Abnormal strengthening effect after annealing of ultrafine-grained metals produced by ECAP

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It is traditionally assumed that the dependence of strength characteristics of submicrocrystalline (SMC) metals on the annealing temperature has three stages: slight changes in strength during annealing below the recrystallization initiation temperature ($T_{ann}<T_1$) due to recovery processes, rapid softening associated with intensive grain growth during heating of SMC metals ($T_1<T_{ann}<T_2$), and slight changes in strength at higher annealing temperatures ($T_{ann}>>T_2$). At the same time, the analysis of published data shows that annealing of some SMC metals causes the abnormal strengthening effect: these metals become stronger while heating to the temperature that corresponds to the recrystallization initiation temperature.

The target of this research is to study the abnormal strengthening effect observed while annealing of SMC metals. To identify mechanical properties (macroelasticity limit σ_o, yield limit σ_y and K ratio in the Hall-Petch equation) microsamples were evaluated using the method of relaxation compression tests.

It was found that the dependence of σ_o and K ratio on the annealing temperature is determined by the nature of recrystallization processes. In case of abnormal grain growth during annealing of SMC metals, the abnormal strengthening effect is observed and a nonmonotonic dependence of K ratio on temperature takes place. In case of common recrystallization, with the increase of the annealing temperature in SMC metals, macroelasticity limit σ_o is gradually falling and K ratio is growing.

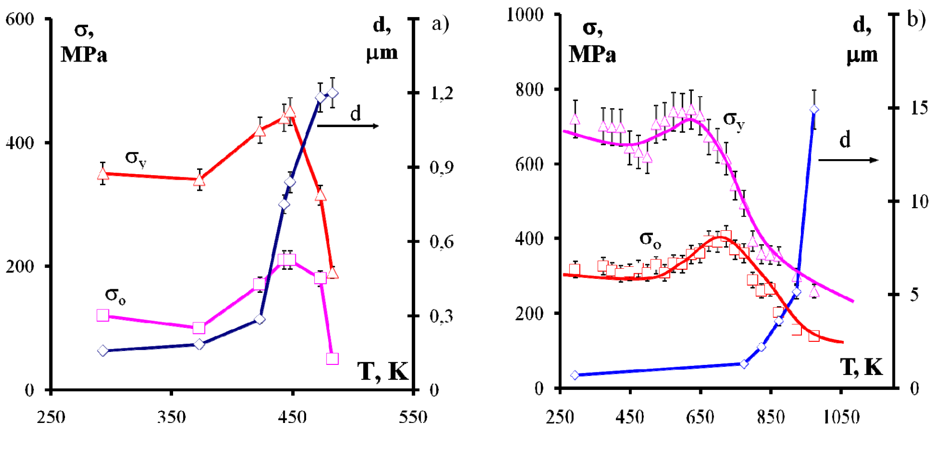

Figure 1: Dependence of $\sigma_o(T)$, $\sigma_y(T)$ and d(t) of SMC copper (a) and SMC titanium (b)

It was shown that the abnormal strengthening effect in SMC metals is rather large-scale: σ_o grows by 50-300% whereas σ_y grows by 10-50% as compared to σ_o and σ_y after ECAP. It was found that the abnormal strengthening effect is observed during annealing at temperatures close to the recrystallization initiation temperature, the scale of increase in macroelasticity limit $\Delta\sigma_o$ far exceeds the scale of changes in yield limit $\Delta\sigma_y$ and microhardness ΔH. Comparative analysis of $\sigma_o(T)$ and $\sigma_y(T)$ dependencies shows that the behavior of dependencies $\sigma_o(T)$ and $\sigma_y(T)$ is uncorrelated, and T_{max} corresponding to maximum strengthening for $\sigma_y(T)$ dependence appears to be shifted to the area of lower annealing temperatures as compared to $\sigma_o(T)$ dependence.

A model was offered for the abnormal strengthening effect that occurs during annealing of SMC metals. The model is based on the ideas underlying the theory of noneqilibrium grain boundaries in metals. It was shown that the abnormal strengthening effect during annealing of SMC metals is related to the accumulation of defects along migrating grain boundaries. Formulae were developed that help to link paramters of the Hall-Petch ratio with the grain boundary migration rate, nonequilibrium level, lattice dislocation density, as well as annealing temerpature and time. Numerical calculations were compared to the experimental results, and their close agreement was proven.

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