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RESEARCH PAPER

CASE STUDY OF ADVANCED PROCESSED OFHC COPPER BY DRY SLIDING WEAR TEST

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ABSTRACT

The wear behaviour of copper material processed by ECAP (Equal Channel Angular Pressing) and orbital forging (OF) is presented in this study. Dry sliding wear tests were carried out for the wear behaviour of the investigated system. Oxygen-free high thermal conductivity (OFHC) copper was used for testing. The new combination of metal forming processes was used because of ease of fabrication. Additionally, wear rate, friction coefficient and wears mechanisms were observed. The friction resistance is caused by the destruction of the adhesion between surface asperities in metal friction. Moreover, increased asperity interactions connected with wear particle entrapment led to a gradual increase in the friction coefficient. These results show the positive influence of the metal forming process to reduce interfacial adhesion and asperity deformation. Finally, the combinations of newly used advanced processing demonstrated excellent wear characteristics of copper.

Keywords: OFHC Cu; ECAP; orbital forging; wear

INTRODUCTION

Metal forming represents the oldest manufacturing technology. Over a long time, the idea of technologies is shifting from traditional processes to the unification of smart techniques for forming highly complex specimens with 3D dimensions [1, 2].
Copper was the first metal used by man and the first that was subjected to forming in history. Moreover, copper represents an ideal element for studying plastic deformation processes. But it has some distinct shortcomings such as low hardness and strength, restricting its applications [1].
Grain refinement is an effective method for metal and alloy strengthening [3]. More papers are interested in the development of nanostructured materials [4-8] with an advanced microstructure of a mean grain size of less than 100 nm, which brings unique mechanical and physical properties. Several processes are used for achieving the structure refinement and therefore increasing the strength properties of materials (light alloys, steels), such as additive manufacturing, Equal-channel angular pressing (ECAP), equal-channel angular rolling (ECAR), cryogenic processes [9-12]. Metal Additive manufacturing (AM) is a process for producing highly complex products as well as unique properties using powder metallurgy (PM). Metal powders are the base materials to produce metallic components through PM techniques. Since metal powders are made by various processes; mainly spherical powders are used for the metal AM. The standard term used to define the AM technique (ISO/ASTM 52900) is as follows; AM allows obtaining net-shape components using a laser source to melt and consolidate thin layers of metallic powders spread onto a building platform by a re-coating system. The layer thickness depends on the size and distribution of the metal powders [13-19].
During the severe plastic deformation (SPD) process a great strain is incorporated into the specimen. Specimen parameters after metal forming remain the same. Additionally, promising grain refinement is achieved [3, 20].
ECAP is a method based on SPD used for reducing the grain size diameter and increasing the dislocation density resulting in unique strength and ductility [21-24].
During the ECAP, specimens are pressed using a die several times to obtain great deformation and structural homogeneity. Repeated passes provide an opportunity to activate the different shear systems through simple specimen rotation before each pass [25]. The number of ECAP passes is also one of the most important parameters affecting material properties. It is well known that the most significant microstructure refinement takes place during the first ECAP pass [26-29].
Based on the ECAP idea carried out by the ECAR. Moreover, overcome limited practical application of ECAP. In the ECAR,

metal sheets are subjected to shear strain through the die channels without changing the dimensions [30-35]. The final rolling temperature increase could improve plasticity and formability [36].

Orbital forging is a metal forming process which incrementally deforms a work-piece using a combination of rotation, rolling, and axial compression processes. The forging force is concentrated on a small local area of the workpiece in contact with the tilted die. The dies are then moved to deform successive small areas of the workpiece until a final shape is formed, which can improve metal flowing and decrease forging load [37-41].

The problem of the fatigue strength and wear resistance of advanced materials, particularly ultra-fine-grained containing voids (pores), defects or inhomogeneities, is significant both from the theory and practical point of view [42-46]. Therefore, the case study of advanced processed OFHC copper by dry sliding wear test is studied in the present paper.

MATERIAL AND METHODS

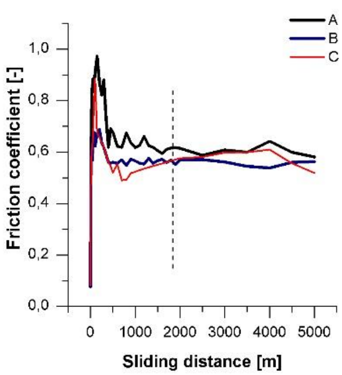
As an experimental material, OFHC copper was used. Samples were carried out by the orbital press, applying a pressure of 200 MPa at a logarithmic strain of 1.95 (samples signed as A). The die used for ECAP consisted of two rectangular channels with a cross-section area of 10 mm x 70 mm intersecting at an angle of 90°. ECAP passes were realized using route C. The billets were coated with Cu nanoparticles containing lubricant to reduce the friction during ECAP between the die and the billets. Specimens signed as B and C were processed by 4 ECAP passes and OF or 6 ECAP passes and OF, respectively.

Pin-on-disc tests were performed using the tribometer entirely developed in the Alessandria Campus of Politecnico di Torino [47-50]. The 15 N applied loads were used. The disc rotation speed was 300 rpm. According to the ASTM standard, abrasive papers were used for polished the tested surface. Each test was interrupted after following a sliding distance starting from 300 up to 5000 meters, and subsequently, discs were weighed with a sensitivity of 10^{-5} g. A Hommel Tester T1000 tangent profilometer was used for determining the surface topography.

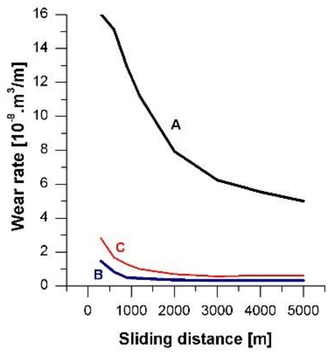
SEM JEOL 7000F was used for the observation of wear tracks and microstructures. Vickers hardness indenter with 50 g load for 15 s. was carried out the apparent hardness HV values.

RESULTS AND DISCUSSION

The frictional coefficient during dry sliding consists of an adhesion force and a deformation force. The friction behaviors of the proposed systems are shown in **Fig. 1**.



(a)

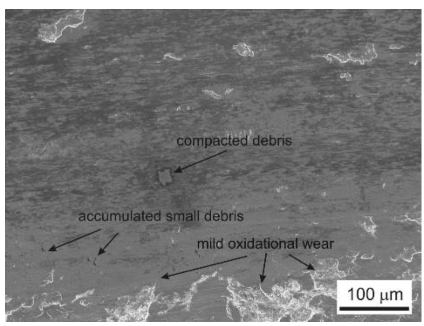


(b)

Fig. 1 Wear characteristics of the investigated OFHC Cu: (a) The behaviour of friction coefficient with different stages; (b) The behaviour of wear rate

The adhesion component is important during the dry sliding wear, and mostly hardness and ductility have affected the results [51]. Consider the dry friction without any medium between contact surfaces. The friction resistance is caused by the destruction of the adhesion between surface asperities in metal friction as has been pointed out by authors [52].

The figures are shown that the friction coefficient in the initial value of its slightly dependent on the load, FN, and that is, the so-called static friction which is typical for dry sliding wear [52, 53]. The higher value of friction coefficient was seen in system A. The metal forming process, represented by OF, leads to smaller stresses and the contrary to ECAP process also with a downsizing of plastic deformation. Surface layer removal during the manufacturing and an increase in adhesion because of the clean interfacial areas were observed. Moreover, increased asperity interactions connected with wear particle entrapment led to a gradual increase in the friction coefficient. These results show the metal forming process's positive influence in reducing interfacial adhesion and asperity deformation. All specimens record a similar change in friction coefficient after 1800 m the friction coefficient falls to the steady state. It is seen from Figure 1b that wear decreases a lot in systems B and C in comparison to specimen A. Since the freshly fractured surfaces can be easily oxidized in dry wear sliding, the oxidized debris on the worn surface also can be involved in a complicated process of mixing, compacting, and smearing under the repeated action of the ECAP process from the loading. The surface oxide layer due to SPD can be better pressed into the base metal and therefore precisely affected it. **Figs. 2a-c** show more compacted or accumulated debris which can be seen on the worn surfaces.



(a)

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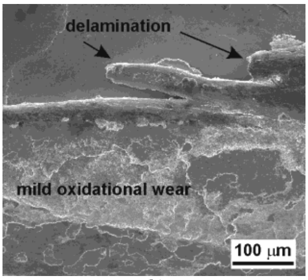
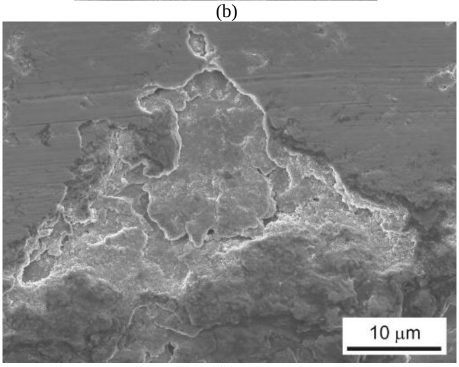


(b)



(c)

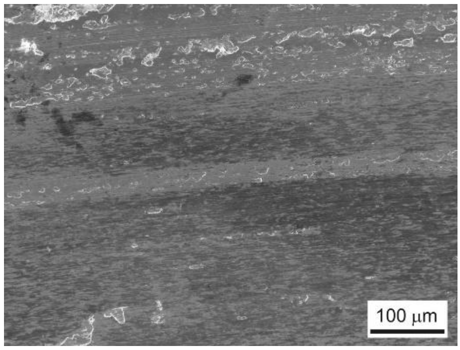
Fig. 2 Wear tracks of the investigated OFHC Cu: (a) Wear track of investigated system A; (b) Wear track of investigated system B; (c) Wear track of investigated system C

The mixed surface layer on the worn surface consists of compacted or accumulated debris and surface oxide layers that are to prevent the contact of metal to metal during the dry sliding, which agrees with the results. As well, it can be seen from the microstructures, which also mild oxidational wear is observed in all investigated systems. The main wear mechanisms have detected delamination and mild oxidational wear.
Table 1 are shown the values of surface roughness.

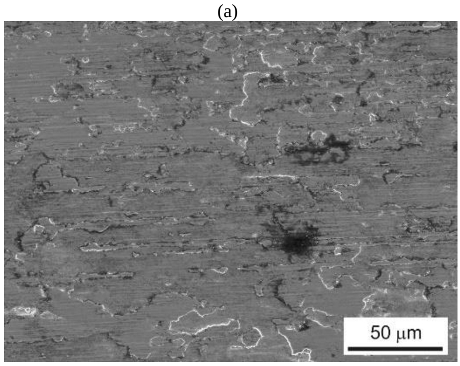
Table 1 The surface topography and Vickers hardness of investigated systems

	A	***B***	***C***
$f_{steady\text{-}state}$ [–]	0,61	0,56	0,57
Rz [μm]	1,10	3,17	2,53
Ra [μm]	0,18	0,41	0,30
HV	248	317	593

Reading **Table 1** is shown that the Ra and Rz surface roughness values should affect the value of the friction coefficient. Also, the hardness value affected the value of the friction coefficient too.
Several authors [54-57] present a statement for correlating the wear behaviour with surface topography. Sub-surface deformation affected surface wear. Other authors showed [58-65] that these results also support the occurrence of material delamination and fracture resulting in its removal. Hanlon et al. [61] observed during nanoscratch tests under repeated sliding contact the effect of grain size on friction characteristics and damage behaviour. Consequently, strength/hardness rather than the grain size occurred to dominate the steady-state friction coefficient and damage accumulation which means each diminishing with substantial increases in material strength. On the contrary, better wear resistance does not always lead to a higher hardness. Moreover, hardness value alone should not necessarily be played the important role in studying wear resistance [51, 62-65].
Don et al. [63] underline, that the better sliding resistance of soft Cu–Cu2O and Cu–Al2O3 alloys in comparison to hard Cu–Be alloys as well as Straffelini et al. [54] in soft Cu–Be alloys.
Reading **Table 1** and **Figs. 2a-c** shows that the processing condition is significantly affected the wear rate. The wear rate decreases continuously in the running-in period during the test and becomes a steady state, seen in systems B and C, after that. The probability of the observance of elementary wear events can be decreased if, through changes in surface topography (**Table 1**), the interaction rate of surface asperity collisions decreases.
For samples B and C, severe plastic deformation occurs during sliding wear, which narrow parallel bands characterized by a larger amount of delaminating, presented in **Fig. 3a, b**.



(a)



(b)

Fig. 3 The larger amount of delaminating causes narrow parallel bands in OFHC Cu: (a) Parallel narrow bands for system B; (b) Parallel narrow bands for system C.

Present results given in the paper clearly outline the wear behaviour, **Fig. 4**.
Since no similar work was done by another research group dealing with present phenomena, it still needs to see more information related to the ECAP and OF processes.
As the properties of sintered parts depend strongly on green density determined by powder behaviour during processing [66-68]. Also, new development processing processes, are not only widely used in PM technologies [69-75]. Most fundamental studies have focused on the interpretation and analytical expression of the experimental dependence of density or porosity on various processing ways. Such an approach was prompted by the

practical need to find an adequate and generally valid characterization of the different powder mixes. Further investigation is therefore open.

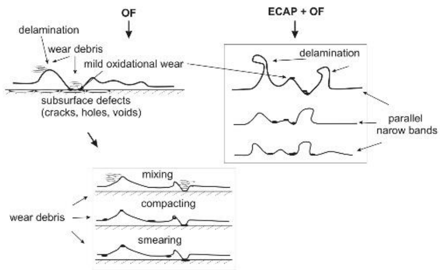


Fig. 4 Wear mechanism of ECAPed and orbital forged Cu OFHC material

CONCLUSIONS

The main conclusions are:
- The combination of newly used advanced processing demonstrated excellent wear characteristics of OFHC Cu.
- The wear tracks observed the delamination and the mild oxidational wear, and both wears are the main wear mechanisms.

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