HIPIMS COATED CARBIDES WITH HIGH ADHESIVE STRENGTH FOR HARD MACHINING

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Hard processing is defined as the machining of ferrous materials with a hardness of at least 50 HRC. Due to the possibility of the substitution of grinding processes, hard processing has grown in importance in recent years. Fundamental to this was the development of heat and wear resistant cutting materials. The turning of hardened steel is currently possible with cubic boron nitride and ceramic tools, however, hard metals offer a higher versatility and optimization potential. With a choice of different substrate compositions, grain sizes, micro and macro geometry and hard coatings, modern manufacturing technology has a large range of tool combinations. By progressive developments in the field of PVD coating technology it is now possible to deposit hard, dense and smooth layers with sufficient toughness by the application of the HiPIMS (High Power Impulse Magnetron Sputtering) process. In this contribution cemented carbide cutting inserts in combination with varying TiAlN HiPIMS films are studied with regards to their wear behavior in model wear test rigs. The tools are tested not only with regard to their individual wear resistance, the layer adhesion compared with conventional DCMS (Direct Current Magnetron Sputtering) tools is also evaluated afterwards. After evaluating the wear of the HiPIMS layers a promising film-substrate system for the cutting tests is selected. The use and wear behavior of the HiPIMS tools is compared to the behavior of the DCMS coated inserts. The objective is to establish the HiPIMS layer for industrial usage in the hard machining process.

KEYWORDS
hard processing, turning, HiPIMS, hard coatings, wear tests

1. INTRODUCTION

Coated cemented carbide tools are currently indispensable in manufacturing technology. Due to the high potential of the HiPIMS coating technology an application in the turning of hardened steels with high process reliability is possible. However, experimental research is needed regarding the optimum surface condition of the tool before the deposition process and coating parameters so as to deposit an optimally adapted layer for a specific application. In this paper modern PVD coated inserts are tested in model wear tests and in hard turning with regards to their wear resistance. To compare the performance of modern HiPIMS tools with commercial DCMS layers, the tools were studied with two types of layers. The wear behavior and process reliability of each layer type are subsequently evaluated.

1.1 HARD MACHINING

The machining of hardened ferrous materials with a hardness of 50 HRC or more is defined as hard machining. Major application of hardened steels are in the area of tool and mould construction, in the area of casehardened components in the automotive industry, such as transmission components, connecting rods, crankshafts, etc. By maintaining the required high surface quality of machined workpieces retrofittings are eliminated, so that additional work sequences and turnaround time can be saved. Comparing the hard machining with grinding material removal rates are higher and greater manufacturing flexibility is possible. Another factor is the possible application of dry cutting, thus allowing a more environmentally friendly production. The chip formation mechanism in machining of hardened steels requires high pressures and high cutting edge stability. This is achieved by low chip thickness and negative effective rake angles. By the multi-axial compression stress state in front of the cutting tool, the critical shear stress limit in the workpiece is reached and can undergo plastic deformation. These conditions are accompanied by high temperature development and higher specific cutting forces compared to conventional turning. Therefore, the hot hard cutting materials polycrystalline cubic boron nitride (PcBN) and mixed ceramics are used for the turning of hardened steels. Cemented carbides are among the most versatile group of cutting materials and provide efficient processing of different material groups. This is possible due to the optimization factors tool coating, substrate composition and micro and macro geometry. Since the 1980s, the abrasion, adhesion and temperature resistance of carbide tools in combination with hard coatings was significantly increased. The reasons for this are advances in substrate composition, preparation and handling of the tools before and after the coating process and the increasing knowledge in the hard material layer deposition. The combination of tough hard metal substrates with wear-resistant hard coatings leads to an enormous increase in the applicable process parameters and tool life. The tasks of a coating are the avoidance of tool wear by adhesive, abrasive, thermal and chemical protection. One of the most promising and latest developments in coating technology is the HiPIMS deposition [Ackerschott 1989, Koch 1996, Klocke 2008, Denkena 2011].

1.2 HIPIMS HARD COATINGS

The physial vapor deposition (PVD) allows the deposition of hard material layers, at temperatures between 200 °C to 650 °C. A further development of the already widely applied DCMS is the HiPIMS deposition, a novel coating technology, which was developed in the year 1999. Here, a pulsed profile of the current voltage characteristic with power pulses in the MW range is used, which can lead to high power densities up to several kW per cm^2 in front of the target (DCMS: 20 – 50 W/cm^2). Due to the high thermal load of the target because of the high power density, the duty cycle of the pulse is in the range of a few percent. The high-energy pulses lead to an enhanced electron density in the target area, resulting in an increased probability of collision between electrons and target atoms. Therefore, the HiPIMS procedure reaches an ionization rate of the sputtered target of up to 90 % (DCMS: 1 %). A large number of energetic sputtered ions combined with the application of a negative bias voltage increase the already high kinetic energy, and thus the expansion of the free path length, so that undercutscan be coated with a high quality. The

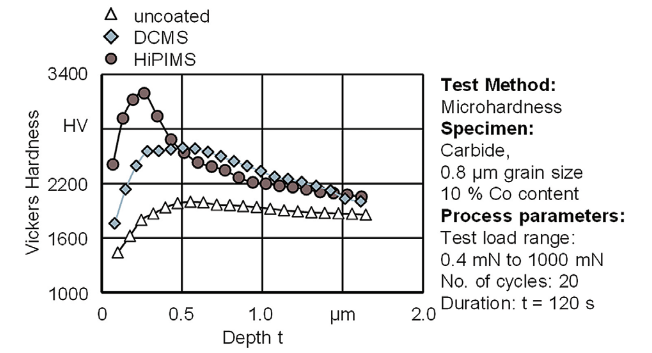

Figure 1. Determination of hardness on the tool surface.

enhanced kinetic energy of the layer ions/ atoms results in increased surface mobility of the layer atoms, and as such the typical DCMS columnar growth can be inhibited, leading to higher densities and favorable layer properties, such as better adhesion and higher hardness (Fig. 1). With these advantages HiPIMS hard coatings are ideal for use in machining [Kouznetsov 1999, Bandorf 2009, Bobzin 2009, Bobzin 2010, Bouzakis 2010]. The process reliability of coated carbide tools in hard turning could thus be significantly increased with this technology.

2 EXPERIMANTAL DETAILS

2.1 TOOL SETUP

In the context of presented studies, carbide cutting inserts with the geometry of CNMN 120408 were used according to ISO 1832 (Fig. 2). For this purpose, two different types of substrates were used. For the investigation of the physical properties of the coated tools, and the model-simulation of different wear mechanisms, 10 % Co-containing cemented carbide was used with a particle size of 0.8 µm, that is referred to as Type I (Tab. 1). For usage in the machinability experiments a 6 % Co-containing cemented carbide was used, referred to as Type II with a grain size of 0.8 µm.

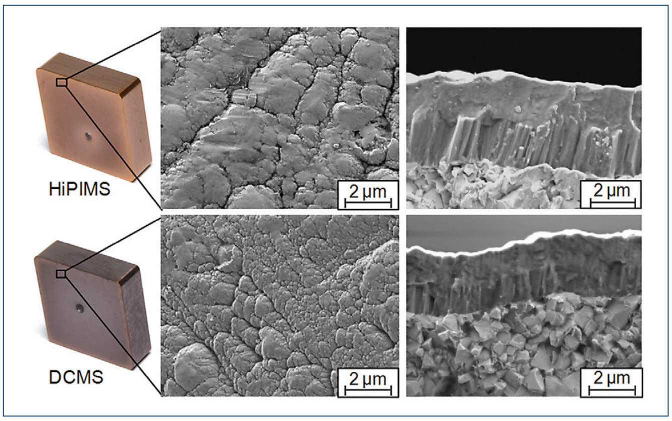

Figure 2. SEM images of the coated inserts with surface morphology and layer morphology after cryofracture.

Type	Type 1	Type 2
Tungsten [%]	89	93
Cobalt [%]	10	6
Other Carbides [%]	1	1
Density [g/cm3]	14.45	14.85
Hardness [HV 30]	1600	1790
TRS [N/mm²]	4300	3900

Table 1. Physical properties of Type 1 and 2.

This is characterized by a higher hardness and abrasive resistance compared to the 10 % cobalt containing type, with a lower fracture toughness. The cutting edge radius of the inserts used in machining was r_β = 30 µm and are designed for the machining of hardened steel. The tools have been coated by HiPIMS and DCMS method with a layer system consisting of an outer TiSiN layer and inner TiAlN layer.

2.2 MODEL WEAR TESTS SETUP

Calo wear test

In order to analyze the resistance against abrasion, calo tests were conducted. A hardened steel ball of AISI 52100 (62 HRC) with a 30 mm diameter rotating in a polishing medium (slurry) was pressed into the specimen with a defined load. The used slurry was a lapping suspension consisting of alcohol and diamond with an average grain size of d_p = 1 µm. Tests were carried out with one rotation. After that the resulting impression was evaluated.

Cylinder-plate tribometer

The adhesion wear mechanism was investigated with a cylinder-disk tribometer. Due to a defined normal force (F_N = 14.5 N), the peripheral surface of the coated tool is contacted in connection with a rotating disk of hardened 42CrMo4V (57 HRC). The rotational speed of the disc is at v_c = 44.6 m/min.

Impact test

The impact test constitutes the wear mechanism by surface fatigue. A piezo actuator operated with diamond tip loaded the investigated layers with a normal force of F_N = 80 N at an impact frequency of f = 100 Hz, the experiment was considered complete when the specimen was exposed to105 impacts. During the experiment, the zero point on the sample surface is determined after each 2 500 impacts, so that the following impacts hit the layer.

Scratch test

In order to analyze the coating adhesion of a coating system, the scratch test is conducted according to DIN 1071-3. A Rockwell C diamond Indenter is moved at a constant speed and a linear increase in the normal force of 10 N/mm over the surface of the specimen. The scratch track is analyzed with force measurements, AE signals and microscope images and evaluated according to loss category results and discussion. LC_1 indicates a beginning, visible cracks on the surface of the assessed sample. The damage LC_2 indicates that the layer has flaked off primarily at the edge of the scratch. A complete penetration of the diamond up to the substrate material is indicated by LC_3.

Turning tests

Cylindrical turning experiments were carried out under wet cutting conditions on the CNC slant bed lathe by Oerlikon-Boehringer, Göppingen, Germany, of the type VDF 180 C U. It has a maximum machining diameter x length of 250 mm x 1000 mm and a DC motor of 31.5 kW. Its maximum rotation speed is 5000 rpm and its maximum torque is 800 Nm. Two different steel types were used for the turning tests. The high alloyed hardened (54 HRC) hot work tool steel 1.2344, which has a high heat resistance and toughness, and a hardened (55 HRC) cold work tool steel 1.2436, which has moderate toughness properties. Both workpieces had a diameter of 195 mm and a length of 160 mm. For examination of the wear form, the flank wear VB and crater depth KT were measured until reaching the defined tool life criterion VBmax = 0.3 mm. In similar studies has already been determined that the usual wear in hard turning is flank wear and crater wear [Uhlmann 2011]. The turning tests in the hot work tool steel 1.2344 were carried out with a cutting speed of v_c = 80 m/m in, a feed of f = 0.1 mm and a depth of cut of a_p = 1.0 mm. The parameters for machining the cold work tool steel 1.2436 were a cutting speed of v_c = 80 m/min, a feed of f = 0.1 mm and a depth of cut of a_p = 0.5 mm.The tools show a working clearance angle of a_{eff} = 10 ° and a working rake angle of y_{eff} = 10 °.

3 RESULTS AND DISCUSSION

3.1 COATING ANALYSIS

The analysis of the layer structure of the DCMS and HiPIMS layers is similar with regard to the inner TiAlN layer and differ in the outer TiSiN layer. The TiAlN layer is in both types of layers characterized by a pronounced columnar structure, which is typical of lower kinetic energy of the layer-forming ions or atoms. Differences in film morphology between the HiPIMS and DCMS-layers are shown by the external TiSiN layers. While in the DCMS layer columnar structures can be recognized, pronounced much finer compared to the underlying TiAlN-layer, in HiPIMS layers no columnar structure of the outer layers of the TiSiN layer can be determined. The structure of the HiPIMS TiSiN is denser, which is due to a higher kinetic energy of the sputtered ions or atoms in comparison to the DCMS and the TiAlN layer. The increased kinetic energy also results in higher lattice distortions of the elementary cell and to higher internal stresses in the layer, resulting in a higher hardness of HiPIMS TiSiN layer. The micro hardness of the HiPIMS insert is approx. 25 % higher and has a maximum Vickers hardness of 3194 HV (DCMS: 2553 HV). The results of micro hardness measurements are not directly attributable to the hardness of the layer system, but are characteristicfor the total hardness of the tool system. It can be assumed that by increasing the force also the substrate is taken into account. The surfaces of the HiPIMS coated samples are finer with a mean average roughness Rz = 1.34 ± 0.09 µm and have smaller layer thickness differences compared to the DCMS layers with Rz = 1.43 ± 0.13 µm (Fig. 3). Moreover, the surface images show a higher concentration of droplets – teardrop shaped coating defects that occur due to the process – at the DCMS layers.

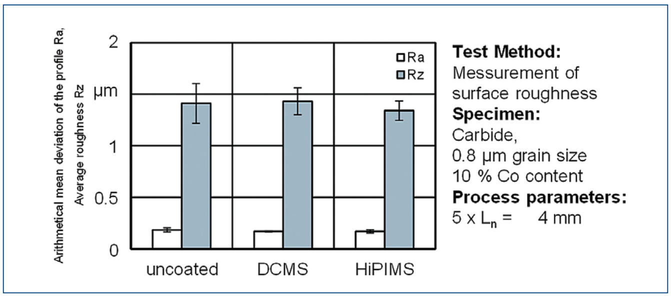

Figure 3. Arithmetical mean deviation of the profile Ra and average roughness Rz of the tool surface.

3.2 TRIBOLOGICAL BEHAVIOR

Abrasion

The diameter of the impressions Di was measured and compared as an evaluation criterion for the abrasion resistance of the surfaces. It could be observed that the HiPIMS coated tools show a higher impression diameter. The measurements revealed an average diameter for the HiPIMS coatings of 223 µm and for the DCMS coatings of 202 µm. Despite higher hardness and thus a theoretically greater resistance of the HiPIMS coatings compared to DCMS this could not be confirmed in the calo test. The reason for this behavior could be the different surface structure of the respective coatings. The DCMS coated tools had a significantly higher number of droplets. The hardened steel ball rubs the droplets and enters the dense layer surface. The HiPIMS coating has hardly any droplets, so the stell ball enters the dense layer at the beginning of the calo test. The impression diameter of the DCMS coatings is reduced by approx. 10 % in comparison to the HiPIMS coatings and has in this case a higher abrasion resistance (Fig. 4).

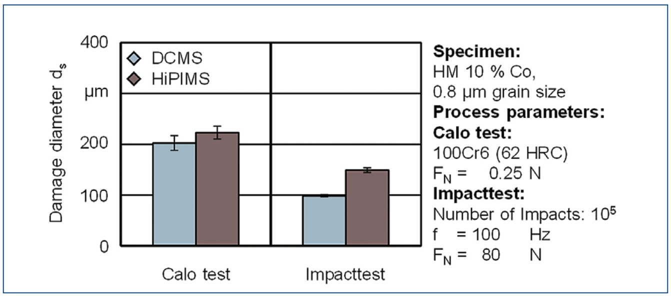

Figure 4. Results of the analysis of the wear resistance of the tools with respect to the individual wear mechanisms: Abrasion and surface distress test.

Adhesion

The friction coefficient of the coated samples shows significant differences in the adhesion test. The HIPIMS tools (µg = 0.30) have lower average friction coefficient by 17 % compared to the DCMS plates (µg = 0.36). This can be attributed to the higher hardness of the HiPIMS layers, since the friction coefficient decreases in general with increasing hardness. Both types of layers have a lower abrasive effect with the friction partner than the pure carbide. (Fig. 5).

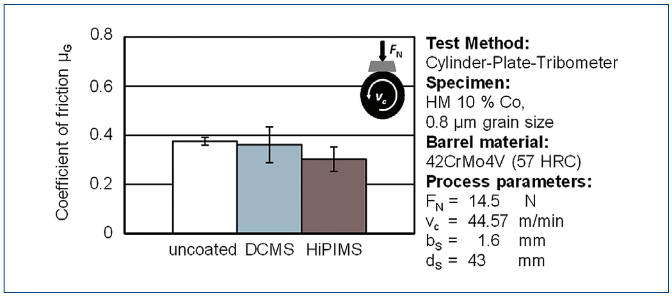

Figure 5. Results of the analysis of the wear resistance of the tools with respect to the individual wear mechanisms: Adhesion testing.

Surface fatigue

The diameter of the impressions Di was measured and compared as an evaluation criterion for the surface fatigue resistance of the surfaces (Fig. 4). The HiPIMS coatings show a higher impression damage with a diameter of 149 µm compared to the impression damage diameter of 99 µm. This is due to the differences in the structures and properties of the deposited coatings. The higher kinetic energy of the sputtered ions or atoms generated denser and harder coatings. However, linked to this is a more brittle behavior of the HiPIMS coatings. This lower toughness has the consequence that the HiPIMS coatings suffer under dynamic loading rather failure or a greater damage than is the case with the DCMS coatings.

Coating adhesion

The first cracks in the area of L_{C1} in the HiPIMS coatings started in an average axial force of 83 N. The L_{C1} area for the DCMS coatings start in an average axial force of 65 N. In this case tangential forces achieve for the HiPIMS coatings an average of 8 N and for the DCMS coatings an average of 6 N. First delamination for the area L_{C2} of the HiPIMS coatingsstart at an averageaxialforce of 153 N and for the DCMS coatings at 150 N. Here the HiPIMS coatings hold an average tangential force of 24 N and the DCMS an average of 20 N. In the area of the complete coating penetration L_{C3} both coating types react quite similar. The average normal force of the HiPIMS coatings is 179 N and for the DCMS at 180 N. The averages of the tangential forces are the same at 34 N. The load capacity for the HiPIMS coatings is in the area of L_{C1} and L_{C2} higher. The coating behavior in the area L_{C3} is equal(Fig. 6).

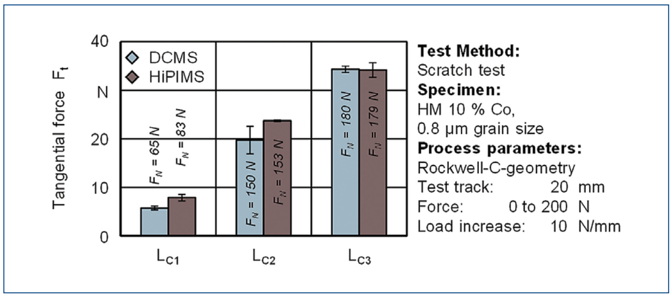

Figure 6. Results of the analysis of the wear resistance of the tools with respect to the individual wear mechanisms: Scratch test.

3.3 RESULTS CUTTING TESTS

The cutting tests show that the wear resistances of the tested coatings behave differently in the two hardened steel types. The DCMS tools machined compared to the HiPIMS coated inserts when turning the hot

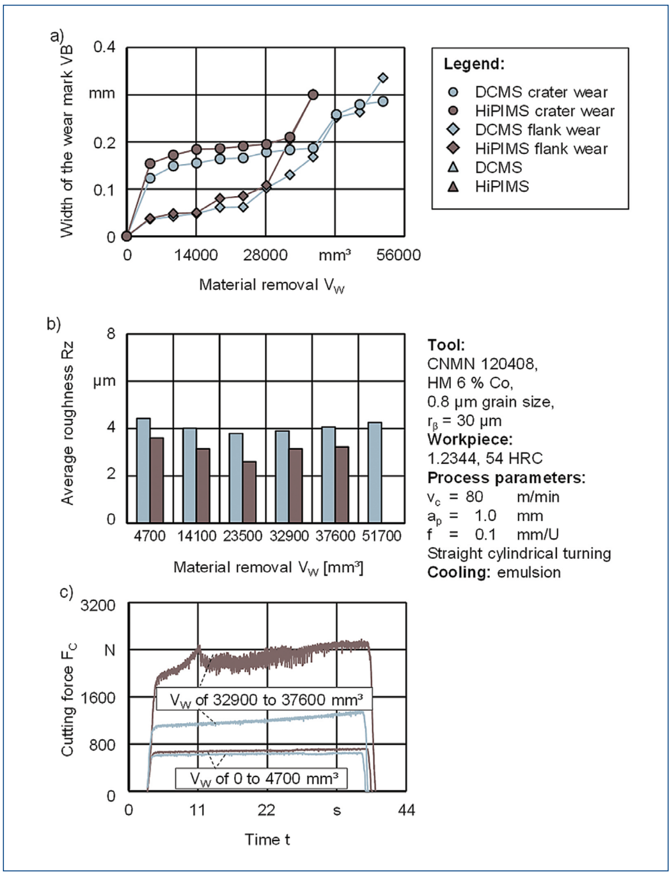

Figure 7. Results of the cylindrical turning experiments of hardened steel 1.2344: a) Development of wear, b) Development of the averaged roughness depth, c) Comparison of cutting forces.

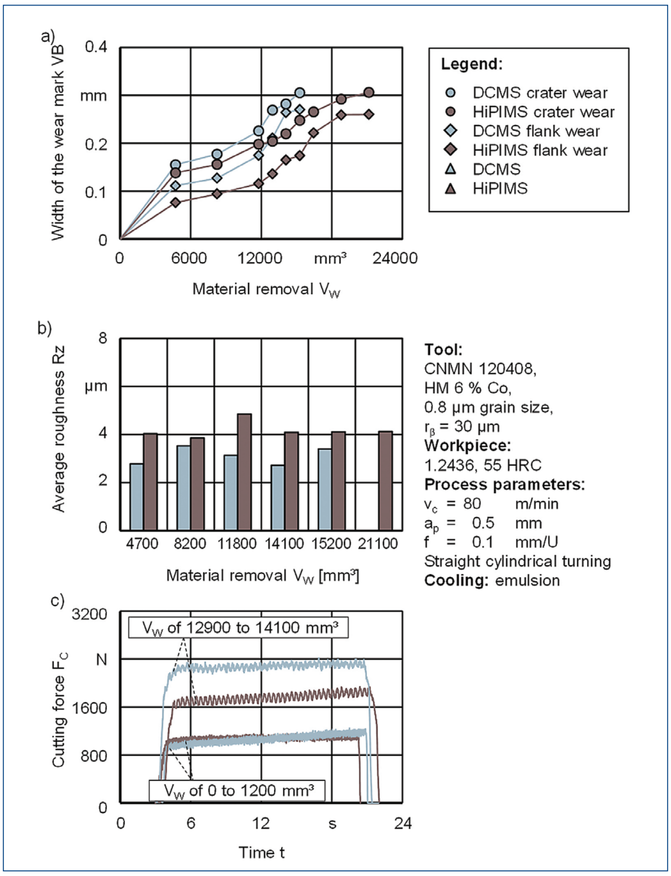

Figure 8. Results of the cylindrical turning experiments of hardened steel 1.2436: a) Development of wear, b) Development of the averaged roughness depth, c) Comparison of cutting forces.

work tool steel 1.2344 with a cutting volume of V_{ZE} = 51 700 mm³ approx. 37.5 % more material (Fig. 7). At a machining volume of approx. V_Z = 28 000 mm³ the HiPIMS coatings were not able to withstand the loads, so entered premature tool wear by the detachment of the coatings due to advanced flank wear and reinforced crater wear. Similar wear characteristics were exhibited the DCMS inserts, however, the critical wear growth began from approx. V_Z = 37 600 mm³. The force values close to the end of the experiments with the HiPIMS coated inserts showed an increase of up to 273 % compared to the start of the experiment and therefore an advanced state of wear. During this test, the force increased in the full load range approx. 700 N (F_{ZMAX} = 2 500 N from V_Z = 32 900 mm³ up to V_Z = 37 600 mm³), established by the strong increase in wear from VB = 0.2 mm up to VB_{END} = 0.3 mm at the flank face and rake face. In the same section the cutting force on the DCMS tools increased slightly and corresponded to a typical, slowly increasing wear mark width. Compared to the first cut, the cutting force grew by 109 %, while the cutting force between V_Z = 32 900 mm³ and V_Z = 37 600 mm³ increased by 250 N and a maximum cutting force of F_{ZMAX} = 1 350 N was reached. The used cutting parameters produced on the workpiece surface a roughness average of approx. Rz = 4 µm (DCMS) and Rz = 3.2 µm (HiPIMS). The result in machining of hardened cold work tool steel 1.2436 is different (Fig. 8). The HiPIMS tools (V_{ZE} = 21 100 mm³) reached a higher material removal rate by 38 % compared to the DCMS-coated insert. The increase of wear up to the cutting volume of V_Z = 12 000 mm³ was similar in both types of layers, but the signs of wear on the DCMS-coated tools were already more pronounced after the first cut in the rake and flank surface. Subsequently, the growth of wear of the HiPIMS layer was constant, while that of the DCMS-layer increased steadily and flattened out just before the end of the experiment. At the start of the experiment, the cutting forces of the two layer types were at a similar level, but the growth was stronger in the DCMS layer (by F_{ZS} = 310 N on F_Z = 460 N) than in the HiPIMS layer (by F_{ZS} = 360 N on FZ = 430 N). The force values in the recent experiment with the DCMS tools showed an increase of up to 96 % (F_{ZMAX} = 900 N) compared to the start of the experiment. This increase of force at V_Z = 15 200 mm³ is to be explained by the increased wear rate on the rake and flank surface. At the same material removal stage, the cutting force (F_{ZMAX} = 700 N) areapprox. 23% and the tool wear approx. 27 % lower and correlate with one another well. The measured average roughness Rz of the workpiece are, independent of the current wear rate,almost constant at approx. Rz = 4 µm after processing with the HiPIMS-tools, up to an irregularity in the material removal of V_Z = 11 800 mm³ (Rz = 4.5 µm). The finished surfaces with the DCMS-tool showed a random distribution of Rz values between 2.7 µm and 3.5 µm and do not reflect the wear rate.

3.4 SUMMARY AND CONCLUSION

During the investigation, the theoretical, positive qualities of HiPIMS compared to DCMS-coating technique, the replication of wear and the hard turning tests were partially confirmed. The higher hardness, density and surface quality of HiPIMS layers could be detected in the experiment. Resulting from this, a lower tendency to adhesion and higher adhesion at the load cases (L_{C1} and L_{C2}) are determined. The abrasion wear mechanisms and surface fatigue, the DCMS layers were more resistant. When turning the hardened 1.2436, the HiPIMS tools reached 38% more material removal in comparison to the DCMS tools. In addition to the above-mentioned advantageous properties, a higher diffusion resistance is a possible factor that must be proven in the oxidation tests. When machining hardened hot work steel 1.2344, these advantageous properties did not lead to an increased wear resistance: The DCMS-coated inserts reached approx.

37.5 % more material removal. By the alloy elements molybdenum (1.4 %) and vanadium (1 %) in 1.2344, the toughness is increased and simultaneously by the elimination of special and mixed carbides, the hardness is increased locally. This cyclic loading in the application of HiPIMS layers is, as can be seen already from the surface fatigue test, problematic and leads to coarser layer outbreaks than in the DCMS coatings. Based on these results, in terms of HiPIMS coating parameters and their influence on the resulting internal stresses, which lead to higher hardening and therefore are subject to the brittle material behavior, further studies need to be undertaken, in order to set optimal layer properties for tougher materials. Especially in the coating adhesion and the coating-substrate-interface there is a demand for development to exploit the potential of HiPIMS layers in hard machining fully.

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