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ALUMINUM ALLOYS: FABRICATION, CHARACTERIZATION AND APPLICATIONS

Corrosion Resistance Performance

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STRENGTH AND FAILURE OF ULTRAFINE GRAIN AND BIMODAL Al-Mg ALLOY AT HIGH TEMPERATURES

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Abstract

Uniaxial tensile tests are conducted at room and high temperatures on a bimodal grain size Al-Mg alloy with an ultrafine grain matrix as the major constituent to evaluate the strength and failure mode of the material. The coarse grain ratio and anisotropy effects are also investigated as parameters that could influence the mechanical behavior. It was found that the strength of the material decreases rapidly with temperature such that at 473 K, it was somewhat weaker than a comparable conventional alloy. Dynamic recovery was observed and found to be dependent on coarse grain ratio. Strength anisotropy was found to be reduced with increasing temperature. No evidence of thermally or mechanically assisted grain growth were observed.

Introduction

Ultrafine grained (UFG) materials have been shown to exhibit greatly improved strengths when compared to their coarse grained (CG) counterparts [1-3]. This is due to Hall-Petch strengthening where reductions in grain size tend to increase the strength of a material due to dislocation pile ups at grain boundaries. Unfortunately, this tends to severely limit the ductility, and thus the applications, of these UFG materials. One way that has been successfully implemented to restore some of the ductility to the material is to incorporate CGs into the UFG microstructure, created a bimodal grain size distribution [4-9].

Due to their prevalence and abundance of other favorable traits, Al-Mg alloys such as Al 5083 have been the focus of a large amount of the work in this area. Bimodal microstructures have shown great improvements in strength with acceptable ductility. However, several studies have shown that the mechanical properties of these alloys depend on a variety of factors including fabrication procedures, CG composition, material orientation, and strain rate [2,6,10-13].

In order to further the understanding of the factors that influence the mechanical properties of these materials, specifically bimodal Al alloy 5083, this study examines the effects of temperature on this material. Additionally, it also considers how test temperature influences some of the other effects known to be present in the material such as CG volume ratio and anisotropy. These factors are investigated through uniaxial tensile tests.

Specimen Fabrication and Mechanical Experiment

Al 5083 powder was cryomilled in liquid nitrogen for 8 hours to create a UFG powder. This powder was V-blended with unmilled (CG) powder to create mixtures of 10%, 20%, and 30% CG by volume. The mixture was hot vacuum degassed at 723 K for 8 hours then consolidated through cold isostatic pressing (CIP). Finally, high strain rate extrusion was used to bring the billet up to its final density and break up the prior particle boundaries (PPBs). Flat dog-bone specimens were cut from the extruded rod (about 20 mm in diameter) using electric discharge machining (EDM) in the configuration shown in Figure 1. To look for anisotropic effects, the specimens were cut both parallel to the direction of extrusion (the longitudinal direction) and perpendicular to it (the transverse direction).

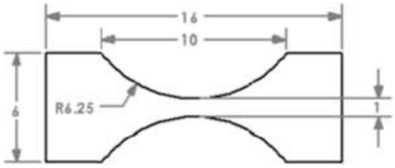


Figure 1. Test specimen, dimensions in mm.

A full factorial experiment was designed to explore the effects of temperature anisotropy, and CG ratio. The levels of each parameter tested are shown in Table I. Uniaxial tension tests were conducted on a TestResources 800LE load frame. Strain was measured with strain gauges attached in the center of the gauge length of the specimens with a two part adhesive suitable for the temperature range tested. Before testing, specimens were allowed to soak at temperature for 30-45 minutes until thermal expansion and thermal drift became negligible. Three specimens were tested for each combination of parameters.

Table I. Levels of parameters tested.

Parameter	Levels
CG Ratio	10%, 20%, 30%
Temperature	293, 383, 473 K
Material Direction	long., trans.

Results and Discussion

Figure 2 shows the engineering stress-strain curves for the material with 10% CG ratio. As seen in this figure the ductility increases significantly at higher temperatures. As expected, the temperature has a negative effect on the yield strength and ultimate tensile strength of material as the strength decreases drastically as temperature increases. Elongation at failure was not able to be measured in tests above room temperature since the increase in ductility found at these temperatures exceeded the range of the strain measuring equipment. However, qualitative observation of the test results indicates that ductility continually increased with rising temperature.. Additionally, the deformation of the specimen cross section at the failure surface was found to be more pronounced at higher temperatures.

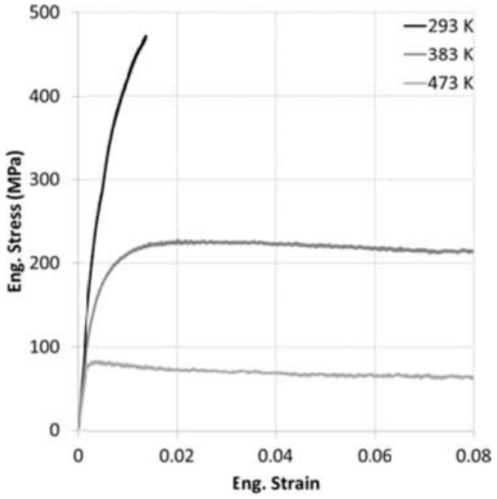


Figure 2. Stress-strain curves for 10% CG longitudinal tests at different temperatures.

Figure 3 illustrates a comparison between the bimodal grain size Al 5083 and the conventional Al 5083 with grains at micrometer range. The Hall-Petch effect is found to significantly increase the strength of material at room temperature by more than three times. However, as the temperature increases, the strength of the bimodal grain size material decreases so drastically that it falls below of that of conventional Al 5083. This indicates that not only reduction in grain size is not helpful at higher temperatures, activation of temperature dependent mechanisms, most likely diffusion and grain boundary sliding, affect the strength of material negatively. Similar effects have been noted in several similar nanostructured materials based on Al-Mg alloys [15-18].

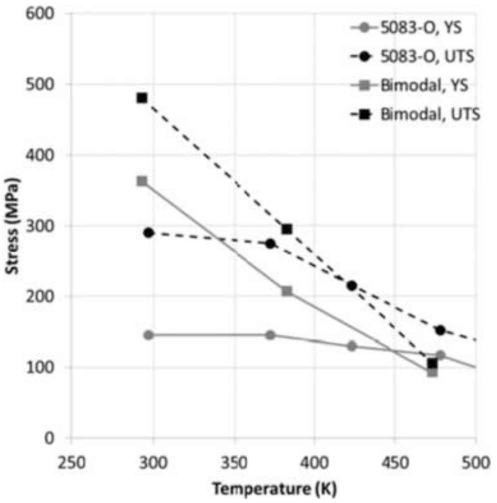


Figure 3. Reduction in yield stress (YS) and ultimate tensile stress (UTS) with temperature of conventional [14] and bimodal Al 5083.

An explanation for this behavior is that at higher temperatures, grain boundary sliding becomes more active in nanostructured materials. Additionally, higher temperatures lead to reductions in the dislocation pile-ups that contribute to the Hall-Petch strengthening mechanism [15]. Together, these effects may explain the dramatic decreases in the strength of these materials at elevated temperatures.

Another interesting observation is that because of dynamic recovery observed at higher temperatures, the yield strength and the ultimate tensile strength in bimodal grain size material are almost equal at 473 K. Dynamic recovery was found to produce significant strain softening in tests at 383 and 473 K. The amount of recovery was observed to increase with temperature, and was also found to be dependent on the CG ratio. Material consisting of a higher volume of CGs was found to be less inclined to dynamically recover, as shown in Figure 4. Since thermally unstable dislocations are the driving force for this recovery, these results are taken as a sign that the dislocation accumulation behavior of the material varies based on CG ratio. This is supported by the fact that the CG regions and interfaces are known to play a large role in how dislocations travel through the microstructure, as well as the uneven distribution of loads and deformation to the different phases during loading [6,19-20].

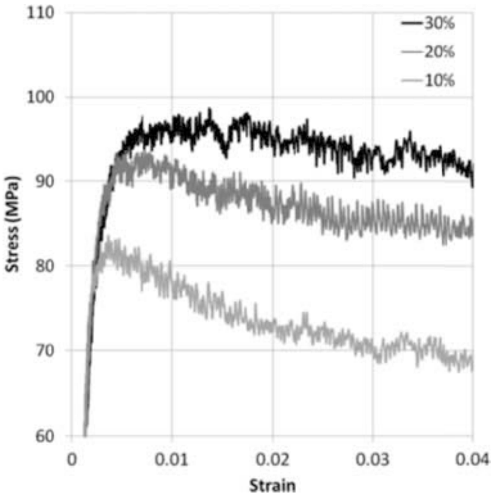


Figure 4. Dynamic recovery in longitudinal tests at 473 K.

Anisotropic effects due to the extrusion process have been observed in this material. The elongation of the microstructure in the direction of the extrusion results in a reduction of strength and ductility in the transverse direction. Tensile tests results conducted in direction transverse to extrusion direction, shows that the material fails in a more brittle manner in this direction, with an average reduction of ductility by a factor of about 2.5 at room temperature.

Temperature was found to reduce some of the effects of this anisotropy. In Figure 5, at room temperature the previously mentioned reduction of strength in the transverse direction is apparent. At higher temperatures, the magnitude of this reduction decreases, so that at the highest temperature tested, there is little difference in strength between the two directions. Although, as mentioned before, there was no way to quantitatively measure the ultimate strain at higher temperatures, Table II attempts to determine whether the anisotropic differences in ductility also decreased with increasing temperature. This data suggests that a difference in ductility, though unquantifiable, persisted through all temperatures tested. Furthermore, it is difficult to tell whether this difference was being reduced with increasing temperature.

Table II. Effect of temperature on ductility.

Temperature [K]	Ultimate Strain [%]	
	Longitudinal	Transverse
293	2.8	1.0
383	>9.0	3.5
473	>9.0	>9.0

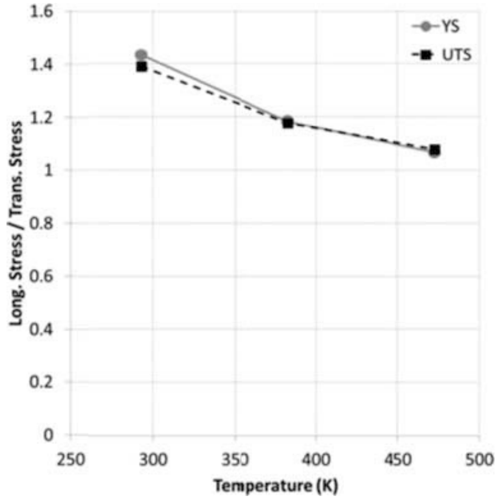


Figure 5. Ratio of YS and UTS in the longitudinal direction to the transverse direction.

Hypothetically, thermally or mechanically induced grain growth could be cause of some of the behavior observed at higher temperatures. The effects of the mechanical and thermal loads during the test on the grain structure were investigated through electron backscatter diffraction (EBSD) analysis. Samples tested at room temperature and at 473 K were imaged at locations near the fracture surface and in the grip area. This provided a way to compare the effects of mechanical loading and temperature.

No significant differences in the grain size and orientation of the microstructure (Figures 6 and 7) were observed between the different conditions. This is perhaps not so surprising since the grain size has been previously shown to be very stable with respect to temperature [16,21-22]. Additionally, with no pre-test picture of the microstructure in the exact same location to compare with, any kind of thermally or mechanically activated grain boundary sliding that may have occurred during deformation would not be necessarily obvious in a post-test image. These images and the grain size distributions contained in them also fail to show evidence for mechanical grain growth. The shortcomings of these EBSD images in clarifying the deformation mechanisms active in the bimodal Al-Mg alloy are currently being addressed through the development of experimental procedures and simulations with the goal of shedding light on this topic.

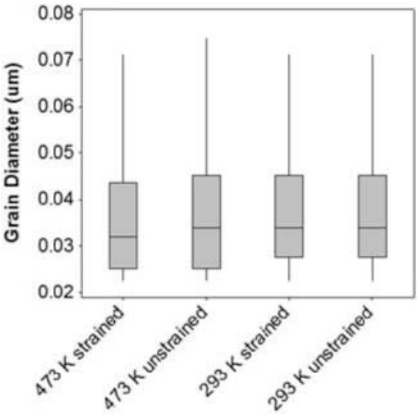
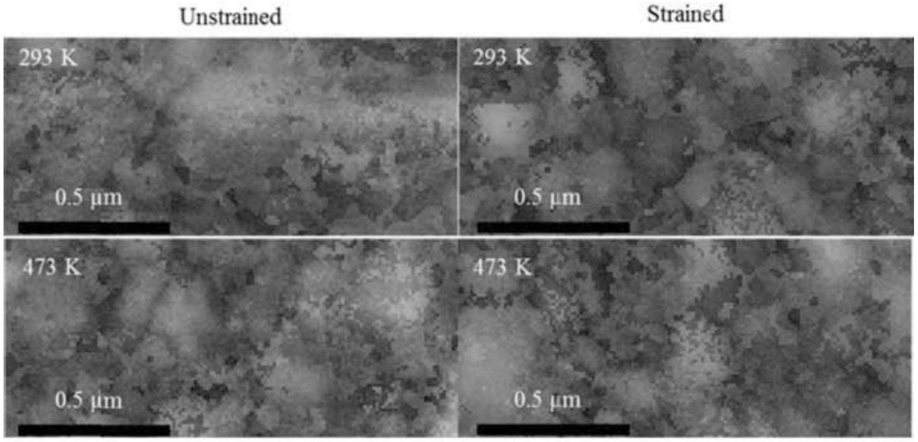


Figure 6. Grain size distribution at each of the locations imaged.

Conclusion

The effects of elevated temperatures on the mechanical properties of a bimodal Al 5083 alloy were evaluated. It was found that Hall-Petch strengthening plays a diminished role in the strength of the material as temperature increases and that at sufficiently high temperature the bimodal material is actually slightly weaker than a comparable conventional Al-Mg alloy. The effect of material orientation on strength was found to also be reduced at higher temperatures. EBSD images of the microstructure failed to show evidence of thermally or mechanically promoted changes in grain structure or size. Other thermally activated mechanisms, such as grain boundary sliding or rotations, are deemed to be responsible for this behavior. These mechanisms are currently under investigations.



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