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WEAR RESISTANCE OF CHROMIUM PRE-ALLOYED SINTERED STEELS

OBRABNA OBSTOJNOST KROMOVIH SINTRANIH JEKEL

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This paper deals with the influence of the processing conditions on the material properties and wear characteristics of chromium pre-alloyed sintered steels. Three different processing conditions were used, involving different cooling rates from the sintering temperatures of 1180 °C and 1240 °C. A conventional (slow) cooling condition and a new progressive condition, sinter hardening, were examined. The results showed that the typical microstructure characteristics of sintered steels represent an important parameter affecting their wear behaviour.

Key words: pre-alloyed sintered steel, sinter hardening, sliding wear, porosity, microstructure

V članku je predstavljen vpliv pogojev procesiranja na mehanske lastnosti in obrabne značilnosti kromovih sintranih jekel. Uporabljeni so bili trije različni pogoji procesiranja z različno hitrostjo ohlajanja s temperatur 1180 °C in 1240 °C. Opredeljena sta vpliv počasnega (konvencionalnega) ohlajanja in naprednega kaljenja sintra. Rezultati so pokazali, da so za vedenje pri obrabi pomembne značilnosti mikrostrukture sintranih jekel.

Ključne besede: sintrano jeklo, kaljenje sintra, drsna obraba, poroznost, mikrostruktura

1 INTRODUCTION

Powder metallurgy (PM) is a well-established processing route for the production of near-net-shape components of complex geometry. The traditional uniaxial powder consolidation process is still widely employed for the production of ferrous parts, especially for the automotive industry. In this field the typical components (i.e., gears, cams) face working conditions giving rise to sliding, rolling or abrasion. Therefore, an understanding of the wear phenomena and characteristics is very important.

The dry sliding behaviours of sintered ferrous alloys have been investigated in several previous studies [1,2,3,4,5,6], which indicated that the wear mechanisms are similar to wrought materials under the same conditions. Nevertheless, sintered materials contain a variable quantity of pores, as well as (eventually) heterogeneous microstructures, which create peculiar wear characteristics for PM products. As a matter of fact, pores represent the first sites for microplastic deformation and they are potential sites for the formation of the first microcracks[7,8,9].

The use of chromium in PM may create some difficulties in reducing the oxides present at the surface and acting as a barrier to interparticle diffusion; nevertheless, chromium is a widely used hardening element in ferrous sintered products[10,11,12,13]. Molybdenum is also commonly used in low-alloy PM steels because of the easily reducible oxides. Chromium and molybdenum are very effective in promoting increased strength and toughness.

Sinter hardening requires controlled cooling after sintering in the austenite range (1120–1240 °C). A new approach to sinter hardening has been proposed using vacuum furnaces[14,15,16]. They show enhanced cooling capabilities, with several advantages related to cost effectiveness, reducing the problems of oil entrapment and distortion, determining the improved dimensional stability and consequently higher yield and quality of the production lots. Moreover, vacuum furnaces may reduce the decarburation typical of continuous furnaces and can be programmed to perform quenching and tempering integrated in the same cycle, thus reducing the internal stresses that cause excessive notch sensitivity and brittleness[17,18].

The main aim of this paper is to show the influence of various sintering conditions on the wear resistance of chromium pre-alloyed sintered steels.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

The investigated chromium pre-alloyed system was Fe + 1.5 % Cr + 0.65 % C + 0.6 % AW. The powders were homogenised in a Turbula mixer. Specimens with a green density of $\approx$ 7.0 g cm^{-3} were obtained using a 2000 kN hydraulic press, in a disc-shaped mould (= 40 mm) applying a pressure of 600 MPa. The sintering was carried out in a TAV vacuum furnace with argon back-filling at 1180 °C and 1240 °C for 1 h. The cooling rate was 0.05 °C/s, while the rapid cooling rate (sinter hardening) was 6 °C/s (**Table 1**). The densities were evaluated using the water-displacement method.

Table 1: Sintering conditions of the chromium pre-alloyed sintered steels
Tabela 1: Pogoji sintranja jekel

Alloy No	Sintering conditions
A	Temperature: 1180 °C; time: 1 h; cooling condition: 0.05 °C/s
B	Temperature: 1180 °C; time: 1 h; cooling condition: 6 °C/s (sinter hardening)
C	Temperature: 1240 °C; time: 1 h; cooling condition: 6 °C/s (sinter hardening)

The wear tests were carried out using a pin-on-disc apparatus. 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 a diameter of 3 mm. The counter-pin was changed after the end of each test, in order to preserve the roundness of its top. All the wear tests were performed in air and without any lubricant. The applied loads were 25 N, and the rotation speed of the disc was 140 r/min. The distances of the pin position from the disc centre were 34 mm. Prior to testing, the surface was polished with abrasive papers in order to determine a medium surface roughness equal to (or less than) 0.8 μm, as specified in the ASTM G99–95a. Each test was interrupted after (300, 600, 900, 1200 and 2000) m of sliding distance and the discs were weighed using a precision balance with a sensitivity of 10^{-5} to determine the evolution of the wear during each test.

The wear characterization of the chromium pre-alloyed sintered steels was carried out with optical microscopy, also determining the volume mass and the interconnected (open) porosity (according to UNI 7825). Wear-track observations were carried out using an SEM JEOL 7000F. Vickers hardness measurements were performed on cross-sections of the samples and the impact-testing procedure using Charpy tests was carried out on un-notched samples.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Microstructures

The microstructure of the chromium pre-alloyed sintered specimens (A in **Table 1**) consisted predominantly of a pearlite microstructure ($HV_{0.010} \approx 240$) with small areas of ferrite ($HV_{0.010} = 125–140$), **Figure 1**. The system B determines the dominant bainite (formed by a mixture of upper ($HV_{0.010} = 330–370$) and lower ($HV_{0,010}$ = 260–285 bainite), with some martensite ($HV_{0.010}$ = 580–648), **Figure 2**. Increasing the sintering temperature to 1240 °C (system C) resulted in the formation of a dominant martensitic microstructure ($HV_{0.010} = 580–692$) with small, upper bainite networks ($HV_{0.010} \approx 415$), **Figure 3**. Different cooling rates did not result, in terms of hardness, in a large difference between systems sintered at 1180 °C. On the contrary, using a higher sintering temperature (1240 °C/s) resulted in harder microstructure constituents with a dominant martensitic microstructure.

3.2 Friction coefficient

Figure 4 shows a plot of the values of the steady-state friction coefficient measured for the chromium pre-alloyed sintered steels tested under different conditions. The values ranged from about 0.90 to 0.82, gradually decreasing as the sliding distance was increased. Higher values of the coefficient of friction were generally measured for samples with higher porosity lev-

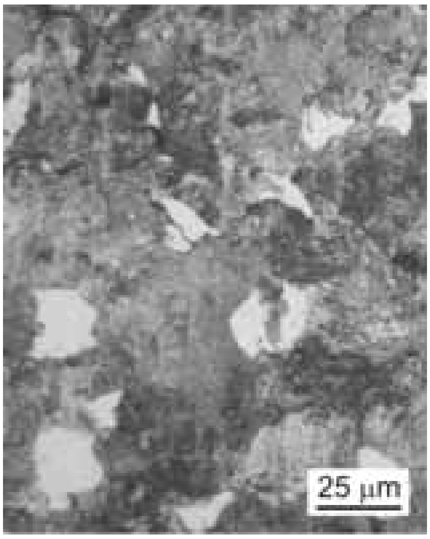

Figure 1: Microstructure of A steel, 1180 °C / 1 h; cooling rate 0.05 °C/s
Slika 1: Mikrostruktura jekla A, 1180 °C/1h, hitrost ohlajanja 0,05 °C/s

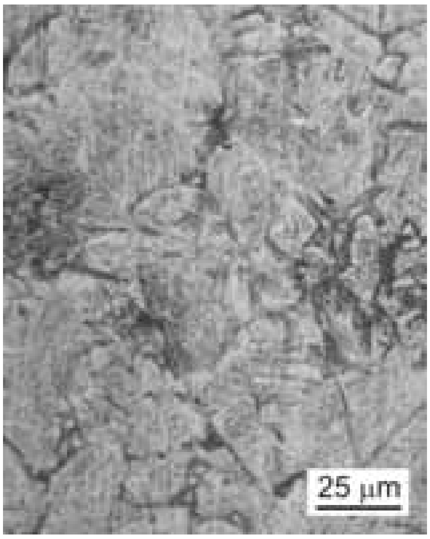

Figure 2: Microstructure of B steel, 1180 °C / 1 h; sinter hardening, cooling rate 6 °C/s
Slika 2: Mikrostruktura jekla A, 1180 °C/1h, kaljeno, hitrost ohlajanja 6 °C/s

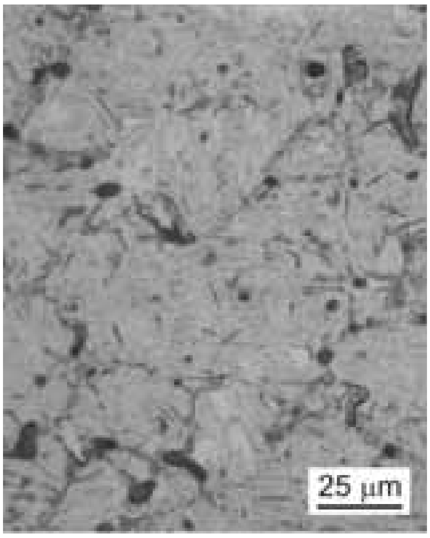

Figure 3: Microstructure of C steel, 1240 °C / 1 h; sinter hardening, cooling rate 6 °C/s
Slika 3: Mikrostruktura jekla A, 1240 °C/1h, kaljeno, hitrost ohlajanja 6 °C/s

els (specimens sintered at 1180 °C), as a cumulative effect of a higher resistance to plastic flow and a slightly greater contact area. The present results of the friction coefficient ranged from 0.7 to 0.9, in accordance with the literature data for sintered materials in the untreated condition[19].

3.3 Wear characteristics

The mass losses were expressed as material removal during the test and were recorded as a function of the sliding distance. The wear of PM materials is more complicated than that of wrought steels and depends on different factors related to the sintered microstructures (such as plasticity and strength) of the different phases, as well as the porosity. Hence, the evaluation of the wear resistance (as the reciprocal value of the amount of wear)

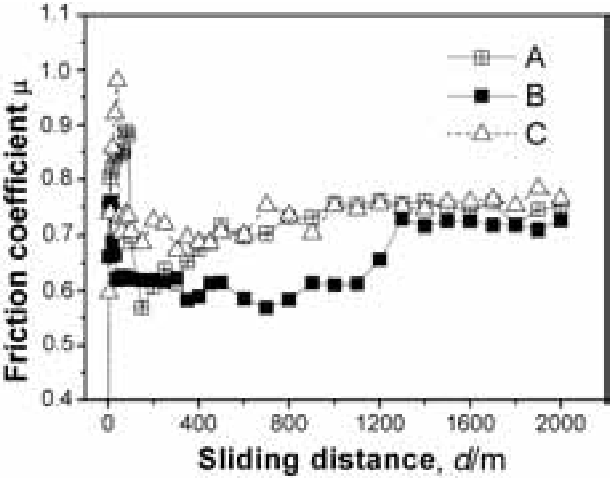

Figure 4: Friction coefficient of investigated materials
Slika 4: Koeficienti trenja za preiskane materiale

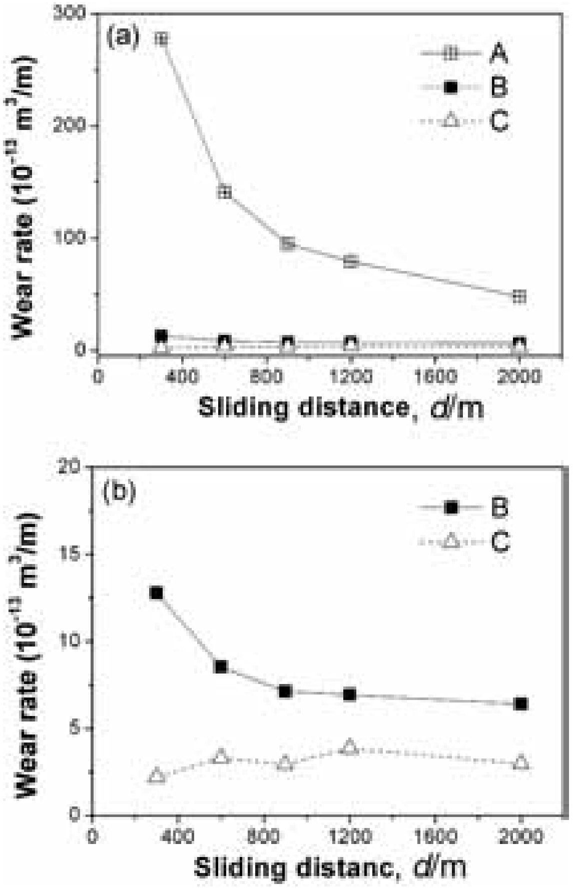

Figure 5: (a) Wear rates for investigated specimens. (b) Wear rates for specimens cooled with greater cooling rate
Slika 5: (a) Hitrosti obrabe za preizkušance, (b) hitrosti obrabe za preizkušance, ohlajene z večjo hitrostjo

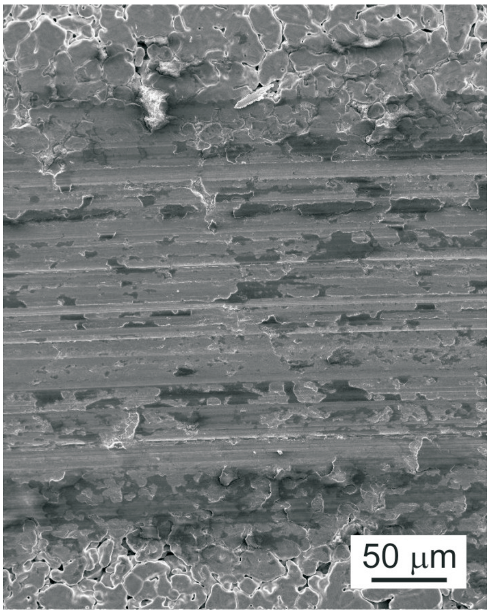

Figure 6: Typical, mild oxidative wear regime, which was observed for all tested specimens, specimen C; 1240 °C / 1 h; sinter hardening, cooling rate 6 °C/s
Slika 6: Rahlo oksidativen režim obrabe značilen za vse preizkušance, preizkušanec C, 1240 °C/ 1h, kaljeno, hitrost ohlajanja 6 °C/s

Table 2: Material properties of the tested alloys
Tabela 2: Materialne lastnosti raziskanih zlitin

Alloy No	ρ_P*	ρ_S*	P_{Total}	*TRS*	*UTS*	*IE*	Hardness *HRA*	Microhardness range; average $HV_{0.010}$
	g/cm^3	g/cm^3	%	MPa	MPa	MPa		
A	6.987	7.002	8.64	893	447	22.86	46.45 ± 0.15	(125–240); 189
B	6.983	6.973	9.01	1335	1035	13.29	63.70 ± 3.60	(260–648); 520
C	7.002	7.113	7.19	1421	1217	10.60	65.55 ± 0.65	(414–692); 589

*P-Pressing, *S-Sintering

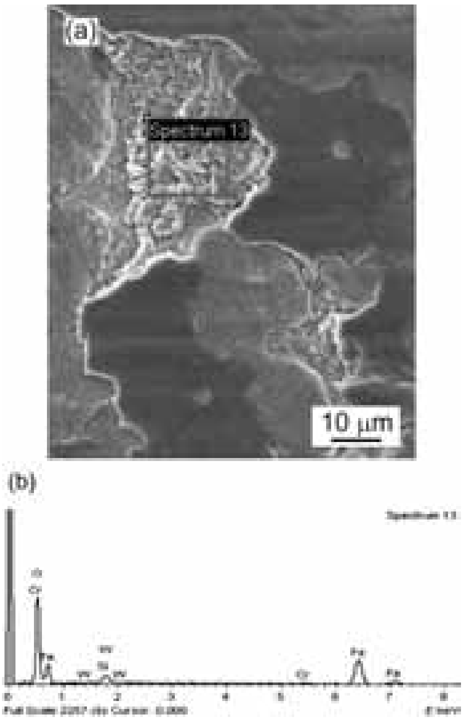

Figure 7: (a) Oxide layers on the chromium pre-alloyed sintered steels (scanning microscopy) and (b) EDX spectra of oxide layers
Slika 7: (a) Oksidna plast na sintranem kromovem jeklu (vrstični mikroskop) in (b) EDX-spektri oksidne plasti

is better expressed in terms of wear rate. The wear rate was calculated using the equation:

$$W_s = \frac{\Delta m}{\rho \cdot L \cdot F_N} \quad (1)$$

where:
W_S is the wear rate [m^3/(N m)],
Δm is the mass loss of the test samples during the wear test [g],
ρ is the density of the test materials [g/cm^3],
L is the total sliding distance [m],
F_N is the normal force on the pin [N].

The wear rates for the investigated specimens are shown in **Figure 5**. The results show that the wear resistances of chromium pre-alloyed sintered steels using higher temperatures and cooling rates (sinter hardening) were improved due to the shift of the ferrite-bainite to the dominant martensitic microstructure.

Useful information on the wear mechanisms of the sintered steels was obtained by SEM observations. The investigation demonstrated the mechanism of delamination: deformed layers and tracks along the direction of sliding during the wear. Plastic deformation took place on the wear surfaces during the wear tests. The contact

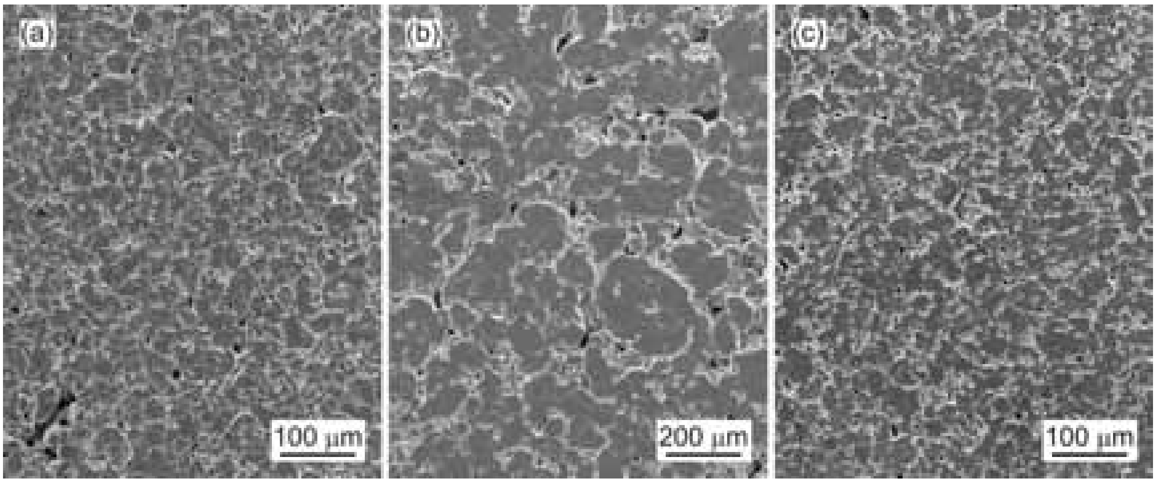

Figure 8: (a) Microstructural discontinuities as pore agglomerates with sharp edges, A specimens. (b) Microstructural discontinuities as pore agglomerates with slightly sharp edges, B specimens. (c) Rounded pores, C specimens.
Slika 8: (a) Diskontinuitete mikrostrukture kot aglomerati por z ostrimi oblikami, preizkušanci A, (b) diskontinuitete mikrostrukture kot aglomerati por z rahlo izostreno obliko, preiskušanci B, (c) zaobljene pore, preizkušanci C

pressure of the wear surfaces increased with the increasing amount of porosity in accordance with [20].

The sliding tests carried out on samples sintered at 1180 °C and cooled at 0.05 °C/s were, in any case, typical of a mild oxidative wear regime, **Figure 6**. Detailed analyses revealed (**Figure 7 (a)** and **(b)**) oxide layers on the chromium pre-alloyed sintered steels in accordance with the literature data[14,15,16]. Therefore, delamination and oxidation wear seems to be the main wear mechanisms.

3.4 Material properties

The sintered material characteristics of a given alloy (i.e., its porosity content and microstructure) also influence the charpy impact energy, as shown by the values reported in **Table 2**. The important parameters that specify the role of porosity are the amount of porosity and the pore size. Earlier studies[1,4,6] have suggested that an amount of porosity higher than 10 % and a pore size that is larger than 12 μm constitute a dominant interconnected porosity. These pores are filled with debris particles during wear. This may enhance the wear resistance of the samples by increasing the real contact area and decreasing the contact pressure. A dominant role can be played by isolated pores and their shapes. Sharp-edged pores can give rise to considerable stress-concentration effects that favour the nucleation and propagation of microcracks, leading to the easier formation of wear fragments. This interpretation is underlined by the lower Charpy impact values measured for the specimens with a higher porosity content, along with the results at the higher sintering temperature of 1240 °C that reduced the negative effects of the porosity by means of roundness, so promoting an increase of the wear resistance. Specimens sintered at a sintering temperature of 1240 °C (HS) present more rounded pores than those sintered at a lower temperature, **Figure 8 (a)-(c)**, along with higher impact energies. The lowest impact values were shown by the specimens sintered at the lower temperature and then slow cooled. The increase in the sintering temperature and cooling rates strongly influenced the microstructure and hardness to the shifting of the microstructures from pearlite to dominant martensite microstructures. Sinter hardening increases the martensite content in the microstructure and this results in a further increase in the strength with a decrease of the ductility and toughness (the plasticity properties represent the impact-energy values). The results suggested that sinter hardening can have a practical interest in view of components where wear resistance can play a decisive role.

4 CONCLUSIONS

The main results obtained in this paper may be summarised as follows:

- A higher cooling rate (sinter hardening), supporting a bainite-martensitic microstructure, and a higher sintering temperature increase both the strength and ductility,
- delamination and oxidation are the main wear mechanisms,
- microstructure and hardness represent the dominant effect influencing the mechanical properties as well as the wear resistance,
- higher temperature sintering (1240 °C) reduces the negative effects of porosity due to the evident effect of pore roundness, if compared to a lower sintering temperature and cooling rates.

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