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HOT DEFORMATION BEHAVIOR FOR A THERMOMECHANICAL PROCESSED 2014 ALUMINUM ALLOY BY TENSILE TEST

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Abstract: *This paper present the hot deformation behavior of the commercial 2014-T6 aluminum alloy. The alloy was thermomechanical processed for grains refining in order to improve deformation characteristics. The characteristics of deformation was investigated by using a uniaxial tensile testing at different temperatures (450, 475, 500 ^{0}C) and constant strain rates (5x10^{-4}, 1x10^{-3} s^{-1}). The research included determinations of flow curves characteristics, the maximum elongation to failure, ultimate tensile strength and the microstructure of the alloy. The results showed that the flow stress increased with deformation temperature decreasing and strain rate increasing and it obtained an increase in the deformation degree of the alloy. A maximum elongation to failure of 188.5 % was obtained at strain rate of 1x10^{-3} s^{-1} and temperature of 475 ^{0}C. The deformation characteristics were correlated with the results of the microstructure analysis.*

Key words: *2014 aluminum alloy, thermomechanical processing, constant strain rate, hot uniaxial tensile test, grain refinement.*

1. INTRODUCTION

2014 aluminum alloy is part of the 2XXX series, the system Al-Cu-Mg-Si, including alloys which are very important in the aircraft industry, due to their combination of engineering properties (low specific weight and high strength). 2014 aluminum alloy with higher silicon content presents at T6 state elevated mechanical characteristics and it is used in the aeronautical field in the manufacture of truck frames and aircraft structures and in several mechanical applications, both in the forms of rolled and extruded products.

The potential for use of 2014-T6 aluminum alloy (in forming processes) at room temperature is limited due to the relatively high resistance and poor ductility (tensile elongation of 13% for round sample with 13 mm diameter) [1]. It was found that aluminum alloys exhibit superior ductility at high temperatures.

The understanding of alloy behavior at hot deformation has a great importance for designers of hot metal forming processes (hot rolling, extrusion) because of its role in metal flow. Hot working behavior of alloys is generally reflected on flow curves which are a direct effect of microstructural changes (the generation and the rearrangement of dislocations, work hardening, dynamic recovery, the nucleation and growth of new grains) [2].

High degrees of deformation can be obtained by using grain refinement techniques, for example by thermomechanical processing [3].

A thermomechanical processing is provided for imparting a refined grain structure to the commercial 2014-T6 aluminum alloy which has precipitating constituents. The alloy is overaged to form precipitates by heating, hot plastically deformed by rolling and recrystallized.

Thermomechanical factors, such as the degree of deformation, deformation temperature and strain rate, are the factors that influence the flow stress and the associated microstructure [4].

Strain rate is an important parameter in production, fabrication and testing of materials. Strain rate can have an important influence on the mechanical properties, particularly the flow stress of a material. For most materials, strength properties increase at higher rates of deformation. Some alloys appear to exhibit a modest increase in flow stress over the 10^{-4} to 10^{3} s^{-1} range [5].

The mechanisms responsible for the deformation behavior of the alloys are work hardening and work softening. Work hardening (the increase of flow stress with strain), depend on the dislocation structure developed with plastic deformation. An increase in the flow stress is due to the dislocations storage at obstacles that contribute to hardening. Cross slip or climb of dislocation contribute to softening (the decrease of flow stress with strain) [6].

The objective of this study is to develop a thermomechanical processing procedure for commercial 2014-T6 aluminum alloy bar material and to investigate the influence of strain, strain rate and temperature on the deformation characteristics of processed alloy by hot tensile tests.

2. EXPERIMENTAL RESEACH

The material studied in this paper is the commercial 2014-T6 aluminum alloy (AlCu4SiMg), received in the form of extruded bar with a diameter of 20 mm, produced by S.C. ALPROM S.A. Slatina, Romania. Chemical composition (in wt %) of the received samples is: 4.22 Cu; 0.79 Mn; 0.745 Si; 0.654 Mg; 0.473 Fe; 0.0908 Zn; 0.0339 Ti; 0.033 Cr; 0.0804 Ni; Al-balance. This bar was heat treated to T6 temper, that means that the extruded bar has been solution heat treated and then artificially aged.

Because the ductility of 2014 aluminum alloy as-received is small (tensile elongation smaller than 61.68 % for round samples with gauge length of 25 mm and diameter of 5 mm, tested by tensile testing at the temperatures and strain rates used in this research), the material was thermomechanical processed for grain refining and to enhance ductility.

The specimens from as-received material with length of 40 mm, were heated to an overaging temperature of 450 ^{0}C for 3 hours, to form precipitates by heating. After overaging followed by water quenching, the material was plastically deformed by rolling. Hot rolling was carried out to introduce strain energy into alloy, at the temperature of 440 ^{0}C with a total reduction of 85 % in thickness, to prepare 3 mm sheet thickness, and water quenched. Then the rolled sheets were fast heated up to a recrystallization temperature of 450 ^{0}C, dwell for 20 minutes and quenched in water.

Tensile flat specimens of 25 mm gauge length, 6.6 mm width and thickness of 3 mm, were prepared from the rolled sheet with the tensile axis parallel to the rolling direction. Constant strain rate tests were performed to assess the hot behavior of 2014 aluminum alloy. All tests were performed at temperatures range of 450 ÷ 500^{0}C and at strain rates of $5x10^{-4}$ s^{-1} and $1x10^{-3}$ s^{-1}.

The hot uniaxial tensile tests were conducted on the testing equipment that was interfaced with a computer to provide complete control of the strain rate.

After heating the specimens in the electrical horizontal furnace Carbolite CTF 12/75/700 type, to the required temperatures, for 20 minutes, to each specimen it was applied a tensile axial load, which produced the deformation until fracture. Simultaneous was recording the tensile load and elongation. The true stress-true strain curves have been obtained from the load-stroke data. True stress and true strain are usually calculated by using following formulas: $\sigma_T = \sigma_N(1+\varepsilon)$, $\delta = \ln(1+\varepsilon)$, where σ_T is the true stress, σ_N is the nominal stress, δ is true strain, ε is nominal strain [7].

After each test, the samples were quenched in water to maintain the resulting structure during the test [8].

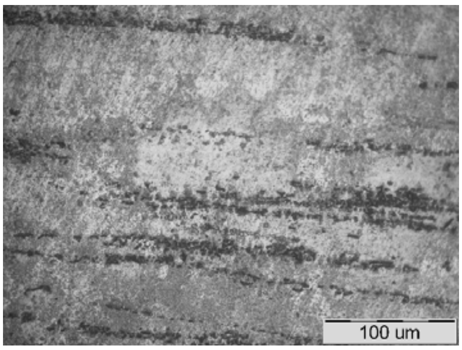
The as received and as-processed aluminum samples were cut in the transversal and longitudinal direction, polydol mounted, and mechanically polished. Keller's reagent was used to reveal microstructure in this material. Microstructures were observed through optical microscopy using a optical microscope type Olimpus Analysis GX51 softwere. The average grain size was determined by the linear intercept method.

3. RESULTS AND DISCUSSION

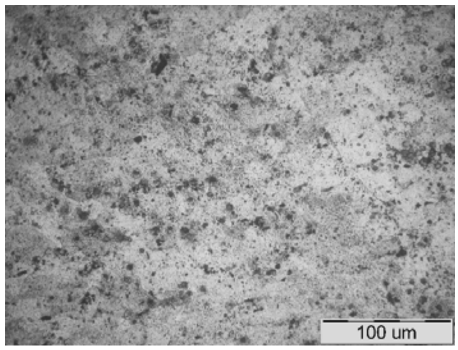
Figure 1 a-d shows the optical micrographs of the 2014 aluminum alloy, as-received, after thermomechanical processing and deformed specimens at temperatures of 475 ^{0}C, 500 ^{0}C and strain rate of 1x10^{-3} s^{-1}, where they had obtained the highest (188.5 %) and the lowest (109 %) elongation to failure.

The 2014-T6 aluminum alloy as received (extruded alloy, solution heat-treated and artificially aged) was characterized by elongated grains, with a transversal size of about 50 μm and by intermetallic particles aligned in the direction of extrusion: globular Al_2Cu particles (bright particles in figure 1.a) and large insoluble particles containing Fe, Mn, Si, Al (darker particles in the same figure). Figure 1.b is an optical micrograph of the thermomechanical processed material. In contrast to figure 1.a, the coarse original structure of as-received 2014 alloy bar has been broken up by the hot rolling process, the processed material did not possess fine grain structure (22 μm), but which was finer that of as-received material.

After thermomechanical processing, intermetallic particles get distributed more uniformly in the matrix of aluminum. The deformed specimen at temperature of 475 ^{0}C and strain rate of 1x10^{-3} s^{-1} exhibited o microstructure characterized of elongated grains and some fine and equaled axes grains and by intermetallic particles distributed in a deformed (and partially recover) matrix, but they are smaller, and in smaller amounts because they entered back into solid solution (Fig. 1.c). The average of grain measured it was of 18 μm. From figure 1.d it can see that for the deformed specimen at temperature of 500 ^{0}C and strain rate of 1x10^{-3} s^{-1}, microcracks were initiated leading to premature fracture, so the deformation process is considered to be unstable.



a)



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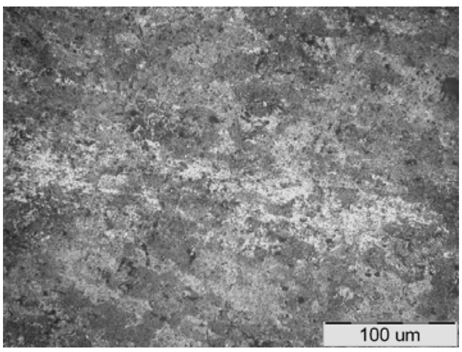
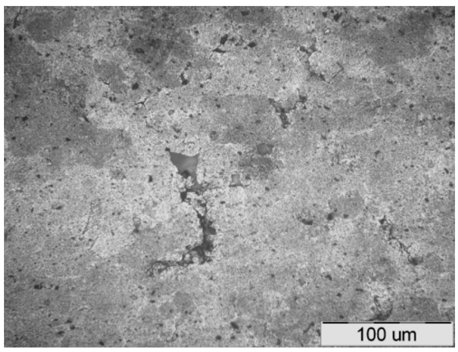


c)



d)

Fig. 1. Optical micrographs of 2014 aluminum alloy specimens in longitudinal section: a) as-received; b) thermos-mechanical processed; c) deformed at temperatures of 475 ^{0}C and strain rate 1x10^{-3} s^{-1}; d) deformed at temperatures of 500 ^{0}C and strain rate 1x10^{-3} s^{-1}.

The flow stress is the most important parameter for characterizing plastic deformation properties of metallic material. It determines the load and energy required during plastic deformation. At hot working temperatures, most metals exhibit a noticeable dependence of flow stress on strain rate and temperature [8].

Figure 2 a-b shows the true stress-true strain curves (flow stress) of as thermomechanical processed 2014 aluminum alloy, obtained from the tensile testing at temperatures of 450 ^{0}C, 475^{0}C, 500 ^{0}C, under constant strain rates of $5x10^{-4}$ s^{-1}, $1x10^{-3}$ s^{-1}. As expected, the magnitude of the flow stress decreases with temperature increasing and strain rate decreasing. This is because lower strain rate and higher temperature provide longer time for the energy accumulation and higher mobility at boundaries for the nucleation and growth of dynamically recrystallized grains and dislocation annihilation and thus reduce the flow stress level [9].

As shown in figure 2 a-b, the flow stress curves exhibit increase up to the peak followed by a gradual softening up to the material fracture. The flow softening is mainly attributed to the dynamic recovery and recrystallization, during hot deformation of aluminum alloy [10]. A lower contribution of work hardening to flow stress level appears at temperatures of 475^{0}C, 500 ^{0}C and strain rates of $5x10^{-4}$ s^{-1}, $1x10^{-3}$ s^{-1}, mainly at temperature of 500 ^{0}C. At the temperature of 475^{0}C and strain rate of $1x10^{-3}$ s^{-1}, where it obtained the highest elongation to failure, the flow stress curve exhibits increase up to the peak value, with a slight hardening and then decreasing gradually after the steady state flow, a nearly horizontal line for an area of flow curve, which suggest that the rate of work hardening is balanced by the rate of thermal softening (Fig. 2.b).

For the specimens deformed at 450 ^{0}C at all the strain rates, after a rapid increase in the stress to a peak value where work hardening predominates, follows the stage with maintaining higher stress level without significant thermal softening and work hardening and then sharp drop of stress.

Ultimate tensile strength and elongation to failure, however, depend on strain rate and temperature. The effect of temperature on elongation to failure is shown in figure 3. Percentage elongation to fracture is between 109 ÷ 188.5%. The maximum elongation of 188.5 % was obtained at strain rate of $1x10^{-3}$ s^{-1} and temperature of 475 ^{0}C. It can be observed that the tensile elongation increases with temperature (in the temperature range of 450 ÷ 475 ^{0}C, at all strain rates) because of the increasing ease of recovery during deformation [8]. At the temperature of 500 ^{0}C, at all strain rates, was obtained the low values of elongation to failure (maximum 114.1 % at strain rate of $5x10^{-4}$ s^{-1}). The cause of lower elongations could be related to the non homogenous grain structure, where relatively high silicon and iron content, so presence of silicon and iron based particles could promote cavitation process [11].

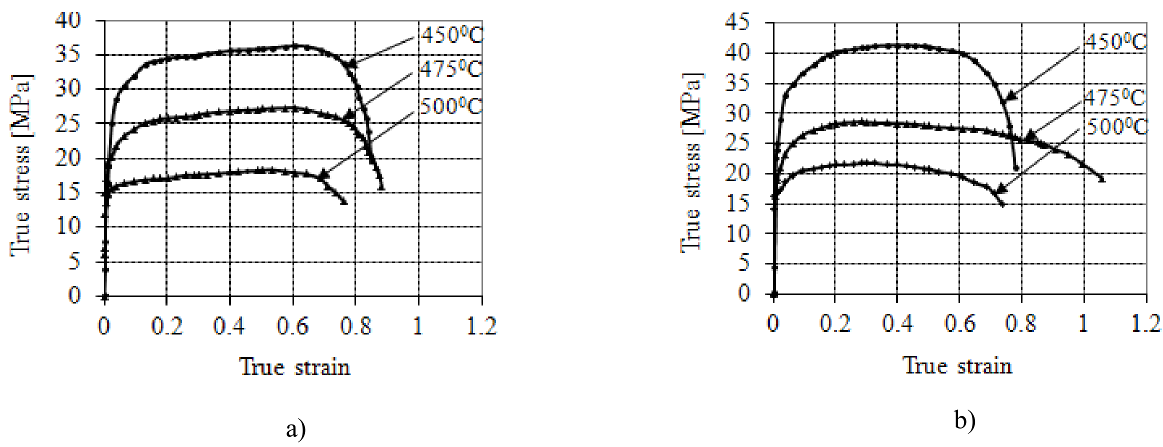


Fig. 2. The true stress vs. true strain curves for 2014 aluminum alloy specimens tensile tested at given temperatures and different stain rates of: a) $5x10^{-4}$ s^{-1}; b) $1x10^{-3}s^{-1}$.

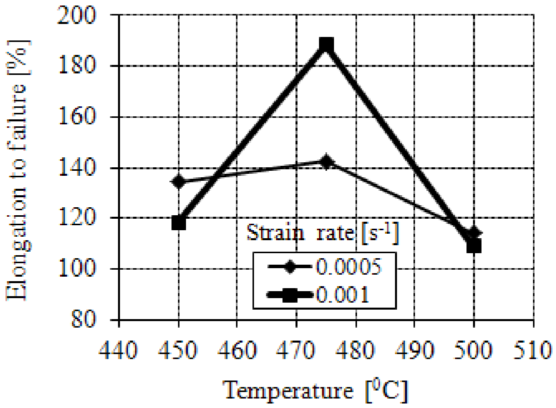


Fig. 3. The variation of elongation with temperature at different strain rate for thermomechanical processed aluminum alloy.

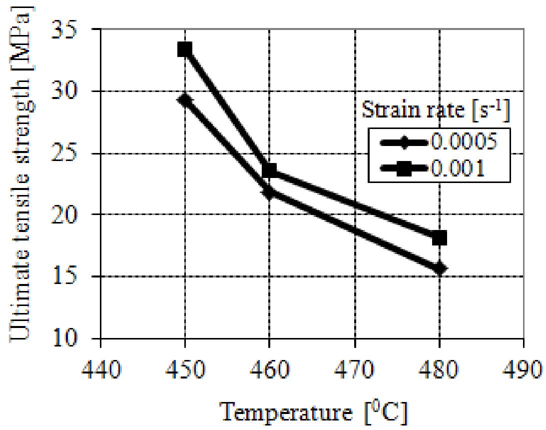


Fig. 4. The variation of ultimate tensile strength with temperature at different strain rate for thermomechanical processed aluminum alloy.

Figure 4 shows that the ultimate tensile strength increases with increasing of strain rate and decreases as the temperature is increased. Decrease of ultimate tensile strength is a consequence of increasing contribution of dislocation climb process, which is characteristic of dynamic recovery [11]. Ultimate tensile strength values range varies between 15.69÷29.29 MPa at strain rate of $5x10^{-4}$ s^{-1} and between 18.20 ÷ 33.37 MPa at strain rate of $1x10^{-3}$ s^{-1}, in the temperatures range 450 ÷ 500^0 C.

4. CONCLUSIONS

- The hot deformation behavior of a thermomechanical processed 2014-T6 aluminum alloy has been investigated by hot uniaxial tensile test at different temperatures (450 ^{0}C, 475 ^{0}C, 500 ^{0}C) and constant strain rates ($5x10^{-4}$ s^{-1}, $1x10^{-3}$ s^{-1}).
- The flow curves analysis showed that the flow stress decreases with temperature increasing and with strain rate decreasing.
- The flow stress curves exhibit increase up to the peak followed by a gradual softening up to the material fracture, but at the temperature of 475^0 C and strain rate of $1x10^{-3}$ s^{-1} is observed gradual decrease after the steady state flow for an area of flow curve.
- The grains of the specimen deformed at temperature of 475 ^{0}C and strain rate of $1x10^{-3}$ s^{-1}, become refined relative towards the initial grains (a grain size of about 50 μm to as-received it was reduced to 18 μm at the specimen deformed).
- Refining of the microstructure leaded to an elongation enhancement of the alloy. The maximum elongation to failure of 188.5 % was obtained at the deformed specimen at a strain rate of $1x10^{-3}$ s^{-1} and temperature of 475 ^{0}C.
- Ultimate tensile strength decreases with increasing of temperature and increases with increasing of strain rate.
- At 500 ^{0}C temperature and strain rate of $1x10^{-3}$ s^{-1}, microstructure becomes unstable, microcracks were initiated leading to premature fracture and there the elongation deteriorates.

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Comportarea la deformare la cald a aliajului de aluminiu 2014 procesat termomecanic prin încercare la tracțiune

Rezumat: Această lucrare prezintă comportarea la deformare la cald a aliajului comercial de aluminiu 2014-T6. Aliajul a fost procesat termomecanic pentru afinarea grăunților, cu scopul de a se îmbunătăți caracteristicile de deformare. Caracteristicile de deformare au fost investigate folosind încercarea la tracțiune uniaxială, la diferite temperaturi (450, 475, 500 ^{0}C) şi viteze de deformare constante (5x10^{-4}, 1x10^{-3} s^{-1}). Cercetările au inclus determinarea caracteristicilor curbelor de curgere, alungirea maximă la rupere, rezistența la tracțiune şi microstructura aliajului. Rezultatele au arătat că tensiunea de curgere a crescut cu scăderea temperaturii de deformare şi cu creşterea vitezei de deformare şi s-a obținut o mărire a gradului de deformare al aliajului. O alungire la rupere maximă de 188.5 % s-a obținut la viteza de defomare de 1x10^{-3} s^{-1} şi temperatura de 475 ^{0}C. Caracteristicile de defomare au fost corelate cu rezultatele analizei microstructurii.

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