Investigation of the deformation resistance of alloy Al-6% Mg alloyed with scandium at hot plastic deformation temperatures

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Abstract
Materials used in transport engineering in addition to high strength characteristics should have a complex of such properties as low density and increased corrosion resistance, as well as the ability to preserve these properties under conditions of continuous operation under loads. To provide these requirements, the chemical composition of aluminum alloys is continuously improved by alloying elements and technological processes for obtaining products from them. One of the most promising alloys is aluminum alloy of the system Al-Mg-Sc.
In the paper, an analysis of the values of the relative coefficients of hardening of metal is given using the hardening-softening technique and also the temperature-velocity parameters favorable from the point of view of the energy efficiency of deformation process are determined for the considered values of the deformation degrees.
It is assumed that the peculiarities in the change in the hardening coefficients are explained by the data on structural changes in Al-Mg-Sc alloys, in particular due to the formation of reinforcing nanoscale particles Al_3Sc and $Al_3(Sc_{1-x}Zr_x)$ and active dynamic recrystallization.
Key words: ALUMINUM, SCANDIUM, DEFORMATION RESISTANCE, TEMPERATURE, DEFORMATION, DEPENDENCE, HARDENING, SOFTENING, METHODOLOGY, ENERGY EFFICIENCY

Alloys of Al-6% Mg type, which are additionally alloyed with scandium (Table 1) are high-strength and are intended to increase the specific strength of structural elements of machines and mechanisms, in particular, welded constructions of rockets and spacecrafts [1].a

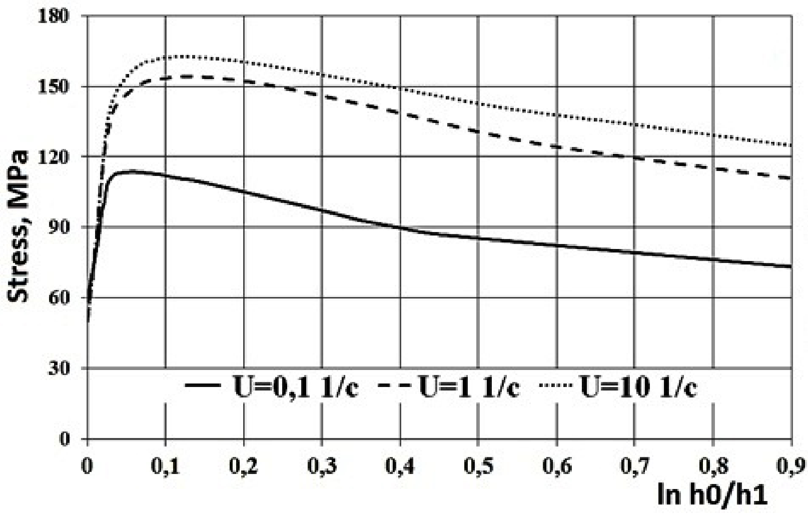
Table 1. The Chemical Composition of Aluminum Alloy 01570 [2, 3]

Basic components, %				Admixture, not more than, %						
Al	Mg	Sc	Mn	Cu	Zn	Zr	Fe	Si	Be	Other amount
basis	6.0	0.35	0.15	0.1	0.1	0.05	0.3	0.2	0.0002	0.1

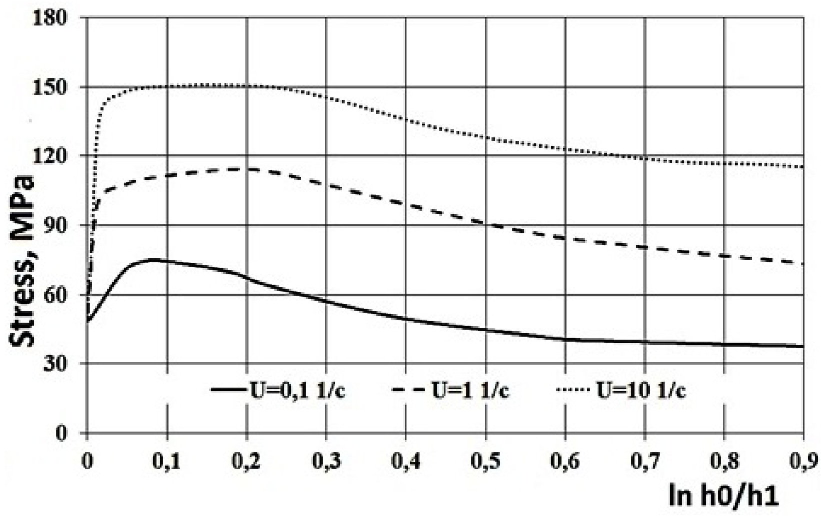
One of the most important tasks in the development and optimization of pressure treatment technologies (rolling, forging, pressing) on existing equipment is the accurate determination of the force parameters of the deformation process. However, the solution of this problem is impossible without information about the rheological properties, in particular the magnitude of the deformation resistance of the materials being processed. Despite the large amount of data on metal rheology (the works of L. D. Sokolov, S. I. Gubkin, V. I. Zyuzin, P. I. Polukhin, P. L. Klimenko, G. G. Shlomchak), the continuous improvement of the chemical composition of materials, which significantly affects the patterns of change in the deformation resistance of materials, stipulates the problem of determining the rheological characteristics of metals.

This is also confirmed by the wide dissemination of mathematical modeling of plastic deformation processes using the finite element method (FEM) [4, 5], for which accurate data on the deformation resistance of metal are important from the standpoint of determining the occurring stresses (quantitative data) in the material and subsequent calculation of energy-related parameters that determine energy efficiency.

A preliminary analysis of published sources has shown that currently data on the rheological properties of this alloy are practically absent and do not fully correspond to the real conditions of conventional forming processes [6-11]. However, the experimental studies carried out by the authors of [12] allowed determining the strain hardening curves of this alloy for the conventional conditions of its deformation (Fig. 1).



a)



b)

a – T=360 °C; *b* – T=420 °C

Figure 1. Stress-strain curves for aluminum alloy 01570 [12]

The objective of this work is to evaluate the parameters of hardening-softening of Al-6% Mg aluminum alloy, which is additionally alloyed with scandium based on analysis of its hardening curves for conditions of hot plastic deformation.

Currently, the authors of [13, 14] have found that the rheological curves of metals cannot be represented as a monotonically increasing function as confirmed by the data in Fig. 1. These curves have a peak of maximum hardening and so-called area of dynamic softening, the account of which has not been used in the design or improvement of the deformation modes.

The hardening-softening technique was used in order to solve the stated research objective, as well as to determine the favorable temperature, in terms of the force parameters of the plastic deformation processes, the temperature range of deformation of the selected aluminum alloy [15]. According to this technique, the intensity of hardening-softening of metals of different rheology was estimated using the coefficients (1) and (2), respectively.

$$K_h = \frac{\sigma_{max} - \sigma_0}{\sigma_{max}} / (\varepsilon_{x1} - \varepsilon_0); \quad (1)$$

$$K_s = \frac{\sigma_{max} - \sigma_2}{\sigma_{max}} / (\varepsilon_{x2} - \varepsilon_{x1}); \quad (2)$$

where: σ_0 – deformation resistance at low deformation values; σ_{max} and σ_2 – the values of deformation resistance at $\varepsilon = \varepsilon_{x1}$ and $\varepsilon = \varepsilon_{x2}$, respectively.

Fig. 2 shows a graphical analysis of these hardening-softening parameters. When analyzing the results, it is evident that the peculiarities in the change in the hardening coefficients are explained by the data on structural changes in Al-Mg-Sc alloys. According to [16], in the structure of Al-Mg-Sc alloys, there are intermetallides of foundry origin: α-phase Al_n(Mn,Fe,Si)m and β-phase (Al_mMg_n), which accumulates on the grain boundaries. In addition, hardening nanoscale particles Al_3Sc and $Al_3(Sc_{1-x}Zr_x)$ can also be formed inside the grains.

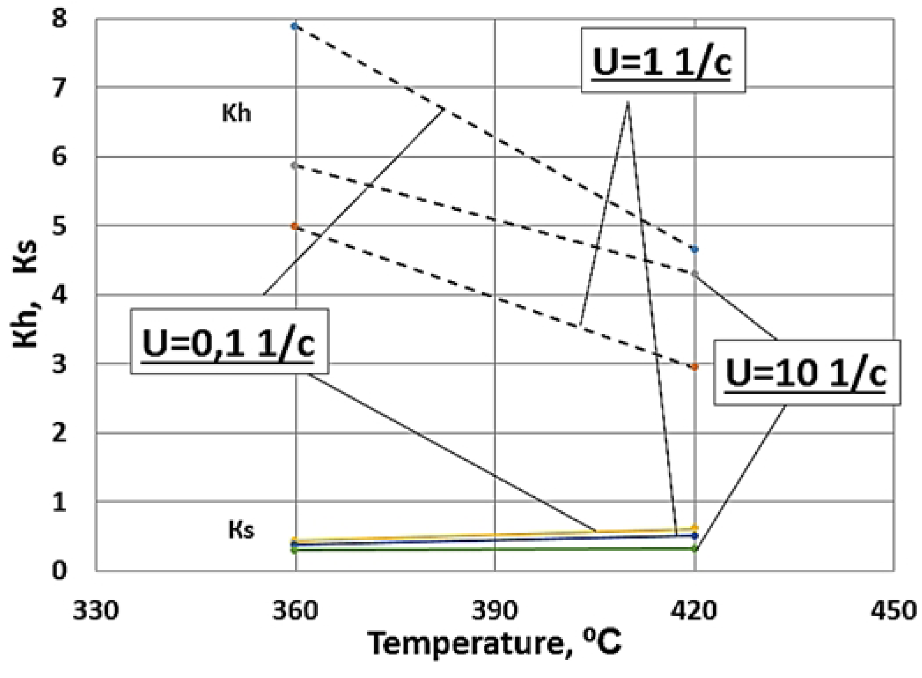


Figure 2. The dependence of hardening intensity (Kh) and softening intensity (Ks) for aluminum alloy 01570

The main process facilitating the material softening in the process of plastic deformation is the active dynamic recrystallization, which occurs through the coarsening of subgrains and their subsequent transition to grains. This circumstance is confirmed by the presence of an unrecrystallized structure in the samples after hot plastic deformation.

Comparing the values of the relative coefficient of metal hardening ($\delta K_h = K_h / K_s$), it is established (Fig. 3) that deformation at temperatures T≤360 °C at the entire range of considered degrees and strain rates is the most unfavorable condition from the point of view of the energy efficiency of the rolling process.

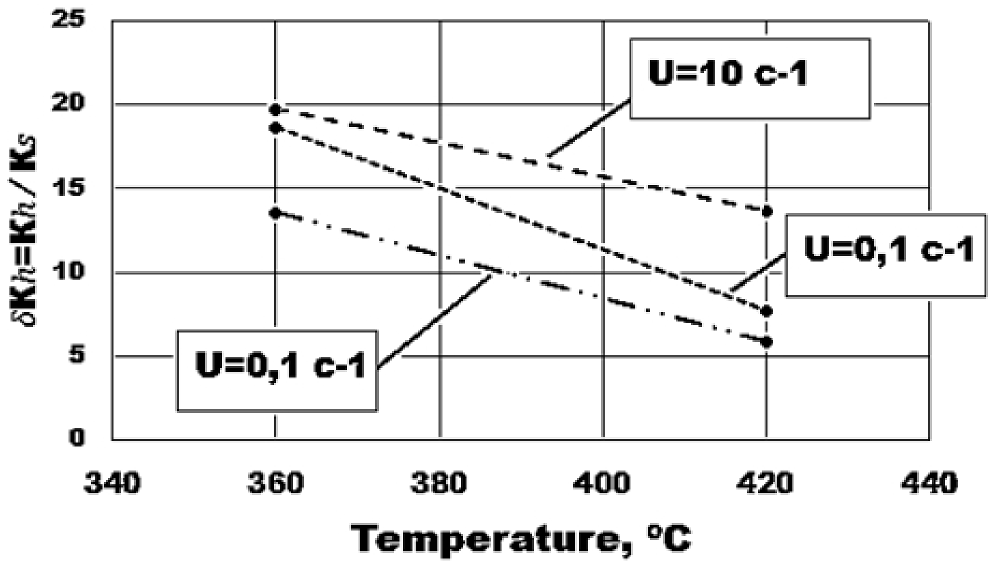


Figure 3. The relative metal hardening coefficient for aluminum alloy 01570

In this case, the most favorable conditions are the temperature-velocity parameters in the range T=380…420 °C $(1 \leq U \leq 10\ c^{-1})$ in the range of deformation degrees of $ln\, h_0/h_1 = 0.3 \ldots 0.9$.

Conclusions

1. The results of the rheology of the Al-Mg-Sc alloy obtained in the course of experimental studies and theoretical analysis allowed confirming the presence of dynamic softening area, which is due to the active dynamic recrystallization during the process of hot plastic deformation.

2. Using the technique for estimating the intensity of hardening-softening, as well as analyzing the values of the relative coefficients of hardening of the metal, it is established that the most favorable from the viewpoint of energy efficiency of the processes of hot plastic deformation are deformation conditions in the range of T=380…420 °C $(1 \leq U \leq 10\ c^{-1})$ in the following range of deformation degrees $ln\, h_0/h_1 = 0.3 \ldots 0.9$.

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