



# Article Selected Properties of Hardfacing Layers Created by PTA Technology

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Abstract: The paper presents research results on the quality of hardfacing layers made during the renovation of unheated mold surfaces designed for injection of aluminum alloys using the plasma transferred arc (PTA) technology. As mold material, the medium alloy steel X38CrMoV5-1 (H11) was used. For the formation of functional layers, three types of additives in the form of powder were applied: two types on an iron basis with the designation HSS 23 and HSS 30 and one type on a nickel basis with the designation DEW Nibasit 625-P. The hardfacing layers were made on a  $120 \times 350 \times 50$  mm plate in two layers on the plasma hardfacing machine PPC 250 R6. The quality of the layers was evaluated by means of nondestructive and destructive tests. The surface integrity of the layers was assessed using visual and capillary tests. The samples passed these tests. The impact of the parameters used and the mixing of the hardfacing metal with base material, as well as the structure analysis, were assessed by means of light and electron microscopy (SEM). The chemical composition of the elements was determined by energy-dispersive X-ray spectroscopy (EDX) analysis using a SEM microscope. The hardness of the individual layers was evaluated. Since, during operation, molds are subjected to significant wear due to friction, the friction coefficients for selected temperatures were determined by the equipment for the evaluation of tribology properties. Based on the experiments conducted, all three types of additives can be used for renovation. However, from a tribology perspective, the additive DEW Nibasit 625-P on a nickel alloy basis is recommended for renovation.

Keywords: plasma; hardfacing; hardface; layers; surface

## 1. Introduction

Properties like high hardness and wear resistance of high-speed steels (HSSs) have directed their utilization to the field of machining, hot rolling, or cold work molding. HSS is characterized by a high content of metallic elements such as W, Mo, Cr, and V [1–3]. HSSs are produced by the plastic deformation of cast ingots or semifinished products made by sintering of powders while achieving reduction to ensure that the homogenization of alloys reaches up to 98%. Intense plastic deformation disrupts the interdendritic network of eutectic carbides, leading to the increased toughness and strength of HSSs at elevated temperatures. However, plastic deformation can lead to an uneven distribution of damaged eutectic carbides, which results in the anisotropy of mechanical properties [4,5]. The larger



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/). the cross section of the forged bar, the higher the microstructural heterogeneity and the more pronounced the anisotropy of carbides, and thus the worse the toughness and strength of the steel. The large reduction required in hot plastic deformation increases the production costs of hot-formed HSSs. In addition, machining bars into the desired shape turns a large amount of expensive forged material (up to 30-50% and more) into waste [6–8].

The issue of the surface integrity of ultra-high-strength steel in the cutting process and the influence of surface integrity on the fatigue resistance of 17-4PH stainless steel after cutting has aroused the interest of researchers [9]. It has been shown that the effect of surface roughness on the fatigue process can be attenuated by curved feed marks generated on face-milled surfaces. The integrity of the resulting surface is also affected by other characteristics—the tip radius, feed, cutting speed, and depth of surface roughness—in finish hard turning of AISI 4340 [10]. The surface integrity of DSS 2304 during grinding by aluminum oxide varies with the grinding parameters [11–15]. Using a smaller grit size or lubrication during the grinding process can greatly improve surface roughness and minimize surface defects. The ground surface then exhibits residual tensile stresses in the grinding direction and residual compressive stresses perpendicular to the grinding direction [16–18]. When machining 303 steel with specific parameters and in various environments, it is shown that the lowest values of microhardness and roughness were achieved when machining in a dry environment.

X38CrMoV5-1 (H11) is a martensitic steel with a hardness in the range of 40–56 HRC, depending on the heat treatment, and it has high mechanical strength and good resistance to thermal shocks due to chromium, molybdenum, and vanadium [19]. The mechanical properties of these martensitic steels are related to the complex microstructure after heat treatment, which is usually performed to achieve good hardness and/or tensile strength with sufficient ductility. Between 550 and 600 °C, softening occurs during tempering, and precipitation is not fully complete as the carbon distribution in the various precipitates is not stable or there is still a transition from iron carbides to special carbides. Above 600  $^{\circ}$ C, further softening of the material occurs due to the coalescence of carbides and reduction in the dislocation density [20]. For high-temperature metal forming operations, such as die casting for the injection of light alloys (aluminum alloys), forging dies, etc., in particular, steels containing 5% Cr (e.g., AISI H11) have been developed [9,21–26]. These steels are used to produce molds for fixed and movable core parts and for thermoforming tools, such as small- and medium-sized dies and die inserts, mandrels, jaws, and punches, in particular those with a high strength (>1800 MPa). If it is necessary to produce safety parts that require high strength (>1300 MPa) and impact notch strength >12 J, the solution is to use tool steel for hot work, X38CrMoV5-1 [27]. It retains sufficient hardness up to a temperature of 600 °C. The yield stress during tempering and fatigue decreases due to the lower dislocation density and the coalescence of secondary carbides [28–31]. Exceeding the critical hardness value for a given application can lead to immediate tool failure. In die casting, tool life is affected more by ductility than by toughness [32,33].

Apart from arc hardfacing [34,35], plasma transferred arc, or laser coating, where the hardfacing layer differs in chemical composition from the base and filler material due to dilution, explosion cladding shows no dilution between the base metal and the cladding layer and thus allows good control of the chemical composition of the hardfacing layer. Because the hardfacing layer is deposited like a solid during explosion cladding, it is possible to join metals that are sensitive to hot cracking [36]. The compactness of the coating is 100%. Due to the high speed of the process, brittle intermetallic components are not formed at the joining interface. It is possible to join only flat sheets, tubes, or shapes with low curvature. It is not possible to plate small sheets. The minimum size is about 350 mm  $\times$  350 mm. The materials must withstand impact and show good ductility. Another disadvantage is the low productivity of the process [37].

High-pressure die casting (HPDC) is an almost pure, mesh-shape manufacturing process in which molten metal is injected into a metal mold at high speed and solidified under high pressure. The mold is filled with molten aluminum alloy at elevated temperatures, usually above 670 °C. This technology is used in the production of thin-walled aluminum components with high dimensional accuracy and high production efficiency, especially in the automotive industry. Due to the rapid fluctuations in temperature, pressure, and melting rate in die-casting molds, the molds are subjected to cyclic thermomechanical loading, which gradually leads to the wear of and damage to the molds. This paper presents the research on plasma welding on the base material X38CrMoV5-1 to extend the life of molds for the pressure casting of aluminum. For the formation of functional layers, three types of additives in the form of powder were applied: two types on an iron basis with the designation HSS 23 and HSS 30 and one type on a nickel basis with the designation DEW Nibasit 625-P. These investigations focus on the interface between the base material and the hardfacing layer. The chemical composition of the materials is presented. The macrostructure and the microstructure are studied in detail. Hardness tests at the interface are presented together with adhesion wear tests.

#### 2. Materials and Methods

Medium alloy tool steel marked X38CrMoV5-1 (W. Nr. 1.2343; HRC 50) was used as the base material to produce test hardfacing layers. It is characterized by high heat strength and resistance to tempering, as well as very good toughness and plastic properties at both normal and elevated temperatures. Furthermore, the steel shows very good resistance to thermal fatigue cracking and low sensitivity to sudden thermal shocks. It is well malleable when hot and well machinable in the soft annealed condition. The chemical composition of the base tool steel and its mechanical properties are presented in Tables 1 and 2, respectively.

Table 1. Chemical composition of the base material X38CrMoV5-1 (in wt %).

С	Mn	Si	Cr	Мо	V	Р	S	Fe
0.37	0.45	1.0	5.3	1.3	0.4	0.017	0.011	Res.

Table 2. Mechanical properties of the base material X38CrMoV5-1 by manufacturer.

Yield Strength (MPa)	Tensile Strength (MPa)	Elongation A5 (%)	Hardness (HRC)	
1420	1680	12	50	

Figure 1 shows the microstructure of the base material X38CrMoV5-1 formed by randomly oriented tempered martensite laths. The lath is about 2  $\mu$ m thick and 15  $\mu$ m long. According to Boher [38], this microstructure has a very high density of tangled dislocations and also a large amount of small carbides, which provide good strength to the steel at room and high temperatures.

As additive, the powder made of HSS 23 and HSS 30 was used, which are high-alloy high-speed steels produced using progressive methods of powder metallurgy. Both materials have high purity, low content of nonmetallic inclusions, high hardness, high compressive strength, toughness, machinability, and high resistance to abrasive wear. Both materials are used to make cold working materials, such as cutting tools for cutting harder materials. In addition, HSS 30 is also used in the production of cutting tools. The DEW Nibasit 625-P additive in powder form is used for high-quality hardfaces and hardfacing joints of materials with a high content of Mo, Ni, and Cr. Refractory and heat-resistant steels used for hardfacing are steels resistant to scale, operating at low temperatures, with heterogeneous joints, with low alloy content, and made of difficult-to-weld materials. The chemical composition of the powder filler materials used is presented in Table 3.

For hardfacing, Vanadis HSS 23, Vanadis HSS 30, and DEW Nibasit 625-P powders were used on the base material X38CrMoV5-1, and a plasma hardfacing machine (Figures 2 and 3) PPC 250 R6 (KSK s.r.o., Česká Třebová, Czech Republic). This automatic hardfacing machine is designed for the hardfacing of rotating and nonrotating parts using the PTA method. Components can be hardfaced on the forehead or around their perimeter. The machine enables pulse hardfacing with a current of 50–250 A and a frequency of 0–200 Hz. The machine

has a hardfacing part with a torch closed by a cover with a protective hardfacing glass. The machine burner is guided in four axes, X, Y, Z, and N, so that the feed is allowed in three axes with rotation of the whole system, while the positioner is controlled in two axes, C and R. The machine is equipped with a feeder of additional material in powder form to supply feed gas. The hardfacing machine can be operated manually or automatically using the programming console.



Figure 1. Microstructure of the base material X38CrMoV5-1 (W. Nr. 1.2343).

Table 3. Chemical composition of the powder filler materials HSS 23, HSS 30, and DEW Nibasit 625-P (in wt %).

Filler Material	Marking According to EN 10025	С	Cr	Мо	W	v	Со	Fe	Si	Mn	Al	Nb	Ni
HSS23	1.3395	1.28	4.2	5.0	6.4	3.1	-	Bal.	-	-	-	-	-
HSS30	1.3294	1.28	4.2	5.0	6.4	3.1	8.5	Bal.	-	-	-	-	-
DEW Nibasit 625-P	-	0.025	22	9	-	-	0.01	0.5	0.4	0.7	0.02	3.3	Bal.



Figure 2. The plasma hardfacing machine PPC 250 R6 with plasma transferred arc (PTA) technology.



Figure 3. The hardfacing process on PPC 250 R6 with PTA technology.

We applied additional material to the base material in two hardfacing layers using the hardfacing machine. Before proceeding with the hardfacing process itself, the surface of the base material was prepared properly. Then we preheated the base material to 250 °C and started the hardfacing process with the hardfacing parameters for individual layers shown in Table 4. Heat treatment was performed as follows: quenching from 1230 °C/2 min, followed by triple tempering at 550 °C/1 h.

First Layer						
Pulsating direct current:	110/45 A, with a frequency of 44.4 Hz					
Trajectory:	swing step 3.9 mm (step speed 2.1 mm $\cdot$ s <sup>-1</sup> ) swing length 80 mm (speed 3.1 mm $\cdot$ s <sup>-1</sup> )					
Serving:	$26.4 \mathrm{g}\cdot\mathrm{min}^{-1}$					
Second Layer						
Pulsating direct current:	140/45 A, with a frequency of 44.4 Hz					
Trajectory:	swing step 5 mm (step speed 4.5 mm $\cdot$ s <sup>-1</sup> ) swing length 80 mm (speed 3.3 mm $\cdot$ s <sup>-1</sup> )					
Serving:	$27.8 \mathrm{g \cdot min^{-1}}$					

Table 4. Hardfacing parameters for the first and the second layer.

After hardfacing, the aim of the current research is microstructural characterization. To analyze the microstructure in different zones (fusion zone (FZ), heat-affected zone (HAZ), and base metal (BM)) in detail and, especially, to determine the mixing of additive and base material, it was necessary to use the combined methods of light microscopy (LM) and scanning electron microscopy (SEM). Polished samples, etched with Cor etchant (120 mL CH<sub>3</sub>COOH,

20 mL HCl, 3 g picric acid, 144 mL CH<sub>3</sub>OH), were used to identify the microstructures HSS 23 and HSS 30. Marble (CuSO<sub>4</sub> + HCl) etchant was used for the DEW Nibasit 625-P alloy. Metallographic observations at a magnification of  $50 \times$  and  $500 \times$  were carried out with a Keyence VHX 5000 light microscope (Osaka, Japan). The morphological details of the microstructural constituents were revealed using SEM (Jeol, JSM 7000F; Jeol Ltd., Tokyo, Japan), with analytical units, and energy-dispersive X-ray spectroscopy (EDX; Oxford Instruments, Abingdon, UK) using back-scattered electrons (BSEs). To determine the chemical composition of the structural phases and for the overall chemical elemental analysis, energy-dispersive X-ray spectroscopy (EDX) was used. Since our samples were embedded in an electrically conductive polymer, carbon was removed from the EDX analysis because the analysis results are affected by the carbon in the polymer. The EDX analysis presented in this work should be considered a semi-quantitative analysis. Observations were performed on Nital-etched samples at an accelerating voltage of 20 kV. The chemical composition of the test materials was verified using a Belec Compact Port spark portable chemical analyzer (Belec Spektrometrie Opto-Elektronik GmbH, Georgsmarienhütte, Germany). Microhardness measurements were carried out across different areas using the Shimadzu HMV-2 microhardness tester (Shimadzu, Kyoto, Japan), by means of the Vickers method according to EN ISO 6507-1. A load of 4.903 N (500 g, HV 0.5) and a full load dwell time of 15 s were used for the test. On each metallograpic section, the hardness was measured in three lines from the weld surface to the base material. The distance of the individual indentations was equal to three times the diagonal of the indentation. The arithmetic mean was calculated from the three measurements. When closing the fixed and movable part of the mold, only the steel parts of the mold are in mutual contact. The wear resistance of these parts of the molds is a superposition of several wear mechanisms, the intensity of which varies with the operating time of the mold. Partial information on the wear resistance of these parts of the mold is provided by tribological tests, which can be used to evaluate the relative change in the coefficient of friction of the hardfacing layers. For this case, it is sufficient to perform a tribological test using a pair of hardfacing layers and a steel ball. The hardfacing layers and friction were tested by a ball-on-disk test using the MFT-5000 multifunctional tribometer (Rtec Instruments, San Jose, CA, USA), a friction and wear tester with a GCr15 ball with a diameter of 5.0 mm. The samples were prepared for analysis using the 0.5 μm polishing solution DiaDuo-2 from Struers. GCr15 is a bearing steel of 52.100 of ASTM A295/295 M-2014—Standard Specification for High-Carbon Anti-Friction Bearing Steel. The test parameters used were as follows: rotation speed -350 r/min, pressure force 4.9 N, temperature  $20 \pm 2$  °C, and friction time 30 min.

#### 3. Results

The results of the hardface metallographic analysis are presented in Figures 4–14. For the hardfacing layers HSS 23 and HSS 30, cracks are visible in the hardface, separating the hardface from the base material. The DEW Nibasit 625-P hardfacing layer is free of microscopically visible defects. That is, the area of melting, eventually the area under the hardface, can be the most common source of defects. On the metallographic section, the presence of globular pores was observed. The transition from hardfacing layer to base material is sharp, without apparent mixing. This was also confirmed by the surface EDX analysis conducted (Figure 4). Figure 6 shows the microstructure of the HSS 23 hardfacing layer formed by tempered martensite, consisting of fine, uniformly distributed carbide phases. The presence of carbides is ensured by strong carbide-formers (Cr, Mo, V, and W) [39]. The microstructure shows both well-defined grain boundaries and their size.

Figure 5 shows a minimum mixing zone between the base material and the HSS30 weld, as confirmed by EDX line analysis.

The structure of the overlay metal HSS 30 is dendritic-cellular, similar to that identified by Saewe [40]. The distance of secondary dendrite arms depends on the cooling rate during solidification. The microstructure of the powder particles consists of martensite, retained austenite, and uniformly distributed fine carbides. Martensitic laths are present in the



dark grains, described by Jovičevic-Klug [41]. A light phase is segregated along the grain boundaries.

**Figure 4.** Energy-dispersive X-ray spectroscopy (EDX) line analysis of the transition region between hardface HSS 23 and base material.



Figure 5. EDX line analysis of the transition region between hardface HSS 30 and base material.

From Figure 6, it is apparent that the transition between hardface structure and base material is smooth. No "cold joints" are observed on the melting borderline of the base material. The presence of pores, eventually inclusions that were not detected, was seen on the metallographic sections. The microstructure of the alloy is dendritic-like, with a cubic face-centered structure and no phase transitions in the solid state. The strength properties of the hardfacing layers DEW Nibasit 625-P are increased by carbon, chromium, and molybdenum. The high strength is achieved by solid solution hardening (Mo and Nb) and by precipitation hardening, which is mainly derived from the metastable  $\gamma$ " phase (Ni3(Nb,Al,Ti)).



Figure 6. EDX line analysis of the transition region between hardface DEW Nibasit 625-P and base material.

In Figure 7, in the mixing zone (1), the eutectic phase at the grain boundaries is missing. Higher in the hardface, this phase is present. There are also isolated pores in the weld (2). These are photographs showing a detail of the macro- and microstructure of the HSS 30 hardface observed using an electron microscope.

Figure 8 shows the connection of the hardfacing layer and the base material in the central part of the hardfaced material. The material connection does not show defects; there is a thin mixing zone at the interface (marked by arrows).

Figure 9 shows a detail of the mixing zone, which is free of defects. More numerous pores are present in the hardfacing layer outside the mixing zone.

In Figure 10, martensitic laths are visible in the grains, and a eutectic phase with a lower melting point is present along the grain boundaries.

Figure 11 shows a clear interface between the hardface and the base material. The interconnection of the materials is continuous, without the presence of defects.

Figure 12 shows the hardfacing layer DEW Nibasit 625-P and the base material transiting area. In the base material melting line, no presence of inner defects or cracks was found. In the hardfacing layers, pores were detected. Their amount on the assessed metallurgic section did not exceed the limit values for the hardfacing metal. Figure 13 shows the transiting line between the first and the second hardfacing layers. The hardfacing metal solidification direction was well defined on the transition line.

In Figure 14, an enlarged microstructure of the hardfacing layer is shown, which is dendritic with numerous micropores up to 2  $\mu$ m in size. Since 98% of the pores in the hardfacing layers are of exogenous origin, we assume an exogenous origin in these pores as well.

In addition to the reference images, the so-called EDX maps, we have an overview of individual chemical element distribution at the interface of the hardfacing layers and the base material.

Figure 15 shows that the content of Fe and Mn in the base material and the hardfacing metal is the same: both elements are evenly distributed over the entire evaluated area. The elements Cr, Mo, V, and W are contained in a higher concentration in the hardfacing metal than in the base material.



Figure 7. Hardfacing layer HSS 23 with base material (scanning electron microscopy (SEM)).



Figure 8. Remelting zone: mixing of HSS 30 hardfacing metal with base material (SEM).



**Figure 9.** HSS 30 hardfacing layer on base material: the visible martensitic structure and absence of the eutectic phase in the mixing zone (SEM).



Figure 10. Detail of the hardfacing microstructure of HSS 30 (SEM).



Figure 11. Remelting zone: mixing of DEW Nibasit 625-P hardfacing metal with base material (SEM).



Figure 12. DEW Nibasit 625-P hardfacing layer on base material (SEM).



**Figure 13.** DEW Nibasit 625-P hardfacing layer: a view of columnar dendritic formations due to rapid cooling of a large amount of mold powder (SEM).



Figure 14. Detail of the dendritic structure of the DEW Nibasit 625-P hardfacing layer (SEM).



**Figure 15.** EDX map of the HSS 23 hardfacing metal on the base material and color-coded chemical elements (Fe, Mo, V, W, and Mn) in the materials (SEM).

Figure 16 shows that the elements Cr, Mo, and V are concentrated in the eutectic phase between the grains, while Co is concentrated more in the martensitic grains.



**Figure 16.** EDX map of the HSS 30 hardfacing metal on the base material and color-coded chemical elements, (Fe, Cr, Co, Mo, V, Mn, and W) in the materials (SEM).

The EDX maps confirm the presence of individual chemical elements in the materials (Figure 17). Since the DEW Nibasit 625-P hardfacing layer is based on nickel, Ni is concentrated in the map of the hardface and Fe in the base material. There is also a higher content of the elements Cr, Mo, Mn, and Nb in the hardface, while Nb is concentrated in the interdendritic phases of the hardface.



**Figure 17.** EDX map of the DEW Nibasit 625-P hardfacing layer on the base material and color-coded chemical elements (Fe, Ni, Cr, Mo, Mn, Nb, Si, and V) in the materials (SEM).

Some EDX analyses of different parts of the interface between substrate and layer are presented next. The results of the analyses are semi-quantitative. Figure 18 shows the results of the HSS 23 hardface analysis.



Figure 18. The HSS 23 hardfacing layer on base material with marked areas of analysis (SEM).

Based on EDX analysis, it is apparent that the materials were mixed in the melting zone, as evidenced by the presence of the elements V, Mo, W, and Cr, whose content in the mixing zone is lower than in the hardface but higher than in the base material (spectrum 10). Figure 19 shows the results of the HSS 30 hardfacing layer analysis.



Figure 19. The HSS 30 hardfacing layer on base material with marked areas of analysis (SEM).

In the melting zone, the materials were also mixed, as evidenced in particular by the content of the elements W, V, and Mo, which lie between the base material and the hardfacing layer. Figure 20 shows the results of the DEW Nibasit 625-P hardfacing layer analysis.

	Spectrum	n 23 🔶	Seatture 27	-	Spectrun	n 24
	Wt%	σ	Spectrum 25		Wt%	σ
Ni	59.8	0.3		Ni	53.7	0.3
Cr	20.8	0.2		Cr	18.7	0.2
Mo	8.1	0.3		Fe	16.8	0.2
Fe	7.5	0.1		Mo	7.1	0.3
Nb	3.4	0.2	Spectrum 22	Nb	2.8	0.2
Si	0.4	0.1		Mn	0.4	0.1
	Spectrum	22		Si	0.4	0.1
	TA710/				Spectrun	1 21
	VV t 70	σ		1	Wt%	σ
Ni	53.4	0.3		Fe	90.0	0.2
Cr	19.4	0.2		Cr	5.8	0.1
Fe	15.9	0.2	Spectr in 24	Мо	1.5	0.2
Mo	7.8	0.3	Spectrum 21	Si	1.1	0.1
Nb	3.2	0.2		v	0.8	0.1
Si	0.3	0.1		Mn	0.5	0.1

Figure 20. The DEW Nibasit 625-P hardfacing layer on the base material with marked areas of analysis (SEM).

Cr and Mo content increased from base material to hardface. There was even a difference in the content of Ni, Cr, Mo, and Nb in the first layer and the second layer of the hardface, while their content was higher in the cover layer than in the first layer. The Fe content decreased toward the cover layer of the hardface, which also indicates the mixing

of materials not only between the base material and the hardface but also between the first and the second hardfacing layer (cover).

After the test, a graph based on the measured values was produced (Figure 21), which shows the hardness of the individual hardfaces as a function of the distance from the hardface surface.



Figure 21. Hardness comparison of individual hardfaces.

The hardness of HSS 23 and HSS 30 hardfacing layers ranged from 650 to 850 HV 0.5. The materially different hardfacing layer DEW Nibasit 625-P reached the base material hardness level, i.e., 210–250 HV 0.5. The tribological and wear properties of the investigated materials are given in Table 5.

Table 5. Tribological and	l wear properties of	f the investigated	l materials.
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Experimental Materials	Sliding Speed (mm/s)	Normal Load (N)	Distance (m)	Coefficient of Friction	Wear Rate $\times~10^{-6}$ (mm³/m·N)
Base material	50	20	50	$0.55\pm0.09$	$33.96 \pm 1.2$
HSS 30	50	20	50	$0.53\pm0.04$	$7.6\pm0.4$
HSS 23	50	20	50	$0.56\pm0.12$	$14.49\pm0.6$
Nibasit 625-P	50	20	50	$0.35\pm0.09$	$21.39\pm0.8$

The lowest value of the coefficient of friction at an ambient temperature of  $20 \pm 2$  °C was achieved by DEW Nibasit 625-P. The cover hardfacing layers made using the additive HSS 23 showed the highest average friction coefficient. The measured values for respective test samples correspond to the chemical composition of the evaluated covering layer surfaces of the assessed samples and to the base material of the casting die. Carbon content and content of the carbide-forming additives Cr, Mo, W, and V have a primary impact on friction coefficients. The friction coefficients of HSS 30, HSS 23, and the base material are almost the same. The hardfacing layer of DEW Nibasit 625-P achieved the lowest friction coefficient value during the tests, which corresponds to a low value of hardness, HV 0.05. It is a nickel-based material with an austenitic structure and a high capacity for plastic deformation. The distribution of the structures is uniform, which was also confirmed by material analysis (Figure 17). This hardfacing layer achieved the widest track after wear with shallow depth and the lowest material removal. The materials HSS 30 and HSS 23 achieved higher values of the coefficient of friction during the tribological test, which is related to their higher hardness. These materials consist of a mixture of hardnesd attractures is related to their higher hardness.

with carbides. A different mechanism of wear was observed. During the test, the surface layers of these materials were smoothed at the point of contact with the counterpart and the carbides present in the structure acted as an abrasive.

### 4. Conclusions

The paper presents the results of research on the quality of functional layers made from the powder filler materials HSS 23, HSS 30, and DEW Nibasit 625-P by plasma transferred arc (PTA) hardfacing technology. Layers were made using the plasma hardfacing machine PPC 250 R6 on X38CrMoV5-1 base material. This type of medium alloy steel is used in the production of die-casting molds for aluminum parts for automotive production. The hardfacing was made in two layers. The quality of the hardfacing layers was evaluated using nondestructive and destructive tests. Surface integrity as well as the occurrence of surface defects were evaluated using visual testing (VT) according to the standard EN ISO 17637 and penetration testing (PT) according to the standard EN ISO 23277. Surface defects were not detected on the hardfacing layers. As part of the destructive testing, metallographic sections were made for observation by light microscopy and electron microscopy, as well as for the evaluation of the chemical composition of the surface spectra of selected parts of the samples. The occurrence of inner defects in the hardfacing layers was recorded on the cross sections. The defects were classified as rare pores. EN 12517-1 classifies this type of defect as permissible in this quantity. After metallographic analysis, the hardness in the lines passing through the hardface metal into the base material was evaluated on the sections. The maximum values of the hardness in the interval 720 HV 0.5–850 HV 0.5 were measured in the covering layers of the HSS 23 hardface metal, which is in accordance with their chemical composition and the observed martensitic structure. The lowest hardness values were measured for DEW Nibasit 625-P samples (210 HV 0.5-250 HV 0.5). As part of the experiments, the tribological properties of the newly formed hardfacing layers were analyzed. The lowest friction coefficient was shown by surfaces with the DEW Nibasit 625-P layer and the highest values of the friction coefficient were measured on surfaces with the HSS 23 hardfacing layer. Based on the experiments performed, it can be stated that the selected energy beam (PTA) technology for the renovation of the functional surfaces of casting molds is suitable. As an additional material for the restoration of exposed mold areas, all investigated additional materials can be used, but due to its low friction coefficient, it is possible to recommend the nickel-based additive DEW Nibasit 625-P.

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