TALAT Lecture 3100

Machining of Products

38 pages and 31 figures

Basic Level

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Objectives:

- In general, aluminium alloys have excellent machining properties compared with other common engineering metals. It is the objective of these lectures to describe the machinability of aluminium alloys, the necessary tools and equipments in order to obtain optimum results.

Prerequisites:

- General background in production engineering, machine tools

Date of Issue: 1994

3100 Machining of Products

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3101 Machinability of Aluminium Alloys

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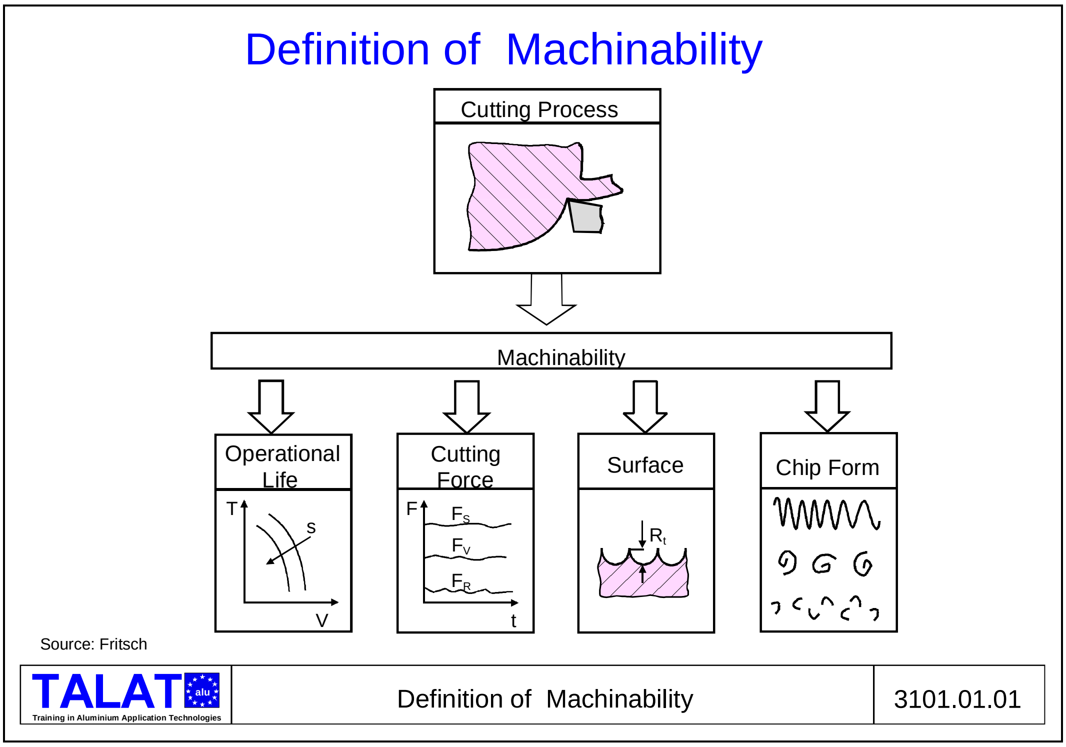
Compared to other construction materials, aluminium is easy to machine. However, considering the wide range of alloys available, it is necessary to go into details regarding the machining characteristics of aluminium alloys. In this chapter such machinability characteristics will be defined.

3101.01 Definition of Machinability

The term machinability includes all those properties which are relevant for the machining and cutting process:

- the wear of tools
- the necessary cutting force
- the resulting form of the chips
- the quality of the surface produced (**Figure 3101.01.01**).



Source: Fritsch

Definition of Machinability 3101.01.01

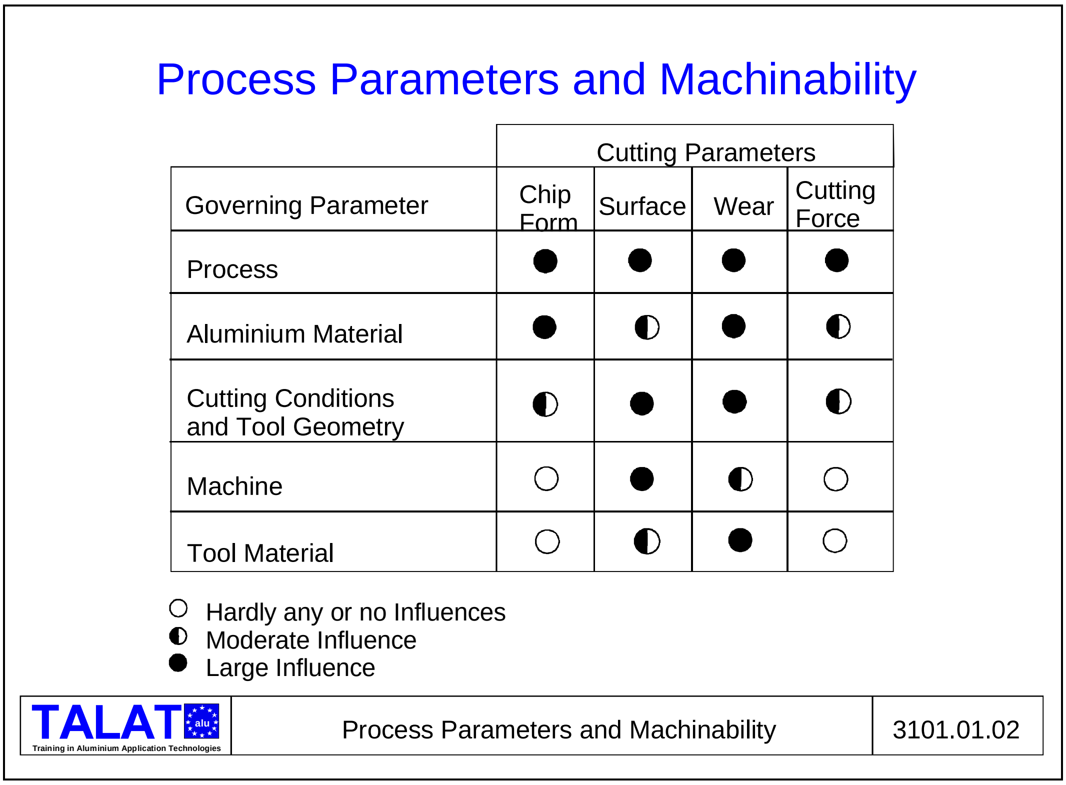
Machinability is not a material property which can be defined using a single characteristic parameter. It is, in fact, a complex technological term. The machinability depends both on the physical and chemical properties of the aluminium as well on the fabrication process used to produce it.

The Machining Process

The kinematical arrangement of tool and workpiece is by far the most decisive criterion for the machining process. Strictly speaking, the term machinability should be defined separately for each individual machining process (turning, drilling etc.). Because of the clearly defined arrangements of tools and workpiece, the term machinability applies generally to the turning process.

The technology used for the machining process itself depends on a number of independent parameters (see also **Figure 3101.01.02**):

> **Cutting parameters and tool geometry:** Even these parameters exert considerable influence. Currently guidelines exist giving the most efficient settings of these values for aluminium.
>
> **The machines used**: This governing parameter has a special importance as far as aluminium is concerned; both the condition of the machine as well as its design must fulfil the special conditions required for cutting aluminium.
>
> **Material of the cutting tool**: This criterion is very important, especially when machining aluminium.



Process Parameters and Machinability

	Cutting Parameters			
Governing Parameter	Chip Form	Surface	Wear	Cutting Force
Process	●	●	●	●
Aluminium Material	●	◐	●	◐
Cutting Conditions and Tool Geometry	◐	●	●	◐
Machine	○	●	◐	○
Tool Material	○	◐	●	○

○ Hardly any or no Influences
◐ Moderate Influence
● Large Influence

TALAT alu Training in Aluminium Application Technologies | Process Parameters and Machinability | 3101.01.02

3101.02 Forms of Aluminium Chips

The form of the aluminium chips is an important criterion, especially when one bears in mind the very large volume of chips created while machining aluminium. The general aim is to obtain short cylindrically wound chips, spirally wound chips and spiral chips.

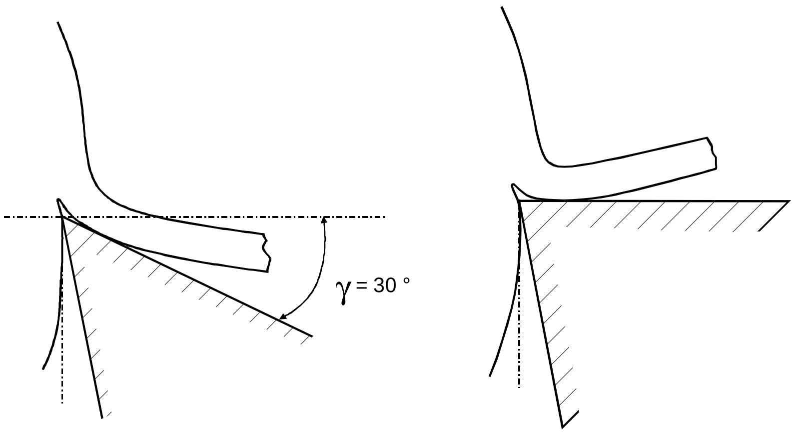
A large variety of aluminium chip forms exist so that, depending on the aluminium alloy, almost all known forms of chips can be produced. Generally the basic guideline is: the harder and stronger the aluminium alloy, the shorter the chips. This leads to the following general rules:

- Pure aluminium and soft wrought alloys produce extremely long chips, making it essential to introduce special corrective measures (chip breakers on the tools).
- High-strength wrought alloys (e.g. AlMg5, AlMgSi1,0) present no problems as far as chip form is concerned.
- Hypoeutectic casting alloys (G-AlSi8Cu3, G-AlSi10Mg etc.) lead to the formation of short coiled and spiral chips which can be removed easily.
- Eutectic casting alloys (G-AlSi12) tend to produce longer chips.
- Hypereutectic casting alloys (piston alloys) inevitably lead to the formation of short fragmented chips which can in some cases be difficult to remove.

Machining alloys are a special group of alloys containing low-melting soft metals which help in forming the preferred short chips. Machining alloys, especially the leaded variety AlCuBiPb, are widely used.

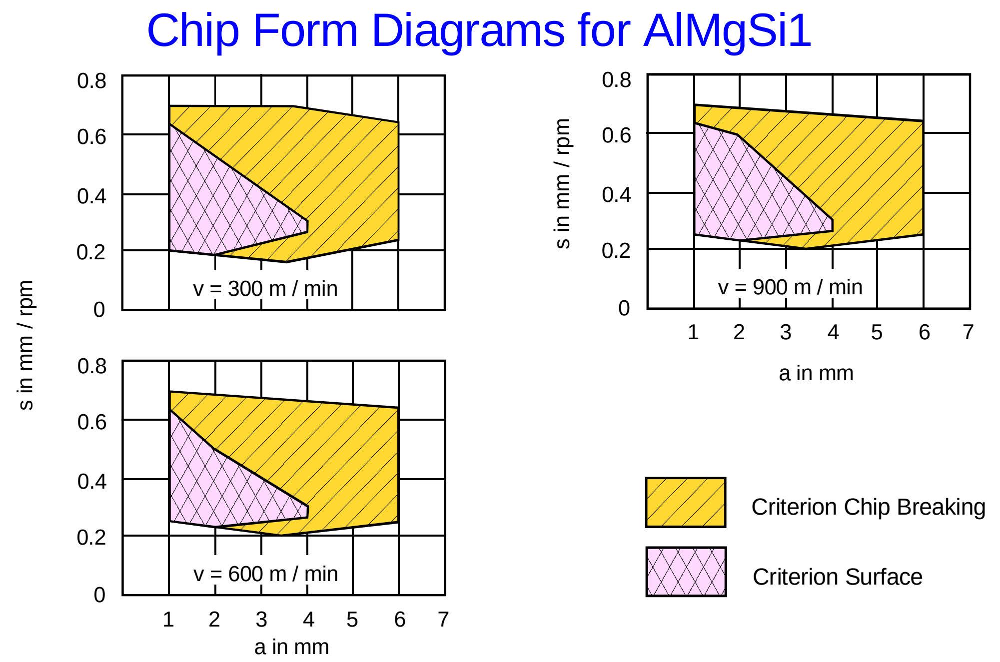
One of the technological parameters affecting the form of chips is the tool geometry. Thus, a reduced rake angle tends to form shorter chips in alloys which would otherwise deliver long chips (**Figure 3101.02.01**).

Chip Compression for Large and Small Rake Angles



TALAT Training in Aluminium Application Technologies | Chip Compression for Large and Small Rake Angles | 3101.02.01

Chip form diagrams can be compiled, thereby making it possible to consider the machining criterion „form of chips“ in setting up the cutting routine. These diagrams show the regions for best chip forms as a function of the variables cutting speed, feed and depth (**Figure 3101.02.02**).



TALAT Chip Form Diagrams for AlMgSi1 3101.02.02

3101.03 Surface of Machined Aluminium Alloys

In general, the quality of the surface produced by machining depends on three independent parameters:

- **The kinematical roughness**: This is the theoretical depth of roughness (peak-to-valley height), calculated on the basis of the relative movement of tool and workpiece.
- **The machined surface roughness**: This reflects the separating behaviour of the material, i.e. the typical characteristics of aluminium alloys in regard to surface quality.
- **External influences**: Such influencing parameters (stability of system, condition of cutting edges etc.) become extremely important especially when machining aluminium at very high speeds.

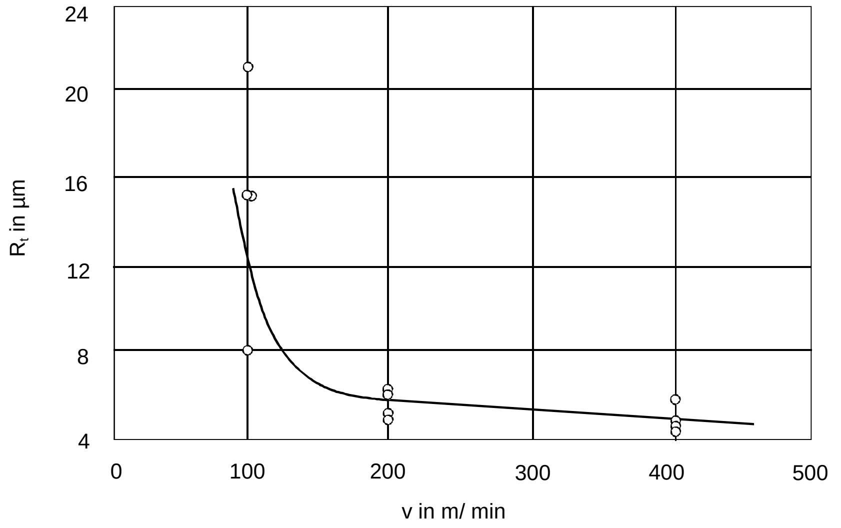
In general, the machined surface roughness, i.e. the influence of material on the quality of the cut surface, adheres to the same rules that apply to the form of chips. The following rule applies for wrought alloys at least: the higher the strength and hardness of the wrought alloy to be machined, the smoother is the surface produced.

As far as casting alloys are concerned, the micro-structure exerts a certain influence, i.e hard particles embedded in a soft matrix can be gouged out, resulting in rougher machined surfaces. On the whole, the quality of the surface produced by machining casting alloys can also be classified as being good to very good.

The purity of the material used is of paramount importance for special-purpose aluminium alloys (e.g. hard disks for storage and drums for copying machines) which have to be machined to deliver extremely smooth surfaces ($R_t < 0.1$ µm). To fulfil these conditions, the wrought aluminium materials used must have an extremely uniform micro-structure, free from inhomogenities and impurities.

The cutting speed is an important machining parameter which influences the surface quality. In general, the roughness is inversely proportional to the cutting speed. At low cutting speeds the roughness of the surface produced increases dramatically, due to the increased edge build-up. The region of low cutting speeds must, as a rule, be avoided when aluminium is to be machined. Edge build-up is a phenomenon which is typical for aluminium and is caused by the periodical sticking and removal of aluminium particles deposited on the cutting tool (**Figure 3101.03.01**).

Edge Build-Up at Low Cutting Speed



TALAT Training in Aluminium Application Technologies | Edge Build-Up at Low Cutting Speed | 3101.03.01

The influence of the tool construction on the quality of the surface produced can be ascertained from the previously mentioned process: It is important that the chips can glide smoothly over the cutting tool surface. This means that a sufficiently large rake angle, good lubrication and a smooth cutting tool surface are essential. A clean smooth surface cannot be obtained using worn cutting tools.

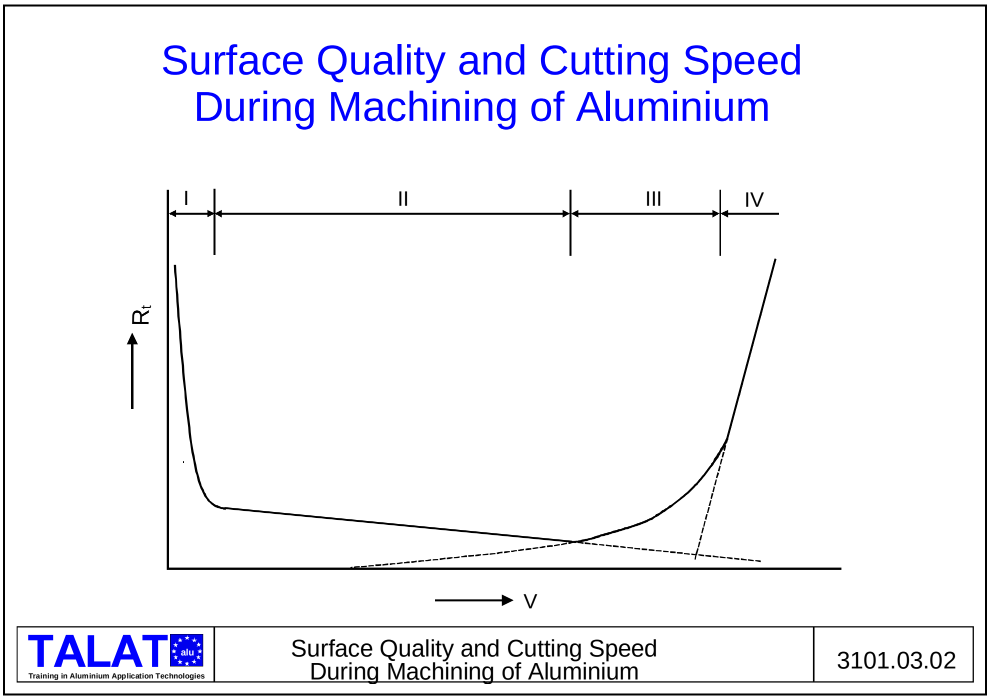
Based on the factors which affect the surface quality, the machining operation can be divided into four separate regions:

Region I: Due to edge build-up, the surface quality is unsatisfactory, the cutting action being replaced by tearing. This region must be avoided.

Region II: Decreasing surface roughness with increasing cutting speed.

Region III: Increasing influence of interferences, e.g. tool chatter and machine vibrations in a region which is otherwise suitable for machining aluminium. Thus, to obtain the best results the machines used have to be specially designed for aluminium.

Region IV: Poor surface quality caused by virtual chips. These virtual chips are an accumulation of the material being worked and which stick (weld) to the surface of the tool, thereby scratching the freshly cut surface. Such build-ups are produced during the machining of casting alloys using worn tools and high cutting speeds (**Figure 3101.03.02)**.

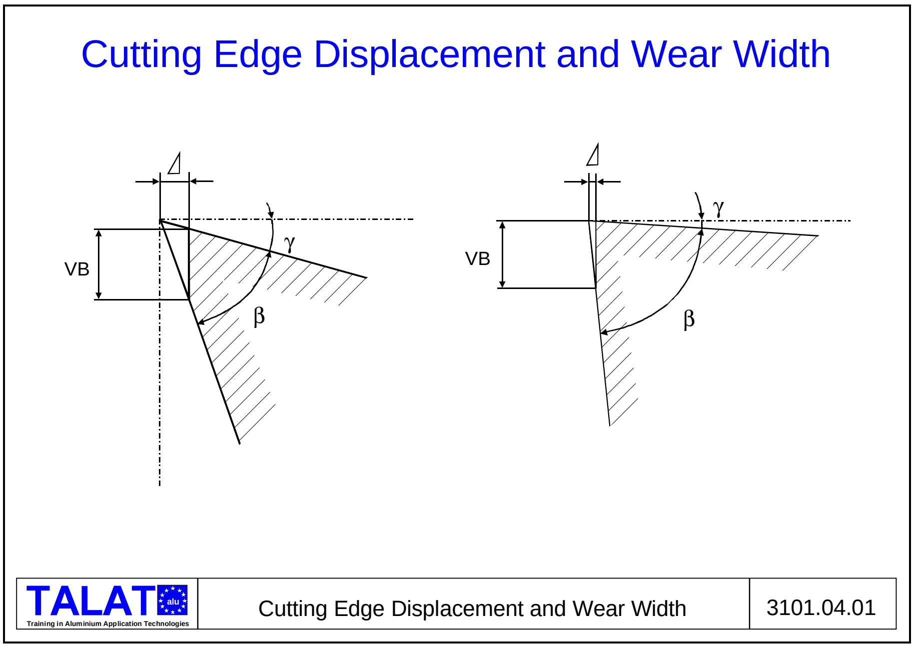


Surface Quality and Cutting Speed
During Machining of Aluminium

TALAT Training in Aluminium Application Technologies | Surface Quality and Cutting Speed During Machining of Aluminium | 3101.03.02

3101.04 Tool Wear while Machining Aluminium

Scouring (as is typical for steel) is practically not observed while machining aluminium. The tool wear while machining aluminium occurs due to abrasion of the free surface. Consequently, the deciding criterion for measuring tool life objectively is the wear width VB. The wear of the free surface depends on the temperature and is caused mainly by abrasion. While using carbide-tipped tools one normally assumes an allowable maximum value of 0.3 to 0.5 mm for VB (**Figure 3101.04.01**).



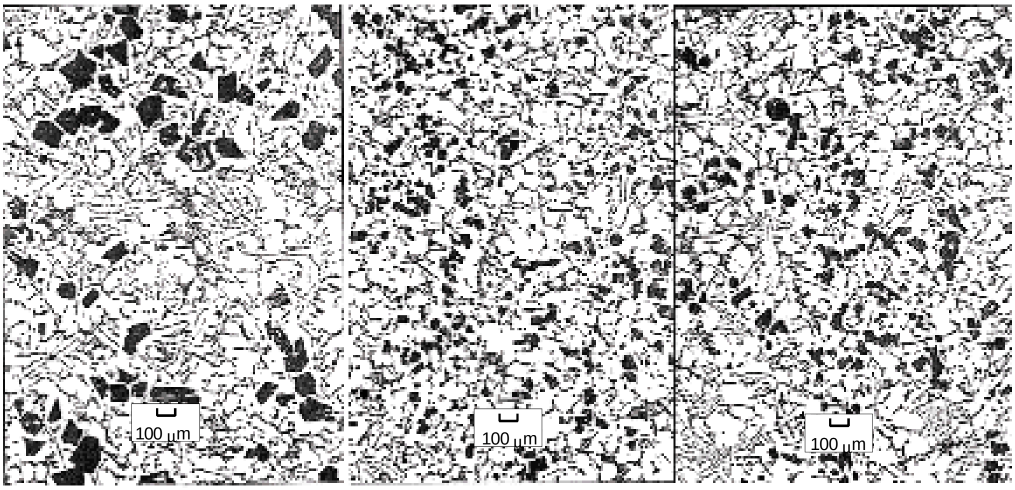
Cutting Edge Displacement and Wear Width

Cutting Edge Displacement and Wear Width 3101.04.01

As far as wear is concerned, the material of the workpiece and the cutting parameters are equally important.

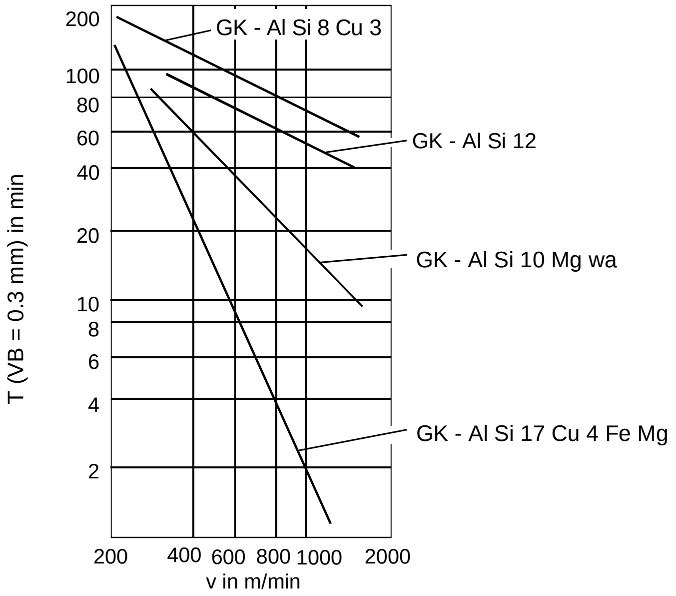
The material of the workpiece has a very important influence. The following model can help us understand the basic underlying principles: The process of cutting can be considered to be a grinding process in which a grinding disk (= the aluminium material to be cut) causes wear of the workpiece (= tool). In fact the aluminium piece to be machined consists of an aluminium matrix in which hard particles are embedded. The desired abrasion of material during grinding is identical to the undesired free surface attrition (wear) of the tool. Based on this model, the most important correlations of the wear process can be derived:

- Wear increases with the number of large hard particles which are embedded in the aluminium workpiece. Such particles could be primary precipitations of silicon particles in a hypereutectic alloy. This is the reason that aluminium castings cause high wear of tools. The wear is extremely high in the case of cast hypereutectic piston alloys. On the other hand, wrought alloys with low silicon contents cause a minimum of tool wear (**Figure 3101.04.02**).
- Wear increases with the strength of the material. Hard particles embedded in a soft matrix can be gouged out easily. However, if the matrix material is harder, inclusions cannot be removed easily, thus increasing tool wear.
- Finally, wear depends on the wear resistance of the free surface of the tool.



TALAT Training in Aluminium Application Technologies	Hypereutectic AlSi Alloys (treated differently) with coarse Si Inclusions	3101.04.02

As far as cutting conditions are concerned, cutting speed has the greatest influence on tool life. The correlation between cutting speed, *v*, and tool life, *T*, is given by Taylor's equation: $v_c = C \cdot T^{1/k}$. This equation, which can be depicted as a straight line in a double logarithmic scale *T*-*v*, correlates very well with experimental values. Such straight life-lines can be derived to show the varying tool wear for different aluminium alloys.



TALAT Training in Aluminium Application Technologies	Operational Life for the Machining of Gravity Die Castings	3101.04.03

The diagram shown in **Figure 3101.04.03** is an example for gravity die casting alloys. It is not possible to plot wrought alloys in this diagram. In the case of wrought alloys, the tool life is measured in number of shifts or days rather than in minutes. Because of the much greater experimental effort required, *T-v* curves have not been constructed for wrought alloys.

Since tool wear also depends on other cutting conditions, the life-lines are valid only for a definite set of cutting conditions. Further factors which influence tool wear are:

- Cooling lubricants. Efficient cooling can reduce tool wear.
- Cutting interruptions. These increases tool wear. Pores in the material act as interruptions during cutting.
- Feed and cutting depth. Tool wear tends to increase with increasing chip cross-section.

3101.05 Cutting Force for Machining Aluminium

The influence of material is reflected in the so-called specific cutting force $k_{s1.1}$ introduced in 1957 by O. Kienzle, who used an empirical equation for its calculation. Because of its ease of use, this equation has come to be widely accepted. The specific cutting force gives the correlation between cutting force, material and chip dimensions.

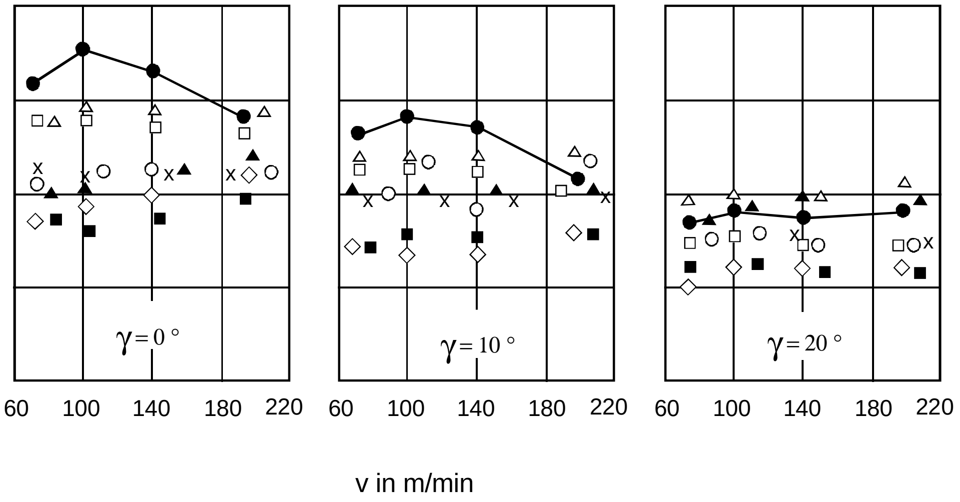
The specific cutting forces for the different aluminium alloys can be obtained from tables. In general, the following rules apply:

- Different alloys have varying specific cutting forces, the variations being, however, relatively small.
- In general one can assume that the specific cutting force for aluminium is about 30 % that of steel.
- The specific cutting force can not be derived from either the chemical composition or the physical properties.
- The specific cutting force has to be determined experimentally for each individual case.

The cutting force required depends not only on the dimensions of the chips but also on the cooling lubricants used and the tool construction:

- A cooling lubricant has opposing influences: The cooling action reduces the temperature at the shear zone thus tending to increase the cutting force required. At the same time, the lubricating action eases chip motion, thereby reducing the cutting force required.
- As far as the tool geometry is concerned, the cutting force can be influenced by the rake angle, γ. A larger rake causes less chip compression resulting in a lower cutting force (**Figure 3101.05.01**).
- The wear condition of the cutting edge has a relatively large influence. As a consequence, the cutting force increases with machining time.

Cutting Forces for Machining Aluminium



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Cutting Forces for Machining Aluminium

3101.05.01

3101.06 Classification of Aluminium Alloys in Groups with Similar Machinability

From the influence of the different parameters as mentioned above, it is clear that the correlations are much too complex to be of help in planning the machining operation. This is especially true for those cases in which the optimum cutting conditions have to be chosen from data bases for operating fully automatic cutting machines.

In order to make it possible to handle the very large palette of available aluminium alloys, it is recommended to classify these in groups having similar machining characteristics. The following classification is adopted:

Group 1: Wrought aluminium alloys of low strength

Group 2.1: Wrought aluminium alloys of high strength
Group 2.2: Free-machining alloys

Group 3.1: AlSi casting alloys with up to 10 % Si
Group 3.2: Eutectic AlSi casting alloys
Group 3.3: Hypereutectic AlSi casting alloys

These alloy groups are described in the following table.

Classification of Aluminium Alloys Based on Machining Characteristics

Group	Alloy type	Alloy example	Characteristic machining properties
Group 1: Wrought low strength Al alloys	• Non-heat-treatable alloys in soft or partially hardened state • Heat-treatable alloys in unaged condition	Pure aluminium, AlMn, AlMg1, AlMgMn AlMgSi0,5, AlMgSi1	Soft, ductile, homogeneous, low strength, no hard components. Sticking during machining Tendency for edge build-up, no virtual chips
Group 2.1: Wrought Al alloys of higher strength	• Non-heat-treatable alloys in strained condition • Heat-treatable alloys in aged and/or strain-hardened state	AlMn, AlMg1 to AlMg5, AlMgMn, AlMg4,5Mn AlCuMg1, AlZnMg1, AlZnMgCu0,5 AlZnMgCu1,5	Strength between 300 and 600 N/mm^2 with good elongation values, no hard components (low tool wear), decreasing tendency for edge build-up with increasing strength, no virtual chips
Group 2.2: Free-machining alloys	• Heat-treatable wrought alloys with chip - breaking components	AlMgSiPb AlCuBiPb, AlCuMgPb	Short chips due to presence of chip breakers, strength 280 to 380 N/mm^2, low tendency for edge build-up, no virtual chips
Group 3.1: AlSi casting alloys with up to 10 % Si	• AlSiCu alloys • AlSiMg alloys	AlSi5Cu1, AlSi6Cu4, AlSi8Cu3, AlSiCu3AlSi5, AlSi7Mg, AlSi9Mg, AlSi10Mg	Strength up to 250 N/mm^2 Strength up to 360 N/mm^2, increased tool wear due to hard alloy components and inclusions, good chip breaking properties and smooth surfaces, tendency for edge build-up for more than than approximately 5 % silicon. Increasing virtual chips
Group 3.2: AlSi casting alloys of low hardness	• AlSi alloys with about 12 % silicon	AlSi12	Low hardness of matrix material. Hard metallic alloying components and eventually inclusions, high tendency for edge build-up and for virtual chips
Group 3.3: AlSi-casting alloys of high hardness	• AlSi alloys with over 12 % silicon	AlSi18CuMgNi, AlSi21CuNiMg, AlSi25CuMgNi, AlSi17Cu4FeMg	Medium strength, high hardness, very low ductility. High wear caused by very hard intermetallic constituents and primary silicon; high tendency for edge build-up and for virtual chips

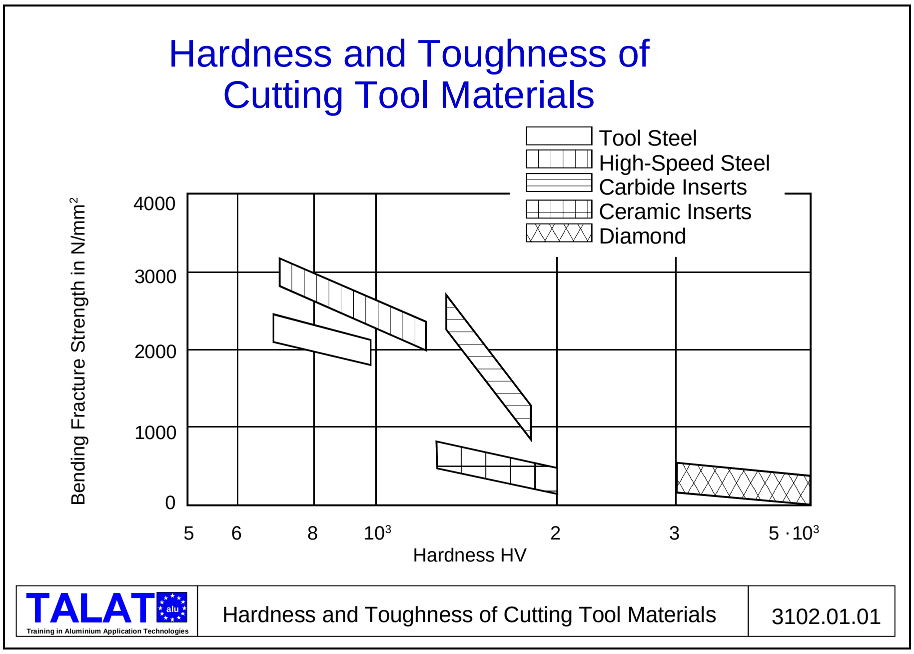
3102 Tools for Machining Aluminium

3102.01 Survey of appropriate cutting materials
3102.02 Machining aluminium with high-speed steel
3102.03 Machining aluminium using carbide-tipped tools
3102.04 Machining aluminium with diamond
3102.05 General remarks regarding tool design
3102.06 Milling tools
3102.07 Drills
3102.08 Saws

Tools suitable for machining aluminium differ from those required for machining steel in as far as both the geometry and the cutting tool material are concerned. Aluminium cannot be worked with tools which are used for steel. This chapter will specify the cutting materials and tool forms most suitable for machining aluminium.

3102.01 Survey of Appropriate Cutting Materials

Aluminium is machined using tools made of tool steel, high-speed steel, cemented carbides and diamond (**Figure 3102.01.01**).



Ceramic cutting materials are not recommended for machining aluminium since the matrix of this material has a chemical affinity for the aluminium thus making it difficult to achieve a satisfactory operating life.

Synthetic cutting materials which can be successfully used for machining steel, are not suitable for aluminium. Thus, tools made of cubic crystalline boron nitride (CBN) are very susceptible to free surface wear and scouring. Such tools fail within a short period even at medium cutting speeds of lower than 1000 m/min.

Even tools with coated cutting edges have proved unsatisfactory. Such tools consist of a relatively tough substrate coated with a thin film of hard material, thus combining good wear properties together with a high toughness. However, since titanium compounds are mostly used as coating material, the same phenomenon occurs as in the case of ceramic cutting tools; titanium diffuses out of the hard coating so that this soon loses its effectiveness.

3102.02 Machining Aluminium with High-Speed Steel

High-speed steels offer the following advantages: high toughness, high bending strength, ease of working, low price. Toughness is important, especially since the slim form of the cutting tool typically used for cutting aluminium has a higher tendency to break than tools with a negative geometry (as are typical for cutting steel). The property of high-speed steel which makes it comparatively easy to form (compared to other tool materials) is especially helpful in designing complicated tool forms (twist drills, form and profile cutters).

For machining aluminium, the following main types of tools are used:

- twist drills S 12-1-1
- taps S 9-1-2
- milling cutters S 12-1-2
- form turning tools S 12-1-4
- profiling tools S 12-1-2

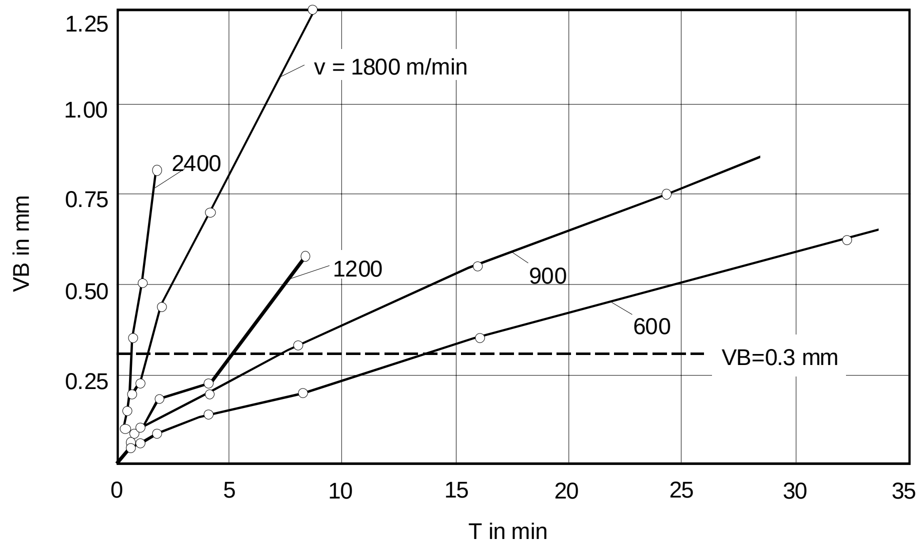
These are mostly made of steel with 12 % tungsten having a relatively high hardness, low bending strength and good temperature stability.

HSS steels have a lower resistance to free surface abrasion (the characteristic wear criterion for aluminium) than carbide-tipped or diamond tools. HSS tools are used almost only for wrought aluminium alloys since it is only here that an acceptable tool operating life can be attained. Wrought alloys contain only few hard inclusions and thus cause little tool wear.

As an added precaution, the cutting parameters chosen should be such that the temperature does not rise too high. This can be achieved mainly by choosing limited cutting speeds - mainly below 500 m/min (**Figure 3102.02.01**).

High-speed steel tools can also be used to drill abrasive castings in cases where the cutting speed is limited due to process technology reasons **Figure 3102.02.02**).

Machining Aluminium with High-Speed Steel

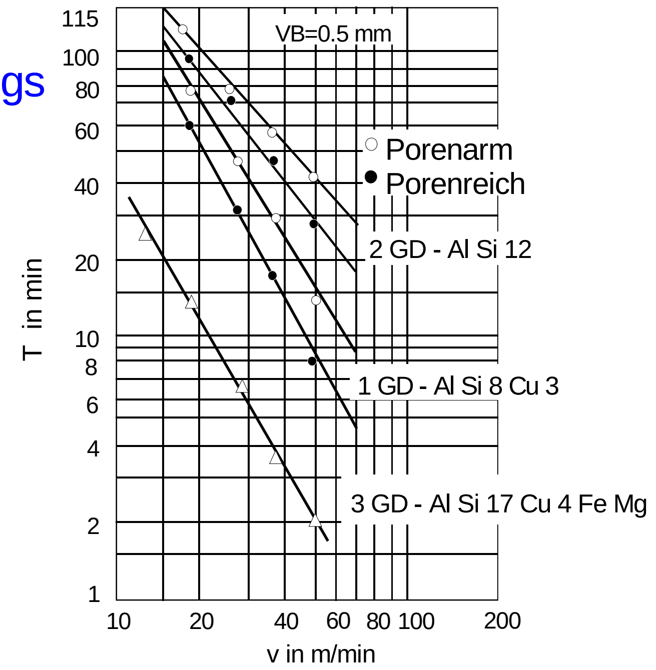


TALAT Training in Aluminium Application Technologies

Machining Aluminium with High-Speed Steel

3102.02.01

Machining Aluminium Castings with High-Speed Steel (Drilling)



γ	α	σ	δ	β	f
7°	8°	120°	35°	75°	0.8 mm

TALAT Training in Aluminium Application Technologies

Machining Aluminium Castings with
High-Speed Steel (Drilling)

3102.02.02

3102.03 Machining Aluminium Using Carbide-Tipped Tools

The use of carbide tipped tools is gaining in popularity. Casting alloys which have a relatively high abrasive action are mostly machined using carbide-tipped tools. High cutting speeds which are characteristic for machining aluminium, cannot be used with HSS tools.

For economic reasons, carbide-tipped tools are being increasingly used for machining the less abrasive wrought alloys also. The extremely long tool operating life - of one week or more - and the high cutting speeds attainable, more than compensate for the higher price of carbide-tipped tools.

The K01 and K10 type of tools with high WC contents have proven to be very successful for machining aluminium. The titanium carbide (TiC) types of tools are not suitable for machining aluminium since the high affinity of TiC for aluminium causes an intolerable diffusion out of the hard surface. The K type tools have a very fine-grained structure so that it is possible to obtain smooth cut surfaces and edges with low roughness. This is indeed one of the top priorities while machining aluminium.

Because of the above mentioned reasons, coated hard metals are not suitable for machining aluminium.

3102.04 Machining Aluminium with Diamond

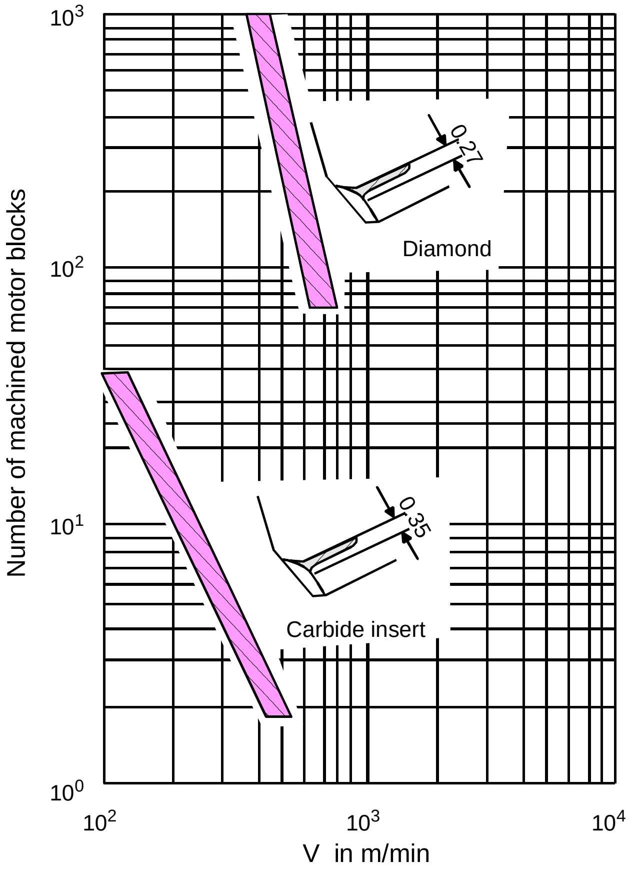
The extremely high hardness of diamond makes it a very suitable material for cutting tools. Such tools are used especially for machining hypereutectic AlSi alloys (piston alloys) which, due to the coarse silicon inclusions present, are extremely abrasive and thus very difficult to machine. Compared to carbide-tipped tools, diamond tools have longer operating lives (**Figure 3102.04.01**), higher precision and better operating stability. It is essentially this last property which makes them ideal for use in automatic machines which are typical for the automotive industry.

Currently polycrystalline diamond (PCD) tools are widely used since these possess much better isotropic mechanical properties than monocrystalline (natural) diamonds. PCD tools are less sensitive to impact loading and can be used where interrupted cutting actions occur (**Figure 3102.04.02**).

PCD tools have cutting properties which are much superior to those of carbide-tipped tools. Depending on the cutting conditions, PCD tools are about 40 to 100 times more efficient than carbide tools. This means that in individual cases the operating life of PCD tools can be up to 100 times longer than that of carbide tools thus more than compensating for their higher price.

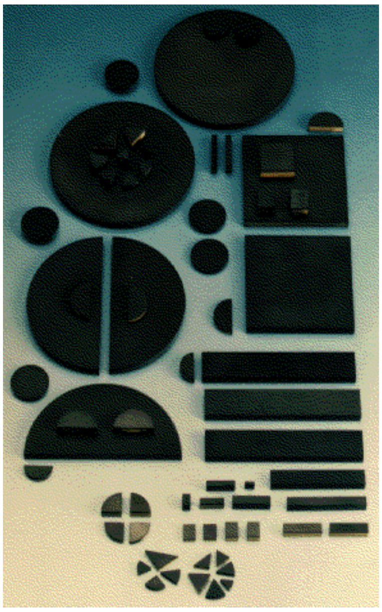
The wear characteristics indicate that Taylor’s rules are valid for diamond tools also. Free surface wear without scouring is observed on diamond tools. Close to the end of the operating life, a rounding of the otherwise sharp tool cutting edge is observed. Intensive cooling of the cutting edge is an effective method of increasing operating life.

Machining Al-Castings with Carbide-Tipped and Diamond Tools



Machining Al-Castings with Carbide-Tipped and Diamond Tools

3102.04.01



Source: De Beers

Cutting Inserts Made of Polycrystalline Diamond

3102.04.02

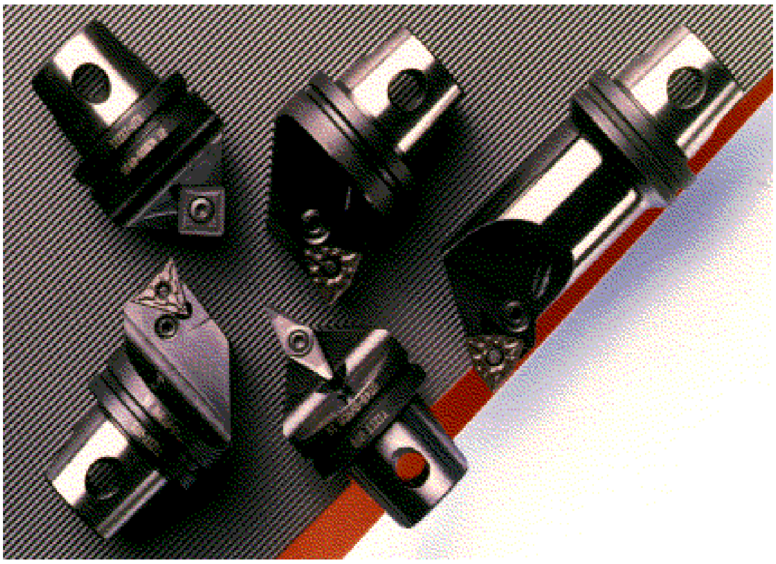
3102.05 General Remarks Regarding Tool Design

Tools have to be designed keeping the processes which occur at the cutting edge in mind. These processes depend on the material, i.e. ductility, plasticity and other material properties of the aluminium workpiece influence the chip type produced and consequently the tool design.

- A positive cutting angle should be used for tools for machining aluminium. The exact values to be used are determined by the tool-workpiece-material combination.
- The cutting edge should be smooth. Tools with polished cutting and free surfaces deliver very good results.
- The tool construction should be such as to allow sufficient stability even at the extremely high speeds used nowadays for machining aluminium. This is especially important for moving tools.

These general comments pertain only to the turning process which is characterised by a clearly defined arrangement of tool and workpiece. For the other cutting processes, a number of other process parameters, which influence the tool design and construction, have to be considered. A description of a few such processes follows.

For turning operations universally adaptable mountings and holders have been developed which allow rapid changes. With the help of these it is possible to position the tool exactly (precision) and to keep the idle time down to a minimum (economy) (**Figure 3102.05.01**).

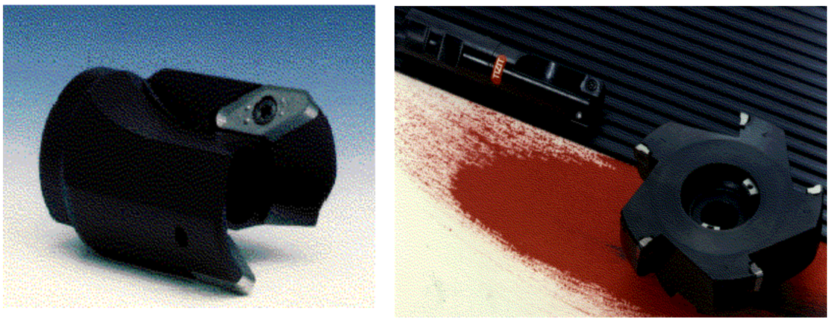


Source: Plansee Tizit

TALAT Training in Aluminium Application Technologies | Mounting Systems for Carbide -Tipped Tools | 3102.05.01

3102.06 Milling Tools

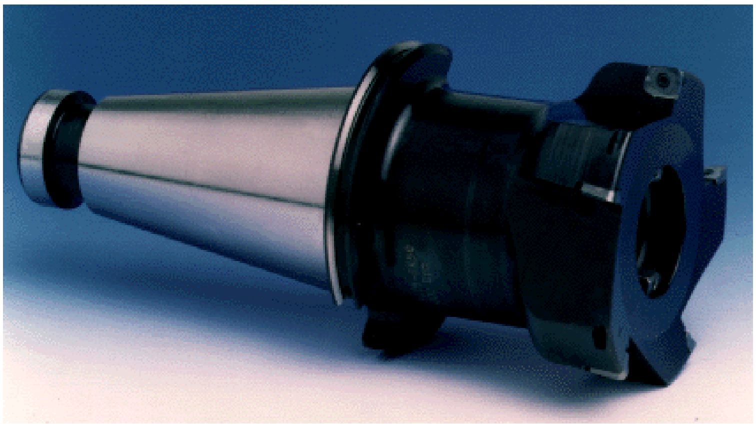
Characteristic for milling tools is the fact that the chips produced are not removed but are instead diverted to closed chip chambers in the tool and are thus transported forcibly together with the tool itself. Consequently, this fact has to be considered while designing the tool (see **Figure 3102.06.01**). Since the chip cross section is relatively large, the number of cutter inserts used is less than that used for machining steel so that a sufficiently large chip room is accounted for. Because of the high cutting speeds used, the cutter inserts experience large centrifugal forces and have consequently to be firmly secured. Milling tools, at least those having diameters of 100 mm and more, should be statically and dynamically balanced.



Source: Plansee Tizit

Interchangeable Tools for Milling Aluminium 3102.06.01

Since the surface quality could be affected by the very high revolving speeds used, the milling tools (**Figure 3102.06.02**) should have a rigid construction and be distributed nonuniformly. Due to the nonuniform distribution, the cutters are loaded unevenly, since at constant feed rates, the cutting depth changes proportionally to the cutter distance. It is important that those cutter inserts which are set to give the precision cut also come into action.

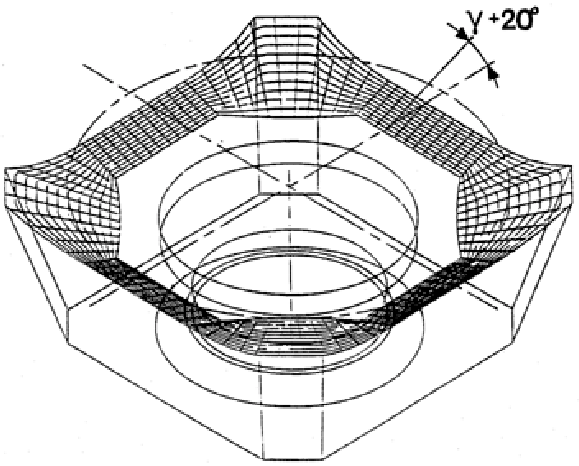


Source: Plansee Tizit

TALAT Tool Systems for High Speed Cutting 3102.06.02

In some cases, the milling tools are fitted with arrangements for fine adjustments so that the individual cutter inserts can be adjusted both radially and axially. Using special adjustment equipment, it is possible to adjust the cutters with a precision of up to a few µm. For milling machines fitted with PCD tools, this adjustment of the individual cutting plates is essential.

Interchangeable tool holders for aluminium (see schematic diagram **Figure 3102.06.03**) must have the appropriate geometry for aluminium with large rake angle (here 20°) and a relatively slim cutting form.



TALAT Geometry of an Interchangeable Tool Holder for Aluminium 3102.06.03

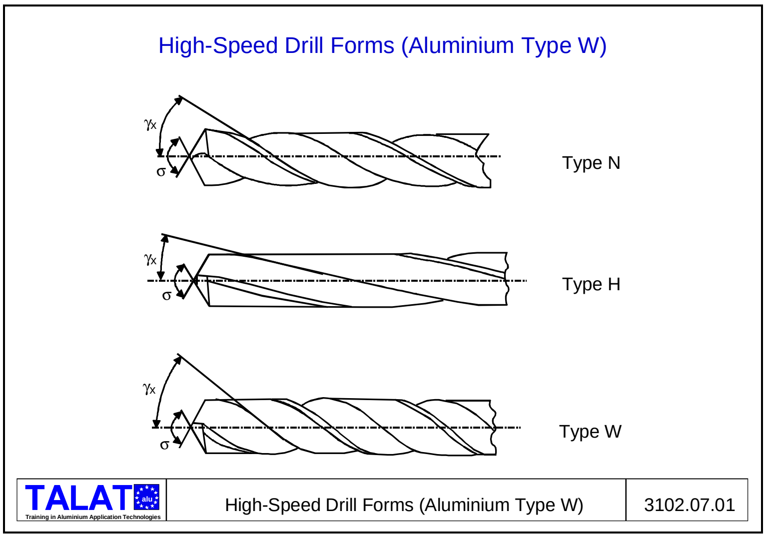
3102.07 Drills

During drilling, the chips cannot be transported freely but are instead forced out through the relatively narrow flute by frictional forces causing the chips to glide along the inside surface of the hole. When drilling aluminium, the drill used must take the deviation of diameter caused by the expansion of the material on one hand, and the differing amounts of expansion of tool and workpiece on the other into consideration.

Twist drills are classified into three groups: N, H and W types (**Figure 3102.07.01**). Each drill type has a different set of point and helix angles. The type W with a point angle of 140° and a helix angle between 30° and 40°is suitable for aluminium. Standardised drills for aluminium differ from those for steel, the larger helix angle used (45°, compared to 25° for steel) being one of the major differences.

It is generally recommended to use drills having keen cutting edges and polished surfaces for aluminium. A high polish in the flutes minimises friction and thus reduces material buildup. Since the cutting speeds (ca. 100 m/min) used while drilling are small compared to other operations, the danger of material buildup is especially large.

Aluminium can be drilled using larger feeds than for drilling steel. Consequently, a much larger amount of chips has to be transported within the same period of time through the flutes.

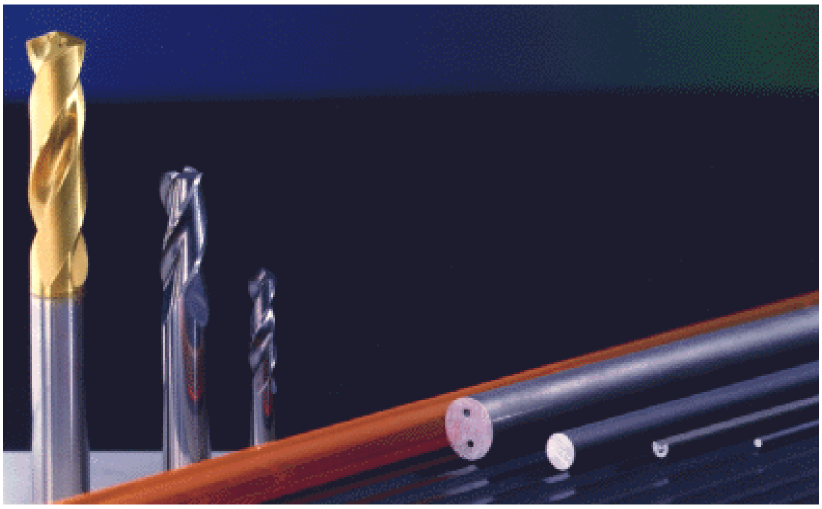


High-Speed Drill Forms (Aluminium Type W) 3102.07.01

When drilling soft, tough alloys, long coiled chips which can clog the flutes are created. Thus it is very important to support the chip transport and removal. This is best achieved using drills with as large flute areas as possible and having highly polished flute surfaces. Cooling lubricants for the cutting edges also facilitate chip transport.

In order to improve the efficiency of drilling, numerous types of special drills have been developed for different applications. The main types of developments are as follows:

- HSS drills with special geometric designs. Here special forms of drills have been designed to do the individual jobs most efficiently.
- Hard metal carbide tools are most suitable for drilling aluminium alloys having very abrasive properties. The drilling tools are made either completely of hard metal or carbide tipped tools are used (**Figure 3102.07.02**).
- Tools tipped with PCD are used for machining piston alloys.



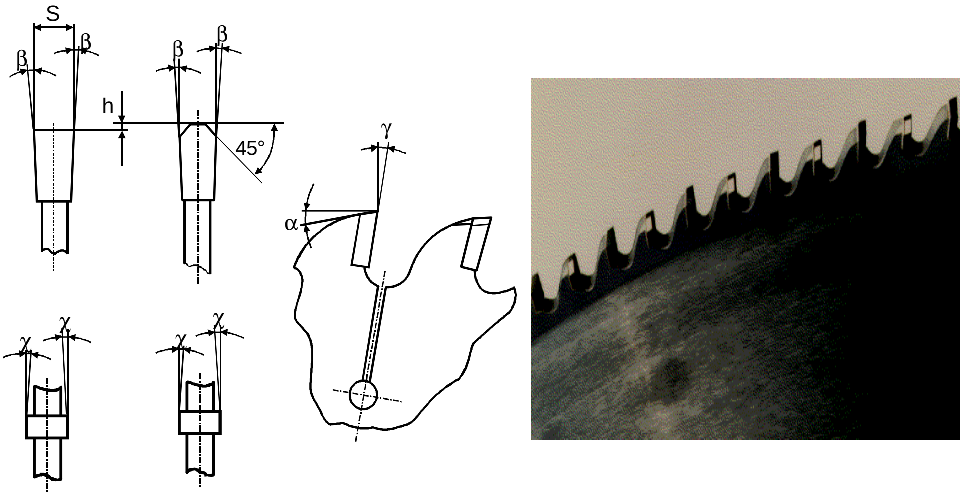
Source: Plansee Tizit

TALAT Training in Aluminium Application Technologies | Carbide - Tipped Drills for Aluminium Castings | 3102.07.02

3102.08 Saws

Either circular or bandsaws are widely used for cutting aluminium although the latter are obviously winning in popularity, especially for sawing compact cross-sections.

Nowadays, the circular saws used are mostly carbide-tipped (**Figure 3102.08.01**). Such saw blades are made of steel and have individually brazed carbide-tipped teeth of type K10. Chip-breaker and finishing teeth are arranged alternatingly on the circumference. The chip-breaker teeth are chamfered on both sides. The finishing teeth cut out the edges and a certain height difference.



Source: Gustav Wagner

TALAT Training in Aluminium Application Technologies | Carbide Tipped Saws and Tooth Geometry for Cutting Aluminium | 3102.08.01

The DIN standards 1837 and 1838 classify three types of bandsaws, N, H and W types. Type N is preferably used for aluminium. The H type is suitable for sawing very hard alloys and the type W for very soft ones. According to DIN 1840, saws with type C teeth (bowed teeth with chip-breaking and finishing teeth) and those with type B teeth (bowed teeth) are suitable for aluminium.

Bimetallic bandsaws are used to cut aluminium. The cutting geometry is mostly problem oriented, especially since this technology is still in the experimental stages. It is now possible to have an acceptable operating life even at very high sawing speeds of up to 2000 m/min. Bandsaws have economical advantages, since the material cut out with a bandsaw is only 10 % as much as that for circular saws. Consequently, valuable metal can be saved while cutting compact cross-sections.

Guide Values for Milling Wrought Aluminium Alloys

Cutting parameter	Tool material**)	Low strength wrought alloys (e.g. non-heat-treatable in unstrained condition or heat-treatable in soft condition)	High strength wrought alloys (heat-treated, highly strained)
Rake angle τ in °	HSS HM Diamond	15 to 30 10 to 20 (25) 2	15 to 30 10 to 20 2
Clearance angle α in °	HSS HM Diamond	9 to 20 9 to 20 6	9 to 20 9 to 20 6
Cutting speed v in m/min	HSS HM Diamond	up to 1200 up to 2500 up to 2500	up to 800 up to 2500 up to 2500
Feed s_z*) in mm/tooth max.	HSS HM Diamond	approx. 0.3 approx. 0.3 approx. 0.3	approx. 0.3 approx. 0.3 approx. 0.2
Cutting depth a*) in mm	HSS	up to 6 (∇) up to 0.5 (∇∇)	up to 6 (∇) up to 0.5 (∇∇)
	HM	up to 8 (∇) up to 0.5 (∇∇)	up to 8 (∇) up to 0.5 (∇∇)
	Diamond	up to 2.5 (∇) up 0.5 (∇∇)	up to 2.5 (∇) up to 0.5 (∇∇)
cooling lubricant	HSS HM Diamond	(emulsion) - -	emulsion (emulsion) (emulsion)

*) For shank-type milling cutters, the feed is also a function of the milling cutter diameter:
up to 6 mm milling cutter diameter: 0.1 mm/t (∇) or 0.08 mm/t (∇∇)
up to 20 mm milling cutter diameter: 0.2 mm/t (∇) or 0.12 mm/t (∇∇)
up to 50 mm milling cutter diameter: 0.25 mm/t (∇) or 0.17 mm/t (∇∇)

**) HM = carbide-tipped tools
HSS = high-speed tools

Guide Values for Milling Aluminium Casting Alloys

(for silicon-free casting alloys, the corresponding values for wrought alloys are approximately valid)

Cutting parameter	Tool material**)	Casting alloy with ≤ 12% Si	Casting alloy with > 12% Si
Rake angle τ in °	HSS	12 to 20	-
	HM	8 to 20	8 to 20
	Diamond	2	2
Clearance angle α in °	HSS	10 to 20	-
	HM	10 to 20	10 to 20
	Diamond	6	6
Cutting speed v in m/min	HSS	up to 600	-
	HM	up to 1500	up to 300
	Diamond	up to 2500	up to 1000
Feed $s_Z^{*)}$ in mm/tooth max.	HSS	approx. 0.2	
	HM	approx. 0.2	approx. 0.2
	Diamond	approx. 0.2	approx. 0.15
Cutting depth a*) in mm	HSS	up to 6 (∇) up to 0.8 (∇∇)	- -
	HM	up to 8 (∇) up to 0.8 (∇∇)	up to 8 (∇) up to 0.8 (∇∇)
	Diamond	up to 2.5 (∇) up 0.5 (∇∇)	up to 2.5 (∇) up to 0.5 (∇∇)
cooling lubricant	HSS	(emulsion)	
	HM	(emulsion)	emulsion
	Diamond	(emulsion)	emulsion

*) For shank-type milling cutters, the feed is also a function of the milling cutter diameter:
up to 6 mm milling cutter diameter: 0.1 mm/t (∇) or 0.08 mm/t (∇∇)
up to 20 mm milling cutter diameter: 0.2 mm/t (∇) or 0.12 mm/t (∇∇)
up to 50 mm milling cutter diameter: 0.25 mm/t (∇) or 0.17 mm/t (∇∇)

**) HM = carbide-tipped tools
HSS = high-speed tools

Guide Values for Sawing Aluminium with Circular Saws

Cutting parameter	**Tool material**)**	**Workpiece material group1)** **I**	 **II**	 **III**	**Remarks**
Clearance angle α in °	HSS HM	8 9 - 7	8 9 - 7	8 9 - 7	
Rake angle τ in °	HSS HM2)	25 10	25 8	15 6	
Cutting speed v in m/min	HSS HM	800 - 2000 400 - 600	500 - 1000 200 - 300 up to 3500	120 - 200 80 - 150 up to 2000	medium tooth pitch rough tooth pitch
Feed per tooth s_z*) in mm	HSS HM	up to 0.04 up to 0.06	up to 0.04 up to 0.06 up to 0.06	up to 0.04 up to 0.06 up to 0.06	medium tooth pitch rough tooth pitch
cooling lubricant	For lower cut lengths and lower cutting speeds: dry For longer cut lengths and higher cutting speeds: emulsion, cutting oil or synthetic lubricants dissolved in water (spray or mist lubrication)				

1) Group I : non-heat-treatable wrought alloys, heat-treatable wrought alloys soft state
Group II : aged wrought alloys, casting alloys with low silicon content
Group III : casting alloys with more than 12 % silicon

2) Circular saws for anodised sections often have smaller rake angles

*) For shank-type milling cutters, the feed is also a function of the milling cutter diameter:
up to 6 mm milling cutter diameter: 0.1 mm/t (∇) or 0.08 mm/t (∇∇)
up to 20 mm milling cutter diameter: 0.2 mm/t (∇) or 0.12 mm/t (∇∇)
up to 50 mm milling cutter diameter: 0.25 mm/t (∇) or 0.17 mm/t (∇∇)

**) HM = carbide-tipped tools
HSS = high-speed tools

3103 Machines for Machining Aluminium

3103.01 Specifications
3103.02 Drives and rigidity
3103.03 Spindle construction
3103.04 Control and regulation
3103.05 Clamping and gripping tools
3103.06 Equipment for cooling lubricants and cutting fluids
3103.07 Chip removal equipment
3103.08 Aluminium specific machines

The very good machinability of aluminium and the very effective cutting materials available can be used to their full advantage only if machines ideally suited for this purpose are available. Conventional equipment is unsuitable, especially since machines which are suitable for working aluminium are fundamentally different from those necessary for machining steel. This chapter will give a survey of these differences and explain the design and construction parameters for machines especially suited for aluminium.

3103.01 Specifications

General requirements for tool machines giving optimum performance for machining of aluminium and its alloys are described as follows:

- High cutting speeds.
  Nowadays, castings can be machined at speeds exceeding 2000 m/min. Wrought alloys can be machined at much higher cutting speeds (up to 4000 m/min). Carbide-tipped tools have acceptable operating lives even at these extremely high cutting speeds.
- High power requirements.
  The fact that the cutting force required for aluminium is only a third of that required for steel, does not in any case mean that the power of a machine designed for machining steel is sufficient for machining aluminium also. On the contrary, much more power is required to be able to operate the machines at the much higher cutting speeds.
- High dynamic rigidity.
  The effect of centrifugal and unbalanced forces at high rotational speeds makes it necessary to increase the dynamic rigidity.

- Fixtures and clamps.
  The low modulus of elasticity of aluminium has to be taken into account while clamping the workpiece. Deformations due to the reaction of clamping and cutting forces should be avoided. Magnetic fixtures are not to be used with aluminium. The surface of aluminium parts is relatively sensitive to scratches caused by clamping fixtures.

- Sufficient chip removal.
  Due to the high cutting speeds, the volume of chips produced is much higher than for steel. The type of chips produced ranges from fragmented to long and straight. While removing the chips, care must be taken to see that the chips do not come in contact with the freshly machined surface.

- High feed rates with efficient control.
  High feed rates are necessary for the high cutting speeds used. This in turn means that a precise control is required, for example when radii are being turned.

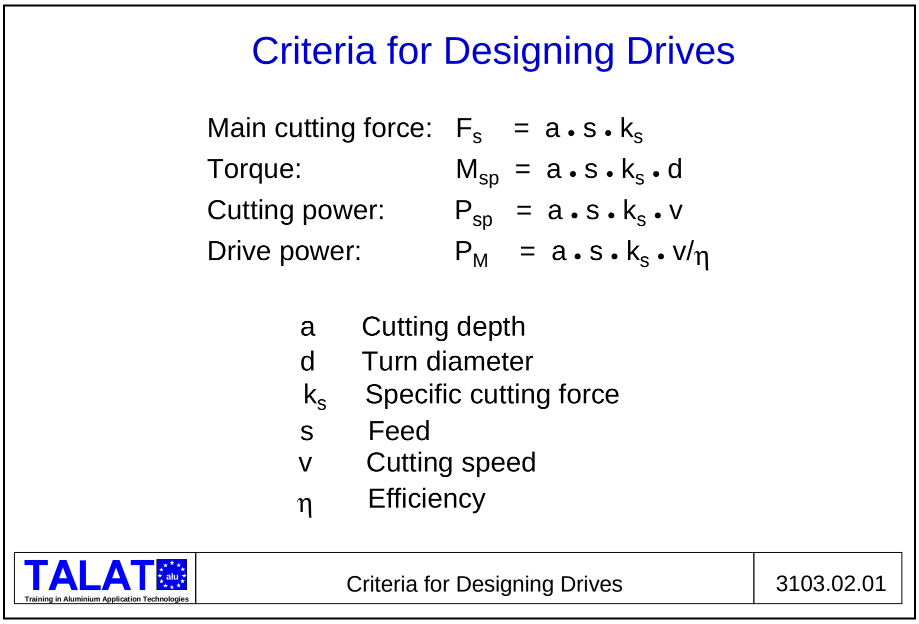
- Equipment for cooling lubricants.
  Although it is possible, in some cases, to machine aluminium without cooling lubricants, the machines used should be equipped with the necessary arrangements.

3103.02 Drives and Rigidity

The machines used must have as high a dynamical rigidity as possible to accommodate the high rotational speeds and the high acceleration and deceleration of the spindle drive. This is achieved by the following measures:

- Careful design and construction using appropriate methods (for example, finite element calculation) and computers.
- Highly ribbed construction and heavy construction of the machine components.
- Using reinforced concrete with good damping properties for supports and stands.
- Light construction for moving parts.
- Broad guiding tracks having a high wear resistance and long life expectancy.

The drive is designed taking the cutting speed and machining rate into consideration (**Figure 3103.02.01**). With increasing speeds, an ever increasing part of the installed power is converted into heat which must then be removed using cooling systems. The reason is that friction in the precision ball bearings and sleeve bearings increases with increasing rotational speeds. The power required increases over-proportionally.



Criteria for Designing Drives

Main cutting force: $F_s = a \cdot s \cdot k_s$
Torque: $M_{sp} = a \cdot s \cdot k_s \cdot d$
Cutting power: $P_{sp} = a \cdot s \cdot k_s \cdot v$
Drive power: $P_M = a \cdot s \cdot k_s \cdot v/\eta$

a	Cutting depth
d	Turn diameter
k_s	Specific cutting force
s	Feed
v	Cutting speed
η	Efficiency

TALAT alu Training in Aluminium Application Technologies | Criteria for Designing Drives | 3103.02.01

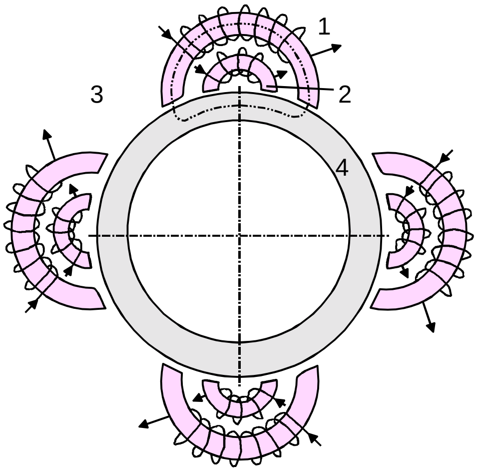
3103.03 Spindle Construction

Most of the parts to be machined have diameters of less than 100 mm. Fast rotating spindles are required to be able to machine these parts at cutting speeds up to 2000 m/min. The same holds true for milling. In order to attain these high cutting speeds, the spindles must rotate at speeds of around 20,000 rpm and reach peak speeds of 40,000 rpm. Besides being able to turn at high speeds, the spindles must be able to transmit this power to the workpiece and, as in the case of drilling and thread cutting, be able to accommodate large axial forces.

Conventionally constructed spindles cannot fulfil these requirements. For this reason, in the last few years, different new types of spindle systems which fulfil the above requirements, have been constructed:

- Special spindle types with ball bearings. Speeds of up to 20,000 rpm can be reached.
- Spindle types in sleeve bearings (for example, ceramic bearings, pressure reduction through trapped air etc.) up to 40,000 rpm.
- Spindles with active magnetic bearings for speeds up to 50,000 rpm. In this system, a cylindrical rotor floats in an electromagnetic field created by electromagnets arranged in symmetrical pairs in a stator (**Figure 3103.03.01**).

Schematic Construction of an Active Magnetic Bearing for a Spindle

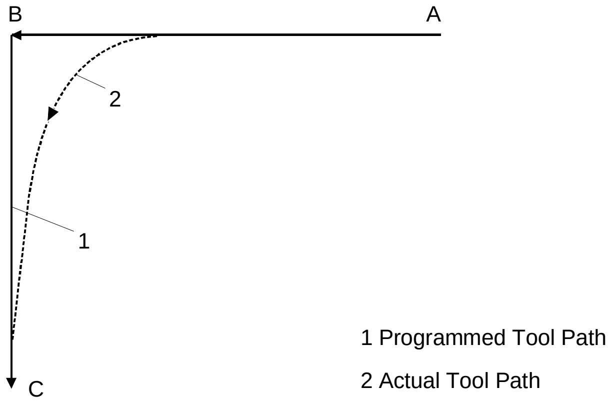


Schematic Construction of an Active Magnetic Bearing for a Spindle 3103.03.01

3103.04 Control and Regulation

The control of the shaft drive at high cutting speeds and feed rates is problematic. The unavoidable switching time-lag causes a difference between planned and actual positions, called the lag error. This error results in an inadmissible rounding-off of the edges which is proportional to the feed rate (**Figure 3103.04.01**). A similar error occurs during milling operations. Due to the lag error, the programmed radius cannot be obtained. The amount by which the radius is shortened depends on the feed rate.

Edge Rounding During High-Speed Cutting



Edge Rounding During High-Speed Cutting 3103.04.01

A further problem which occurs especially at high feed rates is the processing time of the control system. In the free programmed paths, the feed rate depends on the block processing time of the control and on the distance of the programmed coordinates. For the normal block processing times of 10 ms and programmed distances of 0.5 mm, a maximum feed rate of 3,000 mm/min should not be exceeded so that the control system can keep in step with the data processing. This would otherwise lead to interruptions in the feed, which would make themselves felt during machining as vibrations.

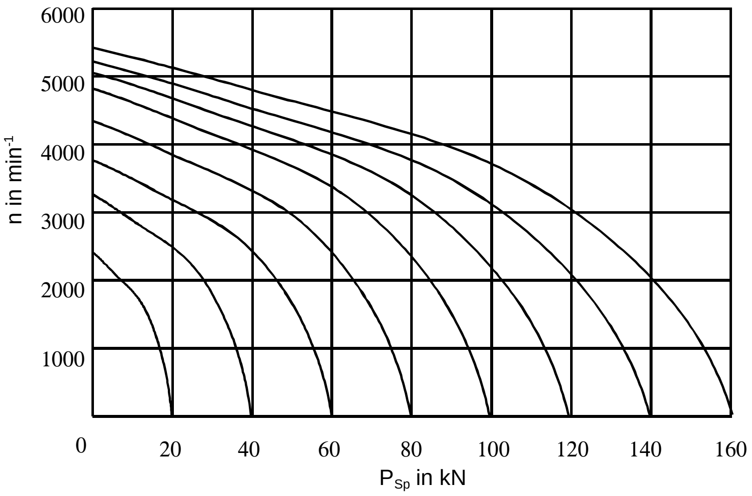
The problems described above show that standard control systems can have only a limited use for controlling machining operations for aluminium efficiently. This has led to the development of special control concepts for high speed machines for aluminium. Such controls have passed the testing phase and are now available.

3103.05 Clamping and Gripping Tools

Torque is transmitted by chucks through friction at the grips. The torque changes proportionally to the main cutting force; for aluminium workpieces, it is about 2/3 less than that for steel. The frictional force is larger in the case of aluminium than with steel. As far as the statics are concerned, it should, therefore, be possible to hold aluminium with much lower clamping forces, thereby reducing the possibility of marring the sensitive aluminium surface with grip markings.

When machining aluminium workpieces, which rotate at high speeds, the centrifugal force acts against the gripping force and causes it to be reduced (**Figure 3103.05.01**).

Reduction of Clamping Force Due to Centrifugal Forces Acting on Chucks



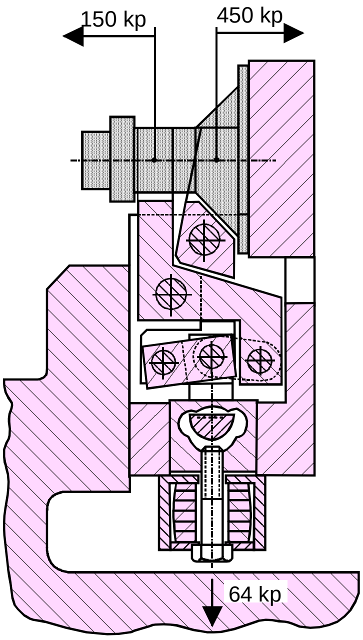
TALAT Training in Aluminium Application Technologies | Reduction of Clamping Force Due to Centrifugal Forces Acting on Chucks | 3103.05.01

This effect has to be taken into account during clamping and can be counteracted by using a number of different measures:

- Chucks with counterbalances.
- Controlling the gripping force by regulating the pressure in the operating cylinder.
- Distributing the clamping force over a large number of gripping locations.

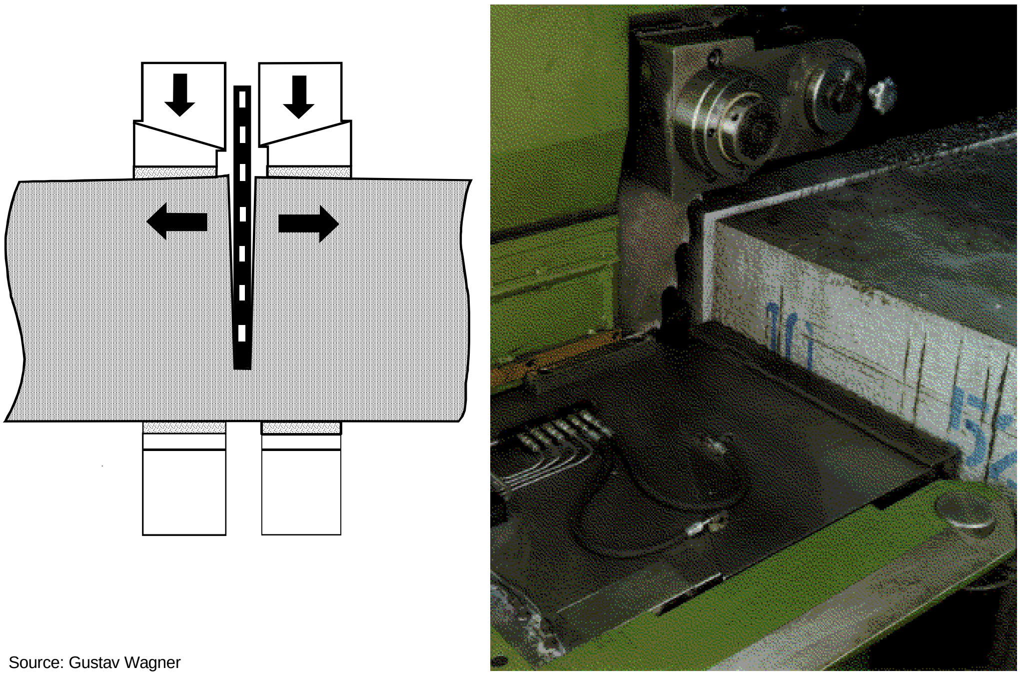
Aluminium is nonmagnetic. When it is to be machined on palettes, it is best to be fixed using vacuum activated grips. As soon as the palette is introduced into the machine, the vacuum is activated, thereby holding the workpiece flat in place.

Special gripping equipment is required for machining large series of parts on automatic machines. Such equipment consists basically of gripping equipment which is adapted for the specific needs of the work material and allows the shortest time for tool changes. Such fixtures are relatively complicated, especially since problematic boundary parameters have to be taken into account. **Figure 3103.05.02** shows an example of a clamping fixture for a petrol pump housing.



Clamping Fixtures for Petrol Pump Housing 3103.05.02

A major problem that occurs during the cutting operation is the tendency of the material to deform elastically under the action of the residual stresses. In the case of aluminium with its relatively low modulus of elasticity, such deformations are rather large. Thus, during sawing operations for example, the equilibrium of the residual stresses is disturbed and the resulting forces set free can cause the saw to jam. To prevent this happening, the clamping fixture shown in **Figure 3103.05.03** causes the cut gap to widen out.



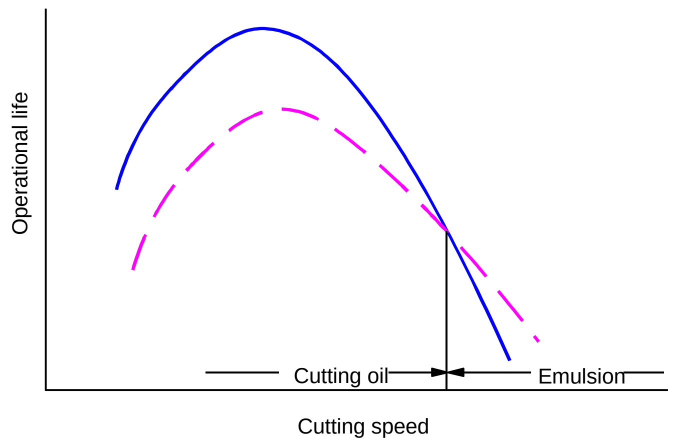
Source: Gustav Wagner

TALAT Training in Aluminium Application Technologies | Elastic Widening of Cutting Gap During Sawing of Aluminium Ingots | 3103.05.03

3103.06 Equipment for Cooling Lubricants and Cutting Fluids

Cooling lubricants (cutting fluids) play a double role: The lubricating action reduces transport friction of the chips and prevents heat generation and wear, whereas the cooling action helps to transport the generated heat. The composition and viscosity used depends on the cutting conditions. In general one can say that the lubricating action should be greater for workpieces which are harder to machine. Aluminium can be classified here as being easy to machine so that the emulsions used should have a high cooling action.

The supply system used should be able to deliver the fluid effectively up to the cutter. Due to the high cutting speeds, special measures are necessary for this purpose. Delivering the fluid under high pressure gives good results especially since the fluid jet can destroy the vapour film which tends to prevent heat exchange. Mist or spray lubrication using exceedingly fine droplets have proven to be very effective. Such spray equipment works economically and has a good cooling action due to the relatively large contact area (**Figure 3103.06.01**).



Influence of Water-Insoluble and Water-Soluble Cooling Lubricants on Operational Life

3103.06.01

3103.07 Chip Removal Equipment

An automatic removal system is indispensable because of the large volume of chips created. An efficient chip removal system must be considered in the design and construction of the frame. It is important that the chips are broken and fragmented. An aggregate consisting of continuous chips cannot be removed easily.

The actual tasks required can vary depending on the chip types and the local conditions. A number of transport and removal systems are available:

- Slat band chain conveyors are the most widely used types since they have clear advantages: They can be used effectively for all types of chips. They do not occupy much space and can be adapted flexibly in the machines. The cutting fluid sticking on the chips can drop down through the conveyor. The volume of chips to be transported can be easily controlled by regulating the conveyor speed.
- Scraper flight conveyors are particularly useful for transporting short chips not longer than 5 cm. A big disadvantage is the high wear. On the other hand, scraper flight conveyors are cheap and almost as flexible in use as link band conveyors.
- Screw (worm) conveyors are used to transport short and medium length chips over short distances. The energy required for transporting is relatively high.
- Pneumatic transport systems are particularly useful for transporting the very light aluminium chips over long distances. Thrust rod conveyors arranged as floor-mounted collective conveyors are used for distances of up to 200 m.

3103.08 Aluminium Specific Machines

The characteristics described above show that machines which can machine aluminium efficiently must meet the very high specific standards required. Such machines are, however, only available as special purpose constructions, since the demand for these is relatively low. In actual practice one may find machines designed specially for machining aluminium mostly there where a sufficiently large machining potential exists: wheel fabrication, milling machines for the aerospace industry, ingot milling machines, machining castings for the automotive industry.

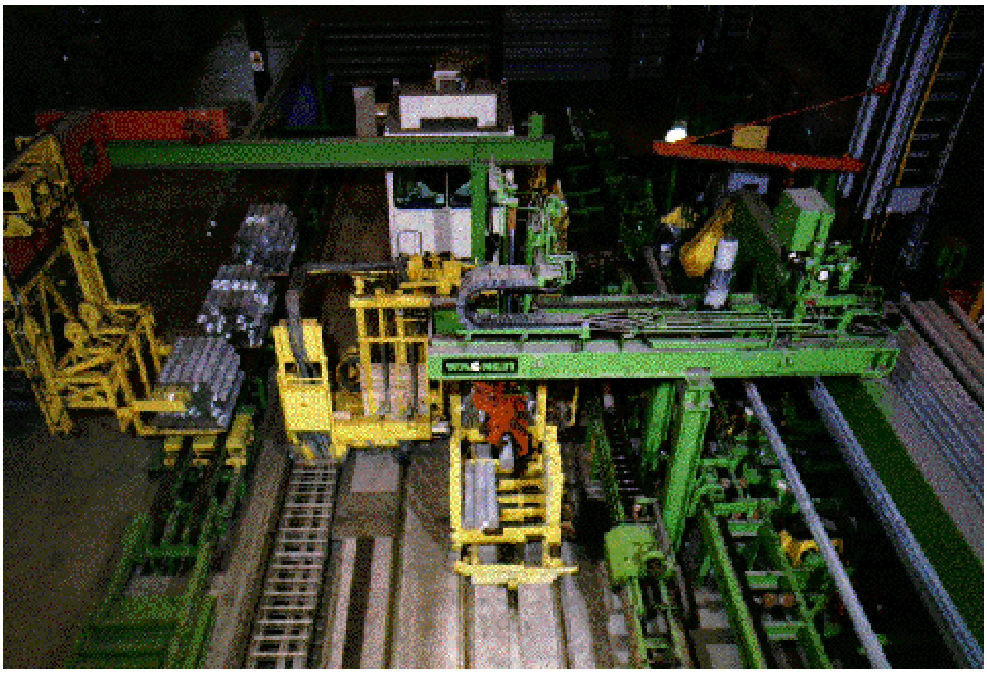
Special purpose machines designed for aluminium are most consequently used for the recently developed high speed machining. High speed milling machines which fulfil all the requirements for machining aluminium are available nowadays. Till now, such machines are used mainly in the aerospace industry for milling integrated components made of high-strength wrought alloys. In such components, about 90 % of the material has to be milled to produce a thin-walled stable component.

With these machines it was possible to reduce the machining time by 50 % or more. Besides the economical advantages, it was possible to improve the quality of the components produced, since both temperature of the components as well as its surface roughness at these extremely high cutting speeds could be drastically reduced (**Figure 3103.08.01**).

TALAT Training in Aluminium Application Technologies | Machines for the High-Speed Machining of Aluminium | 3103.08.01

Another successful application is the use of circular saws in the fabrication of aluminium semifabricates. Efficient sawing equipment is used for cutting rolling and extrusion billets. With the large tool diameters, it is possible to attain high cutting speeds without any additional measures regarding spindles and controls. Extrusion billet saws require a power of about 100 kW, rolling billets about 200 kW.

Sawing equipment used in plants for semifabricates, clearly illustrate the necessity of having efficient peripheral equipment to cope with efficiently designed machines for machining aluminium. The machines can be used to their full capacity only if a very quick transport of the blanks and workpieces is guaranteed. For moving heavy parts (e.g. extrusion billets) to and from the machines a much greater effort is required than for the sawing itself. The sawing of even large billets having diameters of about 200 mm requires only a few seconds. All other handling operations on the workpieces should be ideally completed within this time (**Figure 3103.08.02**).



Source: Gustav Wagner

TALAT alu
Training in Aluminium Application Technologies

Integrated Billet Sawing Equipment
in an Aluminium Smelter

3103.08.02

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3102.**08**.01	Carbide-Tipped Saws and Tooth Geometry for Cutting Aluminium
3103.**02**.01	Criteria for Designing Drives
3103.**03**.01	Schematic Construction of an Active Magnetic Bearing for a Spindle
3103.**04**.01	Edge Rounding during High-Speed Cutting
3103.**05**.01	Reduction of Clamping Force due to Centrifugal Forces Acting on Chucks
3103.05.02	Clamping Fixtures for Petrol Pump Housing
3103.05.03	Elastic Widening of Cutting Gap during Sawing of Aluminium Ingots
3103.**06**.01	Influence of Water-Insoluble and Water-Soluble Cooling Lubricants on Operational Life
3103.**08**.01	Machines for the High-Speed Machining of Aluminium
3103.08.02	Integrated Billet Sawing Equipment in an Aluminium Smelter