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Wear Performance of WC- and TiC-Based Ceramic-Metallic Composites

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Declaration:

Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

/Tõnu Roosaar/

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MASINA- JA APARAADIEHITUS E55

WC- ja TiC-baasil keraamilis-metalsete komposiitide kulumiskindlus

TÕNU ROOSAAR

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CONTENTS

FOREWORD

Combination of desirable properties of different materials is met in composites. Modern composites are a success story from viewpoint of many applications. One of promising fields of composite application is their use under condition of two one more bodies interacting, *e.g.* tribological application where resistance of wear becomes an important factor to improve durability of tools and other wear parts.

In any manufacturing process where materials are in contact with each other the wear is present. Wear resistance is one major characteristics of solid materials used in mechanical engineering. Almost all machines lose their durability and reliability due to wear and the possibilities of new advanced machines are reduced because of wear problems. It has effect on the component lifecycle and also for the total cost of final product. Therefore, wear control has become a strong need for the advanced and reliable technology of the future.

Due to the wide range of materials used and tribosystems appearing in machines as well as manufacturing processes this thesis focuses only on the tribological behavior of carbide composites and their performance as tool materials for metalforming (blanking).

In this thesis relationships between actual tool wear during blanking and used tool materials behavior in different wear conditions (abrasive wear, adhesive wear, sliding wear) are considered.

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Finally I would like to thank my parents and friends for their encouragement and patience.

LIST OF PUBLICATIONS

The present dissertation is based on the following publications, which are referred in the text by the Roman numerals I – IV.

I H. Klaasen, J. Kübarsepp, T. Roosaar, M. Viljus, R. Traksmaa, Adhesive wear performance of hardmetals and cermets, Wear (2010) 268, 1122–1128.

II H. Klaasen, T. Roosaar, J. Kübarsepp, A. Tšinjan, Performance and failure of carbide composites in different wear conditions, Proceedings of European Powder Metallurgy Conference & Exhibition Euro PM2009, 12–14 October 2009, Copenhagen, Denmark, European Powder Metallurgy Association, (2009) 317–322.

III J. Kübarsepp, H. Klaasen, T. Roosaar, M. Viljus, R. Traksmaa, Abrasive wear performance of carbide based composites, Proceedings of European Powder Metallurgy Congress & Exhibition EURO PM2007 Toulouse, France, 15–17 October 2007, European Powder Metallurgy Association, (2007) 221 – 226.

IV T. Roosaar, J. Kübarsepp, H. Klaasen, M. Viljus, Wear Performance of TiC-base Cermets, Materials Science (Medžiagotyra) (2008) 14(3), 238 – 241.

V H. Klaasen, J. Kübarsepp, T. Roosaar, F. Sergejev, A. Talkop, Performance of carbide composites in cyclic loading conditions. Proceedings of European Powder Metallurgy Conference & Exhibition Euro PM2008, Mannheim, Germany, 28 September – 1 October 2008, European Powder Metallurgy Association, (2008) 237 – 242.

The author’s contribution

The author of this thesis took part in the sample preparation routine. Also he carried out experiments collected, processed and further analyzed the experimental data (Papers I–V). The author also took part in the discussion on the content (of the current thesis) (Paper I–V) and participated in compiled manuscripts (paper I–IV). The intellectual merit which is the result of the framework where the contribution of every author of related papers should not be underestimated.

APPROBATION INTERNATIONAL CONFERENCES

1. European Powder Metallurgy Conference & Exhibition Euro PM2007, Toulouse, France, October, 15–17, 2007;
2. The 13th International symposium NORDTRIB 2008, Tampere, Finland, June 10–13, 2008;
3. European Powder Metallurgy Conference & Exhibition Euro PM2008, Mannheim, Germany, 28.09–1.10.2008;
4. The 17th International Baltic Conference “Materials Engineering 2008”, Kaunas, Lithuania, November, 06-07, 2008;
5. European Powder Metallurgy Conference & Exhibition Euro PM2009, October 12–14, 2009, Copenhagen, Denmark.

ABBREVIATIONS, TERMS AND SYMBOLS

Abbreviations
ASTM – American Standards for Materials Testing
HIP – Hot Isostatic Pressing,
HRA – Rockwell hardness number
HV – Vickers hardness number
P/M – Powder metallurgy
SEM – Scanning Electron Microscope
Sinter/HIP – Compression Sintering – concurrent vacuum sintering and hot isostatic pressing
TUT – Tallinn University of Technology
XRD – X-ray Diffraction

Terms and symbols
$1/V$ – abrasive wear resistance
B – broadness of X-ray reflections line
E – modulus of elasticity (Young's modulus)
F – loading during sliding wear
H – depth of groove measured from cutting edge
I – intensity of X-ray reflection line
L – wear length during sliding wear
L_1 – adhesive wear resistance
N – number of cycles/strokes during blanking
N/Δ – wear resistance of blanking die (lifetime in strokes per 1mm of side wear)
R_a – surface roughness
$R_{C0.1}$ – proof stress in compression
R_{TZ} – transverse rupture strength
V – volume loss during abrasive wear
vol % – volumetric content
W – sliding wear rate (volume loss)
wt % – content percent by weight
X – abrasive-erosion wear resistance
$\Delta S_{2\text{-}7}$ – fatigue sensitivity
Δ – side wear of the tool

1 INTRODUCTION

1.1 Carbide composites and their application in metal forming

Application of carbide composites (hardmetals and cermets) enables the service life of tools and wearing machine parts to be prolonged. These materials are mainly used in service conditions where high wear resistance either in abrasive conditions or at elevated temperature (high speed cutting operations) is required. Carbide composites are not so often used in non-cutting (metalforming) operations owing to complicated service conditions, where severe wear is accompanied by high loads of cyclic and dynamic nature.

One of the most common metalforming (chipless forming) operations is the blanking. In this operation, the metal blank is cut from a sheet or strip into a desired shape. One way of reducing the wear of tool in metalforming operations is to use carbide composites (hardmetals, cermets). There are lots of alloys that fall under this category for example TiC-, TiCN- and WC-based composites with different binder materials.

Carbide composites, particularly cermets, are not so widely used in non-cutting operations owing to complicated wear conditions in metalforming. In metalforming, primarily high alloyed tool steels or tungsten carbide-base hardmetals (with relatively high binder fraction) have been successfully used [1–3]. Cemented carbides (hardmetals) are used to perform coining (generally light coining of small pieces), wire-drawing, deep-drawing, blanking and bending dies in large industrial quantities. Of cemented carbides, straight tungsten carbide grades are most frequently used. Steel bonded carbide composites are also occasionally used, *e.g.* for deep-drawing tools [4, 5]. Selection of an tool material most reliable in the given working conditions is difficult because of insufficient information about the wear resistance of such composites in different wear conditions. Carbide composites, particularly hardmetals combine the high hardness and strength of the covalent carbides (WC, TiC, TaC) with the toughness and plasticity of the metallic binder (Co, Ni, Fe). This unique combination of hardness and toughness makes them outstanding as tool materials in the manufacturing industry. Their application is extremely widespread and includes metal cutting, machining of wood, plastics, composites, and soft ceramics, chipless forming (hot and cold), mining, construction, rock drilling, structural parts, wear parts, and military components. The metal cutting group accounts for about 67% of the total use, followed by mining (13%), machining of wood and plastics (11%), and construction (9%) [6].

1.1.1 WC-based composites – hardmetals

Composites based on tungsten carbides are the most widely used wear resistant carbide composites because of their excellent combination of wear resistance and mechanical reliability characteristics (transverse rupture strength, plasticity, fracture toughness) [1]. They are used extensively to improve abrasion resistance.

Binder content and WC grain size influence mechanical and tribological properties of hardmetals [7]. Hardness decreases but toughness increases with increase of carbide grain size [8, 9]. Variations in the carbide-to-binder ratio, as well as in the average grain size of the carbide phase(s), allow adjustment of the desired mechanical and tribological properties [6, 10]. Also, the hardmetal appears to be the most cost-effective material for many applications where wear resistance is the primary requirement, including the machining of non-ferrous metals [10]. WC-based carbides has been proven successful in conditions where the abrasion and/or abrasive-erosion prevail [7, 11–15].

1.1.2 TiC-based cermets

In hardmetal industry throughout the history strenuous attempts have been made to displace tungsten as a basic constituent for carbide composites. The most auspicious carbide, have found to be titanium carbide. Due to the shortage of tungsten and its high and increasing price, new ceramic-metal composites have been developed.

Titanium carbide based cermets came on the market in the mid-1960s. Since around 1968–1970, after systematic investigation by Kieffer and co-workers [16] most research efforts in this field have been subjected to development of TiCN and TiC-based cermets as being promising metal cutting tool material. TiC-basedcermets may be successful because their thermal expansion coefficient and friction coefficient (in contact with different metal surfaces) are lower and oxidation resistance is higher than that of cemented tungsten carbide.

They have been used in special wear applications, such as high-temperature wear [17] or wear in highly corrosive environments. TiC-basedcermets are attractive also due to high specific strength because of their relatively low density [18] and such alloys are used to fill the gap between tough hardmetal and hard and brittle ceramics [19]. As the hardmetal properties and behavior in different wear conditions has been studied quite extensively [11–14, 20,21] there are not so many studies of titanium carbide based composites.

1.2 Wear of metal forming (blanking) tools

Wear has been recognized as meaning the phenomenon of material removal from a surface due to interaction with a mating surface. Almost all machines lose their durability and reliability due to wear and the possibilities of new advanced machines are reduced because of wear problems [22]. In industries like mining, aggregate and recycling the costs of component wear can be significant [23]. Application of wear parts and consumables may represent 40% of life cycle costs. In other industries like metallurgy and recycling industry the share of cycle expenditure can be even higher [24]. Therefore, wear control has become a strong need for the advanced and reliable technology of the future. Wear is one of the major factors in determination of the service life of the machine parts or tools for different operations. Lot of effort has been made to improve materials and technologies to reduce the influence of the wear.

Wear types (abrasive wear, adhesive wear, sliding wear, *etc.*) appearing in different tribosystems and their domination may change from one to another [25, 26] In general, wear does not take place through a single wear mechanism, so understanding each wear mechanism in each mode of wear becomes important.

Depending on the purpose of the machine part or tool different wear conditions can apply. In most cases the resulting wear is combination of different wear mechanisms– abrasive, adhesive, erosion, sliding wear *etc.*

The wear during blanking has many aspects. During the blanking process, the punches and dies wear out, leading to a progressive modification of the geometry of the blanking tools [27] The wear of the cutting elements in a blanking tool affects the quality of the blanked parts. In particular, the appearance of the burr is closely related to the geometrical characteristics of the punches and dies during blanking.

As the first assumption it can be presumed that there take place many types of wear (adhesive wear, abrasion, fatigue wear). Fatigue plays important role since die and punch edges of the blanking die work under cyclic dynamic load conditions and the rate of wear is affected by parameters such as tool material, blanked part material, punch-die clearance, punch velocity, lubrication and material thickness [28].

The studies [29] have revealed that the conventional evaluator of wear resistance– hardness, enables one to estimate wear resistance in blanking (blanking performance) only as the first approximation. Lack of correlation between blanking performance and hardness may result from the high structure sensitivity of hardmetal wear resistance which means that imperceptible changes in microstructure not affecting mechanical properties cause significant alteration of wear. It may be stated that in blanking tool wear (in contrast to abrasive-erosion wear) the role of hardmetals carbide phase (its strength and rigidity properties) is not of the first importance [30]. Also studies have shown that there exists correlation between blanking performance and adhesive wear resistance in case of hardmetals and the dependence of blanking performance on the abrasive-erosion wear resistance seems to be also uncertain [31].

Following subchapters are dedicated to describe different wear mechanism presumably taking place during the wear of blanking tool. Abrasive-erosion wear is described as reference to reveal similarities in wear mechanisms in case of WC and TiC-basedcermets.

1.2.1 Adhesive wear

Adhesive wear occurs when two nominally flat solid bodies are in rubbing contact, whether lubricated or not (Figure 1.1). Adhesion (or bonding) occurs at the asperity contacts on the interface, and fragments are pulled off from one surface to adhere to the other surface. Subsequently, these fragments may come off the surface on which they are formed and either be transferred back to the original surface or form loose wear particles. Although the adhesive wear theory can explain transferred wear particles, it does not explain how loose wear particles are formed.

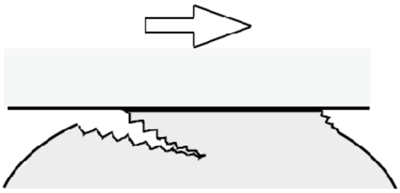


Figure 1.1 Schematic image of adhesive wear mode [32]

Asperity contacts are sheared by sliding and a small fragment of other surface becomes attached to the other surface. As sliding continues, the fragment constitutes a new asperity that becomes attached once more to the original surface. This transfer element is repeatedly passed from one surface to the other and grows quickly to a large size, absorbing many of the transfer elements so as to form a flakelike particle from materials of both rubbing elements [32].

While abrasive-erosion, (three-body) abrasive and sliding wear of ceramic-metallic composites, particularly WC-based hardmetals, have been addressed by many researchers, studies devoted to adhesive wear appear to be infrequent.

Only few studies could be pointed out [13, 33]. These studies conclude that in case of adhesive wear failure of composite starts with adhesive interaction (local plastic strain, frustration of oxide films, formation of physical contact between contacting surfaces of alloys) and finishes with removal of material by extraction. In other words, tensile stresses prevail in the stress state during adhesion failure (wear).

1.2.2 Sliding wear

Wear of most metal forming tools, structural and wear components is usually classified as sliding wear based on their mechanical function. Almost all wear mechanisms could occur during sliding wear. However, only one or two mechanisms may be dominant. For most sliding wear applications abrasion and adhesion are the primary mechanisms. There are lots of studies carried out concerning sliding wear of hardmetals [34–37 *etc*] but not so many dealing with cermets based on TiC [38–40]. In engineering design, the sliding wear rate of materials is usually described also by Archard’s equation (see equation (1.1)) [41]:

$$V = \frac{K \cdot F_n \cdot s}{H}, \tag{1.1}$$

where

V is the volume loss, mm^3;
s is the sliding distance, m;
K is the dimensionless wear coefficient;
F_n is the normal load, N;
H is the Vickers hardness number of the softer material of rubbing pair.

Landcaster [42] proposed a simple empirical wear formula:

$$K = \frac{V}{F_n \cdot s}, \tag{1.2}$$

Wear coefficient K, ($\mathrm{mm^3N^{-1}m^{-1}}$), has proven to be more useful for the comparison of the wear behavior of different materials than Archard's equation.

In studies there have been discovered that the wear resistance of hardmetals under dry conditions is high and depends on carbide/binder ratio, and carbide grain size, being greatly dependent on the bulk hardness of the material [43, 44].

Wear mechanism is different for different carbide composites. While wear of the WC-Co alloys is caused by binder removal, followed by fracture and fragmentation of the carbide grains, the most important factors during wear of TiC-NiMo cermets in cermet/steel pairs are polishing and adhesion [40].

1.2.3 Abrasive wear

In abrasive wear, material is removed or displaced from a surface by hard particles, or sometimes by hard protuberances or asperities on a counterface or embedded hard particles within a surface forced against and sliding along the surface. There are two types of abrasion: two-body or grooving abrasion as shown in Figure 1.2(b) while three-body or rolling abrasion is illustrated in Figure 1.2(a).

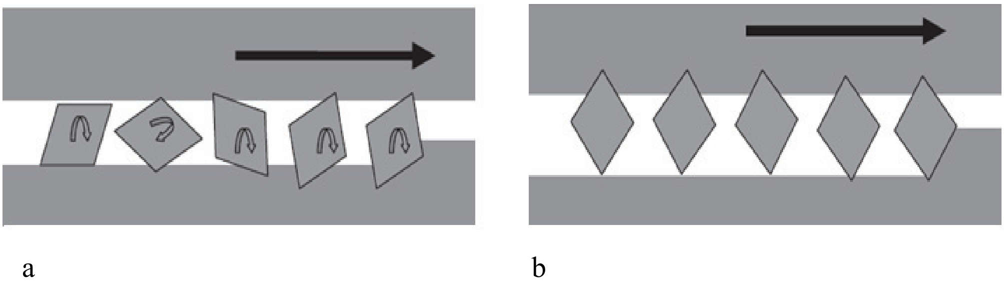


Figure 1.2 Schema of abrasive wear: a – three–body abrasive wear, b – two – body abrasive wear

When wearing material has a ductile property, a ribbon like, long wear particle is generated by the mechanism of microcutting. In the case of brittle material, however, a wear particle is generated by crack propagation [32].

The abrasive wear performance is related to the material mechanical properties and microstructure [45]. Abrasive wear of the WC-Co materials has been intensively investigated during the last decades due to the high industrial importance of prediction of the lifetime and performance of various parts and tools fabricated from WC-Co hardmetals [46]. Describing the abrasive wear most commonly Archard's equation (compare with equation 1.1) is used [41]:

$$\frac{V}{s} = \frac{K \cdot F_n}{H}, \tag{1.3}$$

According to that formula abrasive wear mainly depends on the distance covered and force applied, as well as material hardness.

The studies [47–50] have shown that the abrasive wear of carbide composites results from a combination of three processes – plastic strain, subsurface transgranular and intergranular fracture. The removal of material during wear has a selective nature – it starts preferably in the binder phase.

For example, in abrasion of the WC-Co hardmetal the surface shearing and grooving displace the carbide grains and extrude Co, hardmetal leaving the carbide grains unsupported to fracture, slip and fall out of the surface [20]. The relation between the size of the abrasive grits and the dimensions of the material's microstructure is also important for the wear properties [51, 52]. Some studies have shown that the hardness is not the only and major factor to determine the abrasive wear resistance considering the complexity of the material removal process in chip, groove and ridge formation. This correlation has deviations and can occur in brittle materials and in multiphase materials such as and WC-Co also depending on the abrasive properties [15, 46, 53] Abrasive wear of TiC-based carbide composites has been studied insufficiently.

1.2.4 Erosive wear

Solid particle erosion is the wear caused by hard particles bombarding a surface. Like abrasion, abrasive-erosion wear can involve both plastic deformation and brittle fracture, and the details of the appearing wear mechanism depend on both the wearing material, the erodents, and the condition of the impacts, primarily particle mass, velocity, and impact angle [54]. The erosion behavior of materials is closely linked to the properties of the eroding grit – shape, hardness, toughness, and size all strongly affect the erosion rate of any test material. The effect of impact angle is fundamentally different for materials of different mechanical properties. The erosion rate of brittle materials generally increase continuously with impact angle, from the particles streaming close to parallel to the surfaces, to the case of orthogonal impacts [26]. Many attempts have been made to evaluate erosion resistance of materials based on mainly mechanical properties that are easier to determine (strength, modulus of elasticity, Poisson's ratio, hardness, fracture toughness and *etc.*). There have been many studies [55–62] that analyze those relationships.

In the study of mechanical properties and features of erosion of cermets [60] is shown that the erodent particles of different materials can cause different erosion rates and mechanisms. The brittle materials are very sensitive to the hardness and fragility of erodent [63]. Thus, the erosion rate is higher for materials tested if the erodent hardness is greater than that of the target. If the abrading particles are harder than the test material microcutting or surface scratching may take place. If the hardness situation is opposite the main mechanism of wear is low-cycle fatigue.

Also it is found by Hussainova [47] that behavior of the non-homogeneous materials cannot be evaluated by looking at one measured mechanical characteristic only or by looking at a blend of the bulk properties. In the case of soft erodent, modulus of elasticity can be used as a first approximation. If erodent is hard, fracture toughness (or strain capacity) of carbide skeleton may give some evidence for material selection. TiC- and WC-based carbide composites erosion rate is dependent of the binder content– if the binder content increases also the erosion rate increases at all impact angles [64, 65].

It has also been shown in previous studies [14, 29] that hardmetals abrasive-erosion wear resistance cannot be estimated only by hardness, characterizing resistance to penetration (i.e. large local plastic strains). The hardness can be used for assessment of erosive wear among the same type of composites but in case of different types of alloy like TiC-based cermet and WC-based hardmetal it can be used as first approximation. The difference in wear resistance between ceramic-metallic composites with equal hardness level can be attributed to differences in their resistance to fracture.

One factor that affects the erosive wear resistance is impact angle of the abrasive. It was found [66] that impact angle causing the highest wear differs among carbide composites and the maximum wear rate depends on the material response to impacts.Unlike the abrasive, sliding, and adhesive wear the erosive wear both WC- and TiC-based carbide composites is investigated quite sufficiently.

1.3 Aim of the study

As stated previously, the wear of a blanking tool has a complex nature due to different wear mechanisms taking place during the wear. Material composition and structure are significant for the wear resistance of the tool. Studies have been devoted to abrasive, sliding and adhesive wear whereby different aspects of wear mechanisms and behavior of carbide composites (predominantly WC-Co hardmetals) were revealed but clear correlation of these tribological characteristics and the actual wear of a tool needs yet to be discussed.

The main goal of this work was to investigate the wear behavior of some TiC-based cermets (prospective as tool materials in metal plastic forming) in different wear conditions: abrasive, adhesive and sliding wear and also tool wear in the blanking of sheet metals. The WC-Co hardmetals were used as reference materials.

The following objectives were set in this study:

- to find out differences in the wear behavior of TiC and WC-based ceramic-metallic composites in the conditions of abrasive, sliding and adhesive wear;
- to find out relationships between tool wear in blanking and tool material properties in different wear conditions;
- to specify the surface failure mechanism of carbide composites (TiC-based cermets, hardmetals) taking place during exposure to different wear conditions;
- to propose the principles for selection of blanking tool materials.

2 EXPERIMENTAL

2.1 Materials

The current study focuses on the tungsten and titanium-carbide base carbide composites in particular composites prospective for metalforming (carbide fraction 74–85 vol % and properties: Rockwell hardness HRA≥86.5 (HV ≥1100), transverse rupture strength R_{TZ} ≥2000 MPa) [31].
The composition and mechanical properties of the composites investigated are presented in Table 2.1.

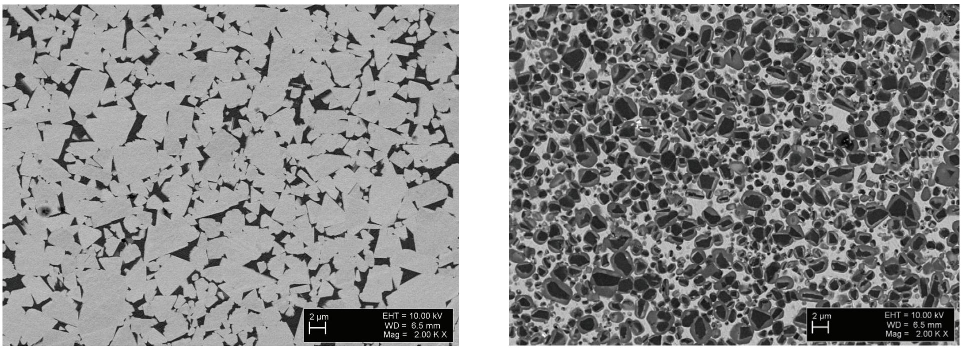
Table 2.1 Structural characteristics and properties (hardness HV, transverse rupture strength R_{TZ}, modulus of elasticity E, proof stress of compression $R_{CO.1}$) of carbide composites.

Grade	Carbide, content, vol %	Binder composition, structure	*HV*	R_{TZ}, GPa	*E*, GPa	$R_{CO.1}$, GPa	Used in experiments			
							Abrasive wear	Adhesive wear	Sliding wear	Blanking wear
H10	WC, 83.5	Co (W)	1350	2.3	610	2.9	x	x		
H13	WC, 79.9	Co (W)	1300	2.8	590	2.9	x	x		x
H15	WC, 76.0	Co (W)	1150	2.9	560	2.5	x	x		
H20	WC, 69.0	Co (W)	1000	3.1	510	2.0	x	x		
T80/14	TiC, 86.5	14Ni- steel austenite-bainite	1450	1.5/2.1*	420	3.0/ 3.2	x	x	x	
T75/14	TiC, 83.0	14Ni- steel, austenite-bainite	1350	1.8/2.4*	410	2.8/ 2.9	x	x	x	x
T70/14	TiC, 79.0	14Ni-steel, austenite-bainite	1250	2.3	400	2.5	x	x	x	x
T60/14	TiC, 74.0	14Ni-steel, austenite-bainite	1050	2.4	380	1.9	x	x	x	
TN30	TiC, 81	NiMo (2:1)	1380	1.7	380	2.3	x	x	x	
TN40	TiC, 74	NiMo (2:1)	1260	1.9	360	2.0	x	x	x	
TN50	TiC, 65	NiMo (2:1)	1000	2.1	340	1.7	x	x	x	

*) sinterhipped

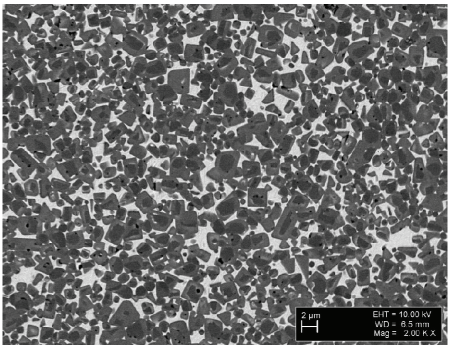
All hardmetals (grades H10, H13, H15 and H20) and TiC-based cermets were produced through ordinary press and sinter powder metallurgy at the Powder Metallurgy Laboratory of the Tallinn University of Technology. Some grades (cermets T80/14, T75/14) were sintered by the sinter/HIP techniques (under gas compression of 50 Bar at the sintering temperature).

Figure 2.1 shows the microstructures of the composites with carbide fraction ≈75 vol %. The microstructure of WC-composites consists of WC grains mainly of angular shape embedded in the binder phase. The shape of TiC grains is more rounded. Porosity of carbide composites was < 0.2 vol % for all materials and the average grain size was 1.9–2.3 μm.



a)

b)



c)

Figure 2.1 SEM micrographs of the carbide composites studied:
a) hardmetal, grade H15,
b) cermet TiC-NiMo, grade TN30,
c) cermet TiC-FeNi, grade T70/14; (see Table 2.1)

2.2 Testing procedure

2.2.1 Wear testing

Adhesive wear tests were performed by a special cutting method by turning mild steel (*HV*=160) at low speed (*v* <12 m/min), simulating blanking tools wear in the prevalence of adhesion [33].

The wear resistance was determined as the length of cutting path L_1, when the height h of the wear land at the specimen (tool) nose achieved 1 mm (Figure 2.2). The critical height h=1 mm of wear land corresponds to the onset of accelerated wear [33]. The wear resistance confidence interval did not exceed 10% when the number of test pieces was at least three. An excellent correlation between the wear resistance of WC-Co hardmetals determined by this method and blanking die wear was reported in [13, 67].

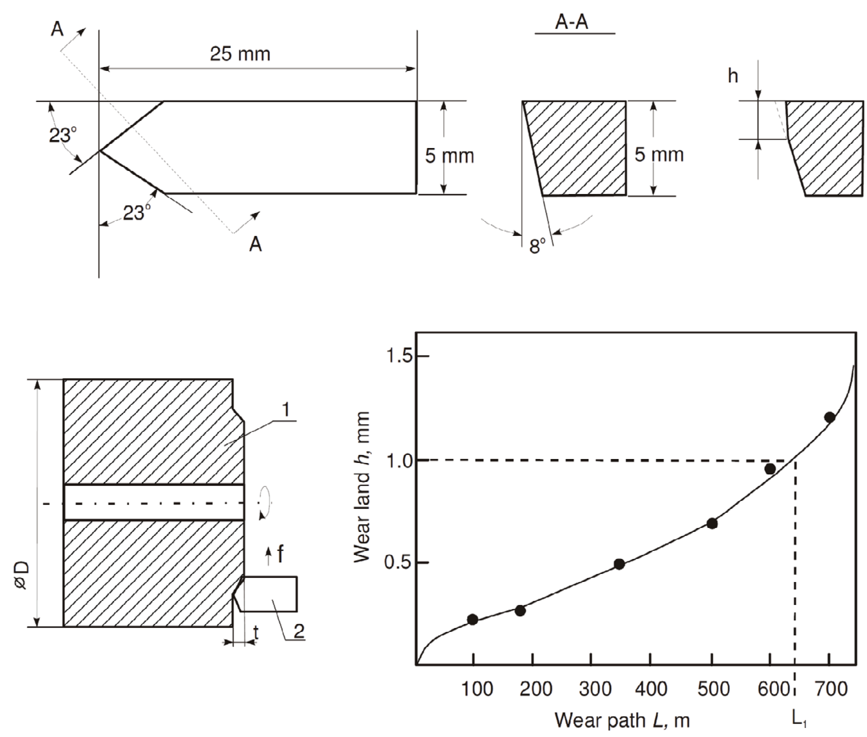


Figure 2.2 The scheme of adhesive wear testing: 1– mild steel to be turned, 2 – specimen, h – height of wear land, L_1 – adhesive wear resistance, L – cutting path.

Abrasive wear tests were performed by help of the rubber-rimmed rotary wheel machine (modified ASTM G65-94 method [68]) as follows (see Figure 2.3): abrasive – quartz sand (amount – 3 kg with a particle size of 0.1 – 0.2 mm and hardness 1100 *HV*), velocity of the wheel – 0.24 m/s, diameter of the steel wheel – 80 mm, wear distance – 144 m, testing time – 10 min and load – 3 N. The wear was estimated as the volume loss *V* in mm^3 and wear resistance as *1/V*, mm^{-3}. A minimum of four abrasive wear tests per composite were performed to ensure the confidence interval of 10% with the probability factor of 95%.

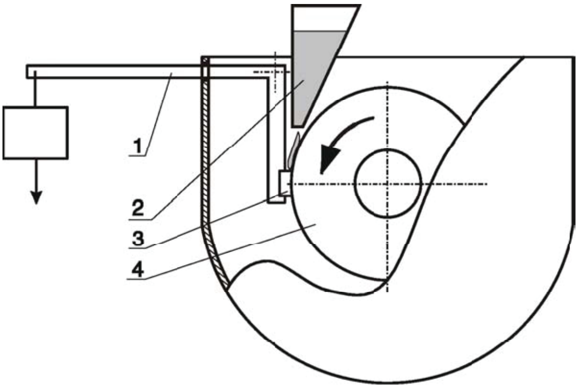


Figure 2.3 The scheme of abrasive wear testing: 1 – loading system, 2 – abrasive particles, 3 – specimen, 4 – rubber rimmed steel wheel.

Sliding wear tests were performed in accordance with the ASTM standard B611-85 [69] procedure, without abrasive at a the loading F= 40 N and a wear length L= 4000 m, (see Figure 2.4). The wear rate was calculated as a volume loss W, mm^3. A minimum of four tests for sliding wear per composite were performed to ensure the confidence interval of 10% with the probability factor of 95%.

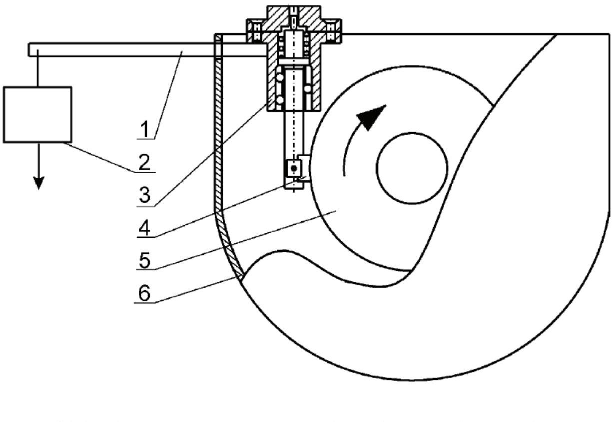


Figure 2.4 Diagram of block-on ring tester used in this study. 1 – bar, 2 – load, 3 – clamp, 4 – specimen; 5 – steel ring; 6 – chamber.

Wear in blanking. The procedure of the durability functional test – wear tests in blanking – resembled that in service, i.e. blanking of grooves into electrotechnical sheet steel (with a hardness of 150 *HV* and a thickness of 0.5 mm) using a three-position die reinforced with the three different composites to be investigated, mounted on an automatic mechanical press [31, 70] (see Figure 2.5).

The wear resistance, i.e. the blanking performance of carbide composites, was evaluated by the measurement of the side wear of the die (increase in diameter) after an intermediate service time $N=0.5 \times 10^6$ strokes, as N/Δ (lifetime in strokes per 1 mm of the side wear). The intermediate service time 0.5×10^6 corresponded to the time between two consecutive prophylactic sharpenings used in the exploitation of blanking dies [31,70]. The side wear was measured using the coordinate measuring machine STRATO 9 - 166 in fixed environmental conditions (constant room temperature and humidity of 40%) as an average of 4–6 measurements to ensure confidence interval of 10% with the probability factor of 95%

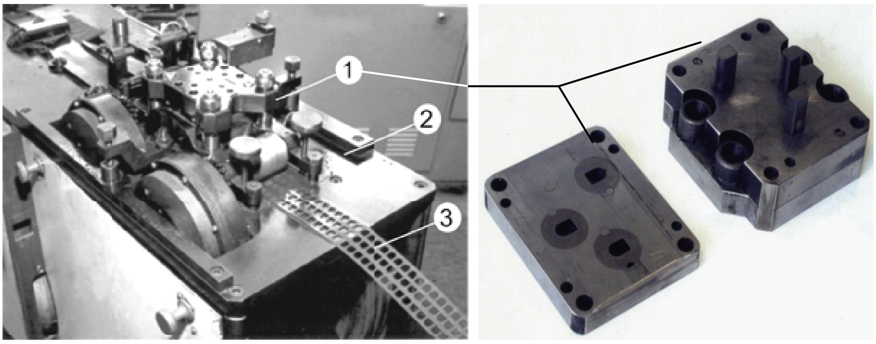


Figure 2.5 Durability testing of carbides composites: 1 – blanking die; 2 – the mechanical press body and 3 – the sheet steel [31]

2.2.2 Mechanical properties

Transverse rupture strength R_{TZ} was determined in accordance with the ISO 3327method (using specimen B) [71] and Vickers hardness in compliance with EN-ISO 6507[72].

The proof stress at compression $R_{CO.1}$, featuring the resistance of a material to the plastic strain and the shear strength (resistance to microcutting) of all composites, was determined. The proof stress was determined in a uni-axial compression test using a specimen of a diameter of 10 and a length of 18 mm [73].

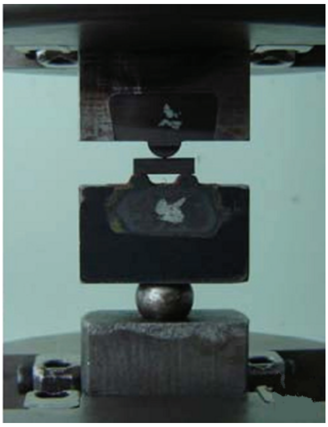


Figure 2.6 Three-point bending fixture

Fatigue testing. Conventional fatigue testing of the ground specimens 5x5x17 mm was carried out on the fatigue testing rig using a three-point bending scheme. The three-point bending device used in experiments, with span between supports equal to 14.5 mm and supports diameters of 5 mm (10 mm for upper part), is shown in Figure 2.6. Specimens were ground to a surface finish of about R_a=1.5 μm for hardmetal and R_a=2.5 μm for cermets. The stress ratio was R=0.1. The loading frequency was 30 Hz [70, 74].

The resistance to fatigue damage was characterized by the factor of fatigue sensitivity – intensity in the decrease of the fatigue strength with an increase in loading cycles from $N_2 = 10^2$ to $N_7 = 10^7$ as $\Delta S_{2\text{–}7}$.

2.2.3 Microstructural study

Microstructural examinations were complemented by SEM and XRD investigations performed on the scanning electron microscope JEOL JSM 840A and the diffractometer Bruker D5005, respectively. The line broadening and intensity of X-ray reflections (measure of local plastic strain) from the composite phases were determined in the XRD studies. Changes in both carbide phases (WC and TiC) were determined.

3 PERFORMANCE OF CARBIDE COMPOSITES IN DIFFERENT OPERATION CONDITIONS

3.1 Wear performance

The wear performance and relationships between material characteristics in abrasive, adhesive and sliding wear condition are considered and discussed.

3.1.1 Abrasive wear

The results from the abrasive wear tests show that the increase in volume fraction of carbides phase causes a monotonous decrease in wear (increase in wear performance) of all composites unlike the carbide and binder composition (see Figure 3.1). The results obtained refer to an obvious dependence of the wear performance (wear resistance) of the test material on carbide composition. At an equal carbide volume fraction, tungsten carbide-based composites demonstrate an obvious superiority over TiC-basedcermets.

Also the results confirm an inconclusive influence of hardness on the wear performance of materials. At equal hardness the abrasive wear of alloys of different composition may vary up to four times, see Figure 3.2.

The fact that no correlation between abrasion performance and hardness exists may be attributed to higher structural sensitivity of the wear resistance of the composite in relation to hardness and differences in the stress states during wear and hardness tests[70, 75].

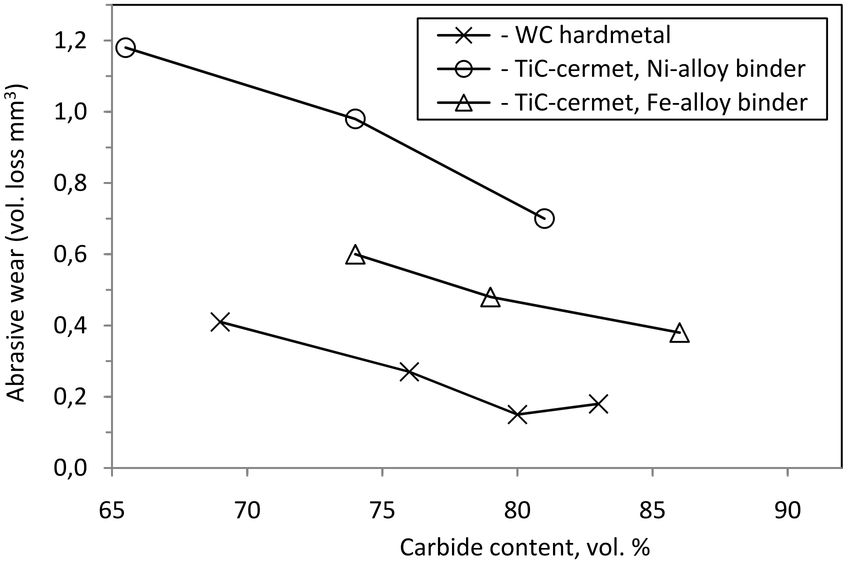


Figure 3.1 Abrasive wear of carbide composites vs. carbide volume fraction in alloy.

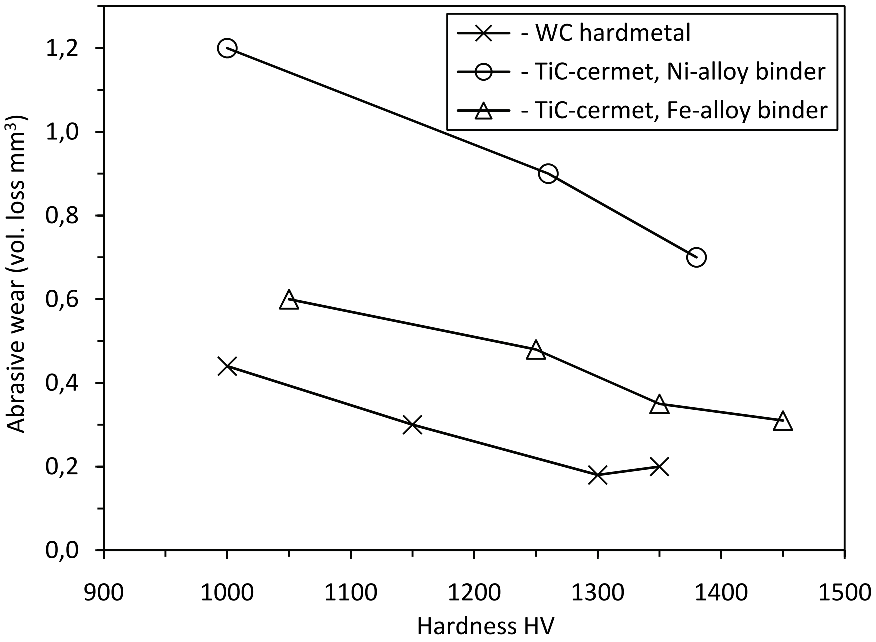


Figure 3.2 Abrasive wear of carbide composites vs. Vickers hardness.

In previous studies [14] it has been shown that the abrasive erosion wear of carbide composite may be described by the equation $R_{\mathrm{C0.1}}^{n} \cdot E^{m}$ (combined effect of proof stress $R_{\mathrm{CO.1}}$ and the modulus of elasticity E). Our results presented in Figure 3.3 confirm the reliability of such approach (utilizing characteristic of rigidity) also for abrasive wear.

In essence, the results are in accordance with wear theories concerning the surface failure of hardmetals and cermets during abrasion and erosion [14, 12]. It may be concluded that the wear of a carbide composite is characterized by a selective failure that starts predominantly in the binder phase by its extrusion and microcutting and continues by a subsurface fracture of carbide (fragmentation – microcracking).

The extrusion of the binder onto the composite surface is controlled by the elastic strain of its carbide skeleton – its elastic compression (during the penetration of abrasive particles). It depends, therefore, on the stiffness (modulus of elasticity) of the carbide phase. An increase in the modulus of elasticity of the carbide results in a decrease of elastic strain and binder extrusion. The plastic flow of the binder (during extrusion), in turn, depends on its resistance to the plastic strain – the proof stress. As the proof stress increases, hindrance to the plastic flow, to extrusion and microcutting (shear failure) will grow.

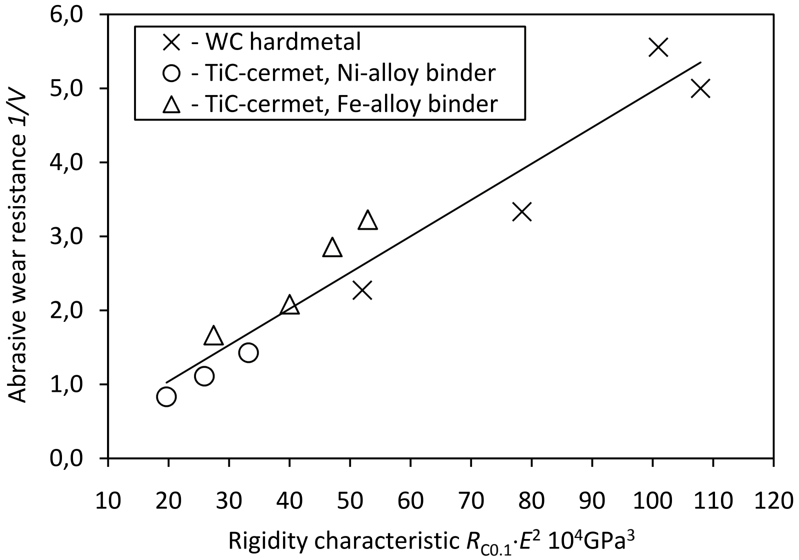


Figure 3.3 Abrasive wear performance 1/V (V – volume loss mm^3) vs. rigidity characteristic $R_{C0.1}·E^2$ (proof stress times modulus of elasticity) of carbide composites

SEM micrographs (Figure 3.4) refer to some differences in wear mechanisms in conditions of erosion and abrasion. The structure worn during abrasive wear is more distinctive in relation to erosion. It refers to the relevance of tension stresses (extraction) in the removal of material.

The ability of a material to resist brittle failure depends on the level of the elastic strain energy transmitted to the surface by abrasive particles (during collisions and fluctuating contact stresses) and storing at tips of flaws in the composite microstructure and ability of the composite phases to absorb elastic strain energy by local plastic strain [45, 76, 77].

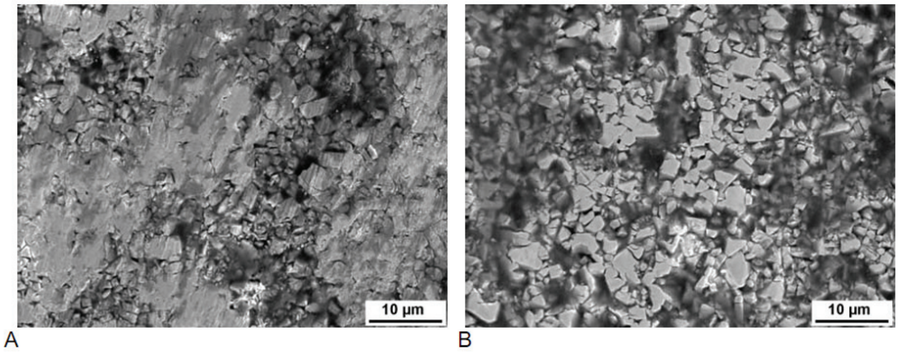


Figure 3.4 SEM micrographs of cemented carbide (WC-Co composite H15) worn in abrasive-erosion (A) and abrasive (B) wear conditions.

The XRD measurements performed in the present study on the worn surfaces of carbide composites revealed alterations in their diffractograms – decrease in the intensities and an increased broadness of the reflection lines of their carbide phases (see Figure 3.5 and Table 3.1). These alterations refer to changes in the fine structure (dispersity of micrograins and density of dislocation network) of the carbide phase induced by their local plastic strain, taking place during abrasive wear.

Table 3.1 Results of the XRD analysis– X-ray reflections from the carbide phases of the composites in different wear conditions (I_o*,* I_w*,* I_s*,* I_A *– intensity,* B_o*,* B_w*,* B_s*,* B_A*,– broadness before (O) and after abrasive (W), sliding (S), adhesive (A) wear, respectively).*

Grade	Carbide, line	Decrease in intensity *I*, times			Increase in broadness *B*, times		
		I_o/I_w	I_o/I_s	I_o/I_A	B_w/B_o	B_s/B_o	B_A/B_o
T75/14	TiC[200]	1.4	1.3	1.1	1.3	1.2	1.1
H13	WC[001]	1.5	1.5	1.2	–	1.3	1.1

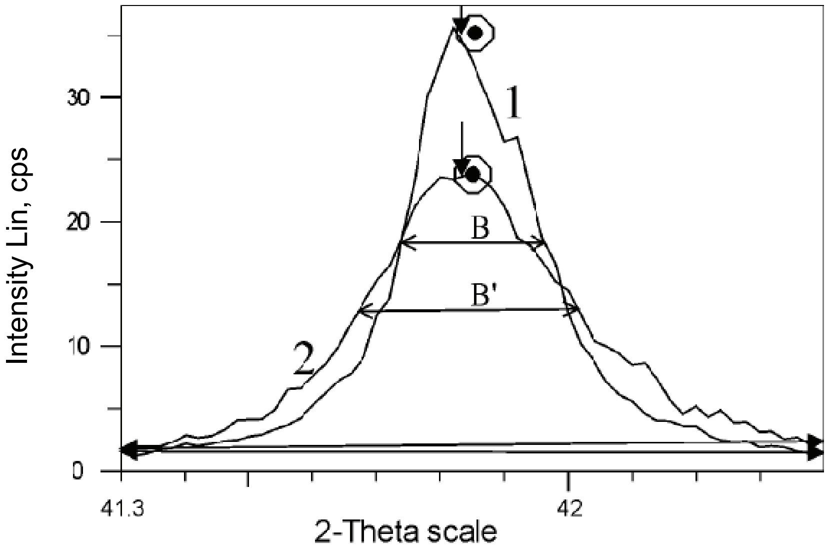


Figure 3.5 XRD diffraction patterns of TiC-based cermet carbide phase [line 200]: 1 – before testing; 2 – after abrasive wear testing

3.1.2 Adhesive wear

The results of cutting adhesive wear test show that the increase in volume fraction of carbides (decrease in binder) leads to a monotonous improvement of wear performance of all composites independent of their carbide and binder composition, see Figure 3.6. The results refer to an obvious dependence of the alloys wear performance on their composition: at equal carbide (binder) fraction WC-base hardmetal and TiC-cermet cemented with nickel steel show a remarkable superiority over ordinary TiC-based cermet cemented with nickel alloy.

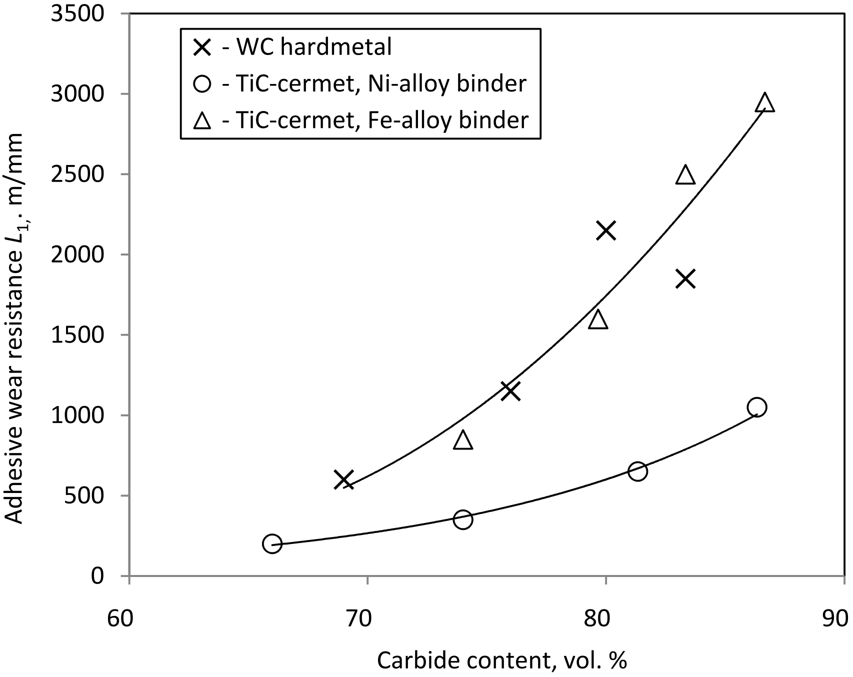


Figure 3.6 Adhesive wear resistance of carbide composites vs. carbide fraction in alloy.

At equal hardness (ordinary characteristic and measure of material wear resistance) adhesive wear of different composites differ up to 4 times, see Figure 3.7. In Figure 3.8 the wear performance of test materials is opposed to their proof stress, featuring material resistance to plastic strain and to shear failure (cutting). The relationships refer to an obvious dependence of wear on proof stress: the increase in proof stress improves monotonously the wear resistance.

Results presented in Figure 3.9 and Figure 3.10 allow us to conclude that at an equal proof stress an additional increase in the wear performance of carbide composites can be achieved by increasing their transverse rupture strength R_{TZ} and modulus of elasticity E. In particular, at equal proof stress of 2.9 GPa the adhesive wear resistance of hardmetal grade H13 is higher than that of grade H10 on account of its higher transverse rupture strength (2.8 GPa for H13 against 2.3 GPa for H10). Also, at equal proof stress of 2.0 GPa the adhesive wear resistance of hardmetal H20 is higher than that of cermet TN40 on account of significantly higher modulus of elasticity of hardmetal.

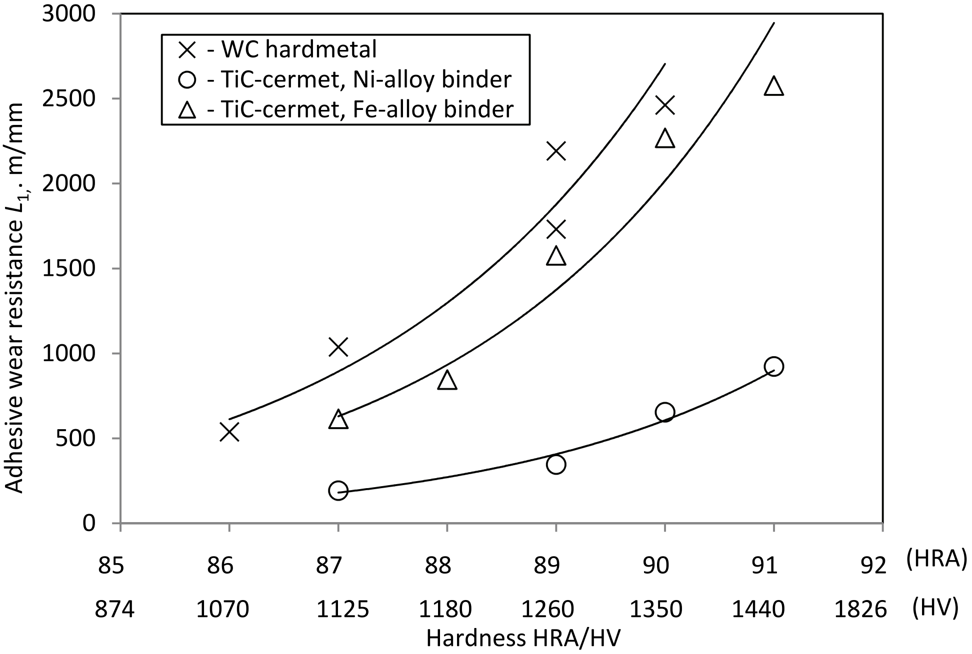


Figure 3.7 Adhesive wear resistance of carbide composites vs. hardness.

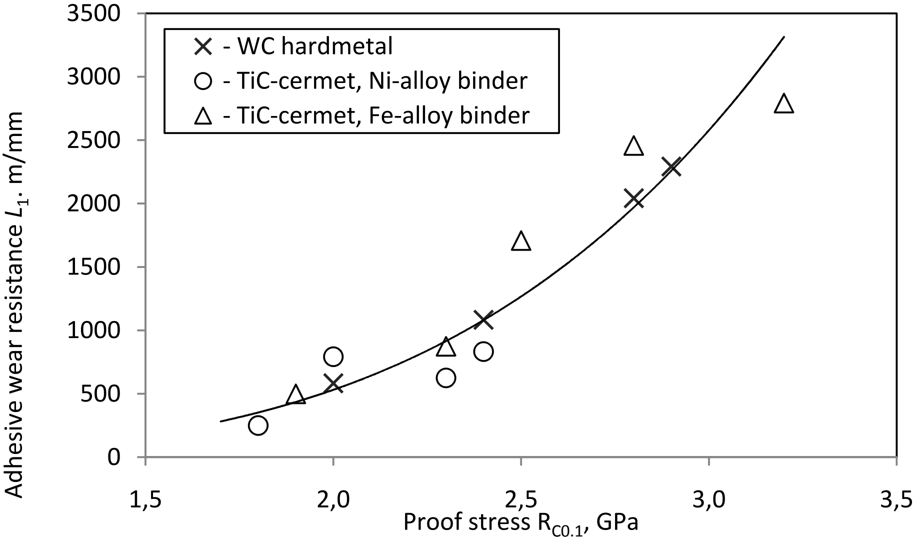


Figure 3.8 Adhesive wear resistance of carbide composites vs. proof stress.

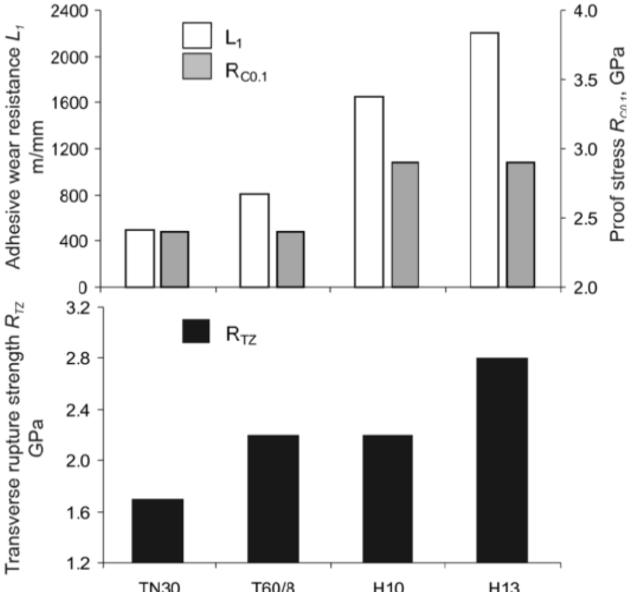


Figure 3.9 Correlation graphs of adhesive wear resistance L_1, transverse rupture strength R_{TZ} and proof stress $R_{CO.1}$ of WC- and TiC-based composites

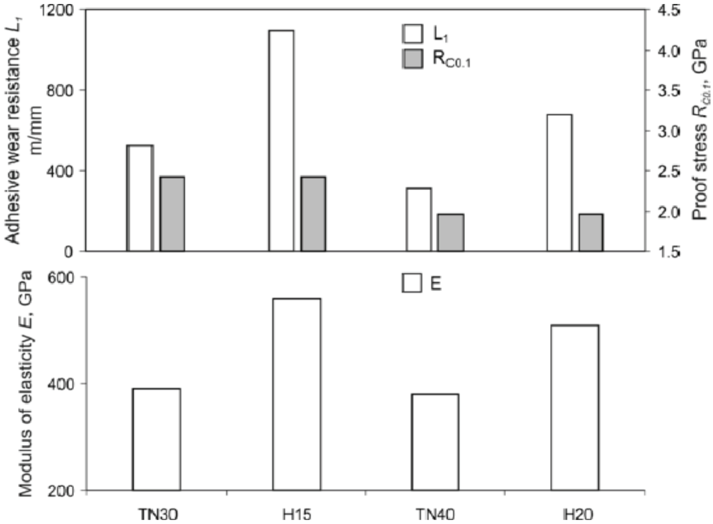


Figure 3.10 Correlation graphs of adhesive wear resistance L_1, modulus of elasticity E and proof stress $R_{CO.1}$ for the WC- and TiC-based composites.

The relationships found refer to the relevance of the carbide-binder content and their properties, to an inconclusive influence of hardness and to an obvious relevance of the proof stress. The transverse rupture strength and modulus of elasticity appear to have a secondary (less definite) importance in the wear conditions when adhesion prevails.

As stated [33, 73] the material removal during wear of carbide composites has a selective nature– it starts preferably in the binder (by microcutting or extraction). As a precondition of material removal the extrusion of its binder and its adhesive interaction with counter material has to occur. For adhesion interaction the plastic strain of asperities, resulting in destruction of oxide films covering surface and hindering formation of physical contact has to occur. Thus the adhesion wear of a composite is controlled by its (its binder) resistance to local plastic strain – the proof stress.

After removal of the binder the carbides lose their protective envelope and its resistance to failure (microcracking) decreases. The fracture energy (of the loading) may relax either by brittle failure (microcracking of carbides) or by a local plastic strain.

As stated, the plastic strain of carbide composite takes place preferably in its ductile binder [74]. The XRD measurements performed in the present study on the worn surfaces of the WC- and TiC-basedcomposites revealed alterations in their diffractograms – a decrease in the intensities and an increase in the broadness of the reflection lines of their carbide phases (Figure 3.11). These alterations refer to changes in the fine structure (increase in dispersity of micrograins (microfragmentation) and density of dislocation network) of the carbide phase induced by their plastic strain taking place during loading [78, 79].

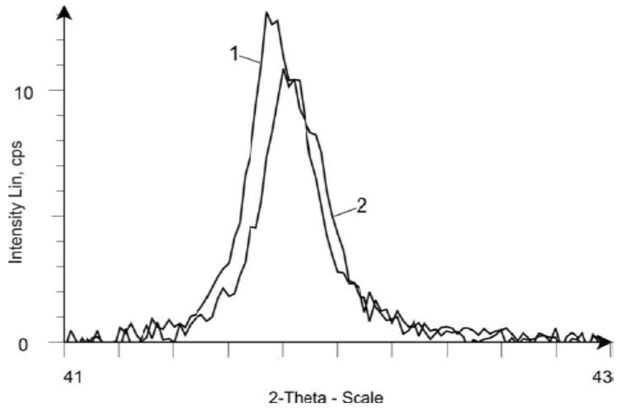
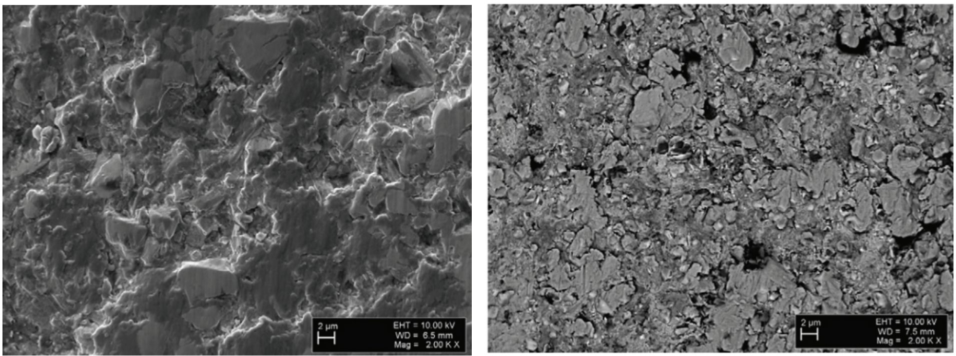


Figure 3.11 XRD diffraction patterns of the carbide phase [line 200] of the TiC-based cermet: 1 – before testing; 2 – after adhesive wear testing.

SEM studies (micrographs presented in Figure 3.12) revealed features of wear mechanism during adhesion. The structure worn during adhesive wear is more distinctive in relation to sliding wear (see Figure 3.17). It refers to the relevance of tensile stresses and removal of material (binder) by extraction.



a) b)

Figure 3.12 SEM image of hardmetal H15 (a) and TiC-cermet (b) surface after cutting-adhesive wear testing

3.1.3 Sliding wear

In essence, the results of sliding wear tests represent those of abrasive and adhesive wear ones. WC-base hardmetal has obvious superiority over tungsten free cermets, and cermet with steel binder over composite with nickel alloy binder (see Figure 3.13). Also the monotonous decrease in wear with increase in carbide fraction in alloy is demonstrated.

In contrast to cutting adhesive wear (and abrasive wear [45]), the sliding wear of carbide composites demonstrated a relatively low sensitivity in terms of composition. An increase in the carbide fraction from 69.0–83.5 vol% in WC-hardmetals results in the improvement of performance in the cutting adhesive wear conditions up to four times and in the sliding wear less than two times (compare Figure 3.6 and Figure 3.13).

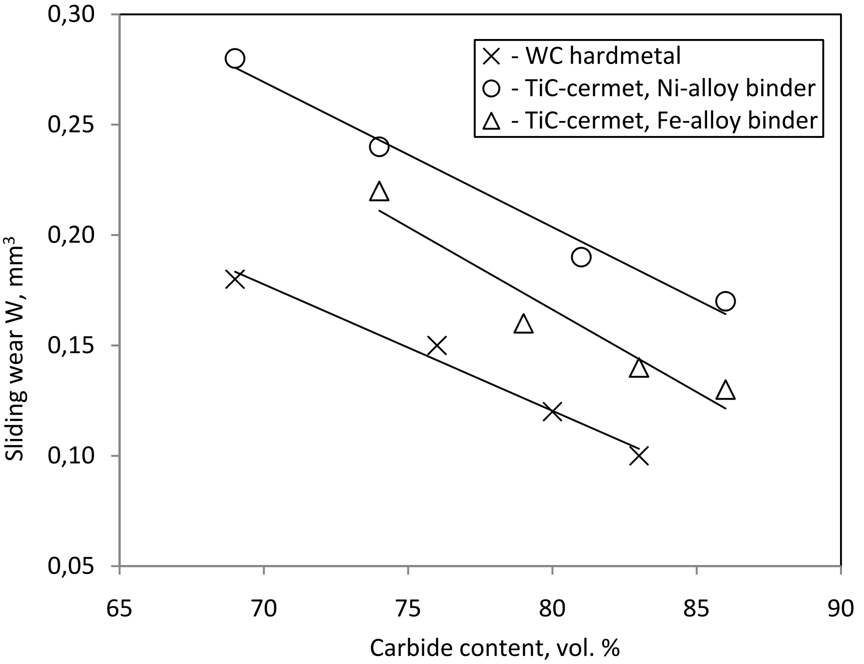


Figure 3.13 Sliding wear of carbide composites vs. carbide fraction

Figure 3.14– Figure 3.16 demonstrate the dependences of the sliding wear of the test materials on the hardness, proof stress $R_{CO.1}$ and modulus of elasticity E (as a combined characteristic $R_{CO.1} \cdot E \cdot$). In general, the relationships repeat those revealed for the cutting adhesive wear – the uncertainty of hardness and the definitive relevance of proof stress. In contrast to cutting adhesive wear, sliding wear demonstrated a more definitive dependence on the modulus of elasticity E (combined characteristic $R_{CO.1} \cdot E$, see Figure 3.16). Results confirm a comparatively low structure sensitivity of carbide composites to the sliding wear. An increase in the proof stress of WC- hardmetal from 2000 MPa to 2900 MPa results in an improvement of performance up to six times in the cutting adhesive wear and less than 1.5 times in the sliding wear conditions, respectively.

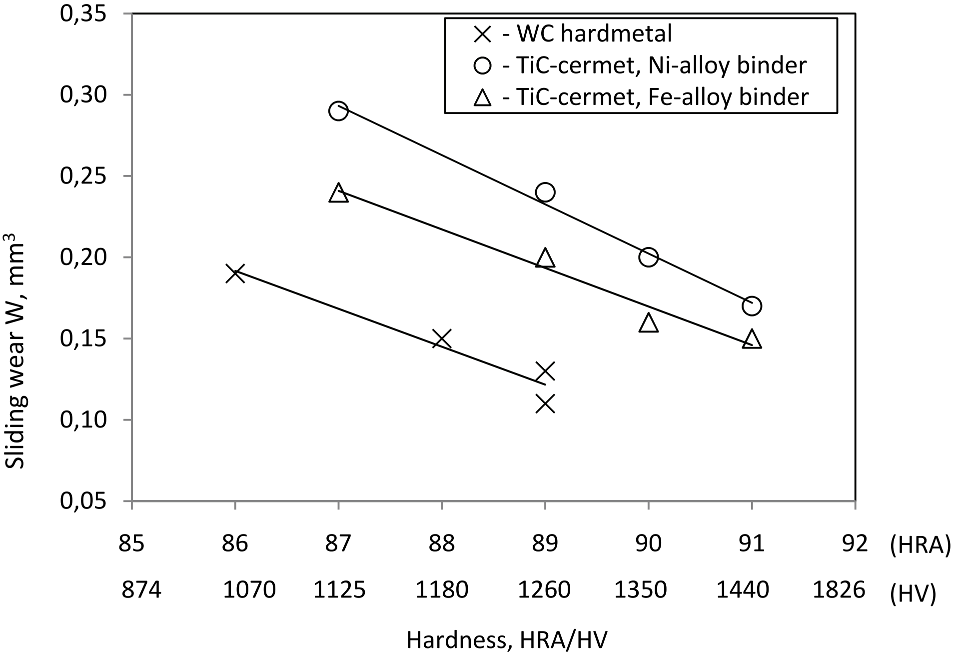


Figure 3.14 Sliding wear vs. hardness of carbide composites.

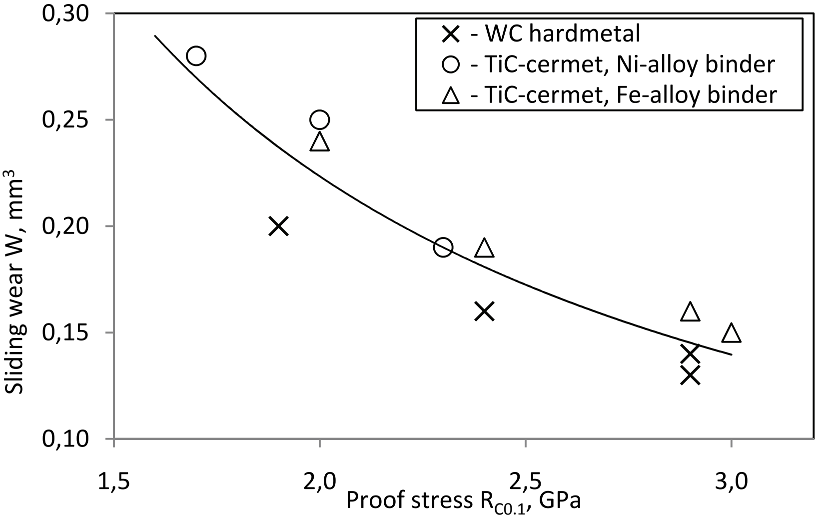


Figure 3.15 Sliding wear vs. proof stress of carbide composites.

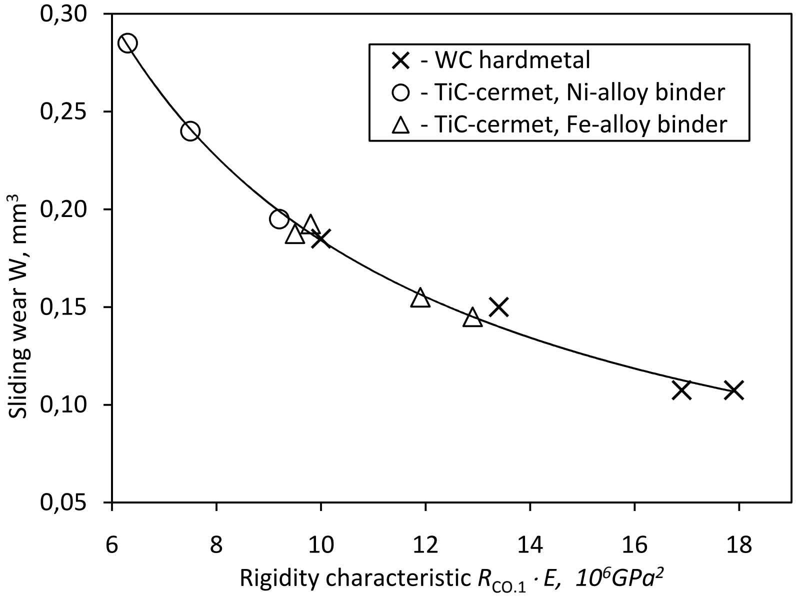
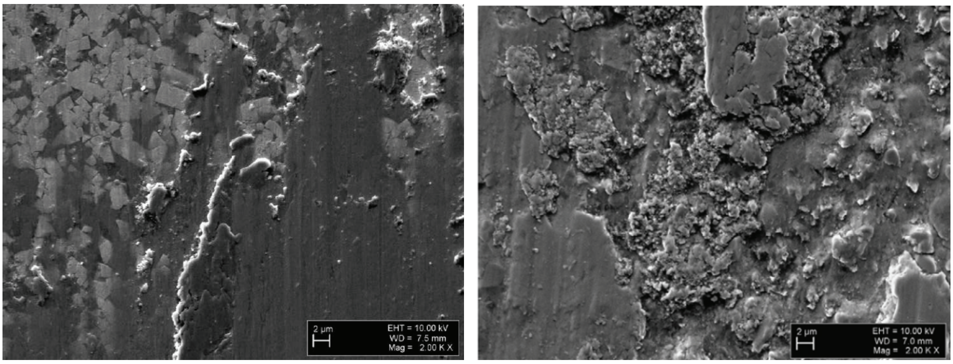


Figure 3.16 Sliding wear vs. rigidity characteristic $R_{CO.1} \cdot E \cdot 10^6 GPa^2$ *of carbide composites.*

The structure worn in sliding wear seems to be more vague in comparison to structure worn in adhesion (compare Figure 3.17 and Figure 3.12). It refers to prevelance of shear stress and removal of binder by combined extrusion and microcutting.

In structure of carbide composites subjected to sliding wear formation of thin tribofilms (between sliding-wearing surfaces) has been observed ([49] and Figure 3.17). These films originated as a result of binder extrusion and adhesive interaction act as a protective lubricating layer inducing reduction in wear and a remarkable decrease in wear sensitivity to alloy composition and properties.



a) b)

Figure 3.17 SEM image cemented carbide H15(a) and TiC-cermet (b) surface after sliding wear testing

3.2 Performance of carbide composites in metalforming (blanking)

3.2.1 Wear of blanking tool

Results of functional wear tests (conducted as the blanking of grooves into the sheet steel) are shown in Figure 3.18 as wear contours *H–Δ* (side wear *Δ* depending on the depth *H* from the cutting edge of the die). During testing (*N*=5 x 10^5 strokes) of the die (three position die reinforced with the sample cermets/hardmetals), neither fracture nor brittle macrochipping of cutting edges was detected.

Cutting edges became blunt as a result of uniform wear. The wear contours (Figure 3.18) and the side wear data for the dies tested demonstrate the obvious superiority of the advanced TiC-based cermetT75/14 over hardmetal H13 and cermet T70/14. The advanced TiC-based cermet demonstrated a blanking performance exceeding that of the ordinary composites up to 1.5 – 2 times.

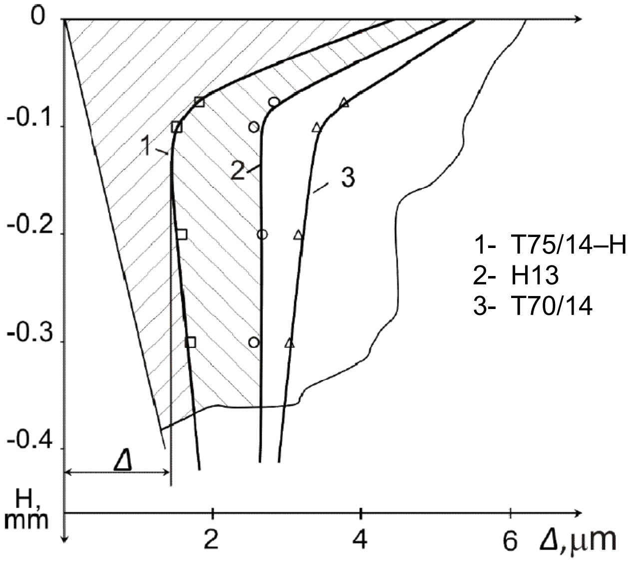


Figure 3.18 Wear contours of carbide tool (die) edges – side wear after blanking of 5·10^5 strokes. H – depth of groove measured from cutting edge, Δ-side wear

SEM studies of worn carbide composite surfaces demonstrate that surface failure mechanisms occurring during adhesive wear (see Figure 3.12) and sheet metal blanking (Figure 3.19) are similar: in both cases surface failure (removal of material) appeared first in the binder phase. The distinctive nature of the worn surfaces confirms that binder extraction prevails in both cases. In contrast to adhesive wear, surfaces worn during abrasive (Figure 3.4) and sliding wear (Figure 3.17) do not show this distinction.

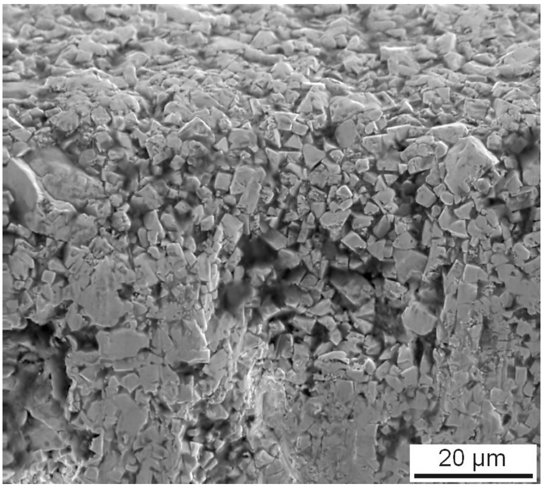


Figure 3.19 SEM image of cemented carbide H13 surface after blanking

3.2.2 Cyclic strength – fatigue resistance

As stated previously the fracture of carbide composite during wear starts in the binder and after removal of the binder the carbide phase loses its protective-envelope (generating favourable compressive stress, resulting in increase of its strength) and on that reason its resistance to brittle failure decreases.

The Figure 3.20 demonstrates the results of fatigue tests of cermet T75/14 and hardmetal H13. The tested carbide composites exhibit an obvious decrease in strength with an increase in loading cycles during fatigue tests – they possess fatigue sensitivity.

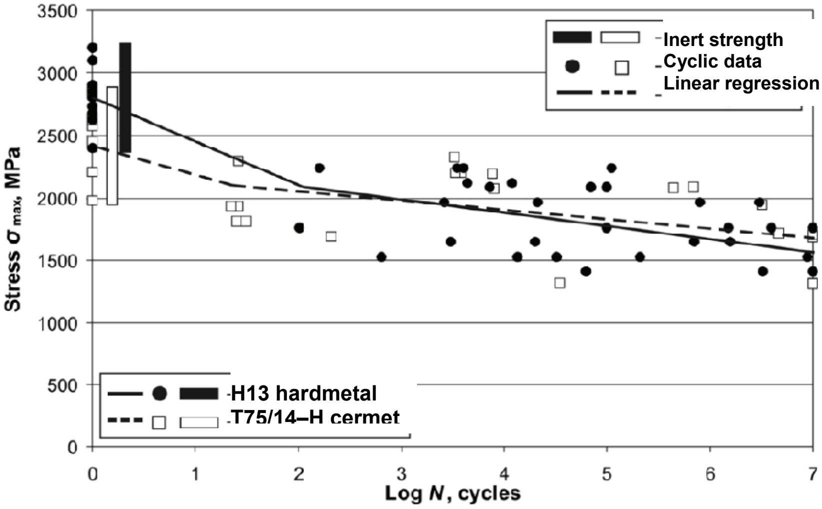


Figure 3.20 Wöhler plots of the carbide composites tested.

Although the transverse rupture strength (R_{TZ} =2.9 GPa) and cyclic strength at low cycle ($N<10^4$) of the WC-hardmetal exceed that of the cermet (R_{TZ} =2.4 GPa) the fatigue limit ($N=10^7$) show an opposite result – the superiority of TiC cermet (N^7=1.7 GPa against 1.55 GPa of WC- hardmetal). It means that the fatigue sensitivity of TiC-cermet is lower than that of WC-hardmetal. High fatigue sensitivity refers to remarkable embrittlement of carbide composite during cyclic loading (fatigue, blanking).

The elastic strain energy storing in a material during loading (wear) may relax either by the formation and propagation of cracks or by local plastic strain. The ability of a material to plastic strain during loading allows the untimely origin of cracks to be avoided, and therefore increases its resistance to failure.

The XRD measurements performed in present study on the fractured surfaces of the WC- and TiC-based composites revealed alterations in their diffractograms – a decrease in the intensities (line peaks) and increase in broadness of the reflection lines of their carbide phase (Figure 3.5, Figure 3.11 Table 3.1). These alterations refer to changes in the fine structure (dispersity of micrograins and density of dislocation network) induced by plastic strain taking place during loading (wear) in both composite phases – in the ductile binder and in the brittle carbide.

Changes in the fine structure of composites appear to depend on the alloy to be tested and, working (wear, cyclic loading) conditions. In cyclic loading conditions the changes leading to embrittlement (decrease of plasticity) carbide phase take place (see Figure 3.21 and Figure 3.22).

It is known that changes in diffracotgrams refer to local plastic strain of material. Thus the ability of cemented carbide to adsorb fracture energy depends on the plasticity (ability to local plastic straining) of its both phases – the ductile binder and the 'brittle' carbide. The results obtained (Figure 3.21and Figure 3.22) show that there exists dependence between the carbide phase plasticity on its composition and the loading mode. Under monotonic loading conditions, WC appears to have higher plasticity compared to TiC (see difference in line intensities). During cyclic loading (fatigue testing), the plasticity of composites carbide phases (WC and TiC) decreases – an embrittlement take place. The intensity in embrittlement depends on the composition of cermet and is more remarkable for WC-based composites (see line 3 in Figure 3.21and Figure 3.22).

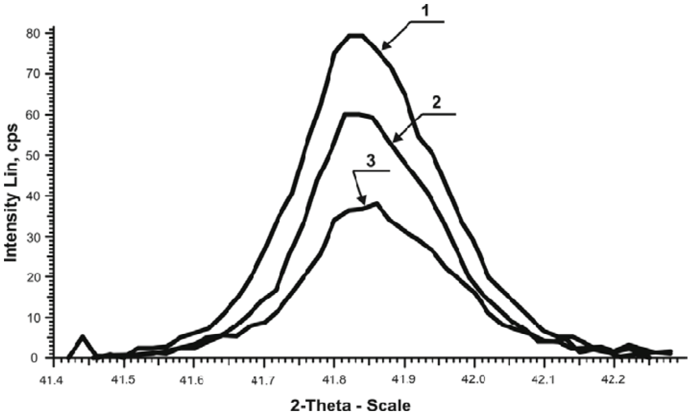


Figure 3.21 XRD patterns (diffractograms) of carbide phase of TiC-cermet: 1 – before testing (etalon); 2 – fractured during cyclic loading; 3 – fractured during monotonic loading.

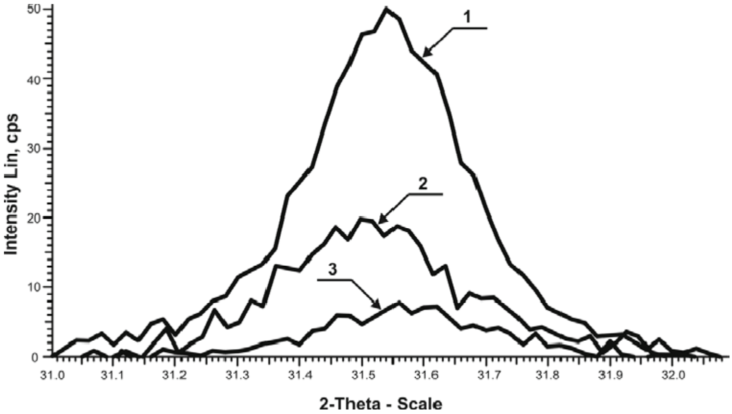


Figure 3.22 XRD patterns (diffractograms) of carbide phase of WC-hardmetal: 1 – before testing (etalon); 2 – fractured during cyclic loading; 3 – fractured during monotonic loading.

3.3 Correlations between different wear conditions

In Figure 3.23 and table Table 3.12 the blanking performance of tested composites are opposed to their durability characteristics in different wear conditions – in abrasive wear, adhesive wear, sliding wear, blanking of sheet metal and in cyclic loading conditions.

Results confirm the considerations and conclusions presented above. They refer to the existence of good correlations between blanking performance of composites and their adhesive wear resistance on one hand and fatigue sensitivity on other hand. High blanking performance of a alloy is achieved if it possess high adhesive wear resistance and low fatigue sensitivity (see Table 3.2).

Table 3.2 Blanking performance of composites, opposed to their properties (L_1– adhesive wear resistance; ΔS_2-$_7$ – fatigue sensitivity; S_1–R_{TZ}, S_2 and S_7 fatigue limit at 10^2 and 10^7 cycles, respectively; Δ side wear of tool)

Grade	L_1, m	Δ, μm	$N/\Delta\cdot10^6$	S_1, GPa	S_2, GPa	S_7, GPa	ΔS_2-$_7$, GPa
H13	1700	4.0	160	2.9	2.3	1.5	0.75
T75/14-H	2500	2.5	300	2.4	2.0	1.7	0.5

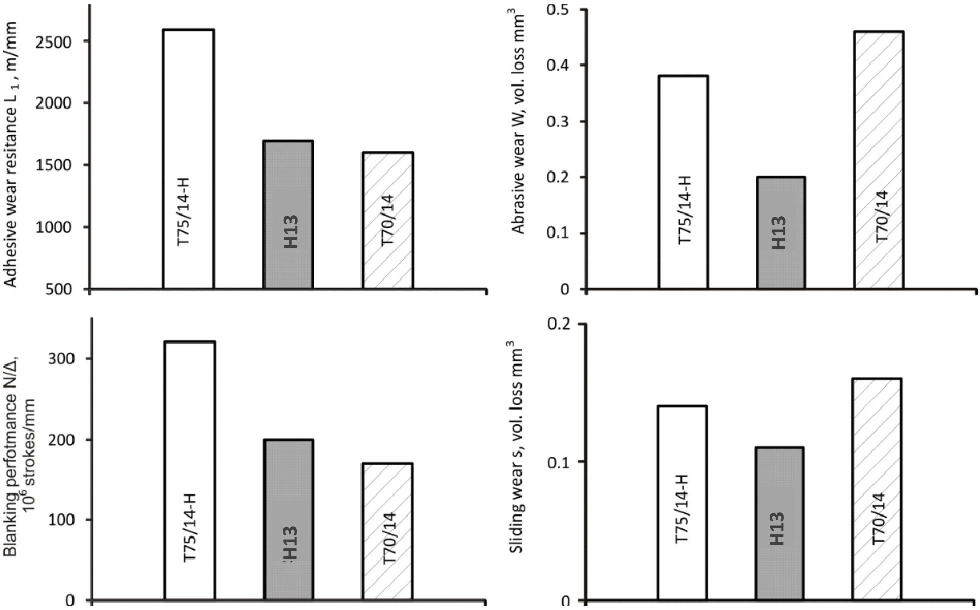


Figure 3.23 Blanking performance N/Δ of carbide composites and their response as inserts in adhesive, abrasive and sliding wear conditions

On the basis of results, presented in Figure 3.23, it can be concluded that between composites blanking performance and their resistance to abrasive, sliding, and erosive wear there does not exists any definite correlation.

The higher blanking performance of TiC-based cermets – compared to WC-based hardmetal, results from its higher resistance to adhesive wear and fatigue damage (lower fatigue sensitivity).

As stated above (Figure 3.1, 3.6 and 3.13) the abrasive wear resistance of a TiC-based cermet compare unfavorably with WC-based hardmetal. Analogical behavior (relationship) showed composites in erosive and sliding wear conditions too. These results refer to an existence of a correlation between performances of composites exploited (tested) in different wear conditions (abrasive, erosive, sliding wear)

4 CONCLUSIONS

The main conclusions of the present thesis are as follows:

1. Wear performance in different wear conditions, including cyclic loading (functional tests in the blanking of sheet metals) of the TiC-based cermet and the WC-based hardmetal, were compared. In abrasive and sliding wear conditions, the hardmetals showed superiority over the TiC-based cermets. In blanking and adhesive wear conditions TiC-based cermets demonstrated the same level of resistance to wear as hardmetals but certain advanced cermets (TiC-based cermets with an iron alloy) compare favorably with the hardmetals.
2. The results of the comparison of tool wear in blanking and tool material (TiC-based cermets and hardmetals) performance in different wear conditions and their wear mechanisms revealed a good correlation between the blanking performance and adhesive wear resistance.
3. The advantage of the TiC-based cermet over the WC-based hardmetal results from its higher resistance to adhesive wear and fatigue damage.
4. Wear performance predicted on the basis of hardness may lead to pronounced mistakes when carbide composites of different composition are considered.
5. The surface failure of a carbide composite during wear (adhesive, abrasive and sliding wear) starts preferably in the binder and is preceded by local plastic strain, taking place in both of the composite phases – in the ductile binder and in the brittle carbide, ensuring absorption of fracture energy and improvement of composites resistance to brittle failure.
6. Novel characteristics– more reliable than hardness – for prognostication of wear performance have been developed. They feature stiffness of a material (composite) – its resistance to elastic strains (estimated by the modulus of elasticity and plastic strain (estimated by proof stress).
7. The fact that certain advanced TiC-based cermets outperformed hardmetals in the wear condition with prevalence of adhesion makes them favorable tool materials in blanking and in other working conditions with prevalence of adhesion.

The novelty of present research is following:

- It is shown that the relative relevance of composite phases in wear performance differs in different wear conditions.
- The high performance of TiC-based cermets in cyclic loading conditions – in the blanking of sheet metals, exceeding that of WC-based hardmetals, was revealed.
- The ability of the brittle phase – the carbide – to resist to local plastic strain during all wear conditions under investigation was revealed, ensuring

absorption of fracture energy and improvement of composites resistance to brittle failure.
- It is shown that during cyclic loading the plasticity of the composite decreases (an embrittlement takes place) and that the higher blanking performance of the TiC-based cermet results both from its higher adhesive wear resistance and higher resistance to embrittlement (lower fatigue sensitivity).
- Development of novel, more reliable than hardness, characteristics on bases of modulus of elasticity and proof stress for prognostication of composites wear resistance.

Suggestions for future plans are as follows:

- The high performance of a TiC-based cermet results from its favorable composition and from the application of advanced sintering techniques (Sinter/HIP). For further improvement of composite's properties, application of alternative high-temperature gas-pressure techniques – the HIP – is of interest. HIP is predominantly used in the production of ceramics, WC-Co based hardmetals, P/M high speed steels and nickel-based super alloys.
- The performance of TiC-based cermets has been studied sufficiently in different wear and loading (including cyclic loading) conditions. Less known is their behavior in the conditions of creep.
- Carbide composites have been successful as powder metallurgy wear resistance materials. Their applicability is somewhat limited by the size of parts and cost. For these reasons hard coatings have been developed. The PVD-coatings have been prospective for cutting tools and abrasive wear parts. Little is known about their prospects for use in the tools (in particular blanking tools) working in the conditions with prevalence of adhesion wear.

REFERENCES

[1] K. Brookes, World Dictionary and Handbook of Hardmetals and Hard Materials, London: International Cabide Data, (1996).

[2] R. Eigi, H. Reshetnyak (H. Klaasen), A. Talkop, G. Viktorov, Hardmetal Dies in Electrotechnical Machinery, Moscow: Energoizdat (1988) [in Russian].

[3] F. Michailenko, Blanking Dies Wear Resistance, Moscow: Mashinostrojenije (1988) [in Russian].

[4] G. B. Errico, Wear of advanced ceramics for tool materials, Wear (1999) 225–229, 267–272.

[5] L. Dobrzanski, W. Kasparzak, M. Adamiak, Cutting performance and erosion resistance of high speed steels, Proceedings of international conference on advanced materials and processing technologies, Kuala Lumpur, Malaysia, (1998).

[6] E. Lassner, W. D. Schubert, Tungsten - Properties, Chemistry, Technology of the Element, Alloys, and Chemical Compounds, Springer (1999).

[7] H. Saito, A. Iwabuchi, T. Shimizu, Effects of Co content and WC grain size on wear of WC cemented carbide, Wear , (2006) 261, 126–132.

[8] P. V. Krakhmalev, T. Adeva Rodil, J. Bergström, Influence of microstructure on the abrasive edge wear of WC–Co hardmetals, Wear (2007) 263, 240–245.

[9] A. L. S. Luyckx, The dependence of the contiguity of WC on Co content and its independence from WC grain size in WC–Co alloys, International Journal of Refractory Metals & Hard Materials (2006) 24, 75–79.

[10] E. A. Brandes, G. B. Brook, Smithells Metals Reference Book (7th Edition), Elsevier (1998).

[11] C. Allen, M. Sheen, J. Williams, V. A. Pugsley, The wear of ultrafine WC–Co hard metals, Wear (2001) 250, 604–610.

[12] H. Enquist, Abrasion and erosion of cemented carbides, Tribology Letters (1998) 4, 251-255.

[13] H. Klaasen, J. Kübarsepp, Wear of advanced cemented carbides for metalforming tool materials, Wear (2004) 256, 846–853.

[14] H. Klaasen, J. Kübarsepp, Mechanical properties of hard metals and their erosive wear resistance, Wear (1994) 177, 195-193.

[15] H. Engqvist, N. Axén, Abrasion of cemented carbides by small grits, Tribology International (1999) 32(9), 527-534.

[16] R. Kieffer, P. Ettmayer New sintered nitride and carbonitride hard metals, Powder Metall (1971) 25, 1335–1342.

[17] C. C. Degnan, PH. Shipway, J. V. Wood, Elevated temperature sliding wear behaviour of TiC-reinforcedsteel matrix composites, Wear (2000) 251, 1444–1451.

[18] J. Kübarsepp, J. Pirso, H. Klaasen, Tribological characterization of TiC-base cermets, Proceedings of the 2000 Powder Metallurgy World Congress, Part 2 November 12-16, Kyoto, Japan (2000) 1633–1636.

[19] S. F. Krar, A. Gill, Exploring Advanced Manufacturing Technologies, New York: Industrial Press Inc. (2003).

[20] J. Larsen-Basse, Effect of Composition, Microstructure and Service Conditions on the Wear of Cemented Carbides, Journal of Metals (1983) 35, 35-42.

[21] K. Jia, T. E. Fischer, Abrasion resistance of nanostructured and conventional cemented carbides, Wear (1996) 200(1-2), 206-214.

[22] M. Schwartz, Encyclopedia of Materials, Parts, and Finishes Second Edition, London, CRC Press (2002) 813-815.

[23] J. W. Martin, Materials for Engineering Third edition, England: Woodhead Publishing Ltd. (2006).

[24] Roadmap of the European Technology Platrform for Advanced Engineering materials and technologies (EUMAT) (Version 23) (April 2006).

[25] G. Stachowiak, A. W. Batchelor, Engineering tribology, Elsevier (2005).

[26] B. Bhushan, Modern Tribology Handbook Volume One Principles of Tribology, CRC Press (2001).

[27] L. Kurt, Handbook of Metal Forming, New-York: McGraw-Hill (1985).

[28] R. Hambli, Blanking tool wear modeling using the finite element, International Journal of Machine Tools & Manufacture (2001) 41, 1815–1829.

[29] H. Reshetnyak (H. Klaasen), J. Kübarsepp, Structure sensitivity of wear resistance of hardmetals. Int. J Refract. Metals. Hard. Mater. (1997) 15; 89–98.

[30] H. Klaasen, J. Kübarsepp, I. Preis, Toughness of carbide composites and their durability in application, Proceedings of European conference on hard materials and diamond tooling, Lausanne, Switzerland (2002) 240–246.

[31] H. Klaasen, J. Kübarsepp, R. Eigi, Peculiarities of hardmetals wear in blanking of sheet metals, Tribology International (2006) 39, 303–309.

[32] B. Bhushan, Modern Tribology Handbook Volume 2: Materials Coatings and Industrial Applications, CRC Press (2001).

[33] J. Kübarsepp, H. Klaasen, J. Pirso, Behaviour of TiC-base cermets in different wear conditions, Wear (2001) 249, 229–234.

[34] H. Engqvist, U. Beste N. Axén, The influence of pH on sliding wear of WC-based materials, International Journal of Refractory Metals and Hard Materials (2000) 18 (2-3), 103-109.

[35] J. Larsen-Basse, Binder extrusion in sliding wear of WC-Co alloys, Wear (1985) 105 (3), 247-256.

[36] K. Jia, T. E. Fischer, Sliding wear of conventional and nanostructured cemented carbides, Wear (1997) 203-204, 310-318.

[37] Q. Yang, T. Senda, A. Ohmori, Effect of carbide grain size on microstructure and sliding wear behavior of HVOF-sprayed WC–12% Co coatings, Wear (2003) 254 (1-2), 23-34.

[38] J. Pirso, Titanium and chromium carbide based cermets, Thesis, Tallinn, TUT (1996).

[39] J. Pirso, M. Viljus, S. Letunovits, Sliding wear of TiC–NiMo cermets, Tribology International (2004) 37, 817–824.

[40] J. Pirso, M. Viljus, S. Letunovitš, Friction and dry sliding wear behaviour of cermets, Wear (2006) 260, 815–824.

[41] J. F Archard, Wear theory and Mechanisms, Wear Control Handbook, New York: American Society of Mechanical Engineers (1980).

[42] J. K. Landcaster, The influence of substrate hardness on the for formation and endurance of molybdenum disulphide films, Wear (1967) 10, 103–107.

[43] E. W. S. Komarnen, Microstructure, mechanical properties and wear-resistance of WC–Co nanocomposites, Nanophase Nanocompos, Mater. II (1997) 457, 303–308.

[44] J. Pirso, S. Letunovitš, M. Viljus, Friction and wear behaviour of cemented carbides, Wear (2004) 257, 257–265.

[45] H. Klaasen, J. Kübarsepp, Abrasive wear performance of carbide composites, Wear (2006) 261, 520-526.

[46] P. V. Krakhmalev, T. Adeva Rodila, J. Bergströma, Influence of microstructure on the abrasive edge wear of WC–Co hardmetals, Wear (2007) 263, 240-245.

[47] I. Hussainova, Microstructure and erosive wear in ceramic-based composites, Wear (2005) 258, 357-365.

[48] J. Larsen-Basse, E. Koyanagi, Abrasion of WC-Co alloys by quartz, ASME 101 (1979) 208–212.

[49] I. Hussainova, J. Pirso, Microstructural aspects of erosive wear of particle reinforced composites, Proceedings of the International Conference on advances in Powder Metallurgy&Particulate Materials, Las Vegas, (2003) 5; 71–81.

[50] A. J. Gant, M. G. Gee, Wear of tungsten carbide–cobalt hardmetals and hot isostatically pressed high speed steels under dry abrasive conditions, Wear (2001) 251, 908-915.

[51] H. Engqvist, N. Axe´n, S. Hogmark, Resistance of a binderless cemented carbide to abrasion and particle erosion, Tribology Letters (1998) 4, 251–258.

[52] H. Engqvist , N. Axe´n, S. Hogmark, Tribological properties of a binderless carbide, Wear (1999) 157–162.

[53] J. Larsen-Basse, Role of Microstructure and Mechanical Properties in Abrasion, Scripta Metallurgica et Materialia (1990) 24, 821-826.

[54] A. J Ninham, A. V. Levy, The erosion of carbide composites, Wear (1988) 121, 347-361.

[55] G. D'Errico, S. Bugliosi, D. Cuppini, E. Guglielmi, A study of cermets' wear behaviour, Wear (1997) 203/204, 242–246.

[56] I. Hussainova, Effect of microstructure and service conditions on tribological performance of cermets, Proceedings of the 2002 World Congress on Powder Metallurgy and Particulate Materials, Orlando, (2002) 8-87.

[57] I. Hussainova, J. Pirso, J. Kübarsepp, The effect of impact variables and abrasive particle properties on the erosion of cermets, Proceedings of 2nd World Tribology Congress, (CD publication), Wien, (2001)

[58] J. Pirso, J. Kübarsepp, erosion of cermets based on titanium and chromium carbides, Proceedings of International Conference Balttrib 99 September 20-22, (1999) 206-212.
[59] I. Hussainova, J. Kübarsepp, I. Shcheglov, Investigation of impact of solid particles against hardmetal and cermet targets, Tribology International (1999) 32(6) 337-344.
[60] I. Hussainova, J. Kübarsepp, J. Pirso, Mechanical properties and features of erosion of cermets, Wear (2001) 250, 818-825.
[61] J. Pirso, J. Kübarsepp, S. Letunovits, Abrasive erosion of titanium carbide base cermets, Proceedings of the 8th International Symposium on Tribology NORTRIB 1998, June 7-10, Ebeltoft, Denmark (1998) 231 -237.
[62] M. G. Gee, L. Fang, B. Roebuck, Mechanism of wear in high stress abrasion of WC-Co hard metals, Proceedings of EURO PM 99, Turin, Italy, (1999) 319–326.
[63] A. Ball, Z. Feng, The erosion of four materials using seven erodents-toward an understanding, Wear (1999) 233–235, 674–684.
[64] S. Letunovitš, Tribology of fine-grained cermets, Thesis, Tallinn: TUT (2003).
[65] J. Kübarsepp, H. Klaasen, J. Pirso, Wear characteristics of TiC-base cermets, Proceedings of 10th International Baltic Conference, Jurmala, Latvia, (2001) 207-211.
[66] I. Hussainova, Some aspects of solid particle erosion of cermets, Tribology International (2001) 34, 89–93.
[67] H. Klaasen, L. Kollo, J. Kübarsepp, Mechanical properties and wear performance of compression sintered TiC-base cermets, Powder Metall. (2007) 132 – 136.
[68] ASTM G65-94, Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus, (1994).
[69] ASTM B611-85, Standard test method for the abrasive wear resistance of cemented carbides, Annual Book of ASTM Standards, (1995) 326–327.
[70] H. Klaasen, J. Kübarsepp, I. Preis, Wear behaviour, durability and cyclic strength of TiC-base cermets, Material Science and Technology (2004) 20, 1006-1010.
[71] ISO 3327:1982, Hardmetals – Determination of transverse rupture strength.
[72] ISO 6507-1:2005, Metallic materials – Vickers hardness test – Part 1: Test method.
[73] H. Klaasen, J. Kübarsepp, Wear behaviour and mechanical properties of sinterhipped hardmetals, Powder Metallurgy, (2004) 2(47), 161-167.
[74] U. Schleinkofer, H. Sockel, K. Görting, W. Heinrich, Fatigue of hard metals and cermets − new results and better understanding, Int. J. Refract. Met. Hard. Mater. (1997) 15, 103 -112.
[75] J. Kübarsepp, H. Klaasen, Characterization of the serviceability of steelbonded hardmetals, Int. J. Refract. Met. Hard Mater. (1994) 12, 341-347.
[76] A. Griffith, Phenomena of rupture and flow in steels, Philos., Trans. Roy. Soc. (1921) 221A 163-168.

[77] P. Bridgman, Strength of brittle materials, Proc. R. Soc. Lond., London (1950) A21.

[78] J. Umansky, Rentgenografia metallov (X-ray analysis of metals), Moscow MasRgiz. (1988).

[79] H. Klaasen, J. Kübarsepp, F. Sergejev, Strength and failure of TiC-base cermets, Powder Metallurgy, (2009) 52 (2), 111-115.

LIST OF OTHER PUBLICATIONS

(NOT INCLUDED IN THE THESIS)

J. Kübarsepp, H. Klaasen, T. Roosaar, H. Annuka, Abrasive Wear and Mechanical Properties of Carbide Composites, Proceedings of 15th international Baltic Conference Engineering Materials & Tribology, Baltmattrib 2006. 5–6 October, 2006, Tallinn University of Technology, (2006) 56 – 57.

T. Roosaar, J. Kübarsepp, Klaasen; M. Viljus, Adhesion wear performance of carbide–base composites, Proceedings of the 13th Nordic Symposium on Tribology, NORDTRIB 2008. 10–13 June, 2008, Tampere, Tampere University of Technology Finland, (2008) 10.

ABSTRACT

Modern composites are a success story from the viewpoint of many applications. One of the promising fields of composites' application is their use under the conditions of two or more bodies interacting, *e.g.* tribological application where resistance to wear becomes an important factor to improve the durability of tools and other wear parts. It has an effect on the component lifecycle and also on the total cost of the final product. Application of wear parts and consumables may represent 40% of life cycle costs Wear types (abrasive wear, adhesive wear, sliding wear, *etc.*) appearing in different tribosystems and their domination may change from one to another. Wear does not take place through a single wear mechanism and understanding of each wear mechanism in each mode of wear becomes important.

Hardmetals are the most widely used wear resistant carbide composites because of their excellent combination of wear resistance and mechanical reliability characteristics (transverse rupture strength, plasticity, fracture toughness). TiC-based cermets may be successful because their thermal expansion coefficient and friction coefficient (in contact with different metal surfaces) are lower and oxidation resistance is higher than that of cemented tungsten carbide.

The current study focuses on the wear performance and failure mechanism of carbide composites, in particular alloys designed for metalforming (WC-based hardmetals and TiC-based cermets with Ni-alloy and Fe-alloy binders). Wear tests including adhesive wear, abrasive wear, sliding wear and wear of blanking tools were performed. The results were compared and related to the mechanical macroproperties and microstructure studied by SEM and XRD. Relationships between actual tool wear during blanking and used tool material behavior in different wear conditions are revealed.

The results obtained from the abrasive wear tests refer to an obvious dependence of the wear performance (wear resistance) of the test material on carbide composition. At an equal carbide volume fraction, WC-based composites demonstrate an obvious superiority over TiC-based cermets. Also, the results confirm an inconclusive influence of hardness on the wear performance of materials – at equal hardness the abrasive wear of alloys of different composition may vary up to four times.

The study revealed that there is an obvious dependence of abrasive wear resistance on the stiffness (combined effect of proof stress $R_{\mathrm{CO.1}}$ and the modulus of elasticity E) of an alloy. Also, changes in the fine structure (dispersity of micrograins and density of dislocation network) of the carbide phase induced by their local plastic strain were revealed. The wear of a carbide composite is characterized by a selective failure that starts predominantly in the binder phase by its extrusion and microcutting and continues by a subsurface fracture of carbides (fragmentation – microcracking).

The results of adhesive wear testing demonstrate an obvious dependence of the alloys wear performance on their composition. At equal carbide (binder) fraction, a WC-based hardmetal and a TiC cermet cemented with nickel steel show a remarkable superiority over an ordinary TiC-based cermet with nickel alloy binder. At equal hardness adhesive wear of different composites differ up to 4 times. The obvious dependence of wear on proof stress was discovered – the increase in proof stress improves monotonously the wear resistance. The XRD studies revealed changes in the fine structure of the carbide phase induced by the plastic strain taking place during loading.

In sliding wear conditions and carbide composition, WC-based hardmetals have obvious superiority over tungsten free ones and cermets with steel binder over composite with nickel alloy binder. Results also demonstrate uncertainty of hardness and the definitive relevance of proof stress in sliding wear. In contrast to cutting adhesive wear, sliding wear demonstrated a more definitive dependence on the stiffness – the modulus of elasticity E. During sliding wear formation of thin tribofilms (between sliding–wearing surfaces) was observed.

Results of functional wear tests demonstrate the obvious superiority of the advanced TiC-based cermet over hardmetal and ordinary cermets. SEM studies of worn carbide composite surfaces demonstrate that surface failure mechanisms occurring during adhesive wear and sheet metal blanking are similar: in both cases surface failure (removal of material) appeared first in the binder phase. Also, it was revealed that there exists a good correlation between the blanking performance and adhesive wear resistance. XRD studies showed the changes in carbide phase taking place as a result of plastic strain.

The ability of cemented carbide to adsorb fracture energy depends on the plasticity (ability to local plastic straining) of its both phases – the ductile binder and the brittle carbide. The results obtained show that there exists dependence between the carbide phase plasticity on its composition and the loading mode. During cyclic loading (fatigue testing), the plasticity of composites carbide phases (WC and TiC) decreases – an embrittlement takes place. The intensity in embrittlement depends on the composition of the carbide composite and is more remarkable for WC-based composites.

KOKKUVÕTE

Võttes aluseks mitmed kasutusvaldkonnad, väärib märkimist kaasaegsete komposiitmaterjalide omamoodi edulugu. Üks paljutõotavamaid valdkondi on nende triboloogiline rakendus, kus kulumiskindlus on oluline tegur tööriistade ja kuluvate detailide vastupidavuse suurendamisel. Komponentide kulumiskindlus määrab nende kasutusaja ja lõpptoote maksumuse. Kulumisega seotud kulutused võivad moodustada kuni 40% kuludest seadmete elutsükli jooksul. Erinevad kulumise liigid (abrasiivkulumine, adhesioonkulumine, hõõrdkulumine jne.) ja nende domineerimine erinevates tribosüsteemides võib olla erinev. Kulumine ei toimu ainult ühe kulumisliigi toimel, mistõttu iga kulumismehhanismi mõistmine on olulise tähtsusega.

WC-baasil kõvasulamid on enamlevinumad karbiidkomposiidid nende hea kulumiskindluse ja mehaanilise vastupidavuse näitajate (paindetugevus, plastsus, purunemissitkus) tõttu. TiC-baasil kermised on huvipakkuvad, kuna nende soojuspaisumistegur ja hõõrdetegur (erinevatel metallipindadel) on madalamad ning nende oksüdeerumiskindlus on suurem kui volframkarbiidi baasil kõvasulamitel.

Käesolev töö keskendub metallide survega töötlemiseks kasutatavate karbiidkomposiitide, (WC-baasil Co sideainega kõvasulamid ja TiC-baasil kermised, Ni-sulamist ja Fe-sulamist sideainega) kulumiskindlusele ja kulumismehhanismidele.

Teostatud on uuringud adhesioonkulumise, abrasiivkulumise, hõõrdkulumise ja tööriista (väljalõikestants) kulumise väljaselgitamiseks. Katsetulemusi erinevates kulumise tingimustes on omavahel võrreldud ja seostatud mehaaniliste omaduste ning mikrostruktuuriga. On tuvastatud seosed tööriista kulumise reaalsetes stantsimise tingimustes ja vastava materjali erinevates kulumistingimustes käitumise vahel.

Tulemused, mis saadi abrasiivkulumisel, viitavad seosele kulumiskindluse ja materjalide karbiidisisalduse vahel. Karbiidi võrdse mahulise sisalduse juures käituvad volframkarbiidi baasil kõvasulamid oluliselt paremini kui TiC-baasil sulamid. Samuti selgub tulemustest materjalide kõvaduse mõju nende kulumiskindlusele, kuid võrdsete kõvadusnäitajate puhul võib kulumiskindlus sõltuvalt karbiidkomposiidi koostisest erineda kuni neli korda.

Uuringud näitasid samuti, et materjalide abrasiivkulumiskindluse ja jäikuse (voolavuspiiri $R_{\mathrm{CO.1}}$ ja elastsusmooduli E kombineeritud mõju) vahel on seos. Samuti tuvastati muudatused karbiidi peenstruktuuris (mikroterade disperssus ja dislokatsioonivõrgustiku tihedus), mis on tingitud lokaalsetest plastsetest deformatsioonidest. Karbiidkomposiitide kulumist võib kirjeldada valikulise purunemisega, mis algab enamjaolt sideainest selle ekstrusiooni ja mikrolõikusega ning jätkub karbiidi terade purunemisega (killunemine, mikropragude teke).

Adhesioonkulumise katsete tulemused näitavad samuti otsest seost materjali kulumiskindluse ja karbiidisisalduse vahel. Võrdse karbiidisisalduse juures on WC-baasil kõvasulamid ja TiC-baasil terassideainega kermised oluliselt parema kulumiskindlusega kui TiC-baasil nikkelsideainega kermised. Võrdsetel kõvadustel võib kulumiskindlus erineda kuni neli korda. Uurimistulemused näitasid samuti seost kulumiskindluse ja materjali voolavuspiiri vahel. Röntgenstruktuurianalüüsi (XRD) uuringute tulemuste põhjal võib öelda, et ka adhesiooni puhul toimusid karbiidifaasi mikrostruktuuris muudatused, mis viitavad kohalikule plastsele deformatsioonile.

Hõõrdkulumise tingimustes, võttes arvesse sulamite karbiidisisaldust, käitusid WC-kõvasulamid oluliselt paremini kui volframivabad kermised ning TiC-baasil terassideainega kermised olid paremad kui TiC-baasil nikkelsideainega kermised. Samuti näitasid tulemused kõvaduse mittetäielikku ja voolavuspiiri paremat relevantsust kulumiskindluse prognoosimisel. Võrreldes adhesioonkulumisega, on elastsusmoodulil *E* hõõrdekulumise puhul kindlam seos kulumiskindlusega. Hõõrdkulumise käigus täheldati õhukeste tribofilmide teket hõõrduvatel pindadel.

Funktsionaalkatsetuste (tööriista kulumine stantsimisel) tulemused näitavad, et optimaalse struktuuri ja koostisega TiC-baasil kermised käituvad paremini kui WC-baasil kõvasulamid ja tavalised TiC-baasil kermised. Kulunud pindade SEM uuringud näitavad, et pinna purunemise mehhanism, mis leiab aset adhesioonkulumisel ja lehtmetalli väljalõikestantsimise tööriistal, on sarnane: mõlemal juhul algab purunemine (materjali eemaldumine) sideainest. Samuti näitasid need tulemused, et adhesioonkulumiskindluse ja tööriista kulumise vahel on kindel seos. XRD uuringute põhjal võib kinnitada, et ka tööriista kulumise puhul toimusid muudatused karbiidi peenstruktuuri, mis on tingitud lokaalsetest plastsetest deformatsioonidest.

Karbiidkomposiitide võime adsorbeerida purunemise energiat sõltub mõlema faasi – sitke sideaine ja hapra karbiidi – plastsusest (võimele alluda lokaalsetele plastsetele deformatsioonidele). Saadud tulemused näitavad, et eksisteerib seos karbiidi plastsuse ja koormamistingimuste vahel. Tsüklilise koormuse tingimustes (väsimuskatsed) komposiitide karbiidifaasi (WC ja TiC) plastsus väheneb – toimub haprumine. Haprumise intensiivsus sõltub materjali koostisest ja on suurem WC-baasil kõvasulamite puhul.

Märksõnad: kermis, kõvasulam, karbiidkomposiit, stantsi kulumine
abrasiivkulumine, adhesioonkulumine, hõõrdkulumine

PUBLICATIONS

PAPER I

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Adhesive wear performance of hardmetals and cermets

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ABSTRACT

This work focuses on the performance of some carbide composites, in particular alloys designed for metalforming in wear conditions with prevalence of adhesion. Wear tests were performed by a special metal cutting method which consisted of turning of mild steel at low speed. The results were compared with those obtained in the sliding wear tests and related to the mechanical properties and microstructure studied by SEM and XRD. It was shown that the surface failure starts preferably in the binder by a combined process (extraction, microcutting) and is preceded by the plastic strain taking place in both phases—in the ductile binder and in the brittle carbide. WC–Co composites and cermets on the basis of TiC, bonded with Fe-alloys demonstrated their noticeable superiority over TiC-base composites bonded with Ni-alloys.

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1. Introduction

Combination of desirable properties is met in multiphase materials, including carbide composites (hardmetals and cermets). Composites are prospective for use under the conditions of two or more bodies interacting, e.g. tribological applications.

Tungsten carbide base hardmetals are the most widely used materials for different wear applications owing to their excellent combination of high wear resistance and strength-toughness [1,2]. Major applications of tungsten carbide based hardmetals cover metal removal cutting tools, rock- and earth drilling tools and sheet metal forming tools [2]. Shortage of tungsten and deficiency of some properties (oxidation, corrosion resistance, and low weldability with steel) result in some restriction of hardmetal applications. For these reasons tungsten free carbide composites on the basis of TiC cemented with nickel alloys and alloyed steels have been developed [2–5].

In general, TiC-base composites are at some disadvantage in respect of strength and abrasive and erosive wear resistance. Application areas of the cermets are still quite restricted. However, recent developments in technology-sintering in combined atmospheres [6], application of gas compression during sintering (HIP and sinter/HIP) [7] that have substantially improved the performance of carbide composites—have created a renewed interest in TiC-base cermets.

This paper focuses on the wear behaviour of some carbide composites, in particular TiC-base cermets with nickel steel binder developed for metalforming [1,7] in the conditions where adhesion (sliding wear and cutting adhesive wear) prevails. The wear performance was related to their mechanical properties and the microstructure was studied by SEM and XRD.

2. Materials tested and experimental details

2.1. Materials

Studies focused on tungsten and titanium carbide-base carbide composites, in particular composites prospective for metalforming (carbide fraction 74–85 vol.% and properties: Rockwell hardness HRA ≥ 86.5, transverse rupture strength $R_{TZ} \geq 2000$ MPa) [1].

Fig. 1 shows the microstructures of the composites with carbide fraction ≈75 vol.%. The microstructure of WC-composites consists of WC grains mainly of angular shape embedded in the binder phase. The shape of TiC grains is more rounded. Porosity of carbide composites was <0.2 vol.% for all materials and the average grain size was 2–2.3 μm.

The materials were produced by means of the conventional vacuum sintering technology of pressed powders [1]. Some grades (cermets T80/14, T75/14) were sintered by the sinter/HIP techniques (under gas compression of 50 Bar at the sintering temperature) [7]. A review of the composition and mechanical properties of the composites investigated is presented in Table 1.

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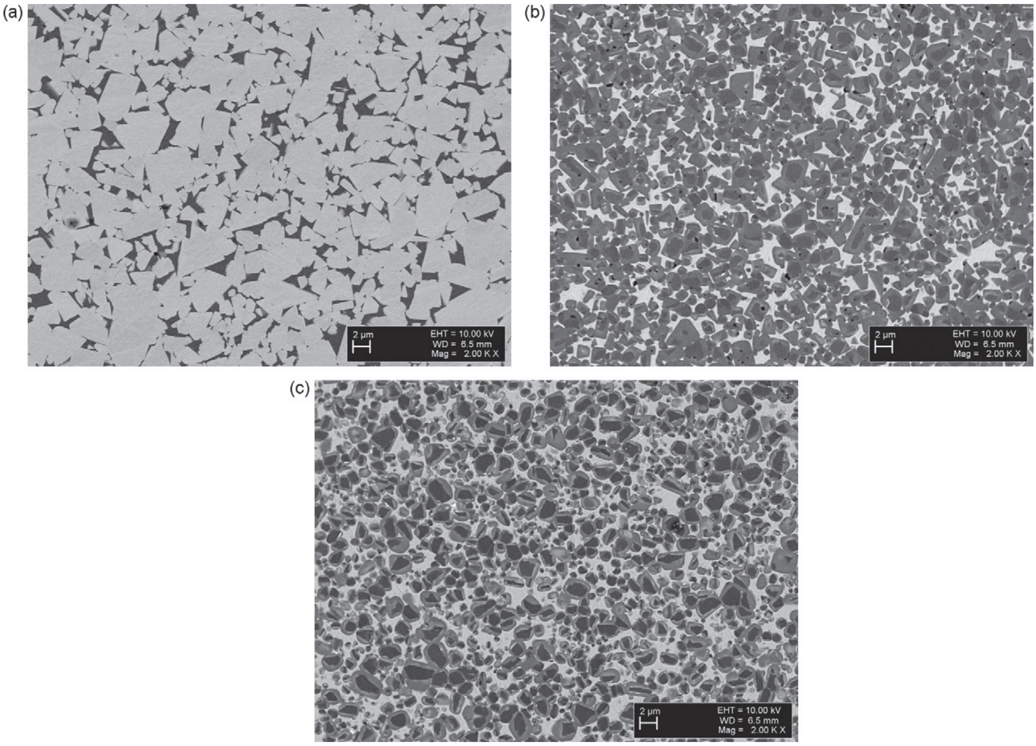

Fig. 1. SEM micrographs of the carbide composites studied: (a) hardmetal, grade H15, (b) cermet TiC–FeNi, grade T70/14; (c) cermet TiC–NiMo, grade TN30 (see Table 1).

2.2. Experimental details

Adhesive wear tests were performed by a special cutting method (by turning mild steel at low speed), simulating the wear of blanking tools—wear in the prevalence of adhesion [6,8]. The wear resistance was determined as the length of cutting path L_1, when the height h of the wear land at the specimen (tool) nose achieved 1 mm (Fig. 2). An excellent correlation between the wear resistance determined by this method and blanking die wear was reported in [1,7].

Sliding wear tests were performed in accordance with the ASTM standard B611–85 (without abrasive). The wear rate was calculated as a volume loss W, mm^3. Transverse rupture strength R_{TZ} was determined in accordance with the ISO 332/7 method (using specimen B) and Vickers hardness in compliance with EN-ISO6567. As an additional characteristic, the proof stress $R_{\mathrm{CO.1}}$, featuring the resistance of a material to the plastic strain and the shear-strength (resistance to microcutting) of all composites, was determined. The proof stress was determined in a uniaxial compression test using a specimen of a diameter of 10 mm and a length of 18 mm [8].

Examinations were complemented by SEM and XRD investigations performed on the scanning electron microscope Zeiss EVO MA15 and diffractometer Bruker D 5005, respectively. The line broadening and decrease in the intensity of X-ray reflections (measure of local plastic strain) from the composites phases were

Table 1
Structural characteristics and properties (hardness HV, transverse rupture strength R_{TZ}, modulus of elasticity E, and proof stress in compression $R_{\mathrm{CO.1}}$) of carbide composites.

Grade	Carbide, content (vol.%)	Binder composition, structure	HV (GPa)	R_{TZ} (GPa)	E (GPa)	$R_{\mathrm{CO.1}}$ (GPa)
H10	WC, 83.5	Co (W)	13.5	2.3	610	2.9
H13	WC, 79.9	Co (W)	13.0	2.8	590	2.9
H15	WC, 76.0	Co (W)	11.5	2.9	560	2.5
H20	WC, 69.0	Co (W)	10.0	3.0	510	2.0
T80/14	TiC, 86.5	14Ni–steel, austenite–bainite	14.5	1.5/2.1[a]	420	3/3.2[a]
T75/14	TiC, 83.0	14Ni–steel, austenite–bainite	13.5	1.8/2.4[a]	410	2.8/2.9[a]
T70/14	TiC, 79.0	14Ni–steel, austenite–bainite	12.5	2.3	400	2.5
T60/14	TiC, 74.0	14Ni–steel, austenite–bainite	10.5	2.4	380	2.0
T60/8	TiC, 74.0	8Ni–steel, martensite	12.2	2.2	390	2.4
TN20	TiC, 86.5	NiMo (2:1)	14.0	1.45	410	2.5
TN30	TiC, 81.0	NiMo (2:1)	13.5	1.7	380	2.4
TN40	TiC, 74.0	NiMo (2:1)	12.6	1.9	360	2.0
TN50	TiC, 65.0	NiMo (2:1)	10.0	2.1	340	1.7

[a] Sinterhipped.

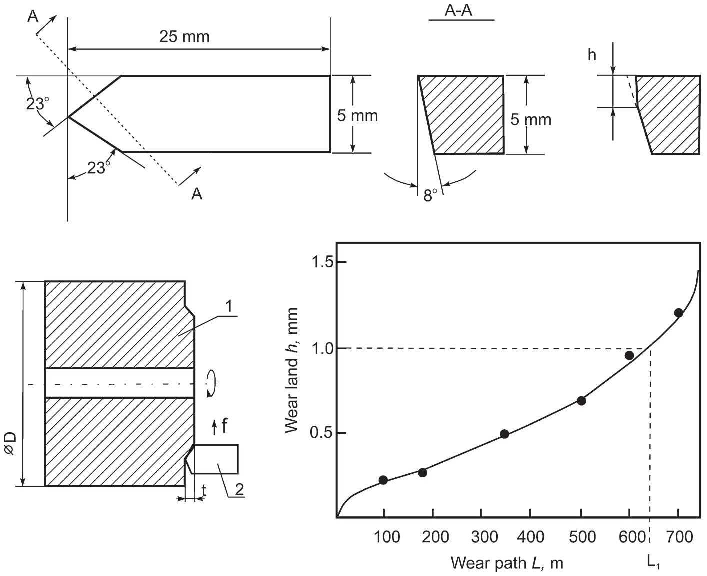

Fig. 2. The scheme of cutting adhesive wear testing: (1) mild steel to be turned, (2) specimen, h: height of wear land, L_1: adhesive wear resistance, and L: cutting path.

determined in the XRD studies [9]. In the present paper different sources of X-ray broadening were not taken up separately.

3. Results

3.1. Adhesive wear

Fig. 3 demonstrates the adhesive wear performance of the tested materials plotted against their carbide volume fraction. It can be seen that the increase in the volume fraction of the carbide phase in the alloy leads to a continuous improvement of the adhesive wear performance of all composites regardless of the carbide and the binder composition. The results obtained refer to an obvious dependence of the wear performance of an alloy on their composition. The wear performance appears to depend both on the properties of the carbide phase and on those of the binder. At an equal carbide volume fraction, WC-base hardmetals and TiC-base cermets with the Fe–Ni binder demonstrate an obvious superiority over TiC-base cermets cemented with Ni-alloys.

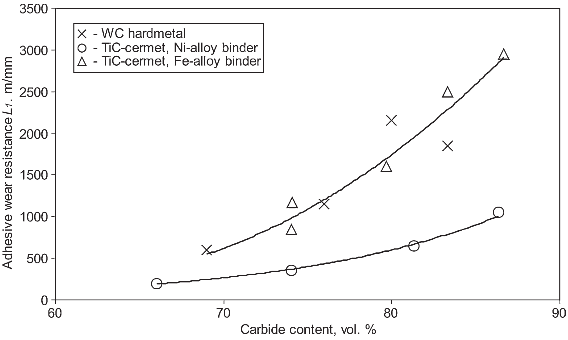

Fig. 3. Adhesive wear resistance of carbide composites vs. carbide fraction in the alloy.

3.2. Adhesive wear performance and mechanical properties

In Fig. 4 the adhesive wear performance of the test materials is plotted against their hardness—the ordinary measure of the material's wear resistance. The results obtained refer to the influence of hardness on the adhesive wear performance being uncertain similarly to abrasive and blanking wear conditions [1,10]. At equal hardness, the adhesive wear of different carbide composites differs markedly (up to four times). The lack of correlation between the adhesive wear performance of carbide composites and their hardness may be attributed to the differences in the stress states during the wear and the hardness test and higher structure sensitivity of the wear resistance of the composites in relation to hardness [7].

In Fig. 5 the adhesive wear resistance of composites is opposed to their strength property—proof stress. The results obtained refer to a definitive dependence of wear performance on the proof stress. Increase in $R_{C0.1}$ results in a continuous improvement of the wear resistance.

Results presented in Figs. 6 and 7 allow us to conclude that at an equal proof stress an additional increase in the wear performance of carbide composites can be achieved by increasing their transverse rupture strength R_{TZ} and modulus of elasticity E. In particular, at

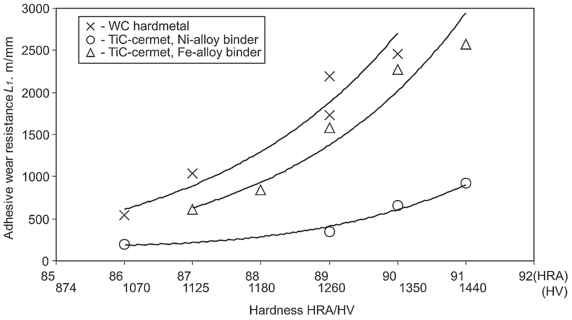

Fig. 4. Adhesive wear resistance vs. hardness of carbide composites.

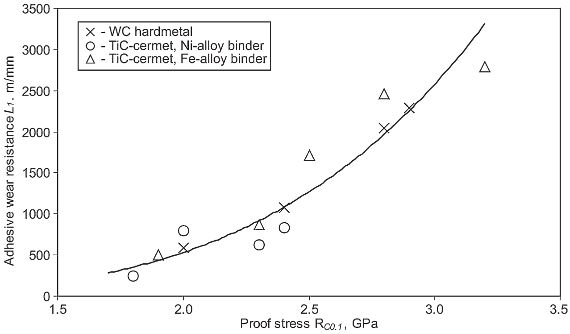

Fig. 5. Adhesive wear resistance vs. proof stress of carbide composites.

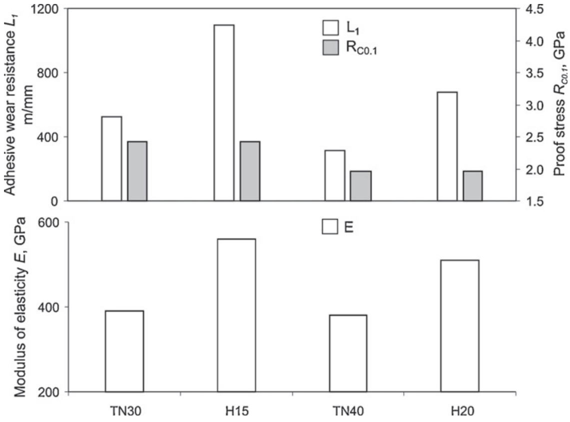

Fig. 6. Correlation graphs of adhesive wear resistance L_1, modulus of elasticity E and proof stress $R_{\mathrm{CO.1}}$ for the WC- and TiC-base composites studied.

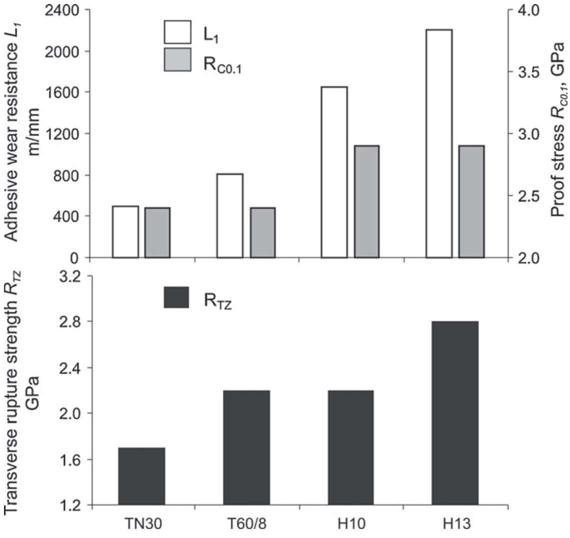

Fig. 7. Correlation graphs of adhesive wear resistance L_1, transverse rupture strength R_{TZ} and proof stress $R_{\mathrm{CO.1}}$ of WC- and TiC-base composites.

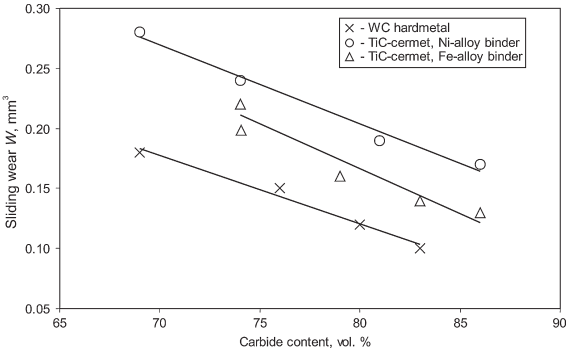

Fig. 8. Sliding wear of carbide composites vs. carbide fraction in the alloy.

equal proof stress of 2.9 GPa the adhesive wear resistance of hardmetal grade H13 is higher than that of grade H10 on account of its higher transverse rupture strength (2.8 GPa for H13 against 2.3 GPa for H10). Also, at equal proof stress of 2.0 GPa the adhesive wear resistance of hardmetal H20 is higher than that of cermet TN40 on account of significantly higher modulus of elasticity of hardmetal.

3.3. Sliding wear

Fig. 8 demonstrates sliding wear rates of the test materials plotted against their composition (carbide volume fraction). In general, the relationships repeat those revealed for cutting adhesive wear (Fig. 3): the continuous decrease in the wear with an increase in the carbide fraction in the alloy and the superiority of WC-base hardmetals and TiC–FeNi cermets over TiC-base cermets with the Ni-alloy binder.

In contrast to cutting adhesive wear (and abrasive wear [10]), the sliding wear of carbide composites demonstrated a relatively low sensitivity in terms of composition. An increase in the carbide fraction from 69 to 83.5 vol.% in WC-hardmetals results in the improvement of performance in the cutting adhesive wear conditions up to four times and in the sliding wear less than two times (compare Figs. 3 and 8).

3.4. Sliding wear and mechanical properties

Figs. 9–11 demonstrate the dependences of the sliding wear of the test materials on the hardness, proof stress $R_{\mathrm{CO.1}}$ and modulus of elasticity E (as a combined characteristic $E{\cdot}R_{\mathrm{CO.1}}$). In general, the relationships repeat those revealed for the cutting adhesive

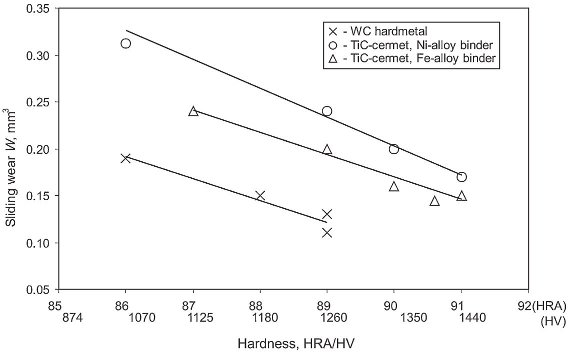

Fig. 9. Sliding wear vs. hardness of carbide composites.

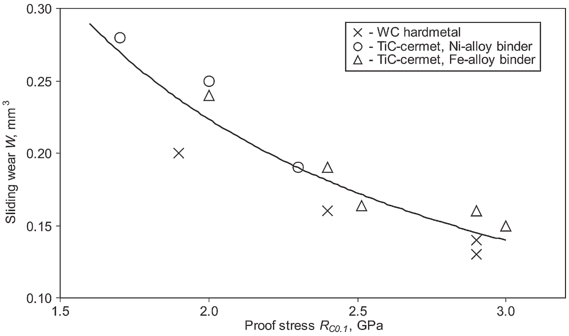

Fig. 10. Sliding wear vs. proof stress of carbide composites.

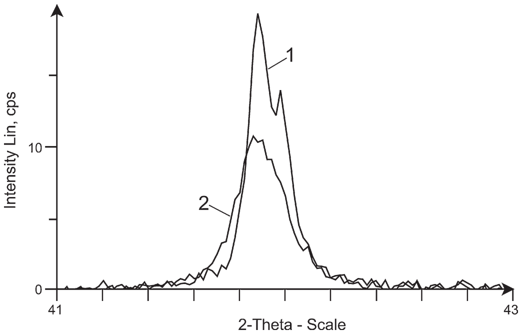

Fig. 12. XRD pattern of the carbide phase of the TiC-based cermet; 1: Before testing; 2: after sliding wear testing.

wear—the uncertainity of hardness and the definitive relevance of proof stress. In contrast to cutting adhesive wear, sliding wear demonstrated a more definitive dependence on the modulus of elasticity E (combined characteristic $E{\cdot}R_{\mathrm{CO.1}}$, see Fig. 11). Results confirm a comparatively low structure sensitivity of carbide composites to the sliding wear. An increase in the proof stress of WC-hardmetal from 2000 to 2900 MPa results in an improvement of performance – up to six times in the cutting adhesive wear and less than 1.5 times in the sliding wear conditions, respectively.

4. Discussion

The present study has found major differences in wear when adhesion (cutting adhesive wear, sliding wear) of alloys differing in their composition (carbide and binder) prevails. The relationships found refer to the relevance of the carbide-binder content and their properties, to an inconclusive influence of hardness and to an obvious relevance of the proof stress. The transverse rupture strength and modulus of elasticity appear to have a secondary (less definite) importance in the wear conditions when adhesion prevails.

In essence, the results comply with the wear theories of hardmetals and cermets [11–17]. On the basis of these studies it may be concluded that material removal during wear has a selective nature—it starts preferably in the binder mainly by microcutting and extraction. As a precondition to material removal, the extrusion of the binder and its adhesive interaction has to occur. For adhesion interaction (mating of contacting phases through solid phase welding of asperities) the plastic strain of asperities, resulting in the formation of physical contact (as a result of frustration of oxide films covering the faces and hindering the formation of the contact) has to occur [1,5,15]. Thus, the adhesion wear of a composite is controlled by its (in particular, its binder) resistance to the local plastic strain—its proof stress.

As stated, for the binder to be extruded (onto the composite surface), the elastic strain of the composite carbide skeleton, its compression, has to occur [10,11]. The extrusion of the binder (and wear) depends therefore on the modulus of elasticity of the composite while the binder flow during extrusion—on its resistance to the plastic strain (proof stress).

The higher adhesive wear resistance of the WC-hardmetal and the TiC-cermet with a steel binder, in contrast that of the TiC-cermet with a nickel-alloy binder, appears to have resulted from their higher rigidity—higher resistance to the elastic (modulus of elasticity) and plastic (proof stress and strength of the steel binder) strains.

After removal of the binder by microcutting and extraction, carbides lose their steady protective envelope (generating favourable compressive stresses in the brittle carbide), resulting in a drop of their resistance to brittle failure (subsurface microfailure) [10].

The resistance of the carbide phase to brittle failure is controlled by the level of elastic strain energy transmitted to the surface during wear and storing at the tips of the flaws of the composite microstructure [10,18,19]. The elastic strain energy may relax either by origin and propagation of microcracks or by a local plastic strain. The resistance of the composite carbide phase to brittle fracture depends therefore on its ability to undergo the local plastic strain (to absorb the fracture energy by the local plastic stain).

As stated, the plastic strain of a carbide composite takes place preferably in its ductile binder [20]. The XRD measurements performed in the present study on the worn surfaces of the WC- and

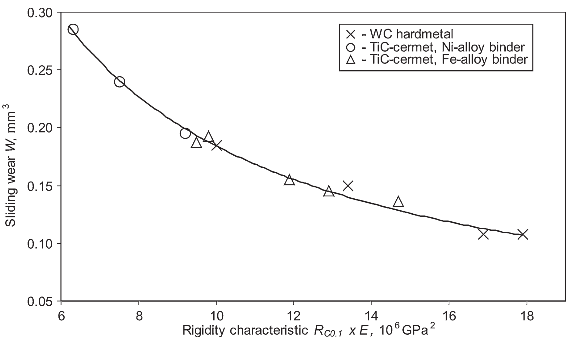

Fig. 11. Sliding wear vs. rigidity characteristic $R_{\mathrm{CO.1}} \times E \times 10^6\,\mathrm{GPa}^2$ of carbide composites.

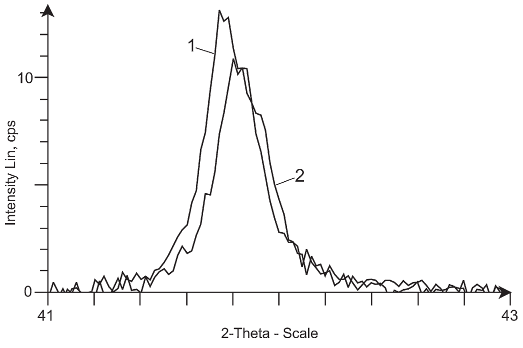

Fig. 13. XRD pattern of the carbide phase of the carbide composite (TiC-cermet). 1: before testing; 2: after cutting adhesive wear testing.

Table 2
Decrease in the intensity (line peak) and increase in the broadness of X-ray reflection lines from the carbide phases of the composites tested in the sliding wear (W) and the cutting adhesive (A) wear conditions. I_0, I_W, I_A and B_0, B_W, B_A—intensity and broadness before (0) and after sliding and adhesive wear, respectively.

Grade	Carbide, line	Decrease in intensity I, times		Increase in broadness B, times	
		I_0/I_W	I_0/I_A	B_W/B_0	B_A/B_0
T70/14	TiC [2 0 0]	1.3	1.2	1.25	1.1
TN30	TiC [2 0 0]	1.25	–	1.1	1.0
H15	WC [0 0 1]	1.5	–	1.3	1.1

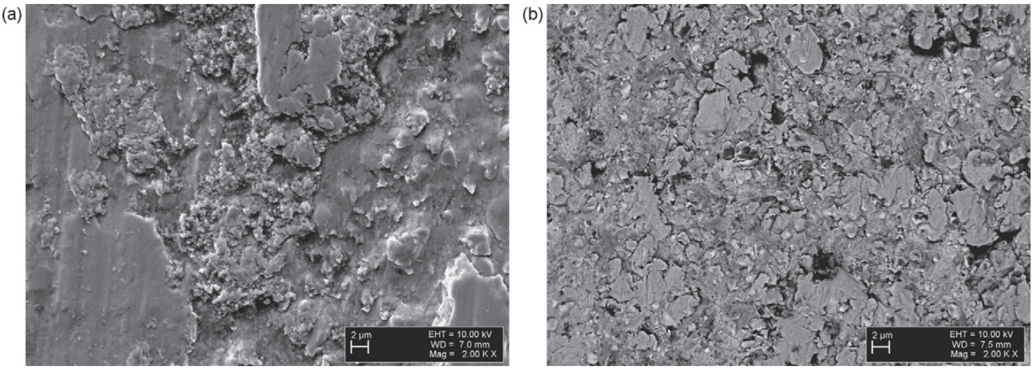

Fig. 14. SEM micrographs of the TiC-cermet (T70/14) worn in sliding (a) and cutting adhesive wear (b) conditions.

TiC-base composites revealed alterations in their difractograms—a decrease in the intensities and an increase in the broadness of the reflection lines of their carbide phases (Figs. 12 and 13). These alterations refer to changes in the fine structure (increase in dispersity of micrograins (microfragmentation) and density of dislocation network) of the carbide phase induced by their plastic strain taking place during loading [9,21].

Changes in the fine structure of the carbides in the composites tested appear to depend on the alloy's composition and wear conditions (Figs. 12 and 13, Table 2): they are more remarkable in the WC-hardmetals (compared with the TiC-cermets) and in those subjected to sliding wear (in relation to the cutting adhesive wear).

These results confirm our previous findings concerning alterations in the fine structure of carbides subjected to cyclic loading (fatigue) and to abrasion [10,21]. They refer to the ability of the carbide phase in a composite to undergo plastic strain during loading and wear and to the dependence of this phenomenon on the stress state (loading-wear conditions) and alloy composition.

Results of SEM studies—micrographs, presented in Figs. 14 and 15 refer to some differences in the surface failure taking place in the sliding wear and adhesion (and confirm those revealed by XRD). These differences may be related to the differences in the stress states—the prevalence of shear stresses (microcutting) in sliding and the relevance of tension stresses (extraction) in adhesion. The structure worn in adhesion is more distinctive in relation to sliding wear. It refers to the relevance of tensile stresses and removal of material (binder) by extraction. The structure worn in sliding wear seems to be more vague, which refers to prevelance of shear stresses and removal of binder by combined extrusion and microcutting.

As reported in [12,16] and shown in the present study (micrographs, Figs. 14 and 15), tribofilms have been observed to form on the surface of carbide composites subjected to wear, in particular sliding wear. These films, resulting from binder extrusion and adhesive interaction, act as a protective-lubricating interlayer inducing reduced wear and marked decrease in the sensitivity to the com-

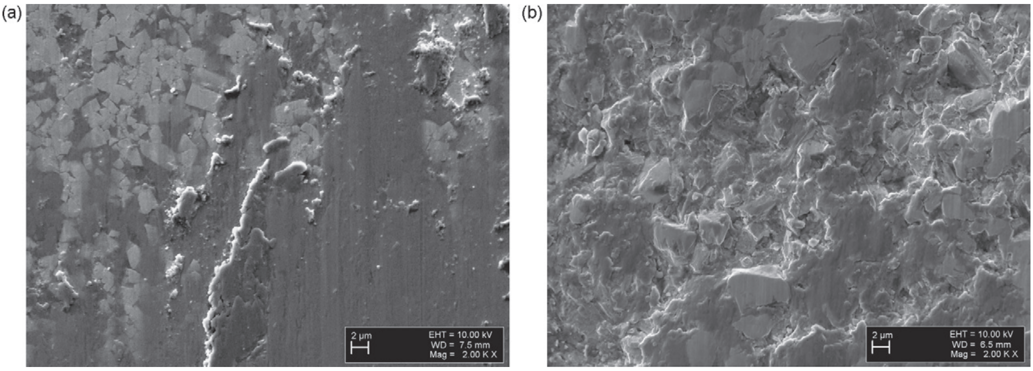

Fig. 15. SEM micrographs of the WC-hardmetal (H15) worn in sliding (a) and cutting adhesive wear (b) conditions.

position and properties (structure sensitivity) of hardmetals and cermets.

5. Conclusions

1 At an equal carbide volume fraction, tungsten carbide-base composites are at some advantage over titanium carbide-base ones, both in sliding and cutting adhesive wear conditions.
2 In respect to cutting adhesive wear performance, TiC-base composites with an iron alloy binder are at a remarkable advantage over TiC-cermets with a Ni-alloy binder (at an equal carbide fraction).
3 Wear performance in the conditions of prevalence of adhesion (sliding wear and cutting adhesive wear), predicted on the basis of hardness may lead to pronounced mistakes when carbide composites of different compositions are considered.
4 The performance of a carbide composite in the wear conditions with prevalence of adhesion is controlled primarily by its resistance to the local plastic strain featured by the proof stress depending on the carbide fraction and properties of alloy phases.
5 The surface failure (removal of material) during adhesion wear starts preferably in the binder by a combined extrusion–extraction–microcutting process, continues by cracking–extraction of carbides and is preceded by the local plastic strain taking place in both phases—in the binder and in the brittle carbide.
6 In the sliding wear conditions tribofilms were found to form, having a protective-lubricating effect between the wearing-contacting surfaces “carbide composite–steel counterbody”. The result is a remarkable decrease in the intensity of wear and its sensitivity to the composition (carbide fraction and binder composition) and properties (proof stress and modulus of elasticity).

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References

[1] H. Klaasen, J. Kübarsepp, Wear of advanced cemented carbides for metalforming tool materials, Wear 256 (2004) 846–853.
[2] K.J. Brookes, World dictionary and handbook of hard metals and hard materials, Int. Carbide Data (1996).
[3] D. Moskowitz, J. Humenik, TiC-base cermets for cutting applications, Mod. Dev. Powder Metall. 14 (1985) 307–320.
[4] M. Foller, H. Mayer, Ferro-titanit in application, in: Proceedings of the 6th International Conference on Tooling, Karlstadt, Sweden, September, 2002, pp. 186–220.
[5] J. Kübarsepp, H. Klaasen, H. Annuka, Characterization of the serviceability of steel-bonded hardmetals, Int. J. Refract. Met. Hard Mater. 12 (1994) 341–347.
[6] H. Klaasen, L. Kollo, J. Kübarsepp, Performance of TiC-base cermets sintered by different techniques, Mater. Sci. Technol. 21 (9) (2005) 1049–1053.
[7] H. Klaasen, L. Kollo, J. Kübarsepp, Mechanical properties and wear performance of compression sintered TiC-based cermets, Powder Metall. 50 (2) (2007) 132–136.
[8] H. Klaasen, J. Kübarsepp, Wear behaviour and mechanical properties of sinter-hipped hardmetals, Powder Metall. 47 (2) (2004) 161–167.
[9] J. Umansky, Rentgenografia metallov, Mashgiz, Moscow, 1988 (in Russian).
[10] H. Klaasen, J. Kübarsepp, Abrasive wear performance of carbide composites, Wear 201 (2006) 520–526.
[11] J. Larsen-Basse, Binder extrusion in sliding wear of WC–Co alloys, Wear 105 (1985) 247–256.
[12] H. Engqvist, H. Högbeg, G.A. Botton, Tribofilms formation on cemented carbides in dry sliding conformal contact, Wear 239 (2000) 219–228.
[13] H. Engqvist, G.A. Botton, Wear phenomena on WC-based seal rings, Int. J. Refract. Met. Hard Mater. 18 (2000) 39–46.
[14] J. Aoki, Wear of blanking tools, J. Soc. Lubr. Eng. 30 (9) (1985) 7–10.
[15] N. Zorev, Influence of wear nature on durability of cutting tools, Vestnik Mashinostrojenia 2 (1965) 19 (in Russian).
[16] J. Pirso, M. Viljus, S. Letunovitš, Friction and dry sliding wear behaviour of cermets, Wear 25 (2005) 150–158.
[17] I. Hutchings, Tribology: Wear and Friction of Engineering Materials, Edv. Arnold, London, 1992.
[18] A.A. Griffith, Strength of materials, Philos. Trans. R. Soc. Lond. 221A (1920) 163–198.
[19] P.W. Bridgman, Strength of brittle materials, Proc. R. Soc. Lond. A 201 (1950) 35–44.
[20] U. Schleinkofer, H.-G. Sockel, K. Göring, W. Heinrich, Fatigue of hardmetals and cermets—new results and better understanding, Int. J. Refract. Met. Hard Mater. 15 (1997) 103–112.
[21] H. Klaasen, J. Kübarsepp, F. Sergejev, Strength and failure of TiC-base cermets, Powder Metal. 52 (2) (2009) 111–115.

PAPER II

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Performance and failure of carbide composites in different wear conditions

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Abstract

This paper describes the wear performance and failure mechanism of some advanced carbide composites (TiC-based cermets and WC-based hardmetals) in different wear conditions. Functional tests were conducted in cyclic loading wear (blanking) and laboratory trials in abrasive, sliding and adhesive wear, complemented by SEM and XRD studies. Correlation between the blanking performance and adhesive wear resistance of the composites proved fair and similarities were revealed in surface failure morphology. In these conditions, the advanced TiC-cermet was found to be superior over the WC-based hardmetal. It is shown that the wear of a carbide composite starts preferably in the binder and is preceded by local plastic strain taking place in both phases – in the ductile binder and in the brittle carbide.

*Key words***:** cermet, hardmetal, carbide composite, blanking performance, abrasive wear, adhesive wear, sliding wear

1. Introduction

Carbide composites on the basis of tungsten carbide – hardmetals – are a success story from the viewpoint of their mechanical and tribological properties and spectrum of applications **[**1**]**. However, deficiency of some specific properties, particularly corrosion resistance and weldability, restricts the use of hardmetals and alternative ceramic and metal composites, e.g. on the basis of titanium carbide have been developed. Among them TiC-based cermets bonded with Fe/Ni alloy (Ni steels) are still the most promising candidates **[**2 - 4**]**. A series of TiC-based cermets have been developed at TUT. One of the most successful so far – the grade T70/14 – has demonstrated its superiority over the ordinary WC- based hardmetal H15 (85 wt% WC) as a tool material for blanking of sheet steels **[**5, 6**]**.

This paper focuses on the blanking performance of an advanced TiC-cermet – the grade T75/14 (75 wt% TiC cemented with Ni-steel and produced by sinter/HIP technology) **[**7**]**.
WC-Co hardmetal grade S13 (87 wt% WC) and the ordinary TiC-based cermet grade T70/14 were investigated as reference materials.

Another important aim of the study was to identify any correlation that might exist between blanking performance and wear resistance (in the abrasive, adhesive and sliding wear conditions) on the one hand and between wear-failure mechanisms on the other hand.

2. EXPERIMENTAL

2.1. Materials

The main microstructural characteristics and mechanical properties of the tested composites are presented in Table 1.

The alloys were sintered by two techniques: standard vacuum sintering (for grades T70/14, T75/14 and S13) and sinter/HIP (combined sintering in vacuum + argon gas compression) – for grade T75/14 – H.

Table 1. Structural characteristics and properties (hardness *HV*, transverse rupture strength R_{TZ},, modulus of elasticity *E*, and proof stress $R_{CO.1}$) of carbide composites

Grade	Carbide		Binder		*HV*	$R_{TZ,}$ GPa	*E*, GPa	$R_{CO.1,}$, GPa
	wt %	grain size d, μm	Composition	Structure				
T70/14	TiC, 70	2.1	14Ni-steel	Austenitic	1250	2.11	400	2.6
T75/14	TiC, 75	2.0	14Ni – steel	Austenitic	1320	1.80	410	2.9
T75/14-H	TiC, 75	2.1	14Ni- steel	Austenitic	1320	2.40*	410	3.0
S13	WC, 87	1.8	Co(W)		1300	2.80	590	2.8

*after sinterhipping

2.2. Testing procedures

The procedure of the durability functional test resembled that in service, i.e.– blanking of grooves into electrotechnical sheet steel (with a hardness of 150 *HV* and a thickness of 0.5 mm) using a three-position die reinforced with the three different composites to be investigated, mounted on an automatic mechanical press [5, 6].

The wear resistance, i.e. the blanking performance of carbide composites, was evaluated by the measurement of the side wear of the die Δ (increase in diameter) after an intermediate service time N=0·5 x 10^6 strokes, as N/Δ (lifetime in strokes per 1 mm of the side wear Δ). The intermediate service time 0.5 x 10^6 corresponded to the time between two consecutive prophylactic sharpenings used in the exploitation of blanking dies [7]. The side wear was measured using the measuring machine STRATO 9 – 166 in fixed environmental conditions (constant room temperature and humidity of 40%) as an average of 4 – 6 measurements.

Abrasive wear tests were performed using the rubber-rimmed rotary machine (modified ASTM G65 – 94 method) as follows: abrasive-quartz sand (amount 3 kg, particle size 0.1 – 0.2 mm, hardness *HV* 1100), velocity of wheel 0.24 m/s, testing time 10 min, and load 3 N. The wear was estimated as the volume lost in mm^3.

A special method was used for adhesive wear tests (elaborated for the evaluation of blanking performance), namely turning of mild steel (*HV*=160) at low speed v <12 m min^{-1}, in which surface adhesive failure generally prevails [5]. The wear rate was determined as the height of the wear land h at the tool (specimen) nose after the specific length of the cutting path L. The adhesive wear resistance L_1 was determined as the length of the cutting path L when the height of the wear land h achieved the critical value of *1* mm. The critical height h = 1 mm of the wear land corresponded to the onset of the accelerated wear.

Sliding wear tests were performed in accordance with the ASTM standard B611 – 85 procedure, without abrasive at a loading F= 40N and a wear length L= 4000 m. The volumetric wear rate was calculated as $\Delta V= \Delta m/\rho$, where Δm is the average (of three specimens) mass loss and p is the density of the alloy.

Examinations were complemented by SEM and XRD investigations performed on the scanning electron microscope JEOL JSM 840A and the diffractometer Bruker D 5005, respectively. The line broadening and intensity of X-ray reflections from the composite phases were determined in the XRD studies [8].

3. RESULTS AND DISCUSSION

3.1. Wear performance

Results of functional wear tests (conducted as the blanking of grooves into the sheet steel) are shown in Fig. 1 as wear contours Δ-H (side wear Δ depending on the depth H from the cutting edge of the die). During testing (N=5 x 10^5 strokes) of the die (three position die reinforced with the sample cermets/hardmetals), neither fracture nor brittle macrochipping of cutting edges was detected.

Cutting edges became blunt as a result of uniform wear. The wear contours (Fig. 1) and the side wear data for the dies tested demonstrate the obvious superiority of the advanced TiC-based cermet over hardmetal S13 and cermet T70/14.

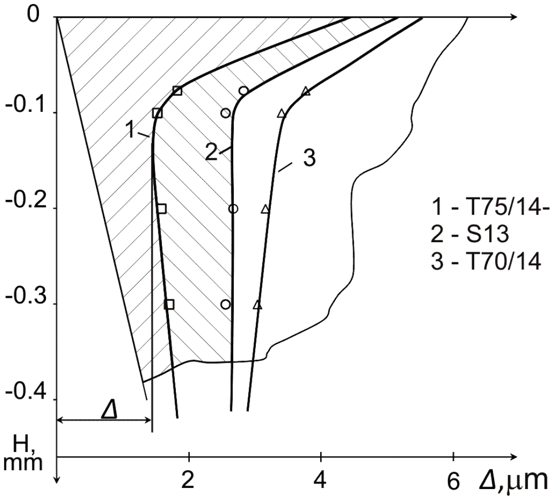

Fig.1. Wear contours of carbide tool (die) edges – side wear Δ *after blanking of* $5\cdot10^5$ *strokes. H – deph of groove measured from cutting edge.*

The advanced TiC-based cermet demonstrated a blanking performance exceeding that of the ordinary composites up to 1.5 – 2 times.

Figure 2 shows the blanking performance *N/Δ* of carbide composites investigated (TiC-based cermets, hardmetal) opposed to their response as inserts in the abrasive, sliding and adhesive wear conditions.

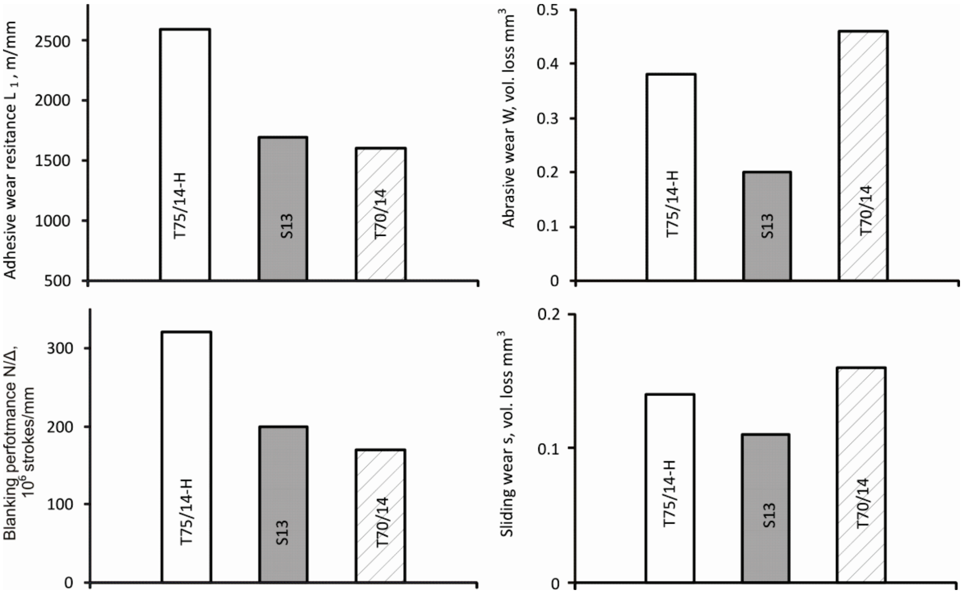

Fig. 2. Blanking performance *N/Δ* of carbide composites and their response as inserts in adhesive, abrasive and sliding wear conditions.

In terms of abrasive wear resistance, both of the TiC-based cermets were considerably worse (up to three times) than the hardmetal.

As stated in previous research, the abrasive wear of carbide composites is controlled by the resistance to elastic and plastic strain and depends first on the properties of the carbide phase (modulus of elasticity) [9]. At approximately equal resistance to plastic strain (measured by the proof stress), the resistance of hardmetals to elastic strain (measured by the modulus of elasticity) exceeds that of TiC-cermets by a factor of 1.6.

In general, the results obtained in the sliding wear trials and in the abrasive tests are in agreement, i.e. they demonstrate the advantage of hardmetals over TiC-based cermets (although their superiority is somewhat less obvious).It also highlights the role of the carbide phase of alloys (their strength and rigidity) to withstand surface failure during sliding and abrasive wear.

Concerning adhesive wear performance of carbide composites, a fair correlation was found between the adhesive wear resistance and the blanking performance. Results demonstrate the superiority of the advanced TiC-based cermet T75/14-H over hardmetal S13 (by a factor ~1.5).

SEM studies of worn carbide composite surfaces confirm the results described above. They demonstrate that surface failure mechanisms occurring during adhesive wear and sheet metal blanking are similar: in both cases surface failure (removal of material) appeared first in the binder phase (Fig. 3). The distinctive nature of the worn surfaces confirms that binder extraction prevails in both cases. In contrast to adhesive wear, surfaces worn during abrasive and sliding wear do not show this distinction.

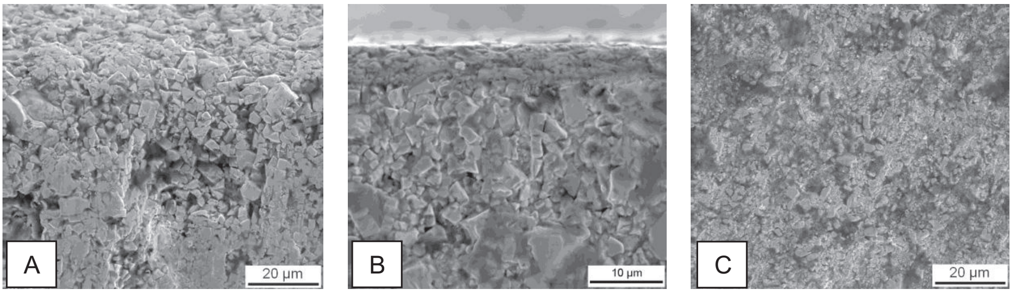

Fig. 3. SEM image of cemented carbide S13 surface after blanking (A), after adhesive wear testing (B) and abrasive wear testing (C).

3.2. Microstructural aspects of carbide composite surface failure (wear)

As reported in previous studies devoted to the wear mechanisms of carbide composites, the removal of material during wear has a selective nature and starts preferably in the binder phase by microcutting (sliding wear, abrasive wear) and extraction (adhesive wear) [5,6, 9 - 11]. After removal of the binder, carbides lose their steady protective envelope (generating favourable stresses in the carbide), resulting in a drop of their resistance to brittle failure (subsurface microfailure) [9].

The resistance of the carbide phase to brittle failure is controlled by the level of the elastic strain energy transmitted to the surface during wear (and storing at the tips of the flaws of the composite microstructure)[9, 12]. The elastic strain energy may relax either by origin and the propagation of microcracks or by a local plastic strain. The resistance of the composite carbide phase to brittle fracture depends therefore on its ability to undergo the local plastic strain (to absorb the fracture energy by the local plastic strain).

As stated, the plastic strain of a carbide composite takes place preferably in its ductile binder [13]. The XRD measurements performed in this study on the worn surfaces of the WC- and TiC-based composites revealed alterations in their difractograms – a decrease in the intensities and an increase in the broadness of the reflection lines of their carbide phases (Figs. 4 and 5). These alterations refer to changes in the fine structure (dispersity of micrograins and density of dislocation network) of the carbide phase induced by their plastic strain taking place during the wear-loading **[**8, 14**]**.

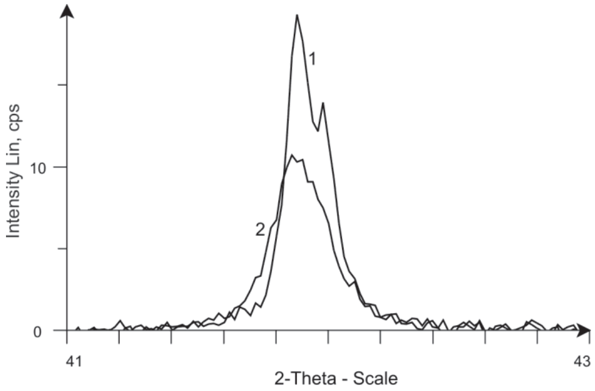

Fig. 4. XRD pattern of the carbide phase of the TiC-based cermet: 1 – before testing; 2 – after sliding wear testing

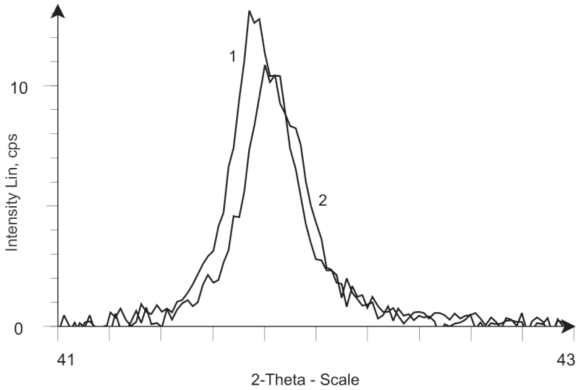

Fig.5. XRD pattern of the carbide phase of the TiC-based cermet: 1 – before testing; 2 – after adhesive wear testing.

Changes in the fine structure of the carbides in the composites tested appear to depend on the alloy's composition and wear conditions – they are higher (see Table 2) in the hardmetal (than the TiC-based cermet) and lower in composites subjected to the adhesive wear (in relation to the abrasive and sliding wear). These differences in changes in the fine structure (featuring plastic strain) of the carbide during the wear-failure refer to the dependence of carbide plasticity (measure I_o/I and B/B_o) on the stress state.

Table 2. Decrease in intensity *I* and increase in the broadness *B* of the lines of X-ray reflections from the carbide phases of the composites tested in the abrasive, sliding and adhesive wear conditions.
I_o, I_w, I_s, I_A – intensity, B_o, B_w, B_s, B_A - broadness before (O) and after abrasive (W), sliding (S) and adhesive (A) wear testing, respectively.

Grade	Carbide, line	Decrease in intensity, times			Increase in broadness, times		
		I_o/I_w	I_o/I_s	I_o/I_A	B_w/B_o	B_s/B_o	B_A/B_o
T75/14-H	TiC[200]	1.4	1.3	1.1	1.3	1.2	1.1
S13	WC[001]	1.5	1.5	1.2	-	1.3	1.1

As stated, during the adhesive wear of composites, material removal occurs preferably by extraction (with prevalation of tension stresses) and therefore failure plasticity is less compared to the abrasive and sliding wear when shear stresses (microcutting) prevail **[**12, 15**]**.

The results received in this study confirm our previous findings concerning alterations in the fine structure of carbides subjected to cyclic loading (fatigue). **[**14**]** They refer to the ability of the carbide phase in a composite to undergo plastic strain during loading and wear and to the dependence of this phenomenon on the stress state (loading-wear conditions) and alloy composition.

CONCLUSIONS

- Wear performance and mechanism in different wear conditions, including cyclic loading (functional tests in blanking of sheet metals) of an advanced TiC-based cermet and that of hardmetal, were compared and as a result, the advantage of the cermet was revealed in blanking and adhesive wear conditions.
- Reasonable correlation between the blanking performance of carbide composites and their adhesive wear resistance and similarity in the surface failure morphology was found.
- The surface failure of a carbide composite during wear starts preferably in the binder and is preceded by local plastic strain, taking place in both alloy phases – in the ductile binder and in the brittle carbide .

- The failure plasticity of a carbide (TiC, WC) depends both on the alloy composition and the stress state and is more remarkable for the hardmetal and in the wear conditions where shear stresses prevail, particularly in the abrasive and sliding wear.

Acknowledgements

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Rerefences

[1] Brookes, K.J. World Dictionary and Handbook of Hard Metals and Hard Materials, Int. Carbide Data, London, 1996.
[2] Foller, M., Mayer, *H. Proc.of the 6 th Int. Conf. on Tooling*, Karlstadt, Sweden, 2002, 186 – 220.
[3] Moskowitz, D., Humenik, H*. Modern Development in Powder Metallurgy*, 1989, **14**, 307 – 320.
[4] Kübarspp, J., Klaasen H., Annuka, H. *Int. J. Refract. Metals Hard Mater*., 1994, **12**, 345 – 348.
[5] Klaasen, H., Kübarsepp, J. *Wea*r, 2004, **256**, 846 – 853.
[6] Klaasen, H., Kübarsepp, J., Preis, I. *Mater. Science & Technology,* 2004, **20**, 830 -837.
[7] Klaasen, H., Kollo, L., Kübarsepp, J. *Powder Metall.,* 2007, **50** (2), 132 – 136.
[8] Umansky, Rentgenografia metallov (X-ray analyses of metals), Mashgiz, Moscow, 1988 (in Russian).
[9] Klaasen, H., Kübarsepp, J. *Wear,* 2006, **261**, 520 – 526.
[10] Roosaar, T., Kübarsepp, J., Klaasen, H. Proc. of *Nordtrib 2008*: 13th Nordic Symposium on Tribology, Tampere, Finland, 2008, (CD-ROM publication).
[11] Pirso, J., Viljus, M., Letunovitš, S. *Wear*, 2006, **260**. 815-824
[12] Griffith, A.A. *Philos., Trans. Roy. Soc*. London, 1921, 221A, 163 – 190.
[13] Schleinkofer, U., Sockel, H., Görting, K, Heinrich, W. *Int. J. Refract. Met Hard Mater.*, 1997,**15**, 103 -112.
[14] Klaasen, H., Kübarsepp, J., Sergejev, F. *Powder. Metall*., (accepted for publication, POM 1433 R1).
[15] Bridgeman, P.W., Proc. R.Soc., (London), 1950, A 201, 35 – 45.

PAPER III

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Abrasive Wear Performance of Carbide Based Composites

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Abstract

The performance of carbide composites (WC-hardmetals and TiC-cermets) designed for metalforming under conditions of abrasive wear was investigated. Wear tests were performed by help of a rubber rimmed rotary wheel machine (ASTM 65-949 method), complemented by SEM and XRD studies of micro and fine structure. It is shown that the abrasive wear of a carbide composite is controlled by its rigidity characteristics (the modulus of elasticity and proof stress). The performance depends primarily on the properties of the carbide phase and its content in the alloy.

Key words. Abrasive wear; carbide composite; cermet; hardmetal.

1. INTRODUCTION

Tungsten carbide based hardmetals are most widely used in different wear conditions because of their excellent combination of high wear resistance and fair strength-toughness [1]. TiC-base cermets (so-called tungsten-free hardmetals) are successful in some applications due to their good adhesive wear resistance, high specific strength and favourable physical properties (corrosion resistance and fair weldability) [2, 3]. Because of lack of common information of different cermets it is of interest to test their wear behaviour under different wear conditions.

The present study was focused on the abrasive wear behaviour of some carbide composites prospective for metalforming. The wear performance of those composites was studied in relation to their mechanical properties and microstructure (to specify the mechanism of wear).

2. Experimental

Tungsten and titanium-carbide based cemented carbides; in particular, composites prospective for metalforming (carbide fraction 74-85 vol.-%, transverse rupture strength ≥ 2000 N/mm^2, Rockwell hardness $HRA \geq 87$) were investigated [6].

The materials were produced by the conventional vacuum sintering technology of compacted powders. Some grades (T75/14H, T80/14H) were sintered by the sinter/HIP technique (under gas-compression of 50 Bar at the sintering temperature) [5]. The composition and mechanical properties of the composites investigated are presented in Table 1.

Abrasive wear tests were performed by using of the rubber-rimmed rotary wheel machine (modified ASTM 65-94 method) (Fig.1) as follows: abrasive – quartz sand (amount – 3 kg with a particle size of 0.1 – 0.2 mm and hardness HV=1100), velocity of the wheel – 0.24 m/s, diameter of the steel wheel – 80 mm, wear distance – 144 m, testing time – 10 min and load – 3 N. The wear was estimated as the volume loss V in mm^3 and wear resistance as $1/V$, mm^{-3}.

Table 1. Structural characteristics and properties (hardness *HV*, transverse rupture strength R_{TZ}, modulus of elasticity *E,* proof stress $R_{co.1}$) of carbide composites

Grade	Carbide composition, wt %	Binder composition, structure	*HV, GPa*	R_{TZ}, *GPa*	*E, GPa*	$R_{co.1}$, *GPa*
H10	WC90	Co(W)	1.35	2.4	610	3.0
H13	WC88	Co(W)	1.32	2.8	590	2.9
H15	WC85	Co(W)	1.15	2.9	560	2.4
H20	WC80	Co(W)	0.98	3.0	510	2.0
T60/8	TiC60	Fe-8Ni, martensite	1.26	2.2	390	2.4
T60/14	TiC60	Fe-14Ni, austenite	1.1	2.4	380	1.9
T70/14	TiC75	Fe-14Ni, austenite	1.21	2.3	400	2.2
T75/14H	TiC70	Fe-14Ni, austenite	1.38	1.9/2.4*	410	2.6
T80/14H	TiC80	Fe-14Ni, austenite	1.47	1.4/2.0*	420	3.0
TN30	TiC70	Ni : Mo (2:1)	1.40	1.7	380	2.3
TN40	TiC60	Ni : Mo (2:1)	1.26	1.9	360	2.1
TN40	TiC60	Ni : Mo (4:1)	1.01	2.2	350	1.8
TN50	TiC50	Ni : Mo (2:1)	1.0	2.1	340	1.7

* sinterhipped alloy

Transverse rupture strength R_{TZ} was determined in accordance with the conventional ISO 3327 method (specimen B) and Vickers hardness in accordance with EN-ISO6567.

As additional characteristics, proof stress $R_{CO.1}$, featuring material resistance to the plastic strain and its shear-strength (resistance to microcutting) of all the composites were determined. The proof stress was determined in a compression test, using a specimen with a diameter of 10 and a length of 18 mm [6].

Examinations were complemented by micro and fine structure studies of the worn surface of the composites (SEM and XRD studies), performed on the scanning electron microscope JEOL JSM840A and on the X-ray diffractometer Bruker D 5005, respectively.

3. Results and discussion

In Fig. 1 abrasion rates of test materials are plotted against their hardness – the ordinary measure of material wear resistance. The results confirm an inconclusive influence of hardness on the wear performance of materials reported before also for adhesion, erosion and blanking wear conditions [2, 4, 7]. At equal hardness the abrasive wear of alloys of different composition may vary up to four times.

The fact that no correlation between abrasion performance and hardness exists may be attributed to higher structural sensitivity of the wear resistance of the composite in relation to hardness and differences in the stress states during wear and hardness tests [2, 4].

The results suggest that the wear of the test material depends on its composition (composition of the carbide and that of the binder). At equal hardness level, tungsten carbide-base composites demonstrate superiority over TiC-base composites. TiC-cermets with a steel binder are better than those with a nickel-alloy.

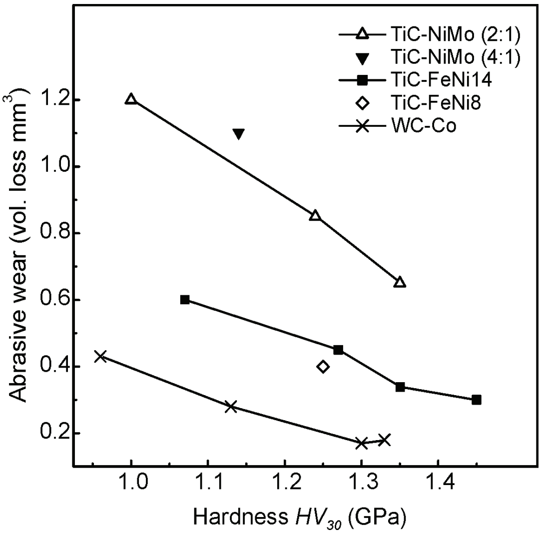


Fig. 1 Abrasive wear of carbide composites vs. Vickers hardness.

Fig. 2 shows the wear resistance $\frac{1}{V}$ (*V* – volume loss) of the composites investigated as function of a combined value – the characteristic of rigidity $R_{CO.1} \cdot E^2$, representing the combined effect of proof stress $R_{CO.1}$ and the modulus of elasticity E [7].

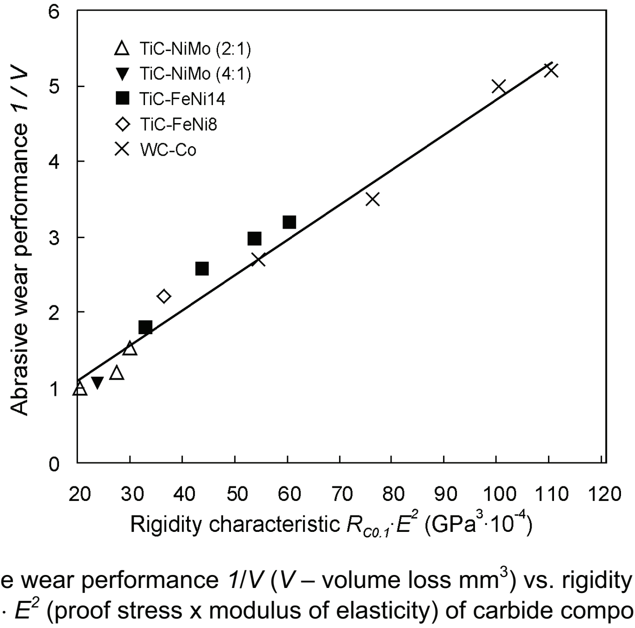


Fig. 2 Abrasive wear performance *1/V* (*V* – volume loss mm^3) vs. rigidity characteristic $R_{CO.1} \cdot E^2$ (proof stress x modulus of elasticity) of carbide composites.

The good correlation obtained – close to linear – suggests that the equation $1/V = R_{CO.1} \cdot E^2$ is reliable to prognosticate and calculate the abrasive wear resistance of carbide composites of different composition.

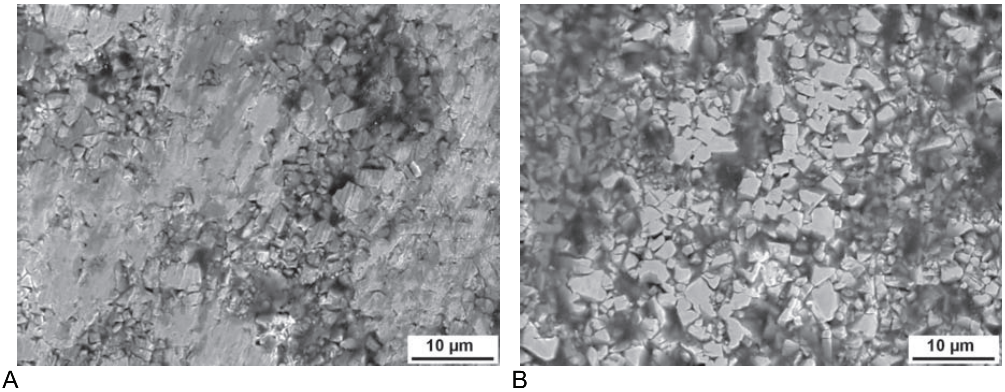
In essence, the results are in accordance with wear theories concerning the surface failure of hardmetals and cermets during abrasive-erosion [7 - 10]. It may be concluded that the wear of a carbide composite is characterized by a selective failure that starts predominantly in the binder phase by its extrusion and microcutting and continues by a subsurface fracture of carbide (fragmentation - microcracking).

The extrusion of the binder onto the composite surface is controlled by the elastic strain of its carbide skeleton – its elastic compression (during the penetration of abrasive particles). It depends, therefore, on the stiffness (modulus of elasticity) of the carbide phase. An increase in the modulus of elasticity of the carbide results in a decrease of elastic strain and binder extrusion. The plastic flow of the binder (during extrusion), in turn, depends on its resistance to the plastic strain – the proof stress. As the proof stress increases, hindrance to the plastic flow, to extrusion and microcutting (shear failure) will grow.

SEM micrographs (Fig 3) refer to some differences in wear mechanisms during abrasion and erosion. The structure worn in abrasion is more distinctive in relation to erosion. It refers to the relevance of tension stresses (extraction) in the removal of material.

The abilty of the carbide phase to resist brittle failure depends on the level of the elastic strain energy transmitted to the surface by abrasive particles (during collisions and fluctuating contact stresses) and storing at tips of flaws in the composite microstructure [17]. Elastic energy depends on the modulus of elasticity of the carbide: an increase in the modulus of elasticity results in a decrease of the elastic strain and strain energy.

Elastic strain in the composite during wear (cyclic contact stresses) may be relaxed either by the origin of cracks or by a local plastic strain. The resistance of a composite (their phases) to brittle fracture depends, therefore, on its ability to undergo plastic strain (to absorb fracture energy by local plastic strain).



A B

Fig. 3 SEM micrographs of a cemented carbide (composite H15) worn in erosive (A) and abrasive (B) wear conditions.

The plastic strain of the carbide composite under static and cyclic loading has been reported to start and propagate mainly in the ductile binder [12].

The XRD measurements performed in the present study on the worn surfaces of TiC- and WC-base composites revealed alterations in their diffractograms − a decrease in the intensities and an increased broadness of the reflection lines of their carbide phases (Fig. 4 and Fig. 5). These alterations refer to changes in the fine structure (dispersity of micrograins and density of dislocation network) of the carbide phase induced by their local plastic strain, taking place during abrasive wear.

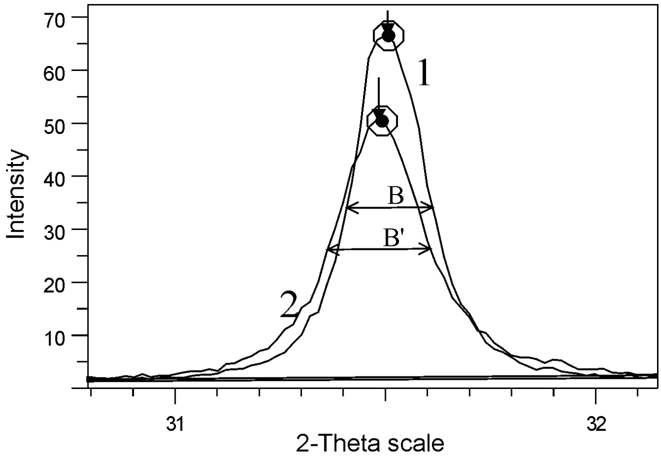


Fig.4 XRD diffraction patterns of WC- hardmetal carbide phase [line 001]; 1 – before testing (etalon); 2 – worn surface.

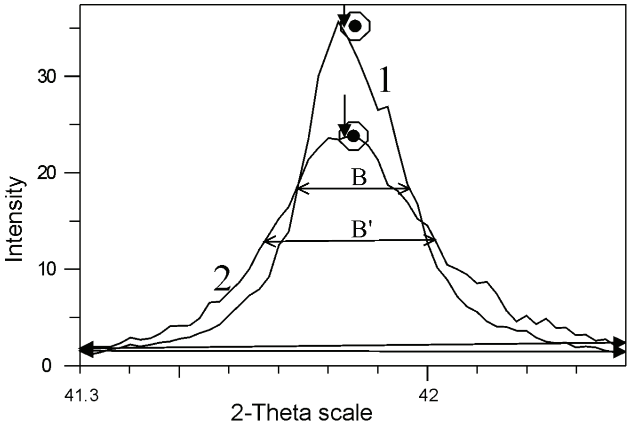


Fig.5 XRD diffraction patterns of TiC-cermet carbide phase [line 200].

4. Conclusions

Based on the results of the experiments, the following conclusions could be drawn.

- The tungsten–based composites outperform tungsten-free cermets in abrasive wear conditions (at the same level of hardness). TiC-base cermets with a steel binder are superior to those with nickel-alloy.
- The surface failure of a carbide composite during abrasion starts predominantly in the binder as a result of a combined process – extrusion, microcutting and extraction. It continues by transgranular cracking of the carbides, preceded by the plastic strain that takes place in both phases – in the ductile binder and in the brittle carbide.
- The performance of a carbide composite in abrasion is controlled by its resistance to elastic (measured by the modulus of elasticity, E) and plastic (measured by the proof stress $R_{CO.1}$) strains and may be evaluated at a good accuracy by the combined rigidity characteristic $E^2 \cdot R_{CO.1}$.

5. REFERENCES

[1] Brookes, K.J. *World Dictionary and Handbook of Hard Metals and Hard Materials*, International Carbide Data, London, 1996.

[2] Kübarsepp, J., Klaasen, H. and Annuka, H., Characterization of the serviceability of steel-bonded hardmetals. *Int. J.Refract. Met. Hard Mater.*,1994, **12**, 341-347.

[3] Foller, M. and Mayer, H., Ferro-Titanit in Application. In Proc. *6th Int. Conf. on Tooling*, Sept. 2002, Karlstadt, Sweden, 186-220.

[4] Klaasen, H., Kübarsepp J. and Preis, I., Wear behaviour, durability and cyclic strength of TiC-base cermets. *Mat. Sci. and Technology*. 2004, **20**, 1006 -1010.

[5] Klaasen, H. and Kübarsepp, J., Wear behaviour and mechanical properties of sinterhipped hardmetals. *Powder Metall.*, 2004, **47 (2),** 161-167.

[6] Eigi, R., Klaasen, H., Viktorov, G. and Talkop, A., *Hardmetal dies in electrotechnical machinery*, Energoizdat, Moscow 1988 [in Russian].

[7] H. Klaasen, J.Kübarsepp, *Wear*, 177 (1994) 185 – 193.

[8] Umansky, J. *Rentgenografia metallov (X-ray analyses of metals*), Mashgiz, Moscow, 1988 (in Russian).

[9] Larsen-Basse, J. and Koyanagi, E. Abrasion of WC-Co alloys by quartz. *Trans. ASME*, 1979, **101**, 208-212.

[10] Enquist, H. Abrasion and erosion of cemented carbides, *Tribol. Lett*. 1998, **4**, 251-255.

[11] Gant, A., Gee, M. and Roebuck, B., Rotating wheel abrasion of WC/Co hardmetals. *WEAR*, 2005, **258**, 178-188.

[12] Hussainova, I. and Pirso, J., Microstructural aspects of erosive wear of particle reinforced composites. In: Proceedings of the International Conference on *Advances in Powder Metallurgy and Particulate Materials*, Las Vegas, USA, 2003, vol. **5**, 71-81.

[13] Schleinkofer, U., Sockel, H., Görting, R. and Heinrich, W., Fatigue of Hardmetals and Cermets – New Results and Better Understanding, *Int. J. Refract. Met. Hard Mater.*, 1997, vol. **3**, 103-112.

PAPER IV

T. Roosaar, J. Kübarsepp, H. Klaasen, M. Viljus, Wear Performance of TiC-base Cermets, Materials Science (Medžiagotyra) (2008) 14(3), 238 – 241.

Wear Performance of TiC-Base Cermets

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Some carbide composites – WC hardmetals and TiC-base cermets with Ni-alloy and Fe-alloy binders – were investigated in different wear conditions. For the simulation of the adhesion wear conditions during blanking of sheet steel special method was used. Results of these tests were compared with the results obtained from sliding wear and abrasive wear. Relations between wear performance, microstructure and mechanical characteristics were found. It was shown that the surface failure of carbide composite during adhesion starts preferably in the binder phase. This is a combined process of microcutting, extraction and extrusion and depends on the amount of carbide phase and its composition. Cermets on basis of TiC bonded with Fe- alloy (steel) binder showed superiority over TiC base composites bonded with Ni alloy in all wear conditions.

Keywords: cermet; hardmetal; carbide composite; abrasive wear; adhesive wear; sliding wear.

1. INTRODUCTION

Tungsten carbide based hardmetals are the most widely used materials for different wear conditions. This is because of their excellent combination of fair strength and high wear resistance. [1].

Tungsten free hardmetals on basis of TiC cemented with nickel alloys and alloyed steels have been developed. [2 - 5] to replace the hardmetals due to a shortage of tungsten and some deficiency of its physical properties (oxidation, corrosion resistance). These reasons restrict the application of hardmetal. In general, TiC-base composites are at some disadvantage in respect to strength and abrasive and erosion resistance. Recent developments in technology (sinter/HIP, HIP) resulting in substantial improvement of performance of carbide composites have created a renewed interest to TiC-base cermets. [6,7].

The present study was focused on the wear behaviour of some carbide composites, in particular TiC-base cermets with nickel steel binder developed for metalforming. [6]. In metalforming the adhesion (wear in blanking, wear in sliding) prevail. The wear performance was related to their mechanical properties and microstructure.

2. MATERIALS TESTED AND EXPERIMENTAL DETAILS

2.1 Materials

Tungsten and titanium-carbide base carbide composites in particular composites prospective for metalforming (carbide fraction up to 85 vol% and properties: Rockwell hardness HRA≥86.5, transverse rupture strength TRS≥2000 MPa) were investigated.

Porosity of all materials tested was less than 0.2 vol.% and average grain size 1.9 – 2.2 μm.

The materials were produced through the ordinary vacuum sintering technology of compacted powders. Some of grades (T80/14, T75/14) were sintered both by vacuum sintering and by the sinter/HIP techniques (under gas compression of 50Bar at sintering temperature) [7, 8]. The composition and mechanical properties of the composites investigated are presented in Table 1.

2.2. Experimental details

Adhesive wear tests were performed by a special cutting method (by turning mild steel at low speed) simulating wear of blanking tools – wear in conditions with prevalence of adhesion [6, 8]. The wear resistance was determined as the length of cutting path L_1, when height h of the wear land at specimen (tool) nose achieved 1 mm.

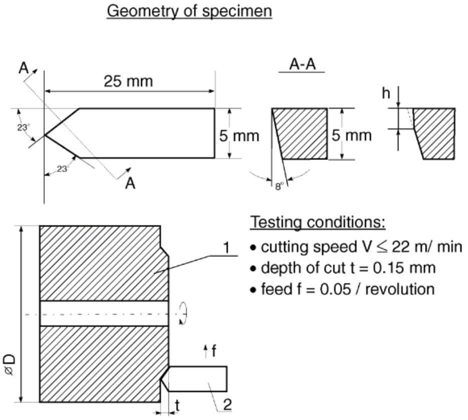

Figure 1: The adhesive-wear testing conditions and geometry of specimen

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Table 1: Structural characteristics and properties (hardness *HV*, transverse rupture strength R_{TZ}, modulus of elasticity *E*, proof stress $R_{CO.1}$) of carbide composites.

Grade	Carbide content, vol. %	Binder composition, structure	*HV*,	R_{TZ}, GPa	*E*, GPa	$R_{CO.1}$, GPa
H10	WC, 83.5	Co (W)	1350	2.3	610	2.9
H13	WC, 79.9	Co (W)	1300	2.8	590	2.9
H15	WC, 76.0	Co (W)	1150	2.9	560	2.5
H20	WC, 69.0	Co (W)	1000	3.1	510	2.0
T80/14	TiC, 86.5	14Ni-steel, austenite-bainite	1450	1.5/2.1 *	420	3/3.2
T75/14	TiC, 83.0	14Ni-steel, austenite-bainite	1350	1.8/2.4 *	410	2.8/2.9
T70/14	TiC, 79.0	14Ni-steel, austenite-bainite	1250	2.3	400	2.5
T60/14	TiC, 74.0	14Ni-steel, austenite-bainite	1050	2.4	380	1.9
T60/8	TiC, 74.0	14Ni-steel, martensite	1200	2.2	390	2.3
TN30	TiC, 81.0	Ni:Mo (2:1)	1400	1.7	380	2.3
TN40	TiC, 74.0	Ni:Mo (2:1)	1260	1.9	360	2.0
TN40	TiC, 74.0	Ni:Mo (4:1)	1050	2.2	360	1.8
TN50	TiC, 65.0	Ni:Mo (2:1)	1000	2.2	340	1.7

*increase after sinter/HIP

Abrasive wear tests were performed by help of the rubber-rimmed rotary wheel machine (modified method) as follows: abrasive – quartz sand (amount – 3 kg with a particle size of 0.1 – 0.2 mm and hardness *HV*= 1100), velocity of the wheel – 0.24 m/s, diameter of the steel wheel – 80 mm, wear distance – 144 m, testing time – 10 min and load – 3 N. The wear was estimated as the volume loss *V* in mm3 and wear resistance as *1/V*, mm $^{-3}$.

Sliding wear tests were performed in accordance with ASTM standard B611 – 85 (without abrasive). The wear rate was calculated as a volume loss W, mm^3.

As an additional characteristic the proof stress $R_{CO.1}$, featuring the resistance of a material to plastic strain and the shearing strength (resistance to microcutting) of composites were determined. The proof stress was determined in a uniaxial compression test [7].

3. RESULTS AND DISCUSSION

3.1. Adhesive wear

Fig. 2 shows the adhesive wear (cutting adhesive wear) resistances of test materials plotted against their composition (carbide volume fraction). It can be seen that the increase in volume fraction of carbides (decrease in binder) leads to a monotonous improvement of wear performance of all composites independent of their carbide and binder composition.

According to the results there is clear relation between wear performance of alloys and their composition. At equal carbide (binder) fraction WC-base hardmetal and TiC-cermet cemented with nickel steel show a remarkable superiority over ordinary TiC-based cermet cemented with nickel alloy.

The ordinary characteristic and measure of material wear resistance is hardness. In Fig.3 the wear resistances of test materials are plotted against their hardness. It is definitively confirmed by the results that there exists the inconclusive influence of hardness on adhesive wear, as also revealed for carbide composites tested in erosion, abrasion and blanking wear conditions [7, 9, 10].

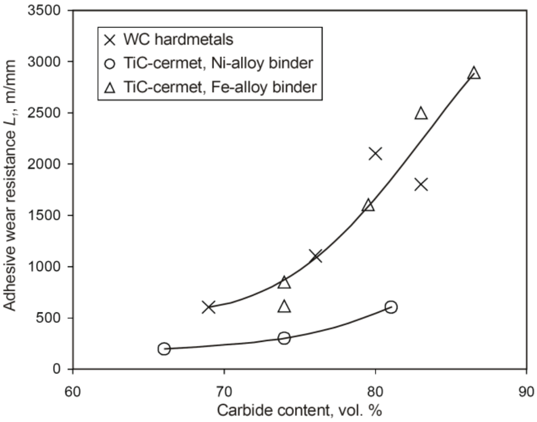

Figure 2: Adhesive wear resistance of carbide composites vs. carbide fraction in alloy

In Fig. 4 the adhesive wear performance of test materials is opposed to their proof stress. The relationships refer to the dependence of wear on proof stress: the increase in proof stress improves monotonously the wear resistance. The results obtained are in accordance with the wear theories of hardmetals and cermets described [10 - 14]. On the basis of these studies it may be concluded that the removal of material during adhesive wear has a selective nature – it starts preferably in the binder mainly by microcutting and extraction. As a precondition for removal extrusion of binder and its adhesive interaction has to occur. Shortly, for wear composites binder must be subjected to elastic and plastic strain. The elastic strain – elastic compression of carbide skeleton results in extrusion of binder, while plastic strain induces frustration of oxide films, protecting composites surface and hindering formation of physical contact (juvenile surfaces) – precondition for adhesion.

Increase in composite resistance to elastic strain (modulus of elasticity) and plastic one (proof stress) results in improvement of wear performance.

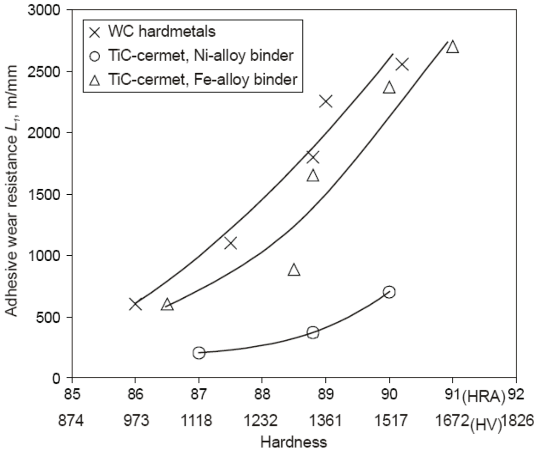

Figure 3: Adhesive wear resistance of carbide composites vs. hardness

The high wear resistance of WC-hardmetals and TiC-cermets with steel binder (compared with cermets with nickel binder) appears to be resulted from their higher rigidity (WC-hardmetal) and higher binder strength (steel binder with austenitic-bainitic structure).

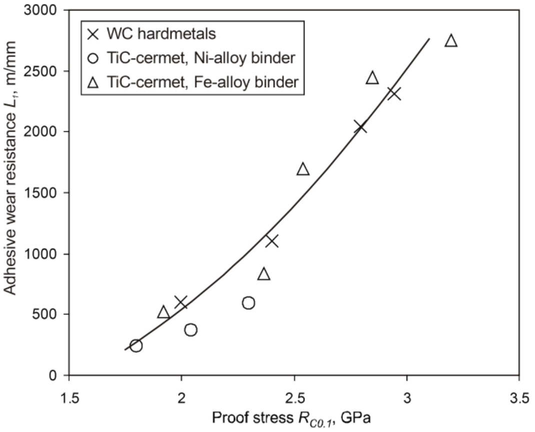

Figure 4: Adhesive wear resistance of carbide composites vs. proof stress

3.2. Abrasive wear

In Fig. 5 abrasion rates of test materials are plotted against their hardness. The results confirm an inconclusive influence of hardness on the abrasive wear performance of materials reported before. At equal hardness the abrasive wear of alloys of different composition may vary up to four times.

The fact that no correlation between abrasion performance and hardness exists may be attributed to higher structural sensitivity of the wear resistance of the composite in relation to hardness and differences in the stress states during wear and hardness test [5, 8].

The results suggest that the wear of the test material depends on its composition (composition of the carbide and that of the binder). At equal hardness level tungsten carbide-base composites demonstrate a superiority over TiC-base ones. TiC-cermets with steel binder are in advantage over those with nickel-alloy.

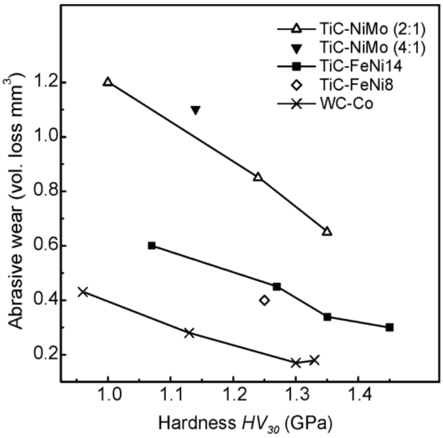

Figure. 5 Abrasive wear of carbide composites vs. Vickers hardness.

3.3. Sliding wear

In Fig. 6 the sliding wear rates of test materials are plotted against their composition.

From the figure 6 it is obvious that the WC-base hardmetal has superiority over tungsten free ones and cermet with steel binder over composite with nickel of alloy binder. Also the monotonous decrease in wear with increase in carbide fraction in alloy is demonstrated. In general these relationships repeat those revealed for cutting adhesive wear (Fig. 2 – 4).

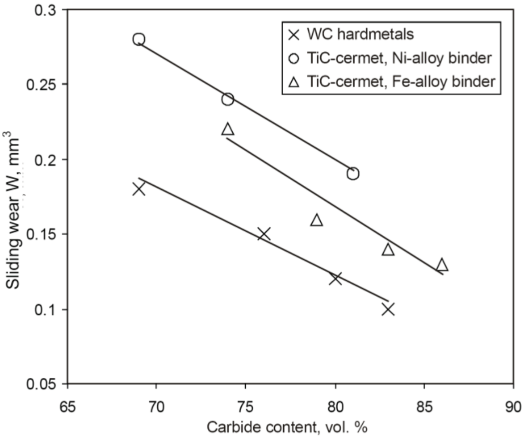

Figure 6: Sliding wear of carbide composites vs. carbide fraction in alloy.

In contrast to adhesive wear and to abrasive one the sliding wear of carbide composites demonstrated a relatively low sensitivity to composition and mechanical properties. Increase in carbide fraction from 69 – 90 vol. % in WC-hardmetal results in improvement of its performance in wear conditions with prevalence of adhesion up to 4 times and in sliding wear less than 2 times (compare Fig. 2 with Fig. 6).

During sliding wear formation of thin tribofilms has been observed [15]. These films – a result of binder extrusion and adhesive interaction, – result in decrease of wear and sensitivity to alloy composition.

5. CONCLUSIONS

1. At equal carbide volume fraction WC-base hardmetals and TiC-base cermets with steel binder are at an advantage over ordinary TiC-cermets with nickel (nickel-alloy) binder in wear conditions with prevalence of adhesion.
2. The performance of a carbide composite in wear conditions with prevalence of adhesion (in cutting adhesive wear and sliding wear) is controlled by resistance to local plastic strain (measured by the proof stress) and depends first on the amount and properties of its binder.
3. The tungsten–based composites outperform tungsten-free cermets in abrasive wear conditions (at the same level of hardness). TiC-base cermets with a steel binder are superior to those with nickel-alloy.
4. In sliding wear conditions formation of thin tribofilms with protective-lubricating effect has been observed. It results in reduce of wear and in remarkable decrease of its sensitivity to alloy composition and properties.

Acknowledgments

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REFERENCES

[1] **K.J. Brookes**, World Dictionary and Handbook of Hard Metals and Hard Materials, *International Carbide Data*, 1996.

[2] **M.Komac, M. Novac**, Mechanical and wear characteristics of titanium carbide-base cermets, *Int. J. Refract. Met. Hard Mater.*, 4 (1985) 21 – 26.

[3] **D. Moskowitz and J. Humenik**, TiC-base cermets for cutting applications, *Mod. Dev. Powder Metall*. 14 (1985) 307 – 320.

[4] M**. Foller and H. Mayer**, Ferro-titanit in application, Proceedings of the 6th International *Conference on Tooling*, Karlstadt, Sweden, 2002, Sept., pp. 186 –220.

[5] J**. Kübarsepp, H. Klaasen and H. Annuka**, Characterization of the serviceability of steel-bonded hardmetals, *Int. J. Refract. Met. Hard Mater*. 12 (1994), 341 – 347.

[6] **H. Klaasen and J.Kübarsepp**, Wear of advanced cemented carbides for metalforming tool materials, *Wear* 256 (2004) 846 – 853.

[7] **H. Klaasen and J. Kübarsepp**, Wear behaviour and mechanical properties of sinterhipped hardmetals, *Powder Metall*., 47 (2) (2004) 161 – 167.

[8] **H. Klaasen, J. Kübarsepp and I.Preis**, Wear behaviour, durability and cyclic strength of TiC base cermets, *Materials Science and Technology*, 2004, 36 – 42.

[9] **H. Klaasen and J. Kübarsepp**, Abrasive wear performance of carbide composites, *Wear*, 261 (2006), 520 -526.

[10] **H. Klaasen and J. Kübarsepp**, Mechanical properties of hard metals and their erosive wear resistance, *Wear* 177 (1994), 193 – 285.

[11] **J. Larsen-Basse and E. Koyanagi**, Abrasion of WC-Co alloys by quartz, *Trans. ASME 101* (1979) 208 – 212.

[12] **H. Enquist**, Abrasion and erosion of cemented carbides, *Tribol*. Lett. 4 (1998) 251 – 255.

[13] **M.G. Gee, R.H. Gee and J. McNaught**, Stepwise erosion as a method for determining the mechanisms of wear, *Wear* 255 (2003) 44 – 54.

[14] **A. Gant, M. Gee and B. Roebuck**, Rotating wheel abrasion of WC/Co hardmetals, *Wear* 258 (2005) 178 – 188.

[15] **I. Hussainova and J. Pirso,** Microstructural aspects of erosive wear of particle reinforced composites, *Proceedings of the International Conference on Advances in Powder Metallurgy & Particulate Materials,* Las Vegas, 2003, vol. 5, pp. 71 – 81

PAPER V

H. Klaasen, J. Kübarsepp, T. Roosaar, F. Sergejev, A. Talkop, Performance of carbide composites in cyclic loading conditions. Proceedings of European Powder Metallurgy Conference & Exhibition Euro PM2008, Mannheim, Germany, 28 September – 1 October 2008, European Powder Metallurgy Association, (2008) 237 – 242.

Performance of carbide composites in cyclic loading conditions

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Abstract

The performance of advanced TiC-based cermets bonded with Fe/Ni alloys (designed for metalforming applications) was investigated in cyclic loading conditions: blanking of sheet metal and three-point bending fatigue. Comparative trials were performed with a standard WC-based hardmetal widely used in metalforming.

TiC-based cermets were found to be superior to a standard WC-based hardmetal in cyclic loading conditions. This superiority is related to better adhesive wear resistance and fatigue characteristics of cermets.

Relations between blanking performance, fatigue characteristics and changes in the fine structure were found.

Key words: cyclic loading, fatigue, blanking performance, adhesive wear

1. Introduction

Hardmetals based on tungsten carbides are the most widely used wear resistant carbide composites because of their excellent combination of wear resistance and mechanical reliability characteristics (transverse rupture strength, plasticity, fracture toughness, etc) [1]. Due to the shortage of tungsten and its high and increasing price, new ceramic and metal matrix composites have to be developed. Among them TiC-based cermets bonded with Fe/Ni alloys are still the most promising candidates. Such composites have proved to be successful in some applications due to their high specific strength, lower coefficient of friction and higher service temperatures as compared to WC-based hardmetals [2 - 4].

A series of TiC-based cermets have been developed at TUT. The most successful so far – grade T70/14 (70 wt% TiC, cemented with Ni-steel) has demonstrated its superiority over the standard WC-hardmetal H15 (85 wt% WC) in the blanking of sheet steels [5, 6].

This paper focuses on the study of blanking performance of an advanced (with improved properties) TiC-cermet – grade T 75/14-H (75 wt% TiC cemented with steel and produced by the sinter/HIP technology) [7]. As reference materials for comparison a WC-hardmetal S13 (87 wt% WC) developed and the standard TiC-cermet T70/14 were investigated.

Another important aim was to identify any correlation that might exist between the blanking performance and fatigue endurance of carbide composites.

2. Experimental

2.1. Materials

The main microstructural characteristics and mechanical properties of the tested composites are presented in Table 1.

Table 1. Structural characteristics and properties (hardness *HV*, transverse rupture strength R_{TZ}, proof stress $R_{CO.1}$) of carbide composites

Grade	Carbide, wt %	Average grain size, μm	Binder composition and structure		*HV*, GPa	R_{TZ}, GPa	$R_{CO.1}$, GPa
			Compos.	Structure			
T70/14	TiC, 70	2.1	14Ni-steel	Austenitic bainitic	1.25	2.11	2.5
T75/14	TiC, 75	2.0	14Ni-steel	austenitic bainitic	1.32	1.80	2.9
T75/14-H	TiC, 75	2.1	14Ni-steel		1.32	2.42*	3.0
S13	WC, 87	1.8	Co(W)	-	1.30	2.81	2.8

* after sinterhipping

The alloys were sintered by two techniques: standard vacuum sintering (for grades T70/14 and S13) and sinter/HIP (combined sintering in vacuum + argon gas compression) – for grade T75/14 – H [7].

2.2. Testing procedures

The durability (blanking performance) trials were carried out as functional ones, i.e. blanking of grooves into electrotechnical steel sheet (thickness of 0.5 mm) by a three-position die (reinforced with alloys in Table 1), mounted on an automatic press [5].

Durability was characterized by the side wear *Δ* (increase of groove dimensions after a service of $5 \cdot 10^5$ strokes) performed by the coordinate measuring machine STRATO9166 in fixed environmental conditions. The blanking performance (N/Δ, strokes/mm) was evaluated as lifetime in strokes *N* when the side wear exceeds 1 mm.

The wear performance of composites was studied in the cutting adhesive wear conditions [5, 8]. The wear resistance L_1 was determined as the cutting path (by turning mild steel at low speed) when the wear track at the nose of the specimen (tool) exceeded 1 mm.

Conventional fatigue testing of the ground specimens 5 x 5 x17 mm was carried out on the fatigue testing rig using a three-point bending scheme. Specimens were ground to a surface finish of about R_a=1.5 µm for hardmetal and R_a=2.5 µm for cermets. Opposite ground faces were parallel within 0.03 mm. The stress ratio was $R = 0.1$. The loading frequency varied from 1 up to 35 Hz [6, 9]. Lower frequencies were used for LCF (Low-Cycle Fatigue, up to $N=10^3$ cycles) and higher for HCF (High-Cycle Fatigue, up to $N=10^6$ cycles).

The resistance to fatigue damage was characterized by the factor of fatigue sensitivity – intensity in the decrease of the fatigue strength with an increase in loading cycles from $N_2 = 10^2$ to $N_7 = 10^7$ as ΔS_{2-7}.

3. Results and discussion

Results of functional tests are shown (see Fig. 1) as wear contours *"Δ - H"* (side wear *Δ* depending on the distance *H* from the cutting edge (depth of the groove) of the tool. During durability testing of the die – the three-position die reinforced with composites – neither fracture nor brittle chipping of cutting edges was detected.

The developed TiC-base cermet grade T75/14-H (cermet with improved properties Table 1) demonstrated the highest blanking performance, exceeding that of the WC hardmetal (grade S13) and the standard TiC-cermet T70/14 by a factor up to 2.

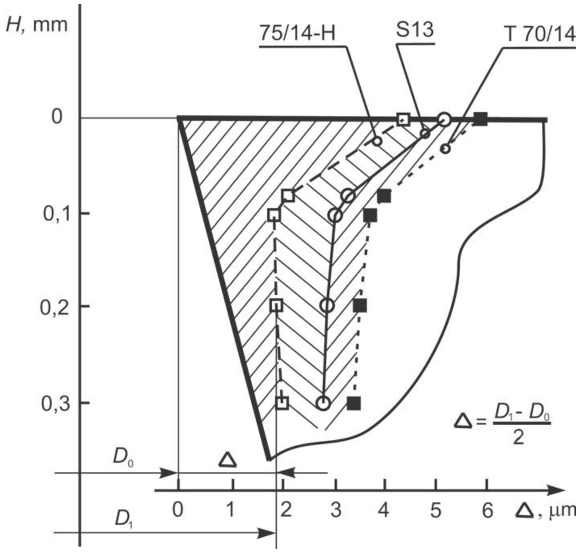

Fig. 1. Wear contours of carbide tool (die) edges.

The results of adhesive wear trials (see wear kinetic curves h – L in Fig. 2) confirm the results of the blanking tests – the superiority of the developed TiC-based cermet (grade T75/14-H) over hardmetal S13 (WC-based composite).

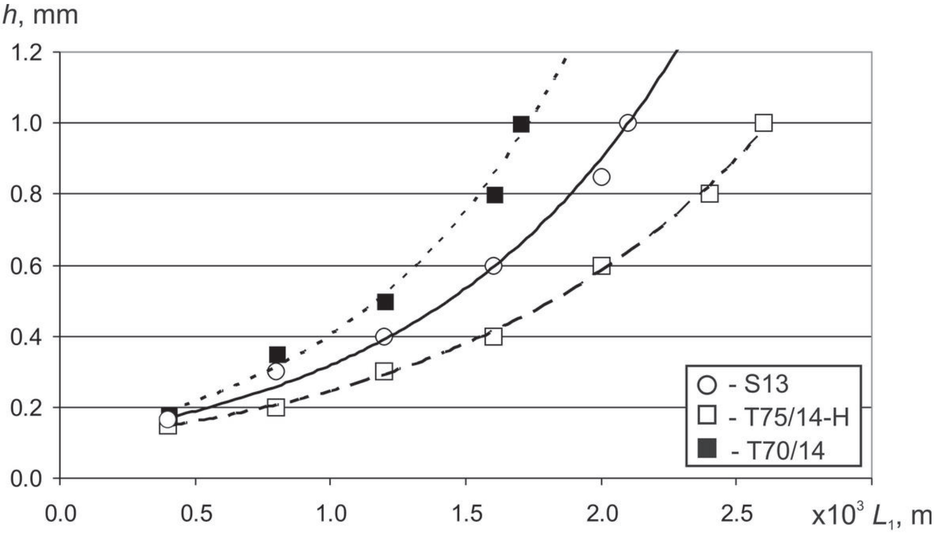

Fig. 2. Adhesive wear kinetics h – L_1 .

Figure 3 demonstrates the results of fatigue testing – the Wöhler plot. The tested carbide composites exhibit an obvious decrease in strength with an increase of loading cycles during the fatigue test – they possess fatigue sensitivity (slope of S-N curve on the Wöhler plot).

Although the mean inert strength (at N=1 and fatigue strength at low loading cycles, N=10^2 cycles) of WC-hardmetal exceeds that of TiC-cermets, the fatigue limits (fatigue strength at N>10^5 cycles) for both composites are almost equal. It means that the intensity in the strength decrease (fatigue sensitivity) of a hardmetal is higher than that of TiC-based cermets.

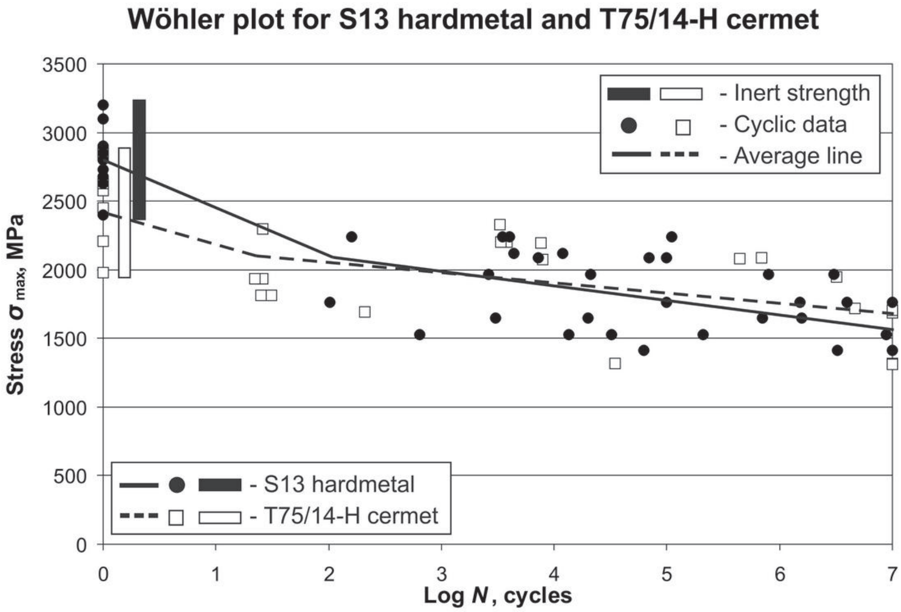

Fig. 3. Wöhler plot of the carbide composites tested.

Our results show that dependence exists between the scatter of fatigue-strength and the material composition: the scatter of WC hardmetal exceeds that of the TiC-cermet. High fatigue sensitivity and high scatter of strength data – both refer to a remarkable embrittlement (fatigue damage) of the alloy during fatigue.

Figure 4 shows the blanking performance *N/*Δ of carbide composites opposed to their response as inserts in adhesive wear and fatigue conditions. These results refer to an obvious correlation between the blanking performance of carbide composites and their resistance to adhesive wear on the one hand and to fatigue damage (fatigue sensitivity) on the other hand. The composite with a higher blanking performance (grade T75/14-H) possesses both higher adhesive wear resistance and higher resistance to fatigue damage (lower fatigue sensitivity).

The results obtained (Figs. 1, 2) confirm that during blanking the adhesive wear prevails in the surface failure of carbide tools **[**5**]**.

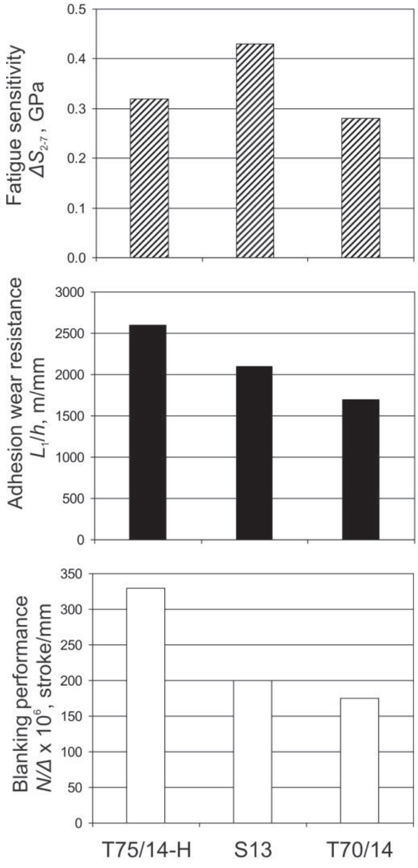

Fig. 4. Correlation graphs of blanking performance, adhesive wear resistance and fatigue sensitivity for the studied composites.

After removal of the binder (by adhesive wear) the carbide loses its protective binder-envelope (generating favourable compressive stresses), resulting in a drop of its resistance to brittle failure (in particular, fatigue failure) [10,11].

Conclusions

Focus was on the performance of an advanced TiC-base cermet in a cyclic loading application – in the blanking of sheet steels and three-point bending fatigue. Comparative trials with WC-based hardmetals (widely used in metalforming) were performed.

The fatigue endurance of carbide composite is featured by its fatigue sensitivity (slope of *S-N* curves on Wöhler plot) and stability in strength (scatter in fatigue strength data).

The cermet was found to have higher performance due to its higher adhesion wear resistance and fatigue endurance.

References

[1] Brookes, K.J. World Dictionary and Handbook of Hard Metals and Hard Materials, Int. Cabide Data, London, 1996.
[2] Foller, M., Mayer, H. Proc. 6th Int. Conf. on Tooling, 2002, 186 – 220.
[3] Moskowitz, D., Humenik, H. Modern Development in Powder Metallurgy, 1989, 14, 307 – 320.
[4] Kübarsepp, J., Klaasen, H., Annuka, H. *Int. J. Refract. Metals & Hard Mater*., 1994, **12**, 345 – 348.
[5] Klaasen, H., Kübarsepp, J.: *Wear*, 2004, **256**, 846 – 853.
[6] Klaasen, h., Kübarsepp, J., Preis, I.: *Mater. Science & Technology*, 2004, **20**, 830 – 837.
[7] Klaasen, H., Kollo, L., Kübarsepp, J.: *Powder Metall*., 2007, **50** (2), 132 – 136.
[8] Zorew, N.: Vestnik Mashinostrojenija, 1975 (2), 19 – 24 (in Russian).
[9] Schleinkofer, U., Sockel, H.G., Görting, K., Heinrich, W.: Int. J. *Refract. Metals & Hard Mater.,* 1997, **15**, 103 – 112.
[10] Klaasen, H. and J. Kubarsepp: *Wear*, 2004, **256** (7-8), 846-853.
[11] Klaasen, H., J. Kubarsepp, and R. Eigi: *Tribology International*, 2006, **39**(4), 303-309.

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Professional Employment	2002 - …	Technical Inspection Centre Ltd – quality manager
	2003...	Estonian Accreditation Centre - assessor
	2000 - 2002	Technical Inspectorate – executive officer of department of technical safety
Field of research	Natural Sciences and Engineering, Process Technology and Materials Science	
Language competence	Estonian – native language	
	English – high level	
	Russian – middle level	
	Finnish – basic level	
	German – basic level	

ELULOOKIRJELDUS

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Kodakondsus	Eesti	
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Hariduskäik	2000 - 2002	Tallinna Tehnikaülikool, transporditehnika õpesuund, Tehnikateaduste magister
	1996 - 2000	Tallinna Tehnikaülikool, transporditehnika õpesuund, Tehnikateaduste bakalaureus, *Cum Laude*
	1994 - 1996	Jõhvi Gümnaasium, Hõbemedal
	1985 - 1994	Illuka Põhikool
Teenistuskäik	2002 - …	Tehnokontrollikeskus OÜ, kvaliteedijuht
	2003...	Eest Akrediteerimiskeskus, assessor
	2000 - 2002	Tehnilise Järelevalve Inspektsioon – Tehnikaohutusosakonna spetsialist
Teadustöö põhisuunad	Loodusteadused ja tehnika, Protsessitehnoloogia ja materjaliteadus	
Keeleoskus	Eesti – emakeel	
	Inglise keel – kõrgtase	
	Vene keel – kesktase	
	Soome keel – algtase	
	Saksa keel – algtase	

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *MECHANICAL AND INSTRUMENTAL ENGINEERING*

1. **Jakob Kübarsepp**. Steel-bonded hardmetals. 1992.
2. **Jakub Kõo**. Determination of residual stresses in coatings & coated parts. 1994.
3. **Mart Tamre**. Tribocharacteristics of journal bearings unlocated axis. 1995.
4. **Paul Kallas**. Abrasive erosion of powder materials. 1996.
5. **Jüri Pirso**. Titanium and chromium carbide based cermets. 1996.
6. **Heinrich Reshetnyak**. Hard metals serviceability in sheet metal forming operations. 1996.
7. **Arvi Kruusing**. Magnetic microdevices and their fabrication methods. 1997.
8. **Roberto Carmona Davila**. Some contributions to the quality control in motor car industry. 1999.
9. **Harri Annuka**. Characterization and application of TiC-based iron alloys bonded cermets. 1999.
10. **Irina Hussainova**. Investigation of particle-wall collision and erosion prediction. 1999.
11. **Edi Kulderknup**. Reliability and uncertainty of quality measurement. 2000.
12. **Vitali Podgurski**. Laser ablation and thermal evaporation of thin films and structures. 2001.
13. **Igor Penkov**. Strength investigation of threaded joints under static and dynamic loading. 2001.
14. **Martin Eerme**. Structural modelling of engineering products and realisation of computer-based environment for product development. 2001.
15. **Toivo Tähemaa**. Assurance of synergy and competitive dependability at non-safety-critical mechatronics systems design. 2002.
16. **Jüri Resev**. Virtual differential as torque distribution control unit in automotive propulsion systems. 2002.
17. **Toomas Pihl**. Powder coatings for abrasive wear. 2002.
18. **Sergei Letunovitš**. Tribology of fine-grained cermets. 2003.
19. **Tatyana Karaulova**. Development of the modelling tool for the analysis of the production process and its entities for the SME. 2004.
20. **Grigori Nekrassov**. Development of an intelligent integrated environment for computer. 2004.
21. **Sergei Zimakov**. Novel wear resistant WC-based thermal sprayed coatings. 2004.
22. **Irina Preis**. Fatigue performance and mechanical reliability of cemented carbides. 2004.
23. **Medhat Hussainov**. Effect of solid particles on turbulence of gas in two-phase flows. 2005.

24. **Frid Kaljas**. Synergy-based approach to design of the interdisciplinary systems. 2005.

25. **Dmitri Neshumayev**. Experimental and numerical investigation of combined heat transfer enhancement technique in gas-heated channels. 2005.

26. **Renno Veinthal**. Characterization and modelling of erosion wear of powder composite materials and coatings. 2005.

27. **Sergei Tisler**. Deposition of solid particles from aerosol flow in laminar flat-plate boundary layer. 2006.

28. **Tauno Otto**. Models for monitoring of technological processes and production systems. 2006.

29. **Maksim Antonov**. Assessment of cermets performance in aggressive media. 2006.

30. **Tatjana Barashkova**. Research of the effect of correlation at the measurement of alternating voltage. 2006.

31. **Jaan Kers**. Recycling of composite plastics. 2006.

32. **Raivo Sell**. Model based mechatronic systems modeling methodology in conceptual design stage. 2007.

33. **Hans Rämmal**. Experimental methods for sound propagation studies in automotive duct systems. 2007.

34. **Meelis Pohlak**. Rapid prototyping of sheet metal components with incremental sheet forming technology. 2007.

35. **Priidu Peetsalu**. Microstructural aspects of thermal sprayed WC-Co coatings and Ni-Cr coated steels. 2007.

36. **Lauri Kollo**. Sinter/HIP technology of TiC-based cermets. 2007.

37. **Andrei Dedov**. Assessment of metal condition and remaining life of in-service power plant components operating at high temperature. 2007.

38. **Fjodor Sergejev**. Investigation of the fatigue mechanics aspects of PM hardmetals and cermets. 2007.

39. **Eduard Ševtšenko**. Intelligent decision support system for the network of collaborative SME-s. 2007.

40. **Rünno Lumiste**. Networks and innovation in machinery and electronics industry and enterprises (Estonian case studies). 2008.

41. **Kristo Karjust**. Integrated product development and production technology of large composite plastic products. 2008.

42. **Mart Saarna**. Fatigue characteristics of PM steels. 2008.

43. **Eduard Kimmari**. Exothermically synthesized B_4C-Al composites for dry sliding. 2008.

44. **Indrek Abiline**. Calibration methods of coating thickness gauges. 2008.

45. **Tiit Hindreus**. Synergy-based approach to quality assurance. 2009.

46. **Karl Raba**. Uncertainty focused product improvement models. 2009.

47. **Riho Tarbe**. Abrasive impact wear: tester, wear and grindability studies. 2009.

48. **Kristjan Juhani**. Reactive sintered chromium and titanium carbide- based cermets. 2009.

49. **Nadežda Dementjeva**. Energy planning model analysis and their adaptability for Estonian energy sector. 2009.

50. **Igor Krupenski**. Numerical simulation of two-phase turbulent flows in ash circulating fluidized bed. 2010.

51. **Aleksandr Hlebnikov**. The analysis of efficiency and optimization of district heating networks in Estonia. 2010.

52. **Andres Petritšenko**. Vibration of ladder frames. 2010.

53. **Renee Joost**. Novel methods for hardmetal production and recycling. 2010.

54. **Andre Gregor**. Hard PVD coatings for tooling. 2010.