GRAIN BOUNDARY DEFORMATION AND FRACTURE OF A FINE GRAINED, HIGH PURITY Al-2% Mg ALLOY AT 150° C (423K)

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ABSTRACT. Intercrystalline deformation and fracture at elevated temperatures are well established phenomena, and are relatively well defined in terms of temperature, stress and grain size. Grain boundary sliding, leading to intercrystalline fracture, is usually considered to be an embrittling behavior, and worsens with decreasing strain rate, decreasing grain size and increasing temperature. Very coarse grained metals and alloys avoid intercrystalline failures even at very high temperatures by undergoing slip and slip band deformation, even up to the melting temperature. Based on the rule that the slip band spacing is inversely proportional to the stress, coarse grained structures can accommodate coarse slip band spacings to very high temperatures. Following this reasoning, a high purity Al-2% Mg alloy, prepared with a grain size finer than about 10 mm, undergoes grain boundary sliding, minor grain boundary migration, and intercrystalline cracking at 150° C (423K). The extent of grain boundary sliding and cracking are a function of the grain size and the stress.

1. Introduction

The importance of the influence of grain size on the mechanical properties and creep behavior of polycrystalline materials cannot be overemphasized. Because crystalline materials are composed of grains and grain boundaries, the deformation and fracture behavior of materials is naturally related to the individual and combined patterns of both structural entities. Grain size, grain shape and grain and grain boundary geometry will affect the mechanical behavior patterns by undergoing different modes and amounts of deformation and fracture over a range of stresses and temperatures. Our understanding of grain size effects and grain boundary behavior has been greatly enhanced by significant experimental and theoretical work in the past.(1-14) Because mechanical behavior depends strongly on temperature and stress, deformation and fracture patterns are usually labeled as high temperature and low temperature types.

For "high temperature behavior" it is routinely accepted that grains boundaries are weaker than grains leading to the concept of an equicohesive temperature(1), a temperature at a specific strain rate, wherein fractures may be crystalline or intercrystalline or both. All metallic alloys will show the existence of a transition deformation and fracture behavior when creep and stress rupture properties are plotted over a significant stress and temperature range.(2,3,6,8,9) Appropriately, microscopic and macroscopic grain boundary

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sliding were observed and extensively measured over a wide range of temperatures and strain rates (15-20), leaving no doubt that grain boundary sliding (gbs) was an extremely important "high temperature" deformation process. The influence on tensile, stress rupture, creep strength and ductility were recorded for many metals and alloys and found to be predictably responsive to temperature and stress(1-22). This led to the development of new creep and creep-rupture theories and was particularly important in understanding the issue of ductility under conditions which lead to intercrystalline cracking.(6,20,22,23) The grain boundaries act as strengthening agents, because they block slip from easy transmission from grain to grain at "low" temperatures, and act as weakening agents because they undergo easy sliding under conditions involving higher temperatures, lower stresses and finer grain sizes.

During granular deformation, the development of fine slip leads to the formation of slip bands which gradually develop inhomogeneously with increasing plastic strain, resulting in a minimum slip band spacing at saturation, responding to the stress as it is influenced by temperature and the amount of strain. (3,4,9,24)

In the early forties, Orowan (24) proposed a theory of the inverse relationship between stress and the slip band spacing; this relationship was confirmed as being independent of temperature.(3,24) Many years later, Servi and Grant's extensive data on high purity Al provided the confirming experimental evidence to prove the validity of Orowan's theory as shown in Fig. 1.(2,3)

In the "low temperature behavior" region, it was found that the effect of grain size on strength generally followed the Hall-Petch relationship. Most theories were developed on the experimental fact that grain boundaries impede crystalline slip transfer from one grain to another; and the models which were proposed were, in essence, of the mantle and core type(26-28). In contrast to high temperature behavior, only grain boundary blocking effects were considered, and grain boundary sliding was not considered as a factor at low temperatures, at least not explicitly, though grain boundary sliding had been reported at low temperatures.(29,30)

Practically all of our understanding of the hot deformation of polycrystalline pure materials and simple high purity alloys is based on experimental work with relatively coarse grained materials, significantly larger than 100 μm and up to 2 mm or more. This is understandable because coarse grains are much more stable than fine grains, and it is much easier to differentiate the behavior of grains and grain boundaries by using coarse grained specimens. We know that fine grained materials have better mechanical properties at low temperatures, and instinctively strive to produce fine grained materials. Although columnar, oriented, coarse grained and single crystal turbine blades have been extremely successful for very high temperature applications, most materials, particularly large structures intended for high temperature use, because of difficult processing and cost considerations, are generally "fine grained".

Coarse grained materials are less ductile at room and low temperatures, whereas the ductility of fine grained materials is superior and more reproducible at both high and low temperatures.(2) Great interest has been generated in fine and ultra-fine grained materials with the growth of rapid solidification technology and makes it particularly important to predict the mechanical behavior of such materials at both very low and high temperatures.