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Effects of Rare Earth Metal Addition on Wear Resistance of Chromium-Molybdenum Cast Steel

J. Kasinska^a *, B. Kalandyk^b

^aDepartment of Applied Computer Science and Armament Engineering,
Faculty of Mechatronics and Machine Engineering, Kielce University of Technology,
Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

^bAGH University of Science and Technology, Faculty of Foundry Engineering
30-059 Krakow, 23 Reymonta Str., Poland

*Corresponding author. E-mail address: kasinska@tu.kielce.pl

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Abstract

This paper discusses changes in the microstructure and abrasive wear resistance of G17CrMo5-5 cast steel modified with rare earth metals (REM). The changes were assessed using scanning microscopy. The wear response was determined in the Miller test to ASTM G75. Abrasion tests were supplemented with the surface profile measurements of non-modified and modified cast steel using a Talysurf CCI optical profilometer. It was demonstrated that the modification substantially affected the microstructure of the alloy, leading to grain size reduction and changed morphology of non-metallic inclusions. The observed changes in the microstructure resulted in a three times higher impact strength (from 33 to 99 kJ/cm²) and more than two times higher resistance to cracking (from 116 to 250 MPa). The following surface parameters were computed: *S_a*: Arithmetic mean deviation of the surface, *S_q*: Root-mean-square deviation of the surface, *S_p*: Maximum height of the peak

S_v: Maximum depth of the valley, *S_z*: Ten Point Average, *S_{sk}*: Asymmetry of the surface, *S_{ku}*: Kurtosis of the surface. The findings also indicated that the addition of rare earth metals had a positive effect on the abrasion behaviour of G17CrMo5-5 cast steel.

Keywords: Wear resistant alloys, Cast steel, Rare earth metals, Miller test, Surface profile

1. Introduction

Material properties dictate the choice of cast steel for particular applications. There is no universal cast steel to guarantee reliability or long operational life. Several grades of steel are widely used in applications requiring very high wear resistance [1]. For example, Hadfield steel exhibits high ductility and wear resistance when subjected to high dynamic loads. However, when high pressures and impacts are not used, the

material wears out fast [2–5]. Also at low pressure and at temperatures above 300°C, Hadfield steel shows poor resistance to abrasive wear [6,7].

Commonly used alloy steel castings are produced with an addition of Cr, Mo, Ni, and Mn to increase strength and wear resistance, attributed to the formation of carbides of high hardness and their distribution. These steel grades are found in steel track shoes, crane wheels, or gears. In the arms industry, Cr-Mo-V-Cu-Ni cast steel is used in light weapon and equipment, e.g., MAG-95 pistols or parts for the AK rifle family [8]. Frequent failure to

form quality castings (castability, forging flaws) was a hindrance to the wider application of the material, but to a large extent the use of adequate alloy additions has eliminated this problem [8]. The energy industry needs foundry products that primarily exhibit creep resistance under elevated temperatures, cyclic loads resistance and fracture toughness. Nevertheless, resistance of the material to abrasive wear and cavitation is also an important, desirable property.

In addition to properties, an economic factor, i.e., the cost of steel castings, has an important role to play. For this reason, low alloy cast steel with improved abrasive wear are used [9, 10]. Increasingly demanding performance expectations are the driving force of research into enhancing the resistance to abrasion through the use of a suitable combination of alloy additions, processes that increase the purity of liquid metal at the smelting phase

(modification; secondary metallurgy), and adequate heat treatment [11 – 15].

2. Materials

The test material, low alloy cast steel G17CrMo5-5, was produced in an electric induction furnace under industrial conditions. Two melt series were made: non-modified melts and melts produced by modifying the liquid metal with a mixture of rare earth metals composed of 49.8%Ce, 21.8%La, 17.1%Nd, 5.5%Pr, and 5.35% REM residue. Table 1 shows the chemical composition of the material under analysis. Test ingots were subjected to heat treatment: normalizing (940°C/1h/pow.) and tempering (710°C/2h/pow.). The specimens for metallographic examination and abrasive wear tests were cut out of the material.

Table 1.

Chemical composition of steel castings from mass industrial Re metals-modified steel smelting

| | Content % mass. | | | | | | | | | | Fe residue |
|--------------|-----------------|------|------|-------|-------|------|------|------|-------|--------|---------------|
| | C | Si | Mn | P | S | Cr | Mo | Ni | Al | MZR | |
| Non-modified | 0.17 | 0.40 | 0.57 | 0.024 | 0.016 | 1.13 | 0.54 | 0.11 | 0.041 | – | |
| Modified | 0.16 | 0.37 | 0.62 | 0.022 | 0.013 | 1.22 | 0.53 | 0.12 | 0.050 | < 0.01 | |

3. Methods

The microstructure of the non-modified and modified cast steels was evaluated using the JSM 7100 F field emission scanning electron microscope. The abrasive wear tests were performed on the Miller tester using a 16-hour cycle with a slurry composed of SiC and water at a 1:1 ratio. The wear specimen with dimensions 25.4x12.7x5±9 mm reciprocates along the bottom of the slurry bath. Every four hour within the cycle, the mass the specimen is measured. The measurement results are used to plot the wear curve. Cumulative mass losses on each specimen are the abrasive wear resistance measure [6].

Geometrical structure of the surface of the material was tested using the Talysurf CCI optical profilometer with a scanning range in vertical axis of 2.2 mm and a resolution of 0.01 nm. The results were recorded in the matrix of 1024x1024 measurement points, which at the lens x10 gives the 1.65 mm x 1.65 mm area. The description of surface degradation after abrasive wear tests was supplemented with scanning examinations. To measure the stereometry of the specimen surfaces after abrasion tests, the coherence correlation interferometry (CCI) was used. This method, combining a vertical scanning technique and optical interferometry, is based on the collection of images of

interference patterns and their locations during vertical scanning. The hardness of the modified and non-modified cast steels was measured using the NEXUS 300 tester.

4. Study results and analysis

4.1. Microstructure

The modification processes used during the smelting of the alloy led to changes in its microstructure (grain refinement) and in the morphology of non-metallic inclusions - a significant second-phase distribution (Fig. 1a and Fig. 1b), discussed in detail in [14, 15]. The observed changes in the microstructure resulted in a three times higher impact strength (from 33 to 99 J/cm²) and more than two times higher resistance to cracking (from 116 to 250 MPa) [15]. Hardness is one of the factors that affect tribological properties of a material. And consequently, the changes described above should increase the resistance of the cast steel to abrasive wear.

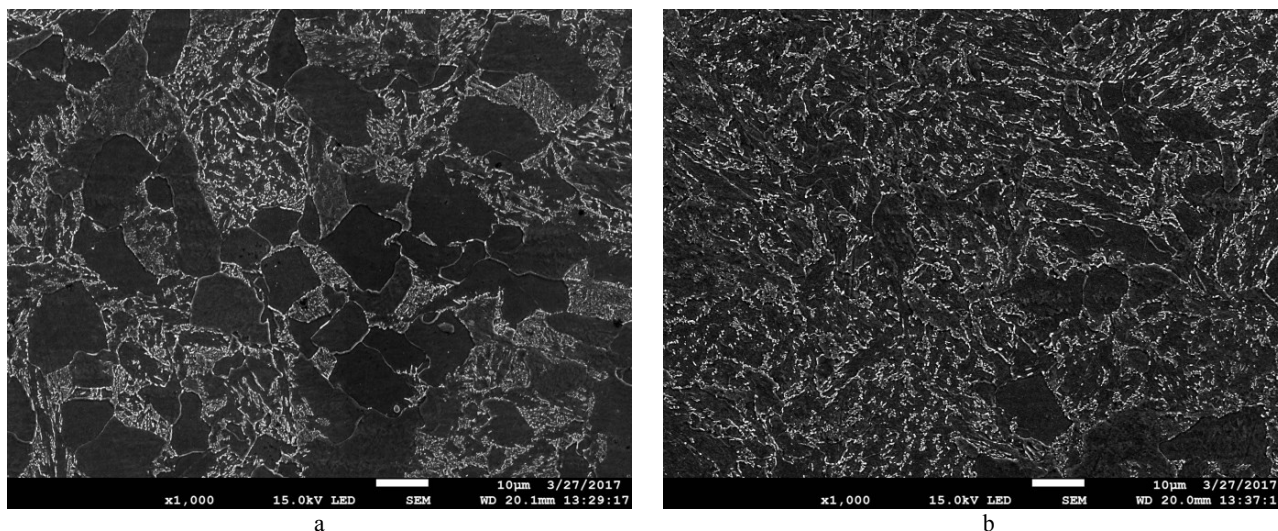


Fig. 1. G17CrMo5-5 microstructure, a) non-modified, b), modified, SEM, etching: nital

4.2. Miller test – wear response

The results from the two series (two series of the 16-hour cycle each – modified and non-modified cast steel) of abrasive wear tests in the SiC particles-containing slurry confirmed mass loss differences between the modified and non-modified cast steel. The modified cast steel exhibited higher resistance to abrasion (Fig.2).

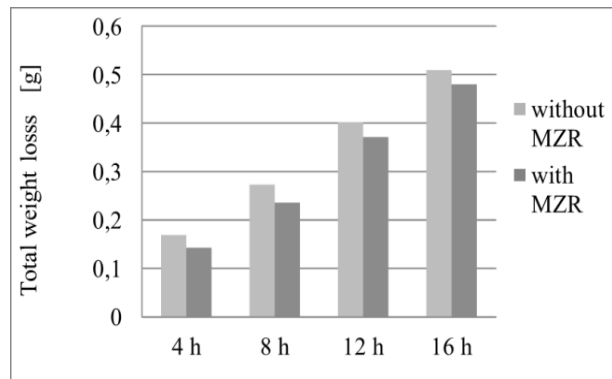


Fig. 2. Mass change of the material during the Miller test – average mass loss after two test series

The lower wear of the modified cast steel was confirmed by surface images taken by the scanning microscope after the abrasion tests. The examination of the surface layer of the specimens that were in contact with the slurry revealed plastic deformations reflecting the direction of the specimen movement during the test. Cracks and grooves observed on the surface of the modified specimen were not as deep as those on the non-modified cast steel specimen (Fig.3). The number and density of the grooves varied greatly due to microhardness differences between the two materials. The tests showed higher microhardness of the ferritic matrix of the modified cast steel by about 20 HV_{0.02}. Thus, in addition to microstructural changes (phase refinement) resulting from the modification of the liquid metal with REM, the matrix microhardness affects the resistance to abrasive wear of the cast steel under analysis.

The microscopic evaluation of the specimen surface layers indicates minor wear scars produced by hard SiC particles present in the abrasive slurry and by the reciprocating motion of the specimens during the test. Analysis of the microarea (Fig.4) confirms these findings. In addition to matrix peaks, the spectrum shows carbon and silicon peaks, which are not observed in the analysis of the cast steel matrix alone.

Due to the complexity of Miller test-related mechanisms that occur between the specimen surface layer and the slurry, additional surface profile tests were performed.

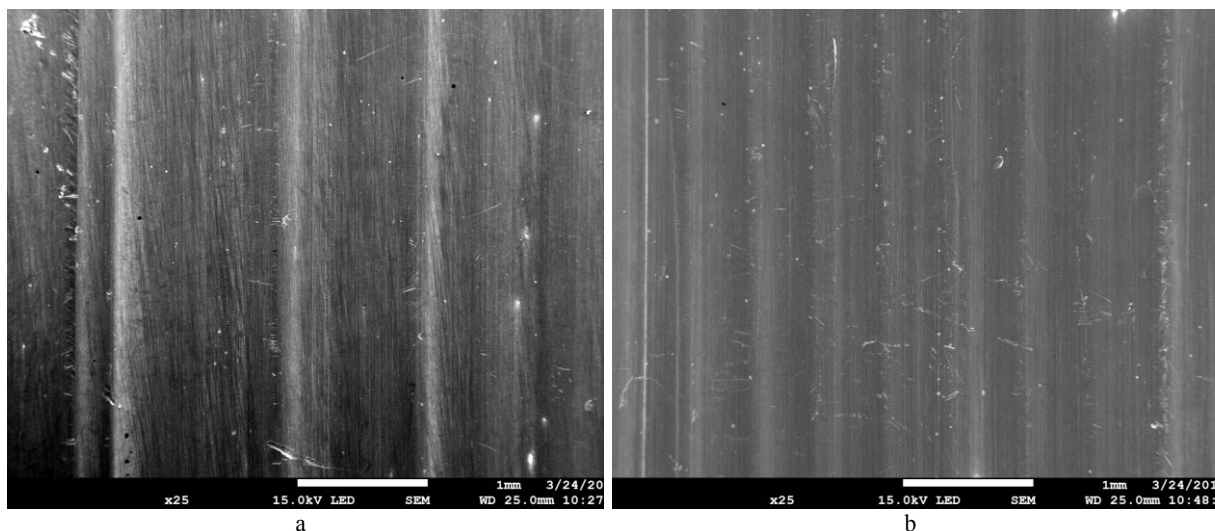


Fig. 3. SEM images of the cast steel after the Miller test, a) non-modified cast steel, b) modified cast steel

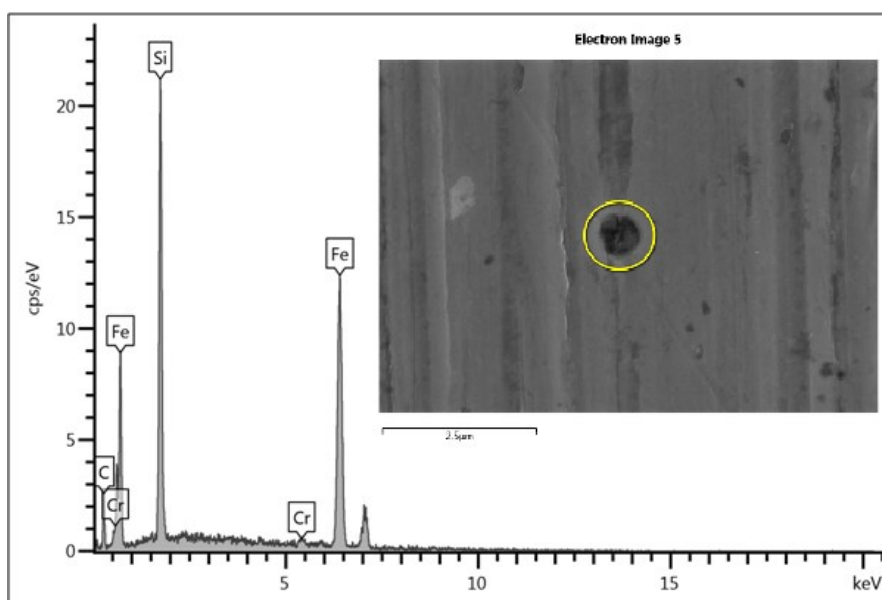


Fig. 4. X-ray spectrum of the marked region, SEM, EDS

4.3. Surface geometric structure

The following surface parameters were computed:

- Sa*: Arithmetic mean deviation of the surface
- Sq*: Root-mean-square deviation of the surface
- Sp*: Maximum height of the peak
- Sv*: Maximum depth of the valley
- Sz*: Ten Point Average
- Ssk*: Asymmetry of the surface
- Sku*: Kurtosis of the surface

The surfaces resulting from the wear due to friction are shown in isometric images (Fig.5) and profilograms (Fig.6). The tests showed that wear changes parameters of the surface.

Table 2.
Compiles the average results

| Parameter | Cast steel | | |
|------------|-------------------|----------------|--------|
| | without RE metals | with RE metals | |
| <i>Sa</i> | µm | 16.103 | 10.438 |
| <i>Sq</i> | µm | 18.723 | 12.582 |
| <i>Sp</i> | µm | 32.513 | 34.584 |
| <i>Sv</i> | µm | 37.827 | 45.602 |
| <i>Sz</i> | µm | 70.341 | 80.186 |
| <i>Ssk</i> | | -0.075 | 0.400 |
| <i>Sku</i> | | 1.986 | 2.319 |

The arithmetic mean deviation of the surface, S_a , decreased from $16.103 \mu\text{m}$ to $10.438 \mu\text{m}$, which indicates lower wear. Parameters S_q and S_p were also reduced. The maximum depth of the valley, S_v , increased from $37.827 \mu\text{m}$ at the beginning of the friction process to $45.602 \mu\text{m}$ after the process. This indicator represents the measure of the fluid retention in the pit of the surface of the specimen. The negative value of the asymmetry parameter, S_{sk} , indicates that the peaks are plateau-like surfaces (Fig. 5a, 6a), and their increasing values reflect surface development (Fig. 5b, 6b). The changes also affected the S_{ku} parameter. However, its

sensitivity to single pits excludes it from the group of parameters determining the character of surface wear.

Due to the variability of parameter changes, i.e., a decrease (S_a , S_p , S_q) and an increase (S_v , S_z , S_{sk} , S_{ku}), it is necessary to look at the character of the resultant profile after wear. No deep grooves were observed in the specimens made with REM. The grooves became shallower and their density rose. The topography of the cast steel surface after the modification is noticeably more regular, which confirms more stabilised wear (Fig. 5b).

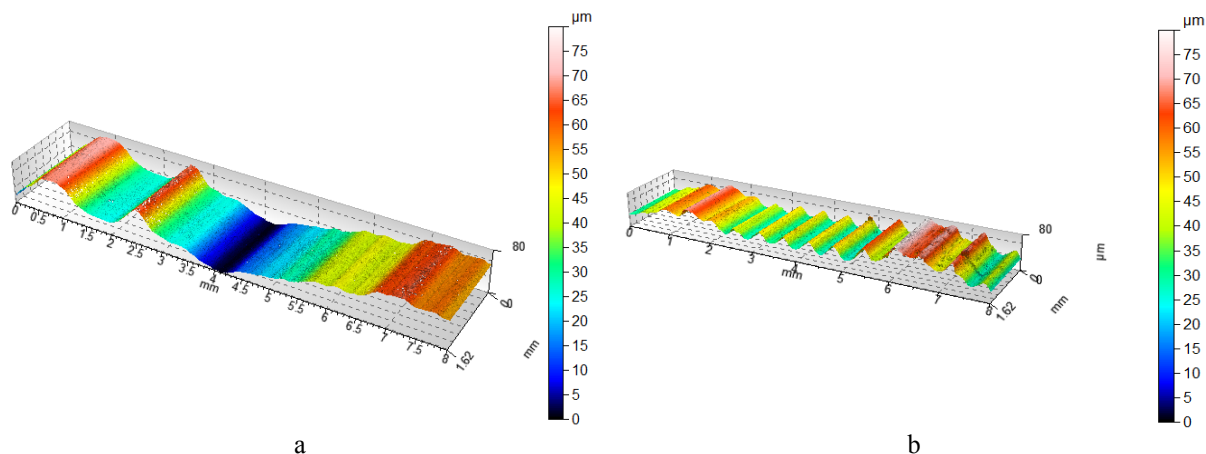


Fig. 5. Spatial profiles of a) non-modified and b) modified cast steels

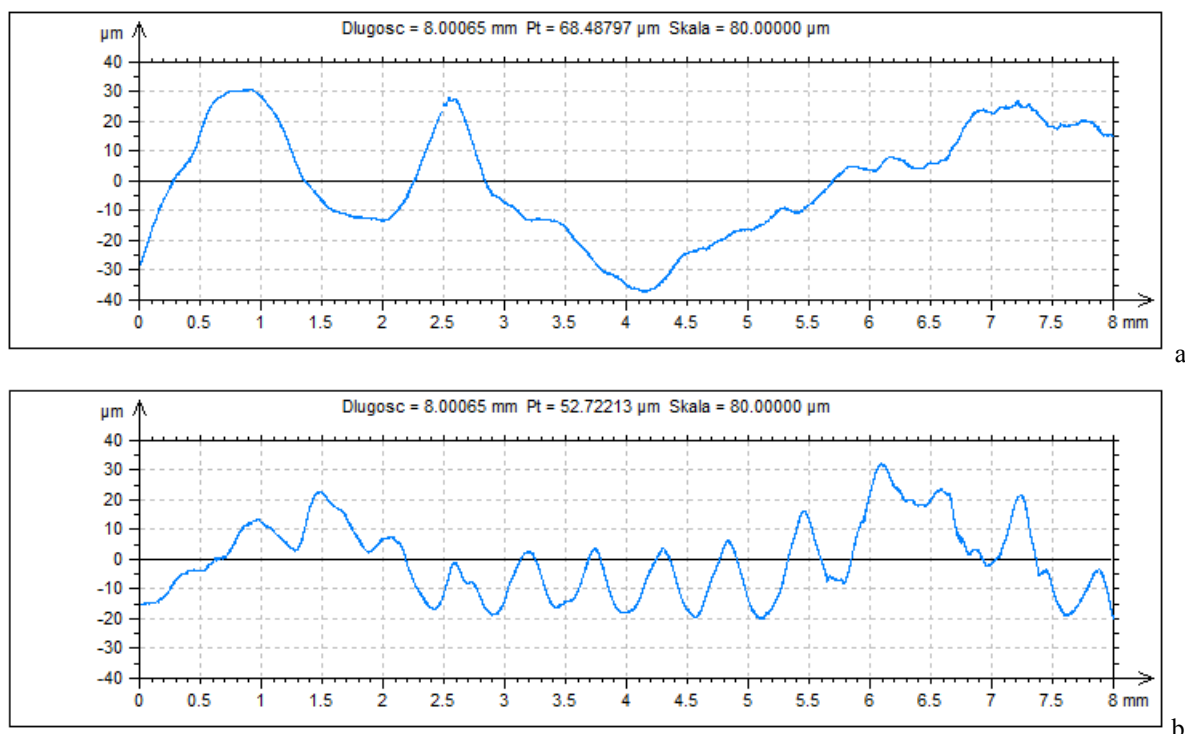


Fig. 6. Surface profile of a) non-modified and b) modified cast steels

5. Conclusions

The tests carried out in this study revealed positive effects of modification through the REM addition on the G17CrMo5-5 microstructure and abrasive wear resistance.

Compared to the non-modified cast steel, the microstructure of the REM-modified specimens exhibited significant refinement and higher matrix microhardness.

The modified cast steel has a better abrasive wear resistance, as shown in the test with the slurry composed of SiC and water. The surface profile measurements of the both materials confirmed smaller depths of the grooves on the modified cast steel surfaces, hence their higher resistance to abrasive wear.

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