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ISSN 0543-5846
METABK 61(3-4) 637-640 (2022)
UDC – UDK 669.15.26.28:536.48:621.785:620.178.1.001.4=111

EFFECT OF FREEZING ON ABRASION RESISTANCE OF CAST STEEL CONTAINING 1,1 % C, 16 % Cr, AND 0,9 % Mo

Received – Primljeno: 2021-11-03
Accepted – Prihvaćeno: 2022-03-10
Original Scientific Paper – Izvorni znanstveni rad

The results of abrasion-resistance tests that were carried out on cast steel containing 1,1 % C, 16 % Cr, and 0,89 % Mo after several variants of heat treatment (including freeze hardening at -70 °C immediately before tempering at 200° and 550 °C) are presented in this paper. The wear-resistance tests were carried out with the ball-on-disc dry-friction method. In the samples that were tempered at 200 °C (with and without freezing), lower mass losses were obtained than in the samples that were tempered at 550 °C. Additionally, it was found that the applied freezing procedure significantly contributed to the reduction of mass losses in those samples that were tempered at both temperatures.

Keywords: high-chromium cast steel, freezing, heat treatment, wear resistance, ball-on-disc test,

INTRODUCTION

According to the ASTM A276/A276M:2017 standard, high-carbon chromium cast steel that contains 16 - 18 % Cr belongs to the family of 440 steels, which were designed to combine high hardness (60 HRC) and strength while maintaining good corrosion resistance [1]. This combination of mechanical and functional properties allows those materials that belong to this group to be classified as both stainless steel and tool steels. Owing to their properties, these steels have been widely used in the machinery and energy industries for components such as valve seats, balls, pump assemblies, bushings, bearing assemblies, and cutting tools [2]. The typical heat treatments that have been developed for these materials include hardening and tempering, and their high contents of C and Cr result in the fact that their structures contain ledeburite eutectic carbides next to their ordinary chromium carbides; these eutectic carbides are released during the solidification of the steel and are not dissolved in the austenite [2]. Because of the possible appearance of residual austenite during the hardening, the heat treatment is supplemented with a freezing process that is applied immediately after hardening and before tempering [3]. Initially, the treated material is cooled from the hardening temperature to a temperature that is within a range of 51° - 66 °C; it is then followed by freezing at approximately -70 °C (where it is held for about an hour). After this freezing, the tempering should be carried out relatively quickly within a temperature range that is typical for this steel (i.e., 149° - 400 °C). In industry, tempering within a temperature range of 427° - 593 °C is also used for 440C steel; however, tempering at temperatures within this range reduces the steel's corrosion resistance and hardness (possibly resulting in lower wear resistance). This article attempts to determine the effect of freezing on the abrasion resistance of cast steel that contains 1,1 % C, 16 % Cr, and 0,9 % Mo.

TEST MATERIAL

The tested cast steel with the chemical composition that is given in Table 1 was melted under laboratory conditions in a 30 kg-capacity induction furnace. Two variants of heat treatment (i.e., with and without freezing at -70 °C for 1 hour) were carried out on test ingots after quenching in air at 1 030 °C, followed by tempering at 200° and 550 °C. The samples that were quenched and tempered at 200° and 550 °C were designated as 1_200 and 1_550, respectively, while those samples that were additionally subjected to freezing were designated as 1_w_200 and 1_w_550, respectively. Each sample's hardness was measured with a Vickers hardness tester under a load of 30 kg (98,06 N). The hardness of the tested material was calculated as the average of six measurements for each sample. For the abrasion-resistance test, samples with dimensions of 20 x 20 x 10 mm and prepared according to the guidelines given in the ISO 20808 standard were used. The tests were carried out with the ball-on-disc method at room temperature using a universal ELBIT tribotester [5,6]. The principle of the tribotester's operation is based on the contact that is made on a flat surface (the tested material) with a ball made of Al_2O_3. The tests were carried out under dry conditions with a load of 5 N (detailed test

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Table 1 **Chemical compositions of investigated cast steels / wt. %**

Grade/Sample	Component contents / wt. %							
	C	Mn	Si	P	S	Cr	Mo	other
440C (A276/A276M:2017)	0,95 1,20	max 1,00	max 1,00	max 0,04	max 0,03	16,00 18,00	max 0,75	-
1	1,17	0,61	0,34	0,02	0,01	16,0	0,89	0,003 B

Table 2 **Conditions for abrasion-resistance test**

Temperature T / °C	Types of balls	Diameter of balls d / mm	Normal load F_n / N	Friction track diameter r / mm	Sliding speed v / m/s	Total sliding distance L / m	Test duration t / s
23	Al_2O_3	1,59	5	5	0,1	1 005	10 000

Table 3 **Selected parameters and formulas for calculations [4]**

Param-eters	Equations	Number of equation
Coefficient of friction	$\mu = \frac{\overline{F}_f}{F_p}$ F_f – average value of friction force / N F_p – applied load / N	(1)
Specific wear rate	$V_{disc} = \frac{\pi \cdot R(S_1 + S_2 + S_3 + S_4)}{2}$ V_{disc} – wear volume of disc specimen / m^3 $S_1 - S_4$ – cross–sectional areas at four places on wear track circle / m^2 R – radius of wear track / m	(2)
Specific wear rate of disc specimen	$W_{s(disc)} = \frac{V_{disc}}{F_p \cdot L}$ $W_{s(disc)}$ – specific wear rate of disc specimen / m^2/N V_{disc} – wear volume of disc specimen / mm^3 F_p – applied load / N L – sliding distance / m	(3)

parameters are presented in Table 2). Table 3 shows various formulas taken from the ISO 20808 standard to calculate the selected wear parameters [4]. A Talysurf CCL profilometer was used to examine the surface after the tests and determine the cross-sectional areas at four places on wear track circles S_1 - S_4 (which are necessary for the calculation of V_{disc}).

After the test, the worn surfaces were examined with a Leica MEF4M light microscope.

EXPERIMENTAL RESULTS

The tested cast steel after hardening, freezing, and tempering at 200 °C had a hardness of approx. 722 HV_{30}, while the hardness decreased to approx. 697 HV_{30} without the freezing. On the other hand, a higher tempering temperature causes a reduction in hardness according to the literature [2]. In both of the applied heat-treatment cases, the cast steel that was tempered at 550 °C showed lower hardness values (i.e., approx. 569 HV_{30} with freezing, and approx. 609 HV_{30} without freezing). In structural steels, higher hardness favors higher wear resistance. In the case of the tested material, however, one should take the precipitation processes that occur during heat treatment that lead to the formation of a multi-phase structure that is composed of two types of Cr carbides into account; i.e., fine carbides that strengthen the matrix, and a grid of ledeburite carbides [7].

Figure 1 shows the changes in the friction coefficients of the tested materials that occurred during the tests, while Table 4 compares the calculated wear parameters (such as the weight loss and friction coefficient).

From Figure 1, it follows that the stabilization of the friction coefficient values took place after about 5 000 s from the start of the test for all of the samples. Additionally, it was noticed that higher values of the coefficient

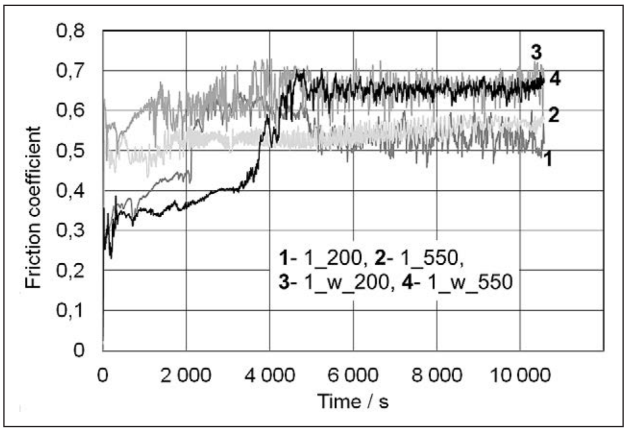


Figure 1 Changes in friction coefficients of tested materials as function of test duration

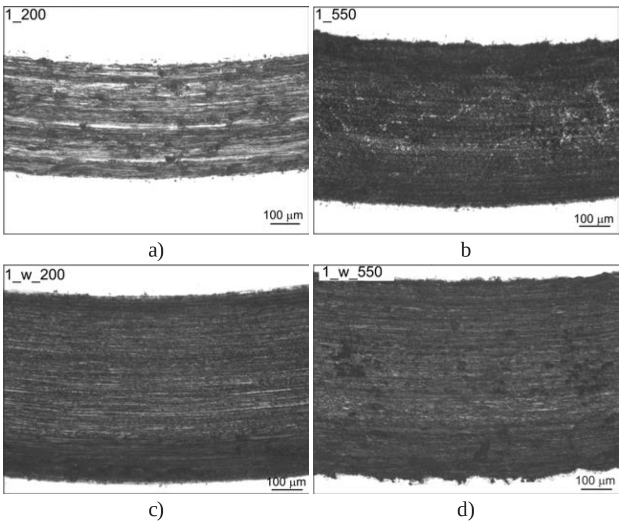
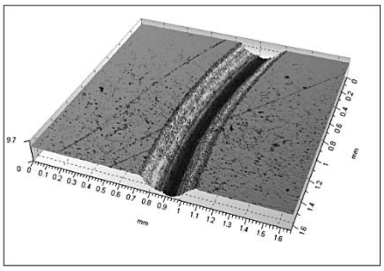


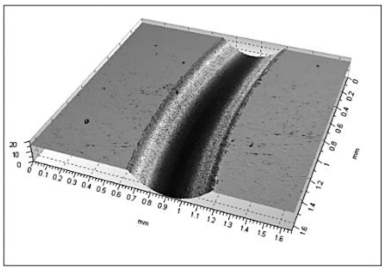
Figure 2 Examples of abrasion-wear track images obtained on surfaces of tested samples

Table 4 **Results of calculations of wear parameters of tested materials**

Samples	Initial weight of sample m_o / g	Final weight of sample m_k / g	Weight loss m / g	Relative weight loss Dm / %	Specific wear rate – $W_{s(disc)}$ / m^2/N	Average friction coefficient m (Eq. 1)	Average friction coefficient m after 5 000 s of test
1_200	36,0578	36,0554	0,0024	0,007	$1,4897 \cdot 10^{-14}$	0,34	0,51
1_w_200	38,9828	38,9775	0,0053	0,013	$5,9403 \cdot 10^{-14}$	0,40	0,67
1_550	38,9308	38,9265	0,0052	0,013	$3,9986 \cdot 10^{-14}$	0,25	0,55
1_w_550	36,0514	36,0502	0,0012	0,003	$5,9882 \cdot 10^{-14}$	0,42	0,67



a)



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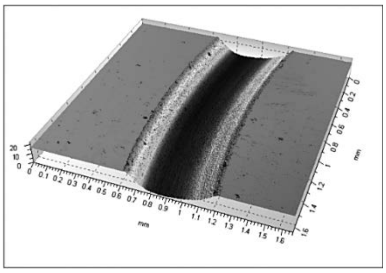

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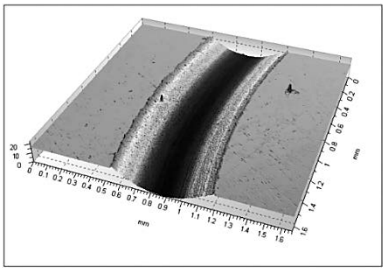

d)

Figure 3 Examples of abrasion wear track images obtained with profilometer, a) 1_200, b) 1_550, c) 1_w_200, d) 1_w_550

of friction (i.e., within a range of about 0,6 - 0,7) were obtained for Samples 1_w_200 and 1_w_550 after about 5 000 s (i.e., those samples that were subjected to freezing). For the samples that were not frozen, the friction coefficients did not exceed 0,6. The observed fluctuations in the values of the friction coefficients during the first periods of the tests were likely due to the multiphase microstructures of the tested materials and the crushing of the particles that were detached during the tests (which were later dispersed), among other things [7]. The calculations of the average coefficients of friction that are presented in Table 4 show that, after 5 000 s from the start of the test, this coefficient was lower for those materials without freezing than for those that were subjected to freezing. Additionally, the weight losses of the tested samples were calculated. No specific correlation was found to exist between the applied heat treatment and the calculated weight losses. In the group of samples that were tempered at 200 °C, the samples after freezing suffered greater weight losses, while this relationship assumed an inverse course in the group of samples that were tempered at 550 °C.

The surfaces that were obtained with the ball-on-disk tests were subjected to microscopic examinations. It was found that the freezing process increased the widths of the wear tracks in the samples after freezing as compared to the samples without freezing (Figure 2).

Additionally, it was observed that the wear tracks that were formed in Samples 1_200 and 1_w_200 were narrower than they were in Samples 1_550 and 1_w_550; this means that tempering at a higher temperature increased the wear tracks' widths. Indirectly, this may be related to the reduction in the sample hardness. A microscopic evaluation of the obtained abrasion wear tracks revealed the wear mode that prevailed in the tested materials; this mainly involved micro-cutting, micro-scratching, and micro-grooving that are consistent with the direction of the motion of the ball that was used in the tribological test (repeated cycles of movement). Additionally, the fine and hard Cr carbides that were present in the matrix of the tested materials were probably detached and crushed during the friction and (acting as loose abrasive particles) participated in the wear process as additional materials that intensified the wear of the parts that rubbed against each other. It should also be remembered that, in the case of dry friction, the generated heat is an additional factor that activates the surface layer. The abrasion-wear tracks that formed on the surfaces of the tested samples were additionally assessed with a profilometer; examples of the obtained micro-topographies of the wear tracks are shown in Figure 3.

An additional quantitative assessment of the wear process that took place in the tested materials as a result of the friction was made by measuring the surface areas of the wear tracks in four perpendicular directions (every 90° according to the ISO 20808 standard). Figure 4 shows an example of a wear track. Based on the performed calculations, it was found that all of the tested samples showed a significant difference in the sizes of

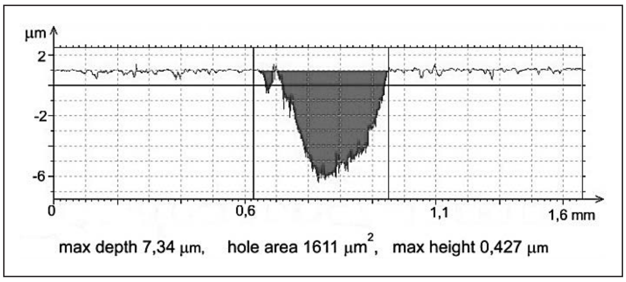

Figure 4 Example of wear-track profile in sample 1_200 (S1)

the areas of the wear-track profiles that were measured in the four directions that are indicated by the standard (Figures 3 and 4).

The obtained wear-track surface areas were used to calculate the average volume of the material that was removed by the ball as a result of its rubbing against the surfaces of the tested samples (Table 3; Eq. 2). The results of these calculations are summarized in Table 5.

The average volume of the material that was removed was found to be lower in Samples 1_200 and 1_550. Freezing increased the volume of the material that was removed during the ball-on-disc tests. Similar relationships were observed in the case of the specific wear-rate parameter that was calculated according to Eq. 3 in Table 3.

Table 5 **Results of calculations of wear parameters of tested materials**

Sample	Wear volume of disc specimen / m^3	Specific wear rate – $W_{s(disc)}$ / m^2/N
1_200	$0,3744 \cdot 10^{-11}$	$1,4897 \cdot 10^{-14}$
1_w_200	$1,4928 \cdot 10^{-10}$	$5,9403 \cdot 10^{-14}$
1_550	$1,0049 \cdot 10^{-10}$	$3,9986 \cdot 10^{-14}$
1_w_550	$1,5048 \cdot 10^{-10}$	$5,9882 \cdot 10^{-14}$

CONCLUSION

Large variations in the S_1 - S_4 values were observed in the tested samples (both frozen and not frozen) after the tribological tests. Freezing was also found to affect the width of the wear tracks (increasing them after tempering at both 200° and 550 °C).

The wear mechanisms that prevailed in the tested materials included micro-cutting, scratching, and grooving, and the patterns of the scratches corresponded to the directions of the movement of the Al_2O_3 ball rubbing against the surfaces of the tested materials.

The calculated coefficients of friction were lower for Samples 1_200 and 1_550; the use of freezing increased these values. Likewise, the wear volumes of the disc specimens and the specific wear rates were lower for those samples that were not frozen.

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Note: The professional translator who was responsible for the English language is named Bret Spainhour