ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 46 (2016) 294 – 298
www.elsevier.com/locate/procedia

7th HPC 2016 – CIRP Conference on High Performance Cutting

Hard coatings to improve the machining of nickel based materials

F. Barthelmä[a], H. Frank[a,*], M. Schiffler[a], A. Bartsch[a]

[a]*GFE Gesellschaft für Fertigungstechnik und Entwicklung Schmalkalden e.V. Näherstiller Straße 10, 98574 Schmalkalden, Germany*

* Corresponding author. Tel.: +49-3683-6900-772; fax: +49-3683-6900-16. *E-mail address:* h.frank@gfe-net.de

Abstract

Difficult-to-machine materials like nickel based alloys have become a key material in many branches of industry, above all in the aerospace industry. The reasons for this mainly lie in the combination of properties such as high strength at increased temperatures, a high degree of chemical resistance and high wear resistance. However, these advantages are offset by a major disadvantage: the machining, in particular milling, is very difficult. Only relatively low cutting speeds can be used and tool life is usually short. Developing tool and technology solutions aimed at obtaining an enhancement of the machining techniques used for milling of difficult-to-cut materials.

The results of research, in particular with regard to the development of hard coatings in conjunction with suitable substrate materials, cutting edge preparation and finishing systems show an improvement in the performance of cutting nickel based alloys. Best results were reached by stable oxynitridic and embedded nanoscale structures. Combinations of these coating structures with optimized coating composition and improved coating adhesion were used to develop coatings with higher strength and hardness as well as an improved stability at higher temperatures. Related to ultra-fine graded solid carbide materials, sharp cutting edges (4 µm) and polished tools, hard coated tools were used for HPC milling of nickel based materials at cutting speeds up to 150 m/min. Various cutting analyses show the applicability of the developed coatings and the corresponding process chain to improve the efficiency of cutting processes.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
Prof. Matthias Putz

Keywords: Nickel alloy; difficult-to-machine, wear, cutting edge, surface modification, PVD-coating

1. Introduction

Difficult-to-machine materials like nickel based 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 good combination of properties such as high strength at increased temperatures, low density, high degree of chemical resistance and high wear resistance. However, these advantages are offset by a major disadvantage: the machining, in particular milling is very difficult and therefore very expensive since only relatively low cutting speeds can be used and tool life is usually short [1].

The prime causes of problems when working with nickel based alloys are high thermal stresses at the cutting edges as a result of low thermal conductivity through the chips and the workpiece, 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 number of 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 of difficult-to-machine materials [2, 3]. Research activities for productivity improvement in machining these alloys based on the optimization of cutting tool material and geometry, cutting edge preparation and hard coating systems [4, 5]. These parameters in combination with optimized machining conditions allow a great potential for wear reduction and high performance cutting of difficult-to-machine materials.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
Prof. Matthias Putz
doi:10.1016/j.procir.2016.04.069

2. Investigation of machining nickel based materials

2.1. Objectives

The objective of extensive studies of machining of nickel based materials was to develop solutions along the process chain: cutting edge preparation - coating - finishing obtaining a significant improvement in the performance of milling difficult-to-machine materials. An optimized process chain in combination with suitable cutting tool material and geometry are crucial for economic and process-stable manufacturing.

A further objective of investigations was the development of cutting strategies for improved machining of nickel based alloys. Depending on process forces and temperatures as well as the tool wear, the cutting parameters can be adjusted to improve process efficiency, e.g. to increase the cutting speed.

2.2. Procedure

To achieve the objectives, PVD-hard coatings with specific requirements were developed. Relevant properties are the thermal and mechanical stability, the thermal protection of the substrate, the reduced friction and a very good coating adhesion. Process simulations were used to calculate process conditions like cutting temperatures and forces and to determine cutting strategies with reduced load.

Hard coating systems and process simulation were used to optimize the milling of the nickel based alloy Inconel 718 with carbide ball nose end mills. To achieve the objectives of an improved machining process, different boundary conditions and processes were taking into account regarding the following procedure of investigations (see Fig. 1.):

- Determination of process characteristic
- Influence of the substrate material
- Development of PVD hard coating systems
- Substrate-pre and coating post-treatment
- Application test

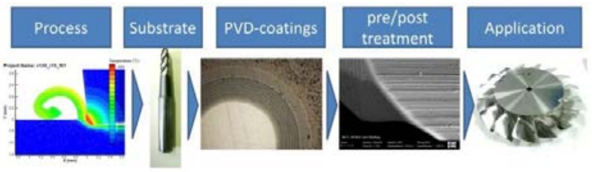
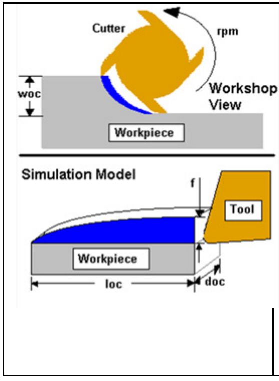


Fig. 1. Procedure of investigations.

2.3. Process simulation

Process characteristics were determined by simulation of the cutting process. For the simulations the software tool AdvantEdge by the company Third Wave Systems (TWS) was used. This software was developed especially for the simulation of cutting processes. The simulation model and the cutting conditions given in Fig. 2 were used to calculate cutting forces and temperatures.



<u>cutting tool:</u>
∅ 5.6-8.5 mm, 4 cutting edges
cutting angle: 8° - 12°
clearance angle: 12°- 15°
cutting edge radius: 4-8 µm
<u>Material</u>
cutting tool: carbide H10F
work piece : Inconel 718
<u>process parameters</u>
cutting speed: 100-200 m/min
tooth feed: f_z =0.04-0.08 mm
cutting width: a_e= 0.1-0.3 mm
cutting depth: a_p= 1-4 mm

Fig. 2. Model of simulation (left) and variation range of used cutting parameter (right).

During the process simulation, process and tool conditions were varied to determine their influence on the cutting process. Based on the calculated cutting forces and temperatures cutting tool geometry (macro and micro geometry) and cutting parameters for further investigations were defined according to a reduced thermal and mechanical load.

2.4. Substrate material

To determine the suitable substrate material, different carbide materials with different properties were used and tested. In cooperation with industrial partners tools with optimized geometry according to simulation results were produced. Main properties of the carbides are:

- Cobalt content : 10.0% to 12.0%
- Other carbides: 1.0% to 1.5%
- Average grain size: 0.5 µm to 1.2 µm
- Hardness: 1380 to 1780 HV 30
- Transverse rupture strength: >4000 N/mm²

2.5. Coating development and post treatment

An Arc-PVD-process was used to develop hard coatings with a high thermal and mechanical stability and with optimized coating adhesion. Coating deposition was done on commercial Arc PVD machines from the company PLATIT AG (Switzerland). To improve coating properties like coating adhesion, hardness and friction, coatings with different structures were used. Of special interest are coatings with:

- Oxynitridic structures (high thermal stability)
- Nanocomposites (high mechanical strength)
- Multilayer structure (high crack resistance)

Tool pre- and coating post-treatment processes were also used for cutting edge preparation and to reduce coating roughness (droplet minimization) and to minimize friction effects during the process. Pre-treatment (cutting edge grading and cutting edge rounding) and post-treatment (film polishing) were both done by stream finishing with the OTEC DF-3 tool.

To improve coating adhesion, a special coating pre-treatment process before deposition was developed. This treatment combines the advantages of mechanical and chemical activation with an intensive ion beam treatment, coating deposition was done after the pre-treatment. Important deposition parameters are given in table 1.

Table 1. Important deposition parameters

Oxygen gas flow	0 – 35 sccm
Nitrogen gas flow	20 – 500 sccm
BIAS voltage	20 – 200 V
BIAS- frequency	0 – 350 kHz
Arc current	80 – 200 A
Process pressure	0.01 – 0.04 mbar
Process temperature	390 – 550 °C

2.6. Application tests

The applicability of the developed coating systems were demonstrated in milling the material Inconel 718. Cutting this material leads to a rapid tool wear due to high cutting temperatures, tool vibration and high abrasive wear. The produced tools were used in cutting tests of the nickel based alloy, the used machine was a DMC 64V. Cooling of the tools was done with external cooling supply of 5% emulsion. Process conditions and tools furthermore were optimized according to the simulation results (see also Fig. 2.).

3. Results

3.1. Process simulation

According to the used process and simulation parameters (see Fig. 2.), process forces and temperatures were calculated during milling Inconel 718. Fig. 3 shows a typical temperature field within the tool, the workpiece and the formed chip. Depending on the used process parameters, the maximum temperature, the cutting forces and the shape of the chip varies in a wide range.

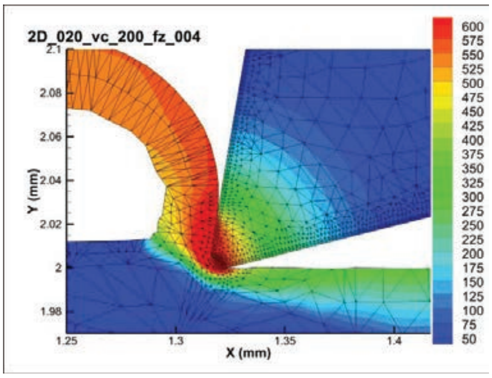


Fig. 3. Typical temperature field, used parameters: f_z=0,04 mm, v_c=200 m/min, a_e=0,3 mm, a_p=2 mm, cutting angle=10°, clearance angle 14°

Calculation results for different micro geometries (cutting edge radius) are given in Fig. 4. Increasing the cutting edge radius leads to higher process forces (Fig. 4). A variation of cutting angles and clearance angles in a range between 8° and 15 ° has only a small influence on process temperature and forces.

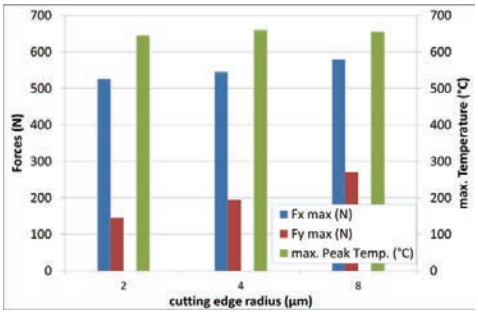


Fig. 4. Cutting forces and cutting temperatures as a function of the cutting edge radius of the milling tools

The calculated cutting forces and temperatures were used to define cutting tool geometry for the following investigations. According to reduced temperatures and forces as well as a stable cutting edge, the cutting edge radius was set to 4 µm. Furthermore the influence of process conditions was calculated. The following parameters were determined (table 2) depending on process parameters and according to a reduced thermal and mechanical load.

Table 2. optimized cutting parameters

Tool diameter	Ø8.54	Ø5.64
Cutting speed [m/min]	100	100-200
f_z [mm]	0.08-0.10	0.06
a_e [mm]	0.3	0.3
a_p [mm]	3	2
Cutting edge radius [µm]	4	4

3.2. Influence of substrate material

Milling tools made of the different carbide materials were produced and optimized according to the simulation results. The produced PVD coated tools were used in cutting tests of the nickel based alloy. Results of the cutting tests are shown in Fig. 5. Two nACRo³ coated carbide materials HM1 and HM3 (new carbides with a lower grain size) show the best results with only a low wear at a tool life of 30 m.

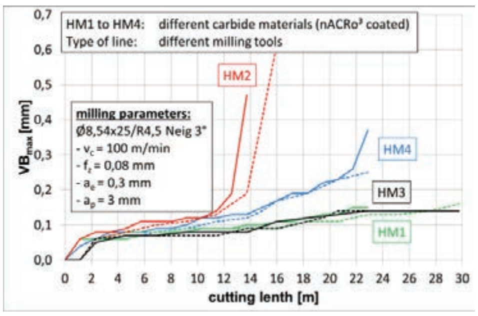


Fig. 5. Milling of Inconel 718 with different carbide materials

3.3. Coating deposition and post treatment

The thermal and mechanical stability of the substrates and of the coating systems is very important for the improvement of the machining of nickel based alloys. According to former investigations [6] nanostructured and oxygen based coatings can be used to improve the cutting of difficult-to-machine materials like titanium based alloys. For the coating development for the milling of nickel based alloys these different coating concepts were modified.

Table 3 summarizes the tested coating systems with relevant composition, structure and coating thickness. For reduction of residual stresses, coating thicknesses were set to 1,5-2,0 µm. Grinded caps of the deposited coatings on polished carbide samples with the corresponding film structures are shown in Fig. 6.

Table 3. Coating systems

Coating	Coating structure base- / top-layer	Thickness
AlCrN-OXI-2A	AlCrN / AlCrON (10% O_2)	1.7 µm
AlCrN-OXI-5A	AlCrN / AlCrON (20% O_2)	1.6 µm
nACRo^3	AlTiCrN-Multilayer/AlCrN/SiN-Nanocomp.	1.6 µm
nACRo^4	AlCrN-Nanolayer/AlCrN/SiN-Nanocomposite	1.7 µm
AlTiN-ML	AlTiN-Multilayer (Ti/Al ⩾ 40/60%)	1.4 µm
AlTiCrN^3	Al/CrN Multi/Nanolayer / AlTiCrN	1.7 µm
AlCrTiN^4	AlTiCrN-Grad./Al/CrN-Multilayer/AlTiCrN	1.7 µm
TiXCo^4	AlTiCrN-Gradient/AlTiCrN-Multilayer / TiSiN	1.6 µm
Reference	AlTiN-based	2,0 µm

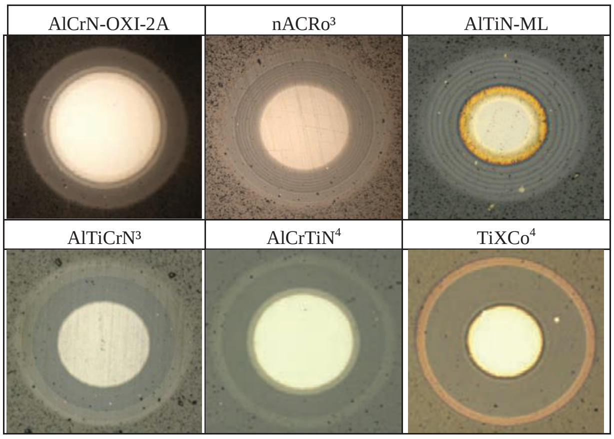


Fig. 6. Film structures of selected coating systems

All these coatings were deposited with a high coating adhesion on the substrates with Lc2 values (first coating delamination) of typically more than 100 N. As Fig. 7 shows all the used coating systems have a high hardness.

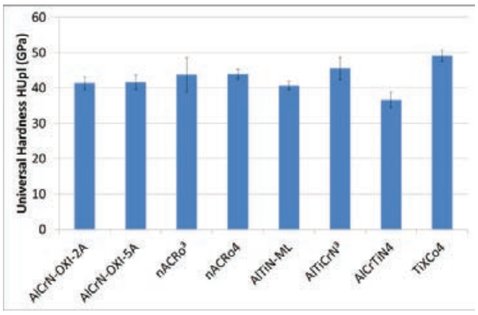


Fig. 7. Coating hardness of the deposited coating systems

After coating of the milling tools with the different coating systems the roughness was distinctively increased by depositing of droplets. To stabilize the cutting process and to reduce friction effects during the process the films were polished after deposition by combined stream finishing. With polishing time of about 8 min and using a fine sized medium (0.4-0.8 mm) the roughness in chip spaces as well as on cutting edges can be reduced. Fig. 8 illustrates that the roughness R_{pk}, which characterizes mainly the droplets, on the cutting edges of the milling tools is reduced by film polishing for most of the used coating systems.

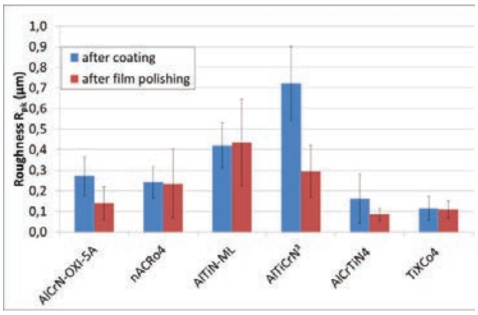


Fig. 8. Roughness R_{pk} on cutting edges pre and after film polishing for different coating systems

3.4. Application tests

Application tests of milling Inconel 718 with the parameters given in Table 2 were used to determine the tool life of the coated and polished end mills. Fig. 9. shows the mean cutting length of different coated tools for a cutting speed of 125 m/min. In comparison with uncoated tools and reference coatings, AlTiCrN-based coatings show a reduced tool wear. A significantly increase in the mean cutting length can be reached for the coating system TiXCo^4, which is a combination of gradient and multilayer structures with a TiSiN top layer (see table 3.).

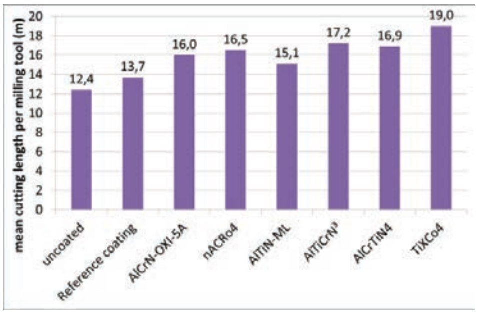


Fig. 9. Mean cutting length per tool for a wear VB_{max} of 0.2 mm

To improve efficiency of the machining process, cutting speed was varied between 100 and 200 m/min (Fig. 10.). It can be seen, that wear increases with increasing cutting speed. This higher wear (wear mark width VB_{max}) leads to a lower cutting length; tool breakout becomes the mean failure mechanism.

Furthermore coating adhesion and coating stability decreases with higher cutting speed. For 150 m/min and 200 m/min all of the tested coatings were delaminated after a cutting length of less than 1.0 m. For a further increasing of the performance of machining nickel based alloys better coating adhesion and higher coating strength is necessary.

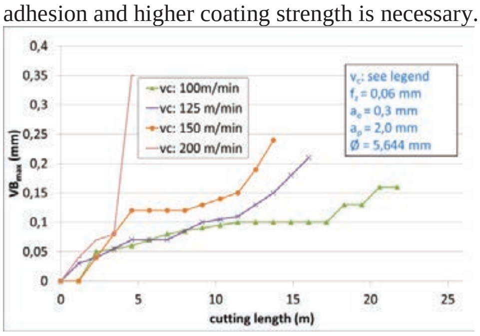


Fig. 10. Wear as a function of cutting length at milling of Inconel 718 with different cutting speeds v_c

5. Conclusion

The presented results show, that process simulation in combination with optimizing the tools (substrate, macro- and micro geometry, hard coating, finishing) can be used to increase the performance of milling nickel based alloys.

To optimize process conditions such as cutting forces and temperatures simulations of process characteristic were done with different variations in cutting conditions and tool geometries. Furthermore specific carbide materials and new hard coatings were verified to reduce wear of the used milling tools and to improve the tool life.

Multilayered structures based on Al-Ti-Cr-N coating systems with a nanocomposite top layer prove to be very resistant to mechanical and thermal load during milling of Inconel 718. Especially at relatively high cutting speeds of 125 m/min, tool life was increased by over 40% compared with the tools originally used for this cutting process.

For a further increasing the performance of machining nickel based alloys better coating adhesion and higher coating strength is necessary.

Acknowledgements

The development of coating systems for machining nickel based alloys was done by the support of German Federal Ministry for Economic Affairs and Energy (research project “Improving the efficiency of milling of nickel-based alloys by new PVD hard coatings”, project number: MF130083).

References

[1] Klocke, F., Lung, D., Binder, M., Seimann, M.: High speed machining of nickel-based alloys; International Journal of Mechatronics and Manufacturing Systems, Vol. 8, No. 1/2, 2015, pp 3-18
[2] Gerschwiler, K., Schiffler, M. (2012). Gewinde in Titan.FKM-Vorhaben No. 265, Issue 316/2012, final report
[3] Abele, E., & Fröhlich, B. (2008). High Speed Milling of Titanium Alloys. Advances in Production Engineering & Management, Vol. 3 (2008) 3, pp. 131-140.
[4] Barthelmä, F.; Frank, H.: Cutting Lightweight Materials with Surface Modified Tools; in B. Denkena (ed.) New Production Technologies in Aerospace Industry; Lecture Notes in Production Engineering 2014, pp. 83-89
[5] Pervaiza, S., Rashid, A., Deiab, I., Nicolescu, M.: Influence of Tool Materials on Machinability of Titanium- and Nickel-Based Alloys: A Review; Materials and Manufacturing Processes, Volume 29, Issue 3, 2014, pp.219-252
[6] Barthelmä F, Frank H, Schiffler M. Oxinitridische und nanoskalige PVD-Hartstoffschichten erhöhen Leistung beim Titanfräsen. VDI-Z 156 2014; Nr. 1/2; 54-57