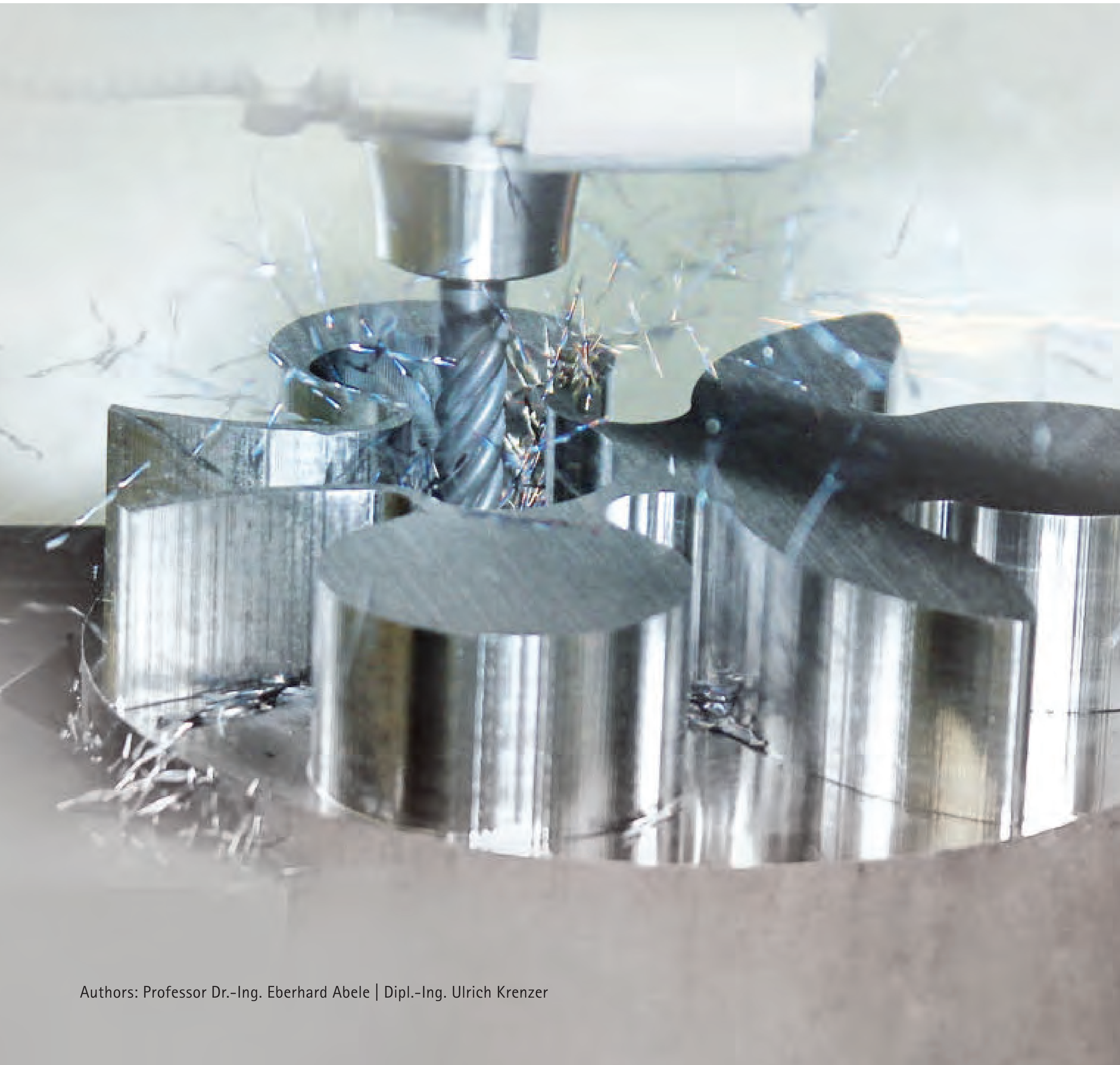
TECHNOLOGY REPORT

04 | Trochoidal milling | With high feed rates to deep cuts



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Trochoidal milling

Abstract

Trochoidal milling enables the machining industry to achieve marked rationalised potential with regard to tool costs and processing times and to reduce machine tool stress in many areas of application. What must be emphasised here on the one hand is the manufacture of engine components for the aviation and astronautic industry and exhaust turbines for the motor vehicle industry. On the other hand, this milling technology is implemented for the manufacture of structural and other small-scale production components in the tool and mould construction industry (hard machining) along with general engineering. The machining of high-alloyed and hardened materials such as case-hardening steels or heat-resistant nickel base alloys can be made significantly more productive, cost-effective and resource-efficient by the use of trochoidal milling.

Viewed in general, the use of trochoidal milling technology makes sense in the manufacture of slots with a high aspect ratio and different slot widths. Very different slot widths or pocket sizes can thus be produced with a single tool. The available cutting length of the milling cutter is also better utilised due to increased cutting depths. Furthermore, due to the considerably optimised contact ratios in full cut compared to conventional milling (tool wrap angle 180°) the resulting machining forces are reduced. Especially due to the reduction of the acting radial force, thin-walled components can be manufactured with process reliability with the greatest precision whilst simultaneously preserving the machine tool. With regard to the material to be machined, trochoidal milling offers considerable advantages due to a reduction of chip length (regardless of the radial feed), an increased chip removal area and reduced machining stress (slot width small tool diameter, no chip congestion and multiple cutting of the chips) and resulting reduced thermomechanical tool stress. Higher cutting data with simultaneously increased tool lives compared to the conventional full cut are thus achievable. For effective use of the trochoidal milling technology however, it is necessary to agree on the programming cycles of CNC controls in addition to using appropriate tool concepts.

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Motivation

The drive for increased mobility with increasing performance and comfort requirements continues and is now stronger than ever. At the same time, mobility is a motor for employment and growth in Germany. Contradictory requirements such as tightened emission regulations and increasing quality requirements with simultaneous cost reduction are thus the primary drivers for ever more efficient drive solutions and their production strategies, both in aviation and the motor vehicle industry. The aviation branch in particular has seen constant growth in previous years. According to the German Aerospace Industries Association the growth in turnover for the entire branch was 7.8 % in 2013. The number of employees also increased by 4.8 % to 105,500 employees directly in aviation and astronautics. At the same time, the requirements increased with regard to engine technology, fuel consumption, pollutant and noise emissions. The higher combustion pressures and temperatures necessary to increase efficiency for example cause increasing material stresses. The manufacturers are thus compelled to substitute the most commonly used classic TiAl6V4 titanium alloy by materials with increased heat resistance, such as Ti6242, titanium aluminides (TiAl) or nickel base alloys. However, in addition to outstanding material qualities, these material alloys are characterised by their impeded machinability compared to TiAl6V4. A considerable increase in productivity and cost-effectiveness in machining of these high-performance materials for future turbine components is therefore a basic pre-requisite for the assurance of competitivity of manufacturing companies.

Titanium or nickel base alloys are characterised by high heat resistance with simultaneously low heat conductivity and hereby open up new design options for the design of aircraft engines. However, the outstanding temperature qualities from the construction perspective pose ever new challenges for machining [1, 2]. In particular, the low heat conductivity causes high temperatures on the cutting edges (T > 1000 °C). In the case of aluminium machining, approximately 75 % of the process heat arising is discharged by the chips, while the majority is absorbed by the tool in the processing of titanium alloys. The high temperatures on the blade force diffusion and adhesion processes. In addition, the great temperature gradient generates thermally induced tensions within the tool which also contribute to failure of the tool. The low elasticity module of the material increases the chance of vibrations during processing which has a negative impact on tool life and process stability [3]. In the case of machining of nickel base alloys, the high strain hardening increases material hardness during processing. This leads to increased tool wear in the region of the transition of the slot to the workpiece surface [4]. Based on EZUGWU, the following seven characteristics are defined in the processing of difficultly machinable materials such as titanium and nickel base alloys, for example:

- High thermal stability combined with great material hardness causes deformation of the tool during processing.
- High dynamic shearing resistance leads to great shearing stresses on the blade which promotes the notch effect on the edge of the blade.
- Low heat conductivity of the material leads to machining temperatures in excess of 1000 °C in the cutting contact area and great temperature gradients within the cutting material.
- Material welding on the cutting edge leads to the formation of edge build-up and an associated deterioration of the surface quality.
- The austenitic matrix of nickel base alloys causes great strain hardening.
- Carbides in the microstructure of nickel base alloys cause strong abrasive tool wear.
- Titanium alloys have high chemical reactivity, whereby tribo-chemical reactions such as the formation of notch resistance, for example, are accelerated.

Motivation

In addition to selection of the correct tool concept, the machine structure has an impact on the processing result. The high process forces arising during processing of materials which are difficult to machine lead to static deflection between tool and workpiece. In order to counteract this problem, it is necessary to adapt the machine structures to the processing tasks. Frequently, highly rigid, play-free guide systems are used for this purpose which can also be clamped. In addition to the rigidity of the machine tool, the qualities of the tool holder continue to be of great importance (see Figure 1). If the overall system has too low rigidity and absorption qualities, self-induced vibration can occur, one of the impacts of which is a negative effect on tool wear.

The cited boundary conditions cause greatly increasing tool wear and thus lead to high tool costs. In addition, machining in this segment competes with other processes such as electrical discharge machining (EDM) or in the recent past with selective laser melting [4, 5, 6]. Different simple geometries and cavities are already manufactured with the aid of the EDM procedure. The particularity of the process is due to the contactless material removal due to the application of electrical voltage which leads to the formation of a high-energy plasma channel when the dielectric strength is exceeded. The use of selective laser melting which facilitates the manufacture of near net shape components by the layer-based construction from powder material is also increasingly widespread. Investigations into the manufacture of engine components from titanium and nickel base alloys have already been conducted [7]. A further increase in the application spectrum of this procedure must be anticipated. The reasons outlined make it vital to continually increase productivity in machining in order to be able to produce high-quality products at competitive prices. An increase in cutting values is often limited by the processing machinery used in practice and their performance features which impedes implementation of the required productivity increase in series. On the contrary, trochoidal milling has the potential to increase material removal rate without a considerable increase in the power requirements of the machine.

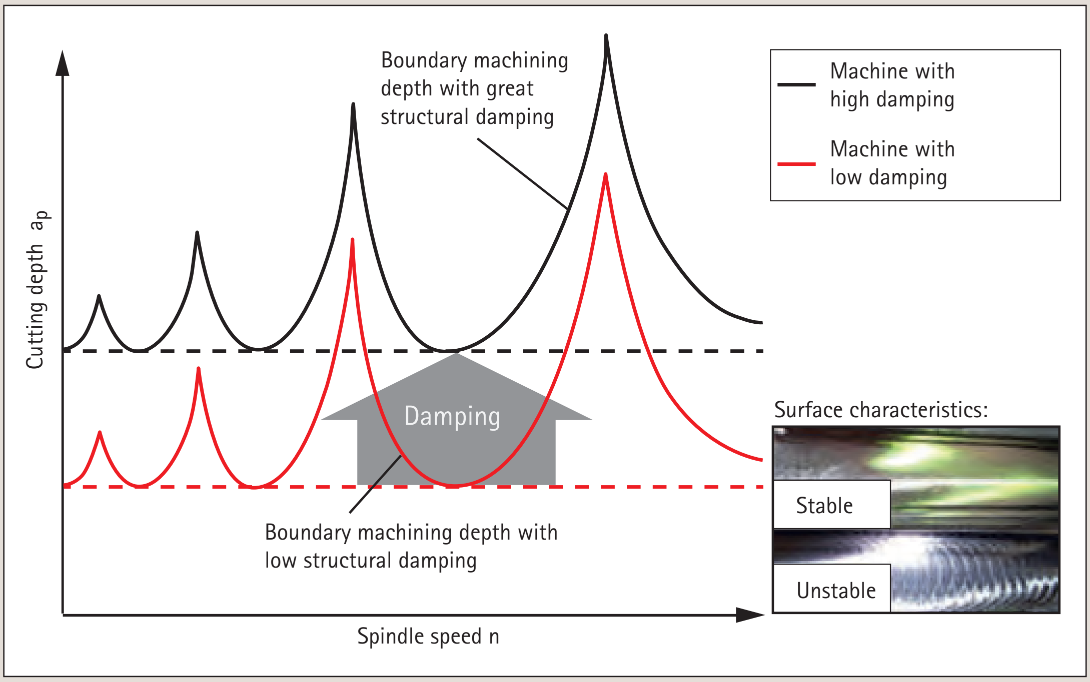


Figure 1: Effect of the machine structure on process stability during milling; based on [3]

Bases of trochoidal milling

Bases of
trochoidal milling

In the past, roughing processes were usually conventionally performed as a full cut. The contact conditions of the milling cutter are determined at a wrap angle of 180°. In addition to the production of long chippings due to the long tooth engagement this causes the tool comparatively high thermal stress. In turn, the consequence of the resulting large chip thickness is high machining forces, whereby process-stabilised peck depths, feeds and cutting speeds are limited.

The specific kinematics of trochoidal milling enable a positive impact on the stated contact conditions, see Figure 2, due to an overlap of the feed movement with a circular movement of the tool. Cyclical material removal with changing contact conditions and variable machining widths along the circuit of the tool occurs. The consequence of this technological approach is reduced machining width and cut length to considerably reduced process forces. Hereby, it is possible in turn to achieve greater cutting depths. While cutting depths of up to 1 x D are possible with conventional milling, cutting depths in excess of 2.5 x D are possible with trochoidal milling [8]. Improved utilisation of the available cutting length can thus be implemented. The reduction of the acting radial force continues to be essential for the process-reliable manufacture of thin-walled components with the greatest precision requirements and simultaneous minimisation of machine tool stress. In contrast to the full cut, neither is the slot width limited by the tool diameter (D). Different slot widths can be produced accordingly with a single tool, whereby the number of tools required can be significantly reduced.

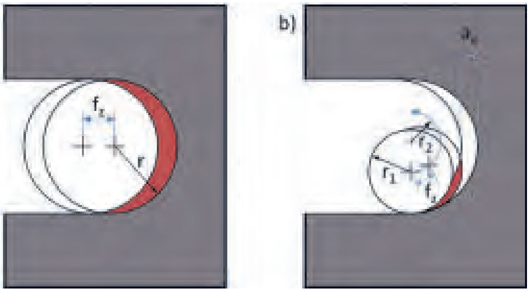


Figure 2: Diagrammatic orbital motion a) full cut, b) trochoidal milling; based on [9]

Considerable increases in productivity in the form of increased metal removal rates are the consequence. There is further optimisation potential in specific adaptation of the programmed movement of the tool to the respective processing task. In the case of a circuit with a constant radius, the wrap angles on the contact tool blade vary dependent on absolute radial infeed within a revolution. Due to an adapted orbital motion of the tool which deviates from the idealised circuit, it is possible to influence the resulting wrap angle. Due to this change in feed motion, the contact angle of the milling cutter can be kept virtually constant over the entire operation. Use of the tool in the region of the specific optimum is thus facilitated.

For holistic process optimization, in addition to the tool path during the intervention, the programmed movements in the air cut need to be viewed. The objective must be to achieve as rapid as possible a movement to the next entry point following exiting of the milling cutter from the material. As the execution of a circuit is not advantageous at this point, a positioning path which is as direct as possible is selected dependent on the machine dynamics.

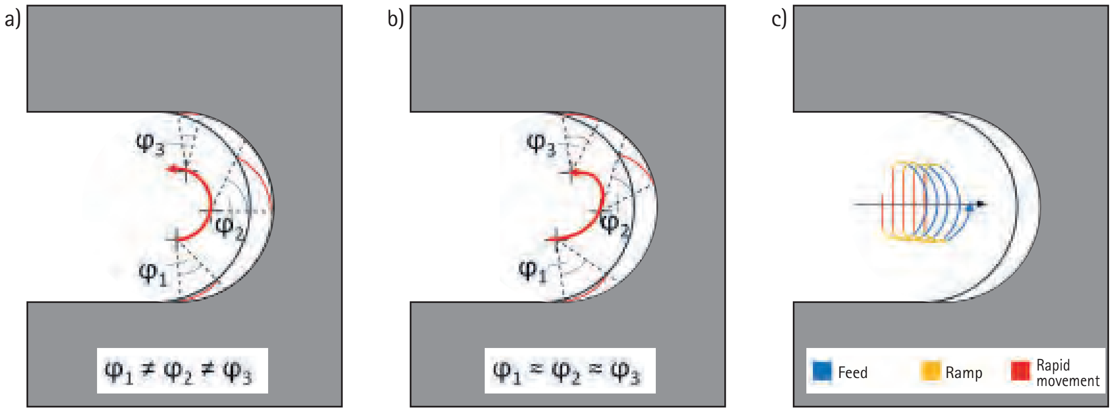


Figure 3: Feed movement a) circuit, b) optimized trajectory, c) optimized air cut; based on [9]

Tools and coatings

In addition, the positioning path is executed in rapid movement. Figure 3 shows the resulting programmed movements. Initial machine controls are already adapted to these new requirements. Programming cycles independently generate the whirling movement of the tool for a given slot. In combination with dynamic speed regulation adapted to the processing point, considerable increases in productivity are thus possible, see Figure 4. Hereby the spindle output can be determined by the operator in a learning step. In addition to safe tool breakage recognition, it continues to be possible to adapt the programmed target value in the event of excessive tool wear.

Tools and coatings

In order to put the potential of trochoidal milling to its best possible use, the tool concept needs to be adapted to its specificities. In addition to the selection of the correct cutting material, a high-performance coating and adapted geometry are also important in this regard. In relation to the cutting material, breaking strength and edge strength in particular are also of vital importance, while impact strength and thermal shock resistance play a subordinate role. In order to fulfil these special requirements, MAPAL uses fine- and ultra-fine grained carbides.

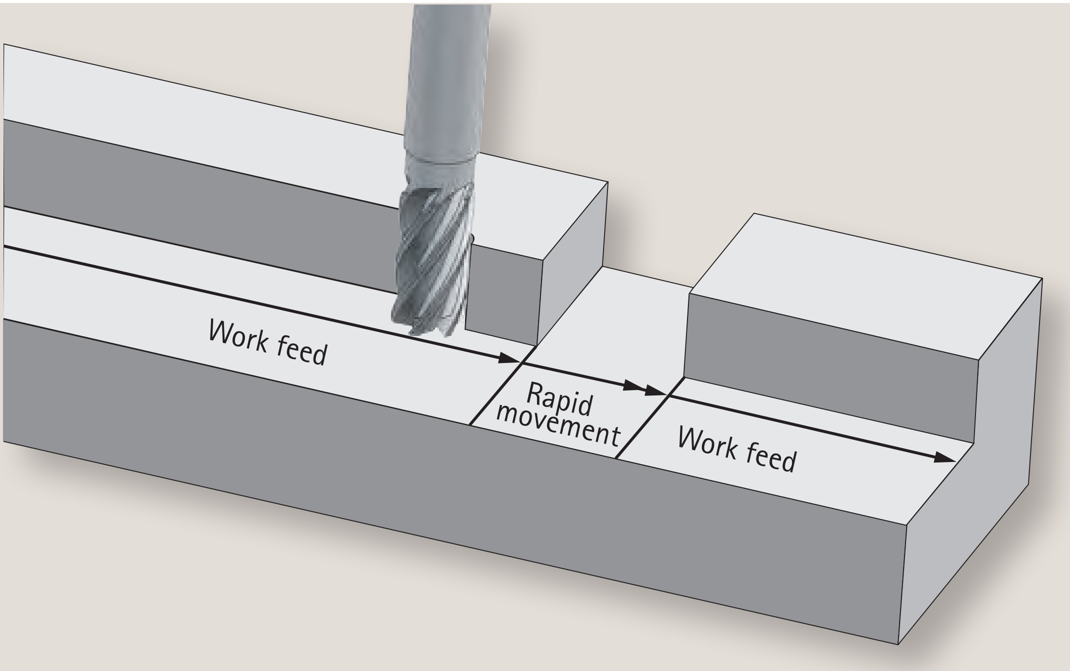
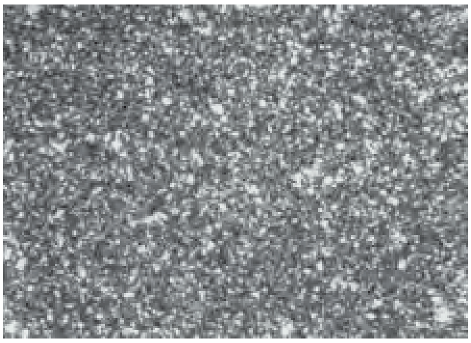


Figure 4: Feed adaptation with adapted programme cycle



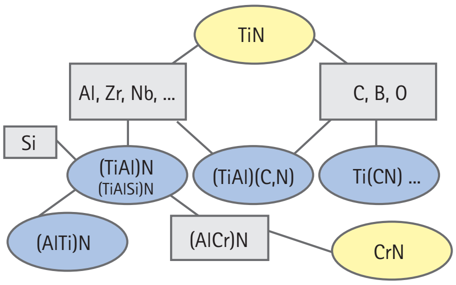
Cutting material requirements:

- Very high edge strength
- High breaking strength
- Great hardness
- Good hot hardness
- Sufficient toughness

Coatings:

- Finest grain carbide
- PVD coating with complex layer structure

Further developments of TiN:



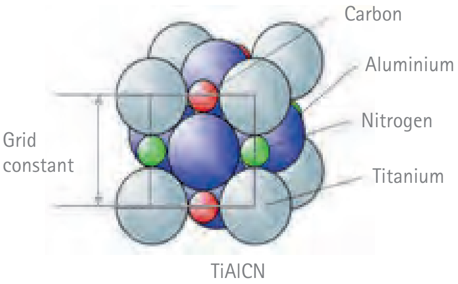


Figure 5: Tool system requirements with regard to trochoidal milling; source: MAPAL

Tools and coatings

Dependent on the component material, varieties with 8-10 % cobalt are used. These are used in conjunction with complex extremely hard layers, which are optimized dependent on the material to be processed with regard to the greatest hardness or the direction of minimized friction. Figure 5 once again summarises the requirements for the tool system. In addition, unequally divided tools have proven advantageous due to their lesser tendency to vibrate. In conjunction to the high speeds used in the process however, the imbalance of an unequally divided tool has a negative impact. In initial approaches, this problem was resolved by using balanced chucks. Thus, in addition to improving surface quality and component quality despite increased cutting speed, a reduction in wear can be achieved. Advanced approaches already include prevention of imbalance in tool development. With the help of a simulation-based approach the tool cross section is adapted over the tool length in such a way that the imbalance is minimised. This is achieved using an algorithm which optimizes the geometry over several iteration loops.

Tools and coatings

Unequally divided tools with minimized imbalance are frequently used in the manufacture of special turbine blades, so-called BLISKS. This involves constructions which combine blade and disc in a single component. The requirement for BLISKS is estimated to at least double by 2020 according to a survey of expert opinion. In contrast to classically used mounted connections of blade and rotor a considerably higher compaction performance can be achieved with decreased component weight. However, the very complex and cost-intensive manufacture with a high risk of faulty products has a negative impact. The process needs to be executed in as low vibration a manner as possible for efficient and successful processing of these thin-walled structures. The HighTorque Chuck (HTC) concept takes into account this requirement and combines mounting of the tool with vibration damping. The operational behaviour of the chuck concept is apparent for example in slot milling. Compared to other chuck concepts, the process remains stable to a considerably increased slot depth, see Figure 6. The resulting advantages are increased cutting values, shorter processing times and a lesser tendency to edge chipping.

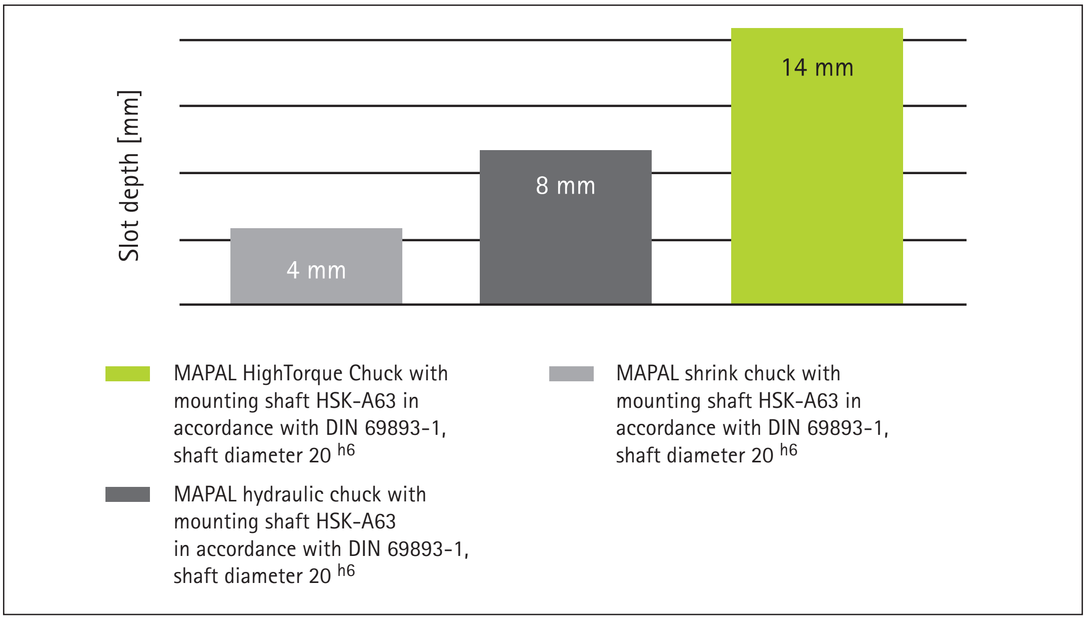


Figure 6: Attainable process-stabilised slot depth dependent on tool chuck concept; source: MAPAL

Savings potential and applications

Savings potential and applications

Investigations by MAPAL [8] give an impression of the rationalization potential of trochoidal milling. A thin-walled structure component made of case hardening steel 16MnCr5 and stainless steel (1.4301), see Appendix 7, was used as a comparative application.

Compared to conventional dry milling, in the processing of case hardening steel the cutting speed of v_c = 140-240 m/min can be almost tripled by the use of trochoidal milling. At the same time, doubling of the tooth feed to f_z = 0.1 mm is achievable. In view of the technological parameters, the particularity must continue to be emphasized that cutting depths of 3 x D can be achieved when Mapal tools are used. Overall, this leads to reduced processing times with simultaneous reduction of tool stress and thus decreased tool wear. The impacts of the procedure are reflected accordingly in three positive ways. In addition to shortened processing times and an improved tool life, smaller and thus more cost-effective tools can be used.

Savings potential and applications

A pre-requisite for this is the optimized generation of the tool path. The 'iMachining' manufacturing solution integrated into SolidCam calculates the optimum technological parameters from the material to be machined, workpiece and tool geometry and the available processing machine. Thus, existing facilities can also be used more efficiently. Other model applications demonstrate an increase in metal removal of 65 % [10] when a slot with a breadth of 32 mm and a depth of 8 mm is applied with the aid of a 16 mm solid carbide shaft milling cutter.

The considerable increases in productivity can not only be achieved in the outlined model applications, but also in serial production. With an application in the area of engine manufacture for example, the tool costs per volume can be reduced by approximately 50 % [9] with processing of the titanium alloy Ti6242 [9]. There is even greater potential in machining of the nickel base alloy Inconel 718. In the case of processing by slot milling the processing time was decreased by 63 %, while the number of tools required was reduced by 72 % and the tool costs by 61 %. Other applications exist in the manufacture of structure components in the field of measurement technology. Processing is characterized by great metal removal, a fixed clamping situation and a solid component from the material X17CrNi16-2. In this case, the processing time was reduced by roughly 70 % during pre-processing by the use of trochoidal milling. Due to the positive experiences, the processing strategy in this company will in future also be used in other areas, for example microprocessing.

Tool:
- 5-cutter
- Cutting length 3 x D with chip breaker geometry.
- Tensed in High Torque Chuck

Material	Cutting values	Conventional milling	Trochoidal milling
16MnCr5	v_c [m/min]	140 – 240	465
	f_z [mm]	0.05	0.10
1.4301 (V2A)	v_c [m/min]	60 – 100	250
	f_z [mm]	0.05	0.05

ADVANTAGES

- Lesser processing forces
- Higher cutting speed
- Higher feed depths
- Wrap of milling cutter variable
- Reduced thermal stress

Figure 7: MAPAL comparative components

Summary

Summary

Against the background of increasing requirements of technical components in numerous branches such as aviation and astronautics or the motor vehicle industry, highly heat-resistant materials such as titanium or nickel base alloys are increasingly used. These pose ever new challenges for tool and machine concepts. In order to attain the required productivity, the tool, machine and processing strategy must be optimally adapted to the machining task. However, full cut processing previously frequently led to great process forces and severe tool wear. Trochoidal milling is a strategy to decrease process forces whilst increasing metal removal rates.

The overlap of the feed movement with a circular movement of the tool can have a positive effect on contact conditions. Cyclical material removal occurs with contact conditions which are changing and can be tailored to tool use and variable machining breadths along the circuit of the tool. The consequence of this approach is a reduced machining breadth and cutting length which leads to considerably reduced process forces and reduced tool wear. Thus, in turn greater cutting depths of over 2.5 x D are possible while the cutting depth is limited to roughly 1 X D in the full cut. Other advantages are that on the one hand considerably higher cutting speeds can be used. On the other hand, there is better utilization of the tool cutting length and the slot breadths are not limited by the tool diameter. Also, as a result, a large spectrum of different slot breadths can be produced with a single tool, whereby resource efficiency in production can be increased. This optimization potential can be further increased by using tool, chuck and path generation concepts which are specially designed for the processing strategy. Due to the previously stated characteristics of trochoidal milling, the rationalization potential for deep slots and components with high material removal is especially high. The procedure is convincing both in model trials and also in industrial practice. In numerous cases of application processing times, tool costs and the number of tools required could be considerably reduced, from which the ambition is derived to extend trochoidal milling to other branches and processing tasks.

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Imprint

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Publisher:
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