HIGH STRAIN RATE PROPERTIES OF AN ALUMINA DISPERSION REINFORCED COMPOSITE

I. W. Hall[1] *and M. Guden*[2]

1 . *Department of Mechanical Engineering,*
University of Delaware, Newark, DE, USA
2 . *Izmir Yuksek Teknoloji Enstitusu*
Gaziosmanpasa Bulvari No.16, Cankaya, Izmir, Turkey

SUMMARY: A metal matrix composite reinforced with submicron sized alumina particulates has been subjected to compression testing at strain rates from $10^{-3}s^{-1}$ to $2.5x10^{3}s^{-1}$ and at temperatures from room temperature up to 350°C. The 5% flow stress of the composite was found to decline from approximately 500MPa to 370MPa as the temperature increased to 350°C, and the composite showed a mild strain rate sensitivity similar to that for unreinforced aluminum. Shear band formation was noted at high strain rates at room temperature but did not occur at higher temperatures. Metallography showed that the properties were associated with an exceptionally fine and temperature insensitive microstructure.

KEYWORDS: metal matrix composite, aluminum, high strain rate, microstructure, strain rate sensitivity

INTRODUCTION

Metal matrix composites generally obtain improved properties through so-called composite strengthening while dispersion strengthened alloys obtain theirs through interaction of dislocations with a fine dispersion of thermally stable particles. A relatively new family of alumina-reinforced aluminum materials is becoming available, termed DSC™, in which a large volume fraction of nano-sized alumina particles can serve both functions. Since these materials rely for their strengthening on the presence of very fine particles, they are used in an essentially unalloyed state. The small size of the particles means that the excellent machining properties of the pure alloy are maintained while the ductility, strength, and particularly the elevated temperature mechanical properties, are greatly improved by the presence of the thermally-stable, non-coarsening particles.

As MMC's enter service in more demanding areas, it is increasingly likely that they will be exposed to loading conditions involving high strain rates during service, for example, during collisions between motor vehicles. In such situations of rapidly increasing loading conditions, the material property response may be considerably different from that which applies during slow loading of normal quasi-static testing and, consequently, dynamic mechanical properties are of increasing interest and importance.

Prior research on metal matrix composites has shown that, in common with their unreinforced matrix alloys, they exhibit strain rate sensitivity to varying degrees. Frequently it is found that the higher the alloy content, the lower is the strain rate sensitivity and, also, the greater the matrix yield strength the

lower the strain rate sensitivity since thermal softening is more pronounced. The present research was undertaken to further examine the mechanical properties of these new composites to determine their high strain rate properties and the extent to which their behavior resembled that of conventional MMC's and, in particular, to investigate further their high temperature properties.

EXPERIMENTAL

Mechanical tests have been performed in compression at strain rates from quasi-static up to $2.5x10^3s^{-1}$ upon cylindrical samples of the composite consisting of pure aluminum reinforced with 40%Al_2O_3 nano-particles. A few tests were also conducted upon 99.99%Al samples to provide a baseline comparison for the unreinforced matrix. All samples were 8mm in diameter and 8mm in height, giving an l/d ratio of 1, a ratio which has been shown to yield consistent and accurate results in this type of test. Tests were performed either on a screw-driven Instron machine at a strain rate of $2x10^{-3}s^{-1}$ or with the Split-Hopkinson Pressure Bar which allows the determination of true stress *vs.* true strain curves at high strain rates. Samples tested at high temperature were allowed to equilibrate for 10 minutes prior to testing and the entire sample region was enclosed in the furnace. Correction for the resulting temperature gradient was not necessary since the elastic modulus of the Inconel 718 bars does not change significantly in the temperature range investigated.

Several reflections of the elastic wave must occur within the sample in order for it to achieve a state of homogeneous stress. This requires several microseconds at the outset of the test, corresponding to a strain of a few percent, during which there is considerable uncertainty in the stress state. For this reason, it is common practice to report the flow stress at 5% strain as the parameter for comparison: this will be the approach adopted herein. Detailed information on the present SHPB and data reduction in this technique are given elsewhere [1,2].

RESULTS

Mechanical Testing

On account of its very low yield stress, only limited room temperature testing of the pure aluminum was carried out but it was found that its flow stress was approximately ~72MPa at room temperature and decreased to ~35MPa at 350°C under quasi-static test conditions. The summary results of the remaining mechanical tests are presented below in Figure 1. The most striking feature of the data is that the flow stress of the composite is a factor of almost an order of magnitude higher than that of the pure Al unreinforced matrix over the entire temperature and strain rate ranges investigated.

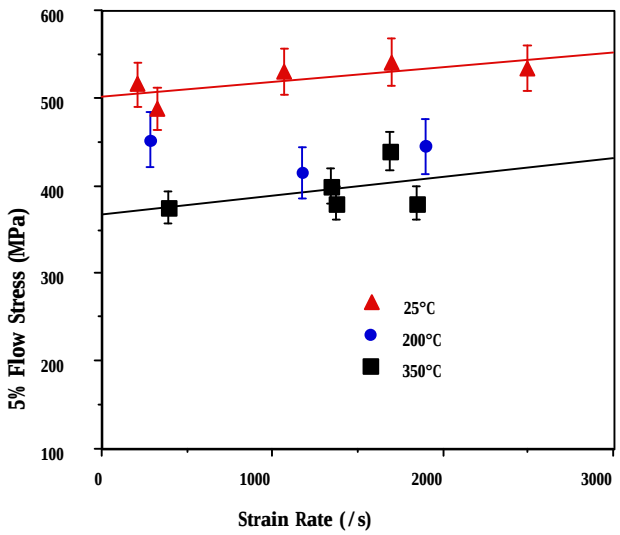

Figure 1. Flow stress at 5% strain as a function of strain rate at various temperatures. Linear data fits are shown for 25°C and 350°C

The composite showed a room temperature 5% flow stress of ~510MPa under quasi-static conditions and this showed a low value of strain rate sensitivity up to strain rates of $2500s^{-1}$. Higher temperatures produced a decrease of ~20% in the flow stress and no significant change in the strain rate sensitivity.

Samples tested quasi-statically at any temperature showed monotonically increasing stress *vs*. strain curves as the sample eventually underwent barreling. At strain rates above 10^3s^{-1}, however, there was an increasing tendency to show shear banding at room temperature. This phenomenon was clearly visible in the stress strain curves and is depicted in Figure 2 which shows data from tests on samples tested at $2.5x10^3s^{-1}$ and $1.7x10^3s^{-1}$. Shear banding was not noted during testing at 200°C or 350°C.

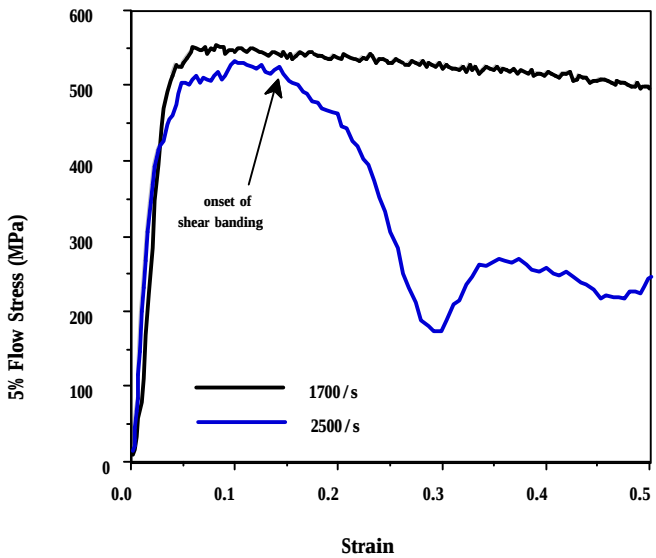

Figure 2. Stress *vs.* strain curves for samples tested at room temperature, showing effects of shear band formation at high strain rates

In addition, whereas high strain rates at room temperature led to a softening phenomenon, testing at 200°C and above did not lead to such an effect. On the contrary, continued hardening was noted at all strains, even before noticeable barreling occurred.. This behavior is illustrated in Figure 3 showing stress *vs.* strain curves from samples tested at room temperature and 200°C and at the same strain rate of $1.7x10^3s^{-1}$.

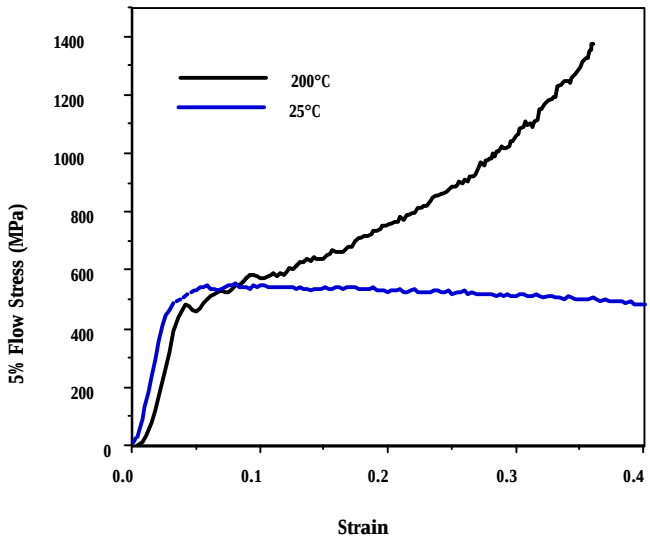

Figure 3. Stress *vs.* strain curves of samples tested at $1.7x10^3s^{-1}$ at different temperatures showing effects of thermal softening at room temperature.

Metallography

The occurrence of shear bands was noted from the stress *vs.* strain curves and these were also located in polished and etched samples. Shear band generation led to cracking and severe local deformation although no details of microstructural effects could be detected because of the fine scale of the microstructure, Fig. 4. In fact, the exceptionally fine grain size of the composite rendered it impossible to reveal conventional optical microstructural detail. Consequently, transmission electron microscopy (TEM) was used to investigate the structures. Figure 5(a) shows the general microstructure of the composite before testing: the grain size is noted to be on the order of 200-500nm and the size of the reinforcing Al_2O_3 particles is approximately 200nm. Figure 5 shows a region of a sample tested to 30% strain at $1.7x10^3s^{-1}$. There was no significant detectable difference in structure between this and the as-received material, either in terms of grain size or average dislocation density.

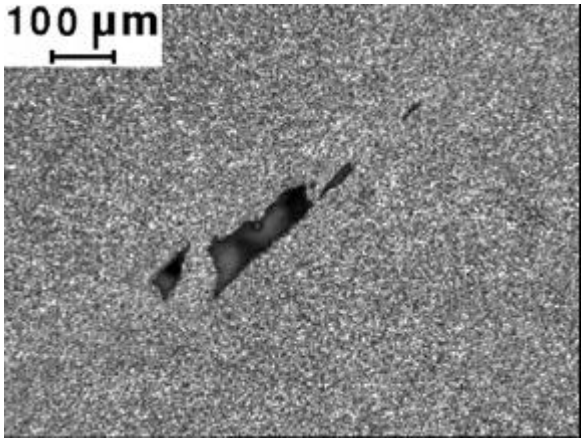

Figure 4. Optical micrograph showing shear band nucleation.

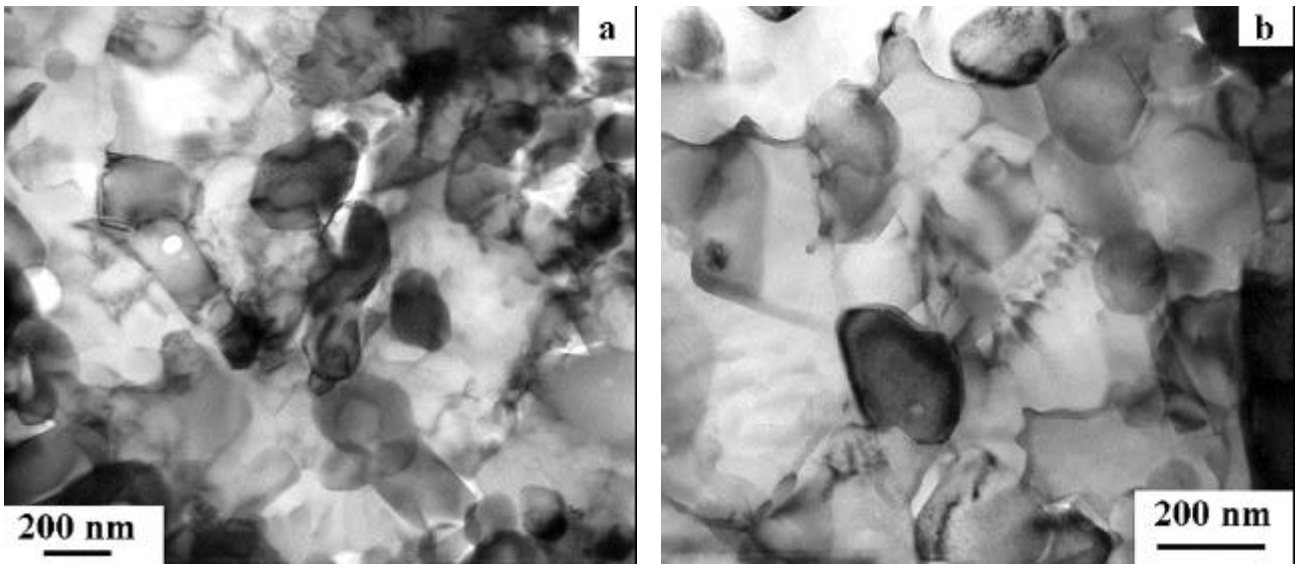

Figure 5: Transmission electron micrographs showing a) structure of composite before testing: Al grain size is ~200-500nm and Al_2O_3 particulate size ~150-250nm; b) composite after testing to >30% strain at 200°C showing no noticeable microstructural alteration.

Fractography

Scanning electron microscope (SEM) examination of fractured samples showed intensive shear dimpling on all those fracture surfaces which had not been obliterated by smearing of the opposing face, Fig 6(a). Closer examination of the surfaces revealed that clusters of the fine alumina particulates could be detected in many of the dimples, Fig. 6(b). SEM examination of polished sections was unable to reveal any details within the shear bands, therefore, their approximate widths could not be used to estimate the total local shear strain generated.

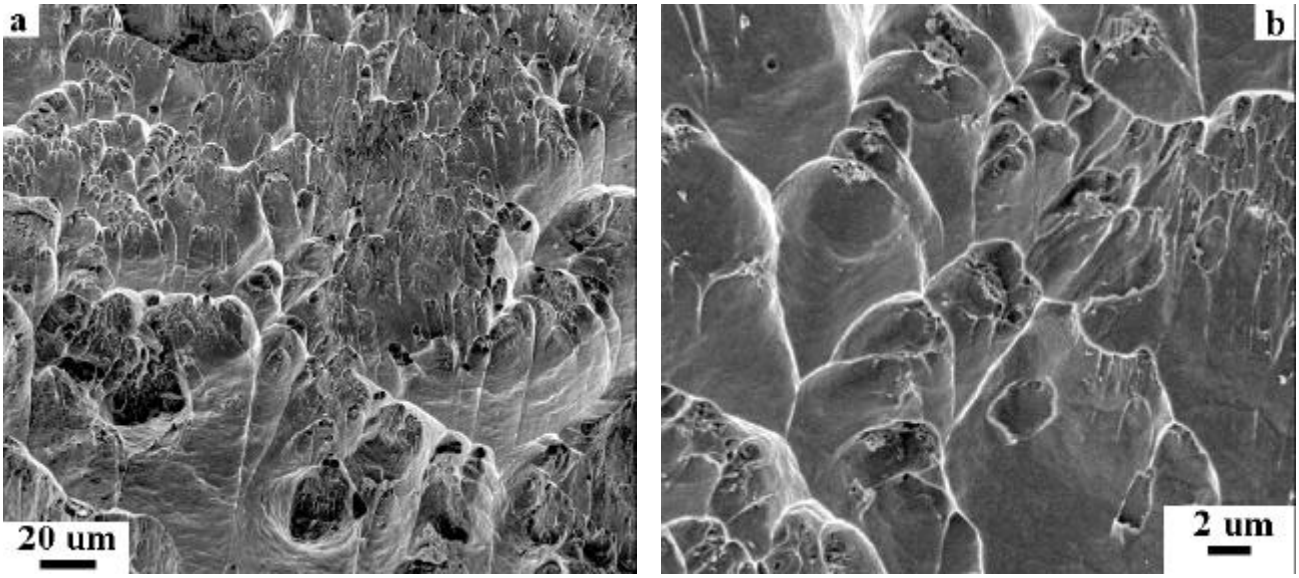

Figure 6: Scanning electron micrographs showing a) low magnification view of shear fracture surface and b) higher magnification view showing clusters of alumina particulates which nucleated each shear dimple.

DISCUSSION

It was found that the flow stress of the composite decreased by 30% over the temperature range from 25°C to 350°C: this may be compared with a 70% decline in the flow stress for unreinforced aluminum over the same temperature range. Also, the scale of the decline in flow stress was essentially constant across the whole range of strain rates tested. The data of Fig. 1 can be analyzed in the conventional way by fitting it to an equation of the form:

$$\sigma = \sigma_o \, \dot{\varepsilon}^{\,n}$$

where n is the strain rate sensitivity. The strain rate sensitivity parameter of the unreinforced aluminum was found to be in the range 0.03 - 0.04, which is within the range reported by Chiddister and Malvern [3]. Furthermore, the same range of strain rate sensitivity values has been calculated for the composite samples, indicating that their deformation characteristics are dominated by the mechanical properties of the matrix.

Nevertheless, it is remarkable that the mechanical properties remain at levels which are very high for unalloyed aluminum. TEM has clearly shown that the nano-sized alumina particulates preserve the microstructural stability at high temperatures, preventing grain coarsening and apparently, and perhaps most significantly, allowing dynamic recovery and recrystallization to proceed during high temperature deformation so that the ductility remains high despite a 40% loading of ceramic reinforcement. The observation of shear banding at room temperature, but only at high strain rates, is in agreement with this rationale whereby uniform recovery processes at high temperature are able to prevent the strain localizations necessary to cause shear band nucleation and propagation.

Further work is underway to clarify several aspects of the behavior of this material which can not presently be satisfactorily explained. For example, it is unclear why samples tested at high strain rate and intermediate temperatures, Fig. 3, do not exhibit the normal strain softening phenomenon associated with homogeneous deformation at high strain rates. It would be expected that heat generated during the essentially adiabatic test would lead to a steady decrease in flow stress as is shown by the sample tested at room temperature.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the provision of the DSC™ material used in this study by Chesapeake Composites Corporation, 239 Old Churchmans Road New Castle, DE 19720.

REFERENCES

1. Guden, M., and Hall, I. W., *Mater. Sci. Engnr*., A232 (1997) 1.
2. Follansbee, P. S., *Metals Handbook 8*, p.198-203, ASM, Metals Park, OH, 1985.
3. Chiddister, J. L. and Malvern, L. E., *Exp. Mech.* (1963) 81.