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CHARACTERIZATION OF WEAR MECHANISMS IN SINTERED Fe-1.5 Wt % Cu ALLOYS

CHARAKTERYSTYKA MECHANIZMÓW ZUŻYCIA SPIEKANYCH STOPÓW Fe-1.5Cu

In this research, increasing amount of ultimate tensile strength and hardness in sintered Fe-1.5 Wt % Cu alloys is observed with increasing the density. The influence of different applied pressure of 300, 450, 600 and 750 MPa on porosity and wear behavior has been also studied.

Cross-section micrographs of worn surfaces show that the pores are closed by plastic deformation or oxides and metallic particles after the wear test. According to the wear test results, specimens with 14 vol. % porosity are more wear resistant than the specimens with low porosity values of 11 vol. %.

Thus, oxidation wear and surface plastic deformation are the main wear mechanisms identified in this investigation. Abrasion wear was also characterized as the result of abrasive debris agglomeration and the asperities of the pins.

Keywords: tribological properties, powder processing, porosity

Obserwowano wzrost wytrzymałości na rozciąganie i twardości spiekanych stopów Fe-1.5Cu (% wag) wraz ze wzrostem ich gęstości. Badano także wpływ różnych wartości ciśnienia 300, 450, 600 i 750 MPa na porowatość i zużycie stopów.

Mikrofotografie przekrojów zużytych powierzchni pokazują, że po teście zużycia pory są zamknięte wskutek odkształcenia plastycznego lub przez tlenki i cząstki metaliczne. Według wyników badań zużycia próbki o porowatości 14% są bardziej odporne na zużycie niż próbki o niższej porowatości 11%. Utlenianie i odkształcenie plastyczne powierzchni to główne mechanizmy zużycia zidentyfikowane w tej pracy. Stwierdzono także, że ścieranie jest wynikiem aglomeracji ściernych drobin i nierówności pinów.

1. Introduction

Powder Metallurgy products are today used in a wide range of industries, from automotive to power tools and household appliances. Each year the international PM awards highlight the developing capabilities of the technology. Many special products are possible with powder metallurgy technology. A nonexhaustive list includes Al2O3 whiskers coated with very thin oxide layers for improved refractories; iron compacts with Al2O3 coatings for improved high-temperature creep strength; light bulb filaments made with powder technology; linings for friction brakes; metal glasses for high-strength films and ribbons; heat shields for space craft reentry into Earth's atmosphere; electrical contacts for handling large current flows; magnets; microwave ferrites; filters for gases; and bearings which can be infiltrated with lubricants [1, 2]. Powder metallurgy is the process of blending fine powdered materials, pressing them into a desired shape, and then heating the compressed material in a controlled atmosphere to bond the material. The powder metallurgy process generally consists of four basic steps: (1) powder manufacture, (2) powder mixing and blending, (3) compacting, (4) sintering. Compacting is generally performed at room temperature, and the elevated-temperature process of sintering is usually conducted at atmospheric pressure [3-6].

A much wider range of products can be obtained from powder processes than from direct alloying of fused materials. In melting operations the ”phase rule” applies to all pure and combined elements and strictly dictates the distribution of liquid and solid phases which can exist for specific compositions. In powder metallurgy, it is possible to fabricate components which otherwise would decompose or disintegrate. All considerations of solid-liquid phase changes can be ignored, so powder processes are more flexible than casting, extrusion, or forging techniques. Controllable characteristics of products prepared using various powder technologies include

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mechanical, magnetic, and other unconventional properties of such materials as porous solids, aggregates, and intermetallic compounds. Competitive characteristics of manufacturing processing (e.g., tool wear, complexity, or vendor options) also may be closely regulated [7-10].

Wear can also be defined as a process where interaction between two surfaces or bounding faces of solids within the working environment results in dimensional loss of one solid, with or without any actual decoupling and loss of material. Aspects of the working environment which affect wear include loads and features such as unidirectional sliding, reciprocating, rolling, and impact loads, speed, temperature, but also different types of counter-bodies such as solid, liquid or gas and type of contact ranging between single phase or multiphase, in which the last multiphase may combine liquid with solid particles and gas bubbles.

P/M steels exhibit better wear behavior than do steels produced by conventional processes. Depending on wear condition, metallurgical structure, composition and porosity of P/M steels, there are several mechanisms contributing to wear behavior of P/M.

Adhesive wear can be found between surfaces during frictional contact and generally refers to unwanted displacement and attachment of wear debris and material compounds from one surface to another. It is caused by relative motion and plastic deformation which create wear debris and material transfer from one surface to another [7, 8].

Abrasive wear occurs when a hard rough surface slides across a softer surface. It is defined as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface. There are a number of factors which influence abrasive wear and hence the manner of material removal. Several different mechanisms have been proposed to describe the manner in which the material is removed. Three commonly identified mechanisms of abrasive wear are: (1) Plowing, (2) Cutting, (3) Fragmentation.

Plowing occurs when material is displaced to the side, away from the wear particles, resulting in the formation of grooves that do not involve direct material removal. The displaced material forms ridges adjacent to grooves, which may be removed by subsequent passage of abrasive particles. Cutting occurs when material is separated from the surface in the form of primary debris, or microchips, with little or no material displaced to the sides of the grooves. This mechanism closely resembles conventional machining. Fragmentation occurs when material is separated from a surface by a cutting process and the indenting abrasive causes localized fracture of the wear material. These cracks then freely propagate locally around the wear groove, resulting in additional material removal by spalling [6-10].

P/M parts generally have more than 5 vol% porosity which is a limiting factor for increased usage of P/M materials for structural components. It is generally believed that the presence of porosity negatively influence the mechanical properties of the materials [11-13].

In this research work, the influence of porosity on tensile strength, hardness and wear properties of P/M steels is investigated.

2. Experimental procedures

As a starting powder for experiments, Fe- 1.5 Wt % Cu powder was used.

Carbon (0.6 Wt %) as fine natural graphite (UF4) and Zinc stearate (0.75 Wt%) as lubricant were blended to the mixture.

The powder mixtures were cold-compacted using a cylindrical die with different compacting pressure of 300, 450, 600 and 750 MPa. Specimens were sintered at 1120°C in 90%N2/10%H2 atmosphere for 30 min.

The sintered densities of samples were measured in accordance with ASTM-B328 standard.

The mechanical properties including tensile strength and hardness were carried out according to ASTM E8-00 and ASTM E92-82 standards, respectively. Each value of ultimate tensile and yield strength is an average of at least three tensile specimens. Dry sliding wear tests were performed under different loads of 10, 20 and 30 N using a pin-on-disc type reciprocate wear apparatus.

The samples were made into the disc and put in contact with AISI 52100 steel pins with 64 HRC. All tests were performed at room temperature (21°C, relative humidity 30-60%). Total sliding distance was selected as 2000 m.

For microstructure study, specimens were prepared by grinding through 120, 400, 600, 800 grit papers followed by polishing with 9 μm diamond paste and etched with 3% nital solution. Worn surface and cross-sections of worn surface were also examined by a CamScan MV2300 scanning electron microscopy with the energy dispersive X-ray analysis accessory. Chemical characterization of worn surfaces and wear debris were performed using energy dispersive spectrometer (EDS).

3. Results and discussion

The effect of the applied pressure on the density and porosity of the studied materials is represented in Table 1. Increasing amount of density and decreasing amount of porosity are observed with increasing the applied pressure. Optical micrographs of the samples with

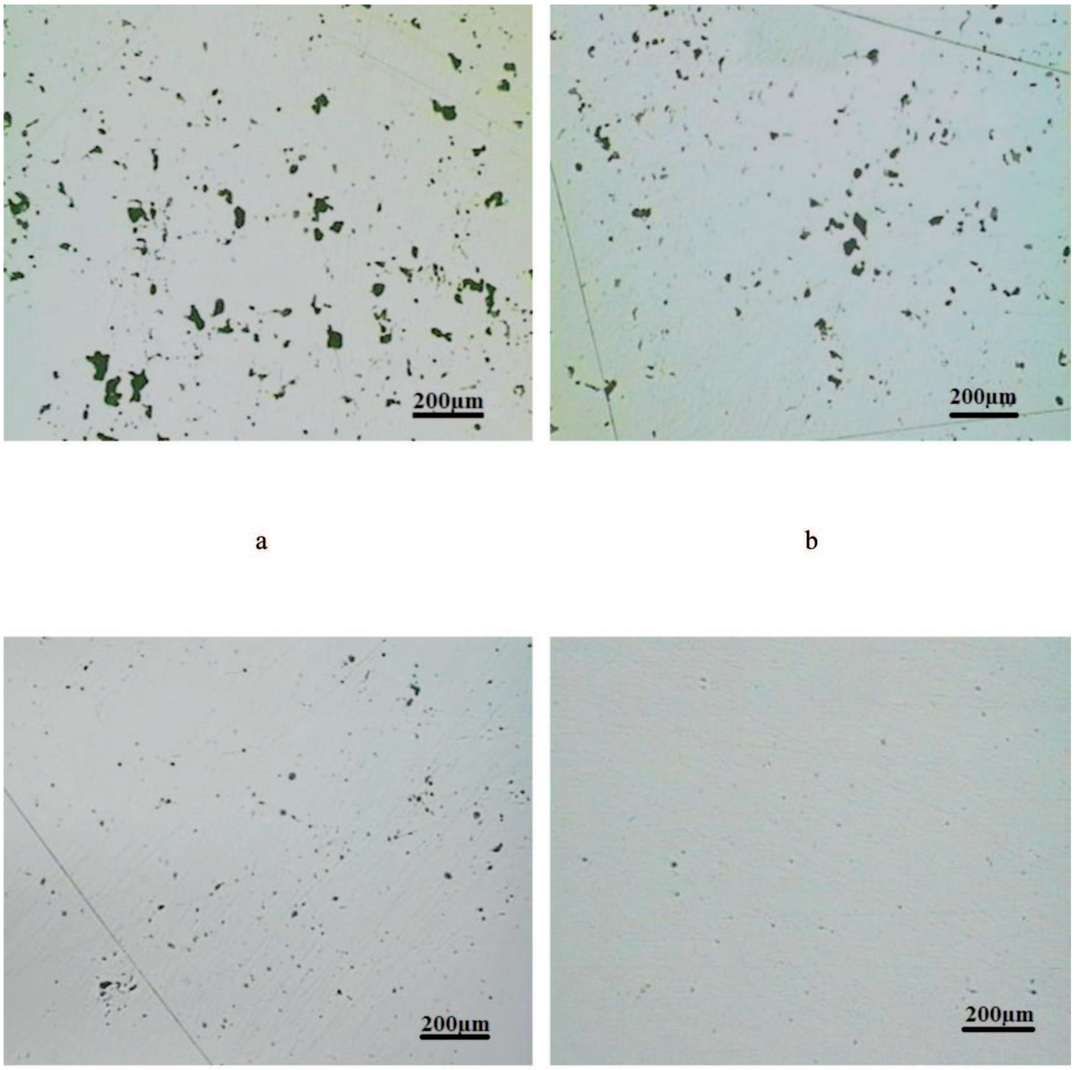

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Fig. 1. Microstructure of the studied materials: (a) PM1; (b) PM2; (c) PM3; (d) PM4

different porosity levels are shown in Fig. 1. The porosity in these samples is the combination of the pores that are present among the compacted powders and not removed by pressing as an intrinsic feature of powder metallurgy products and also residual porosity from liquid phase formation or diffusion of alloying additions, such as copper, at the sintering temperature.

TABLE 1

Effect of the applied pressure on the porosity

Type of sample	PM_1	PM_2	PM_3	PM_4
Applied pressure (MPa)	300	450	600	750
Density (g.cm^{-3})	6.27	6.48	6.75	7.08
Porosity (% vol.)	20	17	14	11

The hardness test was carried out for each sample. Ten hardness readings on randomly selected regions were taken in order to get a representative value of hardness. During hardness measurement, precaution was taken to make indentation at a distance of at least twice the diagonal length of the previous indention. Figure 2(a) shows that the hardness of samples increases with decreasing amount of porosity. It is clearly shown that the hardness takes into account the porosity content of the materials.

Figure 2(b) shows the variations of UTS with the porosity content. It indicates that increasing amount of UTS is observed with increasing the density.

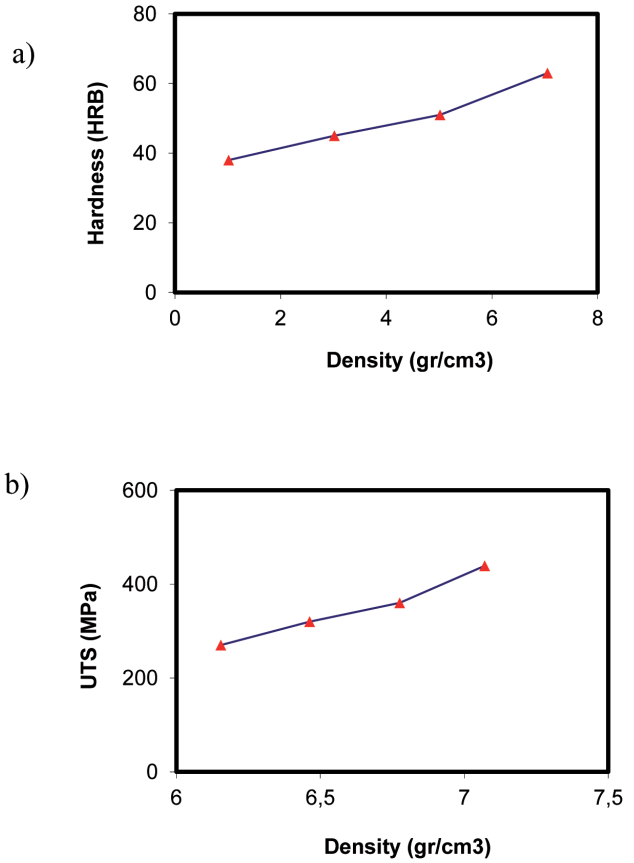


Fig. 2. The effect of density on: (a) HRB, (b) UTS

It is reported that the crack initiation take place at the preferred site like pores, particularly at the surface of the specimen (Fig. 3). Thus, more crack nucleation occurs in the samples with lower density. Then these cracks connect together in all volume of sample and have a destructive effect on the tensile strength and hardness of the materials [3, 14-19].

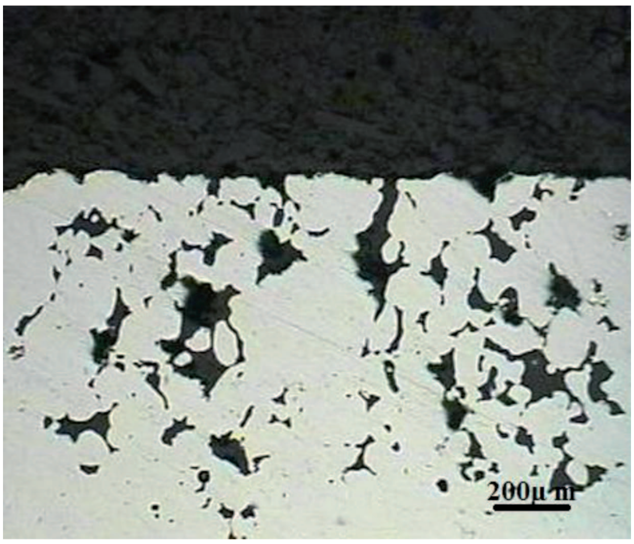


Fig. 3. Typical cross-section micrograph showing pores at the surface of the of sintered samples

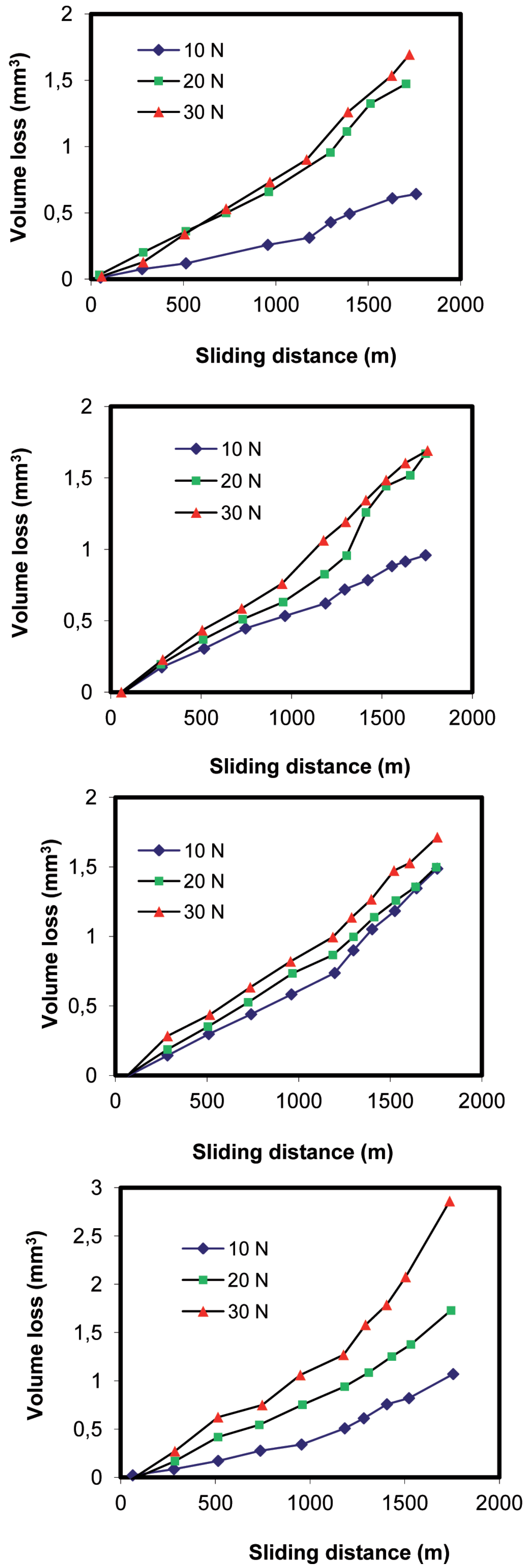
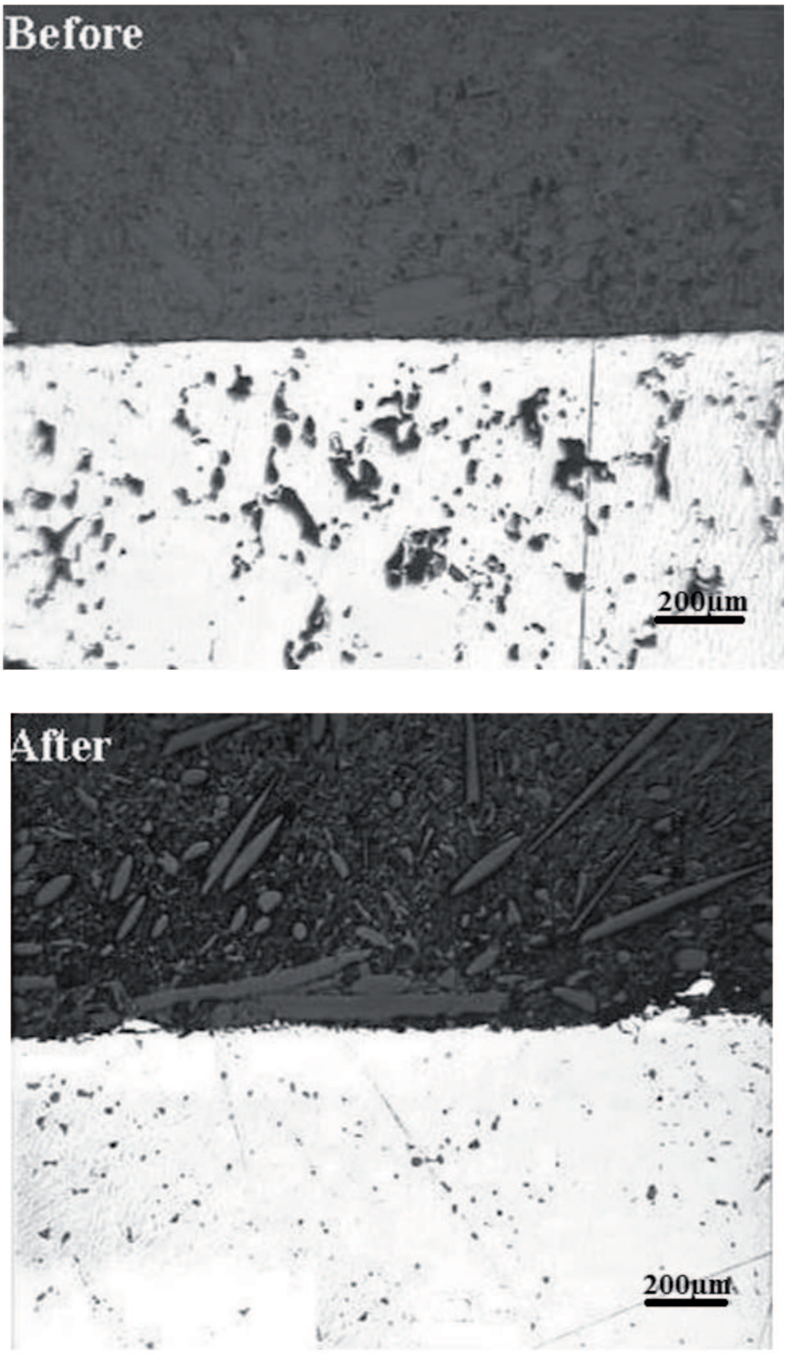


Fig. 4. The variations of volume loss with the sliding distance: (a) PM1; (b) PM2; (c) PM3; (d) PM4

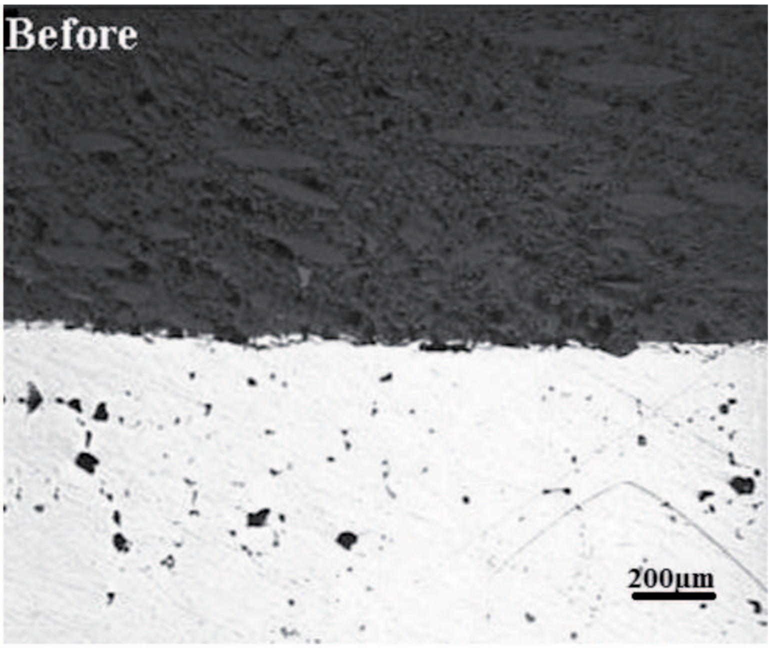
The variations of volume loss with sliding distance for the samples containing different amount porosity are summarized in Fig. 4. It is clear from this graph that the volume loss increases with increasing the applied load. The investigation of the worn surfaces revealed that various mechanisms including surface plastic deformation, oxidation and abrasion wear are involved in the wear of the materials.

Cross-section micrographs of worn surfaces show the amount of the pores at the surface before and after the dry wear of the materials (Fig. 5). It is observed that the pores are closed by plastic deformation after the wear test. Some of the pores might have been filled with the oxides and metallic particles.

a)



b)



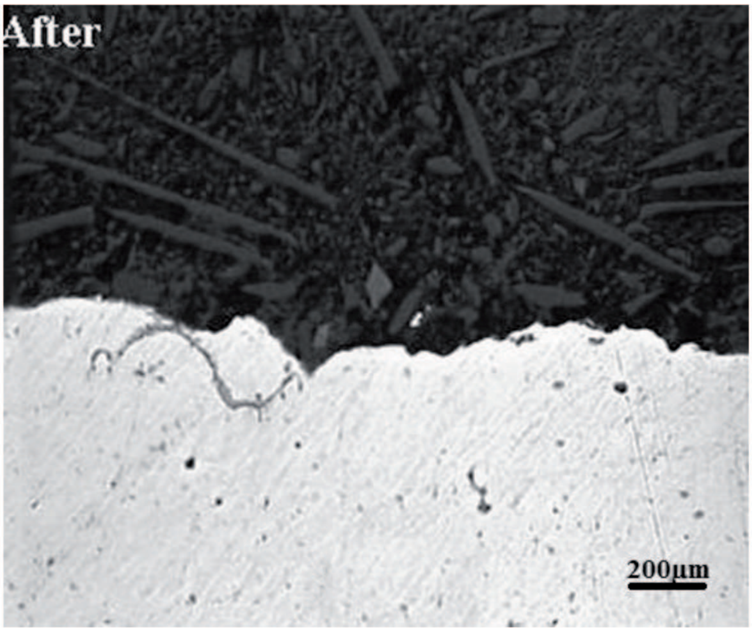
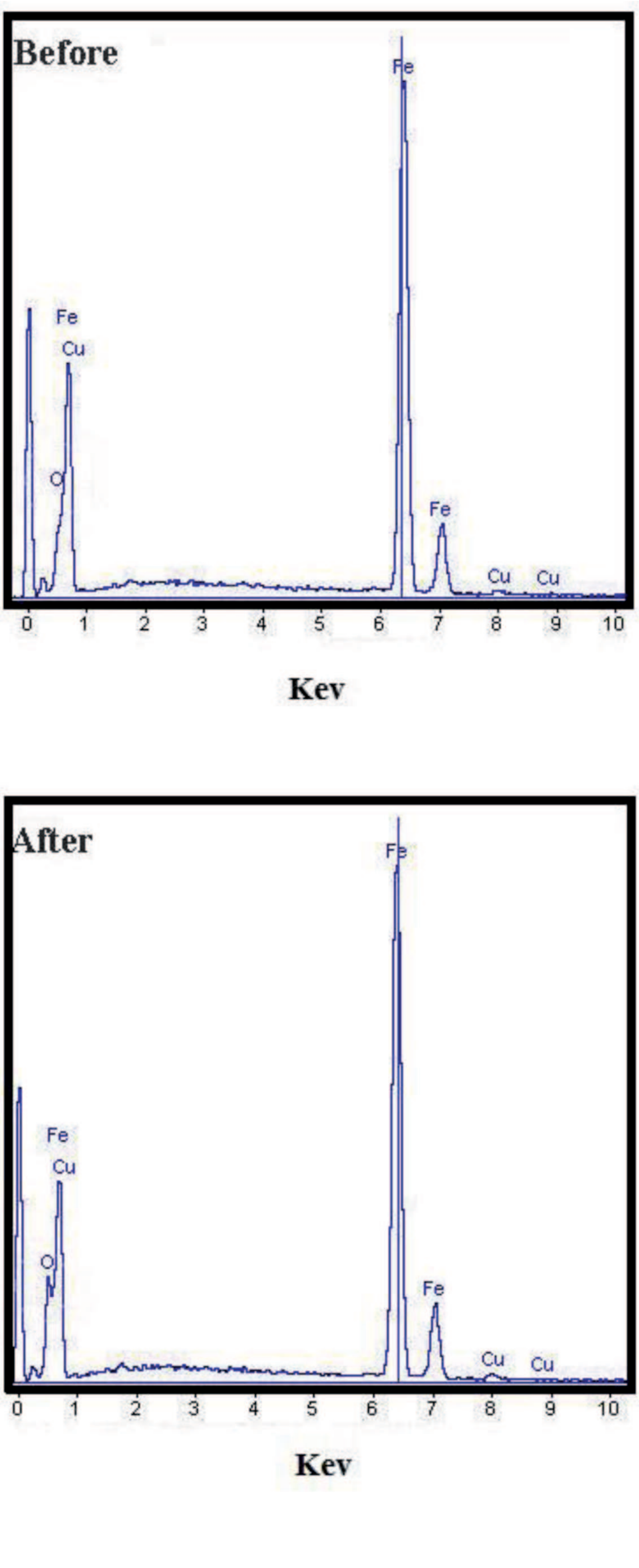


Fig. 5. Typical cross-section micrographs of a worn specimen before and after wear: (a) PM1, (b) PM3

EDS analysis of worn surfaces revealed the presence of oxides which is an implication of oxidation wear mechanism (Fig. 6). Dry sliding of ferrous materials results in high local temperatures and allow the development of oxide films. Oxidation wear mechanism is a predominant mechanism in dry sliding wear of ferrous materials. The wear debris is formed when the oxide films reach a critical thickness and break up (Fig. 7) [6-7].

SEM micrographs of worn surfaces show the existence of abrasion lines, which are attributed to the asperities of the pins and the abrasive action of oxide debris (Fig. 8). It is reported that the wear particles produced during sliding are agglomerated and contribute significantly in the abrasion wear rate [6-9].

a)


Before
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Fe
Cu
O
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Cu
Cu
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b)

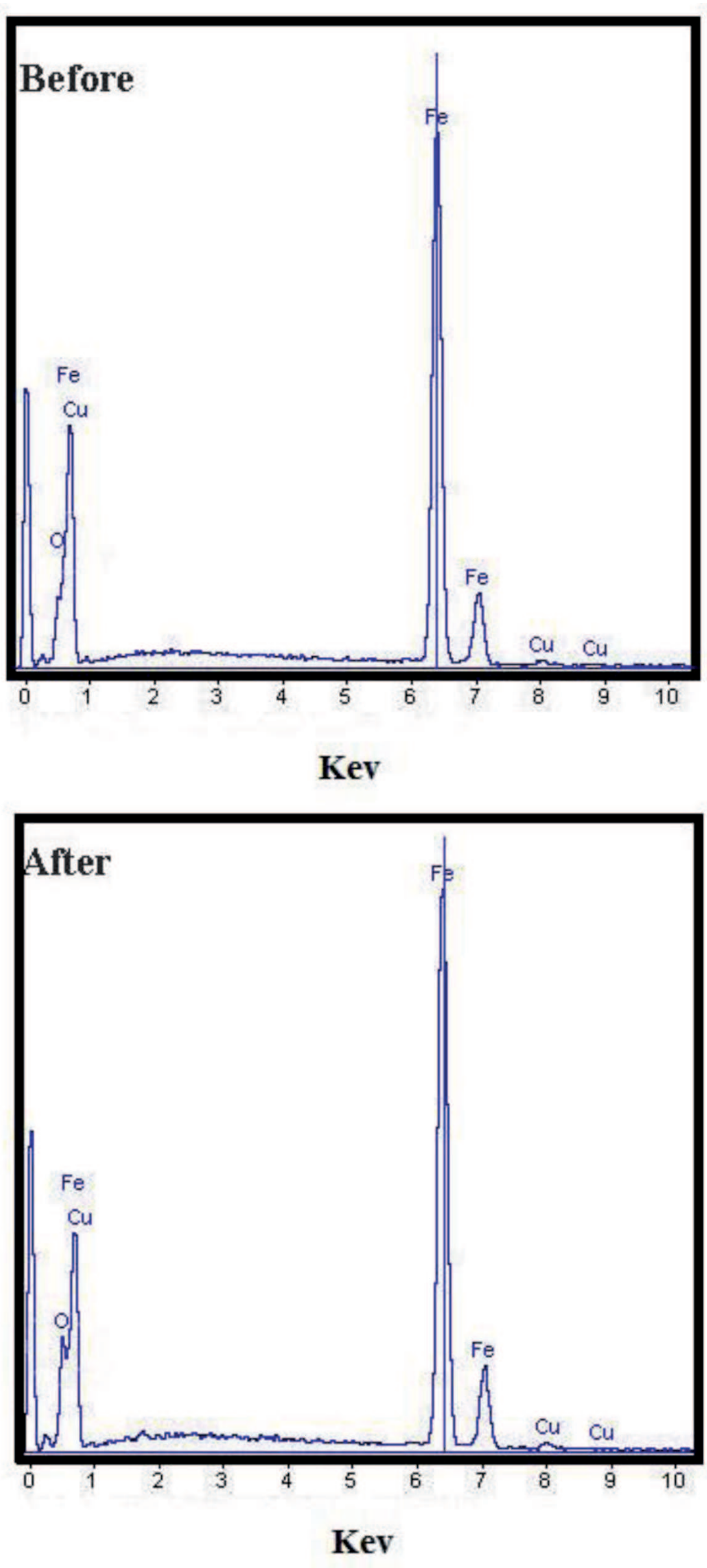

Fig. 6. Typical EDS analysis of worn surfaces (a) PM1 (b) PM4

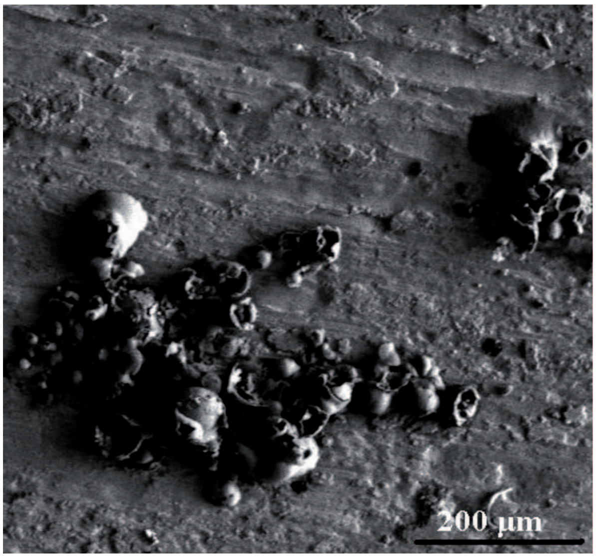

Fig. 7. Formation of debris on the worn surface

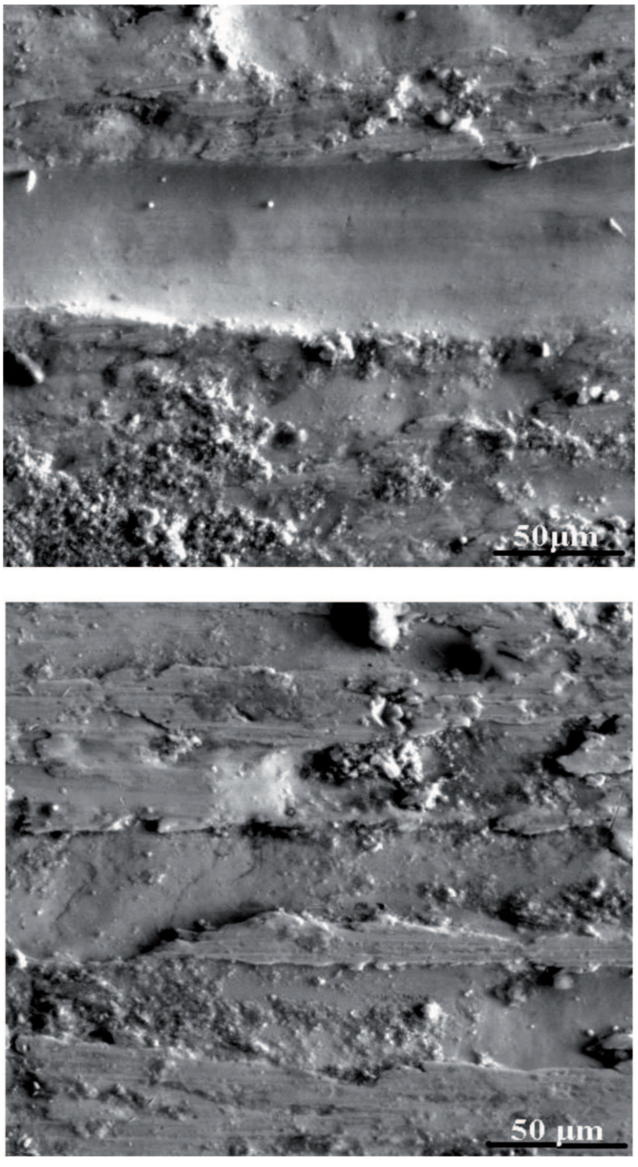

Fig. 8. Typical micrographs of a worn specimen (a) PM1, (b) PM2

According to the wear test results, specimens with 14 vol. % porosity are more wear resistant than the specimens with low porosity values of 11vol. %. However, for the porosity levels higher than 14%, the wear resistance decreases with increasing the porosity (Fig. 9). It is believed that pores have the capacity to be filled with debris particles during sliding which can enhance the wear resistance of the specimens by preventing the particle agglomeration and the abrasion wear. Filled pores i.e. increase in the real contact area result in decrease in the contact pressure. The occurrence of particle detachment at the edges of the filled pores also seems to be more difficult. However, for the porosity levels higher than 14%, complete filling of pores is becoming more and more difficult which leads to decrease in wear resistance.

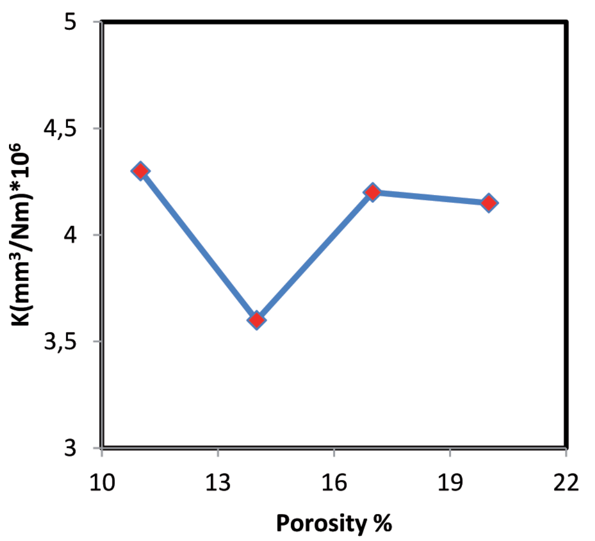

Fig. 9. The variations of volume loss with porosity (Applied load: 20 N)

4. Conclusions

In this paper, the increasing amounts of UTS and hardness are observed with increasing the density. The variation of the dry sliding wear resistance of this alloy with porosity in different loads of 10, 20 and 30 N was then studied. It was observed that the samples with a porosity of 14% display a lower wear rate than the samples with the porosity of 11%. It was concluded that porosity might be beneficial for wear resistance by entrapping the wear debris and preventing the formation of large abrasive agglomerates. The main wear mechanisms identified in this investigation are oxidation wear, abrasion wear and surface plastic deformation.

REFERENCES

[1] D.S. Madan, R.M. German, Structural-property relationship in iron powder compacts alloyed with boron. In: Advances in powder metallurgy and particulate materials. Princeton, NJ: Metal Powder Industries Federation **1**, 147 (1989).
[2] A. Selecka, A. Salak, H. Danninger, The effect of boron liquid phase sintering on properties of Ni-, Mo- and Cr-alloyed structural steels. J Mater Process Technol **141**, 379 (2003).
[3] J. Liu, A. Cardamone, T. Potter, R.M. German, F.J. Semel, Liquid phase sintering of iron-carbon alloys with boron additions. Powder Metall **43**, 57 (2000).
[4] M. Sarasola, T. Gomez-Acebo, F. Castro, Liquid generation during sintering of Fe-35% Mo powder compacts with elemental boron additions. Acta Mater **52**, 4615 (2004).
[5] N.P. Suh, An overview of the delamination theory of wear. Wear **44**, 1 (1977).
[6] K.V. Sudhakar, P. Sampathkumaran, E.S. Dwarakadasa, Dry sliding wear high density Fe-2% Ni based P/M alloy. Wear **242**, 207 (2000).
[7] A. Molinari, G. Straffelini, Wear processes in high strength sintered alloys under dry rolling-sliding. Wear **173**, 121 (1994).
[8] S.C. Lim, J.H. Brunton, The unlubricated wear of sintered iron. Wear **113**, 371 (1986).
[9] E.R. Leheup, D. Zhang, J.R. Moon, Fretting wear of sintered iron under low normal pressure. Wear **221**, 86 (1998).
[10] G. Straffellini, A. Molinari, Dry sliding wear of ferrous PM materials. Powder Metall **44**, 248 (2001).
[11] A. Simchi, H. Danninger, Effects of porosity on delamination wear behaviour of sintered plain iron. Powder Metall **47**, 73 (2004).
[12] A. Molinari, G. Straffelini, P. Campestrini, Influence of microstructure on impact and wear behaviour of sintered Cr and Mo steel. Powder Metall **42**, 235 (1999).
[13] H.O. Gulsoy, Influence of nickel boride additions on sintering behaviors of injection moulded 17-4 PH stainless steel powder. Scr Mater **52**, 187 (2005).
[14] A. Hadrboletz, B. Weiss, Fatigue behavior of iron based sintered material, Int Mater Rev **42**, 1, 44 (1997).
[15] A. Bergmark, Microstructure enhancement for fatigue improvement. In: Proc EURO PM2003. Valencia, Spain, 2003.
[16] E. Gzyryca, Fatigue testing. In: J.R. Davis, Editor, Mechanical testing and evaluation handbook **8**, American Society for Metals 363 (1985).
[17] S. Saritas, R. Causton, W.B. James, A. Lawley, Effect of microstructural in homogenities on the fatigue crack growth response of a prealloyed and two hybride PM steels. Presented at World congress on

powder metallurgy & particular material, Orlando, Florida **16**, 21, June, 2002.

[18] L. Alzati, A. Bergmark, J. Andersson, Fatigue performance of PM steel in as-sintered state. Presented at PMAI conference, Mumbai, India, February, 2005.

[19] S. Carabajar, C. Verdu, A. Hamel, R. Fougeres, Fatigue behavior of a nickel alloyed sintered steel, Mater Sci Eng A **257**, 225, 234 (1998).

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