly into an continuous coiled strip suitable for cold rolling or wire-bars for wire-drawing. They effectively remove the operations associated with traditional mould casting (discontinuous process) or die casting (a semicontinuous process) and subsequent hot mill deformation. Continuous casting has been employed with increasing commercial success for aluminium as well as other metals [20-25].

The alloy selected for the present paper belongs to the AlFeMnSi system. The study has been carried out on both non-homogenized and on homogenized alloys in order to check the microstructure of both samples and to decrease the morphological dissimilarity between the surface layer and the central part of a thin Al alloy sheet. The considered alloy can be rolled up to thin sheets and foils, and consequently it can be effectively used for packaging and microelectronics industries or for the manufacturing of some cooling apparatus.

Development of the microstructure has been observed in as cast state and after annealing at different temperature. In this paper the attention will be oriented to refine the microstructure and to reduce the microstructural difference between the surface layer and the core of the alloy.

2. Experimental procedures

In particular, the AA8006 alloy has been employed for the present research. The samples have been manufactured by continuous casting process: the liquid metal was solidified and rolled through the cylinders of continuous casting tools providing some rolling mills with a thickness of about 6 mm and 7.2 mm respectively, depending on the roll supporting force. In this investigation samples obtained with a roll supporting force of 250 tons have been chosen. The casting velocity was about 0.4 rpm. The achieved alloy is suitable for successive cold rolling. A predetermined thickness of the coils has been realized and it has been reached applying different intermediate steps. By homogenization treatment a refinement of the microstructure has been obtained for 6 h at different temperatures (in a temperature range of 460°C-530°C). This process has the aim to decrease or remove the presence of microsegregations and to attain a homogeneous structure with fine and well distributed particles. The reduction to 0.6 mm has been obtained through an intermediate thickness corresponding to 3 mm followed by an interannealing treatment at 300°C and a fine rolling. The process has been concluded with a final annealing at 300°-320°C. At the end thin Al coils with about 380 μm thickness have been obtained. The characterization of the alloys has been performed using traditional methods. The microstructure evolution has been analyzed by Optical Microscope (OM, MeF4 Reichart-Jung) and by Scanning Electron Microscopy (SEM, Leo 1450VP). The distributions of the elements were evaluated by Energy-Dispersive X-ray Spectrometry (EDS, Oxford microprobe). Tensile test and Vickers microhardness measurements have been adopted for the estimation of the alloy mechanical behavior.

3. Results and discussion

Microstructures of the as-cast sample with 6 mm thickness are reported in Fig. 2: a heterogeneous microstructure has been find both on the surface layer (Fig. 2a) and in the core (Fig. 2b) of the sample. The alloy reveals a deformed grain structure and an elongation of the grains parallel to the rolling direction has also been identified. The final strip structure in both cases is a coarse one with very large grains starting from the surface layer and arriving up to the core of the samples. The presence of Fe-rich microsegregation has been detected which involves a relatively extended area, as shown in Fig. 1c.

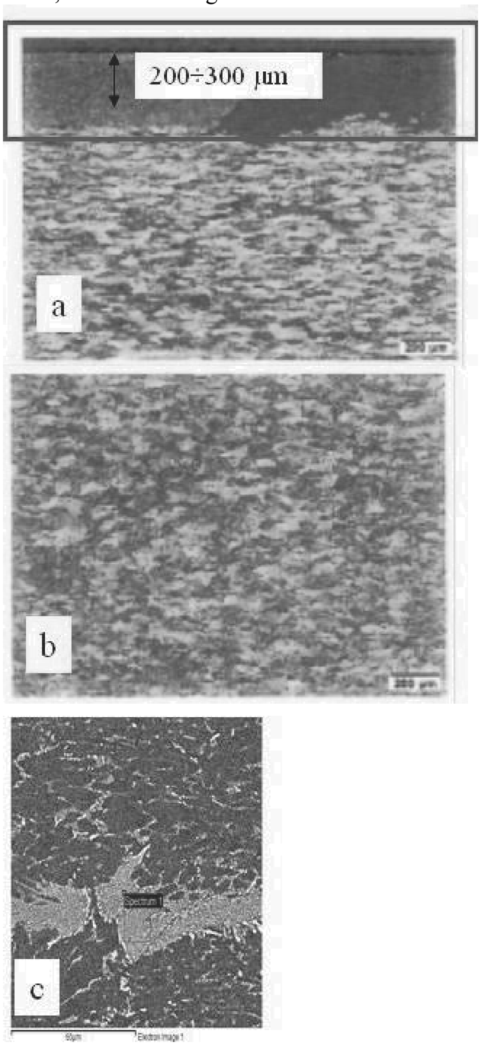

Fig. 2. OM microstructures: a) on the surface layer, b) in the core of the sample and c) SEM microstructure showing the presence of microsegregation

The presence of intermetallic particles and their particular arrangement has been identified and the development of some bands has been observed (Fig. 3): on the surface layer the bands follow a fine structure while moving toward the interior of the sample larger grains have been detected. Such particles are chemically constituted by Al, Si, Fe and Mn, as identified by EDS analysis.

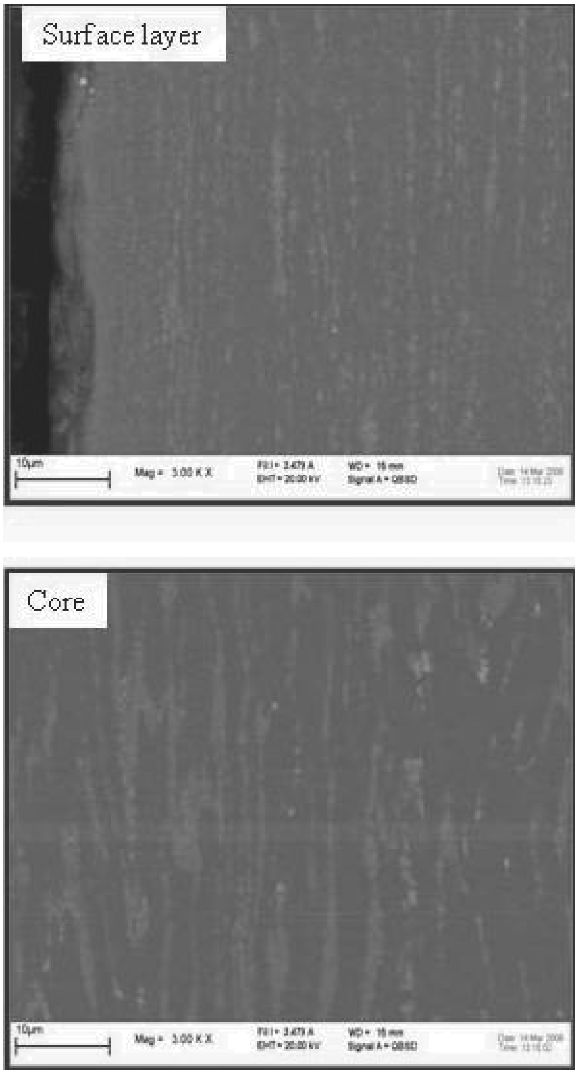

Fig. 3. SEM microstructure showing the evolution of the grain structures on the surface layer (top) and in the core (bottom) of the samples

The Al alloys coils with 6 mm and 7.2 mm thicknesses have been homogenized at different temperatures. The microstructures have been illustrated in Figures 4 and 5. Using a pressure of 250 tons a decrease of the thickness of the surface layer and a decrease of grain size has been reached. This comes together with the dynamic recrystallization of the surface layer during casting. The reorganization of the structure has been observed following the increase of the temperature (Fig. 4). The evolution of the structure has been carried on and at 500°C the finest microstructure has been reached. As temperature further increases to 530°C (Fig. 5) the grains size grow up as an indication of excessively high annealing temperature.

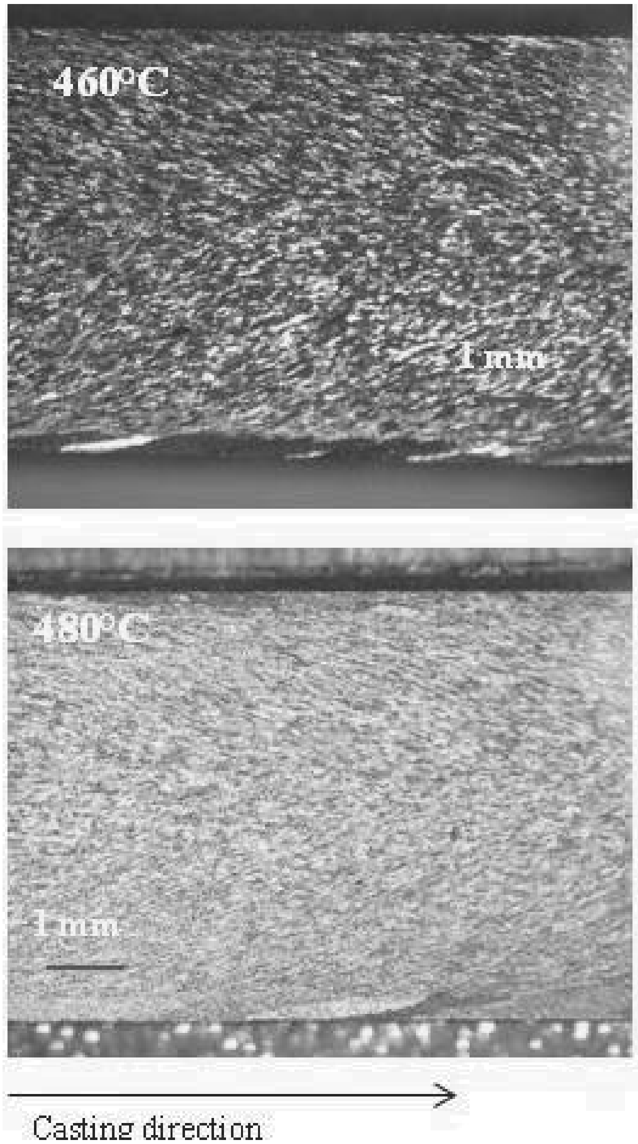

Fig. 4. Evolution of the grain structures across the cross-section of the samples annealed at 460°C and 480°C

Even if the total volume fraction of the intermetallic particles decreased at 500°C and this condition leads up to a more homogeneous microstructure, the disposition of particle is different along the samples: higher number of small particles has been observed in the core of the sample (7.66% of the area results covered) compared to the surface layer (4.66% of the area appear covered) as illustrated in Fig. 6.

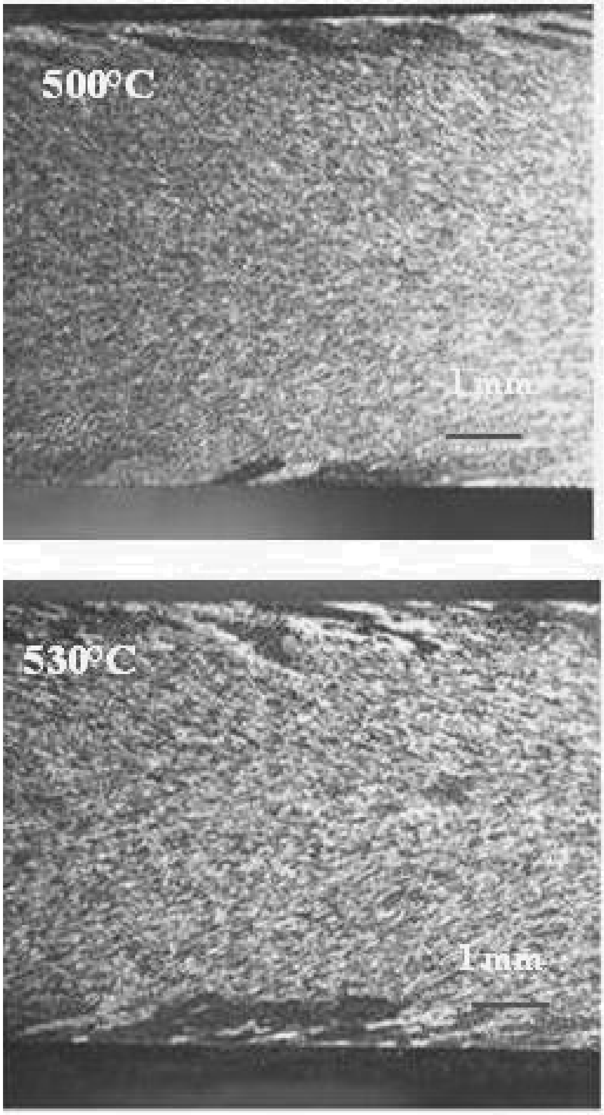

Fig. 5. Evolution of the grain structures across the cross-section of the samples annealed at 500°C and 530°C

The alloys prepared by continuous casting with a roll supporting force of 250 tons homogenized for 6 h at different temperatures have been submitted to cold rolling to obtain a 0.6 mm thickness.

Such condition has been followed by an intermediate annealing treatment in the range of temperatures corresponds to 300°C-320°C and a final rolling and annealing at 300°C-320°C.

The development of the grain structure and the effect of the temperature on the microstructurural evolution has been monitored: at the surface and in the core of the AA8006 samples the structure is significantly different. However in either cases no microsegregation has been detected.

As expected from the microstructural features discussed above, the highest ductility has been obtained at 500°C (Fig. 7): it is an indication of a higher capacity of the alloys to absorb a larger amount of energy and of undergoing large strains prior to failure. Ductility decreases with increasing annealing temperature over 500°C. Much more homogeneous and finer microstructure leads obtaining superior ductile properties.

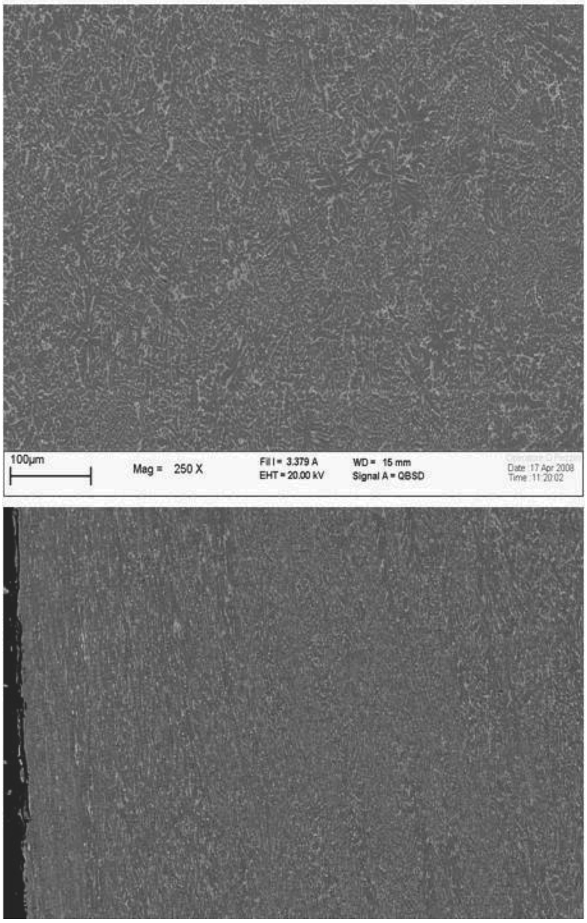

Fig. 6. Distribution of the intermetallic compounds in the core and on the surface layer of the homogenized alloy with the relative SEM microstructures

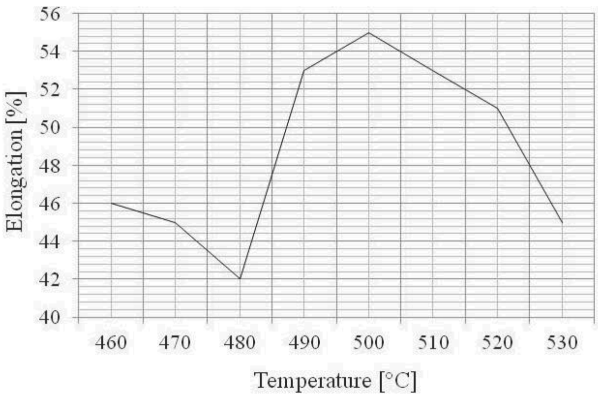

Fig. 7. Elongation vs. homogenization temperature

As a further analysis, the effect of the grain size on the softening characteristics has been evaluated by Vickers hardness measurements. The plot of Vickers hardness as a function of the distance from the surface is shown in Fig. 8.

Different homogenization temperatures have been considered. After homogenization at the optimal temperature a reduction of the alloy hardness of about 20% has been obtained with a consequent improvement of the workability, important aspect in many industrial applications.

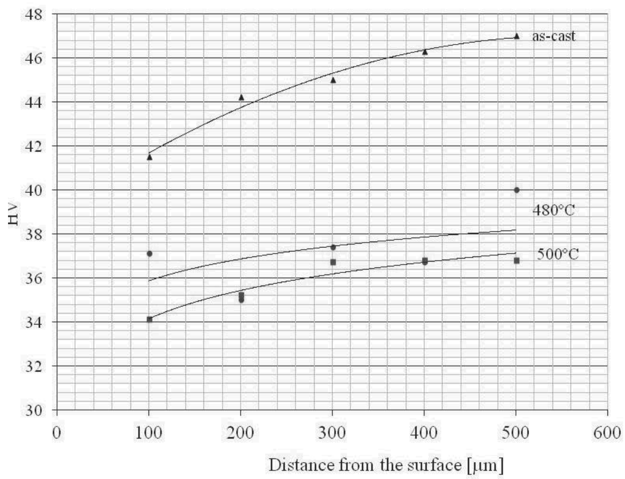

Fig. 8. Vickers hardness evolution in the homogenized and as cast samples

4. Conclusions

The aim of the present research work has been twofold: first to improve the microstructure of the Al sheets and second to reduce the morphological differences between the surface layer and the core of the alloy. Homogeneous and fine microstructure with uniform distribution of the particles allow obtaining higher mechanical properties. The positive effect of the homogenization treatment on the microstructure has been demonstrated. The homogenized alloy presents improved workability and machinability. The most favorable homogenization temperature corresponds to 500°C and such condition guarantees the finest microstructure, the highest ductility and good workability increasing the commercial success of such Al alloy.

Energy savings and eco-friendly characteristics of the considered alloys together with the reliability, safety and high performance end-product make these alloys very attractive for packaging material production.

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