Plasticity in Aluminum Alloys at Various Length Scales

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Summary

Dislocations are the basic carriers of plasticity in metals. In a pure metal the dislocations are not severely hindered and therefore the material exhibits a low yield stress and a low hardness. By alloying the properties of the metal can be changed drastically. Dissolved impurities, precipitates and grain boundaries form obstacles for dislocation motion, which increase the critical shear stress and hence the hardness. By correctly alloying, followed by a proper heat treatment, the mechanical properties of the metal can be tailored so as to meet applications in practice. To optimize this process it is essential to have a thorough knowledge of the mechanisms that govern plasticity. In this thesis plastic behavior of several aluminum alloys is studied at different length scales. At an atomic scale the aluminum-scandium alloy is studied. This binary precipitation-hardened alloy is an ideal model system to study precipitation-dislocation interaction. At a larger length scale, the statistical properties of the surface roughness of deformed metals are treated. Finally, on a macroscopic scale the ultimate consequence of plasticity, fracture, is studied.

Microstructure and properties of aluminum-scandium alloys

Recently a growing interest has emerged from industry for the addition of small amounts of scandium to conventional aluminum alloys. No other element has, when added in a similar concentration, the same strengthening effect on aluminum alloys as scandium. Besides the good properties at room temperature, the Al-Sc alloys possess also excellent properties at elevated temperatures, at which regular alloys quickly age. Furthermore, scandium additions can change the recrystallization behavior drastically. In this thesis the excellent properties of aluminum-scandium alloys are described and explained using a microscopic characterization of the microstructure.

During aging of the alloy many nanometer-sized Al_3Sc precipitates are formed. These particles possess an $L1_2$ ordered structure and are coherent with the aluminum matrix. After applying an image processing operation on high-resolution

transmission electron microscopy (TEM) images the size of the precipitates can be determined. After 24 hours aging at 350 °C the precipitates only coarsen very slowly. This explains the excellent properties of the alloy at elevated temperatures.

The homogeneous dispersion of nanoparticles hinders recrystallization up to very high temperatures. Deformed microstructures and the associated properties can therefore be preserved. Already after a few minutes of aging at 350 °C the peak hardness is achieved, which is much higher than the hardness of the annealed alloy with all the scandium in solid solution. This is a remarkable increase, since the amount of scandium is only 0.2 wt.%. Using ex- and in-situ deformed specimens, dislocation structures have been examined with TEM. These experiments show that already the smallest precipitates form a strong obstacle for dislocation motion. For precipitates with a diameter of only a few nanometers, the critical resolved stress increased enough to make the particles impenetrable for dislocation, forcing them to bypass the precipitates by means of the so-called Orowan looping mechanism. As a consequence, in TEM images of deformed microstructures many Orowan dislocation loops are observed. The increase in the critical resolved shear stress due to order hardening is very large. This forms therefore the main contribution to the increase in hardness.
Adding small amounts of scandium to heat-treatable alloys is troublesome, since the temperatures that are regularly used for solution heat treatment and aging of these materials are not the same as the temperatures that have to be used to dissolve or precipitate the scandium. Adding scandium to non-heat-treatable alloys on the other hand is promising. Often these alloys are lacking a strengthening phase and rely for their properties frequently on a deformed microstructure. By adding scandium and forming the Al_3Sc phase, the alloy becomes stronger and the microstructure can be preserved by the resistance the precipitates exert on advancing grain boundaries and hence on recrystallization. This is illustrated in this thesis by measuring the hardness of an Al-Mg-Sc alloy. The combined effect of solid solution strengthening and precipitation hardening gives this alloy a hardness that is, depending on the aging time, at least 100 MPa higher than that of the binary Al-Sc alloy.

Roughness of deformed metal surfaces

When a metal is plastically deformed its surface will roughen. On the one hand this is caused by dislocations emerging at the surface, thereby leaving a step on the surface. On the other hand the roughness is caused by the polycrystallinity of the metal. The differences in orientation create stresses between the grains. This strain incompatibility leads eventually to a roughening of the surface on a length scale of the order of the grain size. In this dissertation a statistical analysis method is introduced, which offers many advantages when compared to conventional methods. A height-height correlation function is applied to topographic data acquired mainly by confocal microscopy. The analysis yields three parameters, which statistically describe the surface in much detail. The roughness exponent α is a measure for the correlation between neighboring points. This correlation turns out to be constant for many rough surfaces up to a specific separation ξ, which is termed the correlation length, above which the correlation disappears. Finally, the rms-roughness w is the most intuitive characterization of the surface.

The measurements performed in this research show that the analysis technique yields valuable information about the typical length scales at which the roughness manifests itself. Measurements on aluminum alloys show a very high correlation of α=0.9 between points with a separation within the correlation length ξ, which is equal to the grain size. The rms-roughness scales linearly with grain size and strain. A similar behavior is observed in bcc iron and zinc, which has a hexagonal crystal structure. Both these metals clearly have lower roughness exponents than aluminum. This may be explained by the cell formation in aluminum during deformation. The rms- roughness is lower for zinc than for the other two metals, for which w is approximately similar. This is explained by the lower number of active slip systems in the hexagonal zinc lattice. This causes large differences between neighboring grain and hence a rougher surface.

Orientation imaging microscopy is used to determine the relationship between the orientation of the grains and the roughness. It is shown that a relation exists, but that many grains have to be taken into consideration to account for the roughness.

Lead embrittlement in aluminum alloy AA6262

To the aluminum alloy AA6262 small amounts of lead are added to increase the machinability of the material. The lead additions give the alloy good properties at high strain rate operations at room temperature. At higher temperatures and at lower strain rates the mechanical properties may change dramatically under influence of the lead. The lead does not dissolve in the aluminum matrix and is mainly found around intermetallic particles and on grain boundaries.

SUMMARY

Under a tensile stress state lead diffuses towards grain boundaries near stress concentrations, where it may cause embrittlement. This so-called dynamical embrittlement takes place at temperatures below the melting temperature of lead (327 °C). Above this temperature the lead becomes liquid and causes different forms of embrittlement depending on the amount of grain boundary wetting.

In this research the dependence of fracture behavior on temperature, strain rate and stress state is studied. Tensile specimen with different notch configuration and thickness are deformed to fracture at different strain rates and temperatures. In a scanning electron microscope the fracture mechanism is studied by examining the fracture surfaces. The alloy fractures mostly in a transgranular way but at low strain rates and at elevated temperatures and a plain stress state the metal can fracture intergranularly.