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Hardfacing of metal-cutting tools by arc welding in vacuum

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ABSTRACT

Purpose: To present a technology for hardfacing of metal-cutting tools by arc welding in vacuum.

Design/methodology/approach: The experiments were carried out using an installation for arc welding in vacuum. Objects of research were metal cutting tools (lathe knives), made of high-speed steel HS6-5-2 on a base metal of structural steel C45. The structure, hardness and wear resistance after hardfacing and after a triple tempering at 560°C have been determined. The heat resistance of the obtained instruments has been examined.

Findings: The microstructural analysis showed that the structure of the built-up layer consisted of martensite, retained austenite and carbides. This was confirmed by the values of measured hardness after welding which were about 63-64 HRC. The triple tempering led to an increase in hardness by 3-4 HRC. It was found that the built-up layers (cutting edges of tools) retain their hardness (HRC=63-65) up to a temperature of 615-620°C, which shows that the heat resistance of the build-up layers was similar to that of the hardened and tempered tools of the same steel.

The built-up work-pieces (excluding heat treated) and the reference knife showed the same cutting qualities at cutting speeds in the range of 55 to 120 m/min. It has been found that triple tempering after hardfacing led to increased wear resistance and consequently the durability of the tool also increased due to the higher hardness.

Practical implications: The practical application is related to the production of metal-cutting tools.

Originality/value: The proposed technological method allows to produce defects free built-up layers. The cutting properties of the built-up in vacuum layers are comparable to or better than those of new tools made of steel HS 6-5-2.

Keywords: Tool materials, Wear resistance, Hardfacing, Heat treatment, Hollow cathode arc

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PROPERTIES

1. Introduction

A main application of hardfacing (a kind of surfacing or building-up by welding) is to obtain the so-called functional coatings with high hardness, wear resistance, corrosion resistance, etc. [1-4]. Research in this direction requires knowledge of the conditions in which the product operates, the correct selection of filler materials for hardfacing and appropriate process parameters [5-7].

Another area of application of the process is related to the recovery of worn-out machine and other parts with unused resource, the replacement of which with new ones is in the most cases much more expensive [8]. The latter is therefore widely used in mechanical engineering, metallurgy and transport, where some products are subject to extremely intense wear. These include metalworking tools, excavator bucket parts and more. In order to reuse them, they can be coated by hardfacing with special carbide electrodes or wires [9-11]. The obtained coatings have the necessary hardness and wear resistance even at high temperatures [12].

Metal-cutting tools are parts subjected to considerable wear and need to be sharpened frequently. When they have complex surfaces and large dimensions (hole processing tools, profile and multi-tooth tools – broaches, gear milling cutters, drills, countersinks, reamer, taps, dies etc.) most often they are made of different types of high-speed steels. These materials have the required hardness of 63-70 HRC, heat resistance up to about 600-700°C and wear resistance due to the alloying elements – tungsten, molybdenum, cobalt and vanadium which bind to carbon to form heat resistant carbides. This in turn allows tools made of such steels to be used at cutting speeds over 30-40 m/min.

The disadvantages of these instruments are their high cost and the fact that most of the material they are made of remains unused after complete wear out or after partial destruction of the cutting part. In this respect, it is important to create and use an economical tool design which guarantees the necessary durability during work. Suitable for the construction of the tool body are structural steels of the type C40, C45 or C50 with cutting edges made, for example of steel HS18-0-1 (1.3355), HS6-5-2 (1.3343) and similar by surfacing. Thus, the cost savings of high-speed steel can reach up to 80-85% depending on the type and size of the tool.

A main disadvantage of some welding methods (Gas Metal Arc and Gas Tungsten Arc) used in practice is the poor protection of the base and filler metals against the impact of the air. Due to the saturation with oxygen, nitrogen and hydrogen, the quality indicators of the produced coatings sharply deteriorate as there is an increase in the amount of gas pores, slag inclusions, cracks, etc.

A possible technological combination for hardfacing is that of vacuum efficiency as a protective environment for surfacing and the positive features of an arc discharge with hollow cathode. According to [13], the result of such a combination leads to a decrease in the quantity of defects, an increase in the mechanical properties and plasticity of the built-up layers, an increase in the durability of the metal-cutting tools compared to those made entirely of forged high-speed steel of the same type.

The objective of the present paper is to research and develop a technology for the production of a metal-cutting tool by hardfacing with a hollow cathode arc in vacuum and examining some of the properties of the hardfacing layers.

2. Methodology

In the production of metal cutting tools by hardfacing, it is necessary to achieve certain quality indicators of the hardfacing layers that meet the operational requirements. Hardness, heat resistance, wear resistance, dimensions and shape are accepted as quality indicators.

The choice of the tool (lathe knives), whose cutting edge was to be built-up was made considering the technical characteristics of the used installation for arc welding in vacuum (the volume of the vacuum chamber and the available ancillary equipment for handling with the product) [14], possibility for additional heat treatment and subsequent wear resistance tests.

Workpieces of C45 steel (according to EN ISO 683-1:2018) were used as test pieces. As a filler material ingots of high-speed steel (HS6-5-2 according to ISO 4957:2018) with rectangular cross-section and thickness of 3.5 mm were used. Recommended mode for heat treatment of HS 6-5-2 steel is given in Table 1 [16].

Table 1
Recommended mode for heat treatment, hardness and application of HS6-5-2 steel [15,16]

Steel	Maximal working temperature, °C	Temperature,°C		Hardness HRC	Applications
		Hardening	Tempering		
HS6-5-2	615-620	1210-1230	540-560	63-65	Broaches, milling cutters, lathe knives, countersinks, drills, etc.

The dimensions of the channel and the filler materials were selected to meet the strength requirements for the cermets plates. According to this, the channel was with dimensions 4x2.5x20 mm and was made at an angle of 75° to the longitudinal axis.

During the research start on plates with dimensions 20x30x20 mm were used in order to take the crater out of the surfacing area (Fig. 1).

The welding parameters used for hardfacing are presented in Table 2.

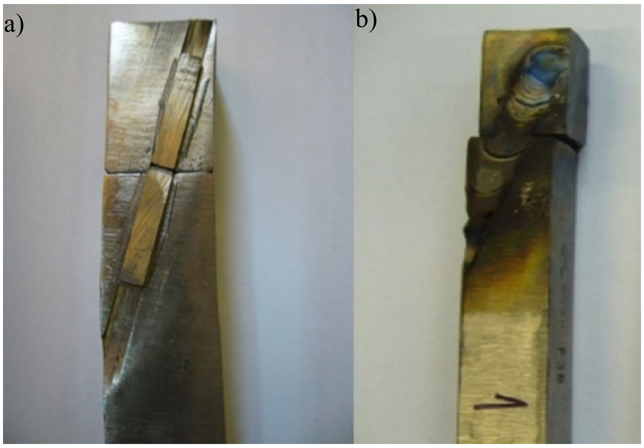

Fig. 1. Test pieces before (a) and after (b) hardfacing

Table 2
Hardfacing parameters

Current	Hardfacing speed	Feed rate of the plasma - forming gas	Diameter of the hollow cathode
I_p, A	v, mm/s	G_{Ar}, l/h	d_{hc}, mm
140	1.5	3.5	6

The experiments were carried out at operating pressure of $5x10^0$ Pa in the chamber and discharge voltage of 18 V, type of polarity DC (-), welding position – PA (according to ISO 6947:2019).

In order to study the relation between the temperature, the microstructure and the hardness of the built-up layers, the temperature at selected points was measured (Fig. 2) using K type thermocouples.

The thermocouples were welded using capacitor resistance welding. Beforehand welding of thermocouples, channels for their position were cut. After building up the samples were cooled in vacuum to room temperature (≈ 20°C) and then were examined by visual testing in order to find visible flaws.

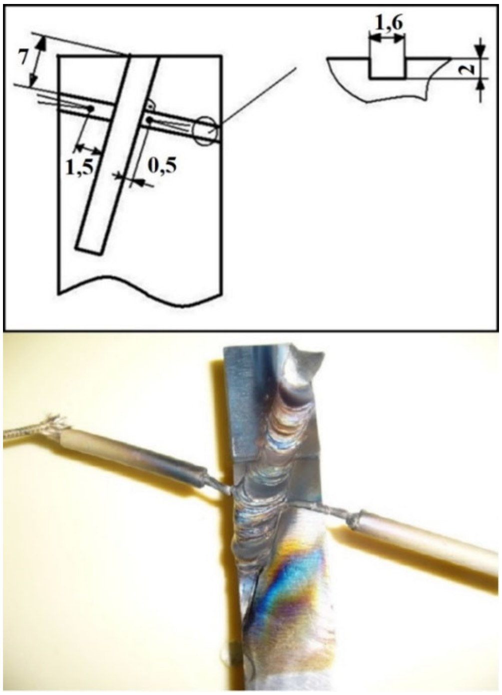

Fig. 2. Place for installation of thermocouples

After hardfacing some of the test pieces were triple tempered at temperature of 560°C as recommended in Table 1. The purpose was transformation of the retained austenite to carbides and martensite. Surface hardness was measured on all test pieces (heat treated and non-heat treated) using the Rockwell method; hardness was also measured in depth according to the Vickers method with a load of 9.81N (HV1) in five points (Fig. 3).

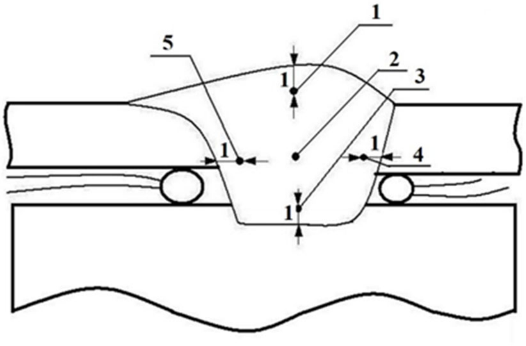

Fig. 3. Localization of the hardness imprints in depth of the built-up layer

Cross-sections were prepared for examination of the macro- and microstructure and the hardness of the built-up layers.

To determine the heat resistance of the built-up layers (an important property of metalworking tools), the test pieces were heated to temperatures in the range of 560-680°C and held for one hour at these temperatures, then cooled in air. Afterwards their hardness was measured in cross-section.

Nine samples were made for determination of wear resistance: three reference knife samples, three surfaced samples and three surfaced and heat treated samples. The wear resistance of the samples was determined by examination of the relationship between wear intensity (U, mm/min) and cutting speed (V_c, m/min), according to ISO 3685: 1993 [17-23]. The specimens were tested during final scraping with cutting depth of 0.5 mm and feed rate of 0.1 mm/rev. The cutting speed has been altered over a wide range – from 50 to 140 m/min. The presented here results represent the mean values of the wear intensity.

All experimental results for built-up layers were compared to those obtained when using a reference knife made entirely of HS6-5-2 high-speed steel.

3. Results of the research

The maximum temperature measured by the thermocouple located at a distance of 0.5 mm from the filling material was 1250°C and was recorded at the eleventh second from the start of welding. The maximum temperature measured by the thermocouple at a distance of 1.5 mm was 870°C for the fifteenth second. The required time for cooling the test piece to room temperature was about 840 seconds.

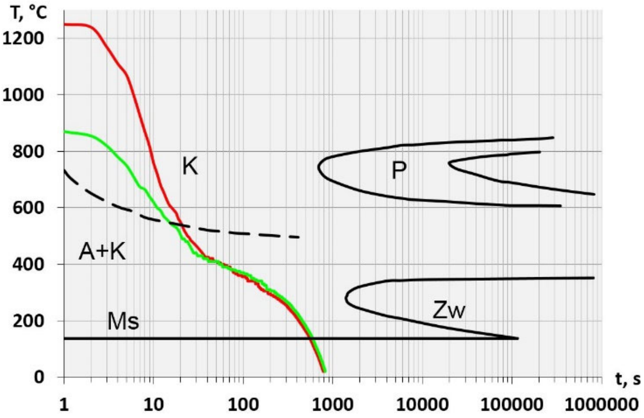

Fig. 4. Relationship between cooling curves and thermokinetic diagram of supercooled austenite for HS6-5-2 steel [24]. The green line represents data from the thermocouple situated at 1.5 mm from the surfacing layer, and the red line – from the thermocouple at 0.5 mm from the surfacing layer. The abbreviations are as follows: K – carbides; A – austenite; P – pearlite; Zw – bainite; Ms – martensite start temperature

Figure 4 shows the thermokinetic diagram of the supercooled austenite transformation of HS 6-5-2 steel. The cooling curves imposed on it are obtained after processing the data from the two thermocouples.

Figure 4 shows that the supercooled austenite transformation by diffusion did not occur as the cooling rate of the surfacing layer was significantly higher than the necessary one for that transformation. As a result the microstructure of the build-up layer consisted of martensite, retained austenite and carbides.

Figure 5a represents this microstructure, typical for cast W-Mo-containing high speed steel after high rates of crystallization.

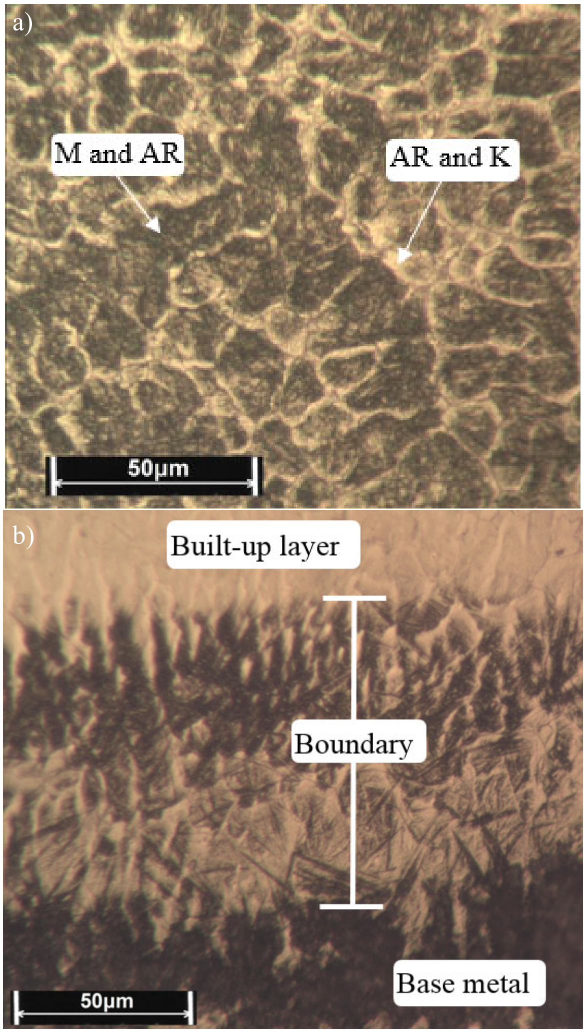

Fig. 5 Microstructure of the built-up layers (a) and the boundary of the built-up layer - base material (b), etched by a 3% nitric acid in ethanol. The abbreviations are as follows: M – martensite; AR – retained austenite; K – carbides

Due to the fast cooling of the melted metal the crystallization products were dispersed which had a positive effect on the mechanical properties. Passing below the temperature of the austenite stability and cooling at speeds higher than the needed for austenite transformation by diffusion, the surfacing layers transformed to martensite. Thus the formed microstructure consisted not only of martensite but also of carbides and retained austenite. In the microstructure shown in Figure 5a, carbides and retained austenite appear as light patches, most probably with eutectic character. The measured hardness values after hardfacing – about 63-64HRC (Tab. 3), correspond to the observed microstructure of the hardfacing layer.

Table 3.
Average hardness of hardfacing layers measured on their surface before and after tempering

No.	Hardness, HRC			
	After hardfacing	After first tempering	After second tempering	After third tempering
1	63	66	67	66.5
2	63	65	66	65.5
3	63.5	-	-	-
4	63.5	-	-	-

Table 4.
Average hardness of the hardfacing layers measured in cross section after tempering

Measuring point (Fig.3)	Hardness, HV1/HRC			
	After welding up	After first tempering	After second tempering	After third tempering
1	815 /64.1	861 /65.9	889 /66.7	870 /66.2
2	820 /64.3	880 /66.2	887 /66.6	872 /66.2
3	838 /65.0	900 /67.0	912 /67.2	884 /66.6
4	822 /64.5	880 /66.3	888 /66.7	865 /66.0
5	812 /64.0	861 /65.7	881 /66.3	862 /66.0

The Rockwell hardness values was received by conversion according to ISO 18265:2013

The values of the measured hardness of the built-up layer before and after tempering are presented in Tables 3 and Table 4. From Table 4 it can be seen that the greatest increase in hardness occurred after the first tempering (≈ 2 HRC). According to the specialized literature [25,26] such an increase in hardness is mainly due to reduction in the quantity of the retained austenite from 30% to 15%. After the second tempering, the hardness increased to a maximum (0.5-1 HRC) due to the additional reduction of retained austenite to about 5% [25,26].

After triple tempering the hardness values decreased (≈ 0.5 HRC) as the third tempering tempered the martensite formed during the cooling after the previous tempering [27]. The greater reduction in stresses after the third tempering also contributed to the observed softening. Figure 6a shows the microstructure of the hardfacing layer after triple tempering. Triple tempering led to the formation of tempered martensite in the build-up layer, and as the retained austenite transformed the white patches visible on Figure 6a are mainly carbides.

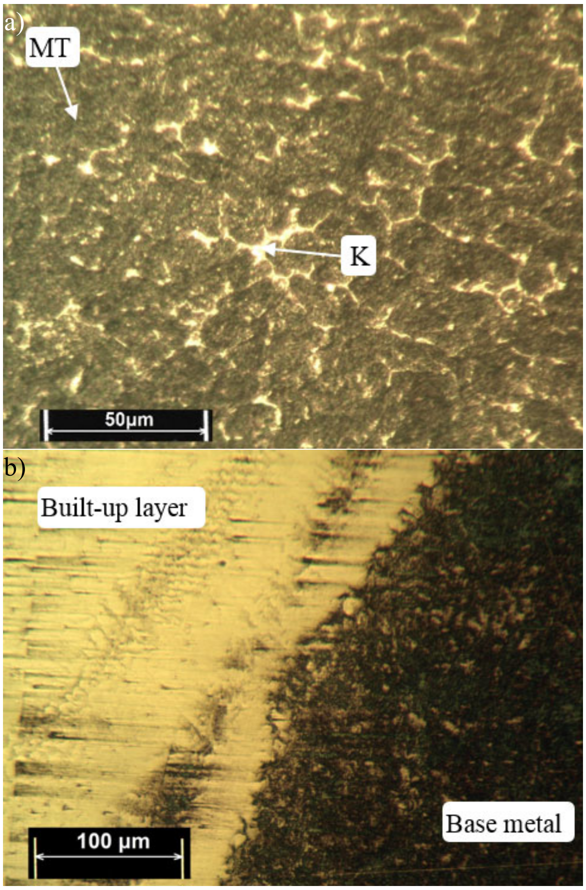

Fig. 6. Microstructure of the built-up coating after three times tempering (a) and on the border of the built-up layer - substrate after three times tempering (b), etched by a 3% nitric acid in ethanol. The abbreviations are as follows: MT – tempered martensite; K – carbides

Figure 5b shows the microstructure on the boundary between the hardfacing layer and the base material. The observed microstructure demonstrates that there was a good mixing between the filler material and the base material. Large needle-like nonequilibrium microstructure constituents are visible in the mixture of both materials (the base material and the filler material). The resulting structure in the heat affected zone adjacent to the fusion zone is eutectoid with decreasing dispersion in direction to the substrate (troostite → sorbite → pearlite). This caused the gradual decrease in hardness in the heat affected zone. At the border of the heat affected zone with the base material gradual decrease in hardness was observed, and the hardness value reached that of the base material.

At the border between the built-up layer and the heat-affected zone, the needle-like nonequilibrium microstructure constituents in the tempered samples (Fig. 6.b) also showed a tendency towards equilibrium morphology (pearlite); that led to the decrease in the registered hardness in these areas before tempering.

Microstructural analysis did not reveal any defects typical for hardfacing in argon protective atmosphere (Gas Tungsten Arc method). Thus, the used here modes for hardfacing in vacuum produced defect free built-up layers.

Figure 7 shows the hardness change with temperature after heating the built-up layers in the temperature range of 560-620°C in order to determine their heat resistance. It could be seen from Figure 7 that the samples retained hardness higher than 64 HRC up to a temperature of about 620°C. Heating to higher temperatures was accompanied by an intense decrease in hardness. This confirms the data from the specialized literature [16], according to which products made of HS6-5-2 steel retain a hardness of 63-65 HRC up to temperatures of 615-620°C.

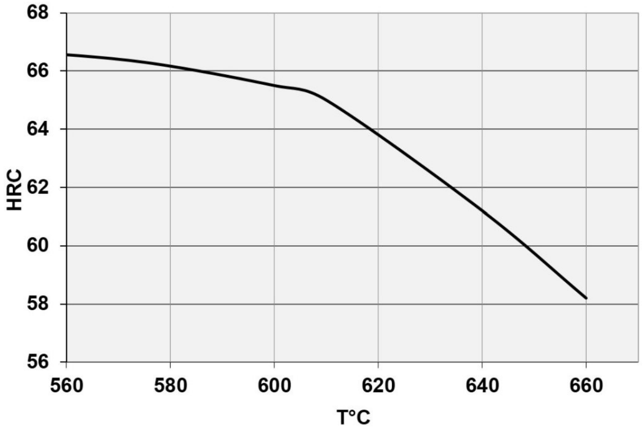

Fig. 7. Heat resistance of built-up layers

The results presented in Figure 7 also prove that the used here modes of hardfacing had as a result structures with heat resistance comparable to those of the structures formed after the traditional combination of quenching and tempering (described in Tab. 1). This makes it possible to use hardfacing without the need for next quenching but only triple tempering.

After surfacing and tempering of some of the test pieces their wear resistance has been determined. The results were compared to those of a reference knife made entirely of HS6-5-2 high-speed steel.

The values of cutting speed and wear intensity are presented in Table 5 and in Figure 8. It is seen that the wear intensity of the hardfacing samples (excluding heat treated) and of the reference knife at cutting speeds V_c in the range of 55 to 120 m/min were practically equal so it can be accepted that they had the same cutting properties.

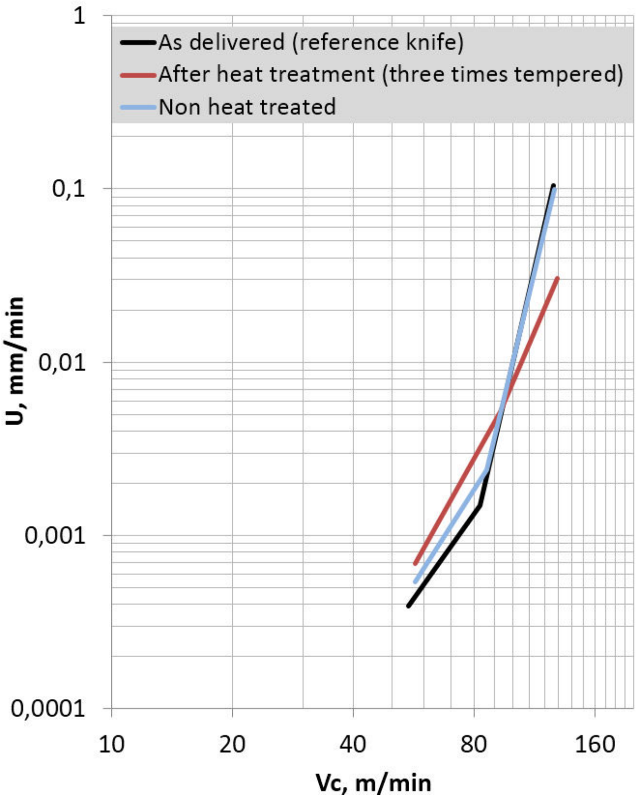

Fig. 8. Experimental dependences between wear intensity and cutting speed

The wear intensity of the surfacing samples depended strongly on the cutting speed. At speeds higher than 100 m/min the samples wore out significantly more intensely than at speeds below that; thus, for non-heat treated knives it is not recommended to operate under these conditions. At speeds below 100 m/min the wear intensity decreased, the cutting qualities were stable and durability increased.

Table 5
Mean values of wear resistance of lathe knives with cutting edge of HS6-5-2 steel

Type of the sample	Heat treatment	V_c	U
	-	m/min	mm/min
HS6-5-2 reference knife	Delivery condition	55	0.00039
		83	0.00150
		126	0.10430
Hardfacing in vacuum	Non heat treated	57	0.00054
		86	0.0024
		127	0.099
Hardfacing in vacuum	Three times tempered	57	0.00069
		93	0.00520
		129	0.03040

V_c – cutting speed,
U – wear intensity.

The comparison between the studied here non-heat treated and heat treated tools definitely shows that performing a triple tempering after welding led to an increase in the wear resistance and respectively in the tool durability due to the hardness increase.

4. Conclusions

1. A way to obtain inexpensive construction of a metal cutting tool along with maintaining or even increasing its wear resistance during its function is hardfacing of high-speed steel upon construction steel by arc discharge with a hollow cathode in vacuum.
2. The cooling rate during hardfacing of high-speed steel HS6-5-2 onto substrate of steel C45 provides austenite to martensite transformation in the built-up layer. This is confirmed by both microstructural observations and the measured hardness values of the built-up layer – about 63-64 HRC.
3. Triple tempering further increases the hardness of the built-up layer within about 2-3 HRC.
4. At cutting speeds in the range of 55 to 120 m/min the wear intensities of the non-heat treated samples and of the reference knife show that the proposed here modes for hardfacing in vacuum ensure formation of structures with cutting capabilities similar to that of the reference knife. Triple tempering after hardfacing in vacuum increases wear resistance and as a consequence the tools durability increases.
5. The knives produced by hardfacing in vacuum retain a hardness of 63-65 HRC to temperatures of about 620°C.

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