Plasticity in Aluminum Alloys at Various Length Scales

Wouters, Onne

Publication date:
2006

Chapter 1

Introduction

Within the course of the last two years ... a treasure has been divined, unearthed and brought to light ... what do you think of a metal as white as silver, as unalterable as gold, as easily melted as copper, as tough as iron, which is malleable, ductile, and with the singular quality of being lighter than glass? Such a metal does exist and that in considerable quantities on the surface of the globe.

The advantages to be derived from a metal endowed with such qualities are easy to be understood. Its future place as a raw material in all sorts of industrial applications is undoubted, and we may expect soon to see it, in some shape or other, in the hands of the civilized world at large.

We write 1857; this was the commentary of Charles Dickens on the introduction of the newest metal: aluminum. Although Dickens exaggerated slightly the comparison with other metals, he was right about the value aluminum would pose in future years. Aluminum is three times lighter than iron. Due to the formation of a very thin passivating oxide layer, aluminum has outstanding corrosion resistance. Furthermore the metal has an excellent electrical conductivity, is non-toxic and non-magnetic. Aluminum can be easily formed, machined and cast. With proper alloying and heat treatment, the mechanical properties can be tailored for a wide variety of applications.

When Dickens made those remarks, it was only two years after the presentation of a bar of aluminum at the 1855 Paris Exhibition. Although aluminum is, after silicon and oxygen, the third most abundant element in the Earth's crust, a piece of the metal was halfway the 19^{th} century still considered a very precious object. This is due to the fact that aluminum, cause of its high reactivity, does not exist in nature in

its pure form, but always in an oxidized state. Extracting the element from its ore bauxite is still a very costly process, as it requires a lot of energy.
The first person to succeed was the Danish scientist Hans Christian Ørsted. In 1825 he managed to extract a minute, relatively impure quantity of aluminum. Friedrich Wöhler however, is generally credited for purifying the metal. In 1827 he described a procedure, which produces powdered pure aluminum by reacting potassium with anhydrous aluminum chloride. This recipe was further improved by Henri Sainte-Clair Deville, making the production commercially possible.
Aluminum remained however precious and was not used industrially until in 1886 two scientists developed independently a method to extract pure aluminum from its main oxide: alumina (Al_2O_3) via electrolysis. This Hall-Héroult process, named after its discoverers, is still the basis for the aluminum production today. The alumina is dissolved in cryolite (Na_3AlF_6), which acts as an electrolyte between cathode and a carbon anode. A small voltage is applied and the resulting high currents facilitate the production of pure aluminum at the cathode. This is still a costly procedure; approximately 16 kWh of energy is needed to extract one kilogram of aluminum from alumina. Consequently most of the aluminum produced today is recycled. After alloying and casting, the aluminum is mostly hot-rolled into plates of varying thickness or extruded with high pressure into the desired shape.

The mechanical properties of an aluminum alloy are highly dependent on its microstructure. By alloying and heat treatment the strength, toughness, stiffness, hardness and ductility of the alloy can be adjusted to meet the requirements set by the application of the final product. To optimize the alloy properties, a good understanding is needed of the different processes that are in operation when a piece of material is deformed. Although deformation takes place on an atomic scale, studies of the deformation characteristics on a larger scale can be very relevant, for instance when the deformation is mainly governed by material properties that vary over larger length scales, such as grain orientations in polycrystalline material. Furthermore, in many instances only the collective processes are relevant. Statistical analyses over larger areas are in those instances essential. In this thesis we will address in particular the deformation of polycrystalline aluminum alloys at different length scales.

At an atomic scale, the deformation characteristics are determined by the interaction among dislocations and between dislocations and other lattice imperfections, such as grain boundaries, impurity atoms and precipitates. In chapter 3 we present a summary of the concepts of dislocations and how they interact with a homogeneous distribution of particles. The chapter is preceded by chapter 2 that describes the various experimental techniques used in this research. To study the deformation of the metal at different length scales, different techniques have to be employed. Most of them will be explained in a concise way. The images produced using transmission electron microscopy, are however less easily interpreted. Therefore, more space is reserved to explain this technique in detail.

In this thesis dislocation-particle interactions are studied experimentally for the aluminum-scandium system. The results are presented and discussed in chapter 4. Recently the Al-Sc system has been given a great deal of attention, because of its remarkable hardening characteristics and its excellent performance at elevated temperatures, which is often the Achilles' heel of conventional aluminum alloys. Only a very minute addition of 0.2 wt.% scandium to a pure aluminum will improve its mechanical properties substantially. The hardness for instance will increase from around 200 MPa for pure aluminum to more than 600 MPa for the Al-0.2wt.%Sc alloy. This is a hardness increase unbeaten by additions of any other elements at this concentration. Clearly, the Al_3Sc precipitates that are formed during proper heat treatment are obstacles for the dislocation motion. This study will shed some light on this using (in-situ) transmission electron microscopy, which is, in the beginning of the chapter, also used to give an appropriate microstructural description of the alloys.

On a much larger scale, plastic deformation of metal alloys leads to surface roughening of the material. Dislocation motion leaves steps at the surface, which appear not to be distributed randomly, but grouped in slip bands. Deformed metal pieces show a roughness, which is clearly visible with the naked eye. This roughness has some major industrial implications since it influences for instance the adhesion of coatings on the metal or because it determines the general (esthetic) appearance of the final product, which has often been subjected to major deformations during the production process. A rough surface may also cause the occurrence of stress concentration and eventually of crack nucleation sites. In chapter 5, the statistical characteristics of this roughness are studied along with its dependence on the grain structure, precipitation, thickness and crystal structure of the material.
The roughness is determined for length scales comparable to the grain size and for smaller scales using confocal microscopy and atomic force microscopy, respectively. Since activity of slip in a grain depends on its orientation with respect to the applied stress, many orientation imaging microscopy measurements are made to determine the orientation of the grain of interest.

In chapter 6, the final experimental chapter of this thesis, a more practical industrial problem regarding deformation and fracture in aluminum alloys is treated. Low melting point metals with a low solubility in aluminum such as lead are often added to an alloy to improve its machinability or are an unwanted addition to the alloy due to improper alloying or cheap scrap recycling. The deliberate addition in order to increase machinability, a low temperature and low strain rate operation, may often prove detrimental when the material is deformed at elevated temperatures (above or even slightly below the melting point of lead) or at low strain rates. Stress-induced diffusion towards and over grain boundaries may transform the mode of fracture from highly ductile to very brittle. Chapter 6 aims at understanding the dependence of the mode of fracture of an AA6262 alloy, which has an addition of only 0.08 at.% lead, on temperature, strain rate and stress state using mainly scanning electron micrographs of fracture surfaces.