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WEAR CHARACTERISTICS OF Cu OFHC MATERIAL PREPARED BY ORBITAL FORGING AND ECAP

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The paper is focused on the wear mechanism of orbital forged and equal-channel angular extruded Cu OFHC (oxygen-free high thermal conductivity) material. The wear behaviour of the Cu OFHC material is investigated through pin-on-disc tests. Two different processing conditions have been used, equal-channel angular processing (ECAP) and orbital (radial) forging. The wear investigations in this orbital formed material are unique; additionally wear properties show interesting wear characteristics. Particular attention has also been paid to the friction coefficient and to the role of the wear rate.

Keywords: Sliding wear; friction coefficient; orbital forging; ECAP.

1. Introduction

The cold forming process is widely used to produce small and medium sized components for various types of industry applications such as automotive, electrical and aerospace. Advantages of this process over little machining include increased wear properties (in terms of wear resistance) as well as reduced manufacturing costs for mass production.

Orbital forging is an incremental deformation bulk forming process which incrementally deforms a workpiece using a combination of rotation, rolling and axial compression techniques. This cyclic activity is interesting for two reasons. It has mirrored precisely the changes in mainstream manufacturing philosophy that have taken place over

the years. Secondly, it has undergone technical developments to match the economic requirements for a successful current metal forming manufacture[1, 2].

Orbital forging is an example of an incremental process with a continuous deformation sequence and mainly uniaxial compressive stresses. This is a mature technology, related to ring rolling and to the processes of tube nosing and flaring. In orbital forming friction is reduced substantially and the metal can flow much more easily in the radial direction (rolling friction instead of sliding friction)[3].

Compared to conventional cold forming, the orbital forging process offers the following advantages[1-4]:
- smaller presses (investment, space requirement),
- smaller stresses in dies (tooling costs),
- longer die life,
- reduction of noise and vibrations,
- reduction expensive progressive dies,
- economically favourable in medium and small batch production.

Copper represents an ideal model material for studying the processes of deformation and microstructure evolution, due to its low-cost, simple face-centered cubic structure, medium stacking-fault energy (SFE) and, most of all, the long history of research of this material prepared by conventional techniques such as rolling, extrusion, compression, wire drawing, etc., that were capable of imparting large strains to the workpiece.
ECAP is one of the SPD techniques, which is rather effective for producing UFG metals with enhanced mechanical and processing properties inherent in various ultrafine-grained materials[5-8]. The ECAP process is a promising method that involves large shear plastic deformation in a deforming layer of a workpiece.

A lot of research work is reported on the development of new nanostructured materials[5-11]. They have a new advanced microstructure with mean grain size less than 100 nm and they manifest advanced physical and mechanical properties. A variety of technologies were developed to prepare nanostructured materials and several experimental data reporting various properties of UFG (Ultra Fine Grained) Cu prepared by SPD are now available in the literature[9-11].

Combination of severe plastic deformation (represented by equal channel angular pressing ECAP) and incremental deformation bulk forming process (represented by orbital forging) is unique. In fact it is not possible to make any comparison with other results, since no similar work appears to be present in the literature.
The aim of this work is to analyze the wear characteristics for oxygen-free high thermal conductivity copper as function of the aforementioned working processes.

2. Experimental Conditions

As experimental material, the oxygen-free high thermal conductivity copper (OFHC) was used. OFHC is produced by the direct conversion of selected refined cathodes and castings under carefully controlled conditions to prevent contamination of the pure oxygen-free metal during processing. The method of producing OFHC copper insures

extra high grade of metal with a copper content of 99.99%. Specimens with dimensions ø 10 x 70 mm were extruded through the use of ECAP technology, with matrix channel angle Φ=90°. The ECAP process was realized by hydraulic press with maximal force of approximately 1 MN. ECAP passes were realized using route C.

Specimens were obtained using an orbital press, applying a pressure of 200 MPa at logarithmic strain of 1.95.

A summary of the investigated samples is reported in Tab. 1.

Table 1. Processing conditions for investigated Cu OFHC materials.

System	Processing conditions
A	Orbital forging
B	ECAP (4 passes) + orbital forging
C	ECAP (6 passes) + orbital forging

Pin-on-disc wear tests were carried out by means of a tribometer entirely developed in the Alessandria Campus of Politecnico di Torino. The disc was made of the investigated material. As a counter face, a WC-Co pin was used, having a rounded shape on top with φ 3 mm. The counter-pin was changed after the end of each test, in order to preserve the roundness of its top. All wear tests were performed in air and without any lubricant. The applied loads were 15 N. The rotation speed of the disc was 300 rpm. The tested surface was polished with abrasive papers in order to determine a medium surface roughness equal (or less) to 0.8 μm, as specified in the ASTM G99–95a. Each test was interrupted after 300, 600, 900, 1200, 2000, 3000, 4000 and 5000 meters sliding distance and discs were weighed, using a precision scales with a sensitivity of 10^{-5} to determine the evolution of wear during each test. The total sliding distance was monitored on an auto-recorder. The surface topography was measurement by Hommel Tester T1000 tangent profilometer and average values were obtained from 5 measurements.

Microstructures and wear tracks observations were carried out using SEM JEOL 7000F. The apparent hardness HV (measured on the tested specimen surfaces) was determined by means of Vickers hardness indenter with 50 kg load.

3. Friction Coefficient

Frictional coefficient (f), an important material's property affecting the wear resistance of structural components sliding one against the other, consists of an adhesion component (f_a) and a deformation component (f_d), resulting respectively from an adhesion force and a deformation force during sliding. The adhesion component plays an important role in sliding wear, which is affected by the mechanical properties such as hardness and ductility[12]. The results of friction coefficient are shown in Fig. 1. The friction behaviours of investigated systems were characterized by the mentioned friction coefficient data in the friction graph, Tab. 2. The friction-time curve during dry sliding consists of four stages of friction coefficient.
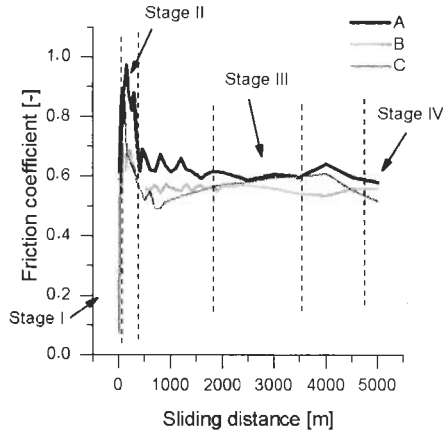
Fig. 1. The behaviour of friction coefficient with different stages.

Table 2. The friction behaviours of investigated systems.

Friction coefficient	A	B	C
Initial friction coefficient, f_0	0.0894	0.0769	0.0834
Maximum value of friction coefficient, f_{peak}	0.9725	0.6763	0.8853
Friction coefficient in steady-state condition, $f_{steady\text{-}state}$	0.6051	0.5572	0.5677
Friction coefficient at the end of test, f_{final}	0.5806	0.5625	0.5184

The initial value of the friction coefficient of Stage I, which is under 0.1 value of f_0, is dependent on the load, F_N, and on the shear resistance of surface contaminants. The higher value of f_0 was achieved in system A. The incremental deformation bulk forming process, represented by orbital forming, lead to smaller stresses with a reduction of shear deformation, which is present during ECAP process.

Surface layer removal and an increase in adhesion due to the increase in clean interfacial areas, as well as increased asperity interactions and wear particle entrapment, lead to a gradual increase in the friction coefficient.

Stage II represents the maximum values, producing the peak value of the friction coefficient (f_{peak} varied between 0.6763 for system B to 0.8853 for system B and 0.9725 for system A). These results show the positive influence of the incremental deformation bulk forming process to reduce the interfacial adhesion and asperity deformation.

In Stage III, a decrease in the friction coefficient may occur, due to the possible formation of protective tribochemical surface layers and a decrease in plowing and asperity deformation processes in accordance with Blau[13]. In this Stage III constant friction coefficients were recorded. Therefore the steady-state values of friction coefficient were determined, $f_{steady\text{-}state}$. The $f_{steady\text{-}state}$ is characterized by steady-state interfacial tribological conditions. The results of $f_{steady\text{-}state}$ are shortly summarized as follows: system A: 0.6051, system B: 0.5572, system C: 0.5677. In Stage IV the value of

the friction coefficient is a bit smaller than the one of the steady-state; this may be attributed to the fact that initially the surface is rough, though with uneven asperities and contact temperatures (the surface temperatures) as well as the metal-to-metal contact causes to different friction coefficient values at the end of the test, f_{final}.

The values of surface roughness are shown in Tab. 3.

Table 3. The surface topography and Vickers hardness of investigated systems.

	A	B	C
Rz [μm]	1.1	3.17	2.53
Ra [μm]	0.18	0.41	0.3
HV	248	317	593

Reading through Tab. 3, it can be observed that the surface roughness values of both parameters Ra and Rz, should affect the value of friction coefficient along with hardness. Hanlon et al.[14] examined the effect of grain size on friction evolution and damage accumulation of UFG metals under repeated sliding contact in nanoscratch tests. It can be
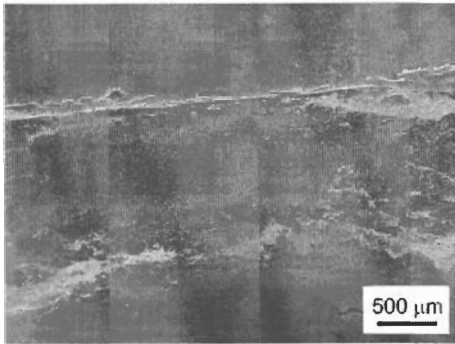

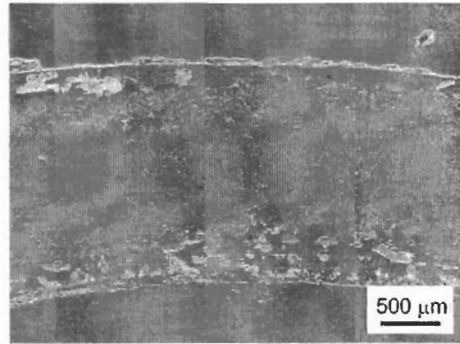Fig. 2a. Wear track of investigated A system.
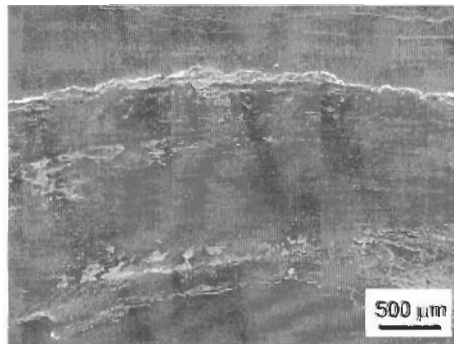

Fig. 2b. Wear track of investigated B system.

Fig. 2c. Wear track of investigated C system.

found that strength/hardness rather the grain size appeared to dominate the steady state friction coefficient and damage accumulation, each diminishing with substantial increases in material strength. On the other hand, it is generally known[12, 15] that a higher hardness does not always lead to a better wear resistance and hardness alone should not necessarily be considered the most critical factor in assessing the wear resistance of a material. Several authors[16-18] present suggestion for correlating the wear behaviour with the surface topography. The fact that surface wear is influenced by sub-surface deformation[19-22] was also effectively used to show the occurrence of delamination and fracture of material resulting in its removal. Therefore, the wear tracks produced during the test run were examined under scanning electron microscope, Figs. 2 a-c and Figs. 3 a-c.
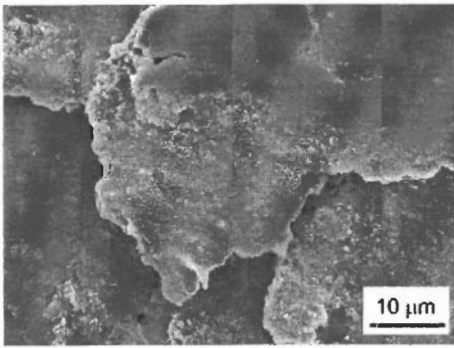

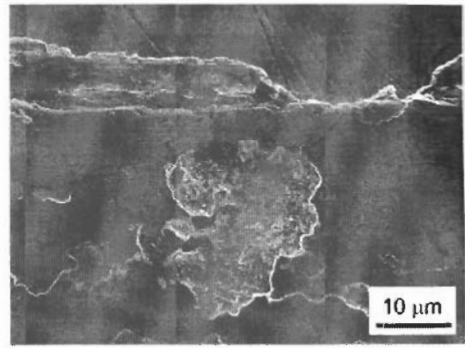Fig. 3a. Detail of mild oxidational wear behaviour in A system.

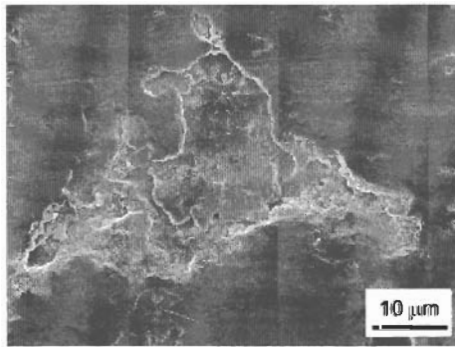Fig. 3b. Detail of mild oxidational wear behaviour in B system.

Fig. 3c. Detail of mild oxidational wear behaviour in C system.

It can be seen from the detailed microstructures that also mild oxidational wear are present in all investigated systems. The delamination and the mild oxidational wears were recorded to be the main wear mechanisms.

4. Wear characteristics

The results of wear rate are presented in Figs. 4 a, b. It may be seen from the figure that the wear rate is significantly dependent on the processing condition. It can be seen from the Figs. 4 a, b that wear rate (wear volume per unit sliding distance) decreases continuously in the running-in period and becomes steady state, mainly in systems B and C, after that. The probability of the occurrence of elementary wear events may decrease if, through changes in surface topography, the interaction rate of surface asperity collisions decreases. The load will be concentrated on parallel narrow bands which are observed in Fig. 5. As time progresses, the true area of contact increases, leading to a lower stress, till a steady state stage is reached. Thus, during running-in-period, the wear rate decreases till it attains a constant value at equilibrium. However, it is observed that system A still decreases in wear rate value with increased sliding distance. The reason can be attributed to the interfacial adhesion and asperity deformation.
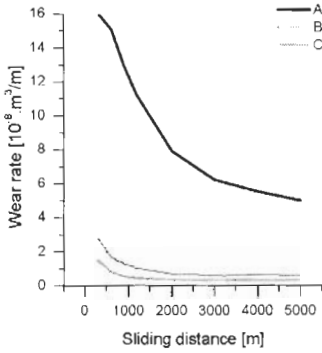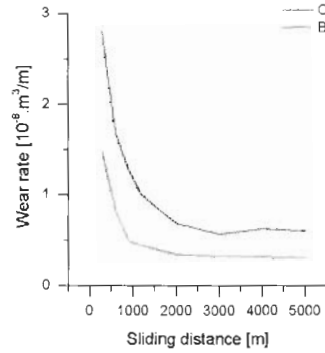

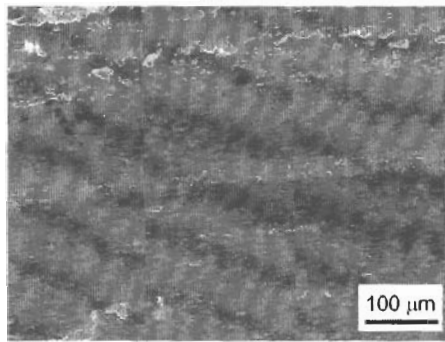Fig. 4a. The wear rate of investigated systems.　　Fig. 4b. The wear rate of systems after the ECAP processes.

Fig. 5.　Parallel narrow bands, system C.

5. Conclusion

The wear behaviour of the Cu OFHC material was investigated through pin-on-disk tests. Two different processing conditions have been used, ECAP process and then orbital forming along with initial condition. The friction-time curve during dry sliding consists of four stages of friction coefficient. The results of $f_{steady-state}$ (mainly represent the friction

properties) are shortly summarized as follows: system A: 0.6051, system B: 0.5572 and system C: 0.5677. Wear rate (represent the wear properties) decreases continuously in the running-in period and becomes steady state, mainly in systems B and C, after that. Orbital forging, as an incremental forming process, and ECAP, as a severe plastic deformation process, support interesting wear characteristics by suppressing the interfacial adhesion and asperity deformation. The wear tracks examined that the delamination and the mild oxidational wears are the main wear mechanisms. The best condition in terms of wear characteristics is orbital forging and 4-passes ECAP system. Moreover, given the high wear resistance, the processes may enhance the competitiveness of the considered material.

Acknowledgments

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