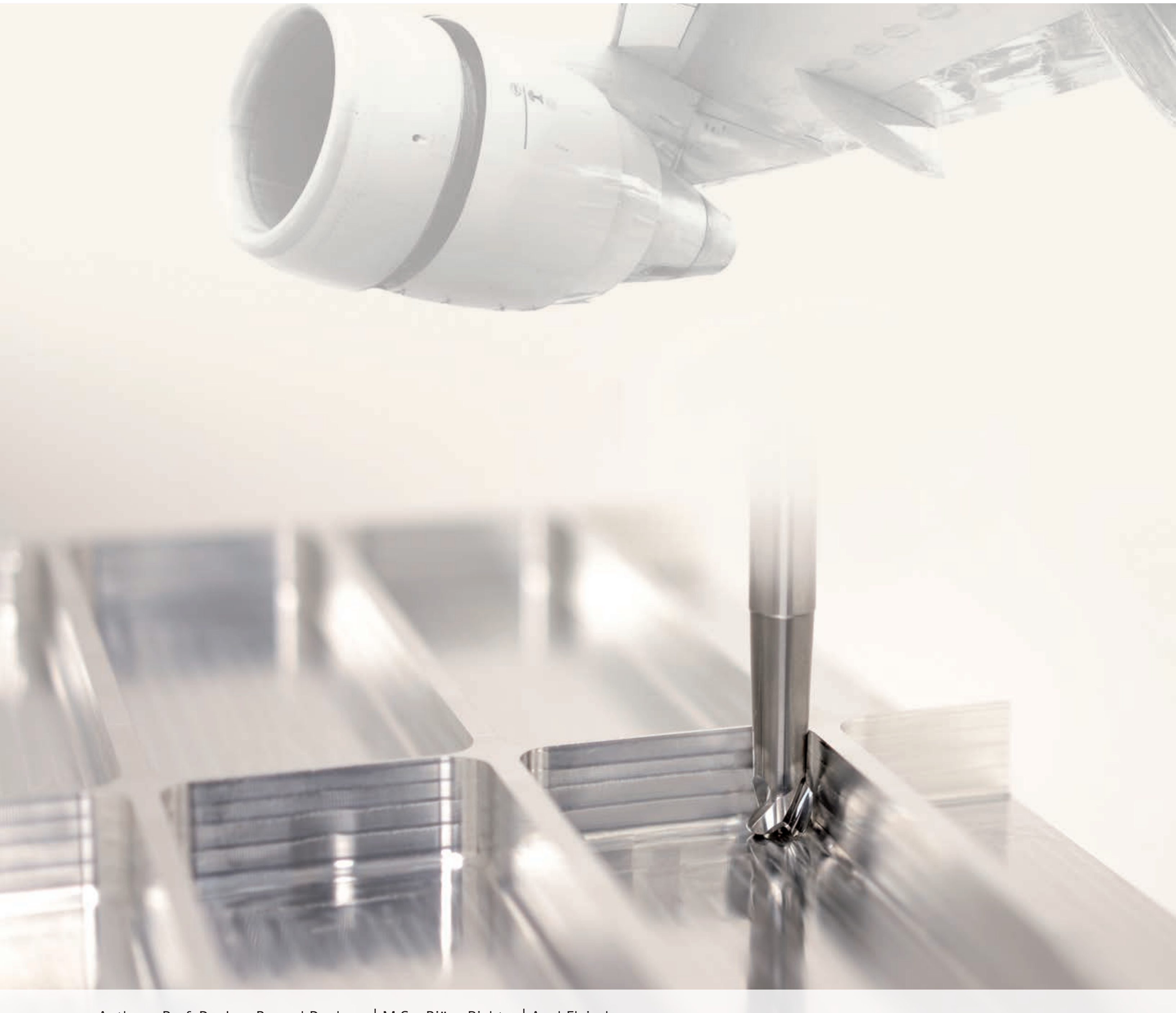
TECHNOLOGY REPORT

06 | High-volume machining - Maximum efficiency in aluminium machining



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Introduction

Introduction

In the aerospace industry, due to the costs and weight savings, structural parts that are milled from a solid material are primarily used in an integral design. During this kind of high-volume machining, high demands are placed on component quality and productivity in particular. The proportion of structural parts made of aluminium alloys, along with composites and titanium, makes up the majority of materials used in modern aircraft.

The challenges concerning the high-volume machining of aluminium include high material removal rates and the resulting chip clearance and an optimum utilisation of the machine tool efficiency. The increase of component- and material-specific process settings and tools in high-volume machining provides great potential for productive and economic aluminium machining.

Motivation

Motivation

The increasing level of air traffic, both in the passenger sector as well as in air freight, requires an estimated increase in transport capacity of up to 5% per year in the coming years (see Figure 1). Tightening of emissions regulations, rising quality standards, and economically and ecologically related resource savings place demands on finding efficient drive solutions, improved aerodynamics and constant weight savings in aircraft.

The increasing proportion of structural parts and increasing cost pressure caused by this lead to increased demands for efficient and highly productive manufacturing. The technological developments of the past 40 years have resulted in a reduction in fuel consumption and CO_2 emissions by 70%,in the noise level by 75% and in unburned hydrocarbons by 90% [1] while simultaneously increasing the comfort for passengers.

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Motivation

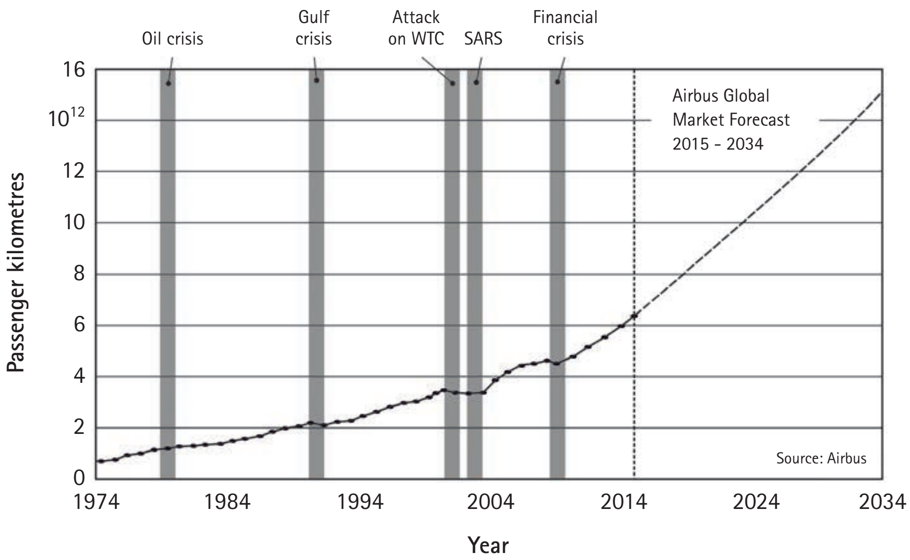


Figure 1: Estimated development in air transport [2]

In addition to materials such as carbon fibre reinforced plastic (CRP) and titanium in particular aluminium alloys for structural parts such as frames and wing parts are widely used in aviation (see Figure 2). The wrought aluminium alloys mainly used here (hardenable) are characterized by their high strength properties with a yield strength of above 500 N/mm² with a simultaneously low density of about 2.7 g/cm³. Aluminium structural parts are usually milled from solid at removal rates of up to 95% of the initial volume of the part and therefore require efficient tools and process strategies during machining.

Thanks to new generations of machine tools with spindle speeds of up to 30,000 rpm and simultaneously powerful drives, it has been possible in recent years to achieve greater productivity in the high-performance machining of aluminium, especially when rough machining. The subsequent optimisation of the tools used, however, means that once again the machines power limit in terms of the spindle power, the maximum speed and the dynamics of the feed axes is often the limiting factor of the process. Other process-specific improvements to the geometry and design of the tool cutting edges and the tool body, as well as the tool and workpiece clamping offer potential to further increase the utilisation of the available machine power and thus to achieve even greater efficiency for the high-volume machining of aluminium.

Figure 2: Aluminium structural parts from the aviation industry; source: MAPAL, iStock

HPC and HSC machining

HPC and HSC machining

A significant increase in the metal removal rate distinguishes HPC machining (High Performance Cutting) from HSC (High Speed Cutting) [3]. In comparison to HPC machining, the even higher speeds (up to n = 60,000 rpm) and cutting speeds (up to v_c = 7000 m/min) of HSC machining reduce the specific process forces occurring, but also cause spindle-side power losses resulting in a decreasing share of the effective power at high cutting speeds [3, 4, 5]. HSC machining differs from HPC machining due to significantly smaller feed rates and a resulting higher number of cuts. The distinction between HSC and HPC machining is summarized in Figure 3.

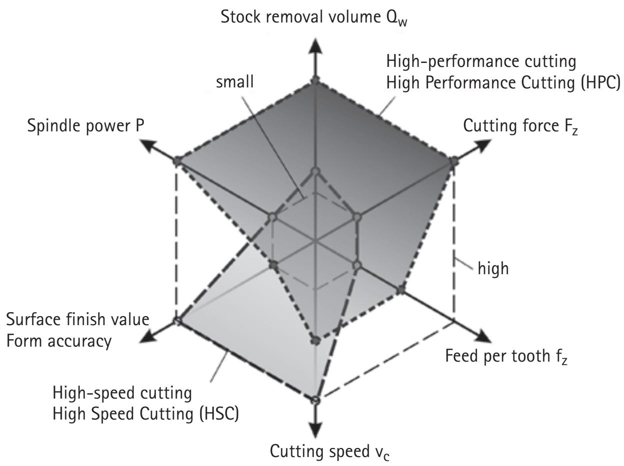


Figure 3: Distinction between HSC and HPC machining [3]

High performance cutting is characterized by a maximisation of the metal removal rate Q_w by a high radial and axial feed a_e and a_p during the milling process. The combination with high feed rates f_z resulting in large chip cross sections as well as increased cutting speeds v_c leads to maximum metal removal rates (see Eq. 1) whilst taking advantage of the available spindle power [3, 4].

Compared to conventional milling, the metal removal rate can be increased with HPC through optimised process settings by 200 to 500%. This increase in productivity caused by increased metal removal rates lowers production costs by 10 to 30% [6].

$$Q_w = a_p \cdot a_e \cdot v_f = a_p \cdot a_e \cdot f_z \cdot z \cdot n = \frac{a_p \cdot a_e \cdot f_z \cdot z \cdot v_c}{\pi \cdot d}$$

Eq. 1

Challenges in HPC machining

Challenges in HPC machining

The restricting factor in the high-volume machining of aluminium structural parts is in most cases not the dimensional and form accuracy or the surface quality, but rather the available driving power of the machine tools [4]. The high process settings that are characteristic of HPC machining result in heavy thermal and mechanical tool loading that require low-vibration tool adapters, optimised insert seats, stable cutting, and powerful stiff spindles. The high chip removal rates due to the large cutting depths and widths for high-volume machining require reliable chip removal to counteract tool breakage and ensure a sufficient coolant supply. The design and size of the chip flutes enables a significant improvement in performance of the tools in terms of process reliability and productivity.

In addition to the available driving power of the machine tool, HPC machining is limited by the dynamic stability of the process. Due to vibrations in the machine tool structure and the tool, a ripple is generated on the workpiece surface. This ripple causes other vibrations in the system during the subsequent cut made by the tool due to changes in the chip thickness. If the system is insufficiently dampened, these vibrations are amplified and can lead to so-called regenerative chatter. Stable regions can be determined by stability maps in which the stability limits are represented as a function of the cutting depth a_p and the spindle speed n (Figure 4). Chatter vibrations occur here only when a critical depth of cut $a_{p,krit}$ is exceeded, underneath this limit the process operates stably in all speed ranges. If the oscillating frequency between the tool and workpiece corresponds to an integer multiple of the tooth engagement frequency of the tool, then chipping thickness modulation does not occur and there are stable ranges above the critical depth of cut $a_{p,krit}$ [7].

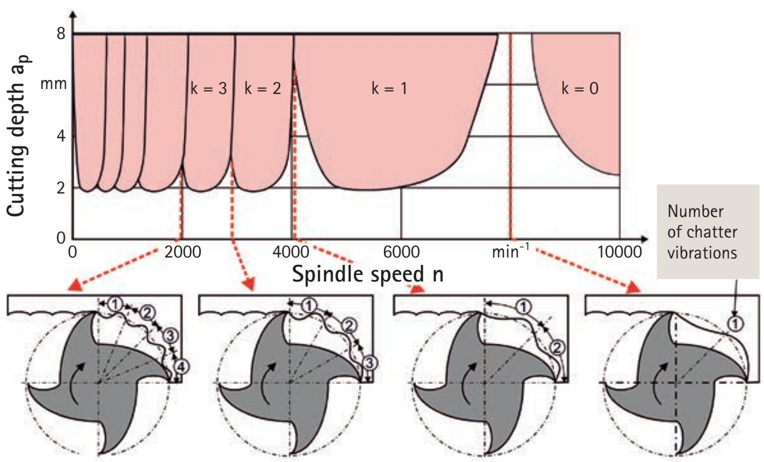


Figure 4: Stability map when end milling [7]

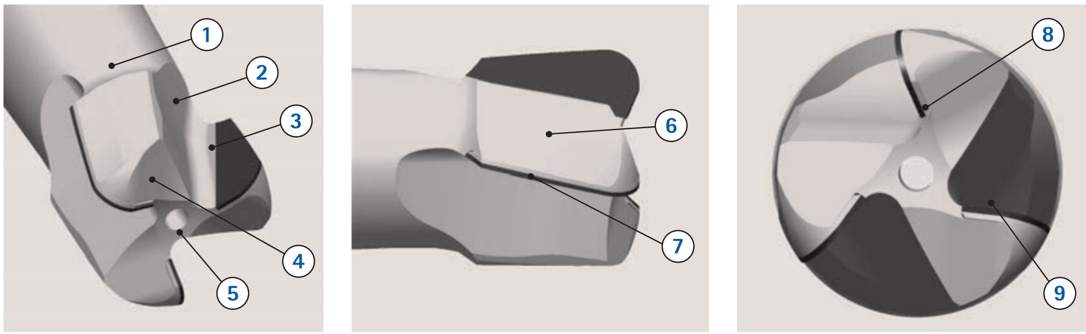
An unstable process leads to a decrease in the quality of the part, increased tool wear as well as stress on the spindle and the tool adapter [7]. Chamfered tools are a way of improving process damping and thereby avoiding chatter. A tool flank chamfer with suitable, process-dependent combinations of chamfer length and chamfer angle increases the contact area between the tool and workpiece, thereby dampening the process. [8] Moreover, process stability can be positively influenced by a division of the cutting cross section (chip breaker and special profile) and the unequal spacing of the end milling cutter. Compared to equally pitched tools, unequally pitched tools and rough serrated end mills in high speed ranges demonstrate a significantly higher process stability [9]. However, the rough serration also leads to a reduction in the cutting edge length during contact, so that locally increased chip thicknesses can lead to chipping of the cutting edge [10]. The tendency toward vibration of the tool can also be reduced by increasing the pitch f_z based on a resulting higher tension in the system [7]. High cutting speeds further reduce the formation of burrs when milling aluminium. This is mainly due to the changed shear angle and increased temperatures and expansion rates [11]. In addition, burr formation using end mills can be significantly reduced by selecting the correct process settings.

Solutions and optimisations during the HPC machining of aluminium

Solutions and optimisations during the HPC machining of aluminium

Tailored tools are required in order to exploit the full potential of the machine tools used for the high-volume machining of aluminium. In addition to the selection of the appropriate cutting material, optimisations to the tool macro- and microgeometry, the insert seat, the tool body, the chip spaces, the tool clamping and the coating are required. At a constant pitch, increasing the number of cutting edges increases the metal removal rate (see Eq. 1) however, due to the geometric limits of the tools, the available chip space per cutting edge is also reduced. If the chip spaces are too small due to larger numbers of teeth, this will lead to problematic chip removal. Furthermore, attention should be paid to designing the chip flutes with large open chambers and avoiding corners and edges that obstruct the chip flow. At speeds up to n = 30,000 rpm, 500 chips are produced per cutting edge in just one second, so that their removal is an important factor in terms of the process reliability of the tools used. Moreover, scratching the walls of the part is prevented by reliable chip removal. The number of teeth also influences the concentricity of the tools, because, due to the symmetry, three- and multi-flute tools have no moment of deviation and compared to two-flute tools usually have larger moments of area. Deformations always occur then in both spatial directions and turn out a magnitude lower than that of tools with two cutting edges [14]. This maximisation of the circle of inertia around the main axes of the tools can further increase the stability of the milling process [14].

Carbide and particularly polycrystalline diamond (PCD) are suitable as a cutting material for high-performance machining of aluminium. Here fine-grain grades with high edge stability are used as PCD cutting materials. PCD end mills with positive radial rake angles of 4° on the front face and maximum 20° on the circumference of the tools as well as the large axial angles (also called flute angle or side-rake angle) demonstrate optimal performance characteristics. The maximum size of the rake angle is limited by the stability of the cutting wedge, as a further increase in the rake angle results in wedge angles that are too small causing a critical weakness to the PCD cutting edge. Bending resistance can be increased through a conical design of the shaft (see Figure 6) with a taper and therefore more clearance for chip removal behind the PCD cutting edges („Bottleneck“, see Figure 5). Another way to increase the bending resistance is to provide wide insert seats that increase the moment of inertia of the tool body. Simple and smooth shapes for the chip spaces and the minor and major flank and insert seats without a projecting PCD cutting edge help to minimise any obstructions when the chips being produced are discharged. Optimisation of the PCD milling cutters are shown in Figure 5.

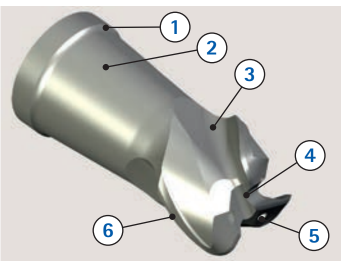


1. „Bottleneck“: clearance for chips
2. Optimised chip flute shape - only one chip flute area
3. Embedded PCD without projections
4. Simple and smooth shape of the minor flank
5. Concave central basic body shape for the best coolant distribution
6. Maximum width of the insert seats
7. Max. axis angle dependent upon of the radial rake angle
8. Optimised insert seats
9. Radial rake angle of 4° (end) up to max. 20° (circumference)

Figure 5: Optimisations on PCD milling cutters; source: MAPAL

Solutions and optimisations during the HPC machining of aluminium

In the field of carbide tools, wear-resistant micro-grain substrates are used that are resistant to vibrations and cutting edge chipping at high cutting speeds thanks to their high flexural strength. Here again tapered shanks as well as radii on the shaft transition lead to a reduction in the notch effect and higher rigidity of the tool body (Figure 6). The advantage of a large flute angle > 40° is an overlapping entry and exit of successive cutting edges. This makes it possible to avoid a pulse-like transition of the process force fluctuations occurring and the resulting vibrations. The highest process stability is achieved through axially uniform milling [7]. Rounded shapes in the major and minor flanks of solid carbide cutters (solid carbide end mills) also improve chip removal. In comparison to PCD tools, the cooling of solid carbide milling cutters is carried out by the minor flanks of the individual teeth thanks to the greater geometric freedom of not using brazed cutting edges.



1. Radius for increasing rigidity
2. Polished taper
3. Rounded chip flutes
4. Round point thinning
5. Cooling channels in the secondary clearance areas
6. Helix angle > 40°

Figure 6: Optimisation on solid carbide end mills; source: MAPAL

Chip breakers for directly influencing the chip form and the direction the chips move can further reduce the cutting forces and heat dissipation of the chip on the tool body. To reduce adhesion when machining aluminium with solid carbide milling cutters, the surface qualities of the tools are increased by polishing or coating them. Wear-reducing coatings may also be used on carbide tools for the high-volume machining of aluminium. Particularly when machining aluminium, hydrogen-free amorphous carbon films, such as ta-C, that combine good thermal stability with a simultaneously high wear resistance thanks to a high level of hardness have become established.

HPC-machining of aluminium structural parts using end mills is usually carried out by climb milling. This allows any possible undercuts caused when reversing the magnitude and direction of the normal force F_{fN} of the feed rate applied in conventional milling to be avoided. In addition, during conventional milling, the so-called minimum chip thickness must be overcome when the tool penetrates, resulting in a very low chip thickness at the start of the cut. The resulting strain hardening during material compaction increases the cutting forces and wear in comparison to climb milling [12, 13]. In particular with thin-walled structures, HPC machining leads to deformation of the part due to the internal stresses introduced, which can be compensated by the component stress and the process strategy. This can reduce deformations of the part and vibrations in the workpiece and the resulting limitations to cutting parameters. Due to the high complexity, it is not yet possible to make an analytical calculation of the optimum, part-specific machining strategy and stress situation. Therefore, empirical values or a reclamping of workpieces is required here (Figure 7).

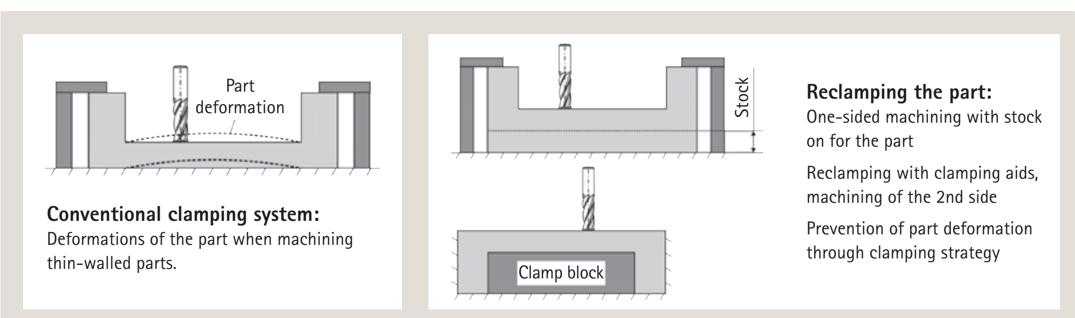
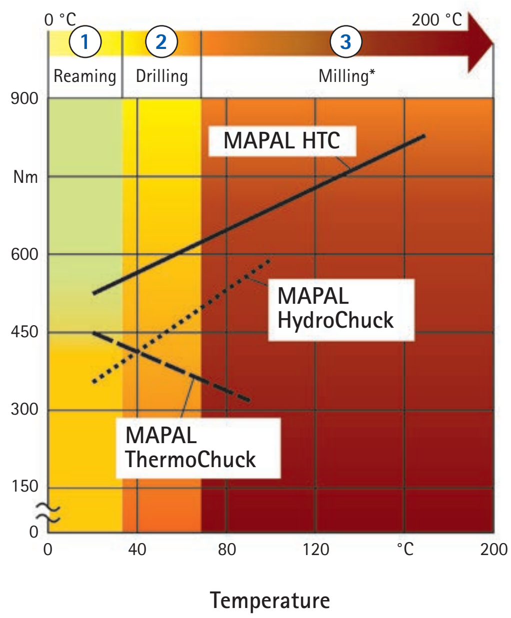


Figure 7: Optimising the clamping process to prevent component deformations

Solutions and optimisations during the HPC machining of aluminium

Furthermore, based on peak loads on the spindle during HPC machining, a reduction in the usable machine-tool efficiency required can be achieved by making circular-shaped first cuts and exits with the tool and minimising jerk movements of the axis. This prevents impact loading of the cutting edges and the machine tool. Lower loads also give rise to an increased tool life [13].

Chuck concepts with integrated damping for shank tools provide ways to improve during vibration-prone processes such as the milling of thin-walled aluminium structural parts. Stable machining can be ensured even at very high process settings. The requirements for the chuck come from the overall process. Particularly with rising temperatures at the tool, the clamping force of thermal expanding chucks (Figure 8) is reduced and may lead to the tool pull-out due to declining clamping torques in the chuck. A high thermal resistance with constant concentricity as well as a high level of repeat accuracy and balancing qualities can increase the process reliability and performance during high-volume machining.



1 Chuck remains in the temperature range of the coolant: No effect on the clamping force

2 Low heat transfer on the tool: Little effect on the clamping force

3 Highest heat transfer on the tool: Large effect on the clamping force

HTC: HighTorque Chuck

HydroChuck: hydraulic chuck

ThermoChuck: thermal expanding chuck

* Dry-and MMS-machining at dia. 20 mm

Figure 8: Chuck potential; source: MAPAL

Results

The high-volume milling of structural parts is used throughout the aerospace industry and in parts of the automotive industry, particularly with aluminium and titanium materials and steels. HPC machining of aluminium is limited at present by the machine-tool efficiency and dynamics as well as workpiece clamping and process stability. Machine tools with a very high torque are necessary when machining titanium. Even if the torque is sufficient, the tools are currently limited by the process. Due to these limitations, an increase in the metal removal rate and the productivity of HPC processes is dependent on the part to be machined. Through part-specific adaptations to the tools and process settings, the utilisation of the available machine-tool efficiency and the resulting removal rate can be increased. To this end, targeted, specific designs for the geometry of the cutting edges and the tool adapter are required. The resulting possible increase in the cutting parameters up to the machine-tool efficiency limit when producing aluminium structural parts can increase the removal rate of Q_W = 7.8 l/min to Q_W = 10.4 l/min with full functionality of the part (Figure 9).

Tool	n [min^{-1}]	a_p [mm]	a_e [mm]	v_f [mm/min]	f_z [mm]	Q_W [l/min]	
PKD, Ø 32 mm, z = 3	18.000	9	32	17.280	0,32	7,8	✓
PKD, Ø 32 mm, z = 3	29.000	12	32	21.750	0,25	8,4	✓
PKD, Ø 32 mm, z = 3	29.000	12	32	27.000	0,32	10,4	✓

Figure 9: High-volume machining of aluminium; source: iStock, MAPAL

During high-volume machining of aluminium, end milling cutters, replaceable head milling cutters and brazed monolith tools are used (Figure 10). Depending on the type of construction, the diameter and the rigidity of the tools, cutting speeds of up to v_c = 4500 m/min and tooth feeds of up to f_z = 0.42 mm can be achieved. The cutting data for high-volume milling with high metal removal rates is based on the available spindle power of the machine tool and the material to be machined.

OptiMill®-Diamond-SPM
OptiMill®-SPM

CPMill®-Diamond-SPM
CPMill®-SPM

OptiMill®-Diamond-SPM
HSK-A63

Tool	$v_{c,\,max}$ [m/min]	$f_{z,\,max}$ [mm]	$a_{p,\,max}$ [mm]	$a_{e,\,max}$ [mm]
OptiMill®-Diamond-SPM	3.000*	0,32*	0,5 xD	D
OptiMill®-SPM	2.250*	0,36*	0,5 xD	D
CPMill®-Diamond-SPM	1.450*	0,28*	0,5 xD	D
CPMill®-SPM	1.450*	0,30*	0,5 xD	D
OptiMill®-Diamond-SPM HSK-A63	4.500*	0,30*	0,3 xD	D

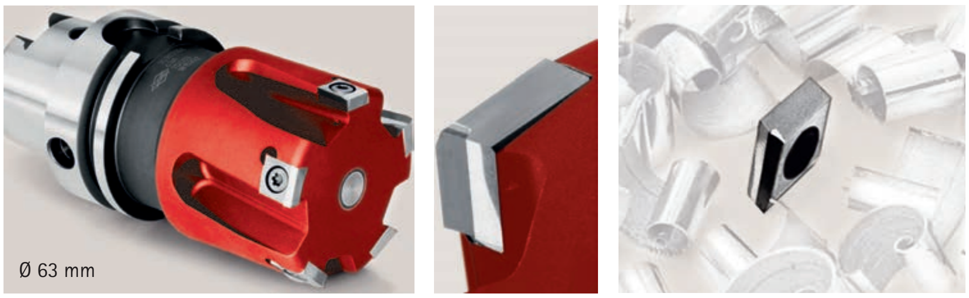
* Maximum value dependent on: Tool, Cutting depth, Type of design (short, long)

Figure 10: Tools for high-volume machining; source: MAPAL

Results

High machining allowances for high-volume machining also often require pre-cutting („roughing") of parts at high cutting speeds and cutting depths for approximating the shape of the part. The removal rates to be achieved make high demands on the rigidity of the tools as well as to the performance of the spindle and drives of the machine tool. Face mills with PCD indexable inserts with positive rake angles can be used for these pre-roughing processes (Figure 11). The positive rake angles result in a good chip flow with low cutting forces, so that the required drive power for the process can be reduced.

Face mill with tangential indexable inserts for pre-cutting of aluminium structural parts



- Cutting speeds of up to v_c = 3000 m/min
- High milling performance thanks to high rigidity
- Cutting depths of up to ap = 12 min
- Tangential technology

Abbildung 11: Werkzeug für die Schruppbearbeitung von Aluminium; Quelle: MAPAL

Summary and Outlook

Summary and Outlook

The increase in air traffic in the coming years and simultaneous reduction of emissions and costs increase the requirements for efficient production of high quality parts. Structural parts in an integral design are suitable for this. These usually thin-walled parts are milled to a large extent from solid aluminium with material removal of up to 95%. The PCD and solid carbide tools used for this purpose are characterised by a high level of rigidity thanks to rounded transitions on the tool shank for preventing notch effects as well as large flute angles and axial angles. Large chip flutes with rounded surfaces result in reliable chip removal, thereby ensuring process reliability. Regenerative chatter vibrations when machining aluminium is counteracted by tool flank chamfers and uneven cutting edge pitches on the tools.

High-volume machining of aluminium is limited by the currently available machine-tool efficiency. Here part- and process-specific optimisations of the tools offer high potential. The resulting potential increases in the process settings enable efficient and productive manufacturing. The available machine-tool capacity can therefore be exploited further. Very high material removal rates in excess of 10 l/min are then possible when machining aluminium structural parts, in particular using PCD tools. Simply improving the tools does not allow the full potential of high-volume machining to be achieved with the greatest efficiency, because with HPC machining, the entire system of the process is crucial. Tool-side improvements require the simultaneous optimisation and full utilisation of the potential of the machine tool and its drives, the spindle, the tool clamping, the selected coolant supply, the component stress and process strategy. Only with a holistic view of the production process for high-volume machining can the best possible and most economical solutions for increasing productivity be achieved.

Possible increases in performance and rigidity of the machine tools as well as the continuous improvement of the cutting materials can be used in the future to further increase the productivity of high-volume machining of aluminium. Additional optimisations to the stress of the parts and tools can also positively influence the process stability and lead to an increase in the metal removal rate.

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