ABRASIVE WEAR RESISTANCE OF STEEL M390P AFTER HEAT TREATMENT

Boyan Yordanov, Iliyan Mitov

University of Chemical Technology and Metallurgy
8 Kliment Ohridski Blvd., Sofia 1797, Bulgaria,
biyordanov@uctm.edu (B.Y.); iliyan_mitov@abv.bg (I.M.)

Received 06 October 2024
Accepted 23 December 2024
DOI: 10.59957/jctm.v60.i2.2025.14

ABSTRACT

In present work abrasive wear resistance after heat treatment of a powder steel M390P with composition 1.9 % C, 0.7 % Si, 0.3 % Mn, 20.0 % Cr, 1.0 % Mo, 4 % V and 0.6 % W was investigated. Machine used for laboratory wear tests is a device that allows to imitate friction conditions in the exploataion of objects. Heat treatment consisting of quenching from 1070ºC in oil and tempering at 450ºC provides maximum hardness of HRC 59 units and suitable for details working at cutting and grinding without high impact load conditions. Quenching from 1150ºC with subsequent twice high temperature tempering at 550ºC achieves hardness of HRC 61. This heat treatment is good for abrasion wear resistance working blades. Hardening at 1070ºC and tempering at 450ºC show wear rate $V = 3.6.10^{-5}$ g m^{-1} and $E = 27778$ m g^{-1} for abrasive wear resistance. The best parameter values are respectively $V = 1.82.10^{-5}$ g m^{-1} and $E = 54745$ m g^{-1} after high temperature quenching at 1150ºC and subsequent twice tempering at 550ºC.

Keywords: *microstructure, powder steel, heat treatment, abrasive wear resistance.*

INTRODUCTION

Abrasive wear of materials is a serious problem in the metallurgical, foundry and mining industries. The metal processing industry consumes increasing amounts of wear-resistant materials subject to equipment with high wear due to friction and impact loading. Properly designed and fabricated steels components offer an attractive combination of price and performance making them excellent substitutors to high-alloy steels and cast irons, as well as ceramics.

The development of new types of steels is necessary to understand the wear phenomena leading to damage caused by contact with wearing particles. Several researchers have made significant efforts to understand the behavior of different materials subject to wear. In addition, the physical interactions between the abrasive particles and the worn surface have been extensively studied to elucidate the deformation and wear mechanisms. These interactions are divided into four stages: microploughing, microcutting, microfatigue and microcracking. Metal deformation tools and casting cleanings aggregates in the metallurgical industry have intensive abrasive wear from particles with various sizes which friction and impact the surface of the workpieces [1 - 3].

Although laboratory tests are not perfect, they can simulate the wear conditions in contact between the workpiece and the wear environment. They even dominate when it comes to evaluating the wear resistance of various materials exposed to abrasive wear. In-situ abrasive wear tests are expensive, time-consuming and difficult to control or quantify. The purpose of the present study is to evaluate in laboratory conditions the abrasive wear resistance of powder steel M390P as produced and after various types of heat treatment exposed to abrasive wear.

Experiments related to specific operating conditions of the workpiece are important for practical dissemination of data. In many cases it is easy to express wear in terms of the reduction of the linear dimensions, mass loss and abrasive wear resistance of the tested bodies in the normal direction of the surface [4, 5].

The powder metallurgical technology makes it possible to obtain products from tool steels whith a higher degree of alloying. The obtained carbides with high hardness and very small size on one hand and their uniform distribution in the microstructure of the tools on the other increase in a high extend their wear resistance. In many cases powder metallurgy can achieve unique properties unattainable by classical technologies using for the same products. Powder steel M390P is a promising material with unique properties. These materials are used to make pumps moving abrasive slurries, dies for cold deformation of metals and components for sand blasting machines. Influence on the microstructure and hence on the final properties of this steel can be carried out by proper heat treatment. The wear resistance and mechanical properties of steel M390P depend on the shape and number of carbides precipitated in the microstructure and their bond with supporting matrix [6, 7]. The matrix microstructure can be changed depending on applied heat treatment. Martensite in the microstructure of the specimens is responsible for a high hardness and tensile strength. High ductility and elongation having powder steels with a pearlite and troostite in the microstructure [8 - 10].

EXPERIMENTAL

For the experiments powder steel M390P with a parallelepiped shape was prepeared [11]. Element content according to producers' data is shown in Table 1. Powder steel M390P (CPM 20CV) company development of "Bohler" is such an example of a synthesized material combining extremely high wear resistance and corrosion resistance compared to the X210Cr12, X165GrMoV12 (D2) and chromium martensite X47Cr14 steels.

Samples for the metallographic tests are prepared by classical technology according to GOST 5950-2000 standard.

The types of applied heat treatment of the M390P steel samples can be seen in Table 2. The hardness value is the average of five measurements on the surface of fiveteen workpieces. Light metallographic microscope for microstructure observing of powder steel M390P and conventional chamber furnace for heat treatment are used.

The machine for abrasive wear possesses ability to change the speed, the applied load and type of wear conditions by means of slurries respectively. The machine created for laboratory wear tests can be classified as a device that allows to imitate friction conditions and reproduce to a greater extent the wear process occurring in the service [11]. The amount of material removed from the tested samples was determined with an analytical balance with an accuracy of 0.0001 g.

The experimental conditions for wear resistance tests are pointed in Table 3.

RESULTS AND DISCUSSION

Hardness changes according to the type of heat treatment can be seen on Fig. 1. The wear parameters after different abrasive treatment times are shown in Table 4.

Table 1. Chemical composition of steel M390P, wt. %, according to produser datas.

C	Si	Mn	Cr	Mo	V	W
1.90	0.70	0.30	20	1.00	4.00	0.60

Table 2. Heat treatment parameters of steel M390P.

Parameters of heat treatment	1	2	3
Quenching temperature, ^{o}C, medium	1070, Oil	1150, Oil	1150, Oil
Isothermal hold, min	30	30	30
Tempering temperature, ^{o}C, medium	450, Water	500, Water	550, Water
Isothermal hold at tempering, min	60	60	60

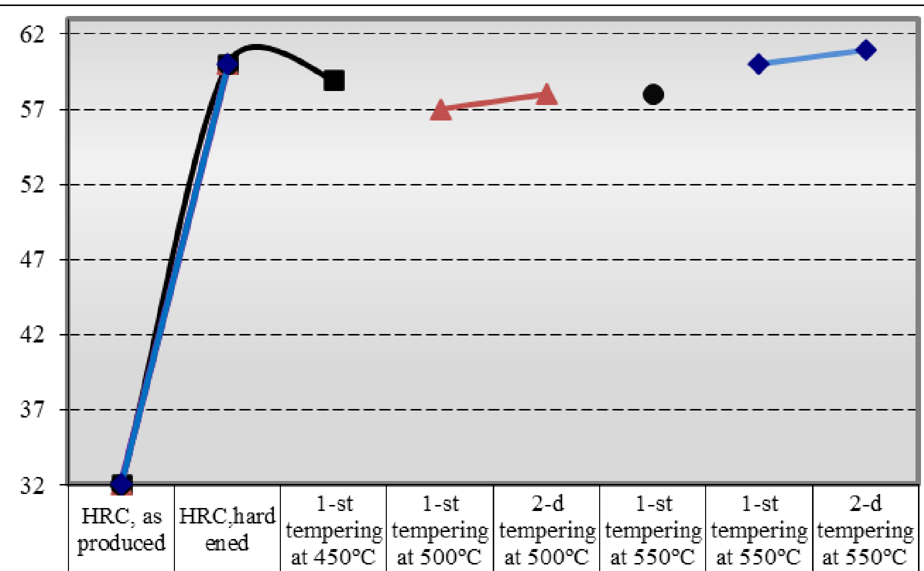
Table 3. Experimental conditions for wear resistance test.

Experimental conditions	Wear parameters
Abrasive emery disc	Grain size P 80
Load on the workpiece F, g	F = 450 g
Test time T, min	T = 25 min, T = 60 min
Distance traveled S, m	S = 3000 m, S = 7200 m

During the friction test a process of surface alteration take part in the wear. Surface alteration is the process of gradually changing the contact because of changing the initial roughness and the mutual fit of working surfaces until a stable roughness and a constant wear value are reached. Usually, the intensity of wear is reduced during this process. Deformation strengthening together with the surface alteration of the workpieces happens. To unify the experiments, the processing time was the same 5 min.

Table 4. Mass loss parameters after different abrasive treatment times.

Weight loss	$\Delta m = m_s - m_r$, g						
	Surface alteration	5 min	10 min	15 min	20 min	25 min	60 min
Powder steel M390P as produced	0.0749	0.1208	0.1569	0.1881	0.2141	0.2508	0.4659
Quenching at 1070°C, tempering at 450°C	0.0275	0.046	0.0626	0.0784	0.0942	0.108	0.2571
Quenching at 1150°C, tempering at 500°C, twice	0.0171	0.0316	0.0414	0.0526	0.0611	0.0675	0.1693
Quenching at 1150°C. Tempering at 550°C	0.0177	0.0305	0.0455	0.0584	0.0688	0.0798	0.1944
Quenching at 1150°C. Tempering at 550°C, twice	0.0139	0.0237	0.0307	0.0403	0.0472	0.0548	0.1032



	HRC, as produced	HRC,hard ened	1-st tempering at 450°C	1-st tempering at 500°C	2-d tempering at 500°C	1-st tempering at 550°C	1-st tempering at 550°C	2-d tempering at 550°C
Quenching at 1070 °C	32	60	59					
Quenching at 1150 °C	32	60		57	58			
Quenching at 1150 °C	32	60				58		
Quenching at 1150 °C	32	60					60	61

Fig. 1. Hardness changes of steel M390P after quenching and tempering at different temperatures.

The mass loss of the powder steel M390P after different types of heat treatments is shown in Fig. 2.

Microstructure of alloy M390P as produced is shown in Fig. 3. Carbide phases with equiaxed shape and high cromium content type Cr_7C_3 and $(Cr, Fe)_7C_3$ which are light in microstructure are observed. Around them is the matrix of alloyed fine pearlite mixture (the darker areas) obtained by annealing the steel.

The samples hardened at 1070°C with subsequent tempering at 450°C show 57 % less mass wear compared to delivered experimental patterns. The mass loss after 25 min of abrasive wear is 0.1080 g, and 0.2508 g as shown in Table 4. The microstructure of the samples quenched from 1070°C in oil and tempered at 450°C can be seen in Fig. 4. Additional rounding of the edges of the complex carbide phases (light crystals in the photo) are observed, as well as the appearance of additional secondary carbides with high dispersion in the matrix of tempered martensite (dark phase). The size of the special carbides of the VC type which have a bright light colour and are separated in the primary complex carbide phase preferentially. They also precipitate in the tempered martensitic matrix, but their size is smaller.

The microstructure of the samples quenched from 1150°C in oil and tempered at 500°C twice can be seen in Fig. 5. The samples showed smaller size of the primary

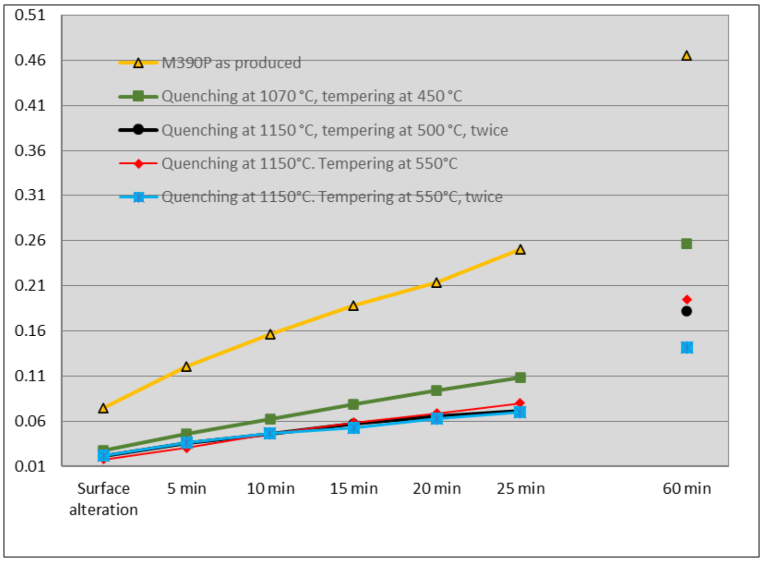


Fig. 2. Mass loss of specimens after different heat treatment.

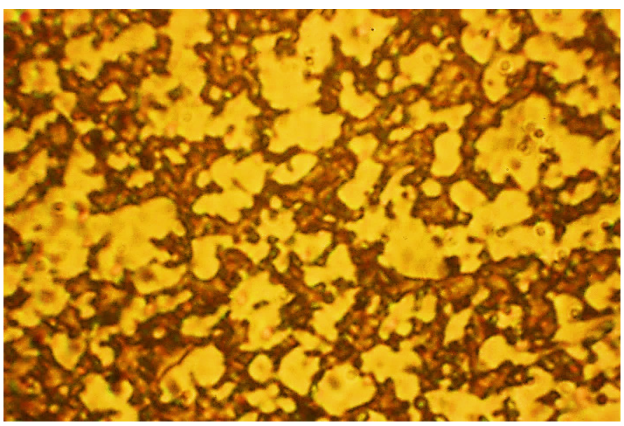


Fig. 3. Microstructure of alloy M390P as produced, 1870x magnification.

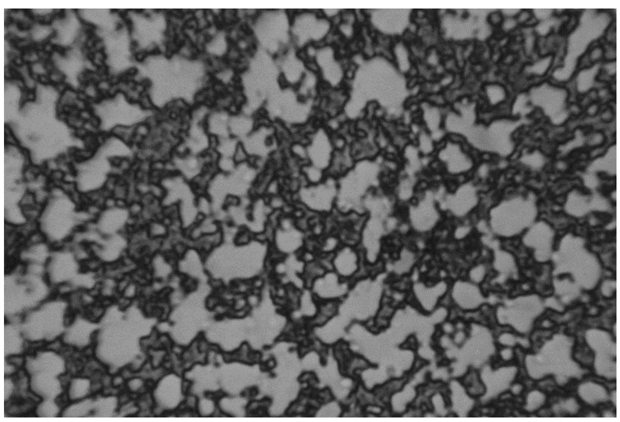


Fig. 4. Microstructure of alloy M390P obtained after hardening at 1070°C in oil and tempering at 450°C, etched, 1870x magnification.

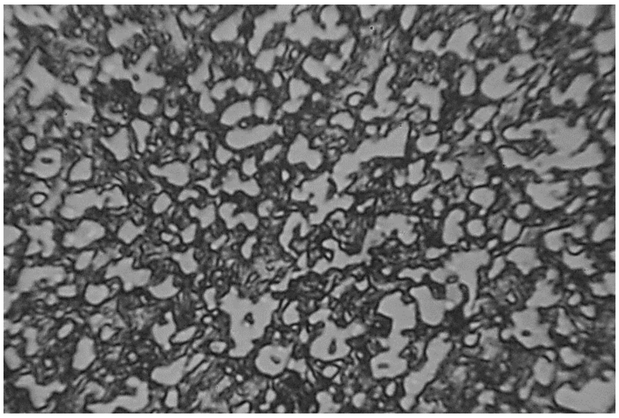


Fig. 5. Microstructure of alloy M390P obtained after hardening at 1150°C in oil and tempering at 500°C twice, etched, 1870x magnification.

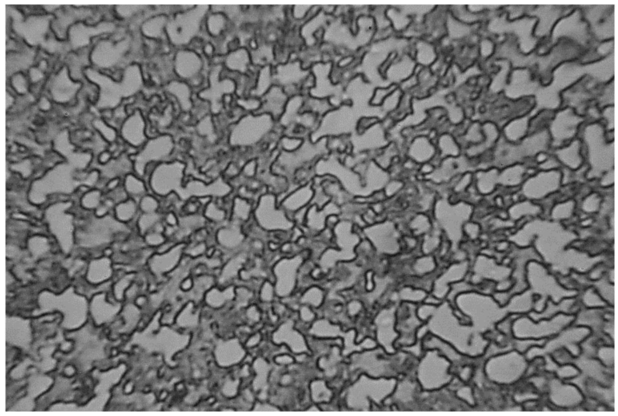


Fig. 6. Microstructure of alloy M390P obtained after hardening at 1150°C in oil and tempering at 550°C, etched, 1870x magnification.

carbides and increase their dispersion. Fine secondary complex carbides as $(Cr, Fe)_7C_3$ and a special type of VC, Cr_2VC_2 are precipitated in microstructure of the patterns.

The samples hardened from 1150°C and tempered respectively at 500°C twice and 550°C once at 25 min abrasive treatment show 73 - 75 % less mass wear then as produced. The values of the weight loss after 60 min treatment of laboratory abrasive wear test machine are 0.1693 g and 0.1944 g respectively compared with 0.4659 g of delivered samples.

High temperature quenching at 1150°C in oil and first tempering at 550°C converted the microstructure of the steel close to this one tempered at 500°C but with increased amount and evenly distributed carbide phases Fig. 6.

The best results in terms of mass wear are shown by the structure of M390P steel hardened at 1150°C and tempered at 550°C twice Table 4. It wears abrasively almost 80 % less than steel samples as produced. High temperature quenching followed by double tempering at 550°C increases the amount of the carbide phase and rounds its edges Fig. 7. The samples showed a decrease in the size of the primary carbides along with an increase in their dispersion and precipitation of very fine secondary complex carbides of Cr_7C_3 and $(Cr, Fe)_7C_3$ and a special type of VC, Cr_2VC_2. The transformation of retained austenite to martensite is the other mechanism for increasing the hardness of macro specimens to a lesser extent during first and second tempering. This structure has increased toughness, wear resistance and high heat resistance while maintaining a high hardness of 58 - 61 HRC. Heat treatment processes are greatly facilitated by the fact that in powder steel the carbide phase is extremely finely dispersed and evenly distributed in the structure of the products. Hence the higher properties compared to steel with identical chemical composition obtained by a classical metallurgical technological scheme.

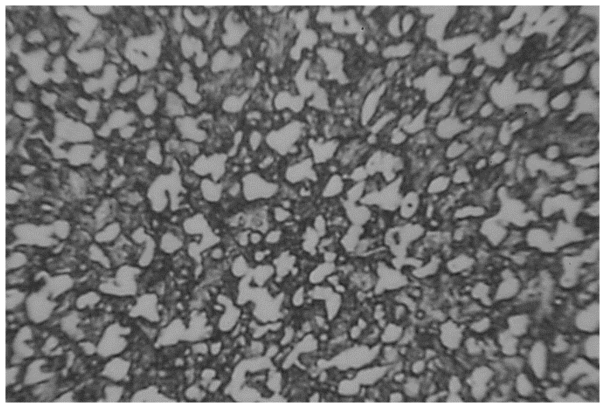


Fig. 7. Microstructure of alloy M390P obtained after hardening at 1150°C in oil and tempering at 550°C twice, etched, 1870x magnification.

The abrasive wear resistance and wear rate values are shown in Fig. 8 and Table 5.

The wear rate and abrasive wear resistance of the samples when delivered from the manufacturer without heat treatment is $V = 8.36\times10^{-5}$ g m^{-1} and E = 11962 m g^{-1} respectively.

The wear rate after quenching at 1070°C in oil and

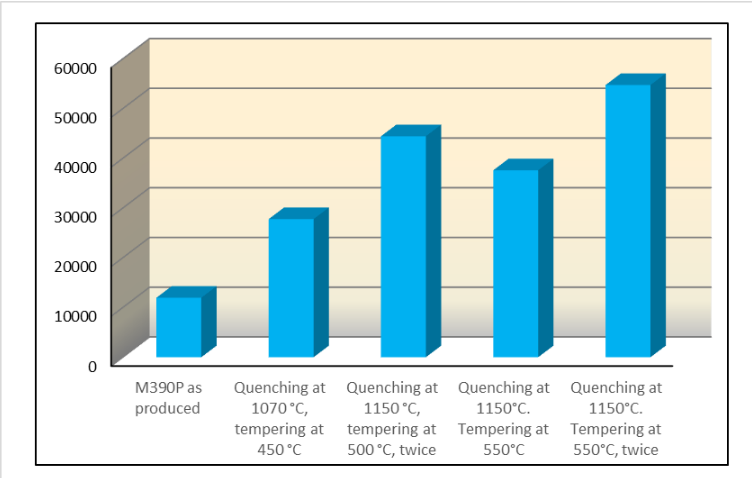


Fig. 8. Abrasive wear resistance of steel M390P after different heat treatments.

Table 5. Values for the abrasive wear resistance and wear rate of heat treated powder steel M390P for distance traveled of 3000 m.

Powder steel M390P	Wear rate, $V = \Delta m/S$, g m^{-1}	Abrasive wear resistance, $E = 1/V$, m g^{-1}
Powder steel M390P as produced	8.36x10^{-5}	11962
Quenching at 1070^{o}C, tempering at 450^{o}C	3.6x10^{-5}	27778
Quenching at 1150^{o}C, tempering at 500^{o}C, twice.	2.25x10^{-5}	44444
Quenching at 1150^{o}C. Tempering at 550^{o}C	2.66x10^{-5}	37594
Quenching at 1150^{o}C. Tempering at 550^{o}C, twice	1.82x10^{-5}	54745

subsequent low-temperature tempering at 450^{o}C is V = 3.6x10^{-5} g m^{-1} and the wear resistance is E = 27778 m g^{-1}. When quenching at 1150^{o}C and tempering at 550^{o}C the values are respectively for V = 2.66.10^{-5} g m^{-1} and E = 37594 m g^{-1}, which increase to V = 1.82×10^{-5} g m^{-1} and E = 54745 m g^{-1} after high temperature quenching at 1150^{o}C and subsequent double tempering at 550^{o}C.

CONCLUSIONS

The following conclusions can be drawn from the research:

- Hardness values of 60 HRC after quenching at 1070^{o}C and 59 HRC after first tempering at 450^{o}C were obtained for the treated M390P powder steel.
- The obtained hardness after quenching at 1150^{o}C is 58 - 60 HRC units of the treated samples, and after carrying out double tempering at 500^{o}C and isothermal holding time of 60 min, it becomes 58 HRC.
- Increasing the tempering temperature to 550^{o}C causes an increase in hardness up to 60 HRC which is associated with processes of precipitation of high chromium complex carbide phase and of special carbides such as VC and Cr_2VC_2 in the martensitic needles. The transformation of retained austenite to martensite is the other mechanism for increasing the hardness of the specimens at lesser extent then repeated tempering proces.
- No heat treated samples shown the lowest abrasive wear resistance E = 11962 m g^{-1}. The wear rate after quenching at 1070^{o}C in oil and subsequent low-temperature tempering at 450^{o}C is V = 3.6×10^{-5} g m^{-1} and the abrasive wear resistance is E = 27778 m g^{-1}. When quenching at 1150^{o}C and tempering at 550^{o}C the values are respectively for V = 2.66×10^{-5} g m^{-1} and E = 37594 m g^{-1}, which increase to V = 1.82×10^{-5} g m^{-1} and E = 54745 m g^{-1} after high temperature quenching at 1150^{o}C and subsequent double tempering at 550^{o}C.

Authors' contribution: *B.Y.: Heat treatment; I.M.: Wear resistance*

REFERENCES

1. S. M. Hsu, M. C. Shen, A. W. Ruff, Wear prediction of metals, Tribology International, 30, 5, 1997, 37l-383.
2. M. G. Gee, S. Owen-Jones, Wear testing methods and their relevance to industrial wear problems, NPL Report CMMT (A)92, 1997.
3. ASTM G65-94, Standard test method for measuring abrasion using the dry sand / rubber wheel apparatus, Annual Book of ASTM Standards, 1997, 239-250.
4. G.E. Totten, Lin Xie, K. Funatani, Modeling and simulation for material election and mechanical design CRC Press, New York, 2003.
5. T.N., Ying, Wear Mechanisms for Ductile and Brittle Materials in a Micro-Contact, Ph.D. dissertation, University of Maryland, College Park, 1996.
6. R.B. Gundlach, Alloy Cast Irons, Properties and Selection: Irons, Steels and High Performance Alloys, 1, ASM Handbook, ASM International, 1990, 85-104.
7. R. Cíger, I. Barényi, M. Krbaťa, Analysis of heat treatment parameters on the properties of selected tool steels M390 and M398 produced with powder metallurgy, Manufacturing Technology Engineeting Science and Reseaech Journal, 21, 6, 2021.
8. D. Kopyciński, E. Guzik, D. Siekaniec, A. Szczęsny, Analysis of the High Chromium Cast Iron Microstructure after the Heat Treatment, Archives of Foundry Engineering 14, 3,2014, 43-46.
9. N. Rashkov, Heat treatment of special steel and slloy, Bulgaria, Sofia, 1993, (in Bilgarian).
10. S.S. Ghazi, K.M. Mashloosh, Influence of Heat Treatment on Resistance of Wear and Mechanical Properties of Die Steel Kind D3, American Journal of Scientific And Industrial Research, ISSN: 2153-649X, 2015.
11. B. Yordanov, D. Krastev, I. Mitov, Heat treatment influence on the abrasive wear resistance of hypoeutectic chromium cast iron, J. Chem. Technol. Metall., 57, 6, 2022, 1267-1274.