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Tribological properties of hybrid aluminum matrix syntactic foams

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ABSTRACT

Hybrid syntactic foams with AlSi12 aluminum alloy matrix were produced by low pressure infiltration and the wear properties were investigated by pin-on-disc method against a low carbon steel disc counterpart. As reinforcement iron (GM; ~Ø1.9 mm) and two ceramic type (GC; ~Ø1.4 mm and SLG; ~Ø0.12 mm) hollow spheres were used. The volume ratio of GM-GC hollow spheres varied and also SLG+GC hybrid composites were produced. The tests in lubricated condition showed significantly different properties to the dry tests, due to the different oil reservoir capacity of the open hollow spheres in the contact zone, depending on the reinforcement type and ratio. The coefficient of friction, specific wear, height loss and surface damage of the specimens were strongly dependent on the reinforcement type.

1. Introduction

In metal matrix syntactic foams (MMSF[1]s) the size and distribution of the composite porosity is achieved through uniformly spaced hollow spheres. MMSFs are advantageous because of their low density (~64 vol% hollow sphere content can be achieved [1,2]) which allows significant mass reduction and outstanding specific mechanical properties (like high energy absorbing capacity) compared to the bulk matrix material. MMSFs could be used for example as brake parts, encasements, anti-shock buffers, shock absorbing armors, collision dampers etc. [3]. In MMSFs lightweight alloys (usually aluminum or magnesium) is used as matrix material [3–6]. For reinforcement ceramic or metallic hollow spheres can be used, in different size range and with different wall thicknesses. MMSFs are normally produced by liquid state mechanical stirring, gravity casting and liquid state pressure infiltration. In the first two methods lower reinforcement content can be achieved but the risk of inhomogeneous reinforcement distribution and fracture are higher compared to the pressure infiltration method, which is a more reliable and controllable production method [7–9]. Pressure infiltration is advantageous because of the high achievable reinforcement volume fraction without large mechanical loading on the hollow spheres (low pressure infiltration). Microstructure of the matrix material, distribution and quality of the hollow spheres and the coherence between the matrix and spheres are the key factors for MMSFs quality. Therefore the main qualifying tests for MMSFs are macro- and microstructural investigations, computer tomography (CT) reconstruction [10,11] and density measurements [3,12–14]. The mechanical properties of the MMSFs, such as quasi-static [13,15,16] and high strain rate [17] compressive properties, as well as their fatigue properties [18] were widely studied. MMSFs are promising materials for machine parts because of their low weight and reduced energy consumption during the operation time of the moving MMSF parts. However for a future application of MMSFs as sliding machine parts (such as bearings, cylinders or hollow shafts), their tribological properties should be properly investigated. There is also an interesting question: how could the mechanically opened hollow spheres (which may occur during machining) influence the wear properties in dry and in lubricated conditions? Is there a possibility to use them as lubricant reservoirs (as in the case of laser surface treated cast iron cylinder bores in combustion engines [19,20])? The sliding and wear properties of a couple metal matrix composites in dry and lubricated conditions have already been investigated [21–38], but the wear properties of MMSFs and aluminum matrix syntactic foams (AMSFs[2]) are insufficiently detailed and even fewer hybrid AMSFs were investigated from this aspect.

In the professional literature a dozen of articles are dealing with the wear properties of various lightweight matrix and various reinforcement combinations. Zhang and Alpas [21] decreased the specific wear of 6061 aluminum alloy with Al_2O_3 particles against

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[1] MMSF – metal matrix syntactic foam

[2] AMSF – aluminum matrix syntactic foam

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steel and against mullite counterparts, respectively. Rohatgi and Guo [22] reported a decreased coefficient of friction (COF) and wear of hypoeutectic AlSi alloy with small amounts (5 vol%) of fly ash particles (< Ø50 μm). Ramachandra and Radhakrishna [23,24] also investigated the wear properties of fly ash particle reinforced AMSFs with 0, 5 vol%, 10 vol% and 15 vol% reinforcement contents. The AMSFs were produced with eutectic AlSi12 alloy matrix material by a liquid state technique. The wear resistance of the AMSFs increased with the fly ash content, but decreased with increasing load and sliding velocity. The microscopic examination of the worn surfaces, wear debris and subsurface showed that the matrix material wore primarily because of micro-cutting, while the AMSFs wore because of delamination, micro-cutting, oxidation and thermal softening. Mondal et al. [25] investigated the unlubricated wear properties of AMSFs reinforced by cenosphere hollow spheres (~Ø90 μm) produced by stirring technique. As a comparison an aluminum matrix composite with 10 wt% SiC particle (< 100 μm) reinforcement was applied. Pin-on-disc wear tests with a hardened steel disc counterpart in the 2–4 $m\,s^{-1}$ sliding velocity range were carried out. The COF of the AMSFs decreased with increasing load and increased with the higher sliding velocity. The specific wear of the AMSFs also decreased with higer sliding speed and increased with the loading. The AMSFs showed significantly lower COF compared to the Al–SiC_p composites in same conditions. The specific wear at lower load was found to be almost the same in both cases. Zhongshan and Shenqing [26] investigated the wear properties of AlSi12 alloy with potassium titanate whiskers-reinforcement. They found in dry condition, that the specific wear increased with the loading for all specimens. The specimen with 20 vol% $K_2O \cdot 6TiO_2$ had the greatest specific wear at any loading, but the specimen with 10 vol% reinforcement had basically the same specific wear as the bulk AlSi12 material up to about 14 MPa surface load, but at higher loading the reinforced specimen had significantly less specific wear. Wang et al. [27] investigated the dry and wet wear behavior of $Al_2O_{3f}/SiC_p/Al$ hybrid metal matrix composites. The specific wear showed a slight increase with the surface loading in dry condition. The authors also found that the fiber orientation had great influence on the wear properties. Jha et al. [28] compared the wear properties of cenosphere hollow sphere (made largely of silica and alumina and filled with air or inert gas, typically produced as a byproduct of coal combustion at thermal power plants) (~Ø60–100 μm) and SiC particles (40–55 μm) reinforced aluminum matrix composites. The matrix material was a nearly eutectic AlSiNiMg11.5-1.5-1 (LM13) alloy, the production method was liquid state stirring. Pin-on-disc tests in the 2–4 $m\,s^{-1}$ sliding speed range showed that the cenosphere reinforced AMSFs had significantly lower COF and lower specific wear than the SiC_p reinforced composites both in dry and lubricated conditions. In dry condition the specific wear decreased with higher sliding speed for both composites. The authors assumed that craters (e.g. exposed cenospheres) may play an important role in the wear mechanism of AMSFs. Ramesh and Ahamed [29] made Al6063-based alloys in-situ reinforced by various mass percentages of TiB_2 particles. According the dry pin-on-disc wear tests and compared to the matrix material the COF and the specific wear decreased significantly with more reinforcement ratio. The COF decreased with higher surface load and increased with higher sliding speeds. The specific wear increased with the higher surface load and with higher sliding speed. Uthayakumar et al. [30] produced AA6331 matrix AMSFs with different volume fraction of fly ash particles by stir casting. The dry pin-on-disc test showed a decrease in the value of the COF and specific wear on higher surface loads. They also predicted the optimum design parameters through Gray relational analysis. Sudarshan and Surappa [31] investigated the dry sliding wear of fly ash particle (also hollow spheres like cenosphere) reinforced (6–12 vol%) A356 matrix composites using a pin-on-disc setup at 1 $m\,s^{-1}$ sliding velocity. The dry sliding wear resistance of Al–fly ash AMSF was quite similar to the heavier Al_2O_3 and SiC particle reinforced Al-alloys. Moreover, the composites always showed better wear resistance compared to unreinforced alloys. The authors also found that the COF increased with the amount of the reinforcement and decreased with higher surface load. The specific wear decreased with the amount of the reinforcement and increased with higher surface load. Both the COF and the specific wear values were found to be slightly better when sieved fly ash particles (Ø53–106 μm particle range) were used instead of the ones as received (Ø0.5–400 μm particle range). Saravanan et al. [32] investigated cenosphere reinforced AA6063 composites which were made by stir casting method. The dry sliding wear behavior of the foams was studied by pin-on-disc wear tests and the results were compared to the properties of pure AA6063. Enhanced wear properties were observed with addition of cenospheres in aluminum alloy.

Kumar et al. [33] synthesized fly ash reinforced aluminum matrix composites by stir casting method. Fly ash content with various volume ratios (9 wt%, 14 wt% and 19 wt%) were used with aluminum metal by adding magnesium content 1%. Tribological properties such as COF and specific wear for various fly ash compositions were obtained and the results were discussed in detail. Later Kumar et al. [34] studied the mechanical and wear properties of Al6061 (Al alloy with 4 wt% Mg content) based composites filled by fly ash (10 vol%, 15 vol% and 20 vol%) and with or without 4 vol% graphite. Specific specific wear decreased with the addition of fly ash up to a certain volume whereas with graphite addition it also decreased.

The dependence of the coefficient of friction and the specific wear on the sliding speed and on the loading, in dry sliding condition for the afore mentioned [21,22,24–31] composites are summarized in Fig. 1. According to the diagram the composition of the aluminum composites have the largest influence on these parameters.

The effect of particle size on the wear properties was investigated by Bindumadhavan et al. [35] on Al–Si–Mg alloy (A356) composites reinforced with SiC (up to 15 vol%) The reinforcement had a bimodal distribution with nominal particle diameters of 47 μm and 120 μm. Unlubricated ball-on-disc wear tests with small loads showed decreasing weight loss of the specimens with increasing reinforcement volume fraction. Composites containing both small and large SiC reinforcement particles showed higher wear resistance than composites reinforced by only small particles.

Some efforts during the investigation in connection with the effect of other reinforcement types have also been done.

For example Chang et al. [36], Liu et al. [37] and also Cree and Pugh [38] investigated the dry sliding wear behavior of co-continuous ceramic foam/aluminum alloy interpenetrating composites and achieved significantly lower specific wear compared to the pure matrix material itself.

In summary the COF values were lower, but the specific wear was higher than for AMSFs with fly ash or cenosphere (hollow) reinforcement compared to the matrix metals or composites with solid reinforcements. Moreover, some contradiction between the published results of similar composite systems can be found.

Besides the above-mentioned relevant works, the wear properties of AMSFs reinforced by larger hollow sphere reinforcement (average diameter in the 1 mm magnitude) and AMSFs with hybrid reinforcement have not yet been investigated. Therefore, this paper deals with pin-on-disc wear tests on hybrid AMSFs with two grades of relatively large hollow spheres having ~1.5 mm average diameter.