Available online at www.onecentralpress.com
One Central Press
proceedings webpage: www.onecentralpress.com/functional-nanostructures-proceedings

Tribological behaviour of nanostructured iron processed by equal channel angular pressing

Wassim Zein Eddine[1], *Jean-Pierre Celis*[1,2*]

[1]KUleuven, Dept. MTM, Kasteelpark Arenberg 44, B-3001 Leuven (Belgium).
[2]Falex Tribology N.V., Wingepark 23b, B-3110 Rotselaar (Belgium).
[*]corresponding author

ABSTRACT

The effect of grain size on strength and tribological behaviour of nanostructured and coarse-grained iron is presented. Nanostructured iron was obtained by equal channel angular pressing (ECAP) starting from drawn coarse-grained ARMCO Fe cylinders of industrial purity (>99.85%). The evolution of surface and subsurface due to thermo-mechanical effects during sliding, is discussed in the light of surface and subsurface microstructures developed during reciprocating sliding tests performed at RT in ambient air.

I. INTRODUCTION

The tribology of coarse and ultra-fine grained iron is closely linked to microstructural and mechanical properties [1-3]. Strength of single-phase materials can be ascribed to grain boundary strengthening, work hardening or a combination of both. Benson *et al*. [4] compiled data on the yield strength (σy) of iron vs. its grain size (d). These two properties are related in the following Hall-Petch type relationship [4] for iron with grain sizes larger than 250 nm:

$$\sigma y = 100 + 480 \times d^{-1/2} \qquad (1)$$

This increased resistance to plastic flow has been associated with the enhanced pinning of dislocations by the increased number of grain boundaries as the grain size continues to drop into the nanoscale [5]. Upon decreasing grain size, hardness and strength reach their maximum at grain sizes between 10 and 30 nm, just before the transition from dislocation-based plasticity to grain-boundary deformation [6]. The arbitrary limit of 100 nm below which ‘nanocrystalline’ materials are defined may not be realistic as many interesting mechanical properties are still found in materials within the ‘ultrafine’ grains (100 - 500 nm) regime [6]. This regime is more accessible from an industrial point of view. Sliding on ductile materials is often accompanied by severe plastic deformation localized within a small volume of material adjacent to contact surfaces [7, 8]. Metallography of subsurface revealed the formation of a well-defined cell structure elongated in the sliding direction [9, 10] which increases the microhardness of this subsurface vs. bulk material. Considering Archard equation, ultrafine-grained materials with higher hardness are expected to exhibit lower wear when compared to coarse-grained counterparts under abrasive or adhesive wear modes. Current research has suggested instead a general inconsistency with the Archard behaviour [11].

II. MATERIALS INVESTIGATED

Nanostructured iron was obtained by equal channel angular pressing (ECAP) starting from drawn coarse-grained ARMCO Fe cylinders of purity >99.85% (Fig. 1). Fe-ECAP consists of equiaxed ultrafine grains (~350 nm), while Fe-coarse consists of large grains (> 30 µm).

III. EVOLUTION OF FRICTION AND WEAR DURING RECIPROCATING SLIDING

The average coefficient of friction (CoF_{av}) during reciprocating sliding (Fig. 2) reveals a running-in period characterized by an evolving CoF_{av} during the first ~10.000 sliding cycles on both Fe-coarse and Fe-ECAP. The running-in can be seen as the time needed to deform surface asperities and to create a constant (in statistical sense) surface topography/state and sub-surface microstructure. CoF_{av} fluctuates on further sliding around a "steady state" value of 0.54 for Fe-coarse, and 0.49 for Fe-ECAP.

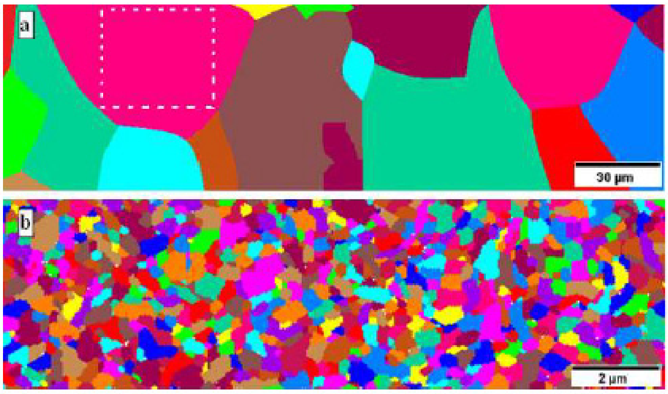

Figure 1 EBSD showing grains with grain boundary angles > 10° in starting materials: (a) Fe-coarse, and (b) Fe-ECAP.

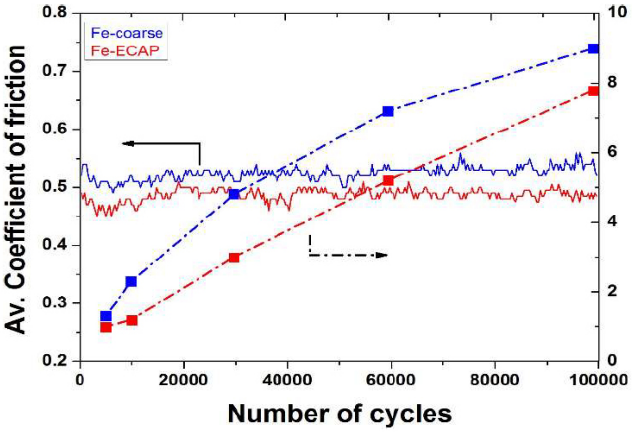

Figure 2 Evolution of the coefficient of friction and wear depth during reciprocating sliding tests against a corundum ball at 5 N normal load, 5 Hz, and 500 µm displacement amplitude.

The wear depth of Fe-ECAP is lower than that of Fe-coarse at all sliding cycles (see Fig. 2). Aside from a relatively higher wear rate on Fe-coarse during the running-in period, the wear rate on the two materials becomes quite similar at further increasing sliding cycles.

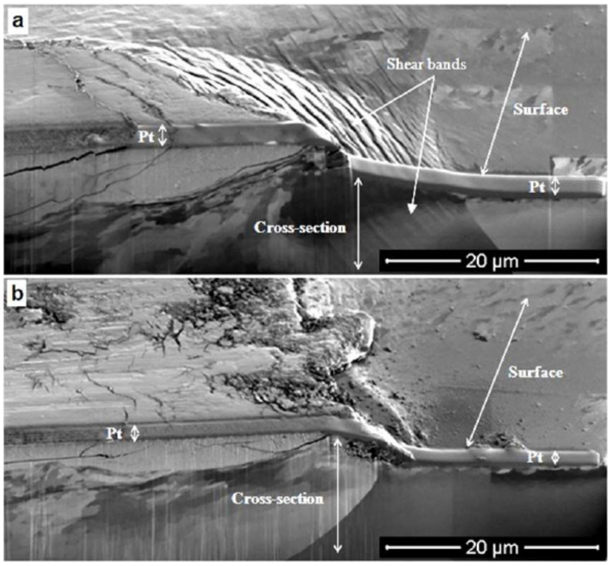

Figure 3 FIB cross-sections on Fe-coarse showing (a) shear bands at the turning point of the sliding track after 10,000 sliding cycles, (b) absence of shear bands after 100,000 sliding cycles.

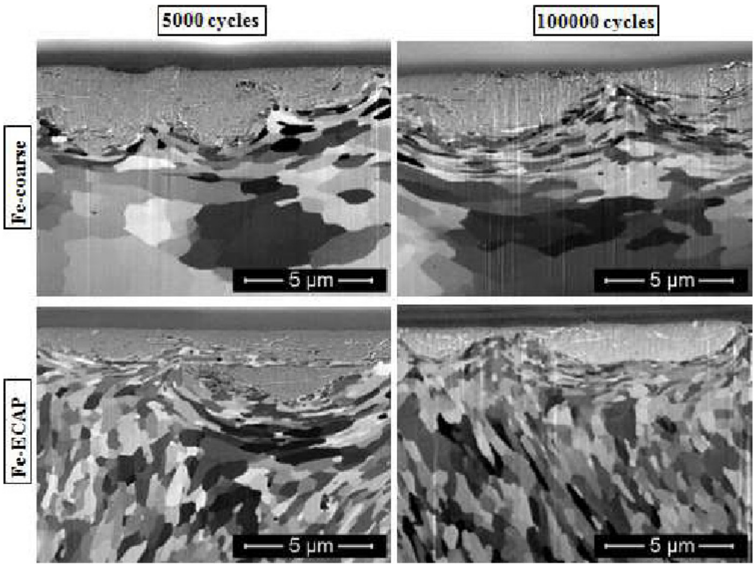

Figure 4 FIB-cross sections across the sliding tracks on Fe-coarse and Fe-ECAP showing a sub-surface deformation after 5,000 and 100,000 sliding cycles.

A grain deformation and refinement occur in the subsurface on Fe-coarse at increasing number of sliding cycles as a result of a friction induced severe plastic deformation (Fig. 3-4). At that stage the running-in comes to an end, and no major difference in hardness of the sliding tracks on both Fe-coarse and Fe-ECAP was noticed. At the same time the wear rate recorded during the running-in phase drops down and becomes at increasing number of sliding cycles comparable to the one noticed on ECAP-Fe. The similar wear rates and the steady CoF_{av} recorded on both samples can thus be attributed to the relatively constant subsurface microstructures that develop by near-surface "mechanical mixing" underneath the sliding track. Even though Fe-ECAP with sub-micron grains and higher hardness than coarse-grained iron, showed a smaller wear depth compared to Fe-coarse, that difference is modest and does not vary with sliding cycles. That is mainly associated with the higher ability of Fe-coarse to accommodate the friction induced severe plastic deformation by absorbing the energy through a subsurface deformation and a grain refinement as compared to Fe-ECAP.

To achieve a stronger beneficial effect of grain refinement on wear resistance, an initial grain size smaller than that achieved by severe plastic deformation under current sliding conditions is needed. This could be achieved by using techniques with lower grain size refinement limits such as high energy ball-milling. Additionally, pinning the microstructure with small inert hard particles helps retaining a nanostructure during subsequent sintering.

IV. SUMMARY

Based on the observations made, it can be stated that, to harvest a more noticeable improvement of the wear resistance by nanostructuring, the initial grain size should be below the grain size reachable by friction induced severe plastic deformation (SPD), namely ~200 nm in our case which was limited to discontinuous layers less than 1µm thick. Such subsurface nano-structures can’t add much to the load-bearing capacity of a material in sliding contacts.

V. REFERENCES

[1] P. J. Mutton, J. D. W., Some effects of microstructure on the abrasion resistance of metals. Wear, 1978. **48**: 385-398.

[2] Gahr, K.-H. Z., Formation of wear debris by the abrasion of ductile metals. Wear, 1981. **74**: 353-373.

[3] Warren, C.D., The influence of implanted transition metal ions on the adhesive wear of iron Wear, 1989. **134**(1): 149-164.

[4] D. J. Benson., M. A. Meyers, On the effect of grain size on yield stress: extension into nanocrystalline domain. Materials science and engineering A, 2001. **319-321**: 854-861.

[5] Cottrell, A.H., Trans. TMS-AIME, 1958. **212**.

[6] V. Kopylov, Ultimate Grain Refinement by ECAP, in Nano-structured Materials by High-Pressure Severe Plastic Deformation, V. V. Yuntian T. Zhu, Editor. 2006.

[7] W. Hirst, J.K.L., The influence of speed on metallic wear. Proc. R. Soc. A, 1961. **259**: 228-245.

[8] J. H. Dautzenberg, J. H. Z., Quantitative determination of deformation by sliding wear. Wear, 1973. **23**: 9-19.

[9] P. Heilmann, W. A. C., D. A. Rigney, Orientation determination of subsurface cells generated by sliding. Acta Metallurgica, 1983. **31**: 1293-1305.

[10] D. A. Rigney, L. H. C., M. G. S. Naylor, A. R. Rosenfield, Wear processes in sliding systems. Wear, 1984. **100**: 194-219.

[11] N. Gao, C. T. W., R. J. K. Wood, T. G. Langdon, Tribological properties of ultrafinegrained materials processes by severe plastic deformation. Journal of Materials Science, 2012. **47**: 4779-4797.