Arch. Metall. Mater. **69** (2024), 3, 809-817

DOI: https://doi.org/10.24425/amm.2024.150900

L. TÓTH[1], R.E. FÁBIÁN[1], P. PINKE[1], T.A. KOVÁCS[1], M. NABIAŁEK[2],
A.V. SANDU[3,4,5*], P. VIZUREANU[3,6]

COMPARISON OF THE PROPERTIES OF COLD WORK TOOL STEELS WITH THE SAME HARDNESS BUT DIFFERENT MANUFACTURING PROCESSES

The required important properties of cold work tool steels are hardness, wear resistance, suitable toughness and in many cases corrosion resistance. For cold work tool steels, hardness can be well controlled by heat treatment, but steels of the same hardness do not necessarily have similar wear, corrosion resistance or even toughness. These properties are influenced by the chemical composition of the steels and their manufacturing processes. The study is performed on Böhler K390 PM produced by powder metallurgy (PM) process, Böhler K360 ESR made by electro-slag remelting (ESR) methods and Böhler K110 produced conventionally (C). The specimens were heat treated to obtain the same hardness of 61 HRC. It was made a comparative test of the abrasive wear resistance, corrosion resistance and toughness of the heat-treated cold work tool steel test specimens. The comparative test results show that the Böhler K110 steel has the best corrosion resistance against the 20% acetic acid, and the Böhler K390 PM steel has the best wear resistance and toughness. The goal of the research was to find the optimal cold work tool steel quality for special applications (as a function of wear resistance, corrosion resistance and toughness). The K390 reached the best wear resistance which is two times better than the K360 and about ten times better than the K110. About the corrosion test results, it can be concluded that K110 showed the lowest weight loss after the corrosion test, and the K390 and K360 showed higher weight loss and lower corrosion resistance. Impact energy values from the Charpy impact test were the highest in the case of K390 followed by the K360 and the K110. The results were confirmed by the microscopic analysis.

Keywords: metallurgic process; corrosion; wear behavior; tool steel; hardness; heat treatment

1. Introduction

Tool steels are high-quality steels useful for working and shaping other materials. Tool steels can be unalloyed and alloyed steels, which are particularly useful in tool manufacturing [1]. They are usually melted in electric furnaces or produced by a powder metallurgy process.

Tool steels classification in industry applications are cold work tool steels, hot work tool steels, plastic mould tool steels and high-speed steels.

Cold work tools are essential to produce metal parts in various industries. Nearly 44% of metal parts on the global market were applied by the automotive industry in 2015 and this demand is increasing [2]. Cold working is defined as an operation temperature which is below 200°C but often at room temperature.

Cold work tool steels are used to perform bending, punching, cutting, rolling, deep drawing [3,4] and last but not least in the food industry. These steels are characterized by very good through-hardening properties, good toughness, good wear resistance, high compressive strength, and high hardness after hardening [5,6]. The basic properties of steel primarily depend on its chemical composition and microstructure. The microstructure of the steels is determined by the metallurgical process and the applied heat treatment technology [7,8]. Tool steels used in the food industry often require corrosion resistance in addition to properties such as wear resistance and suitable toughness. The environment affects the corrosion resistance of steel. Brajcinovic et al. [9] observed that K110 steel is susceptible to pitting corrosion in NaCl-soluble environments but not in water and emulsion. For the corrosion behavior testing it can find several

---

[1] BÁNKI DONÁT FACULTY OF MECHANICAL AND SAFETY ENGINEERING, ÓBUDA UNIVERSITY, 1081 BUDAPEST NÉPSZÍNHÁZ U. 8. HUNGAY
[2] CZĘSTOCHOWA UNIVERSITY OF TECHNOLOGY, DEPARTMENT OF PHYSICS, 42-214 CZĘSTOCHOWA
[3] GHEORGHE ASACHI TECHNICAL UNIVERSITY OF IASI, FACULTY OF MATERIALS SCIENCE AND ENGINEERING, DEPARTMENT OF TECHNOLOGIES AND EQUIPEMENTS FOR MATERIALS PROCESSING, BDUL. MANGERON, NO.51 700050 IASI, ROMANIA
[4] ROMANIAN INVENTORS FORUM, 3 SF. PETRU MOVILA ST., L11, 3-3, 700089 IASI, ROMANIA
[5] ACADEMY OF ROMANIAN SCIENTISTS, 54 SPLAIUL INDEPENDENTEI ST., SECT. 5, 050094 BUCHAREST, ROMANIA
[6] TECHNICAL SCIENCES ACADEMY OF ROMANIA, DACIA BLVD 26, 030167 BUCHAREST, ROMANIA

* Corresponding author: sav@tuiasi.ro

© 2024. The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (CC BY-NC 4.0, https://creativecommons.org/licenses/by-nc/4.0/deed.en which permits the use, redistribution of the material in any medium or format, transforming and building upon the material, provided that the article is properly cited, the use is noncommercial, and no modifications or adaptations are made.

methods as a function of the kind of the metals (carbon steels, tool steels and aluminium) and applications. For the corrosion tests the selected inhibitor can be a low concentration of HCl or acid acetic as a function of the metal's chemical composition and expected corrosion rate [10-12].

The main objective of the study of the selected cold work tool steels with equal hardness but made by different metallurgical processes is to analyze and compare the wear resistance, toughness, and corrosion resistance. It investigated a grade of K110 tool steel produced conventionally (C), a K360 ESR produced by electro-slag remelting (ESR) technology, and a K390 PM produced by powder metallurgy (PM) process. Grade K110 is a high-alloy cold work tool steel with a ledeburite microstructure [13]. Thanks to the chemical composition of this steel, it has good toughness and excellent wear resistance. It is suitable also for surface treatments like PVD, and CVD coating and also for nitriding due to its secondary hardening properties. The application possibilities of this steel are very large, like cutting tools, woodworking tools, blanking and punching tools, shear blades, drawing tools, cold extrusion and pressing tools [14,15].

K360 produced with an electro-slag remelting process has a remarkably high wear resistance together with high toughness and good compressive strength. Has very good resistance to tempering, is a secondary-hardening cold work tool steel with good dimensional stability, is suitable for gas and plasma nitriding, and is suitable for PVD coating. The structure of this steel is clean and homogenous with fine carbide distributions due to its chemical composition and remelting manufacturing process [16,17].

K390 is high-performance powder-metallurgy steel which is a reliable solution for difficult cutting and cold-forming operations with extremely high wear resistance, excellent toughness, ductility and high compressive strength. This steel is suitable for several applications like machine knives, coining, screw and barrels, roller, blanking, stamping, cold forming, powder pressing etc. [18,19]. K390 PM steel because its uniform structure and mechanical properties have good machinability, excellent grindability, uniform low dimensional changing during heat treatment and optimal EDM characteristics.

The manufacturing process has a major influence on steel properties. There are usually three metallurgical processes to produce cold work tool steels: conventional (C), electro-slag remelting process (ESR) and powder metallurgy (PM) made by hot isostatic pressing [20].

In the case of conventionally produced tool steels, solidifications occur slowly. These results in coarse carbide bands in the tool steel after rolling or forging [21].

These carbide streaks are beneficial for the wear resistance properties but have a negative influence on toughness and fatigue.

With the electro-slag remelting (ESR) process, this negative influence is reducible. In ESR technology a conventionally produced ingot is remelted, drop by drop through the slag. The small volume of melted steel solidifies much faster than the big volume of melted steel, giving less time for carbide growth after solidifying. The electro-slag remelting metallurgical process gives the steel improved homogeneity and smaller overall carbide sizes than the conventional process [22]. The ESR process also includes a slag filter, which improves the steel's cleanliness [23]. The advantages of the ESR process compared to conventional metallurgy are the fine-grained microstructure, structural homogeneity, and the absence of macro segregation [24,25].

In the powder metallurgy (PM) process, the remelted steel is pulverized into small fine grains using nitrogen shielding gas. These small grains solidify quickly and there isn't enough time for carbides to grow. The small grains of powder are then compacted into ingots using high isostatic pressing at high temperatures [26,27]. The cold work tool steels produced with the powder metallurgy (PM) process's most significant property is homogeneity. A characteristic advantage of steels produced by this process is the improved hardness, wear resistance and corrosion resistance [28].

In our work, three cold work tool steel (Böhler K110, K360 ESR, and K390 PM) were investigated which were manufactured by different technological processes, but after heat treatment had the same hardness. This research aimed to compare the wear behaviour, toughness, and corrosion resistance of the selected cold work tool steels heat treated to the same hardness, produced with different metallurgical processes, namely conventionally, electro-slag remelted, and using powder metallurgy. The wear resistance has a good correlation with the hardness but in this work, we want to highlight the microstructure influences the wear resistance, mechanical properties, and corrosion resistance. Hardness is a typical mechanical property which one has a good correlation with the wear resistance and toughness of the practice. We wanted to confirm or deny this statement by the way of experimental methods in this work. The expected results are useful in tool production because, in the industrial area, the designer specifies the steel grade as a function of the hardness. We didn't find in the literature experimental results which give the true relationship between hardness and wear resistance, toughness, and corrosion.

2. Materials and methods

The influence of the microstructure regarding the mechanical and chemical properties in the case of the cold work tool steels (K110, K360, K390) are tested by experimental methods.

2.1. Materials and Methods

The experimented materials were K110 cold work tool steel produced conventionally, K360 cold work tool steel produced by the electro-slag remelting process, and K390 cold work tool steel produced by the powder metallurgy process. The specimens were supplied by Böhler Voestalpine High-Performance Metals Hungary Kft. and cut from annealed bars, with an advanced universal metallographic cutting machine type Servocut 302 MA machine produced by Metkon Instruments Inc. Bursa/TURKEY, and with a wire electrical discharge machine (EDM) type Charmilles FI 240 SLP produced by GF Machines and Technologies, Biel Switzerland.

Before testing the specimens were cleaned with an ultrasonic cleaning machine type Elmasonic S60 H, produced by Elma Schmidbauer GmbH, Singen/GERMANY.

The chemical composition of the specimens (TABLE 1) was determined with a Hitachi PMP2, spectrometer (Hitachi Uedem/GERMANY).

TABLE 1

The chemical composition of the specimens. All values are given in mass-%.

Steel grade	C	Si	Mn	Cr	Mo	V	W	Co	Fe
K110	1.53	0.29	0.31	13.2	0.79	0.78	—	—	bal.
K360	1.23	0.89	0.33	8.79	2.71	1.19	—	—	bal.
K390	2.45	0.52	0.38	4.22	3.81	9.02	1.11	2.08	bal.

2.2. Heat treatment

The specimens were heat treated in a horizontal vacuum furnace type IVA Schmetz IU72/1F 2RV 60×60×40, 10 bar, made by IVA Schmetz GmbH, Menden/ GERMANY.

All samples were preheated in two steps, austenitized (shown in Fig. 1) and quenched with 9 bar pressure N2 gas. The preheating step reason is to equalise the temperatures between the surface and the center of the samples before phase transformations [1]. At the hardening temperature (TA, austenitizing temperature) after temperature equalisation there were applied a holding time for the austenite homogenization. When the austenitization is made at 1070°C secondary hardening, and high hardness can appear if there the applied tempering is near 500°C [14-16]. The quenching was followed immediately by triple tempering (Fig. 1). The temperature of the second tempering determines the desired hardness. The third tempering temperature must be lower than the second one. The reason for the triple tempering is to minimize the retained austenite [8,21,34]. The applied heat treatment diagram is provided in Fig. 1.

The heat treatment parameters are listed in TABLE 2.

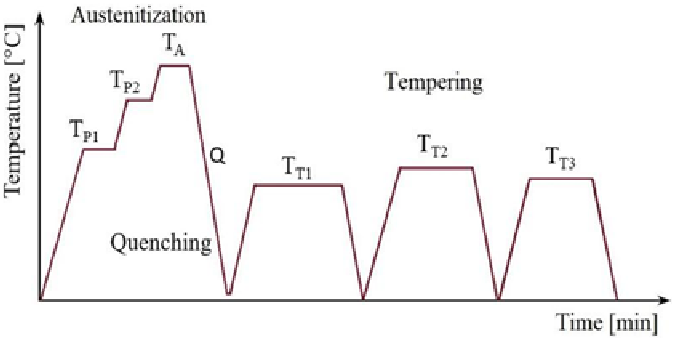


Fig. 1. Heat treatment diagram (Tp1 and Tp2 are the preheating temperatures, TA = austenitizing temperature, TT1, TT2 and TT3 are the tempering temperatures, Q = quenching).

TABLE 2

Heat treatment parameters.

Tp_1 (°C)	Tp_2 (°C)	T_A (°C)	T_{T1} (°C)	T_{T2} (°C)	T_{T3} (°C)
650	850	1070	540	550	530

2.3. Testing of the mechanical properties

The effectiveness of the heat treatment was checked by hardness measurement. The heat-treated specimens' hardness was measured with a Rockwell C Hardness Tester ERNST AT 130 DR-NX. Three measurements were performed on each specimen and the results were averaged.

To determine the toughness, we used a Charpy Impact test machine of type RM 201 by VEB WPM, Leipzig, Germany on unnotched specimens. The test was performed at room temperature on 10-10 samples of each steel grade with dimensions: 55×10×7 mm.

The fractured surface was analyzed with scanning electron microscopy type Jeol JSM 5310.

2.4. Corrosion test

The test specimens are properly fine-ground to the same roughness and cleaned in Ethanol, and used an ultrasonic cleaning machine type Elmasonic S60, Elma Schmid-Bauer GmbH, Germany, for any contamination present on the surface before the corrosion test (Fig. 3). To determine the corrosion behaviour of the test samples, we used the immersion test evaluated based on the weight loss of specimens. Before and after the corrosion test the weight of the specimens was measured using the Kern ALJ 220-4NM type precision weighing machine.

The corrosion tests are performed in a 500 ml solution of 20% acetic acid. The specimens were immersed in the 20°C solution for 48 hours (Fig. 2). The corrosion rate was determined from the weight loss of the specimens.

Fig. 2. Corrosion test in climate test chamber

The vcorrosion is the corrosion rate of the specimens was calculated by equation (1) [29]

$$v_{corrosion} = \frac{\Delta m}{A \cdot t}, \left[\frac{\text{g}}{\text{m}^2 \cdot \text{h}}\right] \tag{1}$$

where:

Δm – weight loss resulting from corrosion (g),

A – contact surface area of the specimen in the solution (m^2),

t – immersion time (h).

2.5. Wear test

To test the wear behaviour of the specimens, we used a modified ball cratering method tester which one developed at Óbuda University, Bánki Donát Faculty of Mechanical and Safety Engineering Department (Fig. 3). All the samples and the testing ball were cleaned with ethanol and dried with compressed air before testing. The wear coefficients are determined from the volume mass loss as a function of the length of the wear and the normal load.

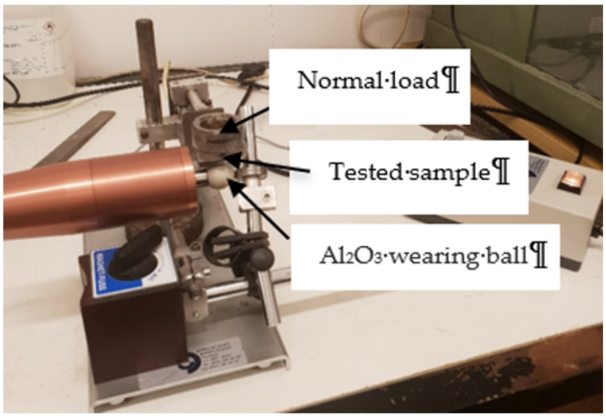


Fig. 3. Ball cratering wear resistance tester

The tests were performed at room temperature with a Al_2O_3 wearing ball ($R = 10$ mm) with an $n = 570$ rot/min rotation speed. The diameters of the worn craters were measured by an optical microscope and used to evaluate the wear coefficient. The wear coefficient (K) was used to determine the wear resistance, calculated from the volume mass loss (Vv), the sliding distance (S) and the normal load (N), by the following equation (2) [30,31].

$$K = \frac{V_v}{S \cdot N}, \left[\frac{\text{mm}^3}{\text{Nm}}\right] \tag{2}$$

Where:

K – wear coefficient (mm^3/Nm),

Vv – the volume of the wear crater (mm^3),

S – length of the wear (m),

N – normal load (N).

The wear volume can be calculated from the diameter of the wear crater d (mm) and the depth of the crater h (mm) (3).

$$K = \frac{V_v}{S \cdot N}, \left[\frac{\text{mm}^3}{\text{Nm}}\right] \tag{3}$$

The depth of the wear crater can be calculated from the radius R (mm) of the abrasive ball and the diameter of the wear crater d (mm) by a simple relationship (4).

$$h = R - \sqrt{R^2 - \left(\frac{d}{2}\right)^2}, [\text{mm}] \tag{4}$$

The wear length (S) is calculated from the wear time (t), the rotation number of the abrasive ball, the radius of the ball and the number of revolutions (n) (5).

$$S = n \cdot 2 \cdot \pi \cdot R \cdot t, [\text{m}] \tag{5}$$

In order to be accordingly with the literature [30,31], the speed was 570 rot/min, the abrasion time lasted 5 minutes.

3. Results and discussion

Even though the hardness of the samples was similar (Fig. 4), their wear coefficient was different (Fig. 5).

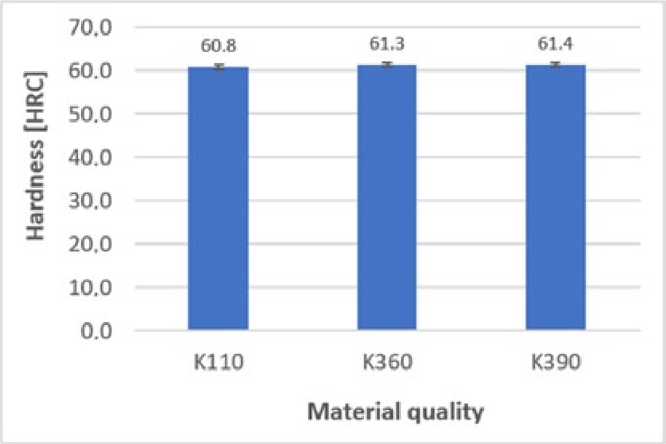


Fig. 4. Sample hardness after heat treatment

The wear resistance can be determined with the wear coefficient which one calculated from the loss volume. The mass loss-based method is suitable for comparative wear resistance testing. Fig. 5 shows the results of the comparative wear test when the highest wear resistance is characterized by the smallest wear coefficient.

For microscopic examination the specimens were prepared with Ecopress 52 Metcon automatic mounting press and grinding, polishing with Forcipol 102 Metcon machine followed with etching by 5% Nital solution using Ethanol Anhydrous.

An optical microscope type Olympus DSX 1000 was used for the microstructure examination.

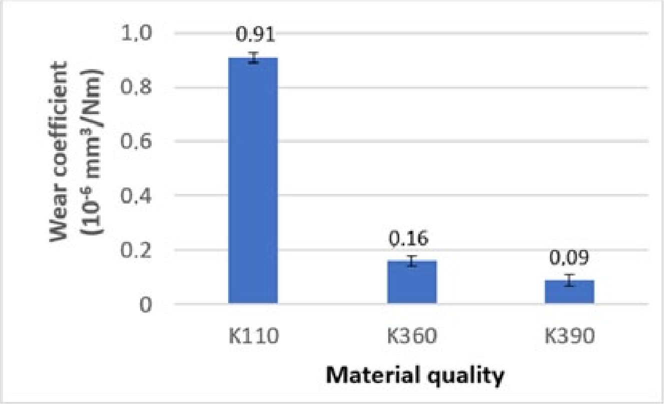


Fig. 5. The wear coefficient of the specimens

Generally, the wear resistance is related to the microstructure. The microstructure of the test specimens in accordance with the metallurgical processes shows a difference. In the case of the polished and Nital etched tool steel specimens, the carbides are unetched and are seen as white colour. Grain boundaries are etched and appear black.

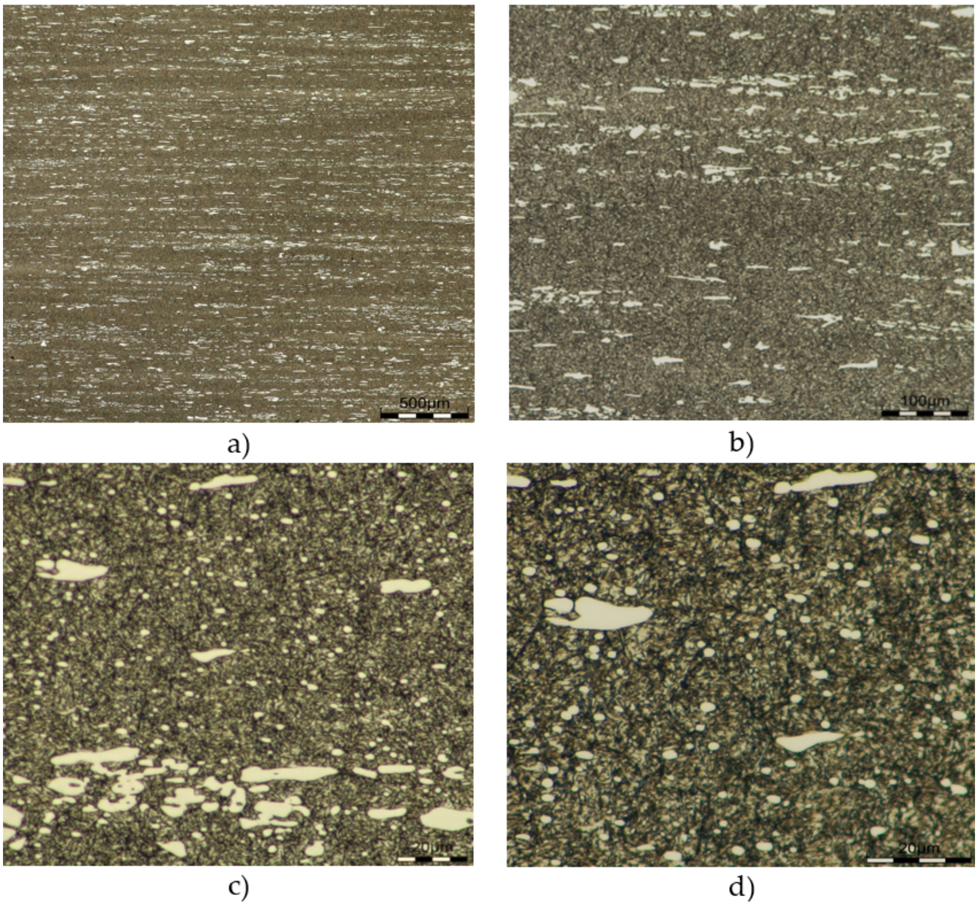
The conventional produced K110 sample presents well distributed fragmented carbides in bands (Figs. 6a, 6b) in the longitudinal section. In the quenched and tempered martensitic matrix specimen microstructure, it can be observed the primary coarse chromium carbides. The bands containing carbides are of eutectic origin. The average size of primary carbides is 5-50 μm × 3-5 μm. The secondary carbide (SC) structures could be studied by high-resolution magnification (Fig. 6c, d). The sizes of rounded SC are about 1μm. The average grain sizes of the K110 sample are about 15 μm.

The microstructure of the K340 test sample is presented in Fig. 7. The primary carbide (PC) sizes are smaller than in the case of the K110 test sample. The distribution of primary carbides was homogenous, and no bands were observed (Fig. 7). The average grain size of the K340 sample is 12 μm.

The specimen microstructure made by the power metallurgy was very fine and homogeneous. In the case of high magnification, the carbide morphology is detectable by optical microscopy. The grain sizes are smaller than 5 μm. The grain structure and sizes can seen in the SEM images of the Charpy specimens' fracture surface (Fig. 11). The carbides could be distinguished (Fig. 8) using high resolution. The rounded carbide average diameters are 1-2 μm.

Between the tested steels the uniform fine microstructured Böhler K390 steel presented the best wear resistance. The worst result of wear resistance among the tested specimens showed at the conventional produced Böhler K110 steel, which included the largest quantity of primary carbides.

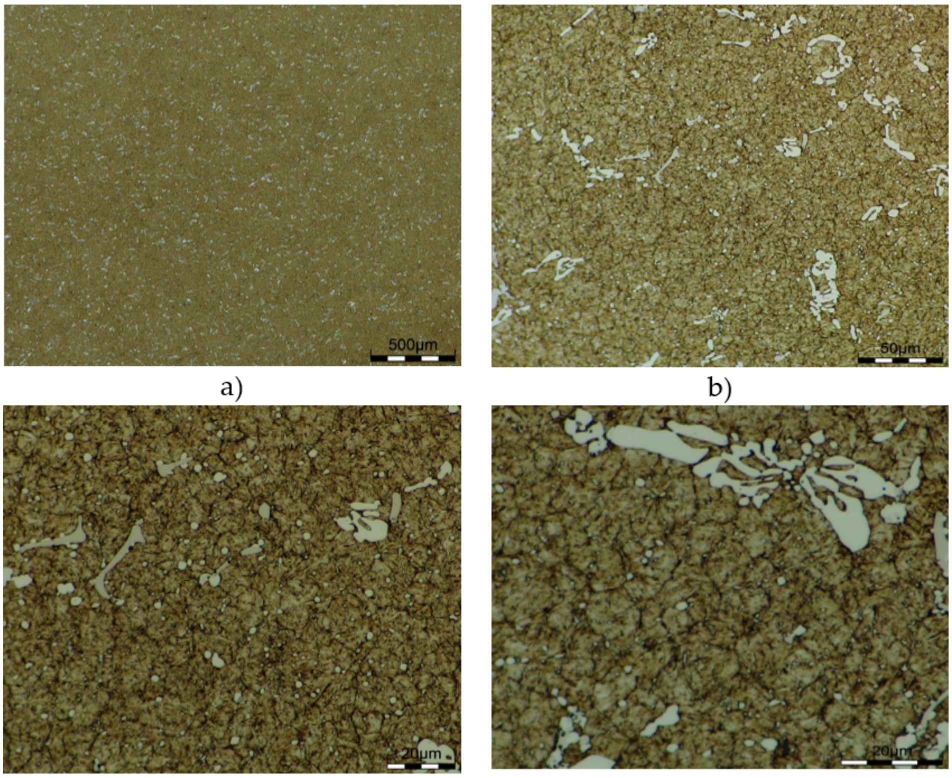
Based on the corrosion weight loss test results (Fig. 9) it can be concluded that the corrosion resistance of conventional produced Böhler K110 steel is the best, followed by the powder



a) b)

c) d)

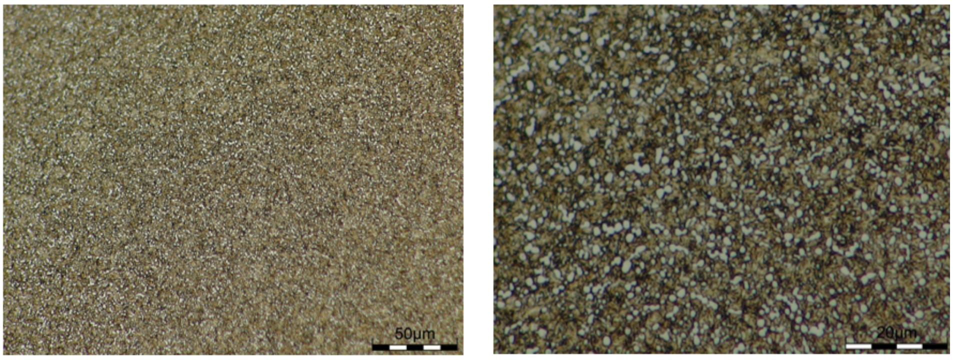
Fig. 6. Microstructure of the heat–treated, conventional produced K110 steel: a) Norig = 100×, b) Norig = 500×, c) Norig = 2000×, d) Norig = 3000×



a) b)

c) d)

Fig. 7. Microstructure of the heat-treated, ESM technology produced K360 steel: a) Norig = 100×, b) Norig = 1000×, c) Norig = 2000×, d) Norig = 3000×



a) b)

Fig. 8. Microstructure of the heat-treated, produced by powder metallurgy K390 steel: a) Norig = 1000×, d) Norig = 3000×

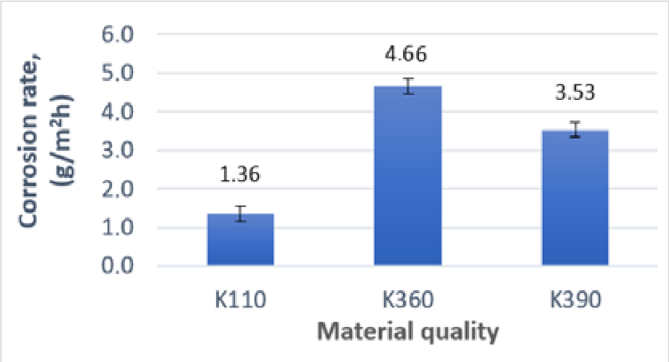


Fig. 9. The corrosion rate of the tested specimens

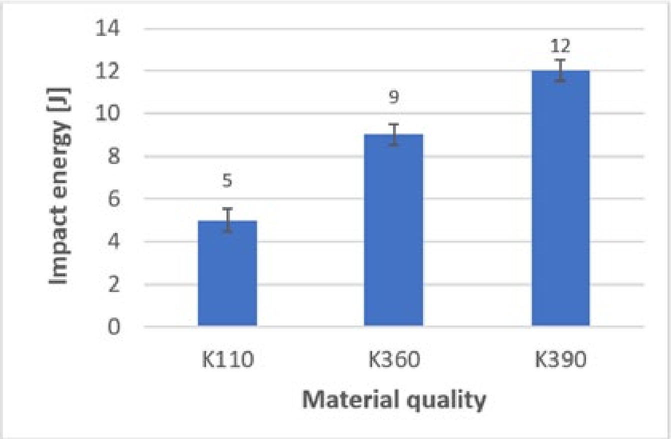
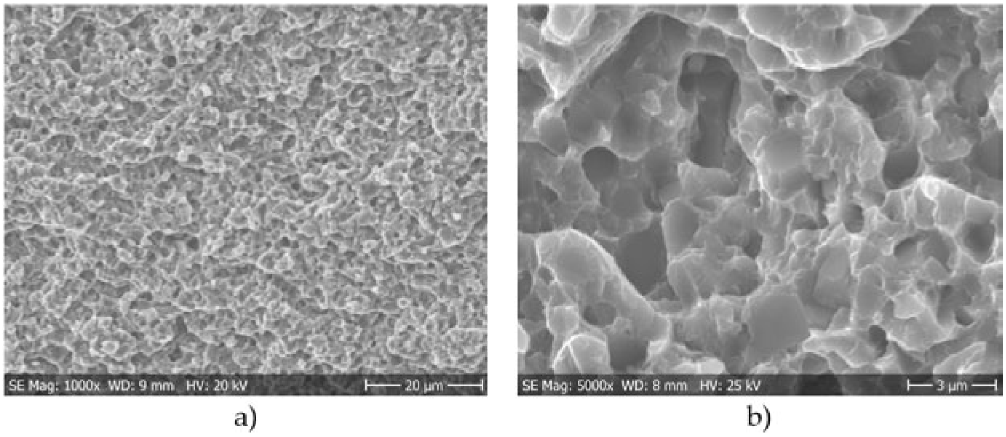


Fig. 10. The average impact energy of the specimens (J)

metallurgy produced Böhler K390 material. The electroslag remelted Böhler K360 ESR steel specimen presented the worst corrosion resistance in acid acetic.

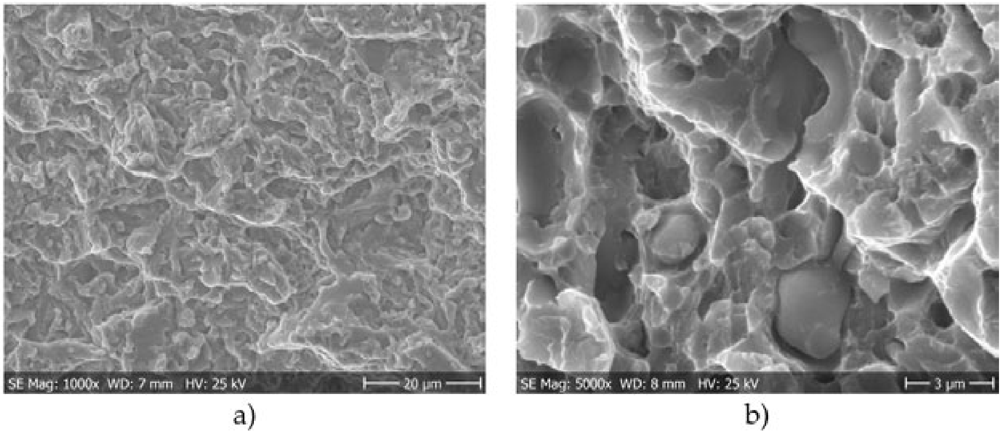
Impact energy values of tested cold work tool steels (Fig. 10) show significant differences between them. The Charpy Impact test result shows that the best toughness is the K390 steel specimens which have been manufactured with a powder metallurgy process. This steel specimen has a homogeneous clean structure with a small dispersed carbide distribution. The most rigid comportment is presented by the K110 steel. Studying the fracture surfaces with a scanning electron microscope observed fine structure in the case of the powder metallurgy-produced K390 steel (Fig. 11). Scanning electron microscopy of the fractured surfaces found that the K360 steel test sample shows a slightly coarser grain structure than the K390 steel (Figs. 11, 12).

It can be seen in Fig. 13, that the fracture surface of the K110 steel was partially formed on the surface of the massive carbides.



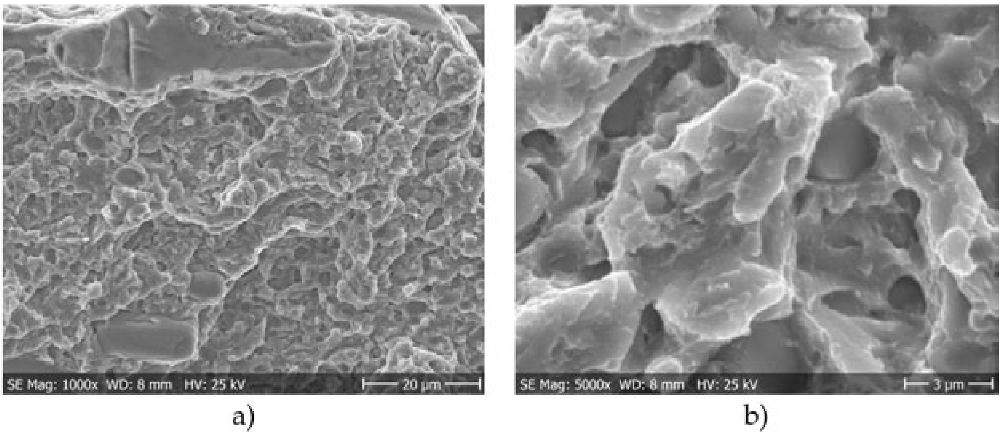
a) b)

Fig. 11. SEM micrograph of the fractured surface at the K390 specimen a) Norig = 1000×, b) Norig = 5000×



a) b)

Fig. 12. SEM micrograph of the fractured surface at the K360 specimen a) Norig = 1000×, b) Norig = 5000×



a) b)

Fig. 13. SEM micrograph of the fractured surface of the K110 steel specimen a) Norig = 1000×, b) Norig = 5000×

4. Conclusions

In this research, it was examined the properties of three grades of cold work tool steels manufactured by different technological processes, but heat treated to the same hardness. The tested Böhler K390 steel is made by powder metallurgy process, Böhler K360 steel is made by the electro-slag remelting process and Böhler K110 steel is made by conventional metallurgical process. The tests focused on the wear resistance, corrosion resistance and toughness results.

Based on the test results it was found that the metallurgical process technology of cold work tool steels significantly influences the properties of the tool steel [32-36]. The fine-grained, homogeneous structured powder metallurgical produced K390 PM tool steel has the best abrasive wear property and fairly good toughness followed by K360 ESR steel. Based on the corrosion weight loss test the conventional K110 steel proved to be the best, followed by K390 PM steel. The less corrosion resistance presented by the K360 steel is due to less chromium content and the inhomogeneous distribution of fine primary carbides. The Charpy impact test showed that among the tested steels, the K390 PM steel had the highest toughness, followed by the K360 ESR steel. K110 steel had the lowest toughness due to the presence of massive primary carbides in the microstructure. It can be concluded that even though the hardness and several properties have a good correlation, the wear resistance, corrosion behavior and mechanical properties can't be guaranteed by the hardness.

Acknowledgments

The authors would like to express their gratitude to Titan 94 Ltd. for the technical support.

REFERENCES

[1] G. Roberts, G. Krauss, R. Kennedy, Tool Steels, 5th edition, Materials Park, OH ASM International pp.7-28, 1998,

[2] Global Metal Forming Machine Tools Market 2016-2020, December 2015. http://www.researchhandmarkets.com/reports/3534920/global-metal-frming-machine-tools-market-2016 (accessed on 20 October 2023).

[3] L. Bourithis, G.D. Papadimitriou, J. Sideris, Comparison of wear properties of tool steels AISI D2 and O1 with the same hardness. Tribology International **39**, 479-489 (2006).

[4] P. Jovicevic-Klug, L. Tóth, B. Podgornic, Comparison of K340 Steel Microstructure and Mechanical Properties using Shallow and Deep Cryogenic Treatment. Coatings **12**, 1296 (2022). DOI: https://doi.org/10.3390/coatings12091296

[5] M. Algarni, Mechanical Properties and Microstructure Characterization of AISI ”D2” and ”O1” Cold Work Tool Steels. Metals **9**, 1169 (2019). DOI: https://doi.org/10.3390/met9111169

[6] F. Kara, Y. Kücük, O.Özbek, A.N.Özbek, S.M. Gök, E. Altas, I. Uygur, Effect of cryogenic treatment on wear behaviour of Sleipner cold work tool steel. Tribology International **180**, 108301 (2023).

[7] S. Eksi, Effect of Different Heat Treatment on Mechanical Properties of AISI Steels. Sakarya University Journal of Science **24** (3), 472-491 (2020).

[8] L. Tóth, E.R. Fábián, The Effects of Quenching and Tempering Treatment ont he Hardness and Microstructures of a Cold Work Steel. International Journal of Engineering and Management Sciences (IJEMS) **4**, 1 (2019).
DOI: https://doi.org/10.21791/IJMS.2019.1.36.

[9] S. Brajcinovic, A. Begic Hadzipasic, L. Slocar Benic, Influence of Medium on Corrosion and Microstructural Properties of K110 Tool Steel for Cold Work. Metal, (2020).
DOI: https://doi.org/10.37904/metal2020.3558

[10] A. Thakur, S. Kaya, A. Kumar, Recent Trends in the Characterization and Application Progress of Nano-Modified Coatings in Corrosion Mitigation of Metals and Alloys. Appl. Sci. **13**, 730 (2023). DOI: https://doi.org/10.3390/app13020730

[11] M.M. Alemnezhad, A. Ghaffarinejad, F. Omidali, White turnip bark extract as a new green and cost-effective corrosion bioinhibitor for carbon steel in 1.0 M HCl solution: experimental and theoretical studies, Chemical Physics Letters **831**, 140855 (2023). DOI: https://doi.org/10.1016/j.cplett.2023.140855

[12] N. Nnaji, P. Sen, I.Y.Openda, A. Berisha, O. Dagdag, E.E. Ebenso, T. Nyokong, Assessing the potentials of free base and gallium metalated tertbutylphthalocyanines as aluminium corrosion inhibitors, International Journal of Electrochemical Science **18**, 12, 100345 (2023).
DOI: https://doi.org/10.1016/j.ijoes.2023.100345

[13] L. Tóth, Examination of the Properties and Structure of Tool Steel EN 1.2379 Due to Different Heat Treatments. European Journal of Materials Science and Engineering **3**, 3, 165-170 (2018). www.ejmse.tuiasi.ro

[14] Voestalpine Böhler Edelstahl GmbH&Co KG, Böhler K110 Datenblatt, 2023. bohler-edelstahl.com/de/products/k110/ (accessed on 20 September 2023).

[15] Hariningsih, H.; Lutiyatmi, L.; Daryanto, T. Effects of heat treatment on microstructure and hardness of D2 tools. Applied Research and Smart Technology **3** (1), (2022).

[16] Voestalpine Böhler Edelstahl GmbH&Co KG, Böhler K360 Datenblatt, 2023, bohler-edelstahl.com/de/products/k360/ (accessed on 20 September 2023).

[17] R. Pierer, R., Schneider, H. Hiebler, The Behaviour of Two New Tool Steels Regarding Dimensional Change, Proc. of the 6th International Tooling Conference, Karlstad, Sweden (2002).

[18] Voestalpine Böhler Edelstahl GmbH&Co KG, Böhler K390 MICROCLEAN (PM) Datenblatt, 2023, bohler-edelstahl.com/de/products/k390/ (accessed on 20 September 2023).

[19] K. Surekha, A. Els-Botes, Effect of Cryotreatment on Tool Wear Behaviour of Bohler K390 and AISI H13 Tool Steel During Friction Stir Welding of Copper. Trans Indian Institute of Metals, (2012). DOI: https://doi.org/10.1007/s1266-012-0127-8

[20] Y. Zhao, S. He, L. Li, Application of Hot Isostatic Pressing in Nickel-Based Single Crystal Superalloys. Crystals **12** (6), 805 (2022). DOI: https://doi.org/10.3390/cryst12060805

[21] E.R. Fábián, L.Tóth, Cs. Huszák, Examination of Heat Treatment Effect on Properties and Behaviour of Tool Steel. Műszaki Tudományos Közlemények (2019). ISSN: 2393-1280; 2668-1390.

[22] B. Arh, B. Podgornik, J. Burja, Electroslag remelting: A process overview. Materials and Technology **50**, 6, 971-979 (2016). ISSN 1580-2949.

[23] A. Pribulova, P. Futás, M. Bartosova, Cleanless and Mechanical Properties of Steel after Remelting under Different Slags by ESR. Key Engineering Materials **635**, 112-117 (2014).

[24] H. Halfa, A.M. Reda, Electroslag Remelting of High Technological Steels. Journal of Minerals and Materials Characterization and Engineering **3**, 444-457 (2015). DOI: http://dx.doi.org/10.4236/jmmce.2015.36047

[25] N.F. Yakovlev, Yu. M. Skrynchenko, S.I. Tishaev, L.D. Moshkevich, A.N. Prohorov, Yu.M. Politaev, Electroslag Remelting for The Production of Tool Steels. Electroslag Technology, (1991). DOI: https://doi.org/10.1007/978-1-4612-3018-2_7

[26] A. Fölzer, C. Tornberg, Advantages in processing technology for powder-metallurgical tool steels and high-speed steels giving excellent cleanliness and homogeneity. Materials Science Forum **426-432**, 4167-4172 (2003). DOI: https://doi.org/10.4028/www.scientific.net/MSF.426-432.4167

[27] C. Tornberg, A. Fölzer, New optimised manufacturing route for PM tool steels and High-Speed Steels. 6th International Tooling Conference: The Use of Tool Steels, Karlstadt, Sweden. 2002 Sept.

[28] Böhler Edelstahl GmbH&Co KG, High Performance Steels Produced by Powder Metallurgy Methods MICROCLEAN 3rd Generation, ST035 DE- 08.2014-1.000CD, www.bohler-edelstahl.com (accessed on 20 September 2023).

[29] G. Körösi, L. Tóth, P. Pinke, Investigations to increase the PVC granulating tool life. Proceedings of the Engineering Symposium at Bánki, (2022).

[30] T. Kovács, L. Dévényi, Wear test procedures developments. Anyagok világa **5/1**, (2004).

[31] S. Kumar, M. Nagaraj, N.K. Khedkar, A. Bongale, Influence of deep cryogenic treatment on dry sliding wear behaviour of AISI D3 die steel, Materials Research Express **5**, 11, 116525, 1-9 (2018). DOI: https://doi.org/10.1088/2053-1591/aadeba

[32] J. Xiong, H. Li, L. Kong, X.Zhang, W. Cao, Y. Wang, Dependence of Charpy Impact Prop-erties of Fe-30Mn-0,05C Steel on Microstructure. Crytals **13** (2), 353 (2023). DOI: https://doi.org/10.3390/cryst13020353

[33] Y. Liu, Q. Ding, X. Wei, Y. Zhang, Z. Zhang, H. Bei, The Microstructure and Mechanical Proper-ties of Welded Ni-Based Hostalloy X Superalloy. Crytals **12**, 1336 (2022). DOI: https://doi.org/10.3390/cryst12101336

[34] J. Chen, Y. Liu, Y. Wang, R. Xu, Q. Shi, J. Chen, Y. Wu, Design and Optimization of Heat Treatment Process Param-eters for High-Molybdenum- Vanadium High-speed Steel for Rolls. Materials **16**, 7103 (2023). DOI: https://doi.org/10.3390/ma16227103

[35] M.G. Minciuna, D.C. Achitei, P. Vizureanu, M. Benchea, A.V. Sandu, The Effect of Heat Treatment and Corrosion Behavior of AISI420, IOP Conference Series: Materials Science and Engineering **374**, 1, 012039 (2018).

[36] M.G. Minciuna, P.Vizureanu, C. Hanganu, D.C. Achitei, D.C. Popescu, S. Focsaneanu, The structural characterization of some biomaterials, type AISI 310, used in medicine. IOP Conference Series: Materials Science and Engineering **133**, 1, 012019 (2016).