COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

THE INFLUENCE OF CHEMICAL COMPOSITION OF HIGH-SPEED STEELS ON THE WEAR DURING CUTTING AND EROSION TESTS

Leszek A. Dobrzanski
Wojciech Kasprzak[a]
Marcin Adamiak
Institute of Engineering Materials and Biomaterials, Silesian University of Technology
Konarskiego St. 18A, 44-100 Gliwice, Poland,
Mirko Soković
Janez Kopač
Faculty of Mechanical Engineering, University of Ljubljana, Askerceva St. No 6, 1000 Ljubljana, Slovenia
Giampaolo. D'Errico
Instituto Lavorazione Metalli, Consiglio Nazionale Ricerche via Frejus 127-I-10043 Orbassano-TO, Italy

Abstract. *The paper presents the results of investigations of the 5% cobalt and 2% molybdenum additions in the W-Mo-V and W-V high-speed steels of the 9-2-2, 11-2-2 and 11-0-2 types with economically designed chemical composition on the wear mechanism during cutting and erosion tests. The 5% cobalt addition results in increasing the secondary hardness effect by 1.6 to 1.9 HRC, depending on a steel grade. Secondary hardness effect is caused by the dispersive carbides of the* M_4C_3 *type and martensite transformation of the retained austenite. The maximum secondary hardness effect about 66.3-67.6 HRC, depending on a grade of steel, occurs in each steel after tempering at* 540^oC *and austenitizing at* 1240^oC*. The 5% cobalt addition results in enhancing the working properties of tools, longer tool life and makes it possible to increase cutting speed by about 50%, compared with the steels of identical concentration of other alloying elements but without cobalt addition. Cobalt does not have any significant influence on erosion resistance, which is independent of the steel hardness but depends on molybdenum addition in steel.*

Keywords: *high-speed steels, cobalt, molybdenum, secondary hardness effect, precipitation strengthening effect, cutting ability, erosion resistance.*

1. INTRODUCTION

High-speed steels are still one of the main materials nowadays used for production of tools for machining as well as for cold working [1,12,13,18,19]. In spite of a rapid development of contemporary tool materials such as sintered carbides, special ceramic materials or extremely hard materials, high-speed steels are still commonly used, owing to their satisfactory hardness, ductility and good machinability in soft-annealed state [12,13,18]. Due to powder metallurgy processes and development of the PVD coating techniques life expectancy of products made from high-speed steels has been extended by far, which makes the high-speed steels current complimentary tool material [10,11-13]. Limiting the content of expensive or not easily available elements such as W, Mo, V, Co, and their possible substitution by cheaper and more easily available ones e.g., Si, Ti, Nb was sparked by the worldwide crisis of the eighties in the market of alloying elements [12,13]. Cobalt, as the alloying element, is usually used in high-speed steels in concentration up to 13%, depending on tool type. It is known, based on the information available in literature, that in high-speed steels, cobalt addition in concentration over 5% but below 8% is economically unjustified since the obtained results are out of proportion to the expenses [15-17,20]. Hence the increase of cobalt concentration in high-speed steels, leads to hardness extension. The increase of the secondary hardness effect of steel has the direct connection with enhancing working properties of tools which were made of cobalt steels, expanding wear resistance while working at high temperatures and decreasing impact resistance which is also in relation to strong tendency to chipping of the main cutting edge during machining. The decrease of impact resistance is extremely evident with increasing cobalt concentration from 5 to 8%, which is probably caused by reduction of the volume fraction of the retained austenite (because of the increasing cobalt concentration in steel) and by tendency to destabilization of this structural constituent [12,13]. Taking in to account that cobalt is regarded as a considerably expensive alloying element, and in high-speed steels including from 8 to 10% Co, its price can reach 50% of the costs of the all alloying elements, it was useful to investigate the possibilities of limiting the concentration of this addition in the investigated high-speed steels to approximately 5%, compared to current grades of steels.

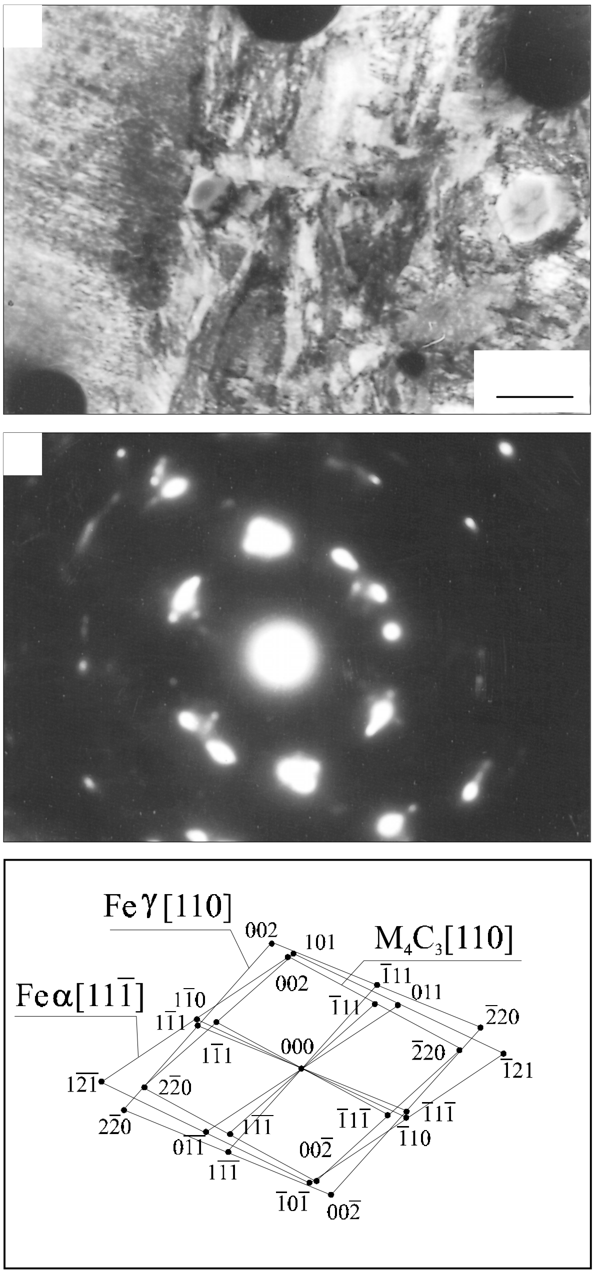
The goal of this paper is the investigation of influence of the chemical composition in the W-Mo-V and W-V of the 9-2-2, 11-2-2, and 11-0-2 high-speed steels with or without 5% addition on the wear during cutting and erosion tests.

Table 1. Chemical composition of investigated high-speed steels

<table>
<tr><th rowspan="2">Steel type</th><th rowspan="2">Designation</th><th colspan="8">Average composition, wt %</th></tr>
<tr><th>C</th><th>Mn</th><th>Si</th><th>Cr</th><th>W</th><th>Mo</th><th>V</th><th>Co</th></tr>
<tr><td>9-2-2-5</td><td>SW9M2K5S</td><td>0.95</td><td rowspan="6">0.4</td><td rowspan="6">0.7</td><td rowspan="6">4.5</td><td>9.0</td><td rowspan="2">2.0</td><td rowspan="6">1.8</td><td rowspan="3">5.0</td></tr>
<tr><td>11-2-2-5</td><td>SW11M2K5S</td><td>1.05</td><td rowspan="2">11.0</td></tr>
<tr><td>11-0-2-5</td><td>SW11K5S</td><td rowspan="2">0.95</td><td>0.0</td></tr>
<tr><td>9-2-2</td><td>SW9M2S</td><td>9.0</td><td rowspan="2">2.0</td><td rowspan="3">0.0</td></tr>
<tr><td>11-2-2</td><td>SW11M2S</td><td>1.05</td><td rowspan="2">11.0</td></tr>
<tr><td>11-0-2</td><td>SW11S</td><td>0.95</td><td>0.0</td></tr>
<tr><td colspan="10"><0.02% P, <0.02% S</td></tr>
</table>

2. EXPERIMENTAL PROCEDURE

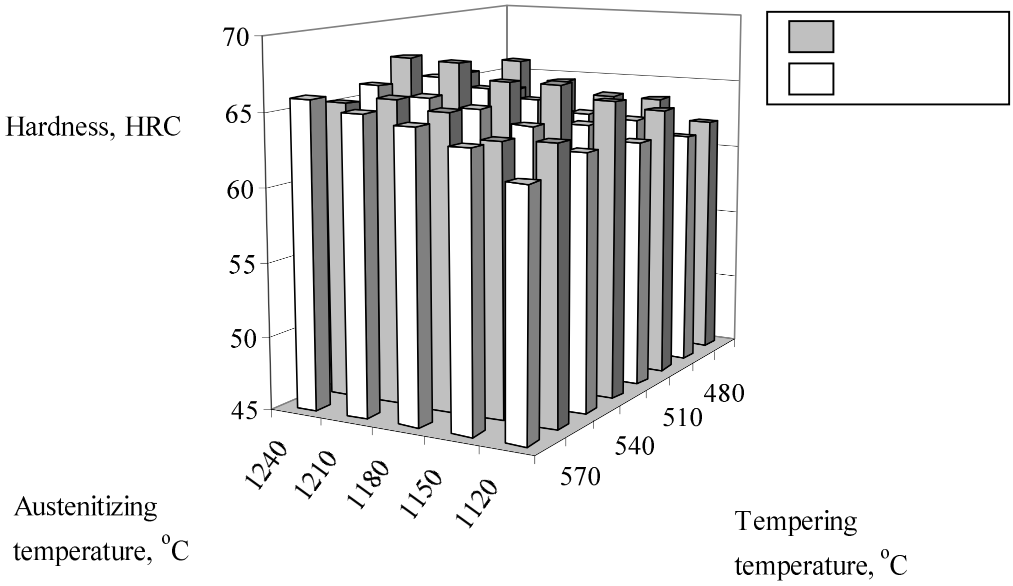
The investigations were carried out using specimens of the experimental high-speed steels: W-Mo-V-Co and W-V-Co of the 9-2-2-5, 11-2-2-5, and 11-0-2-5 types. The relevant chemical compositions are included in table 1.



Heat treatment of the specimens made from forged and soft-annealed bars was carried out in a battery of salt bath furnaces. The specimens were heated up to the austenitizing temperature in two stages, during 15 minutes at about 560°C and 850°C. The austenitizing was made at temperatures from 1120 to 1300°C, with gradation every 30°C within 50, 100, 200, 400 and 800 seconds. The specimens were quenched gradually with a 5-minute cooling in a salt bath at 560°C and then in the air, up to the ambient temperature. The specimens allocated for the measurement of primary austenite grain size were investigated in as-quenched state. The samples for structure and hardness investigations were once tempered for 2 hours at 480-600°C with gradation every 30°C. The structure examinations were carried follows methodology presented in paper [7,9].

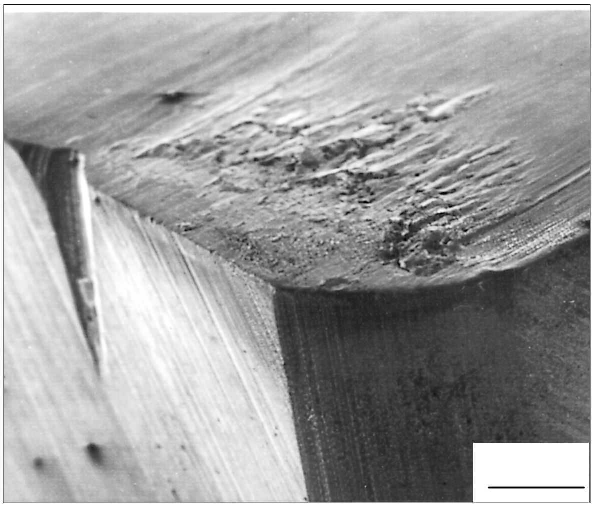
The cutting ability tests were carried out on an ES1 45 kW power experimental lathe. The machined material was, according to ISO 3685, the C45E4 type of steel, which had already been quenched and tempered. Cutting inserts were made from investigated high-speed steels heat treated in conditions secured the maximum secondary hardness effect, e.g., austenitized from 1240°C during 100 s and tempered from 540°C. Tool life was estimated basing on measurements of the width of the flank wear of the tool. They were made by measuring the average flank wear *VB* and the maximum VB_{max} after machining for the allocated time. Machining tests were being stopped when *VB* exceeded the value speciated for the roughing test, i.e., VB_k= 0.2 mm. The *VB* and VB_{max} measurements were taken with 0.01 mm accuracy, using the Carl Zeiss Jena 5226 microscope at 7x magnifying power.

The examinations of the erosion resistance of the investigated high-speed steels were performed with the Falex Air Jet Eroder of Falex Company. In this device the investigated specimen was set up at an angle of 20° to the jet and exposed to Al_2O_3 powder erosion agent with granularity of 70 μm and exhaust pressure of about 270 kPa. In order to estimate the erosive wear, a precise laboratory balance at measuring accuracy of 10^{-5} g was used to measure the mass decrement every 6 seconds. The results of investigations were evaluated and tabulated using the available computer software.

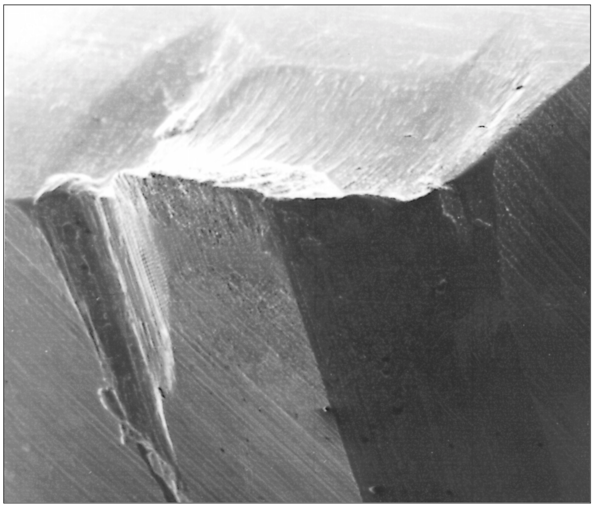


3. DISCUSSION OF THE RESULTS

As a result of the structure investigations it was found that there are no significant changes in structure of the investigated steels caused by the 5% cobalt and 2% molybdenum additions compared to steels without these additions. It was found out that structure of the all investigated steels, both cobalt and non-cobalt ones, there is the dislocated martensite, partially



Wear parameters			
VB, mm	VB_{max}, mm	KM, mm	t, min
0.05	0.23	0.38	2
Turning parameters			
V_c, m/min	f, mm/obr	a_p, mm	t, min
30	0.1	1.0	2



Wear parameters			
VB, mm	VB_{max}, mm	KM, mm	t, min
0.21	1.40	0.47	46
Turning parameters			
V_c, m/min	f, mm/obr	a_p, mm	t, min
30	0.1	1.0	46

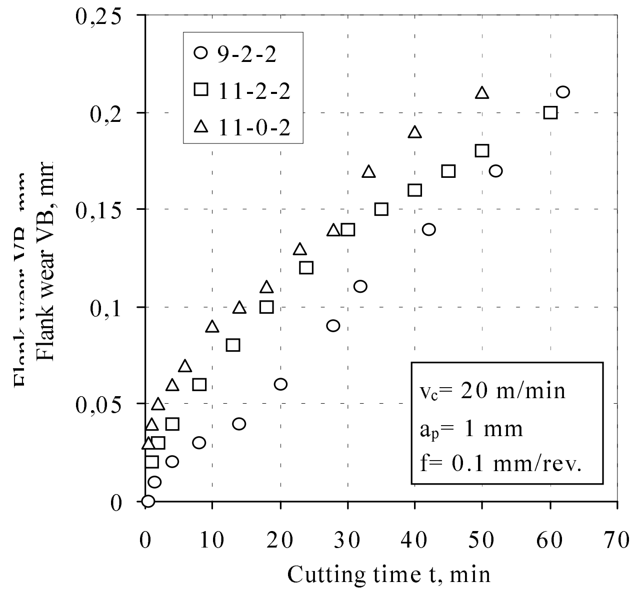
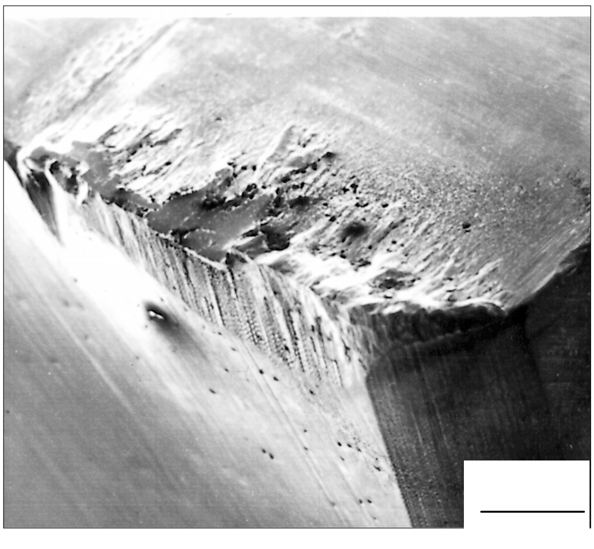


Figure 4 - Flank wear (*VB*) as a function of cutting time (*t*) for investigated cobalt high-speed steels.

twinned with the retained austenite and primary carbides of M_6C and MC types [7,9,20]. The retained austenite, similarly to other high-speed steels, fills areas between and it occurs in a form of thin layers between adjacent lathes of martensite (Fig. 1).

Hardness of the investigated steels in the as-quenched state is differentiated depending on the strengthening of the solid solution by cobalt, tungsten and molybdenum in steels with these additions and in each case by the precipitation strengthening of the austenite matrix by M4C3 carbides (Fig.1) and by martensite transformation of the retained austenite [1,2-



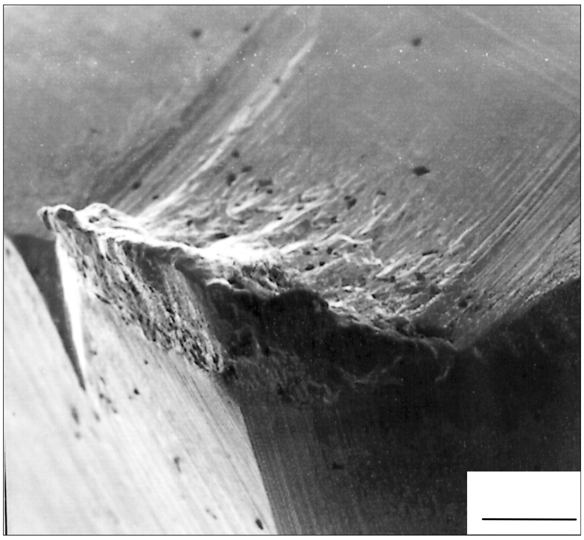
Wear parameters			
VB, mm	VB_{max}, mm	KM, mm	t, min
0.21	0.37	0.57	0.5

Turning parameters			
V_c, m/min	f, mm/obr	a_p, mm	t, min
30	0.1	1.0	0.5

Figure 6 - Flank wear (*VB*) as a function of cutting time (*t*) for non-cobalt high-speed steels.

14,19,22]. The increased hardness of investigated quenched and tempered cobalt steels, compared to equivalent grades without this element, is also caused by the strengthening of the solid solution by Co and, as it was proved before, by W and Mo [21]. This phenomenon is caused by presence of atoms of these substitutional elements in the solid solution, where they enable the axi-symmetrical strain of atomic lattice, develop stress fields around these atoms and limit the shifting of dislocation in material structure. The investigated high-speed steels of 9-2-2-5, 11-2-2-5, and 11-0-2-5 types show that the maximum secondary hardness effect is by 2-4 HRC higher than the hardness of these steels in the as-quenched state after austenitizing at 1240^{o}C for 100 s, after quenching and tempering at 540^{o}C. Cobalt influences the increase of the secondary hardness effect of quenched and tempered high - speed steels, adequately for 9-2-2-5 type by about 1.6 HRC, for 11-2-2-5 type by about 1.9 HRC and for 11-0-2-5 by about 1.7 HRC, compared to non-cobalt steels with identical concentration of the other alloying elements (Fig. 2).

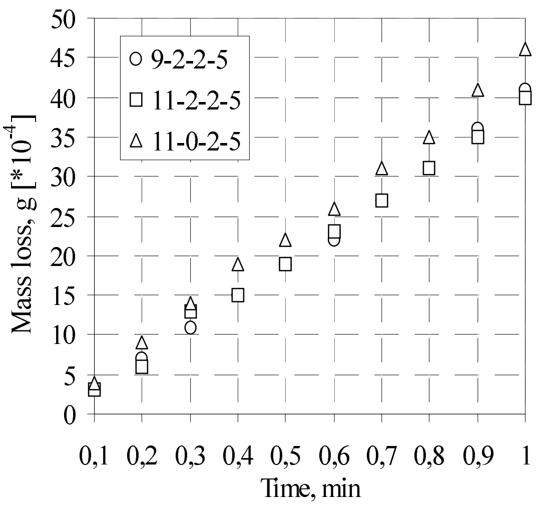
In order to find out the relation between hardness of investigated steels and working properties of tools made of these steels, the single point turning tests were carried out. Under identical turning parameters, within a given group of high-speed steels, one could specify cutting ability of the multipoint cutting tools made of the investigated steels, which were heat treated in conditions providing the maximum secondary hardness. As a result of performed investigations, it was found out that cobalt addition up to 5% makes it possible to machine at speed v_c = 30 m/min, at rate of feed f = 0.1 mm/rev. and at depth of cut a_p = 1.0 mm for 50-60 min, depending on a grade of steel. The longest tool life of the cutting tool demonstrates the steel of the 9-2-2-5 type, whose flank wear on a tool VB_k = 0.2 mm was exceeded after about 62 min, and the shortest – the steel of 11-0-2-5 type, whose VB_k = 0.2 mm was exceeded after about 50 min (Fig. 3,4). In case of machining cutting inserts made of non-cobalt high-speed steels it was found out that cutting speed v_c = 30 m/min at rate of feed f = 0.1 mm/rev. and at depth of cut a_p =1.0 mm, causes the criterion cutting edge wear VB_k = 0.2 mm after the very short working time (Fig. 5); therefore the speed is too high, which causes the reduction of cutting speed for these tests to v_c = 20 m/min, at unchanged rate of feed f and depth of cut a_p.

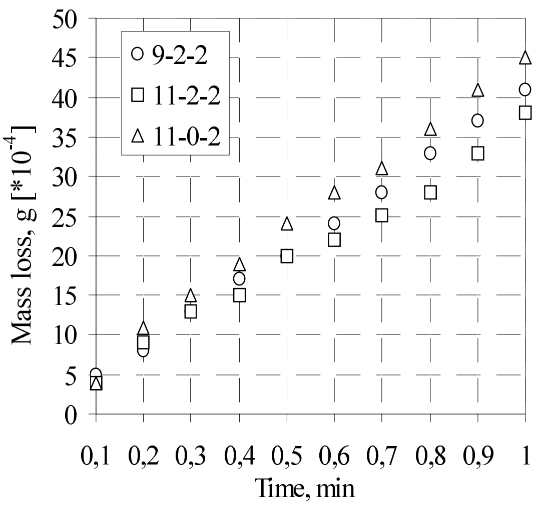


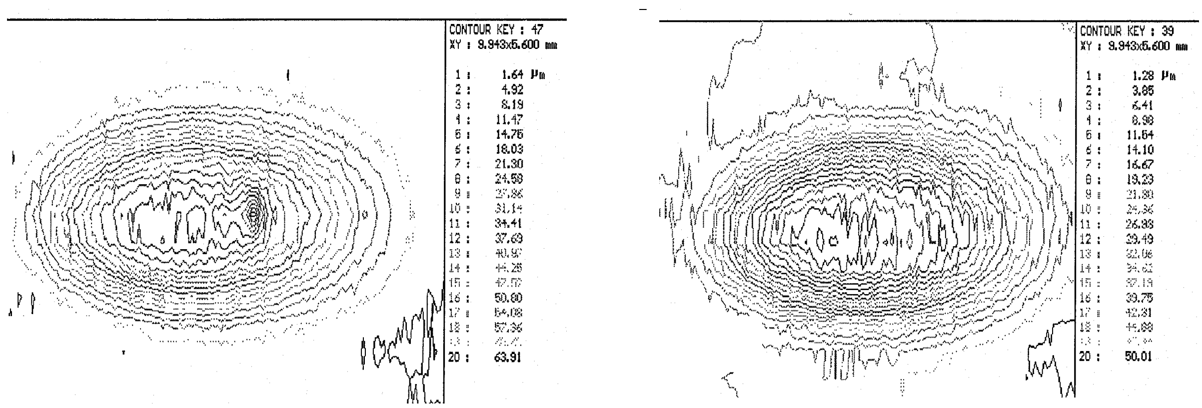
Wear parameters			
VB, mm	VB_{max}, mm	KM, mm	t, min
0.06	0.09	0.34	20
Turning parameters			
V_c, m/min	f, mm/obr	a_p, mm	t, min
20	0.1	1.0	20

Wear parameters			
VB, mm	VB_{max}, mm	KM, mm	t, min
0.21	0.26	0.53	62
Turning parameters			
V_c, m/min	f, mm/obr	a_p, mm	t, min
20	0.1	1.0	62

Under these parameters of machining it was maintained that the longest tool life is granted by the steels of 9-2-2 type, whose critical width of flank wear on a tool VB_k = 0,2 mm is exceeded after approximately 62 min. The shortest tool life is produced by the steel of 11-0-2 type, whose flank wear on a tool reaches the criterion rate after approximately 50 min (Fig. 6,7). It was also found out that of all the examined molybdenum high-speed steels, the W-Mo-V-Co and W-Mo-V steels of 9-2-2-5, 11-2-2-5 types, and correspondingly 9-2-2 and 11-2-2 steel types have a longer tool life of cutting edge than non-molybdenum W-V-Co steels of 11-







0-2-5 type and W-V steels of 11-0-2 type. This data conforms well with the results of hardness tests, as molybdenum W-Mo-V-Co steels of 9-2-2-5 and 11-2-2-5 types show hardness of approximately 67.6 and 67.2 HRC, and non-molybdenum W-V-Co steels of 11-0-2-5 type – lower, i.e., approximately 66.3 HRC. Similar analogies take place in case of non-cobalt steels – hardness of W-Mo-V steel of 9-2-2 and 11-2-2 types is relatively approximately 66 and 65.3 HRC, and hardness of W-V steels of 11-0-2 is 64.6 HRC. Lower hardness, typical of steels without 2% molybdenum addition, is probably connected with lower strengthening of the solid solution compared to molybdenum steels. Moreover, a characteristic of non-molybdenum steels, is lower volume fraction of primary carbides than in steels with this addition. The comparison of results of hardness measurements and of cutting ability tests makes it possible to claim that the increase of tool life of the investigated machining inserts, caused by 5% cobalt addition, is directly related to the increase of steel hardness. Basing on the hardness tests results of one can determine the ranking of working properties of tools made of these steels [7,20]. The comparison of the results of erosion resistance of investigated cobalt and non-cobalt high-speed steels shows that cobalt addition, however, does not affect erosion resistance, which is not dependent of hardness of investigated steels after heat treatment, either. Presumably, almost identical erosion resistance of all the investigated steels (Fig. 8,9,10) may depend on fraction of primary carbides and their morphology. It is noteworthy that the lowest erosion resistance was observed in the non-molybdenum steels, both with and without cobalt addition. Molybdenum is an element which participates in producing primary carbides of MC type and its concentration in them is from 2 to 10% in cobalt steels and from 4 to 5% in non-cobalt steels [7,20]. Cobalt introduced in to the investigated steels can increase their fraction in the matrix. These carbides of higher hardness, approximately 3000 HV0.02 compared to carbides of the M_6C type of hardness approximately 1500 HV0.02 can decide the higher erosion resistance, which is characteristic of molybdenum steels, both with and without cobalt addition [7,20].

4. CONCLUSIONS

After carrying out investigations of W-Mo-V-Co and W-V-Co high-speed steels of the 9-2-2-5, 11-2-2-5, and 11-0-2-5 types with economically designed chemical composition, including decreased to 9-11% concentration of tungsten, decreased to approximately 2% concentration of molybdenum and increased to approximately 1% concentration of silicon, it was found out that cobalt causes an increase of the maximum secondary hardness effect by 2-4 HRC after tempering the investigated steels at 540^o C and previous austenitizing at 1240^{o}C for 100 s, compared to hardness of the investigated steels in the as-quenched state. The maximum hardness, approximately 67.6 and 67.2 HRC, after quenching and tempering is reached by the 9-2-2-5 and 11-2-2-5 types of steel, the minimum hardness, approximately 66.3 HRC, by the 11-0-2-5 type of steel. The reason for the secondary hardness effect of the investigated both cobalt and non-cobalt high-speed steels is precipitation of M_4C_3 dispersion carbides in the matrix of the tempered martensite and transformation of the retained austenite into α phase, hardened by cobalt, tungsten and molybdenum in steels, in which this alloying element is present. Changes of the chemical composition do not affect structure of the investigated high-speed steels compared to non-cobalt and non-molybdenum steels. In all the cases in the as-quenched state the structure is a dislocation martensite with numerous twinnings as well as with the retained austenite and primary carbides of the MC and the M_6C types. The 5% cobalt addition results in possibility of a 1.5 times increase of cutting speed of tools made of cobalt steels, compared to the tools made of steels without this addition at the same life wear of the edge. Nevertheless, 5% cobalt addition does not influence the erosion resistance of the investigated cobalt steels, which does not depend on the increase of hardness caused by cobalt addition compared to non-cobalt steels with identical concentration of the other alloying elements. Although it is easy to perform erosion tests, they can not be used to estimate the efficiency of influence of the chemical composition of heat-treated high-speed steels on their cutting properties since, as it was discovered, there is no correlation between the results of these tests and of the cutting ones.

5. REFERENCES

[1] Ding P., Shi G. and Zhou S., Metall. Trans., 24A, (1993).

[2] Dobrzanski L.A. and Adamiak M., Powder Metallurgy World Congress, Granada, 1998.

[3] Dobrzanski L.A. and Ligarski M., Journal of Mat. Proc. Technology, 64 (1997) 101.

[4] Dobrzanski L.A. and Zarychta A., Journal of Mat. Proc. Technology, 77 (1998) 180.

[5] Dobrzanski L.A., Adamiak M. and Kasprzak W., Journal of Mat. Proc. Technology (in print).

[6] Dobrzanski L.A., Gegenwärtige Entwicklun-gstendenzen von gesinterten Werkzeugwerk-stoffen, Fachhochschule Würzburg-SchweinfurtAschaffenburg, Schweinfurt, (1995) 1.

[7] Dobrzanski L.A., Kasprzak W. J. Mat. Proc. Techn. (in print).

[8] Dobrzanski L.A., Kasprzak W., Adamiak M., Sokovic M., D'Errico G. and Bugliosi S., 4th Int. Conf. „Advances in Materials & Processing Technologies AMPT'98", Malaysia (1998) 772.

[9] Dobrzanski L.A., Kasprzak W., Zarychta A., Ligarski M. and Mazurkiewicz J., J. Mat. Proc. Techn., 64 (1997) 93.

[10] Dobrzanski L.A., M. Adamiak and D'Errico E., Proc. Of the Intern. Conf. on Advances in Materials and Processing Technologies (AMPT'97), University of Minho, Gusmaraes, 1 (1997) 306.

[11] Dobrzanski L.A., Proc. 2nd Australian Int. Conf. Surface Engineering, Coating and Surface Treatments in manufacturing, Adelaide, 1 (1994) 55.

[12] Dobrzanski L.A., Proc. Int Conf. Advances in Materials and Processing Technologies, AMPT'93, Dublin, 3 (1993) 1867.

[13] Dobrzanski L.A., Proc. Int. Conf. Advances in Materials and Processing Technologies AMPT'93, Dublin, 3 (1993) 1849.

[14] Dobrzanski L.A., Zarychta A. and Ligarski M., Journal of Mat. Proc. Technology, 63 (1996) 531.
[15] Gümpel P. and Haberling E., TEW Tech. Ber., 5 (1979) 129.
[16] Gümpel P. and Haberling E., Thyssen Edelst. Tech. Ber., Spec. Issue, 13 (1983).
[17] Haberling E., TEW Tech. Ber., 13 (1987) 93.
[18] Hoyle G., High Speed Steels, Butterworth & Co., Ltd, The University Press, Cambridge (1988).
[19] Karagöz S. and Andrén H.-O., Z. Met., 83 (1992) 386.
[20] Kasprzak W., doctoral thesis, Gliwice (1998).
[21] Pickering F.B., Physical metallurgy and the design of steels, Applied Science Publishers Ltd, London, (1978).
[22] Rong W., Andrén H.-O., Wisell H. and Dunlop G.L., Acta Metall. Mater., 40 (1992) 1727.