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To cite this article: I N Orbulov et al 2010 J. Phys.: Conf. Ser. 240 012168

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Compressive strength and hardness of metal matrix syntactic foams

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Abstract. Six types of metal matrix syntactic foams (MMSFs) were produced by pressure infiltration technique. The foams were investigated by upsetting tests at increased (220°C) and at room (25°C) temperature. The parameters were the constituents of the composites and the aspect ratio (height-diameter ratio, H/D) of the specimens. The characteristic properties were: the compressive strength, the fracture strain, the structural stiffness of the foams and the absorbed energy. The strength, the strain and the energy were decreased while the stiffness was increased by increasing the H/D. Increased temperature caused ~25 % drop in the strength and in the stiffness. Macrohardness, depth sensitive and dynamic hardness tests were also performed on MMSF blocks: macrohardness is a structural property and independent from the matrix material. The depth sensitive hardness is sensitive to the deformation capability of the matrix and to a possible change reaction. The dynamic hardnesses of the MMSFs were higher than the hardness of the matrices and this is a microballoon related property.

1. Introduction

Metal matrix syntactic foams (MMSFs) are particle reinforced composites containing ceramic microballoons. The most common production methods are pressure infiltration [1] and blending method [2]. MMSFs have been investigated by many groups: for example Rohatgi et al. and Wu et al. investigated the effect of the microballoon volume fraction on the compressive strength, which is increased by increasing the volume fraction of the particles [3, 4]. Some groups investigated the coefficient of thermal expansion (CTE) and the creep resistance of aluminium-fly ash composites. They proved that, the CTE decreased while the creep resistance increased by increasing the microballoon content in the composites [5, 6]. Balch and Dunand produced MMSFs by pressure infiltration. The volume fraction of the microballoons was maximized and they investigated the compressive failure modes of the foams [7, 8]. Palmer et al. made tensile, upsetting and bending tests on pressure infiltrated MMSFs, too [9]. Dou et al. proved that, the foams show strain rate sensitivity: both the compressive strength and the energy absorption capacity increased by increasing the strain rate [10]. Kiser et al. performed upsetting tests on MMSFs under both uniaxial and multiaxial loadings [11]. It can be concluded that, MMSFs have been widely investigated, but the lack of increased temperature is a motivating reason to perform upsetting tests at increased temperature.
The common matrix materials (Al alloys) have usually low hardness and wear resistance; this can be improved by the ceramic microballoons: the wear resistance and the hardness increased by increasing the microballoon content [2, 12]. MMSFs wear by microcutting and delamination caused by crack propagation below the rubbing surface [13] and in general the conventional Al foams have lower wear resistance compared to MMSFs having the same Al volume fraction [14]. MMSFs also take part in industrial applications. They are good energy absorbers, mechanical dampers. They have low weight, outstanding specific properties, localized failure, etc. They can be used as low weight moving components and energy absorbers. Because of the wide application range their compressive properties and hardness should be characterized.

2. Materials and specimens
Al99.5 or AlSi12 was used as matrix material. Three types of ceramic microballoons were used as fillers (Envirospheres Pty. Ltd.). Their constituents were the same (36-40 wt% Al$_2$O$_3$, 55-60 wt% SiO$_2$, 1-5 wt% other oxides); their name and geometrical properties are listed in table 1. Overall six MMSF blocks were produced by pressure infiltration. The microballoon content was ~64 vol%. The infiltration pressure (0.4 MPa) was ensured by Ar gas for 30 s. The infiltration temperature was 600°C and 710°C in the case of AlSi12 and Al99.5 matrix respectively. A 10×35×55 mm specimen for hardness tests and Ø14 cylindrical specimens with H/D=1, 1.5 and 2 were machined from each block.

| Type  | Outer diameter (μm) | Wall thickness (μm) | Specific surface area (μm$^{-1}$) |
|-------|---------------------|---------------------|----------------------------------|
| SL150 | 100                 | 3.7                 | 0.060                            |
| SLG   | 130                 | 5.4                 | 0.046                            |
| SL300 | 150                 | 6.7                 | 0.040                            |

3. Experimental
The upsetting tests were done by a Zwick 50 testing machine. The die had four guide bars, polished and lubricated surfaces. The strain rate was 0.01 s$^{-1}$ and the tests were performed at increased (220°C) and at room (25°C) temperature until 50% of engineering deformation was reached. Overall 216 specimens were compressed (2 matrices×3 microballoon types×3 H/D×2 temperatures×6 specimens).

Brinell macrohardness tests were done by a VPM HPO 13/6062 testing machine with an Ø10 mm hardened steel ball. The loading force was 1840 N or 2450 N in the case of Al99.5 and AlSi12 matrix respectively and they were applied for 10 s. In the depth sensitive hardness tests [15, 16] an Ø2.5 mm hard metal mandrel with hemisphere ending was pushed into the specimens by 0.02 mm/s. The load was increased by a MTS 810 type hydraulic testing machine until a previously set force level (1600 N) was reached, and then the specimen was unloaded. Three measurements were done on each specimen. Dynamic hardness tests were done by Equotip tester. The device shots an indenter at the surface and measures its velocity at 1 mm distance from the surface before and after impact. The dynamic hardness can be calculated from the velocities. Ten measurements were done on each specimen.

4. Results and discussion
As main strength properties the compressive strength and structural stiffness should be analyzed. Figure 1 and 2 shows the strength as the function of H/D in the case of the two matrices. In the case of Al99.5 matrix strength strongly decreased between H/D 1 and 1.5 at room temperature. The strength decreased further by increasing the H/D in the case of SL150 filler, but remained the same in the case of SLG and SL300 fillers. This indicates that at higher H/D the load was carried by the microballoons and SL150 microballoons were simply too weak. As the H/D increased the shearing like stress also increased in the specimens because the specimens became higher and the small deviations of the specimen and the stress field resulted in an increasing shearing effect. Due to their small wall thickness SL150 microballoons were the most sensitive. At increased temperature this effect appeared only in the case of higher H/D (between 1.5 and 2).
Figure 1. The strength of Al99.5 matrix MMSFs

In the case of AlSi12 matrix the situation was reversed. In the case of SLG and SL300 fillers the strength was almost constant at lower H/D; the microballoons and the matrix carried the load together. After that – at higher H/D – the strength decreased. This means AlSi12 matrix tolerated higher shear load than Al99.5 matrix, because the effect of shearing (the decrease of strength) appeared in the case of higher H/D only. In general, increased temperature caused ~25% drop in the compressive strength in every case. Figure 3 and 4 show the structural stiffness of the MMSFs as the function of H/D in the case of the two matrices; their gradient was almost the same in every cases.

Figure 2. The strength of AlSi12 matrix MMSFs

The structural stiffness increased linearly in all cases and was independent from the type of microballoons. The gradient of the stiffness was the same at room and at increased temperatures also. The microballoons and matrices had a small effect on the stiffness and it was determined by the H/D. Increased temperature caused ~25% drop in the structural stiffness in the case of both matrices.

Figure 3. The stiffness of Al99.5 matrix MMSFs

The measured global hardness is shown in figure 5. In the case of Al99.5 and AlSi12 the incorporation of ceramic microballoons hardened and softened the base material respectively. The largest MMSF hardness can be ensured by SL150 microballoons, having the largest specific surface area (surface area/volume ratio). In general the macrohardness is a structural property and proved to be independent from the matrix material. The depth sensitive hardness measurements gave force-depth diagrams as results. The area under the registered curve is proportional to the energy absorbed during the test (figure 6). In the case of Al99.5 matrix the energy was decreased by incorporating SL150 and SLG type microballoons because a change reaction (4Al+3SiO$_2$=2Al$_2$O$_3$+3Si) took place between the microballoons and the matrix during the manufacturing, which resulted in lower energy absorbing capability. With SL300 fillers the MMSFs showed the same energy absorbing as pure Al99.5 matrix material because the change reaction mentioned above did not take place [17]. In the case of AlSi12 matrix the energy absorption increased, so the material “softened”, the levels of dissipated energy were almost the same in every case. The dynamic hardness of AlSi12 matrix was approximately two times higher than Al99.5. The foams were harder than matrices, but the original hardness difference between the matrices (~70%) decreased to ~20% in the case of MMSFs, so the matrix materials have
small effect on the dynamic hardness of MMSFs and therefore this is a microballoon related property. Similarly to Brinell hardness testing, syntactic foams with SL150 type fillers showed the highest hardness.

5. Conclusions
The compressive strength decreased by increasing the H/D. SL150 type microballoons were the most sensitive because of their smallest wall thickness. The structural stiffness increased almost linearly by increasing the H/D and the gradient was always the same. The effect of microballoon type was negligible. Increased temperature caused ~25% drop in compressive strength and structural stiffness.

The macrohardness is a structural property and independent from the matrix; it cannot demonstrate the change reaction. The depth sensitive hardness tests showed sensitivity to the deformation capability of the matrix and to the presence of the change reaction. The dynamic hardness of the MMSFs was higher than the hardness of the matrices and this is a microballoon related property.

Acknowledgements
Our Metal Matrix Composites Laboratory is supported by grant # GVOP 3.2.1-2004-04-0145/3.0 and by Hungarian Research Fund, NKTH-OTKA K69122. Special thanks to Róbert Tóth and C. H. Erbslöh Hungária Speciality and Industrial Minerals Ltd. for providing microballoons.

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