www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES
of
FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 21
Issue 2/2021

35 – 40

10.24425/afe.2021.136095

5/2

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Arc welding renovation of permanent steel molds

J. Šutka *, R. Koňar, J. Moravec, L. Petričko
Department of Technological Engineering, University of Zilina,
Univerzitna 1, 010 26 Zilina, Slovakia
* Corresponding author. E-mail address: jozef.sutka@fstroj.uniza.sk

Received 29.10.2020; accepted in revised form 15.02.2021

Abstract

The paper deals with the possibility of the renovation of permanent steel molds for casting using electric arc welding technology. When casting liquid metal into permanent steel molds, there is chemical-thermo-mechanical wear of the surface of the mold cavity and the inlet system, which causes a deterioration of the surface quality and dimensional accuracy of the casting. For this reason, it is necessary to renovate the steel mold after a certain casting interval - mold life. In this case, the technology of manual electric arc welding with a coated electrode was used for the renovation. The welding renovation aims to increase the service life of the mold using carbide hardfacing welds, which after welding achieve high mechanical properties of the renovated mold parts. Two types of hardfacing coated electrodes were used for welding, namely the OK Weartrode 55HD electrode and the OK Weartrode 50T electrode. Macroscopic analysis, tribological tests as well as the measurement of the hardness of the welded layers were performed to evaluate the quality and the friction coefficients of the additional materials used. The properties of hardfacing welds were compared with the properties of the basic material of the high-alloy steel mold. The main advantage is in addition to increasing the durability and longevity of the mold, also reducing the cost of mold renovation compared to other renovation technologies.

Keywords: Casting mold, Renovation, Welding, Hardfacing, Tribological test

1. Introduction

Current topics of technical-scientific research today are the maximum economic efficiency of the use of materials and machine parts in the field of mechanical engineering. Due to the lack of raw materials on world markets and their increasingly difficult and costly extraction, the effort is to increase the life of engineering products and thus achieve savings in materials, raw materials, and energy. The most common causes of failures of machine parts and structures are tribological processes, which take place on functional surfaces. Therefore, the tribological characteristics of the materials used are of great importance for the correct function of machine parts and structural units. The interaction of functional surfaces during their relative movement causes undesirable changes in the surface layers leading to their wear [1, 2].

The interaction of functional surfaces can also be observed in the area of casting. It is primarily a form-liquid metal interaction. The interaction of the mold and the liquid metal wears the surface of the mold. Wear of functional surfaces causes a reduction in the quality and dimensional accuracy of the castings produced. The number of pieces that can be produced with the required accuracy and quality in a mold is called the life of the mold. The service life of the mold is directly affected by the required accuracy and quality of casting production. At present, even in the field of the service life of casting molds, it is mainly a question of the economic efficiency of production. The increasing share of increasingly complex equipment in production brings demands for complexity and thus the cost of the mold. In particular, long service life and reliability are required from a mold whose production has been economically demanding. The term service life is understood in the technical sense as a period during which the device can perform the required function in a specified quality. For a long time, the aim is not only to prolong the periods between the necessary repairs but also to ensure that the active parts of the mold show high reliability and accuracy in the production during all the time. The reliability of the form can be assessed according to the reliability factor K_S [1, 3].

$$K_s = \frac{T_s - \sum_1^n t_1}{T_s}\ [-] \tag{1}$$

where,

$T_S\ [s]$ - time between necessary exchanges of parts, resp. repairs or modifications (hours);

$t_1\ [s]$ - time of individual downtime required to perform the exchange, adjustments (hours) [3].

The mold and mold cores for casting must have suitable physical and mechanical properties not only at ambient temperature but especially at elevated temperatures. These properties are defined by thermal and mechanical stress and interaction at the mold-melt interface. In particular, high rates of turbulent to the dispersive filling of the mold cavity with the melt, high hydrodynamic pressures generated by the melt on the mold part, and relatively high temperatures on the surface of the mold parts can significantly shorten the life of molds and cores. All these phenomena cause degradation of the surface of the molded parts by the mechanisms of erosion, abrasion, corrosion, and thermal fatigue of the mold, each of which acts simultaneously. Because the molds operate at high temperatures, they are made of complex alloy steels, the main alloying elements of which are Cr, V, Mo or W, or a combination thereof. Materials for the production of molds must meet the properties resulting from the in-service stress of die casting molds [3, 4].

Hot work alloy steels require high deformation resistance, abrasion resistance, erosion resistance, and thermal fatigue resistance. Steels contain 0.28 - 0.60% C. Furthermore, Cr up to 5.50%, Mo up to 3.00%, and V up to 1.10% are alloyed [4].

Chromium-nickel steels contain about 1.00% Cr and up to 0.12% V. They are used for dies and molds (55NiGrMoV6 and 56NiGrMoV7). The steels are hardened from 850° C in oil or air. Both chromium steels alloyed with V (up to 1.00%) in combination with Mo (up to 2.00%) are used. The C content is about 0.25%. These types of steels are not very sensitive to hot cracking [4].

A detailed analysis of the wear of various types of molds and dies for casting was performed by Jhavar. He identified abrasive and adhesive wear, erosion, and mechanical and thermal fatigue as the main mechanisms of mold damage. Jhavar identified the factors that affect wear. These are the working temperature, atmosphere, contact surface, mold load, material properties, surface treatment, filling speed, shape, vibrations. In gravity casting molds, abrasive wear can occur due to insufficient cleaning of the mold between casting cycles in the area of the shaped surfaces between the mold parts. During this process, solidified cast metal particles can act as abrasive particles [5,6].

In practice, different types of wear occur in combination with each other, which interact with each other and contribute to the resulting complex wear. The prevailing wear mechanism may vary at different stages of mold life. However, the resulting wear will also be affected by the solubility of the molding material in the melt. The dissolution of the molding material in the melt can be prevented by applying thin coatings to the functional surface of the mold using PVD (physical vapor deposition) or PE-CVD (plasma-enhanced chemical vapor deposition) technology. However, during operation, these coatings can also be locally damaged and worn.

According to Chander, the cost of producing molds can represent up to 30% of the total cost of production of a product. According to Chen, up to 80% of molds for automotive components have been renovated. For this reason, the topic of finding suitable ways of repairing and renovating molds is very topical. One of the possibilities is the use of arc welding technology using the technology of manual welding with a coated electrode [6, 7, 8, 9].

The experimental part of the article aims to verify the suitability of the use of coated electrodes OK Weartode 55 HD and OK Weartrode 50T for the renovation of the cavity of a steel mold for gravity casting. The evaluation will be carried out based on a comparison of wear resistance and hardness to the base material of the mold.

2. Experiment methodology

Low-carbon steel S355JR with dimensions of 200×35 ×15 mm was used as a substrate for making comparative welds. It is structural carbon steel with usual properties with 0.22% C and guaranteed weldability. The welds were performed by method 111 according to STN EN ISO 4063 (MMA - Manual Metal Arc Welding). This method is especially suitable for the renovation of smaller worn areas. OK Weartrode50T (designation No. OK50T) and OK Weartode 55 HD (designation No. OK55HD) hardfacing electrodes were used in the weld formation experiment. To ensure pure weld metal without mixing with the substrate, the welds were made as two layers. The finished weld contains two layers. Every layer was made of 6 welds.

The Weartode OK 55HD electrode is a coated basic electrode that creates a martensitic deposit resistant to wear, shock, and corrosion. The producers recommended preheating temperature is from ambient temperature to 200° C, depending on the strength of the welded part. The hardness of the weld is achieved already during the welding of the first layer, regardless of the cooling rate. It is used for welding working parts of highly stressed machine parts. The weld is not heat treated. Welding is possible by machining and grinding.

The Weartrode OK 50T electrode is a rutile-basic coated electrode. It creates a martensitic deposit resistant to wear and shock up to a temperature of 400° C. The producers recommended preheating temperature is from ambient temperature to 200° C, depending on the thickness of the welded part. It is used for welding functional parts of high-stress parts operating at elevated temperatures. Welding is possible by machining and grinding.

The chemical composition and hardness of welding electrodes from technical sheets are given in Table 1.

Table 1.
Chemical composition and hardness of hardfacing welds

Marking of hardfacing	Chemical composition (wt.%)					Hardness [HV1]
	C	Mn	Si	Cr	Mo	
OK55 HD	0.67	0.70	0.70	10.40	0.10	543 - 675
OK50 T	0.20	0.60	0.30	13.00	-	513 - 543

The chemical composition and hardness of the mold are given in Table 2. It is a high-alloy chrome tool steel with the designation X210Cr12 according to STN EN ISO 4957. The steel is characterized by very good hardenability in oil but also in the air, has very good wear resistance with both metallic and mineral substances, has high strength in such. This steel shows good dimensional stability during heat treatment, but this steel is sensitive to rapid and uneven heating. The variance of X210Cr12 hardness is so different (576 - 775 HV1), because it depends on the type and time of heat treatment.

Table 2.
Chemical composition of the mold

Marking of steel	Chemical composition (wt.%)				Hardness [HV1]
	C	Mn	Si	Cr	
X210Cr12 (19 436)	1.90 – 2.20	0.20 – 0.60	0.10 – 0.60	11.00 – 13.00	576 - 775

The mechanical properties experimental steel S355JR a mold X210Cr12 are given in Table 3 and 4.

Table 3.
Mechanical properties of steel S355JR

Marking of steel	Yield Rp0.2 (MPa)	Tensile Rm (MPa)	Impact KV/Ku (J)	A (%)	Hardness [HV1]
S355JR	355	470	27	22	150 - 215

Table 4.
Mechanical properties of the mold

Marking of steel	Yield Rp0.2 (MPa)	Tensile Rm (MPa)	Impact KV/Ku (J)	A (%)	Hardness [HV1]
X210Cr12	154	231		56	302

The welds were made with an inverter welding power source with a DC+ welding polarity. All welding beads were made with the welding current set to $I_Z = 95.0$ A. The average value of the welding voltage during welding was $U_Z = 21.6$ V. The welds were made on the base material preheated to 200° C. The interpass temperature was also 200° C. The hardfacing weld surfaces were grinding to the roughness of Ra = 3.6 μm. No defects were present on the weld surface such as cracks, pores, lack of fusion, etc. The surface was tested by visual and penetrant inspection. Macrostructure analysis, hardness test, and a tribological test by the method „ball on flat“ was performed on the hardfacing weld. [10, 11, 12, 14].

The task of the tribological test is to determine the value of the coefficient of friction for a given material pair and other conditions under which the friction takes place. The value of the coefficient of friction can range from 0,0 to 1.0. A value of 0.0 indicates very low sliding resistance - causes low wear, a value of 1.0 indicates very high sliding frictional resistance - causes high wear. From a measurement point of view, the coefficient of friction depends on several factors such as the internal structure of the material, the contact surface pressure, the sliding speed, the temperature and humidity, the surface roughness, and the material pair [10,12, 13].

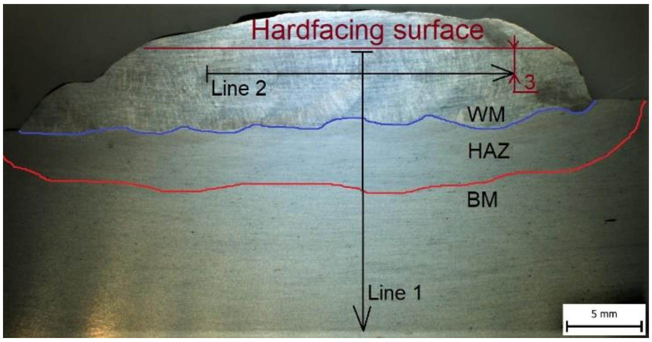

Fig. 1. Hardness measuring lines

Hardnesses were measured in two lines. The first measurement was performed in Line 1. Line 1 was oriented perpendicular to the surface of the weld in the direction of the base material. This line passed through the weld metal, HAZ (heat affected zone) into the base material, steel S355JR. Line 2 was oriented parallel to the sample surface and passed through the second weld layer. The measurement lines are shown in Figure 1. The hardness of the mold and hardfacing was determined by the Vickers hardness test (HV1). The hardness results of the welds are shown in Figures 5 and 6.

The coefficient of dry friction of the mold and hardfacing welds was experimentally determined by the „ball-on-flat" method. Tribological pairs were hardened steel ball - mold (designated MOLD), hardened steel ball – hardfacing weld OK Weartode 50T hardener (No. OK50T), and hardened steel ball – hardfacing weld OK Weartode 55HD (No. OK55HD) were tested in this method. The ball is placed on the flat plate plane and touches its surface. The hardness of the 100Cr6 steel ball was 64 HRC with a diameter of 3 mm. The test was performed by moving the ball over the surface in a linear trajectory with a length of 50 mm. The ball was loaded with a normal force F = 1 N; 5 N; 10 N in the tribological test. The ball-on-flat tribology test was performed at a temperature of 20° C, the sample speed was $0.017 m.s^{-1}$ and the test duration was 5000 s for all 3 types of load. The result of the tribological test is the coefficient of friction for a particular material pair and test conditions. Loads 1; 5 and 10 N were chosen for comparison at lower contact pressures of 1; 5 N and for comparison at higher contact pressures of 10 N. If it is converted to Hertz pressures, even at a load of 1.5 N, these are very high pressures. However, no calculated application pressures were used. [10,12, 13].

3. Results and discussion

From individual samples, are created images of macrostructures after hard welding to the substrate Also were created samples of each sample for mechanical properties (hardness) and tribological properties (coefficient of friction).

3.1.The macrostructure of the welds.

The macrostructure of the welds is shown in Figures 2 and 3.

Fig. 2 Welding macrostructure OK 50 T

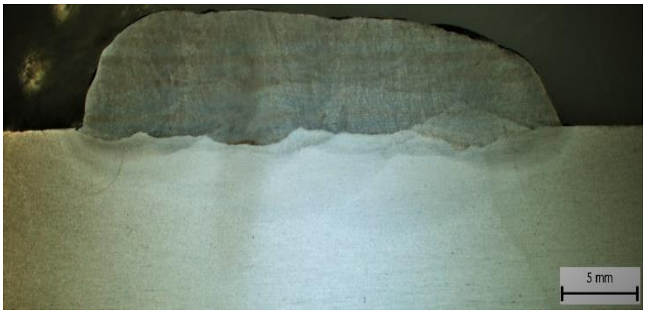

Fig. 3 Welding macrostructure OK 55 T

Unacceptable defects such as cracks, cavities, non-welds, etc. did not occur in the macrostructures of the welds.

3.2.Hardness

Figure 4 shows the results of measuring the hardness on the surface of the mold and hardfacing.

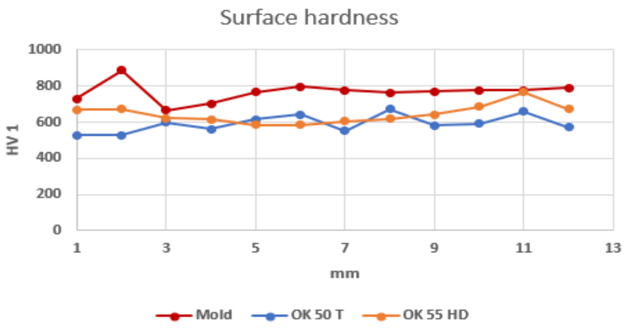

Fig. 4. Surface hardness

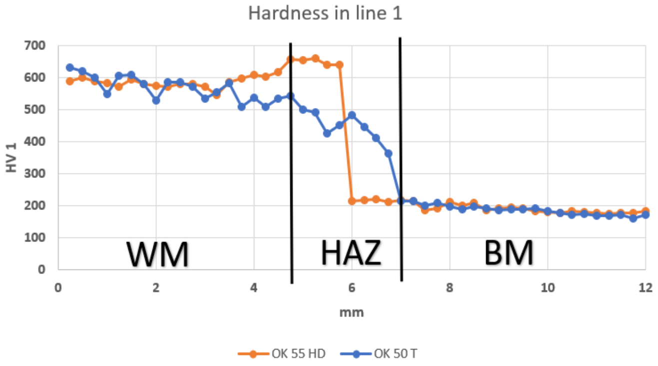

Fig. 5. Hardness profile

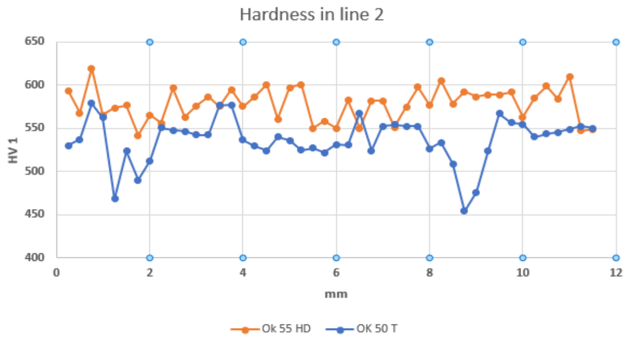

Fig. 6. Hardness in the second layer of hardfacing

The course of hardnesses in the direction of Line 1 for both hard welds is shown in Figure 6. The hardness was measured in the direction from the weld through the HAZ to the base material. It is possible to observe a lower hardness of the first layer in comparison with the second layer of the hardfacing No. OK50T. This is mainly due to the tempering of the first layer during the welding of the second, but also by mixing the filler material with the substrate. The decreasing tendency of hardness smoothly passes into the area of the base material, where the hardness of the material corresponds to the structure of the substrate with ferritic-pearlitic structure.

The hardness of the first layer of hardfacing No. OK55HD is approximately 200 HV1 higher than the hardfacing OK50T. This is due to the chemical composition of the material and the effect of subsequent heating during welding of the second layer, which caused the first layer of the weld to harden. However, on the course of the hardness of the hard weld No. OK55HD, a decrease of the hardness by 400 HV1 in the area of the construction boundary can be seen. This hardness difference was caused by the first weld layer hardening and at the same time, the substrate tempering by the heat supplied to the sample during the second layer welding. During the hardness of hardfacing No. OK55HD, a continuous decrease in hardness in HAZ is not observed, as in the case of hardfacing No. OK50T, although the HAZ is visible on the macrostructure.

The measured hardnesses in Line 2 for both hardfacing welds are shown in Figure 6. The hardness values course is smooth for both welds and no significant difference in hardness is observed for individual weld beads of the second layer. The course of hardness is smooth for both hard welds and no significant differences in hardness were observed for both layers. Average hardness value in Line 2 for hardfacing No. OK55HD is 530 HV1 and hardfacing No. OK50T is 578 HV1. The hardnesses correspond to the hardness values from the material sheet of the additional materials.

3.3.Tribological test - „Ball-on-flat“

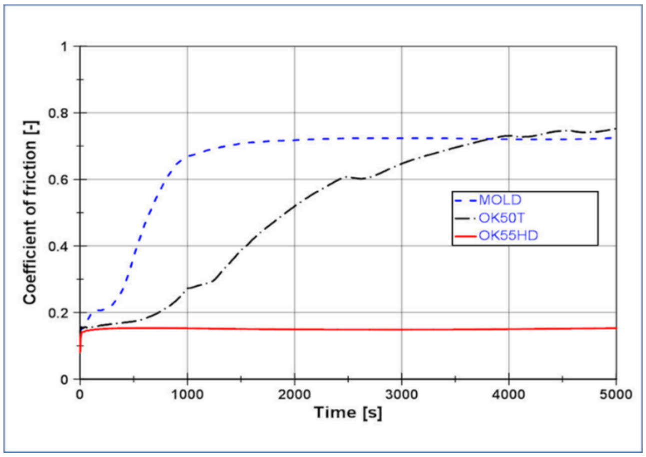

Fig. 7. Comparison of dry friction coefficient under load F = 1 N

The time friction coefficient values course under the load 1 N is shown in Figure 7. A slight increase in friction coefficients was observed in the time interval from 0 to 50 s. The value of the mold material friction coefficient reached 0.735 at the time of 2000 s. After this time, the value of the friction coefficient was stabilized at 0.745. The friction coefficient hardfacing weld No. OK50T under 1N load has been constantly increasing since the beginning of the test. The value of the friction coefficient was 0.768 et the end of the test. Hardfacing weld No. OK55HD after a slight increase at the beginning of the test was stabilized at a constant friction coefficient value of 0.179. The hardfacing weld No. OK55HD achieved the best results in terms of wear under load 1 N.

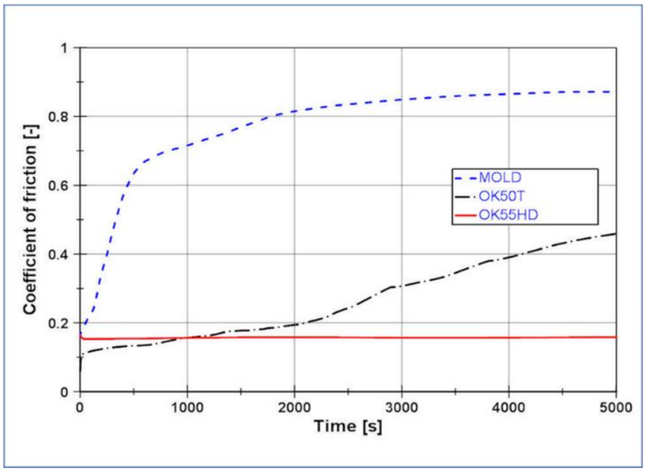

Fig. 8. Comparison of dry friction coefficient under load F = 5 N

The time friction coefficient values course under a load of 5 N is shown in Figure 8. A slight friction coefficients increase was observed in the hardfacing weld No. OK50T in the time interval from 0 to 50 s. The hardfacing weld No. OK55HD friction coefficient was a decreasing character. The friction hardfacing weld No. OK50T coefficient has the same increasing friction coefficient character as with the lower load 1 N. The friction coefficient of the hardfacing weld No. OK50T at a load of 5 N was steadily increasing character since the beginning of the test. The value of the friction coefficient was 0.447 at the end of the test. The friction coefficient of the hardfacing weld No. OK55HD at a load of 5 N slightly decreased to 0.179 at the beginning of the test and maintained a stable value during the test. The friction mold material coefficient value sharply increased in a time interval from 0 to 500 s. The value reached 0.875 at 5000 s at the end of the test. From the point of wear view, the hardfacing weld No. OK55HD achieved the best results at a load of 5N.

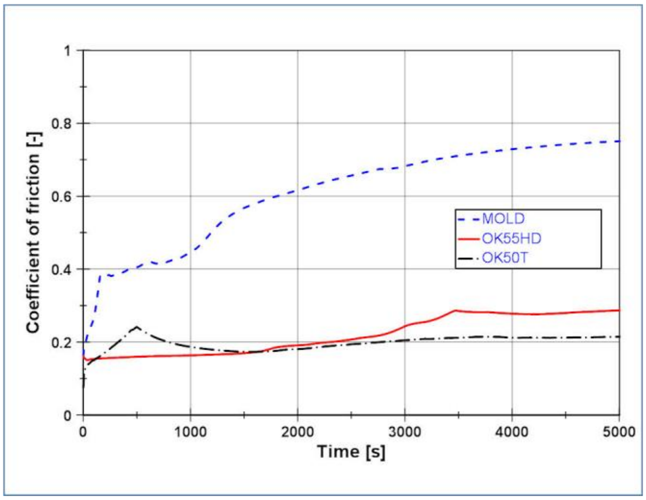

Fig. 9. Comparison of dry friction coefficient under load F = 10 N

The time friction coefficient values course under a load of 10 N is shown in Figure 9. The friction mold material coefficient value increased sharply in the time interval from 0 - 100 s and further increased non-simultaneously up to the value 0.721 in time 5000 s. The friction coefficient hardfacing weld No. OK50T under load 10 N showed the same increasing character of the friction coefficient as at a lower load (1 N and 5N). The friction hardfacing weld No. OK50T coefficient value reached at 0.232 in time 500 s. After this time, the friction coefficient value began to gradually decrease and it was stabilized at 0.201 at the end of the test. The friction hardfacing weld No. OK55HD coefficient increase from the test beginning. The maximum value reached 0.301 in 3500 s. After this time, the value of the friction coefficient was stabilized at 0.300. From the point of wear view, hardfacing weld No. OK55HD under 10 N load achieved the best results.

4. Conclusions

The paper deals with the analysis of the hardfacing welds made of selected filler materials intended for the renovation of steel molds for casting. Hardfacing coated electrodes OK Weartode 50T and OK Weartode 55 HD were used to create welds using MMA technology. These welds can be made without special welding requirements (preheating, reheating, etc.). The guaranteed hardness and properties are achieved by the welds already in the first layer. This information from the technical sheets of coated electrodes is also confirmed by the performed experiments. Experimental hardfacing welds were formed at preheating of 200° C and their average hardness reached 530 HV1 in hardfacing weld No. OK50T and 578 HV1 in hardfacing weld OK55HD. The reference material with which the properties were compared was high-alloy chrome tool steel with the designation X210Cr12. The average hardness of this mold steel was 767 HV1. Surface hardness measured on the hardfacing weld after machining was 591 HV1 in hardfacing weld No. OK50T, 645 HV1 in weld No. OK55HD. The average surface mold hardness was 766 HV1.

Differences in the values of the friction coefficients at approximately the same hardness are due to the different structure of the materials. The lowest friction coefficient was measured at hardfacing weld No. OK55HD, namely 0.179 under loads 1 N and 5 N, and 0.300 under load 10 N. The lowest friction coefficient guarantees the lowest wear of the material in operation. From this point of view, the best results were achieved by hardfacing weld No. OK55HD.

It is clear from the results of the measurement of the friction coefficients that the hardness of the material is not a decisive factor for the assessment of wear. This was seen in the differences of the measured values of the friction coefficients, where the highest value of the friction coefficient was measured for the reference material of the mold, despite the highest measured hardness. Thus, the wear resistance depends in particular on the type, distribution, and interconnection of the structural components and material precipitates

References

[1] Jankura, D., (2013). Wear evaluation of renovation layers based on hardfacing (Hodnotenie opotrebenia renovačných vrstiev na báze tvrdonávarov). *Transfer Inovácií.* 26,126-129.

[2] Moravec, J. et.al. (2018). Experimental casting of forging ingots from model material. In 22nd Slovak_Polish Scientific Conference on Machine Modelling and Simulations, 5-8 September 2017 (article No. 05017). Sklene Teplice, Slovakia: Univerzity of Zilina.

[3] Moravec, J. et.al. (2001). *Forming machines (Tvárniace stroje).* Žilina: Edis, 2011, ISBN: 978-80-554-0446-2. (in Slovak).

[4] Ptáček, Luďek et. al. (2002). *Materials science (Nauka o material II).* Brno: Akademické nakaldatelství CERM, s.r.o, ISBN: 80-7204-248-3.

[5] Jhvar, S.; Paul, C.P.; Jain, N.K. (2013). Causes of failure and repairing options for dies and molds. A review. *Engineering Failure Analysis.* 34, 519-535.

[6] Mician, M. et al. (2018). The Repair of Foundry Defects in Steel Castings Using Welding Technology. *Archives of Foundry Engineering.* 18(2), 177-180. DOI: 10.24425/ 122524.

[7] Chander, S., Chawla, V. (2017). *Failure of forging dies an update perspective*. Mater. Today Proc.,4, 1147-1157

[8] Chan, C.; Wang, Y.; Ou, H.; He, Y.; Tang, X. (2014). A review on remanufacture of dies and moulds. *Journal of Cleaner Production*. 64, 13-23.

[9] Pliszka, I. et al. (2018). Surface improvement by wc-cu electro-spark coatings with laser modification. in 10th conference on terotechnology, 18-19 October 2017 (pp. 237-242). Kielce, Poland: Kielce University of Technology.

[10] Pastircak, R., Scury, J. (2017). Effect of Pressure on Crystalization of AlSiMg Alloy. *Archives of Metallurgy and Materials.* 62 (4), 2193-2198. DOI: 10.1515/amm-2017-0323.

[11] Gucwa, M., Beczkowski, R. & Winczek, J. (2017). The effect of type of welding sequence during hardfacing chromium cast iron for erosion resistance. *Archives of Foundry Engineering.* 17(3), 51-54. DOI: 10.1515/afe-2017-0089.

[12] Brenček, J., Vicen, M., Fabian, P., Radek, N., 2020, Investigation of the tribological properties of the nitride layer on heat-treated steel 100Cr6, Lecture notes in mechanical engineering, 59th International Conference of Machine Design, 11-14 September 2018, (pp. 463-471). Žilina, Slovakia: University of Žilina.

[13] Mician, M. et al. (2020) Effect of the t(8/5) cooling time on the properties of S960MC steel in the HAZ of welded joints evaluated by thermal physical simulation. *Metals.* 10(2), 229. DOI: 10.3390/met10020229

[14] Winczek, J. et al. (2019). The Evaluation of the Wear mechanism of High-Carbon Hardfacing Layers. *Archives of Metallurgy and Materials.* 64 (3), 1111-1115. DOI: 10.24425/amm.2019.129502.