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ENVIRONMENTAL EFFECTS ON THE MECHANICAL PROPERTIES OF SMALL STRUCTURES

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ABSTRACT

Size-effect is known to influence the mechanical properties of materials at micro- and nanoscales. Mechanisms of fracture and failure are often affected by environmental factors such as temperature and humidity. The latter is postulated to cause stress corrosion cracking in metallic and ceramic Microelectromechanical Systems (MEMS) components. A recently-developed hybrid microtester enclosed in an environmentally-controlled chamber was used to study the effects of temperature on the mechanical properties of small structures. MEMS-scale specimens, prepared from aluminum foam struts as well as covetic aluminum were tested in microtensile testing. Results of these micromechanical tests show that the tensile behavior of Al struts are similar at temperatures of 11 and 42 °C. Further, covetic Al samples show a higher strength at a lower temperature (15 °C), but higher ductility at a higher temperature (44 °C).

KEYWORDS: Temperature Effect, Mechanical Properties, MEMS, Small Structure

INTRODUCTION

Reliability is of utmost importance for applications where MEMS devices control vital functions such as triggering airbags and weaponry, medical procedures, navigation of airplanes and cars, or where these devices play an important role in processes where human life is at stake. Mechanical testing of MEMS structures has been conducted over the last two decades to characterize the behavior of small structures in different loading conditions [1]. While size effect plays a great role in mechanical behavior of small structures, the shear microstructure, by itself can have a profound effect on MEMS components. Environmental factors play a great role in the failure of structures, especially in humid environments [1]. Combined with the effect of temperature, these can affect the functionality of MEMS mechanical components, especially those which have to operate under stress in ambient environments. Metallic MEMS have been shown to suffer from environmental effects. These include LIGA Ni that are postulated to fail due to the formation of surface oxides leading to surface cracks. However, further experiments are needed to shed light on environmental factor effects on the mechanical behavior of other metals.

PRIOR WORK

Mechanical tests [1-13] have been conducted to determine the mechanisms of fatigue and fracture failure. Size effect, as the most distinguishing characteristics of small structures, has been studied by microtesting MEMS devices. Characteristic length scale parameters in the range of 5 to 15 μm (in microbending and pure tension respectively) have been reported for LIGA Ni structures [2,3]. Tensile and fatigue testing of thick and thin LIGA Ni has shown a higher strength for the thinner samples [4]. Microtensile tests have been performed on various metallic samples to determine the strength and elastic modulus at room temperature [5-6]. Fatigue testing of MEMS devices has also been conducted to determine the mechanisms of fatigue and fracture [4, 7-10]

MATERIALS

Two types of aluminum were used in this study: aluminum foam struts extracted from open cell aluminum foam (Fig. 1), and covetic aluminum specimens machined from bulk. This block was obtained from ERG Materials and Aerospace Corporation (Oakland CA) designated as Duocell ®10PPI aluminum foam. The foam block density is about 3% of that of bulk aluminum. The second type was cast covetic aluminum bulk provided by Third Millennium Metals, LLC (Dayton, Ohio). Covetic metals are considered to have retained up to 6% carbon. Carbon nanoparticles are postulated to have a hybrid type of bonding comprised of covalent and metallic bonds. The tensile properties of extruded covetic Al is stated to be about 12% higher than that of base aluminum metal (extruded 6061). Dog-bone shaped samples were carved from this material using CNC.

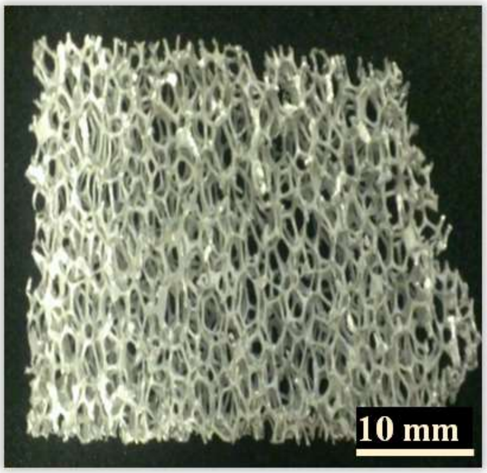

Fig. 1 – Aluminum foam block used for extraction of struts

The CNC machining operation included programming a dog-bone shape contour in G language and milling the perimeter of the structure to a depth of 1 mm. A ST-Supertec (Paramount, CA) CNC-EDM, model number ZNC-310 was used for electrodischarge machining operations. The EDM was used to cut a strut's attached ligaments. Fig. 2 displays an image from a extracted foam strut. Dog-bone shape samples were carved in the bulk. To release the samples, the back side of the structures had to be machined using the EDM. The voltages was set at 100V (12-14A current) for aluminum. Other parameters included 180ms Time-ON and 150ms for Time-OFF.

MICROMECHANICAL TESTING

Micromechanical testing was conducted in an environmentally controlled chamber (Fig. 3). Details of the microtensile tester have been presented elsewhere [2]. A brief description of the components and their functions are presented here. The drive train consists of a millimeter-scale movement providing micrometer-level accuracy. In line with this, microscale movement is achieved with nanometer accuracy by a piezoelectric actuator. The latter (PI-180 Physik Instruments, Germany) provided up to 180μm of travel with frequencies of up to 1000Hz.

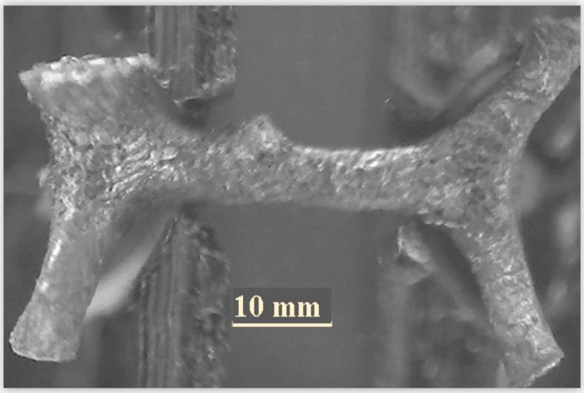

Fig. 2 – Aluminum foam strut mounted in fork-like grippers during tensile test

The piezo actuator end is connected to a set of grippers in which the sample was mounted. The other side of the grippers was connected to a load cell measuring loads up to 220 N. The loadcell, iLoad (LoadStar Sensors, Fremont, CA), monitors the load then communicates it with LabVIEW® program from NI (National Instruments, Houston, TX) for feedback controlled test.

A microscope camera recorded images during the deformation process. These are analyzed and the deformation extent is determined on the fly. Vision software from NI allows the analysis of the images and the recording the extent of the deformation. There are other ways to determine the deformation of the samples. These include the use of laser beams for characterization of MEMS devices [11,12]. It should be noted that at the onset of necking, occasionally, even before that laser interferometry patterns generated to measure elongation start to fade away when the roughening of the surfaces negatively affect the reflectivity of the mirror-like finish of the reflecting surfaces.

Other ways to record deformation include the positioning feedback from the actuators. The monitoring sensor of the piezo actuator is the more accurate of the two actuators within the load train.

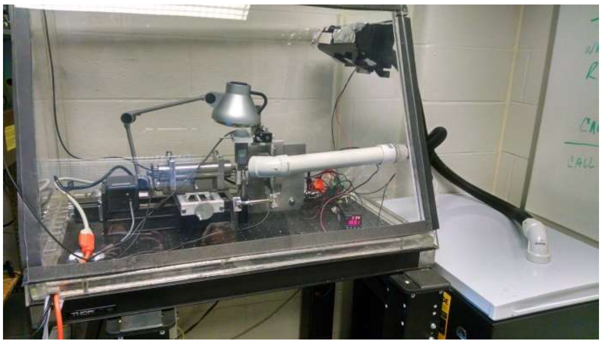

Fig. 3 –Heating and cooling of the sample area within the environmental chamber

The heating and cooling of the system was performed using a heater within the chamber and a chest freezer outside of it. The cold air was pushed into the chamber by forced convection through air hoses (Fig. 3). The temperature and humidity were controlled and displayed by an Omega digital controller and display unit. The details of the location of the sensor with respect to the grippers in presented in Fig. 4. The loadcell is shown on the right, the camera on the top and piezo actuator on the left. At the bottom is shown the humidity and temperature sensor.

Microtensile tests were conducted at high and low temperatures. High and low temperatures were fixed at 40 °C and 11 °C respectively. The relative humidity was established at 11% for lower- and 35% for higher temperatures.

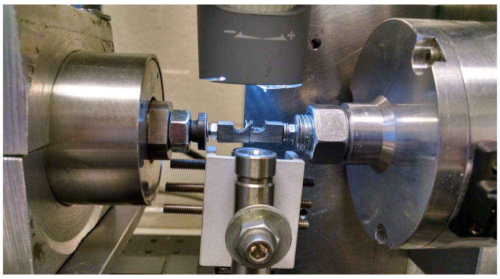

Fig. 4 –Temperature and humidity sensor located directly below the microsample grippers

For the aluminum foam struts, the grippers had a forked design that grasped the end nodes of the struts. The grippers that were used for the covetic aluminum samples were machined by CNC milling operations from stainless steel.

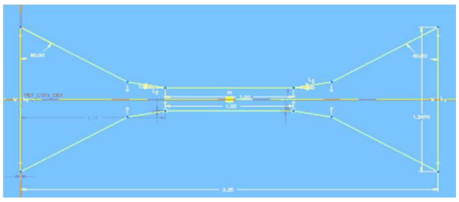

Fig. 5 –Schematic of the Dog bone shape specimens prepared by machining as well as EDM.

The grippers measured 10 mm by 10 mm in cross section. On top, a triangular shape was carved out to create a recessed area to seat the end of the dog-bone shape sample. The depth of the recessed area was the same as the thickness of the sample (200 μm). A small 1.6M screw held a small washer in place on top of the triangular end of the sample. The edges of the recessed triangle in the grippers, came in contact with the two sides of the ends of the sample, transferring the load during the test.

Fig. 6 – Carving dog bone shape samples in covetic aluminum

RESULTS

The results of micromechanical testing on the foam struts at high and low temperatures are shown in Fig. 7. The data shows the variation of load with the elongation of the samples. Since the shape and geometry of the ligaments are not identical, it is not possible to compare them side by side. However, the results show nearly identical strength levels for struts tested at low and high temperatures. The breaks in the cold curve are due to stop of the test and restart for better images. The results of the tests conducted on covetic aluminum have been plotted in terms of stress vs. strain (Fig. 8).

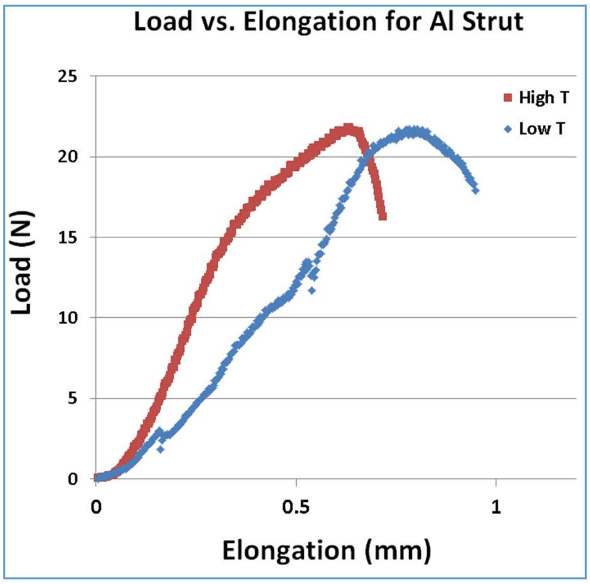

Fig. 7 –The load-elongation curves for foam struts tested at high (42C) and low temperatures (11C)

DISCUSSION

The micromechanical test results obtained from tensile testing of open cell aluminum foam struts do not show a significant difference in mechanical behavior at the temperatures tested. In fact the maximum load carried by both samples were similar. Since both samples have a relatively similar cross section, the ultimate tensile stress is the same in both. The information about strain cannot be compared since the two samples do not have clearly defined identical gage lengths. This is why elongation of the samples has been reported for comparison purposes.

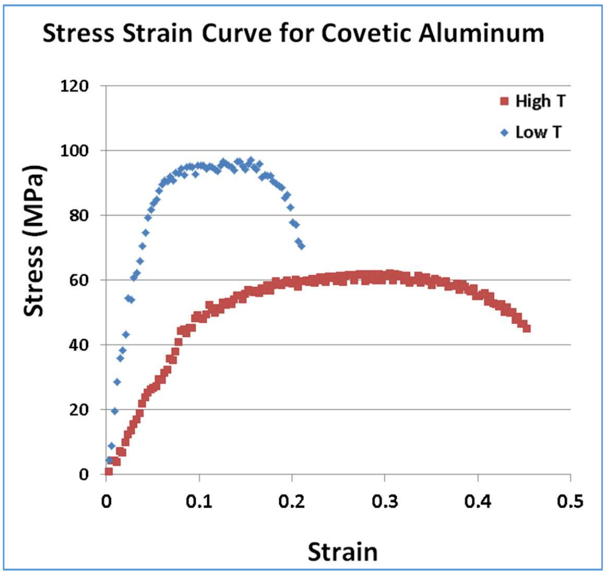

Fig. 8 –The stress-strain curves for covetic aluminum tested at high (44C) and low temperatures (15C)

On the other hand micromechanical tests conducted on small structures machined from covetic aluminum does show the effect of temperature. Although the temperatures utilized here were slightly different (e.g. by 2-4 degrees), the behavior has significantly changed for the covetic aluminum samples. At the higher temperature (44 °C), the elongation increased with temperature and strength decreased to nearly 2/3 of its previous value.

It should be noted that the electronics within the chamber do not allow the use of high temperatures.

On the other hand, freezing temperatures may not be achieved within the vacuum chamber. It is possible to use a vortex cooler to achieve very low temperatures. Higher temperatures are also achievable by passing an electric current directly through the sample. For the two cases examined in this study, brittle fracture did not occur. For both, ductile fracture was observed all the way down to zero load.

Previous published work on extruded covetic aluminum indicates strengths as high as 14000 psi which equals 96.5 MPa. This study shows a UTS as high as 95 MPa for the samples extracted from cast covetic aluminum tested at 15 °C. The second covetic sample tested at 44 °C, however, shows a much reduced a UTS of 60 MPa.

SUMMARY AND CONCLUDING REMARKS

Small structures were extracted from open cell aluminum foam and covetic cast aluminum. They were tested in microtensile loading configuration at low and high temperatures. The results show that:

a) The tensile behavior of Al struts are similar at temperatures of 11 and 42C.

b) Covetic Al samples show a higher strength at a lower temperature (15 °C), but higher ductility at a higher temperature (44 °C).

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