Robot based deposition of WC-Co HVOF coatings on HSS cutting tools as a substitution for solid cemented carbide cutting tools

W Tillmann¹, C Schaak¹, D Biermann², R Aßmuth² and S Goeke²
¹TU Dortmund, Institute of Materials Engineering, Germany
²TU Dortmund, Institute of Machining Technology, Germany
E-mail: wolfgang.tillmann@udo.edu

Abstract. Cemented carbide (hard metal) cutting tools are the first choice to machine hard materials or to conduct high performance cutting processes. Main advantages of cemented carbide cutting tools are their high wear resistance (hardness) and good high temperature strength. In contrast, cemented carbide cutting tools are characterized by a low toughness and generate higher production costs, especially due to limited resources. Usually, cemented carbide cutting tools are produced by means of powder metallurgical processes. Compared to conventional manufacturing routes, these processes are more expensive and only a limited number of geometries can be realized. Furthermore, post-processing and preparing the cutting edges in order to achieve high performance tools is often required.

In the present paper, an alternative method to substitute solid cemented carbide cutting tools is presented. Cutting tools made of conventional high speed steels (HSS) were coated with thick WC-Co (88/12) layers by means of thermal spraying (HVOF). The challenge is to obtain a dense, homogenous, and near-net-shape coating on the flanks and the cutting edge. For this purpose, different coating strategies were realized using an industrial robot. The coating properties were subsequently investigated. After this initial step, the surfaces of the cutting tools were ground and selected cutting edges were prepared by means of wet abrasive jet machining to achieve a smooth and round micro shape. Machining tests were conducted with these coated, ground and prepared cutting tools. The occurring wear phenomena were analyzed and compared to conventional HSS cutting tools. Overall, the results of the experiments proved that the coating withstands mechanical stresses during machining. In the conducted experiments, the coated cutting tools showed less wear than conventional HSS cutting tools. With respect to the initial wear resistance, additional benefits can be obtained by preparing the cutting edge by means of wet abrasive jet machining.

1. Introduction
Cemented carbide, also called hard metal, is a metal matrix composite (MMC) based on a mixture of a hard material, commonly tungsten carbide (WC), and a metal e.g. cobalt (Co). In this case, cobalt is the metallic binder which imbeds WC particles. Cemented carbide components are produced by means of powder metallurgical processes. These hard cutting materials can be classified in conventional hard metal (HW), fine grain hard metal (HF), and coated hard metals (HC) [1]. Cemented carbide tools show a superior high temperature strength and low wear. In general, there are two different design types of these tools. The first tool type is fully made of cemented carbide (solid cemented carbide tools). The second type of tools consists of a steel tool body (e.g. high speed steel) that is improved by
bonding cemented carbide onto the cutting edges [2]. The morphology of the cemented carbide component strongly influences the properties of the final cutting tool. Especially, fine carbide and grain sizes (< 1 µm) improve the wear resistance and the toughness of the cemented carbide. The low toughness is one big disadvantage of conventional cemented carbide components [2,3]. The second disadvantage are the higher production costs of solid cemented carbide tools compared to HSS tools. The reason for this are the higher raw material costs as well as the expensive processes of fine powder production and powder conditioning. Furthermore, the post-processing and preparation of the cutting edges is more extensive, because of the high hardness and strength of the material. One alternative to reduce the need of cemented carbide and to improve the toughness of the tool is the usage of cemented carbide inserts on steel tool bodies. Furthermore, the effort of machining or grinding the hard material is reduced. These cemented carbide inserts are bonded to the surface of the tool by means of brazing or diffusion bonding [4-6]. The main disadvantages of this multi-stage method are the complex processing (positioning, loading, etc.) and the thermal load during processing.

Based on the concept of WC-Co cemented carbide tools, a partial reinforcement with a cemented carbide could also be realized by means of thermal spraying. WC-Co and WC-CoCr deposited by means of thermal spraying are well established coating systems [7-9]. These coatings can be deposited by atmospheric plasma spraying (APS) or high velocity oxygen fuel (HVOF) spraying. Overall, HVOF shows the lowest porosity and the lowest wear rates resulting in the highest coating quality [10].

The benefits of tools coated by means of HVOF with WC-Co are a tough substrate combined with an extremely hard and wear resistant surface layer. The coating process is easy to operate and suitable for mass production. Furthermore, a worn out tool can be reconditioned by depositing a new WC-Co layer on it. Yet, near net shape thermally sprayed coatings are still a challenge to solve [11,12]. Especially, complex parts with radii, gaps, and edges are hard to coat with a homogenous coating thickness. Modern robot systems can help to solve these challenges. However, the spray strategy has to be optimized for this purpose and the robot kinetics have to be taken into account. The challenge of the planned application is to get a homogenous, thick, full covering sprayed WC-Co layer on a small HSS cutting tool. Considering the use of cutting tools, especially the cutting edge has to be coated very well. Otherwise, a fatal delamination would occur in this area because of the high cutting forces which act on the coating. Additionally, in order to reduce the post-processing effort and time, the coating should be near-net-shaped. A post-processing cannot be avoided, because of the high roughness of the as-sprayed coating. The cutting edges and flanks have to be ground and prepared prior to the usage. The post-processing generates the final shape of the cutting edge and thus of the tool.

In the present paper, different coating process strategies were tested to coat a HSS cutting tool. The results were analyzed and discussed. Furthermore, two different post-processing methods were investigated. To complete the experiments, the coated and post-processed cutting tools were used to cut a steel sample of AISI 1060 in an experimental rig.

2. Experimental Details

2.1 Materials and Coating Process

A tungsten carbide cobalt base powder was used (Type: Woka 3102. Supplier: Oerlikon Metco) as feedstock material. The powder is composed of 88WC-12Co (12% cobalt powder). The powder is agglomerated and sintered and the tungsten carbides have an average grain size of 2.5 µm. The range of the agglomerate size ranged between 15 µm and 45 µm (-45 +15).

For the coating experiments, a Woka Jet 400 system (supplier: Sulzer Metco) were used with a Sulzer Metco MultiCoat controller system and a Twin-120-H powder feeder. The spraying parameters are summarized in table 1. The spray gun was mounted on an ABB IRB 4600 60/2.05. The software ABB RobotStudio 5.13 was used for path programming.
HS6-5-2C (1.3343), ASP2023 (1.3395) and X38CrMoV5-3 (1.2367) were used as substrate material (table 2). These steels are typical tool steels. A sketch of the used tool shape and their dimensions is shown in figure 1. For the planned application of WC-Co HVOF coatings as cutting tool coatings, it is important to get a covering coating at the cutting edge and the flanks. For this purpose, different coating strategies were investigated. For spray strategy I, the spray gun is leant down 30.5° and the spray gun path follows the cutting edge. This ensures that the spray jet directly targets at the cutting edge. The aim of this strategy is to obtain a good coating at the cutting edge. For spray strategy II, both flanks including the cutting edge were coated subsequently. The third spray strategy combines strategy I and strategy II. Figure 1 shows spray strategy III. The spray path covers the flanks and the cutting edge. In this case, the spray gun follows the contour of the tool’s body with a distance of 300 mm. The run up distance was kept long, thus guaranteeing a constant speed. Additionally, a long turning distance was used between the overruns for an extended cooling time. For strategy II and III the spray angle was set to 90 °. Prior to the coating process, the samples were grit blasted with corundum (EKF 100, 4 bar). The full experimental plan is summarized in table 2.
2.2 Post-Processing and Analysis Methods

After the coating processes, several samples were used to investigate the coating morphology and to measure the coating thickness. For this purpose, metallurgical cross-sections were produced and analyzed with a light microscope (LIMI) and scanning electron microscope (SEM). A few samples were post-treated after the coating process. The cutting edge of these samples were ground or ground and prepared. Grinding the coated samples results in sharp cutting edges. However, to remove minor defects along the cutting edge and to achieve a favorable cutting edge micro-shape in terms of a rounding, some edges were prepared by means of wet abrasive jet machining. The preparatory work was conducted with corundum ZWSK F220 in water, pressurized by air at $p_{\text{jet}} = 2.5 \ldots 6$ bar. The results of the post-treatment were investigated by means of SEM. Finally, all samples with different conditions (without post-treatment, ground, ground + wet abrasive jet machined) were tested in a cutting test (see figure 2). The fundamental chip formation machine at the Institute of Machining Technology allows detailed investigations of cutting processes with cutting speeds up to $v_c = 180$ m/min. In this regard, bars of AISI 1060 with a length of $l = 400$ mm were machined. The uncut chip thickness was set at $h = 0.05$ mm and the cutting speed was $v_c = 30$ m/min. Five cuts were made for each tool. The cutting process was observed with a high speed camera and the cutting forces were recorded. The cutting test parameters were kept constant for all tested tools.

**Figure 1.** a) Sketch of the used cutting tool (substrate) with its dimensions and shape. b) Sketch of the spray strategy III. The red lines indicate the pathways of the spray gun.
3. Results and Discussion

3.1 Coating

Representative light microscope images of cross-sections of the coated tools are visible in figure 3. The different spray strategies (spray gun paths) lead to completely different results. For strategy I, the coating is almost non-existent (see figure 3a). Even with many overruns, only small amounts of WC-Co were deposited at the flank faces. This result is insufficient and this strategy is not expedient. The reason for these bad results is the high kinetic gas flow during HVOF spraying. The cutting edge deflects the gas flow, thus the particles do not adhere on the surface. This effect is comparable to spraying with very low spray angles. The deposition rate correlates directly with the spray angle [13]. Spray strategy II leads to significantly better results (see figure 3b). The flank faces are well-coated but the cutting edge is still not fully covered with WC-Co, even though the spray path was set to coat the cutting edge. Both coating strategies showed a deformation of the cutting edge (see figure 3a and 3b). In the initial state, all cutting edges had the same shape. This deformation could be caused by the kinetic and thermal energy during the HVOF coating process.

The best result as shown in figure 3c were obtained with spray strategy III. The flanks and the cutting edge are fully covered with WC-Co, no delamination is visible, and the interface is free of gaps. It is visible that the coating thickness is smaller in the area of the cutting edge. This effect might be related to the changing spray angle caused by the rotation of the robot around the cutting edge. The spray gun follows the contour of the tool but the spray angle might not be ideal (90°) due to the kinetics of the robot. Overall, this spray strategy (see also figure 1) is more complex than strategy I and II. Furthermore, the industrial robot needs a larger movement area. However, overall the results are much better.
Figure 3. Cross-section image (light microscope) of the WC-Co coated cutting tools. Spray strategy: a) type I (sample P2, 30 overruns); b) type II (sample P4, 20 overruns); c) type III (sample P6, 10 overruns).

The third spray strategy was chosen as the best strategy of the three tested strategies. Additional coating experiments were conducted with strategy III and with different numbers of overruns (see table 2). To obtain quantifiable values, the coating thickness was measured at different positions (No. 1 to 11) on the flank faces and the cutting edge (position No. 7). The distance between the different measuring positions was 1000 µm. The results of the coating thickness measurements are given in the diagram in figure 4.

Figure 4. Results of the coating thickness measurements at different positions for the experiments P7-P12.
It can be seen that the lowest coating thickness is always found in the area of the cutting edge (figure 4). This effect is more visible for a higher number of overruns. Furthermore, the coating thickness is more inhomogeneous with more overruns. In the diagram, the left part next to the cutting edge represents the rake face (see figure 1) of the cutting tool. The rake face shows an increasing and large coating thickness (up to 850 µm). The flank face, the right part in the diagram, shows a decrease of the coating thickness for areas not close to the cutting edge. It is suspected that these effects are related to the suboptimal spray angle when the robot rotates the spray gun around the small cutting edge. Only at the back of the flank (position 1 – 3), the spray angle seems to be 90°, thus resulting in a high deposition rate. To obtain an adequate coating thickness (coating thickness $t_{\text{coat}} > 100$ µm) at the cutting edge, at least two overruns with spray strategy III should be realized. Overall, the results of the experiments reveal that the cutting edge can be coated with a covering and dense WC-Co layer if the spray strategy is adapted to the geometry. Of course, there are further different spray strategies which may provide even better results. For this purpose, the kinematics of the robot should be taken into account.

3.2 Post-Processing and Cutting Test

After the coating process, the produced WC-Co layer were post-treated by means of grinding or grinding and wet abrasive jet machining. Both methods were described in chapter 2.1. Representative SEM images of the coated and post-treated tools are shown in figure 4. After grinding, the cutting edge is very sharp (figure 4a/c). The bright area is the WC-Co coating, see figure 4. The gray area is the HSS tool body. The coating does not show any cracks after processing. With the grinding process, a constant coating thickness can be adjusted. After grinding and wet abrasive jet machining, the cutting edge is round and smooth and the surface tends to be slightly rougher (figure 4b/d).

![Figure 4. SEM image of the cutting edge and cross-section of WC-Co coated cutting tools after post-treatment by grinding a) and grinding + grit blasting b).](image)

Figure 5 shows the results of the cutting tests of the WC-Co coated and uncoated HSS tools. The uncoated HSS tools shows large deformations and outbursts at the cutting edge as well at the flank and rake face (figure 5b). Energy-dispersive X-ray spectroscopy (EDS) did not show adhesions of the
workpiece at the tool surface. The measured loads change intensely due to the breakouts during cutting (figure 5a). Peaks up to 1800 N are visible. The ground and ground + prepared samples show significant lower and almost constant forces (figure 5c and 5e). For the WC-Co coated and ground tools, the cutting force is approx. 350 N at the beginning. At the end of the process time, the loads change slightly and increase up to approx. 430 N. This effect might have occurred due to breakouts at the cutting edge that are visible in figure 5d. Compared to the uncoated HSS tool, the breakouts are smaller and only located at the cutting edge.

![Figure 5. SEM image of the cutting edge of WC-Co coated cutting tools after the machining test. a) + b) HSS tool without coating c) + d) HSS tool with ground WC-Co coating e) + f) HSS tool with ground and prepared WC-Co coating.](image)

The WC-Co coated, ground and prepared HSS tools show minor wear. In figure 5e, the coating on the rake face was nearly removed due to the grinding process. Because of the inhomogeneous coating thickness after spraying (figure 4), the rake face showed only a very small WC-Co coating after grinding. Otherwise, a homogenous cutting tool surface was not realizable.

The measured forces are slightly higher than for the WC-Co coated tools, which were only ground. This effect depends on the shape of the cutting edge. The ground cutting edge is sharper and has a lower contact area during cutting. Hence, this cutting edge provides a higher contact pressure and reduced loads are measured when cutting the steel sample. The prepared cutting edge is round and thus it has a higher contact area during cutting. This results in higher forces up to 600 N (figure 5e) that are necessary for cutting the steel bar. However, the round cutting edge seems to be more stable, probably due to a better force transmission into the coating and from the coating to the substrate (HSS tool body). Breakouts and deformations of the WC-Co coating are not visible.
4. Summary and Conclusion

HSS cutting tools were coated with WC-Co (88/12) by means of HVOF. Different spray strategies were tested to obtain a close and homogenous coating on the cutting edge, the rake and flank face. The best results were achieved when the spray gun path follows the contour of the tool as accurately as possible. This was achieved by a large rotation of the spray gun around the cutting edge by the robot system. Although the movement speed of the robot system was kept constant, the coating thickness on the flanks was not homogenous. This effect was related to the kinematics of the robot, the resulting suboptimal spray angle, and the emerging flow turbulences. To achieve more constant coatings (near-net-shape coatings), these effects have to be taken into account for future investigations.

The coated HSS tools were post-treated by means of grinding or grinding and wet abrasive jet machining. Grinding leads to very sharp cutting edges whereas grinding combined with subsequent preparations leads to a round cutting edge. Conducted cutting tests with the produced HSS tools show that ground and prepared tools perform most sufficiently. The round shape of the WC-Co cutting edge seems to lead to an increased stability. Reasons for this finding could be a higher contact area during cutting and hence, a lower area pressure. Furthermore, a better load transmission related to the round shape could be another reason for this effect. Overall, the behavior under load and the detailed failure mechanisms need to be investigated in comprehensive future research.

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