Influence of Porosity on the Sliding Wear Behavior of Sintered Fe-1.5Mo-0.7C Steels

Jun'an Wang, Ying He, and Herbert Danninger

(Submitted 16 January 2003)

Fe-1.5Mo-0.7C steels with different porosity can successfully be prepared by using traditional compacting, vacuum sintering, and in part Hot Isostatically Pressing (HIPing). Their dry sliding wear behavior in both as-sintered and heat treated states were investigated. When porosity is lower than 6.2%, further decreases of porosity have less influence on the wear coefficient of both as-sintered and heat treated steels. Pores in the sintered steels collect the debris during the rubbing process, and therefore the disadvantage in wear process due to the poor hardness and mechanical strength caused by high porosity is partly compensated for. During dry sliding the as-sintered steels have three types of wear mechanisms (i.e., oxidational wear, abrasive wear, and delamination wear), while oxidational wear and delamination wear are the main regimes in heat treated steels. Oxidation leads to the wear of sintered steels and in the meantime the oxides attached to the rubbing surface further lower intense wear of the rubbing system. Abrasive wear and delamination wear, which result in flake debris, are responsible for high wear coefficients.

Keywords porosity, sintered steels, wear behavior

1. Introduction

Porosity is the most representative feature of sintered steels compared with other intrinsic physical or mechanical properties, such as hardness, impact energy, and transverse rupture strength. Because porosity strongly influences the properties and determines the applications of sintered steels, it draws much attention of the powder metallurgist.[1-3] Higher porosity results in lower values in all mechanical properties of sintered steels.[1] It has been proved that the total porosity lowers the fatigue limit of Mo alloyed sintered steels.[3] In comparison with the numerous studies concerned with other mechanical properties, the influence of porosity on wear behavior of sintered steels has not been extensively investigated.

The volume fraction of porosity and the pore size have considerable effect on the sliding wear behavior of sintered steels. The beneficial and detrimental roles of porosity in wear resistance strongly depend on wear conditions. In lubricated wear process, porosity provides a considerable advantage because the pores act as lubricant reservoirs and/or lubricating channels. In contrast, while in dry sliding wear condition, the influence of porosity on the wear resistance does not appear to be monotonic and transition stages introducing modifications in wear resistance have been proposed.[4,5] The latter case is based on the pores on the worn surface that not only supply the possibility to bring about severe wear as large metallic wear debris could be worn out, but also supply the sites to collect the wear debris, especially oxides, which greatly lighten the wear and therefore obviously compensate their negative effect in wear resistance.[6] For different sintered steels those effects alternate depending on factors such as the composition and heat treating condition. Therefore, until now, it has been hard to make a universal conclusion about the influence of pores on various sintered steels, especially for the series of sintered Fe-Mo-C steels, the dry sliding wear behavior is always associated with the state of the sinter and wear condition beyond the porosity inside. For successful sinters, it is still necessary to evaluate their wear behavior before practical application.

In this paper, the influence of porosity on the dry sliding wear behavior of sintered Fe-1.5Mo-0.7C steels was investigated.

2. Experimental Details

Two powders (i.e., Astaloy1.5Mo that is a pre-alloyed powder of iron and molybdenum with particle size less than 160 μm and natural graphite UF4 [Kropfmuehl]), were used to produce sintered steels with the composition of 0.7 wt.% C and Astaloy1.5Mo base. A 0.25 wt.% HWC was used to be a pressing lubricant. Specimens were pressed at 250, 400, 700 MPa, and double pressed at 700 MPa, respectively, and were sintered at 1270 °C in vacuum for 2 h. Some specimens that were double pressed at 700 MPa and then sintered in vacuum were Hot Isostatically Pressed (HIPed). Parts of the specimens were quenched in oil after soaking in a tube nitrogen furnace at 890 °C for 45 min and then were further tempered in air at 300 °C for 60 min. The basic properties of sintered Fe-1.5Mo-0.7C steels prepared at different compacting pressures are listed in Table 1.

The wear behavior of sintered Fe-1.5Mo-0.7C steels was evaluated on a pin-on-disk test-bed, which is based on ASTM standard G99-95a[7] except that the disk material was replaced by 100Cr6 with a hardness of HRC62. The 6 mm diameter pins were machined from sintered and heat treated steels. Based on the consideration of wear test stability and practical application, the wear test condition was chosen as a sliding speed of 3

Jun'an Wang and **Ying He,** School of Materials Science and Engineering, Shanghai University, State Key Laboratory of Mechanical Transmission, Chongqing University, People's Republic of China; and **Herbert Danninger,** Institute of Chemical Technologies and Analytics, TU, Vienna, Austria. Contact e-mail: jawang@mail.shu.edu.cn.

Table 1 Basic Properties of Sintered Fe-1.5Mo–0.7C Steels

	Density, × 10^3 kg/m^3	Porosity, %	HV30	
Specimens	AS/Q + T(a)	AS/Q + T	AS	Q + T
Pressed at 250 MPa	6.41	18.5	112	222
Pressed at 400 MPa	6.90	12.4	154	417
Pressed at 700 MPa	7.22	8.3	210	447
Double pressed at 700 MPa	7.38	6.2	237	568
Double pressed at 700 MPa and HIPed	7.81	0.8	305	739

(a) AS: as-sintered steels; Q + T: quenched and tempered steels

m/s and load of 30 N after the optimization of the wear test conditions.[8]

The wear was evaluated by measuring the mass loss of the steels in regular intervals during the wear testing process. The wear coefficient of sintered steels (k) was defined after the following formula,

$$k = \Delta V/(F_N \cdot s) = \Delta m/(\rho \cdot F_N \cdot s) \quad (\text{mm}^3/\text{N*m})$$

where ΔV is the worn volume which was calculated from mass loss (Δm) and density (ρ) of sintered steels, F_N load, and s the sliding distance which is calculated from the formula, $s = 2\pi \cdot r \cdot n$, where r is the radius of the worn circle (50 mm) and n the rotation speed of the motor.

Throughout each test, the mass loss in a period of test time was measured to construct plots of wear against sliding distance. By using linear regression analysis, the slope (a) of a line (i.e., $W_{\text{mass loss}} = a \cdot s + b$) was obtained. The wear coefficient in terms of volume loss per unit load and sliding distance, $\text{mm}^3/(\text{N} \cdot \text{m})$, can be easily calculated by the following formula,

$$k = \frac{a}{\rho \cdot F_N}$$

Worn surfaces of pins and wear debris were SEM analyzed on a JEOL JSM-6400 Scanning Microscope (JEOL Ltd., Tokyo, Japan).

3. Results and Discussion

3.1 Pores

The size, shape, and distribution of pores are largely dependent on processing. As all the specimens were sintered under the same sintering parameters (i.e., sintering at 1270 °C in vacuum for 2 h), the compacting pressure plays the decisive role in pore size, shape, and distribution. With the decrease of porosity the pore shape changes from large irregular angular form to a small, rounder shape, which is same result reported in Ref. 2. Although the pores have different shapes, they are almost evenly distributed in all specimens.

For either as-sintered or heat treated specimens, the size of pores decreases with the decrease of porosity (Table 2). Heat treating does not lead to any appreciable changes in the pore shape and size. Specimens compacted at 250 MPa have the largest pores, while the specimens that were HIPped have the fewest and smallest pores. Double pressing for compacts slightly decreases the pore size of specimens and makes the pores rounder as well as decreases the porosity in specimens.

Table 2 Dimensions of the Pores in Specimens(a)

	Dimension (μm), AS		Dimension (μm), Q + T	
Porosity, %	Max	Average	Max	Average
18.5	100	30–35	92	25–32
12.4	84	20–25	80	20–25
8.3	60	15–20	55	10–20
6.2	45	15–20	40	10–15
0.8	6	4	6	4

(a) The pores were measured in the largest diagonal direction for irregular shape.

3.2 Frictional Coefficient

Figure 1 shows the frictional coefficient of the sintered steels as the pins sliding against 100Cr6 disks. It can be seen that all the sintered steels have almost the same lowest (about 0.4) and highest (about 0.6) frictional coefficient except those with highest porosity, which have relatively low highest frictional coefficient. This indicates that the processing methods and heat treating have little influence on the frictional coefficient under the given wear test condition. In this case the formation and worn away of oxides on the surface of sintered steels during the sliding process contribute significantly to the frictional coefficient. When much oxide is formed on the sliding surface the frictional coefficient will reach the value of oxides (i.e., about 0.4 or lower as reported).[8] Under this condition the oxides act as solid lubricant and reduce the friction and wear of the matched steels. After a period of sliding and all of the oxides are worn away the two steels will contact directly. In this case the frictional coefficient will rise above 0.6.

Usually frictional coefficient remain high for only a short time because under the wear condition used, friction heat raises the surface temperature of the sintered steels to their critical oxidation temperature in a short time and new oxides form on the surface in the meantime.[9] Therefore, most of the time during sliding the frictional system maintains a lower frictional coefficient. The friction process is controlled by the formation of oxides, worn away of oxides layers, and the contact of fresh metal area; therefore, the frictional coefficients alternate between the lower limit (when contact surfaces are separated by oxide layers) and upper limit (when metals direct contact).

Sintered steels have many large pores, which are exposed in the frictional process. These pores may collect the debris, usually oxides. The collected oxides not only increase the real contact area between the pin and disk but also act as the solid

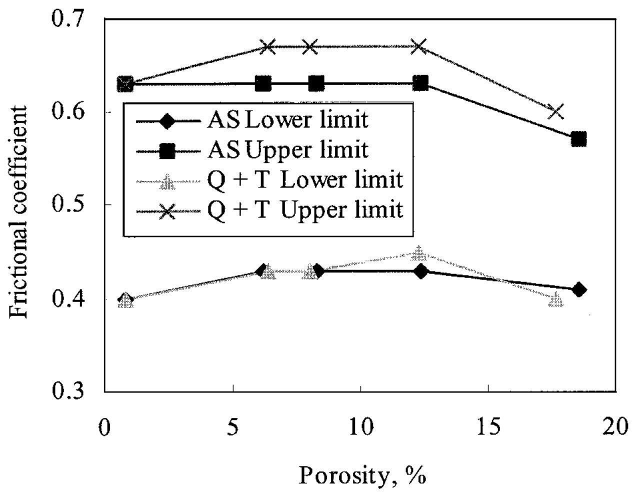

Fig. 1 Frictional coefficient of the specimens as pin sliding against 100Cr6 disk

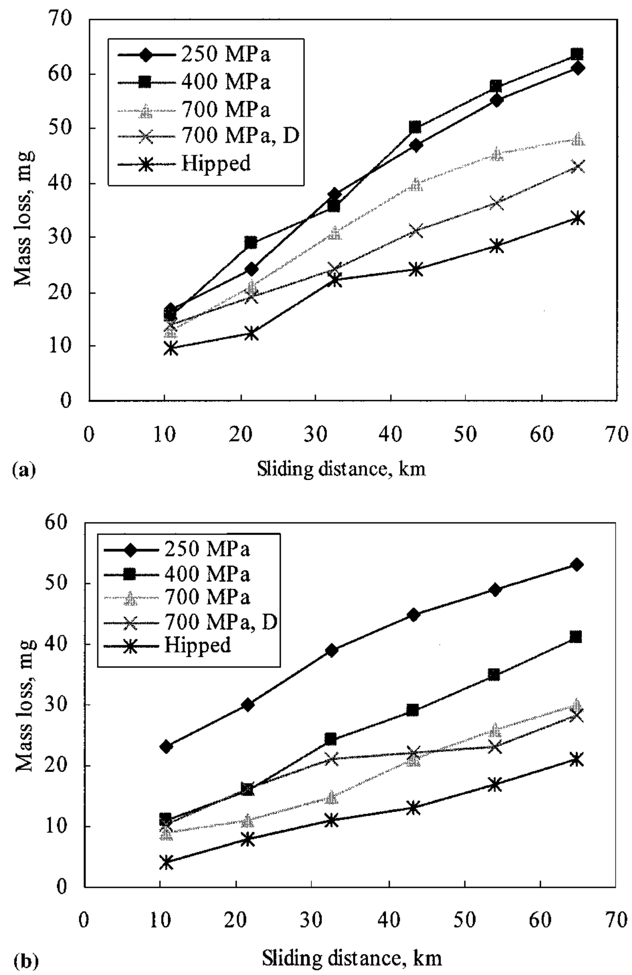

Fig. 2 Mass loss variation with sliding distance of as-sintered Fe-1.5Mo-0.7C steels. D means double pressed at 700 MPa. **(a)** as-sintered; **(b)** Q + T.

lubricant source when the non-pore areas have metallic contacts with the disk. In this sense the high porosity sintered steels have relatively low upper-frictional-coefficient limit because oxides always exist on the contact area even in the case of so-called metal-metal contact. On the other hand, as there are many pores on the frictional surface, this type of sintered steel has a high wear coefficient, which will be discussed later.

3.3 Wear of Sintered Fe-1.5Mo-0.7C Steels

The mass loss variation with sliding distance for sintered Fe-1.5Mo-0.7C steels with different porosity is plotted in Fig. 2. As-sintered steels with high porosity have high mass loss and those with low porosity have low mass loss after both 10.8 km and 64.8 km sliding. This indicates that during the whole sliding wear testing, the mass loss of the as-sintered steels decreases with decrease of porosity.

With the decrease of porosity the mass loss of quenched and tempered Fe-1.5Mo-0.7C steels significantly decreases for both 10.8 km and 64.8 km sliding. The steels with highest porosity have highest mass loss and the ones with the lowest porosity have the lowest mass loss. Compared to as-sintered steels, quenched and tempered steels have lower mass loss at the same porosity, and the function of porosity in the first hour of sliding becomes more evident for the quenched and tempered specimens. All of this indicates that there must be other factors that also influence the wear resistance of sintered Fe-1.5Mo-0.7C steels.

Figure 3 gives the wear coefficient of sintered Fe-1.5Mo-0.7C steels as a function of the porosity. It can be seen that with the increase of porosity, the wear coefficient of sintered Fe-1.5Mo-0.7C steels slightly increases when the porosity is lower than 6.2%. When the porosity is between 6.2 and 12.4% the wear coefficient increases obviously and then once more slightly with the further increase of porosity. Compared to as-sintered steels, the Q+T steels have obviously lower wear coefficient at correspondent porosity. It means that the heat treated steels not only obtain high hardness but also get high wear resistance. In average, after heat treating the wear coefficient decreases by a factor of 1/3. From the above experimental results it can be concluded that the mass loss and wear coefficient of sintered Fe-1.5Mo-0.7C steels increase with the increase of porosity.

The wear coefficient of sintered Fe-1.5Mo-0.7C steels can also be linked to their load bearing cross section (Ac) as seen in Fig. 4. With the increase of Ac the wear coefficient decreases for both as-sintered and heat treated steels. Especially, when Ac increases from 47.8-55.7%, the wear coefficient falls down rapidly. This trend of wear coefficient with Ac supported the idea that under a given test condition the wear coefficient decreases with the decrease of contact pressure between the frictional pairs, as well as that only from the point of view of friction and wear, a fairly high load bearing cross section is enough to achieve good tribological properties. The "jump" in the curves shown in Fig. 4 also indicates that isolated porosity is apparently beneficial for the wear resistance compared to the interconnected one.[3,10]

Porosity and hardness of sintered steels, especially quenched and tempered steels, have significant difference on wear resistance during the first hour of testing, i.e., the running-in period as seen in Fig 5. At high porosity, quenched and

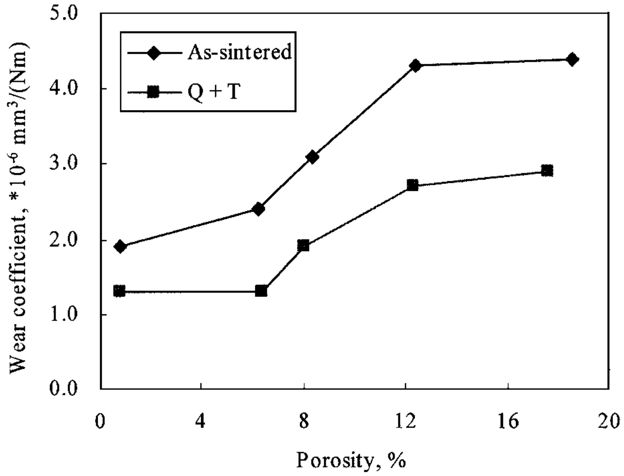

Fig. 3 Wear coefficient of sintered Fe-1.5Mo-0.7C steels with different porosity

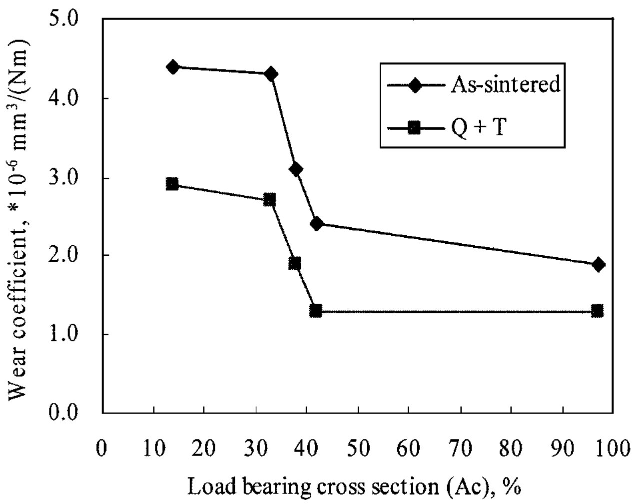

Fig. 4 Relationship between wear coefficient and load bearing cross section (Ac)

tempered steels have even higher wear coefficient than as-sintered ones. But at lowest porosity, the wear coefficient after heat treatment is much lower than that of as-sintered. As-sintered steels with high porosity deform easily because of their low hardness. Under the force of normal load, the pore area on the surface will be filled by the plastically deformed materials and therefore the real contact area increases, which results in decreased contact pressure and therefore low wear coefficient. When these steels are in the heat treated state, the deformation becomes difficult owing to the increase in hardness. In this case, the real contact area is smaller and the high contact pressure makes the thin connected area between pores easily worn off. Usually these worn materials are in a metallic state and coarse, which can be verified through SEM analysis for the debris. These hard metallic debris may plow or cut the pin surface as abrasives or plow the disk surface when they were inserted in surface pores. At low porosity there is a large contact area between the pores, and the pores are very small and

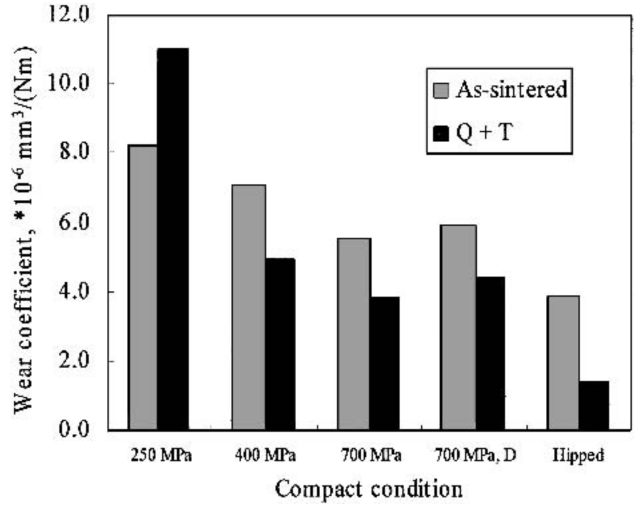

Fig. 5 Wear coefficient of the specimens during the first hour of testing (running-in period)

isolated, so the real contact area is much larger than that at the situation of high porosity. Under the same wear test condition, owing to high hardness and low porosity, the wear coefficient becomes much smaller. This implies that low porosity and high hardness are mainly responsible for the low wear coefficient in the running-in process. Within this work, when porosity decreases from 17.6%-0.8%, the wear coefficient of heat treated steels decreases by over 80%, while the as-sintered steels decrease by only 50%.

3.4 Wear Mechanism

To identify the wear mechanisms of the sintered steels rubbing against the 100Cr6 disks, the worn surfaces of the pins and wear debris were observed by SEM. Fine oxides are on all the specimen surfaces, the size of the oxides does not considerably change with the different porosity specimens, and the amount of oxides increases with the decrease of the porosity (Fig. 6). It follows that during wear testing oxidational wear occurred in all sintered steels and the lower porosity specimens are much more prone to form oxides. The formation of oxides consumes some of the pin material and induces the oxidational wear, and on the other hand these oxides do lubricate the rubbing system and therefore reduce the further wear of the system.

Pits are also seen on the worn surfaces of sintered steels. The pits on the surface of high porosity steels come mainly from the inherent pores, which are on the surface of sintered steels or were disclosed when the material above was worn away during the wear test. At lower porosity, the size of pits decreases and which are mainly caused by the surface fatigue (Fig. 6e), i.e., delamination wear happened; and the wear debris as abrasive plow both the oxide layer (Fig. 6c) and metallic area (Fig. 6f) and therefore induce the abrasive wear. So as-sintered steels underwent oxidational wear, delamination wear and abrasive wear.

As the high porosity as-sintered steels have more interconnected pores, they have lower strength and are much easier to

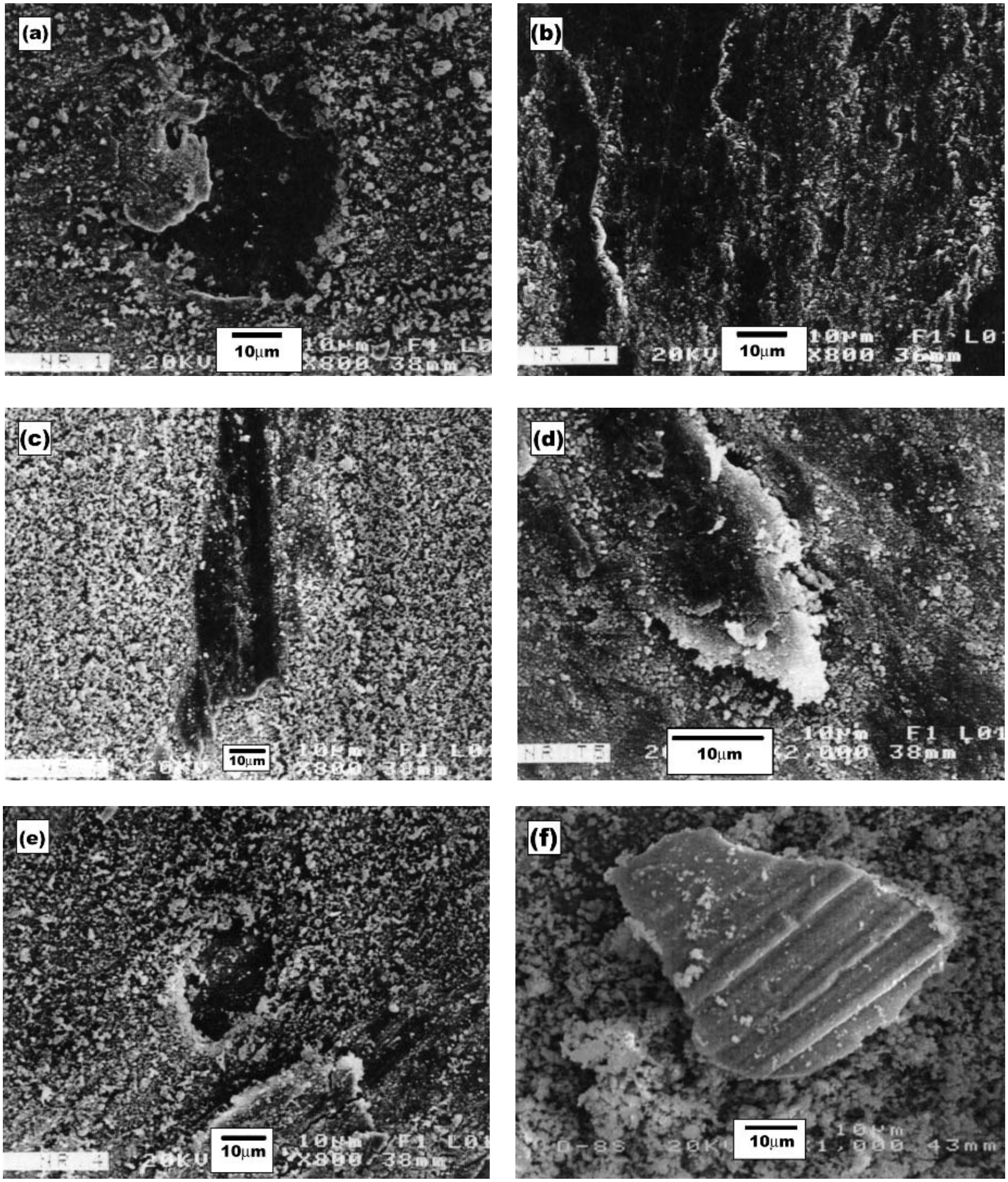

Fig. 6 Worn surfaces of sintered Fe-1.5Mo-0.7C steels and wear debris. **(a)** pressed at 250 MPa, AS; **(b)** pressed at 250 MPa, Q + T; **(c)** double pressed at 700 MPa and HIPed, AS; **(d)** double pressed at 700 MPa and HIPed, Q + T; **(e)** double pressed at 700 MPa, AS; **(f)** double pressed at 700 MPa, AS, under high magnification

deform and to be torn off, esp. at the beginning of the wear process. So high porosity steels have high mass loss and, therefore, high wear coefficient as shown in Fig. 3 and 4. After long periods of sliding, due to the largely reduced pits and smoother worn surfaces contributed by the debris filled into the pits as well as the surface hardening by the friction heating,[11] the difference in mass loss caused by porosity becomes very small although the average wear coefficient of high porosity steels is still higher than that of the more dense ones, which mainly happened in the running-in process.

Like the as-sintered steels, oxidational wear has also taken place on all surfaces of the heat treated steels during the wear test. Besides delamination wear also occurred because pores serve as the origin of fatigue crack generation and the end of fatigue crack propagation. In this case the materials were worn away in flake as seen in the collected debris. Steels with high porosity and interconnected pores (Fig. 6b) have a large amount of debris around the pores, which were peeled away along the cracks between pores. It can be supposed that this type of tear-off takes place easily, especially when subsurface layers contain pores. For the lower porosity steels (Fig. 6d), the cracks causing delamination wear can only be found under even higher magnification. With the decrease of porosity, the delamination wear apparently decreases. Markedly for all the quenched and tempered steels, abrasive wear becomes less important, which is to a large extent due to the increased hardness. Heat treating process not only increases the hardness of the high porosity steels, but also makes the steels more brittle and enhances the damage of steels in delamination wear regime. This may explain why quenched and tempered high porosity steels have higher wear coefficient than the as-sintered ones during the running-in process.

All the wear debris collected from the as-sintered steels rubbing against 100Cr6 disks is a brownish-red mixture, which contains iron oxides and Fe-1.5Mo-0.7C metallic materials. The size of most debris is about 4 μm, which was characterized by Fe_2O_3, Fe_3O_4, and FeO.[12] These fine oxides act as solid lubricants reducing friction and therefore reducing wear. Debris collected from high porosity as-sintered steels contain the largest particles ranging between 20 and 200 μm which is demonstrated to be the metallic materials from the sinters, while the debris from the steels with less or nearly no porosity range between 20 and 60 μm. All the larger debris is in the form of flakes, which is the feature of delamination wear. On the surface of large debris there are some oxides. These indicate that oxides had already formed on the surfaces of large flake debris before the large flake debris detached from the bulk steels. In addition the plowing can be clearly seen on the surface of flake debris under high magnification (Fig. 6f), which shows that abrasive wear has already happened before the flake debris detached. Combined with the result of the worn pin surface, it can be concluded that during the wear process, oxidational wear, abrasive wear, and delamination wear coexist.

Wear debris collected from quenched and tempered steels rubbing against 100Cr6 are the mixture of fine oxides and flakes as are the debris from as-sintered ones. The oxides in debris increase with the lowering of porosity, which can be demonstrated by the interference of the debris on SEM analysis. The number and size of the flakes apparently decreases with the decrease of porosity. The debris collected from tempered HIPed steels contains fewer and smaller (about 30 μm flakes). It seems that with the lowering of porosity the oxidational wear becomes predominant and the delamination wear decreases. For this reason, the wear coefficient of sintered steels decreases as porosity decreases.

4. Summary

Porosity strongly influences the dry sliding wear behavior of sintered steels. In principle, sintered steels with high porosity have poor wear resistance. When the porosity is lower than 6.2%, further decreases in porosity play a smaller role on the wear coefficient of both as-sintered and Q + T steels. Because disclosed pores can collect the debris and oxides during the rubbing process, the disadvantage due to the poor hardness and mechanical strength caused by high porosity can be in part compensated for. As-sintered steels have three types of wear mechanisms (oxidational wear, abrasive wear, and delamination wear), while the quenched and tempered steels two wear mechanisms (oxidational wear and delamination wear). Oxidation makes the sintered steels lose some material; in the meantime, the oxides attach to the surface of the rubbing pairs and lower further intense wear. Abrasive wear and delamination wear are responsible for high wear coefficients.

Acknowledgments

The authors would like to thank ÖAD (Austrian Academic Exchange Service) and the Chinese Ministry of Education as well as the Shanghai Municipal Commission of Education for financial support of this work.

References

1. B.M. Astashkevich: "Porosity Effect on Properties of Sintered Materials for Internal Combustion Engine Piston Rings," *Metallovedenie i Termicheskaya Obrabotka Metallov,* 1996, *7*, pp. 20-23 (in Russian).
2. H. Danninger, D. Spoljaric, A. Arakil, and B. Weiss: "Mo Alloyed PM Structural Steels Prepared by Different Alloying Techniques," *Adv. Powder Metall. & Particulate Mater.*, 1996, *13*, pp. 177-88.
3. H. Danninger, D. Spoljaric, G. Jangg, B. Weiss, and R. Stickler: "High Cycle Fatigue Behavior of Mo Alloyed Sintered Steel," *Z. Metallkd.*, 1998, *89*(2), pp. 135-41.
4. C. Amsallem, A. Gaucher, and G. Guilhot: "The Unlubricated Frictional Behavior of Sintered Iron," *Wear*, 1973, *23*, pp. 97-112.
5. M. Vardavoulias, C. Jouanny-Tresy, and M. Jeandin: "Sliding-Wear Behavior of Ceramic Particle-Reinforced High-Speed Steel Obtained by Powder Metallurgy," *Wear*, 1993, *165*, pp. 141-49.
6. S.C. Lim and J.H. Brunton: "The Unlubricated Wear of Sintered Iron," *Wear*, 1986, *113*, pp. 371-82.
7. Anon: "Standard Test Method for Wear Testing With a Pin-On-Disk Apparatus" in *Friction and Wear Testing, Source Book of Selected References from ASTM Standards and ASM Handbooks*, S. Lampman, ed., 1997, pp. 124-28.
8. J. Wang and H. Danninger: "Dry Sliding Wear Behavior of Molybdenum Alloyed Sintered Steels," *Wear*, 1998, *222*, pp. 49-56.
9. S.C. Lim and M.F. Ashby: "Wear-Mechanism Maps," *Acta Metall.*, 1987, *35*, pp.1-24.
10. H. Danninger, D. Spoljaric, G. Jangg, B. Weiss, and R. Stickler: "Characterization of Pressed and Sintered Ferrous Materials by Quantitative Fractography," *Prakt. Metallographie*, 1994, *31*(2), pp. 56-69.
11. H. Uetz and K. Sommer: "Investigations of the Effect of Surface Temperatures in Sliding Contact," *Wear*, 1977, *43*, pp. 375-88.
12. J. Wang: "Dry Wear Sliding Behavior of High Strength Sintered Steels," Ph.D. Thesis, Vienna University of Technology, Vienna, Austria, 1999.