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Changes of Grain Sizes and Flow Stresses of AA2014 and AA6063 Aluminum Alloys at High Temperatures in Various Strain Rates

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Abstract

Changes in the grain sizes and flow stresses of AA2014 and AA6063 aluminum alloys subjected to compression tests at high temperatures in various constant compression head speeds were investigated. When assessing the test results, constant strain rates were considered instead of compression head speeds of the uniaxial compression testing system after making the necessary mathematical transformation. Specimens used in the test were prepared in cylindrical form and deformed until 0.7 true strain. As a result of compression tests, true stress-true strain curves were obtained. Test specimens were quenched as soon as the tests ended. The microstructures that occurred after various hot deformations, which materials better mechanical properties were studied with respect to experimental work. Data dealing with mechanical and microstuctural properties under isothermal forging conditions were obtained for industrial applications.

Key words: Aluminum alloys, Plastic deformation, Grain size, True strain, Compression head speed and True strain rate

Introduction

The elasto-plastic behavior of metallic materials is affected by various factors. Temperature, deformation and deformation rate as well as material parameters can be used in constitutive equations for describing the relations between stress and strain or grain size. Temperature is one of the most important parameters, since it directly influences the mechanical behavior of the materials. Temperature also affects material parameters such as grain growth, dislocation density and diffusion mechanisms. The effect of grain size on mechanical properties was investigated by Lui *et al.* (1997) and their results were introduced as the Hall-Petch equation. Similar research was also carried out by Wang *et al.* (1995) to determine a possible dislocation mechanism in the deformation of nano-crystalline metals in contrast to previous research. Moreover, in their research, depending on the deformation conditions, the dislocation pile-up theory was used and it was found that the grain size remained at a reasonable limit. Other research on the formulation of deformation curves of aluminum alloys at elevated temperatures was conducted by Takuda *et al.* (1993) on various aluminum alloys. In their studies changes flow stresses of these alloys were shown by depending on strains, strain rates and temperatures. Research on aluminum alloy was carried out by Charpentier *et al.* (1986). Characteristics and modeling of high temperature flow behavior of aluminum alloy 2024 was examined in their study and they also explained how the microstructures of AA2024 alloy under deformation conditions were affected. Furthermore, Alniak *et al.* (1994) carried out similar research on the effect of high temperatures on the micro-dynamic behavior of super alloy p/m rene 95.

AA2014 alloy is used for rocket chambers while AA6063 alloy is used in the aircraft industry. To obtain better mechanical properties, extrusion of both alloys under elevated temperatures is applied in industrial applications.

The objective of this study was to investigate the effect of high temperature and deformation rate on grain sizes, flow stresses and stress-strain curves. Specimens with deformed microstructures were examined in order to determine the correlation between flow stress and microstructural changes. Data obtained from this experimental work may be used in determining the design characteristics of high pressure and high temperature resistant tubes.

Experimental Studies

Wrought AA2014 and AA6063 aluminum alloys were used in compression tests. The spectrometric analyses of these alloys are given in Table 1.

Test temperatures and deformation rates were specially selected so as to be similar to those in missile and industrial applications. The compression axis of the test machine was parallel to the rolling direction of specimens. During the tests, applied loads on specimens were automatically measured by a loadcell replaced at the lower platen of the test machine and were sent to a printer to be printed as outputs of Force (kg)-Displacement (mm) curves. Then, in order to calculate true stresses, forces were divided among relevant areas of the specimen, which were calculated by means of displacements with a computer.

The isothermal forging characteristics of the compact were evaluated by means of carefully controlled uniaxial compression tests using a high temperature test furnace developed at TÜBİTAK-Gebze. With this system, the compression test piece can be quenched immediately (within seconds) after completion of the test to be preserved for metallographic studies.

In this study compression tests were conducted at 625, 675 and 725 K and at head speeds in ranges from 0.5 cm/min^{-1} to 20 cm/min^{-1}, using small cylindrical compression tests pieces 10 mm in diameter and 15 mm in height. A 1.5 height/diameter ratio was selected to assure a geometrical dimensional factor and homogeneous deformation (Johnson and Mellor, 1973). Test temperatures were kept constant at ±4°C and were controlled by calibrated thermocouples.

In order to reduce friction, to prevent sticking at the die/specimen interfaces and to induce homogeneous deformation, graphite powder was used in the tests.

Results and Discussion

True stress-true strain curves at various test temperatures are shown in Figure 1 for the AA2014 and AA6063 alloys. The true stress gradually and slightly decreased with increasing strain at the given strain rate. In other words, while flow stresses of AA2014 and AA6063 were both dramatically influenced by temperature changes, all flow stress curves showed nearly the same declivity as if flow stresses were independent of applied strain.

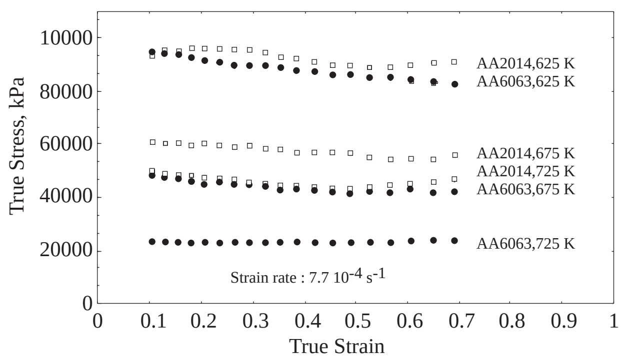

Figure 1. True stress-true strain curves.

Another point is that although AA2014 and AA6063 alloys have different chemical compositions, it is clearly understood from Figure 1 that the declivity of all flow stress curves of these alloys under selected strain rates and temperatures were very similar.

Table 1. Chemical composition of aluminum alloys.

Aluminum	Chemical Compositions, %					Melting
Alloys	Cu	Si	Mn	Mg	Fe	Range, K
AA2014	4.4	0.8	0.8	0.4	-	783-913
AA6063	-	0.45	-	0.43	0.21	824-889

In this study, since compression tests were conducted at constant head speeds, the mathematical equation below was used to transform the constant head speeds into the avarage true strain rates (Johnson and Mellor, 1973).

$$\bar{\dot{\varepsilon}} = \frac{\varepsilon_0}{v_t/\left(H_0 - h\right)} \equiv v_t \frac{\ln H_0/h}{H_0 - h} \tag{1}$$

where

$\bar{\dot{\varepsilon}}$ average true strain rate

ε true strain

h_o initial height of specimen

h : deformed height of specimen

v_t head speed of uniaxial compression testing system

The stress-strain curves of aluminum alloys used in the analysis generally vary with temperature and strain rate. At high temperatures, with increasing strain, stress increases, and then decreases after a peak. However, in almost all cases the degree of work hardening changed at a strain of 0.2 or so. Therefore, a strain of 0.2 and the stress at 0.2 strain are adopted as representatve strain and stress, $\varepsilon_{0.2}$ and $\sigma_{0.2}$ respectively, for the analysis. In this study, flow stresses of AA2014 at 0.2 strain are determined and the changes in flow stresses corresponding to test temperatures and strain rates were given in Figure 2.

In Figure 2, flow stresses increased with increasing strain rates while temperatures decreased.

Strain rate and high temperature parameters also affect the recrystallization of materials. Nucleation and growth reactions of new grains are the most important reaction in metallic materials. New grains nucleate previously at grain boundaries, and recrystallization, as deformation of grains continues, continues at high temperatures (Furu *et al.* 1990). In this study, changes in the grain structures of alloys were observed by means of microstructural analysis. As seen in Figures 3 and 4, grain size increased with a decrease in strain rate and/or an increase in forging temperature, whereas, in Figure 2, flow stress increased with an increase in strain rate and/or a decrease in forging temperature.

By means of microstructural analysis, grain boundaries were determined. In Figure 3, black particles in the main matrix, which belongs to AA 2014, were $CuAl_2$ precipitates, the second phase particles. Grain boundaries of AA6063 alloy can be seen in gray in Figure 4. Growth of grain sizes was seen at 725 K and at relatively low strain rates, such as 7.7 10^{-4} s^{-1}.

It was also observed that, at 725 K, as the strain rate decreased, the growth of grains progressed towards its maximum value. On the other hand, in the case of the lowest temperature and the highest deformation rates, the grains were of minimum size. This phenomenon can possibly be explained the nucleation and grain growth rates.

To calculate the average grain sizes of deformed alloys, the linear intercept method was used. Average grain size values are given in Table 2.

In Table 2, it can be said that the higher the temperatures and the slower strain rates are, the coarser the grain sizes are. The lower the temperatures and the higher strain rates are, the finer the grain sizes are.

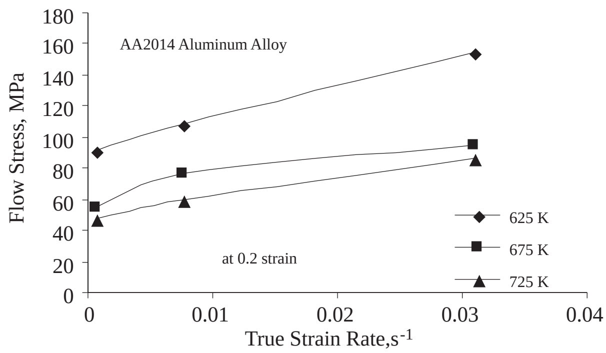

Figure 2. Changes in flow stresses with respect to temperatures and true strain rates

Table 2. Average grain sizes.

True Strain Rates	Average Grain Sizes, μm					
	AA2014			AA6063		
	675 K	675 K	725 K	625 K	675 K	725 K
3.1 10^{-2} s^{-1}	4.7	6.8	8.6	19.8	23.9	27.3
7.7 10^{-3} s^{-1}	5.8	7.5	10.9	22.9	27.3	31.1
7.7 10^{-4} s^{-1}	6.7	10.2	12.4	27.3	31.0	35.9

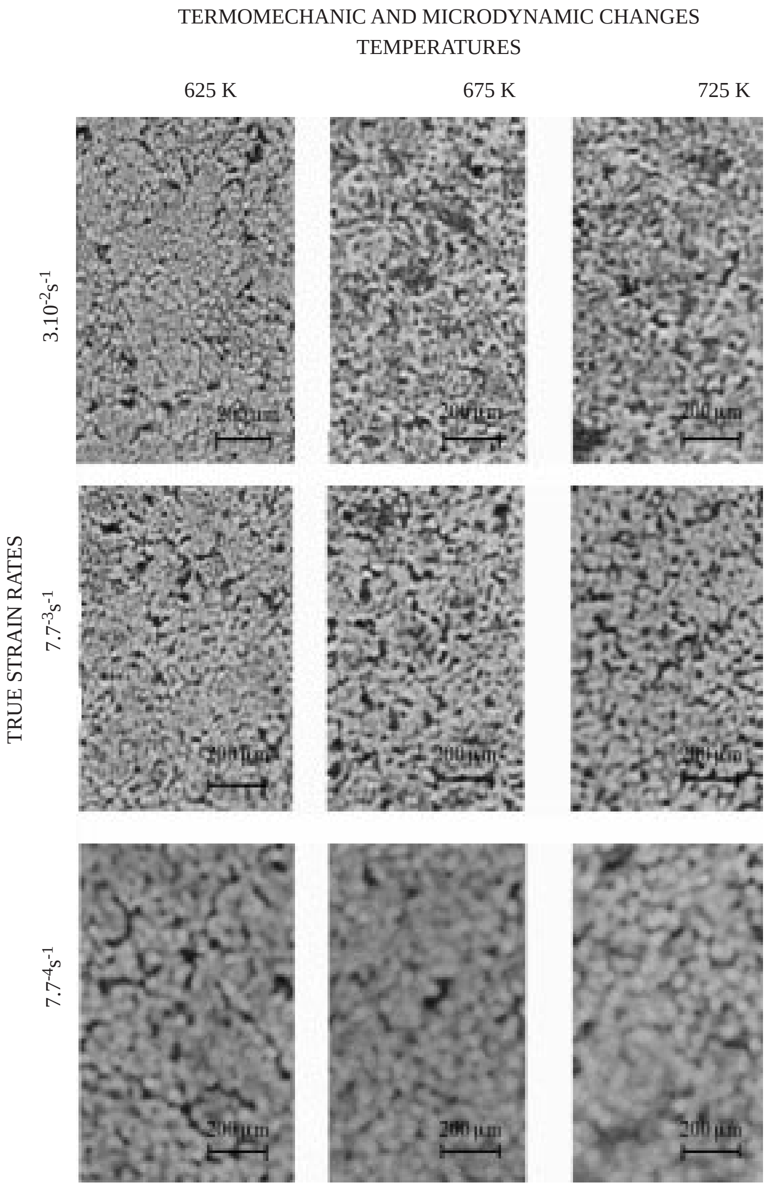

Figure 3. Micrographs of AA 2014 aluminum alloy after different tests.

To see these functional changes, the linear relationship between grain sizes at 0.7 true strain and true strain rates at various temperatures were also plotted (see Figure 5).

It can be easily seen that at constant temperature the linear relationships of average grain sizes-true strain rates curves of both alloys have a negative slope. If this study can be enlarged to include a wider range of various temperatures, especially above recrystallization temperature, and deformation, these functional changes can be expressed as mathematical formulas showing how the lower and upper optimal limits of grain sizes change with the outer and inner parameters of materials.

The Deformed Microstructure

Deformed microstructures were examined in order to correlate strain rates and high temperature with microstructural changes. In this examination, care was exercised to avoid the corners of the specimens and the dead zones where the strains significantly deviate from the average strain.

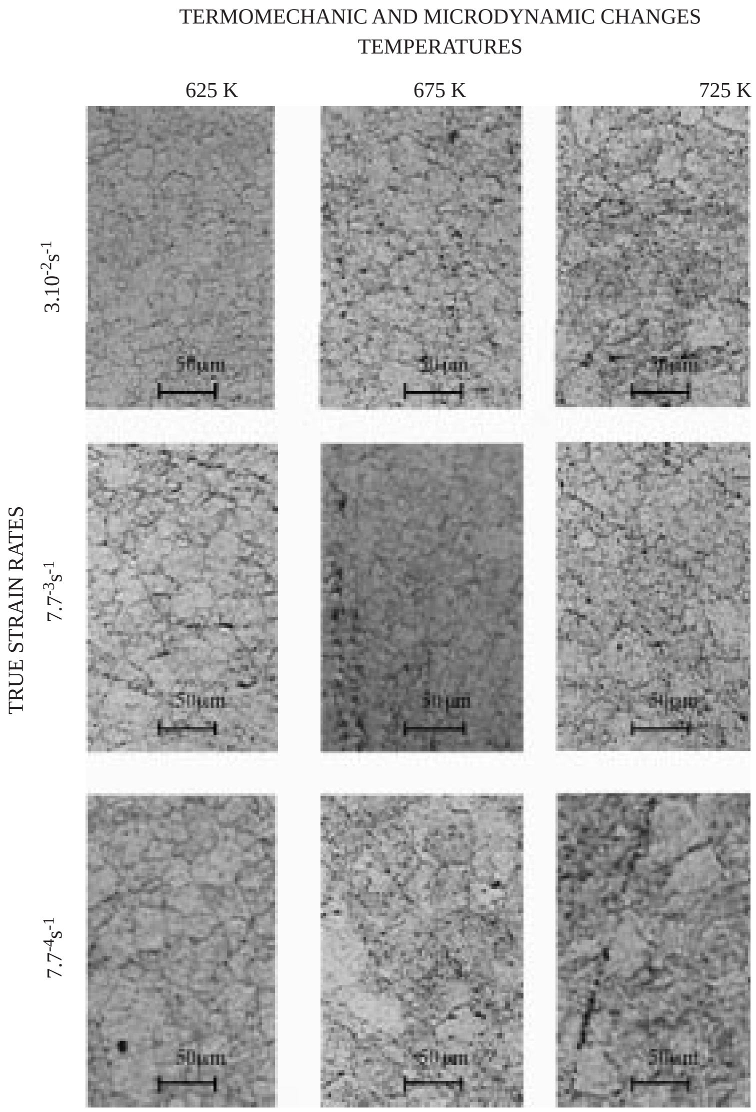

Figure 4. Micrographs of AA 6063 aluminum alloy after different tests.

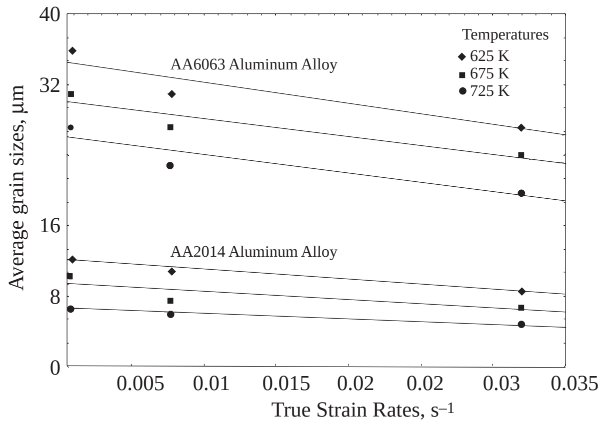

Figure 5. Functional changes in average grain sizes.

Compression at 625 K resulted in a gradual change in microstructure, which increased with increasing strain rate. In these specimens, the grain boundaries were easily etched. At a high strain rate ($3.2\ 10^{-2}\ s^{-1}$), very fine equiaxed grains were seen, especially in AA2014.

Conclusions

1. In this work, the effect of temperatures and deformation on flow stress values during experiments was investigated. It was found that this effect could be expressed by a linear change.

2. It was observed that at high temperatures, flow stresses decreased, whereas grain sizes became

coarser. In contrast, at relatively low temperatures, finer grain sizes were obtained while flow stresses increased.

3. Although AA2014 and AA6063 alloys have different chemical compositions, it is clearly understood from Figure 1 that the declivities of all flow stress curves of these alloys under selected strain rates and temperatures were very similar, whereas there was an important difference between grain growths of alloys under the same conditions. As seen in Figure 5, AA6063 has a larger grain size than AA2014. Grain growth was marginally affected by strain rates, but was dramatically affected by elevated temperatures.

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