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MECHANICAL AND MICROSTRUCTURAL ASPECTS OBSERVED IN 6063 ALUMINUM ALLOY AFTER THERMOMECHANICAL TREATMENTS[1]

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Abstract
In this work is shown the influence of some deformation processes on the mechanical and microstructure of initially annealed 6063 Al alloy (cold rolling or torsion or extrusion and also tensile deformation, individually or a combination of them). The combination of strength and toughness is intimately related to the work hardening. The analysis and control of work hardening has proven to be one of the problems of materials science due to the complexity of the dislocation processes involved and the non homogeneity of their operation within the deforming microstructure together with presence of a multiphase microstructure on the 6063 aluminum alloy (Al-Mg-Si-Fe). During deformation, particles will affect the deformation microstructure and texture (heterogeneities at larger particles; non homogeneity of slip, e.g. shear bands). The obtained results indicate a significant effect of second-phase particles on recrystallization and how to control the resulting microstructure and texture by the use of particles.

Key words: 6063-aluminum alloy, deformation processes, microstructure, second-phase particles

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1 INTRODUCTION

In this work is shown the influence of some deformation processes on the final grain size structure, utilizing transmission electron microscope (TEM), of an initially annealed 6063 Al alloy, specifically cold torsion, cold extrusion and tensile deformation, individually or a combination of both of them. Several studies have shown that for many structural aluminum alloys, the combination of strength and toughness is intimately related to the work hardening. Cold forming is usually associated with the “work hardening” of the material being processed. The magnitude of hardening depends on the initial and final dimensions of the product, on the temperature and strain rate during processing, and also on the way the straining is imposed (the so called “strain path”). A wide range of temperatures and strain rates is not common in usual processes. High temperatures are usually employed in intermediate or final annealing cycles, leading to complete or partial softening of the material.

The analysis and control of work hardening has proven to be one of the problems of Materials Science, both because of the complexity of the dislocation processes involved and the non homogeneity of their operation within the deforming microstructure together with presence of a multiphase microstructure on the 6063 aluminum alloy (Al-Mg-Si-Fe).

Strain rate effects are important only for many orders of magnitude in the change of this parameter (Longo & Reed-Hill 1989, Bate 1993, Tanner et al. 1999), which is technically difficult. On the other hand, forming often submits the material to complex strain histories during the deformation. There is thus obvious interest in the analysis of the effect of processing paths. Most of the published studies, however, analyze the mechanical behavior of sheets or straining types typical of standard mechanical tests.

Studies with different materials show that sequential plastic deformation in different directions or of different natures can lead to a low work hardening or even to the work softening of a previously work-hardened material (Backofen & Ghosh 1973, Laukonis & Ghosh 1978, Armstrong 1982, Wagoner 1982, Thomsen 1983, Wilson at al. 1990, Sillekens et al. 1991, Richert & Korbel 1995, Vieira & Fernandes 1995). It has also been observed that cyclic deformations tend to remove or to minimize effects of previous deformations (Polakowski & Palchoudhuri 1954, Coffin & Tavernelli 1959, Yuebo at al. 1989, Subramanyasarma & Padmanabhan 1997). These effects also promote transients in the flow stress, which are caused by the instability of the dislocation structure generated during the initial straining. A further deformation involves the reorganization of the dislocations, which depends on the strain path (Doucet & Wagoner 1989, Yuebo at al. 1989, Richert & Korbel 1995, Subramanyasarma & Padmanabhan 1997).

Drawing is a process where the material is cold reduced and work hardened in one or more successive stages. The inclusion of cyclic torsion after drawing, at the end of the process or between successive stages, would be interesting in order to change the processing strain path and to control the final properties of the products. This association has been investigated using 6063 aluminum alloy rods (Cetlin et al. 1998). The results show that drawing followed by cyclic torsion causes a significant increase of the ductility and a decrease of the yield and tensile strength of the material. The present paper investigates the influence of cyclic torsion on the properties of a 6063 aluminum alloy. A better way to understand the influence of the deformation processes on the microstructure in an annealed 6063 aluminum alloy is by TEM observation.

2 MATERIALS AND METHODS

Initially, the 6063 aluminum alloy was cold deformed in torsion for 20 cycles, 2.8% strain per cycle. Secondly, the annealed 6063 Al alloy was cold deformed in cyclic torsion (2.8%) and cold deformed on tensile test. In the third mechanical processing, the annealed 6063 Al alloy was cold drawn (2 steps, 20% strain in each one). In the fourth, the annealed 6063 Al alloy was cold drawn (1 step, 20% strain) and cold deformed on torsion (20 cycles, 2.8%). Finally, in the fifth processing, the annealed 6063 aluminum alloy was cold drawn (20%) and cold deformed on tensile test. The final microstructure of each deformation process was observed by TEM (JEOL, JEM - 200C, 200kV) and was made with samples obtained from the cross section of the cylindrical pieces of the wrought alloy. Three mm discs for the TEM observation was prepared at -25^{o}C in a double jet electropolish (30% perchloric acid + 70% ethanol).

3 RESULTS AND DISCUSSION

The mechanical behavior of metallic material is entirely dependent of the microstructure of the deformed material. The metallic material hardening depends of the processing, temperature, strength rate and also deformation path. The temperature modification may include softening or hardening rate growth due to spatial dislocation rearrangement (cellular structure) in each temperature.
The analysis and control of work hardening has proven to be one of the problems of materials science, both because of the complexity of the dislocation processes involved and the non homogeneity of their operation within the deforming microstructure together with presence of a multiphase microstructure on the 6063 aluminum alloy (Al-Mg-Si-Fe).
The experimental true stress - true strain curve obtained for the above straining sequence are shown in figure 1. It can be observed that cyclic torsion promotes lower flow stress for pre-drawn material, whereas annealed and twisted material tends to have higher flow stress than material that was only annealed.

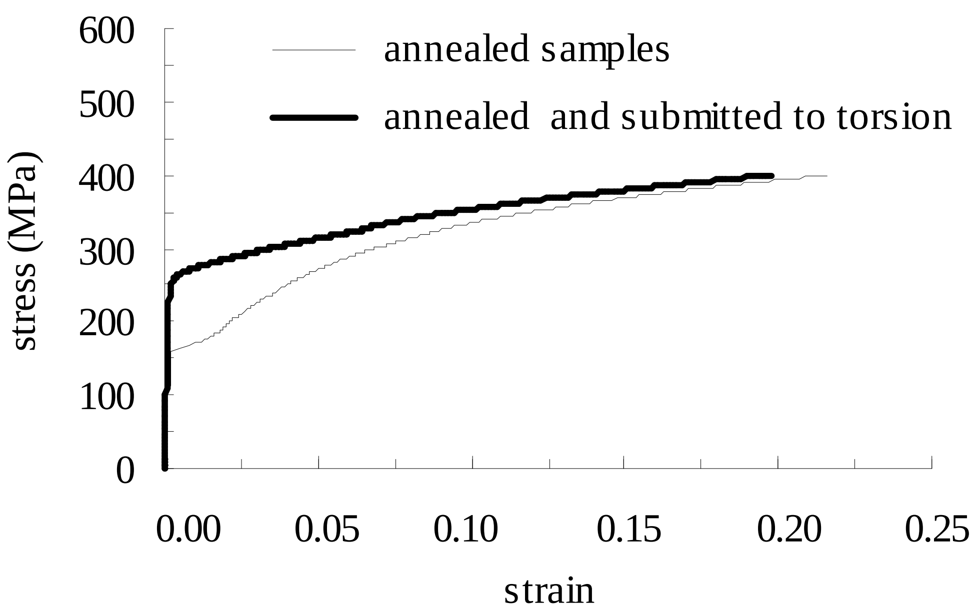

Fig.1. Stress x strain curves obtained in 6063 aluminum alloy (annealed; annealed and torsion process)

Dislocation density for the identical introduced deformation grows while the temperature decreases. The beginning of the cells formation can be delayed with the decreasing of the deformation temperature. At low temperatures the dislocation structure can be complex and at high temperatures, less tangled and with the cells walls well defined.
With the increase of the deformation velocity is possible to obtain a softening of the metallic material; it is an analogous effect to the temperature decreasing: more uniformly arranged dislocations with increasing deformation velocity. Depending of the path of the deformation could have softening or increasing of the hardening rate of the metallic material (Polakowski and Palchoudhuri; Coffin and Tavernelli; Armstrong). The path of the deformation process affects the material hardening characteristics, that is, if occurs a reverse of the path application force the metal undergoes a softening that is related to the geometric arrange of the dislocations (Bauschinger Effect).
At low temperatures the dislocation structure can be complex and at high temperatures, less tangled and with the cells walls well defined. With the increase of the deformation velocity is possible to obtain a softening of the metallic material; it is an analogous effect to the temperature decreasing: more uniformly arranged dislocations with increasing deformation velocity. Depending of the path of the deformation could have softening or increasing of the hardening rate of the metallic material (Armstrong et all 1982, Polakowski & Palchoudhuri 1954, Coffin & Tavernelli 1959). The path of the deformation process affects the material hardening characteristics, that is, if occurs a reverse of the path application force the metal undergoes a softening that is related to the geometric arrange of the dislocations (Bauschinger Effect).
The analysis and control of work hardening has proven to be one of the problems of materials science, both because of the complexity of the dislocation processes involved and the non homogeneity of their operation within the deforming microstructure together with presence of a multiphase microstructure on the 6063 aluminum alloy (Al-Mg-Si-Fe).
In previous work (Cetlin et all 1998), it was shown that cyclic torsion promotes lower flow stress for pre-drawn material, whereas annealed and twisted material tends to have higher flow stress than material that was only annealed. It is noteworthy that the stress-strain curves of the material drawn in two passes and cyclically twisted are quite similar to those of the material that underwent a single drawing pass. That is, cyclic torsion was able to practically eliminate the hardening effects of the second 20% drawing pass. For a second time it is observed that the mechanical properties of the material drawn in two passes and cyclically twisted are similar to those resulting from simple drawing in one pass. The cyclic torsion was able to eliminate almost completely the hardening effects caused by the second drawing pass.
The figure 2 shows an intense and regular cell structure in the three observed grains in the annealed 6063 aluminum alloy that was cold deformed in torsion for 20 cycles, 2.8% strain per cycle. There is also presence of $FeAl_3$, Fe_3SiAl_{12} and $MgSi_2$ precipitates random distributed.
The Fig. 3 shows a more fine and regular cell structure and presence of same identified precipitates in the annealed 6063 Al alloy that was cold deformed in cyclic torsion (2.8%) and finally cold deformed on tensile test.

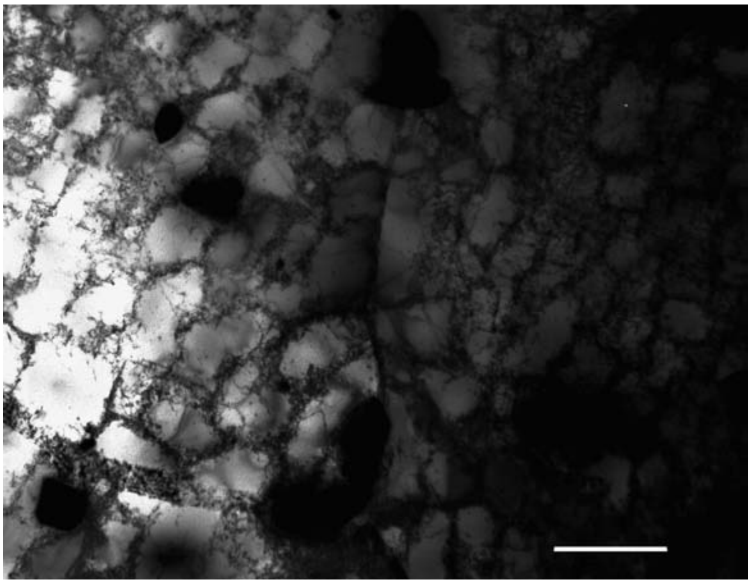

Fig.2 - TEM micrograph: An intense and regular cell structure in the three observed grains in the annealed 6063 Al alloy that was cold deformed in torsion for 20 cycles, 2.8% strain per cycle. Z ≈ (011); (Bar = 5µm)

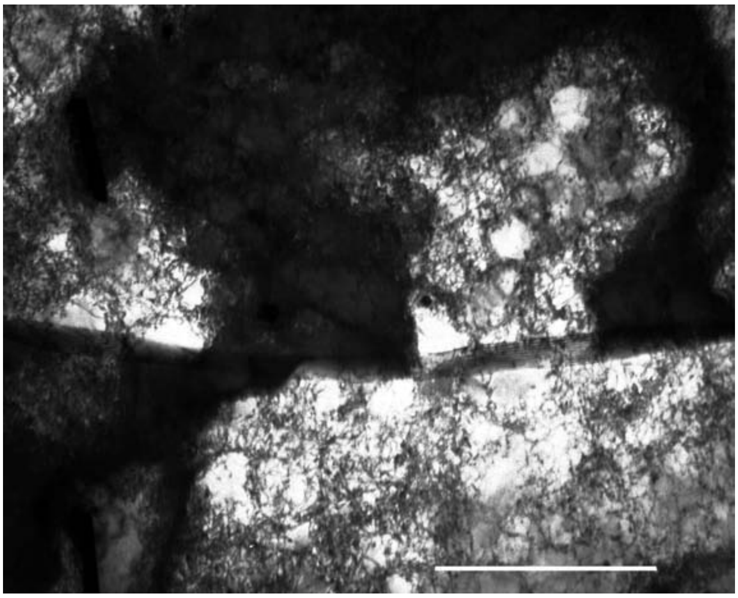

Fig.3 - TEM micrograph: Fine and regular cell structure and presence of same identified precipitates in the annealed 6063 Al alloy who was cold deformed in torsion (2.8%) and finally cold deformed on tensile test. Z ≈ (013); (Bar = 5µm)

The figure 4 shows a random sub-grains structure and a dislocation network inside the grains in the annealed 6063 Al alloy that was cold drawn (2 steps, 20% each one).

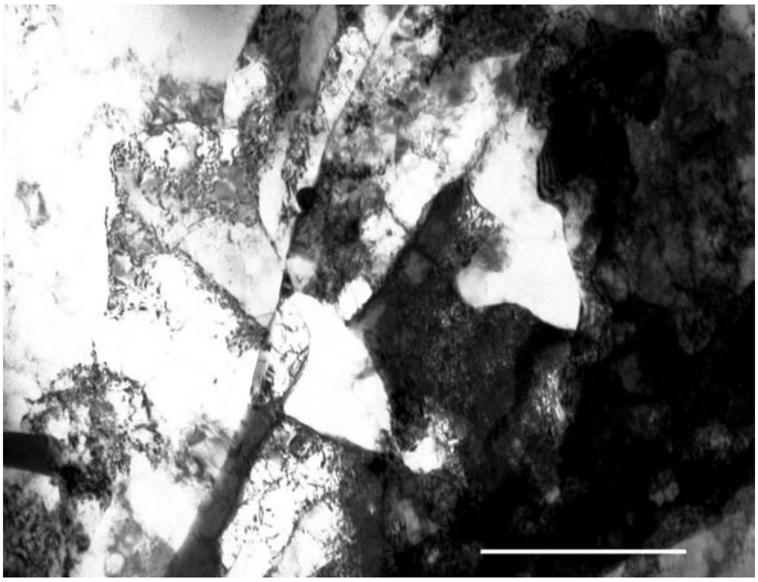

Fig.4 - TEM micrograph: Sub-grains structure and a dislocation network inside the grains in the annealed 6063 Al alloy who was cold drawn (2 steps, 20% each one). Z ≈ (011); (Bar = 5μm)

The figure 5 shows several grains containing a random sub-grain structure with some cellular structure inside them and some identified precipitates in the annealed 6063 Al alloy that was cold drawn extruded (1 step, 20%) and cold deformed on torsion (20 cycles, 2.8%).

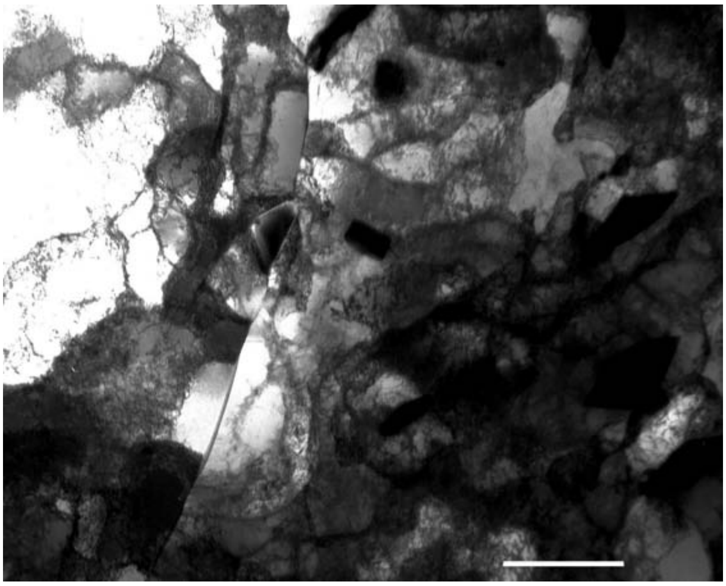

Fig.5 - TEM micrograph: Several grains containing a random sub-grain structure with some cellular structure inside them and some identified precipitates in the annealed 6063 Al alloy who was cold drawn (1 step, 20%) and cold deformed on torsion (20 cycles, 2.8%). Z ≈ (011); (Bar = 5μm)

Finally, in the figure 6, fine sub-grains, dislocation tangles near each sub-boundary and some types of precipitates is shown in the annealed 6063 aluminum alloy who was cold drawn (1 step, 20%) and cold deformed on tensile test (2.8%).

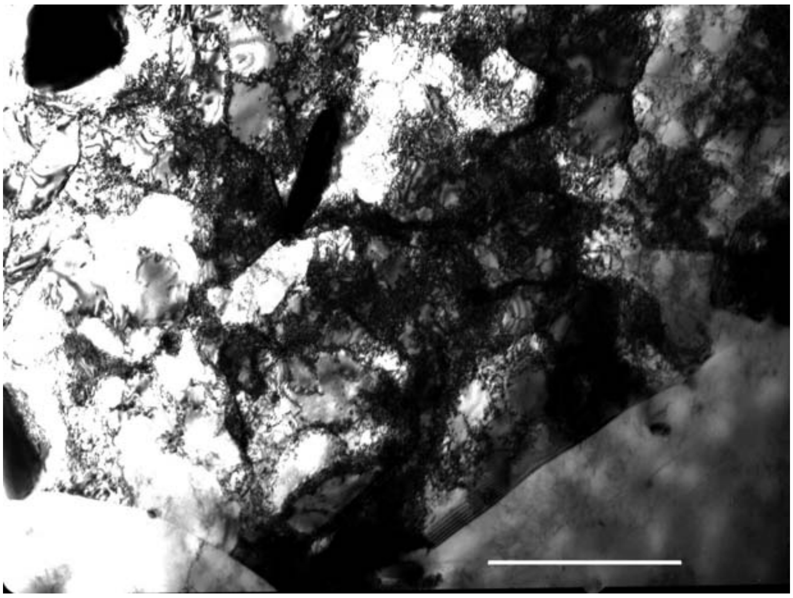

Fig.6 - TEM micrograph: Fine sub-grains, dislocation tangles near each sub-boundary and some types of precipitates in the annealed 6063 aluminum alloy who was cold drawn (1 step, 20%) and cold deformed on tensile test. Z ≈ (011); (bar = 5μm)

The electron micrographs (TEM) show the dislocation structure of the material close to the rod surface, for the drawn and drawn/cyclically twisted material, respectively. Drawing leads to small, irregular dislocation cells displaying relatively intense dislocation tangles in their interior. Cyclic torsion drastically reduces the presence of these tangles and causes an evolution of the cells to a larger size and thinner walls, associated to a “blocky”, aligned aspect. These phenomena are in line with the observed changes in the mechanical properties of the materials. Besides, the observations are similar to those described in the literature for strain path changes in sheets (Wilson & Bate 1994), but seem to be much more intense, probably due to the high straining caused by the cyclic processing.

4 CONCLUSIONS

The work hardening behavior of metals subject to complex processing paths is different from that in monotonic deformation. The sequential association of plastic deformations in different directions or of different types can lead to a lower hardening than monotonic processing or to the softening of a work hardened metal. It is of interest to associate these phenomena to an industrial process such as drawing. In this case the strain softening could promote a “mechanical annealing” between forming stages or in the final product.
It is shown that the cyclic deformation causes changes in the mechanical behavior of the metal, and that the effect will depend on the previous “history” of the material, on the drawing die semi-angle and on the number of passes. These effects were associated to changes in the dislocation structure.
Cyclic torsion was able to practically remove the hardening caused by the second drawing pass, bringing back the material to a condition similar to that for single pass drawing. Cyclic torsion causes a rearrangement of the dislocation structure in the drawn material, eliminating dislocation tangles inside the cells, which become larger and display thinner walls.

The sequence of TEM micrographs, the cell structure or sub-grain formation/ morphology, the dislocation network interaction with precipitates or grains/sub-grains, can elucidate some theoretical aspects about the possible involved hardening mechanism and consequently could enhanced the final structural properties of the wrought 6063 aluminum alloy for industrial purposes as an example.

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