



Properties of Cemented Carbides Alloyed by Metal Melt Treatment

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Summary:

The paper presents the results of investigations into the influence of alloying elements introduced by metal melt treatment (MMT-process) on properties of WC-Co and WC-Ni cemented carbides. Transition metals of the IV - VIII groups (Ti, Zr, Ta, Cr, Re, Ni) and silicon were used as alloying elements. It is shown that the MMT-process allows cemented carbides to be produced whose physico-mechanical properties (bending strength, fracture toughness, total deformation, total work of deformation and fatigue fracture toughness) are superior to those of cemented carbides produced following a traditional powder metallurgy (PM) process. The main mechanism and peculiarities of the influence of alloying elements added by the MMT-process on properties of cemented carbides have been first established. The effect of alloying elements on structure and substructure of phases has been analyzed.

Keywords:

Cemented carbide, properties, metal melt treatment, alloying elements

1. Introduction:

Cemented carbides are, as a rule, alloyed by adding a chemical element to the initial mixture of powders from which specimens are prepared following a traditional PM technology. It should be noted that addition of an alloying element to the mixture can significantly change conditions of the formation of cemented carbides during sintering. Thus, additions of V, Ta and Cr favor the formation of very fine-grained structure [1].

At present a new technology is developed of treatment of as-sintered carbide articles with a metal melt (MMT-process) [2], which allows both local and bulk alloying of cemented carbide articles. The MMT-process is based on the

phenomena of the metal melt imbibition by sintered pore-free composition materials [3]. One of the special features of the MMT-process is the reconstruction of a high-melting skeleton during the metal melt imbibition. This can affect the cemented carbide properties. Our studies have shown that the common practice for alloying cemented carbides and the adding of alloying elements by the MMT-process differ essentially. The data on the influence of alloying elements on properties of cemented carbides produced by a traditional technique cannot be applied to cemented carbides prepared by the MMT-process. There is only small quantity of publications concerned with alloying cemented carbides by the MMT-process [2, 4, 5]. For this reason, a need has arisen for generalizing the findings [2, 4, 5] and to supplement them with our new results.

2. Experimental:

Studied were WC–Co and WC–Ni cemented carbides. To alloy the cemented carbides, metals Ti, Zr, Ta, Cr, Re, Ni and silicon were used. At first we take a look at the procedure used to study WC–Co cemented carbides. The initial specimens were made using a traditional PM method from WC–6Co cemented carbide. The specimens contained 6.0 mass % Co, 94.0 mass % WC, graphite and the η_1 -phase were not present. The specimens were dipped in cobalt melts alloyed with the above elements (except for Re) in a vacuum furnace at 1390 °C. The cobalt melt alloyed with Re was heated to 1410 °C. Compositions of the melts used in tests are given in Table 1. The metal melts were saturated on carbon and tungsten, which was due to the introduction of excess W and C into the melts. The specimens were held in the cobalt melt for 20 s. During that time the specimens imbibed the cobalt melt together with alloying elements. Thereupon the specimens were removed from the melt and subjected to homogenizing annealing at the same temperature for 600 s. During annealing the liquid phase content and composition equalized throughout the bulk specimens. Once the cobalt melt had been imbibed, the binder content of the specimens increased from 6.0 mass % to 9.5±0.1 mass % (15.5 vol %). Specimens whose binder content was not in that range were rejected. Every alloying element and as-received test specimen were given a serial number, a binder elemental composition was specified. For comparison, cemented carbide specimens (9.5 mass % Co + 90.5 mass % WC) were prepared following a traditional technology (compaction of the mixture followed by sintering). The specimens were designated WC-10Co. In WC–Co cemented carbides, the binder was a

solid solution of W and C in Co. Hereafter the solution will be subsequently referred to as “ β -phase”.

Table 1. Compositions of metal melts

Melt	Composition, mass %				
	Co	Ni	W	C	Alloying element
1(Co)	65.0	-	32.8	2.2	-
2(Co, Ti)	65.0	-	28.2	2.8	4.0 Ti
3(Co, Zr)	65.0	-	28.2	2.8	4.0 Zr
4(Co, Ta)	65.0	-	27.8	2.2	5.0 Ta
5(Co, Cr)	65.0	-	27.7	2.3	5.0 Cr
6(Co, Ni)	35.0	30.0	32.8	2.2	-
7(Co, Re)	31.0	-	32.2	2.8	34.0 Re
8(Co, Si)	65.0	-	30.8	2.2	2.0 Si
9(Co, Ni, Si)	35.0	30.0	30.8	2.2	2.0 Si
10(Ni)	-	65.0	32.8	2.2	-
11(Ni, Re)	-	31.2	32.0	2.9	33.9 Re
12(Ni, Si)	-	65.0	30.2	2.3	2.5 Si
13(Ni, Re, Si)	-	32.0	30.1	2.9	32.5 Re, 2.5 Si

The composition and structure of the specimens were studied by optical, SEM and TEM methods as well as by X-ray spectrum and X-ray diffraction analyses following the procedures described in [2, 4 - 6]. To study the effect of mechanical stresses on cobalt polymorphic transformation in the β -phase, the specimens were annealed in vacuum at 950 °C for 1800 s and allowed to cool. Some of the specimens were subjected to cyclic three-axial compression at 1500 MPa (10 cycles). X-ray diffraction analysis and transmission electron microscopy were used to determine the content of Co_{fcc} and Co_{hcp} polymorphic phases.

Specific surface of WC particles (S_V^{WC}) and specific WC/Co interface ($S_V^{WC/Co}$) were measured on an optical microscope (2000x magnification) by the method of superposition of random intercepts. Relative errors of measurements did not exceed 5% with a degree of certainty of 0.95. Particle contiguity (C_{WC}) was calculated from the equation put forward by Gurland

$$C_{WC} = 2N_{WCWC} / (2N_{WCWC} + N_{WC/Co}),$$

where N is the number of intercepts of the secant and the contact surface (WC/WC) and the interface (WC/Co) per unit intercept length.

Stereological characteristics of the test specimen structures are listed in Table 2.

Table 2. Structure of WC–Co specimens

Specimen designation	Phase composition, vol%		Stereological characteristics of the specimen structure			
	WC	β -phase	S_V^{WC} , mm^2/mm^3	$S_V^{WC/Co}$, mm^2/mm^3	C_{WC}	d_{WC} , μm
WC-6Co	90.0	10.0	2160	660	0.694	3.60
WC-10Co	84.5	15.5	2140	805	0.623	3.63
1(Co)	84.5	15.5	2120	910	0.570	3.64
2(Co, Ti)	84.5	15.5	2140	915	0.572	3.62
3(Co, Zr)	84.5	15.5	2140	910	0.572	3.62
4(Co, Ta)	84.4	15.6	2160	920	0.574	3.50
5(Co, Cr)	84.4	15.6	2160	920	0.574	3.56
6(Co, Ni)	84.4	15.6	2140	920	0.570	3.64
7(Co, Re)	84.6	15.4	2100	905	0.570	3.67
8(Co, Si)	84.4	15.6	2140	950	0.556	3.63
9(Co, Ni, Si)	84.4	15.6	2140	950	0.556	3.63

The bending strength (σ_{bend}) and the fracture toughness (K_{Ic}) were measured according to the ISO Standards. The compression strength (σ_{comp}), yield stress ($\sigma_{0.1}^c$) and total deformation (ε_{tot}) were measured on cylindrical specimens 8 mm in diameter and 16 mm in height. From the compression diagram, which was constructed on the load - deformation coordinates, plastic and elastic components of deformation (ε_{pl} and ε_{el} , respectively) as well as the total work of deformation (A_{tot}) and its plastic (A_{pl}) and elastic (A_{el}) components were calculated. The $A_{\text{pl}}/A_{\text{el}}$ ratio is the energy absorbability coefficient (λ) of a material [7]. The λ coefficient was calculated for all test specimens.

The microhardness (H_{μ}) and the elastic modulus (E) of the β -phase were measured on a Nano Indenter II device under a varying load, which increased

up to 10 μN at a rate of 1 $\mu\text{N/s}$. The specimens were held under that load for 20 s and then unloaded at a rate of 1 $\mu\text{N/s}$. The load measuring error was ± 75 nN.

To evaluate the effect of alloying elements on the β -phase properties, alloys of the composition identical with that of the β -phase in specimens 1 through 9 were additionally prepared from which specimens 8 mm in diameter and 16 mm in height were casted. These specimens were tested for compressive yield stress and ultimate strain. The results are tabulated in Table 3. It should be noted that the tabulated values of the yield stress ($\sigma_{0.1}^c$) and deformation (ε) were measured on bulk specimens, and for this reason, as applied to thin interlayers of the β -phase in the specimens, these data should be used as approximate ones.

Table 3. Composition and properties of the β -phase

Specimen designation	Chemical composition of the β -phase*, mass %			Phase composition of the β -phase**		Properties of the β -phase			
	W	Co	Alloying elements	As-annealed	As-pressure-treated	H_{μ} , GPa	E , GPa	$\sigma_{0.1}^c$, MPa	ε , %
WC-6Co	12.4	87.6	-	α	$\alpha+\varepsilon$	5.8	264	0.30	19.8
WC-10Co	12.2	87.8	-	α	$\alpha+\varepsilon$	5.8	265	0.30	19.8
1(Co)	11.6	88.4	-	α	$\alpha+\varepsilon$	5.8	264	0.30	19.8
2(Co, Ti)	11.5	88.3	Ti < 0.2	α	$\alpha+\varepsilon$	5.4	265	0.31	19.2
3(Co, Zr)	11.6	88.2	Zr < 0.2	α	$\alpha+\varepsilon$	5.6	268	0.32	19.4
4(Co, Ta)	11.5	88.3	Ta < 0.2	α	$\alpha+\varepsilon$	5.5	284	0.34	19.6
5(Co, Cr)	11.8	85.1	3.1 Cr	α	$\alpha+\varepsilon$	5.9	250	0.32	19.0
6(Co, Ni)	12.1	68.9	19.0 Ni	α	α	3.9	262	0.21	29.8
7(Co, Re)	9.2	69.6	21.2 Re	$\alpha+\varepsilon$	$\alpha+\varepsilon$	7.9	348	0.45	19.0
8(Co, Si)	9.1	89.7	1.2 Si	$\alpha+\varepsilon$	$\alpha+\varepsilon$	5.9	272	0.34	19.6
9(Co, Ni, Si)	10.5	69.8	18.5 Ni 1.2 Si	α	α	3.9	260	0.25	28.9

* Chemical composition is given without regard for the carbon content.

** α - and ε -phases stand for Co_{fcc} and Co_{hcp} , respectively.

The cyclic fracture toughness experiments were performed on SENB cemented carbide specimens measuring 5×5×35 mm [4, 5] in resonance mode in the 280 to 330 Hz range under asymmetric loading cycle (the asymmetry coefficient was 0.5 - 0.8). The load for each lot of specimens was selected by experiments such that the time of the fatigue crack initiation from the notch was the same for all the specimens and was limited by a base of 400,000 cycles. The test results were represented as a fatigue failure diagram constructed on the fatigue crack growth rate (lgv) - stress intensity factor (K_I) semilog coordinates. From the diagram, a relative threshold stress intensity factor (K_{th}) and a relative critical stress intensity factor (K_{fc}) were determined for each lot of specimens. The K_{th} and K_{fc} coefficients were measured as the stress intensity factor K_I at the fatigue crack growth rate v of 10^{-9} m/cycle and 10^{-6} m/cycle, respectively.

To study the effect of alloying elements on physico-mechanical properties of WC–Ni cemented carbides, initial specimens of WC-6Ni cemented carbide (6.1 mass % Ni, 93.9 mass % WC) were prepared following a common procedure. After treatment with the 10(Ni) melt, the composition of the above specimens was as follows: 9.5 ± 0.1 mass % Ni and 90.5 mass % WC, average WC particle size was 2.3 μm . The WC-6Ni specimens were alloyed with Re and Si using 11(Ni, Re), 12(Ni, Si) and 13(Ni, Re, Si) melts following the above procedure.

3. Results and discussion:

Our findings have shown that Ti, Zr, Ta, Cr, Ni, Re and Si alloying elements did not exert any action on the composition and structure of WC. These elements had an impact on the compositions and structures of the β -phase and interfaces.

The WC-10Co specimens prepared by a traditional procedure and the 1(Co) specimens produced from WC-6Co cemented carbide by the MMT-process were the same in composition, the β -phase and WC contents, the size of WC particles, and differed in values of specific interface $S_V^{WC/Co}$ (see Tables 2 and 3). The 1(Co) specimen featured a more developed WC/Co interface which was responsible for higher values of bending strength, work of deformation, the coefficient λ , and plastic and fatigue characteristics as compared with the WC-10Co specimen (Table 4). The develop WC/Co surface of the 1(Co) specimen formed during the imbibition of the cobalt melt. This process was accompanied by a partial fracture of the carbide skeleton [3]. Thus, using the

MMT-process, one can produce cemented carbides with higher mechanical properties. In the subsequent discussion we will compare physico-mechanical properties of alloyed specimens with those of the 1(Co) specimen used as a reference.

The findings of our investigations have shown that Ti, Zr and Ta alloying elements did not exert a pronounced effect on the composition, properties and structure of the β -phase as well as on the stereological properties of the specimens under study. X-Ray spectrum analysis did not reveal the above elements in the β -phase as their content was below the instrumental resolution (0.15 mass %). Specimens 2(Co, Ti), 3(Co, Zr) and 4(Co, Ta) exhibited lower σ_{bend} values and the fatigue characteristics as compared to the reference specimen 1(Co), the other properties were comparable with those of the reference specimen. Electron microscopy has revealed that these elements deposit at the WC/WC and WC/Co interfaces as submicron particles of complex carbides [5]. These particles weaken the interfaces, which is likely to be the cause of lower σ_{bend} values.

Table 4. Physico-Mechanical properties of WC–Co cemented carbides alloyed by the MMT-process

Specimen designation	K_{IC} , MPa·m ^{0.5}	σ_{bend} , MPa	σ_{comp} , MPa	$\sigma_{0.1}^c$, MPa	$A_{\text{def}}^{\text{tot}}$, MJ/m ³	A_{pl} , MJ/m ³	λ	ϵ_{tot} , %	ϵ_{pl} , %	K_{th} , MPa·m ^{0.5}	K_{fc} , MPa·m ^{0.5}
WC–6Co	12.3	2000	5000	4620	65	33	1.0	1.1	0.5	6.8	10.6
WC–10Co	14.6	2310	4550	4010	78	46	1.4	1.4	0.8	7.4	11.0
1(Co)	14.9	2530	4460	3890	84	53	1.7	1.8	1.1	8.0	11.7
2(Co, Ti)	14.2	2410	4460	3890	80	49	1.6	1.8	1.1	7.7	11.4
3(Co, Zr)	14.1	2420	4460	3890	80	50	1.7	1.8	1.1	7.9	11.6
4(Co, Ta)	14.3	2450	4480	3940	90	58	1.8	1.9	1.2	7.2	11.9
5(Co, Cr)	14.4	2480	4480	4020	91	59	1.8	2.0	1.3	8.0	11.6
6(Co, Ni)	15.3	2460	4340	3780	101	71	2.4	2.4	1.7	9.7	13.2
7(Co, Re)	12.0	2720	4680	4290	77	43	1.3	1.6	0.8	7.0	10.7
8(Co, Si)	14.9	2620	4470	3820	90	62	2.2	2.2	1.5	8.7	12.6
9(Co, Ni, Si)	15.3	2680	4370	3780	110	78	2.5	2.6	1.8	10.2	13.8

Chromium dissolved partially in the β -phase, however it did not cause any pronounced changes either in its properties or in the stereological characteristics of the specimens. The effect of Cr on elastic and plastic properties of the specimens was unessential as well. Addition of Ni caused a marked improvement in plastic and fatigue characteristics of the specimens

(see Table 4), in this case, a slight decrease in σ_{bend} and σ_{comp} was observed as compared with the reference 1(Co) specimen. It should be noted that nickel did not affect stereological characteristics of the specimen structure, but changed the phase composition of the β -phase. Nickel stabilized the cubic modification of cobalt in the β -phase. Cubic modification of Co (Co_{fcc}) is more plastic phase as compared to hexagonal modification of Co (Co_{hcp}), as it has four planes of easy slippage in the $\langle 110 \rangle \{111\}$ system, while Co_{hcp} has only one plane of easy slippage [8]. This means that in cemented carbides in which the β -phase has a cubical crystal lattice, stress relaxation proceeds easily by the β -phase deformation. These processes have been responsible for both lower H_{μ} values of 6(Co,Ni) specimens and higher plastic characteristics of the β -phase as compared to the 1(Co) specimen. It should be noted that in as-annealed 1(Co), 2(Co, Ti), 3(Co, Zr), 4(Co, Ta), and 5(Co, Cr) specimens, cobalt in the β -phase was in its cubic modification (Co_{fcc}), however, under the action of stresses induced by volume compression partial $\text{Co}_{\text{fcc}} \rightarrow \text{Co}_{\text{hcp}}$ transformation took place thus reducing the plastic properties of the β -phase (see Table 3). It is clear from these findings that in testing the above specimens for strength as well as in hardness testing, the $\text{Co}_{\text{fcc}} \rightarrow \text{Co}_{\text{hcp}}$ polymorphic transformation occurs in the β -phase too, thus affecting the specimen properties [9].

Rhenium formed the Co(Re, W, C) solid solution in the β -phase which had high H_{μ} , E and $\sigma_{0.1}^c$ values. From our investigations (see Table 3), the as-annealed specimens showed the presence of Co_{hcp} interlayers in the β -phase. The volume compression of the 7(Re, Co) specimens promoted further $\text{Co}_{\text{fcc}} \rightarrow \text{Co}_{\text{hcp}}$ transformation, as evidenced by an increase in the characteristic line intensity in X-ray patterns. Our previous electron microscopic observations have also shown that Re facilitates the $\text{Co}_{\text{fcc}} \rightarrow \text{Co}_{\text{hcp}}$ polymorphic transformation in the β -phase [10]. These changes in the β -phase were responsible for higher elastic properties (σ_{comp} , $\sigma_{0.1}^c$) and lower plastic properties (ε) in the 7(Co, Re) specimens. Also, lower values of K_{IC} , work of deformation and the energy absorbability coefficient λ were obtained for these specimens. Analysis of both the structure of the 7(Co, Re) specimens and the composition and structure of the β -phase does not allow the explanation of the ultimate bending strength growth. An additional lot of Re-alloyed specimens was prepared using a traditional technology. The binder content of those specimens was 16.1 vol%, the size of WC particles was 3.81 μm . The β -phase contained 20.8 mass % Re and 9.0 mass % W. The ultimate bending strength of the specimens was

2200 MPa, i.e. below the values for the WC-10Co and 1(Co) specimens. Thus, an increase of σ_{bend} up to 2720 MPa for 7(Co, Re) specimen is the phenomenon of the MMT-process and calls for further investigation.

Our findings have shown that addition of silicon facilitated formation of more developed $S_V^{\text{WC/Co}}$ interface in the 8(Co, Si) specimens. Despite the fact that compared to the reference 1(Co) specimen, an increase in $S_V^{\text{WC/Co}}$ was only $40 \text{ mm}^2/\text{mm}^3$, which is within the interface measuring error, this result is considered to be reliable, as it is reproduced in all Si-alloyed specimens and was proved by us in [2]. Also, silicon is a surfactant in the Co melt [2], breaks the carbide skeleton very actively when penetrating into cemented carbides [11] and is adhesion active at the WC/Co interface [2]. Combined action of the above factors allowed an increase in ultimate bending strength, work of deformation, coefficient λ and plastic characteristics of the 8(Co, Si) specimens (see Table 4). Addition of Si decreased the W solubility in the β -phase of the 8(Co, Si) specimens to 9.04 mass %. A decrease of the W solubility in the β -phase of WC-Co cemented carbides produced by a traditional procedure reduces physico-mechanical properties of the alloys [12]. In addition, according to our findings presented in this paper and the data given in [2], silicon, as well as rhenium, contributes to the $\text{Co}_{\text{fcc}} \rightarrow \text{Co}_{\text{hcp}}$ polymorphic transformation thus reducing plastic characteristics of cemented carbides. In case where Si is added by the MMT-process, the effect of these negative factors is compensated for by a number of the above-enumerated positive factors peculiar to the MMT-process (an increase in the WC/Co interface, a partial breakage of the carbide skeleton, etc.).

Combined alloying of specimens with nickel and silicon, increases plastic and elastic properties of the 9(Co, Ni, Si) specimens due to the joint action of these elements on the specimens' structure and composition. Despite the presence of Si, cobalt in the β -phase of the 9(Co, Ni, Si) specimens was in its cubic modification. This fact was responsible for higher values of the work of deformation, the λ coefficient and plastic characteristics of cemented carbide. Of special interest are values of fatigue fracture toughness of alloyed specimens (see Table 4). The 1(Co) specimens produced by the MMT-process surpassed the WC-10Co specimens in fatigue behavior. Ti, Zr, Ta, and Cr, alloying elements affected only slightly the specimens' fatigue fracture toughness. Addition of Ni and Si considerable increased the fatigue fracture toughness and particularly in the case of combined alloying (Ni + Si) of the 9(Co, Ni, Si) specimens. Addition of Re reduced the value of this parameter.

The influence of both the MMT-process and alloying elements on the fatigue fracture toughness is explained from the mechanism of the fatigue cracks initiation. Under fatigue loading, Co_{fcc} transforms into Co_{hcp} in the β -phase [9], the β -phase loses its plastic properties and the ability to relax local stresses. For this reason, microcracks initiate at the WC/Co and WC/WC interfaces, extend along these interfaces and arrest in the β -phase interlayers. Silicon, as a surfactant, can greatly improve the adhesion between the β -phase and WC particles, thus retarding the fatigue microcracks initiation at interfaces. Nickel, which stabilizes the Co cubic modification in the β -phase, preserves its high ability to retard the microcracks development in the β -phase. Combined action of Ni and Si enhances the above effects and allows one to improve the fatigue characteristics of WC-Co cemented carbides.

A high elasticity of the Co(Re, W, C) solid solution, the presence of a great amount of the Co_{hcp} in the β -phase contributed to the microcracking of the β -phase thus decreasing the fatigue fracture toughness of the 7(Co, Re) specimens. A special feature of the WC-Co cemented carbides is that the alloying elements under consideration did not affect the WC carbide phase, but changed the composition and the structure of the β -phase and the interfaces. Analysis of the experimental results (see Tables 2 - 4) has shown that elements which show a great affinity for carbon, e.g., Ti, Zr, and Ta, affected, mainly, the composition and the structure of the WC/Co and WC/WC interfaces. These data are supported by TEM observations [5]. Analysis of our findings allows us to predict the same dependence of the WC-Co properties on Hf and Nb. Chromium dissolves partially in the β -phase, affect its structure and properties only slightly, and for this reason its influence on the WC-Co properties is of no significance. It should be noted that V, Nb, Ta and Cr added into the WC-Co cemented carbide by a traditional technology strongly affect the cemented carbide structure formation during liquid-phase sintering, which makes it possible to produce very fine-grained cemented carbides [1]. These elements when added by the MMT-process does not affect the size of WC particles because they penetrate into the cemented carbide after termination of liquid-phase sintering.

A strong influence of Re and Ni on the WC-Co cemented carbide properties is due to substantial changes in the β -phase composition, structure and properties. We believe that Ru, Os and Ir will influence the cemented carbide properties just in the same manner as Re does. When alloying WC-Co cemented carbides with the above elements, one should take into account that Ru and Os contribute to the $\text{Co}_{\text{fcc}} \rightarrow \text{Co}_{\text{hcp}}$ polymorphic transformation, while Ir stabilizes the Co cubic modification.

Our investigations make it possible to decide on the methods of alloying WC-Ni cemented carbides by the MMT-process. In these cemented carbides, the binding metal (the Ni(W, C) solid solution) has a stable cubic modification and is a plastic material. For this reason, the most efficient elements added by the MMT-process are Re, Ru and Si. Our experiments on specimens prepared by the above procedure supported this idea (Table 5). Addition of Re and Si allowed higher values of σ_{bend} , σ_{comp} and $\sigma_{0.1}^c$ to be obtained with retaining a high level of plastic characteristics of the WC-Ni cemented carbide.

Table 5. Physico-mechanical properties of WC-Ni cemented carbides by the MMT-process

Specimen designation	K_{Ic} , MPa·m ^{0.5}	σ_{bend} , MPa	σ_{comp} , MPa	$\sigma_{0.1}^c$, MPa	$A_{\text{def}}^{\text{tot}}$, MJ/m ³	A_{pl} , MJ/m ³	λ	ϵ_{tot} , %	ϵ_{pl} , %
WC-6Ni	13.0	1900	4620	4270	72	41	1.3	1.2	0.7
10(Ni)	16.0	2380	4110	3540	121	90	2.9	2.7	2.0
11(Ni, Re)	15.8	2500	4500	3920	119	87	2.7	2.6	1.9
12(Ni, Si)	16.1	2590	4490	3860	120	90	3.0	2.7	1.9
13(Ni, Re, Si)	15.9	2640	4520	3940	122	89	2.7	2.7	1.9

4. Conclusions:

Cemented carbides produced following the MMT procedure possess higher physico-mechanical properties as compared with those produced by traditional PM methods. The properties of WC-Co and WC-Ni cemented carbides are strongly affected by alloying elements. They alter the composition, structure and state of a binder metal as well as of WC/Co, WC/Ni and WC/WC interfaces. Alloying WC-Co, WC-Ni cemented carbides using the MMT-process allows one to obtain physical and mechanical properties in just the right combination, i.e. high levels of both elastic and plastic characteristics. Alloying elements, which stabilize the cubic modification of cobalt in the binder and improve adhesion between the binder and the carbide phase, considerably increase the fatigue fracture toughness of cemented carbides.

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