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Optimized process chains ensure economic success

Oxynitride and nanoscale PVD carbide coatings improve the performance of titanium cutters

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(Introduction, "leader")
Titanium alloys have become a key material in many branches of industry, above all in the aerospace industry. The reasons for this lie mainly in the combination of properties such as high strength at increased temperatures, low density, a high degree of chemical resistance and high wear resistance. However, these advantages are offset by a major disadvantage: the machining, in particular milling, of titanium and titanium alloys is very difficult and therefore very expensive since only relatively low cutting speeds can be used and tool life is usually short..

The prime causes of problems when working with titanium materials are high thermal stresses at the cutting edges as a result of low thermal conductivity through the swarf and the workpiece, a strong tendency for titanium to form an alloy with the material of the cutting tool, the low E modulus, which can lead to serious deflection and consequently cause vibration or chatter, and the high strength of the material at high temperatures.

A great many R & D projects are therefore devoted to developing tool and technology solutions aimed at obtaining a significant improvement in the performance of the machining techniques used for milling titanium. [1;2] etc.

The results of our research, in particular with regard to the development and impact of new types of PVD carbide coatings in conjunction with suitable edge rounding and finishing systems for coatings, are reported below.

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Preparation of the cutting edge, coating and finishing considered in context

The objective of extensive studies specifically concerning the milling of the titanium alloy TiAl6V4 was initially to conduct test runs in order to compare uncoated solid carbide cutters with cutters covered with a PVD coating and used by partners in industry to mill TiAl6V4. A further objective was to develop solutions along the process chain coating *preparation – coating – finishing* in order to obtain a significant improvement in the performance of the milling process.

Tools

Solid carbide cutters with 4 cutting edges (Ø 8mm) made from an optimized carbide substrate and having axial internal cooling were used for the tests. The hard metal used is a tungsten carbide with a content of 12% cobalt and a medium grain size which is especially suitable for cutting titanium and nickel-based alloys. The tools have a geometry adapted to the task in hand with a specially chamfered cutting edge and a polished finish in the flutes.

Preparation of the cutting edge

The preparation of the tools prior to coating was carried out by means of the so-called drag finishing process. During this process and drawing on extensive insights into the design of parameters ideally suited to the coating process (cf.[3] et al), the cutting edge radius, the shape of the cutting edge and the surface parameters on the rake and face surfaces of the tools were varied appropriately.

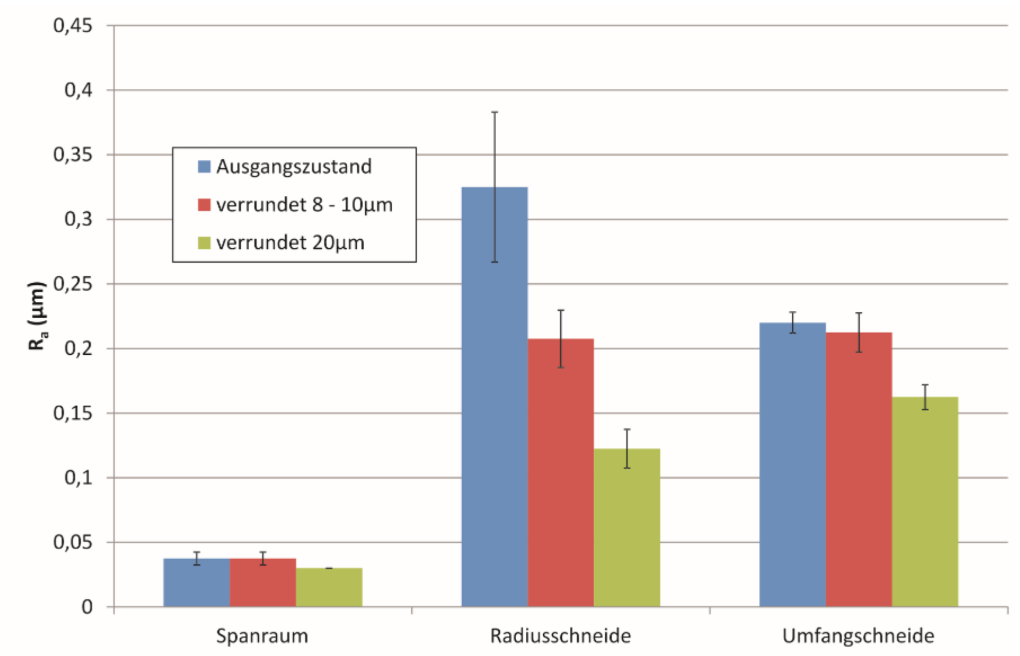

Fig. 1: Roughness Ra in the area of the flute and at the cutting edge before and after rounding of the cutting edge

The cutting edge radius of the tools in their initial state measured between 3µm and 4µm depending on the point on the edge at which the measurement was taken. Different process parameters were selected for the drag finishing process depending on the target cutting edge radius. Subsequent tests were carried out on tools with the following cutting edge radii: a.) without finishing (original state), b.) cutting edge smoothing with only a minimum of rounding (<5µm), c.) 8µm – 10µm and d.) 20µm. **Fig. 1** shows, for example, how the roughness at the cutting edges decreases as the radius of the cutting edge increases. This effect is most noticeable at the radius of the cutting edge.

Layer build-up and test coatings

The coatings were built up, i.e. layers were applied, by means of the PVD coating equipment available in the research facility at the Society for Production Engineering and Development (GFE e.V.), Schmalkalden.
GFE e.V, Schmalkalden; this is also where the coatings were analysed.
The tests were carried out and the coatings built up partly with the aim of combining conflicting coating properties in a single system, e.g.

- High resistance to mechanical wear (hardness, E-modulus)
- Low friction values (in order to avoid particles from adhering)
- Good thermal insulation (to protect the tool substrate from heat)
- High working temperature

In order to achieve this, oxynitride layers on the basis of aluminium, chromium, oxygen and nitrogen (AlCrN-OXI) and zirconia, oxygen and nitrogen (ZrN-OXI-7), as well as layers of hard material with embedded nanoscale structures (nACRo³), were deposited on solid carbide cutters. These coatings consist of coating systems which are always made up of three individual layers: bonding layer, base layer and top layer [4]. With the AlCrN-OXI coating system in particular, a wide variety of coating parameters, such as bias stress, pressure, layer thickness and the layer thickness ratios of the individual layers, oxygen partial pressure and layer structures (monolayers, multilayers, graduated layers) were varied. These variations enabled layer properties to be changed selectively in a variety of directions, e.g. adhesive strength, compactness, hardness, internal stresses, wear resistance and chemical and mechanical stability.

Finishing

In order to remove or smooth down the droplets typical of the Arc PVD process, which result in increased roughness at the flute and rake surfaces and in the flutes themselves, a finishing stage was carried out. As with the preparation of the cutting edge prior to coating, the drag finishing process was chosen for this operation.

Test runs and field trials

The cutters which had been subjected to different treatment and given different coatings as described above were tested in extensive test runs in which the titanium alloy TiAl6V4 was milled and the results were analysed with regard to tool life behaviour and wear. In addition, field trials were carried out on site.

Oxynitride coating systems and nanoscale structures as success factors
Pursuing development in the direction of oxynitride coating systems and coating systems with nanoscale structures demonstrated a series of positive effects: For example, the following results were obtained by using *structures containing oxygen* in carbide layers:

- Stable chemical bonds as a result of oxide formation
- Improved thermal stability as a result of the oxides formed
- Reduced thermal conductivity as a result of insulating oxides
- Improved mechanical stability as a result of including oxygen in the lattice structure

In the studies carried out to date it was demonstrated that the combination of various structures (oxide, nitride, oxynitride) enabled considerably harder layers to be obtained than with nitride coatings [5].
Coating systems with nanoscale structures, such as nanocomposites or nanolayered coatings, enable the properties of the layers to be selectively modified. Such structures result in a high number of grain boundaries and increased grain boundary migration, which in turn leads to very good mechanical properties such as increased hardness but also greater thermal stability and lower thermal conductivity.

By varying and combining the layer options available, coatings were deposited with the following key properties:

- Layer thickness: 2µm to 3µm.
- Universal hardness: 33GPa to 40GPa
- Adhesive strength, calculated as the vertical force Lc2 at which the coating begins to flake at the scratch test stylus: 65N to 125N

Varying the parameters had a significant impact on the adhesive strength in particular. This effect was greatest with the AlCrN-OXI-2B coating system, as can be seen in **Fig. 2**. Above all, varying the bias stress and pressure had a critical impact on the adhesive strength of the coating. It was borne in mind that varying the parameters can bring about a change in the internal stress properties of the coating and thereby affect the bond.

Once the coating had been applied, the surface needed to be treated in order to remove or smooth down the droplets typical of the arc PVD process. For smoothing the coating, the drag finishing process was used, as it had been for preparing the cutting edges. As can be seen in **Fig. 3** on the basis of the roughness value R_a at the cutting edge, the roughness has in part been reduced and after the coating has been polished, this value is much lower than that of the reference tools examined.

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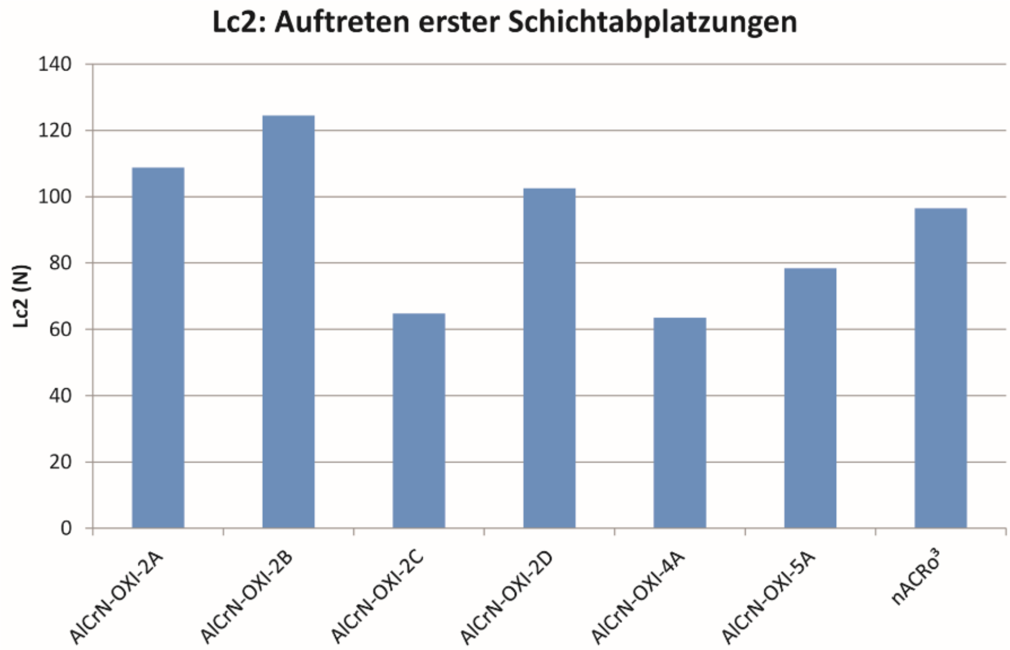

Fig. 2: Adhesive strength of the coating systems

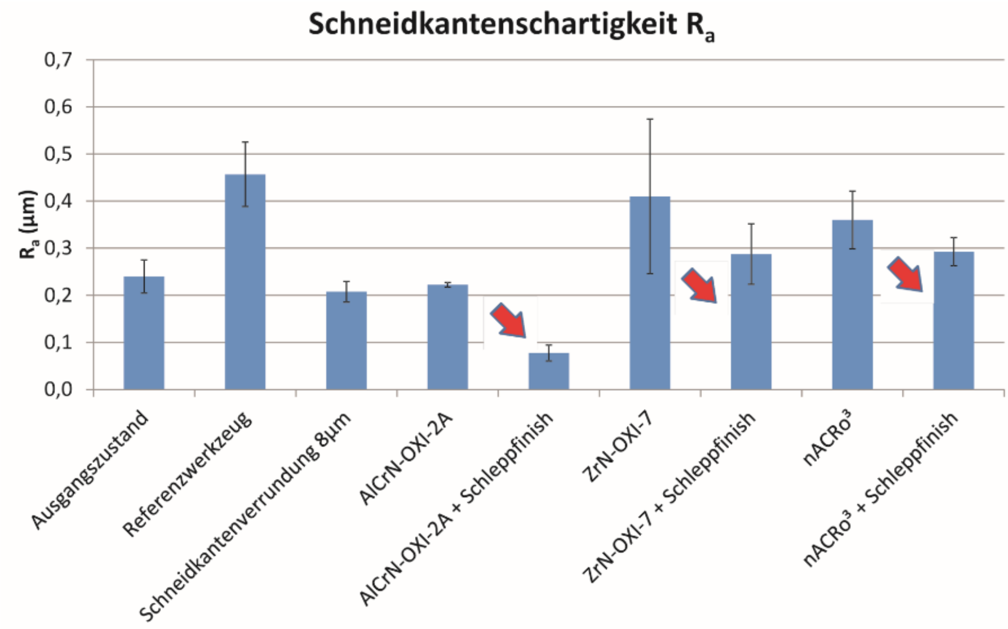

Fig. 3: Chipping at the cutting edge

Test runs confirm improved performance

Extensive milling tests were carried out on the titanium alloy TiAl6V4 whereby cutting tools which had been treated and/or coated differently were subjected to com-

prehensive tests and the results were then analysed and compared in terms of tool life and wear properties. The aim was to achieve a significant increase in cutting speed in order to considerably improve the cost-effectiveness of the titanium milling cutter. For this reason, v_c was increased to 130m/min or under extreme conditions to 150m/min.
Full slot milling was carried out using the following parameters:

- Milling cutter Ø8x13 R2 with IKZ
- Width of cut: a_e=8mm
- Depth of cut: a_p=4mm
- Feed per tooth: f_z=0.03mm
- Cutting speed: v_c=130m/min and 150m/min
- Coolant : emulsion 5%

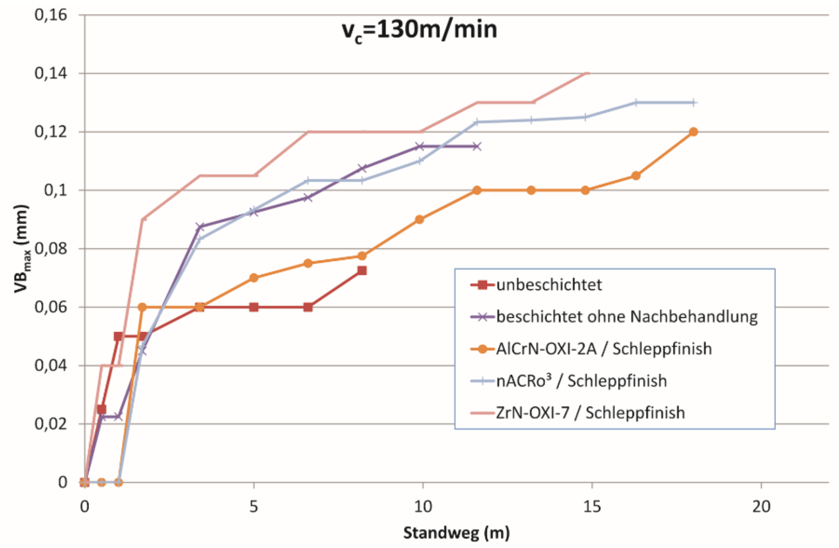

Fig. 4: Width of wear mark as a function of tool life distance at v_c =130m/min

As **Fig. 4** shows, the tool life distance of the uncoated cutters at a cutting speed of 130m/min was the lowest of all tools tested at a maximum of 8m despite the lesser wear mark width. Coating enabled the average tool life distance of all coatings to be increased to 12m; suitable polishing of the coated surface by means of drag finishing enabled the tool life distance to be increased to 18m. In the comparison of the 3 coating systems, AlCrN-OXI-2A, ZrN-OXI-7 and nACRo³, the aluminium oxynitride coating delivered the greatest tool life distance with the lowest wear mark width at 130m/min.

Increasing the cutting speed to 150 m/min delivered considerable longer tool life distances for cutters with the coating systems AlCrN-OXI-2A and AlCrN-OXI-2D or nACRo³ than with the reference tools – with equally low tool wear.
These considerable improvements in tool life are especially due to the very high thermal resistance of the AlCrN-OXI coating systems. Corresponding thermogravimetric studies of the respective coating systems have also confirmed this.

Conclusion

Oxynitride coating systems on the basis of Al-Cr-O-N and multilayer coating systems with a nanocomposite top layer prove to be very resistance to heat and oxidation during full slot milling of TiAl6V4. Furthermore, the multilayer coating systems with a nanocomposite top coating are marked by considerable mechanical strength and abrasion resistance. Especially at relatively high cutting speeds of 150 m/min, tool life was increased by over 40% compared with the tools originally used for this cutting process.

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This project was supported via EuroNorm Gesellschaft für Qualitätssicherung und Innovationsmanagement mbH by a grant from the German Federal Ministry for Economic Affairs and Energy (BMWi) pursuant to a resolution of the Bundestag within the framework of the INNO-KOM-Ost funding programme under Reg. No. MF100090.
Our thanks are due to Rolls-Royce Deutschland Ltd & Co KG and Walter AG for providing the tools and test materials and to PLATIT AG and OTEC Präzisionsfinish GmbH for technical assistance during the course of carrying out the tests.