A comparison between asymmetric rolling and accumulative roll bonding as means to refine the grain structure of an Al-Mg-Si alloy

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ABSTRACT

The possibility of refining the grain structure of a commercial Al-Mg-Si alloy was evaluated using asymmetric rolling (ASR) and accumulative roll bonding (ARB) in the severe plastic deformation (SPD) regime. Bars of annealed alloy having a thickness of 10 mm were asymmetrically rolled down to a thickness of 0.23 mm with a laboratory rolling mill featuring the possibility of independently modifying the rotational speed of its two rolls. The effect of the rolling temperature was investigated by tests in the range 150-250°C. A parallel campaign was also conducted to investigate the effects of warm accumulative roll bonding of the same alloy and in the same temperature range. These tests were carried out on annealed samples of 1 mm thickness. The experimental characterization (both mechanical and microstructural) demonstrated that asymmetric rolling and accumulative roll bonding can readily promote the achievement of ultrafine grained structures in Al-Mg-Si alloys.

RIASSUNTO

La possibilità di affinare la microstruttura di una lega commerciale della serie Al-Mg-Si è stata valutata usando le tecniche sia di laminazione asimmetrica (ASR) che di saldatura per "accumulative roll bonding" (ARB) laminazioni ripetute (ARB), ambedue effettuate in regime di deformazione plastica severa (SPD). Le barre ricotte, spesse 10 mm, sono state laminate fino allo spessore di 0,23 mm mediante un laminatoio di laboratorio che consentiva di modificare in modo indipendente la velocità di rotazione dei due cilindri. L'effetto della temperatura di laminazione è stato inoltre studiato con prove effettuate nell'intervallo di temperature tra 150-250°C. Nello stesso intervallo di temperatura, parallelamente è stata condotta una campagna di prove per valutare gli effetti di una laminazione ARB a tiepido sulla stessa lega. Queste prove sono state eseguite su campioni ricotti spessi 1mm. La caratterizzazione sia meccanica che microstrutturale ha mostrato che ambedue i sistemi di laminazione sono in grado di produrre nelle leghe Al-Mg-Si strutture a grano ultrafine.

KEYWORDS

Aluminum alloys, severe plastic deformation, ultrafine grained materials.

Contribution presented to the 1st TMS-ABM International Materials Congress, Symposium "Mechanical Properties of Materials with Emphasis on Grain-size Effects", July 26-30, 2010, Rio de Janeiro, Brazil.

INTRODUCTION

It has been widely proved that a reduction in grain size corresponds to enhanced mechanical properties of metallic alloys [2]. The generation of Ultrafine Grained (UFG) materials, with a grain size in the submicrometer scale thus leads to materials with higher strength and improved ductility at room temperature compared to coarse grained materials, as well as better formability at high temperature (under appropriate strain rate and temperature superplastic behavior can easily occur) [3]. One of the available mechanisms that allows strong refining of the grain structure is continuous dynamic recrystallization (cDRX) [4]. According to this process, the material experiences the formation of deformation/microshear bands for low and medium equivalent strain, while at higher degree of strain, in the Severe Plastic Deformation (SPD) regime, grain subdivision occurs due to the increase in boundary misorientation, eventually leading to high-angle grain boundaries.

Second phase particles are known [1] to ease and accelerate the fragmentation of shear bands, so allowing to reach an UFG structure sooner, expecially for small and medium sized particles.

Alternatively, many other thermo-mechanical processes exist giving the possibility to refine the grain structure by discontinuous recrystallization.

However, the attempts to reduce grain size in commercial aluminum alloys exploiting this phenomenon have encountered many difficulties due to its high stacking faults energy [5]. This characteristic strongly facilitates the phenomenon of recovery instead of recrystallization. Several SPD techniques have been developed in last decades in order to impart high amounts of equivalent strain to materials, either at lab or at industrial scale, by exploiting cDRX mechanism. In the former group, it is possible to cite Equal Channel Angular Extrusion (ECAE) and High Pressure Torsion (HPT). The latter group includes both Asymmetric Rolling (ASR) and Accumulative Roll Bonding (ARB). Rolling processes are among the most attractive processes for SPD since they can be industrially exploited with modest modifications of the rolling mill. The aim of this work is to compare two rolling techniques (ASR and ARB) as a means to refine the grain structure of a 6082 alloy.

In ASR, different peripheral speeds of the upper and lower rolls are adopted and the sheet is thus subjected to enhanced shear deformation, in addition to compression strain. It has been suggested that this would readily promote the development of ultrafine grains. Cui and Ohori [6] investigated the structure evolution of high-purity aluminium during room temperature ASR with reduction of thickness exceeding 90% and asymmetry ratio of 1.4 (the mismatch speed ratio between upper and lower rolls).They suggested that the evolution of microstructure results from the development of high-angle grain boundaries (HAGBs) due to the simultaneous action of compression and shear strain. Jin and Lloyd [7,8] also performed ASR followed by annealing on a commercial 5754 aluminum alloy. After appropriate processing with an asymmetry ratio of 2, they were able to produce grain sizes as small as 1 μm featuring a tensile response comparable to that of ultrafine-grained alloys produced by other SPD methods.

ARB is a discontinuous process that keeps the geometry and size of the billets constant. It has been shown [9,10] that the formation of UF grains during intense plastic deformation is the simultaneous action of grain subdivision and recovery of the deformed structure. An important concern when exploiting the technique is that is possible to achieve a reasonably homogeneous microstructure and texture using a small number of passes.

MATERIALS AND EXPERIMENTAL PROCEDURES

Commercial bars of a type 6082 alloy, having a thickness of 10 mm and width of 40 mm, were annealed at 450°C for 30 minutes and cold rolled down to a thickness of 0.23 mm. This overall reduction was achieved by a multipass procedure with no intermediate annealing treatments. A laboratory rolling mill (roll diameter 150 mm, width 200 mm) featuring the possibility of independently modify the rotational speed of its two rolls was adopted for this purpose. The rolling schedule imposed a reduction of thickness of 20% at each step and the rotation of the billet along its longitudinal axis before each pass. The asymmetry ratio adopted was 1.4 on the basis of previous studies [11]. To improve the formability of the alloy and to investigate the effects of warm rolling, the process was conducted at 250°C, with an inter-pass heating of 5 minutes. For accumulative roll bonding, bars of the same material were conventionally rolled down to 1 mm thickness and then annealed with the same heat treatment of the original samples. Special surface preparation was performed to improve sheet bonding: wire brushing and acetone washing was performed before stacking the two sheets together by rivets. As for the ASR, the ARB was performed at 250°C.

The investigation here presented is mainly focused on microhardness and microstructure as a function of rolling conditions. Microhardness measurements with a load on the indenter of 1 N were performed to evaluate mechanical properties. Microstructure analyses were carried out by scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

SEM and TEM samples were prepared by mechanically grinding the materials down to about 85 μm thickness. Final twin jet thinning was performed at 18V with a solution of 30 vol% HNO_3 in methanol at -30°C. Results have been analyzed as a function of equivalent strain, considering a strain of 0.8 for each ARB pass (corresponding to 50% reduction in thickness) [12] and calculated according to the equation (1) for ASR [13]:

$$\bar{\varepsilon} = 1.155 \ln\left(\frac{h_0}{h_f}\right) \quad (1)$$

RESULTS AND DISCUSSION

In Figure 1 the evolution of microhardness as a function of equivalent strain is plotted for both processes.

The two curves appear quite different. While there is an initial stage of hardness increase for low and medium equivalent strains, for ARB a decrease in microhardness occurs for high levels of strain. The behaviour of asymmetrically rolled specimens is quite different: the initial increase is more moderate and reaches a maximum for equivalent strain of about 200%, then remains almost constant. The microstructural analysis allowed understanding this behaviour considering the different structures that are formed in the first part of the process. In Figure 2 representative micrographs are shown, referring to samples with similar equivalent strain.

In the micrographs it is clear that asymmetrically rolled sample has the tendency to create microshear bands, while ARB gives rise to a more homogeneous microstructure. Furthermore, the dislocation density seems to be higher in Figure 2 a) and this evidence can be a good explanation for the higher value of microhardness of the ARBed material. Further plastic straining leads to a progressive evolution of the microstructure. While asymmetrically rolled sample tends to decrease the width of the shear bands and fragment them, the ARBed material still remains homogeneous and the apparent dislocation density increases. This behaviour is well recognized in figure 3 a) and b).

The analysis of Figure 3 a) and b) is important to understand the different mechanical behaviour of the samples processed by the two methods at very high strains. By considering the continuous increase of dislocation density for the ARBed material, it is clearly explained why it possesses higher value of microhardness. Instead, the asymmetrically rolled material, reduces the size of microshear bands without any increase in dislocation density and this can be the reason why the curve in Figure 1 has a smoother evolution.

Figure 4 refers to the last step of both rolling process. The value of equivalent strain is approximately the same (400% for ARB and 438% for ASR) and the microstructures are quite similar as well.

It is interesting to note that the microstructure of ASRed material is definitely homogeneous, since the process of fragmentation already started at lower strains. Not only fragmentation, but also recovery occurred. In particular, recovery eases the fragmentation of shear bands

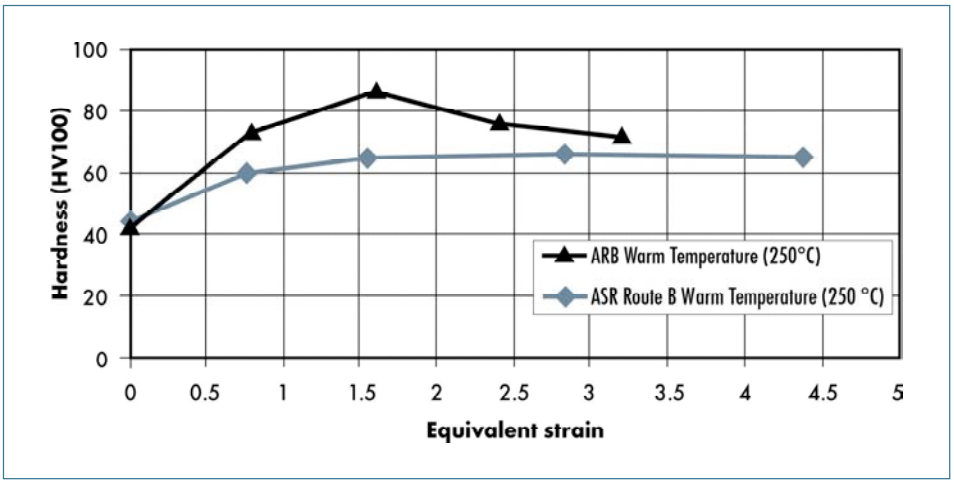

Fig. 1: Evolution of microhardness as a function of equivalent strain for both ARB and ASR process at 250°C.

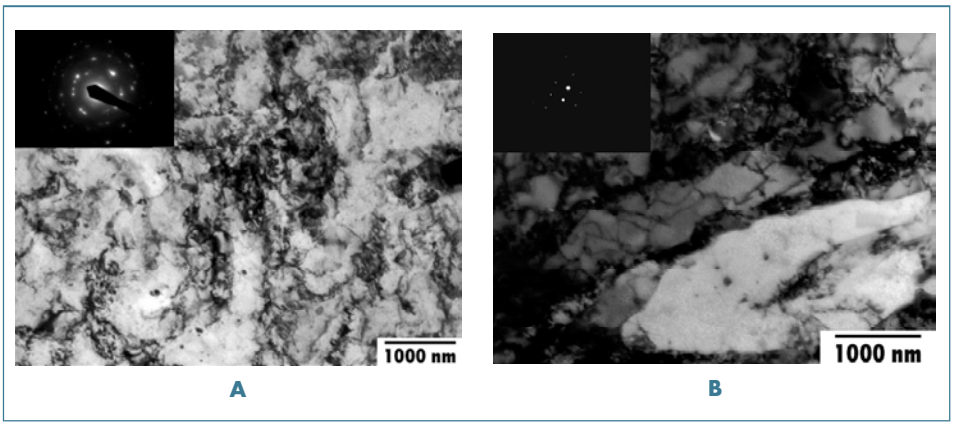

Fig. 2: TEM Micrograph of ARBed a) and ASRed b) samples subjected to equivalent strain of 80% and 77% respectively.

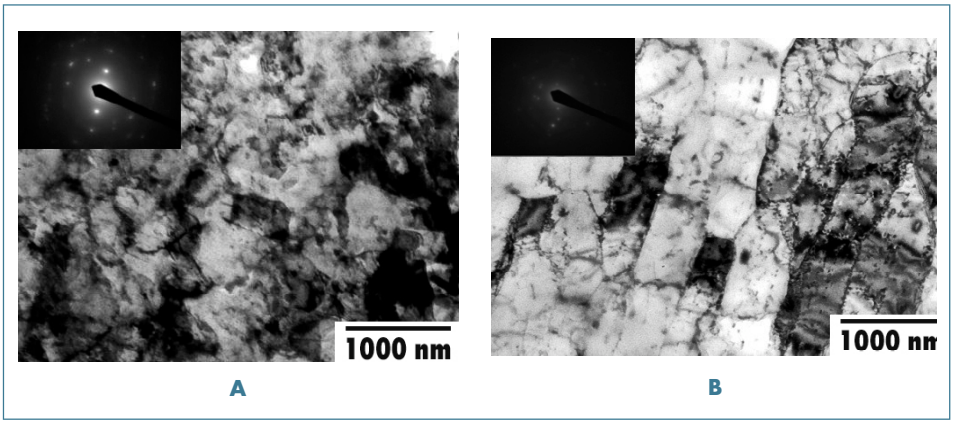

Fig. 3: TEM micrographs of the rolled samples; a) ARBed sample at 160% of equivalent strain; b) ASRed sample at 154% of equivalent strain.

and this implies the reduction of dislocation density. It is possible to state that both the reduction of grain size by fragmentation and of dislocation density by recovery concur to keep the microhardness constant for high levels of equivalent strain.
ARBed material (Fig. 4 a)) shows, as expected, a more homogeneous structure. The main difference with respect to the ASRed material is the dislocation density. During the process the material underwent heavy recovery thet lowers mechanical properties due to decrease in work hardening. This evolution of the two microstructures reflects the microhardness curves for both materials.
Another important feature that can be drawn for both rolling processes is the stimulation of precipitation and coarsening of second phase particles due to holding at 250°C and possibly to enhanced diffusion related to the heavy deformation experienced. As depicted in Figures 5 and 6, due to strain and temperature, the fraction and size of second-phase particles increase dramatically, preventing clear observations of the grains with the backscattered electron channelling technique. Furthermore, coarsening of the particles clearly occur by increasing the number of passes (i.e. the strain).
Finally, Figure 6 confirms the formation of microshear bands for the asymmetrically rolled material at the beginning of the rolling process, detected also by a different technique. For the last sample (Fig. 6 c)) a homogeneous microstructure is highlighted.

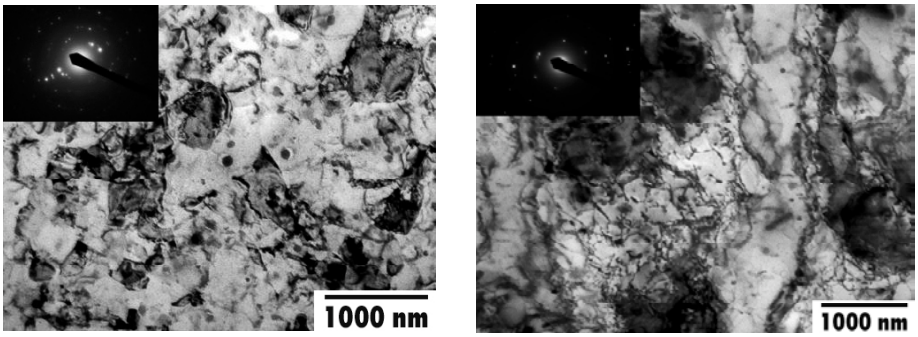

Fig. 4: TEM Micrographs of a) ARBed sample at 400% of equivalent strain and b) ASRed sample at438% of equivalent strain.

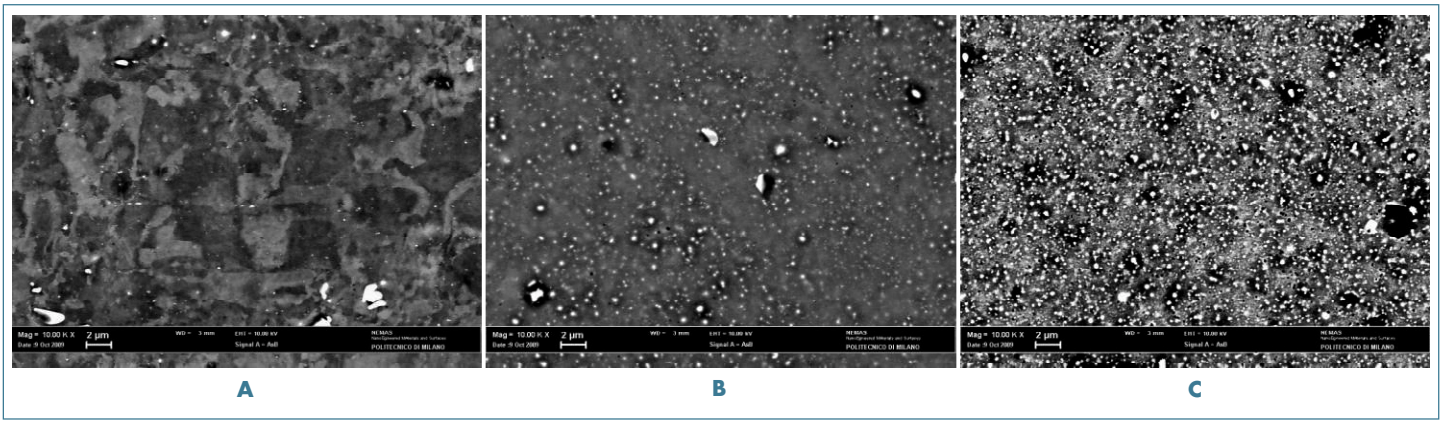

Fig. 5: SEM BSE micrographs of ARBed samples with equivalent strain a) 80%, b) 160%, c) 400%.

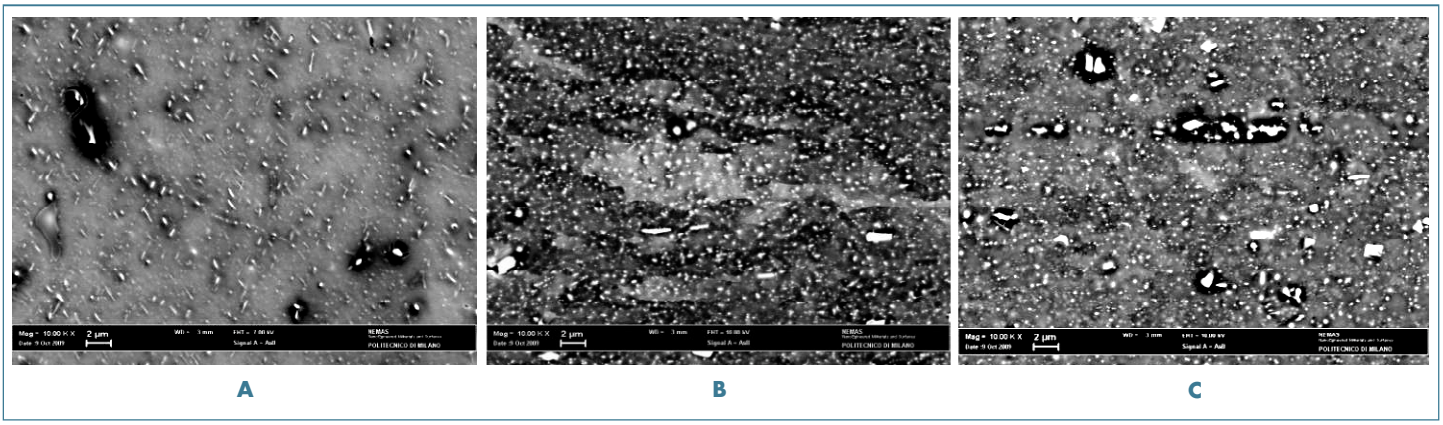

Fig. 6: SEM BSE micrographs of ASRed asymmetrically rolled samples with equivalent strain of a) 77%, b) 154% and c) 438%.

CONCLUSIONS

The evolution of the microstructure strongly depends on the process adopted. For asymmetric rolling of the 6082 alloy, the first part of the process is spent to create microshear bands (up to an equivalent strain of about 150%) and to reduce their width. For higher values of equivalent strain, the material undergoes fragmentation of the microshear bands and the subsequent creation of an ultrafine structure, even at a warm temperature of 250°C. At the end of the process, recovery and work hardening are almost balanced so that the mechanical properties do not change significantly with further strain.

ARB, due to a different state of strain, does not impose a severe orientation of the grains and the microstructure generated at each pass remains fairly homogeneous. The largest part of the evolution is concentrated at the beginning of the process and the contribution of work hardening is considerable, determining a great response in terms of mechanical properties, as shown by the microhardness curve. At the end of the process, recovery is more important than work hardening so that the material shows a decrease in mechanical properties when deformed at 250°C to very large strains.

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