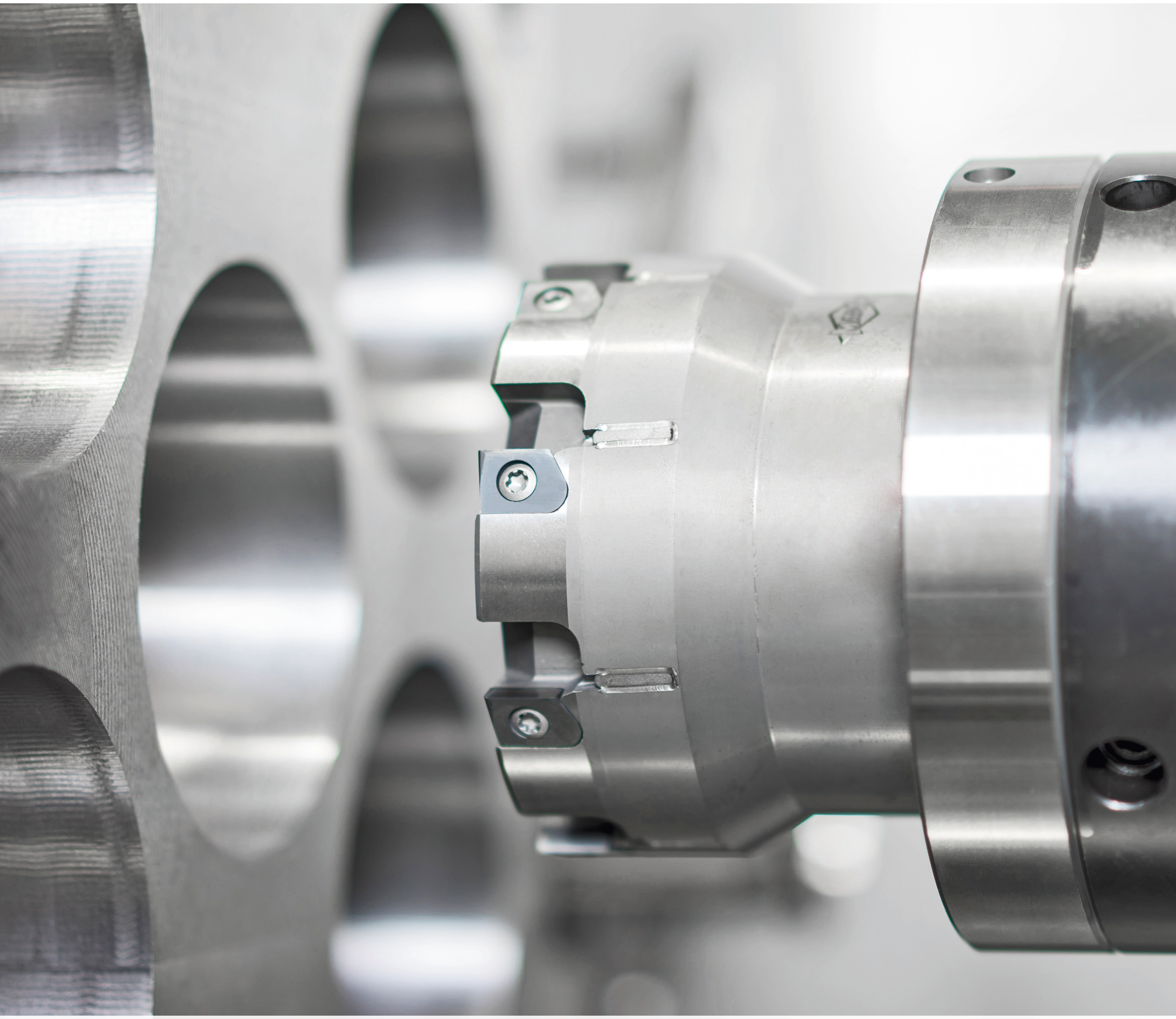
TECHNOLOGY REPORT

07 | Fine machining of functional surfaces in grey cast iron materials



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Motivation

Motivation

Grey cast iron continues to be a material in high demand because the manufacturing costs are low and its properties can be specifically adjusted using alloying elements. In this way it is possible to obtain optimal combinations of properties for specific applications. The excellent tribological sliding and dry-running properties are further special material-related aspects of cast iron. These properties result from exposed graphite layers in the cast iron material and are retained even if graphite is lost during the usage phase because voids act as solid lubricant reservoirs. Cast iron materials can be categorised into white and grey cast iron, refer to Figure 1. Cast steel and special cast alloys also belong to this material group. Due to the characteristics stated above and the good mechanical properties, such as high strength and rigidity along with excellent damping characteristics, among other areas grey cast iron materials are currently used in diesel engines subjected to high loads (heavy duty, lorry engines). Here cast iron with lamellar graphite (GJL), cast iron with vermicular graphite (GJV) and cast iron with spheroidal graphite (GJS) compete with each other.

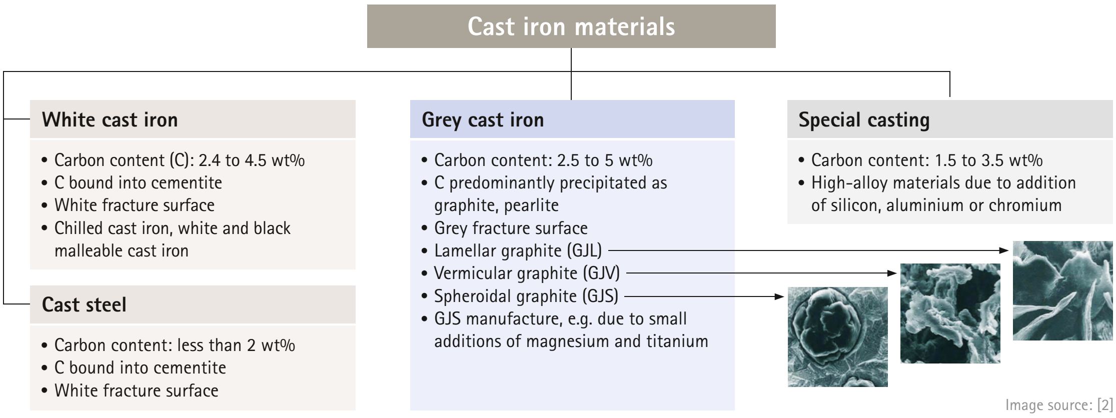

Figure 1: Categorisation of cast iron materials, [1]

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Motivation

Based on the annual cast iron production, 57 % of cast iron is grey cast iron [3]. Due to the good casting properties of grey cast iron, parts can manufactured close to their final contour. Nevertheless, further machining is required during the manufacture of functional surfaces to ensure characteristic properties such as sliding, guiding, sealing and adhesion. The requirements on functional part surfaces as well as the part quality are in general continuously increasing. For reliable compliance with the required macro and microgeometric properties, increasing use is made of fine and precision machining methods and it is necessary to develop appropriate tool and cutting material solutions adapted to the machining task. For this reason this technology report addresses the fine machining of functional surfaces on grey cast iron parts.

Properties of grey cast iron materials

Properties of grey cast iron materials

This technology report considers a selection of grey cast iron materials that are shown in Figure 2 with their mechanical and manufacturing-related characteristics. The term „grey cast iron" is derived from the grey appearance of the material when fractured and is caused by a colouration of the surface by the embedded graphite. Graphite and pearlite are in turn produced primarily due to the precipitation of carbon. Grey cast iron materials are primarily differentiated based on the manner in which graphite is formed (lamellar, vermicular or spherical). A further structural feature is the steel-like base structure made of ferrite and pearlite. Only by alloying with silicon is the characteristic grey cast iron structure formed. Grey cast iron has excellent casting properties as well as a good capacity for filling moulds allowing complex contours and thin walls to be created [4].

The main alloying elements for cast iron materials are iron (Fe), silicon (Si) from 0.8 % to 3 % as well as carbon (C) from 2.5 % to 5 % [5]. Chromium, molybdenum and vanadium additives are carbide forming elements that result in greater strength and hardness, but worse machinability. In particular the carbon content is crucial for the subsequent structure of the cast iron alloy.

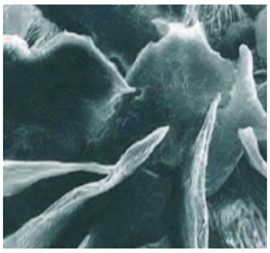
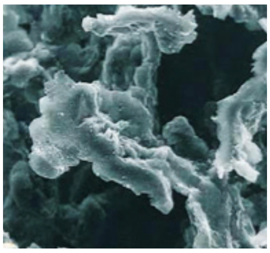
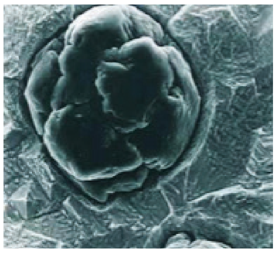
Grey cast iron materials (C content 2.5-5%)			
	Lamellar graphite casting (GJL)	Vermicular graphite casting (GJV)	Spheroidal graphite casting (GJS)
Structure Image source: [2]			
Density in g/cm^3	7,2	7,2	7,2
Tensile strength in MPa	250 to 400	300 to 500	400 to 800
Modulus of elasticity in GPa	100 to 135	130 to 160	160 to 185
Fracture toughness in N/mm$^{3/2}$	320 to 560	295	150 to 310
Ultimate strain in %	0,3 to 0,8	1 to 5	2 to 22
Castability	very good	good	good
Use	Car, commercial vehicle engines	Large engines	Commercial vehicle, large engines

Figure 2: Graphite structures in grey cast iron and their mechanical and manufacturing characteristics, [6]

Machinability of grey cast iron – influence of specific material characteristics

Machinability of grey cast iron – influence of specific material characteristics

The reliable machining of parts made of grey cast iron by cutting requires the consideration of a few special aspects during the design of machining processes; these aspects are addressed in the following. In various studies it has been found that ageing has a positive effect on the machinability of cast iron. Due to ageing, the cutting forces and the tool wear reduce, and the surface quality and form accuracy increase [7]. Studies by RICHARDS were able to demonstrate a statistically verified influence due to ageing effects on the machinability of clutch and brake discs made of GJL. Figure 3 a) shows the significant improvement in the machinability after natural ageing at room temperature for up to 1000 hours. After an ageing period of 30 days, 2 - 4 µm nitride precipitates form that cause a strength increase of up to 13 %. Microhardness measurements showed a hardness increase in the ferritic pits around the graphite nodules from 190 HV to 260 HV in 30 days. The material brittleness, which increases with the increasing material strength, produces shorter chip breaking that has a positive effect on the tool wear [4].

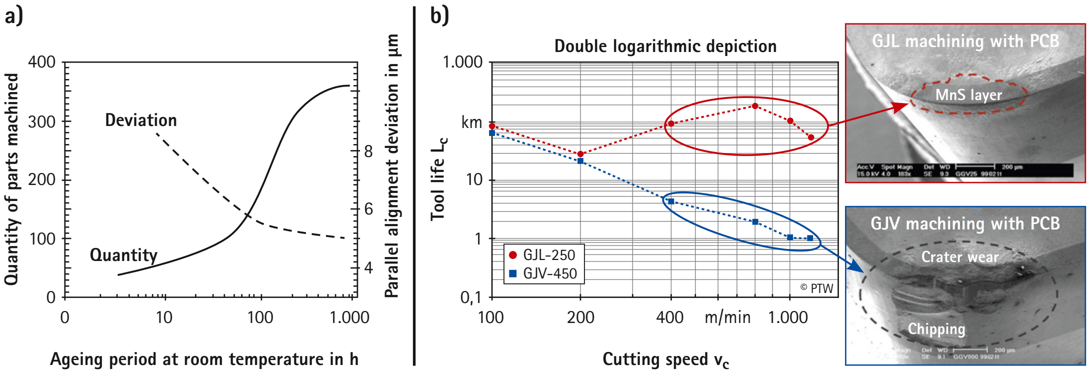


Figure 3: **a)** Effect of ageing on the machinability, [4];
b) Tool life as a function of the cutting speed during the fine machining of GJL and GJV with PcBN, [1]

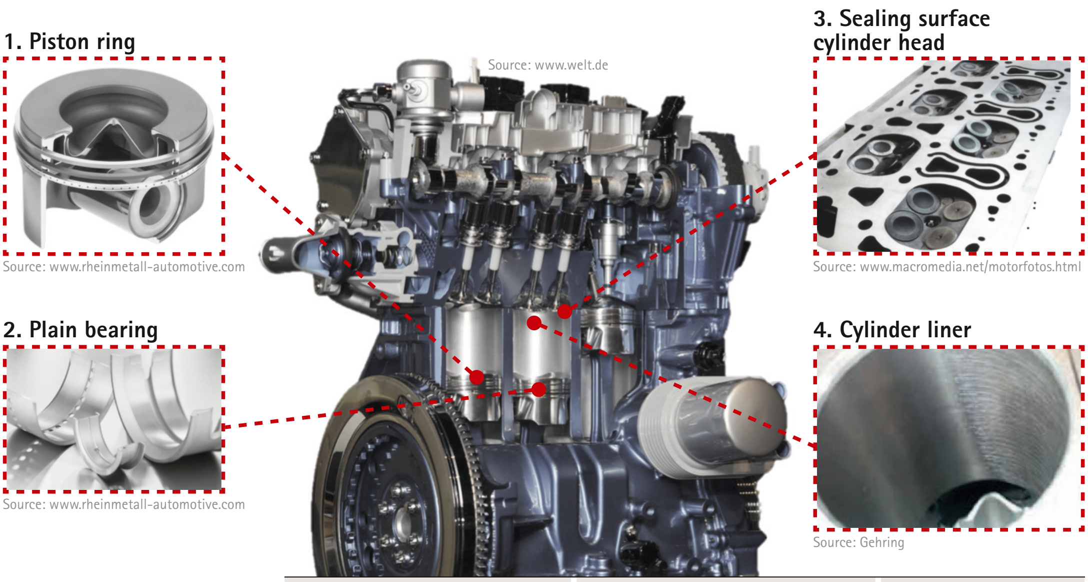
Along with the ageing effects, it was also possible to demonstrate the positive effect on the tool wear of a manganese-sulphide layer that is formed. A comparison of the three cast iron materials in Figure 2 shows that the cost-effectiveness of the fine machining of GJV and GJS is significantly lower than that of GJL. The difference is due to better machinability as a result of the formation of a wear-minimising manganese-sulphide layer on the tool's cutting edge. This provides long tool lives during the fine machining of lamellar cast iron materials (GJL) using polycrystalline cubic boron nitride (PcBN) or cutting ceramics [8, 9]. If, due to the material composition, a wear protection layer does not form during the fine machining of bores in GJV, lower tool lives may result, see Figure 3 (b). In addition, the material composition has a significant effect on the machinability, particularly of GJV alloys. If, for instance, the titanium content of the GJV alloy is limited to values less than 0.006 mass per cent, significantly longer tool lives can be expected [1].

Cutting materials and tool concepts for machining functional surfaces by cutting

Cutting materials and tool concepts for machining functional surfaces by cutting

What are functional surfaces?

Iron-carbon cast materials are in the group of tribo-technological materials in machine and plant engineering and are particularly suitable as structural materials for functional surfaces subjected to tribological loads. A selection of functional surfaces in the combustion engine is shown in Figure 4. Requirements on functional surfaces include sliding, guiding, accumulation as well as adhesion and sealing. The graphite lamellae embedded in the grey cast iron material act as solid lubricant phases, as a consequence functional surfaces have dry-running properties if lubrication is inadequate. In addition, both the thermal and mechanical material properties have a significant effect on the tribological behaviour of the part, although the friction and wear behaviour of material pairs cannot be derived directly from their properties.



Component	Function	R_z according to VDI/VDE2601
1. Piston ring	Sealing, guiding, sliding	0.6 - 6 µm
2. Plain bearing	Sliding	0.3 - 10.5 µm
3. Sealing surface cylinder head	Sealing	6 - 11.5 µm
4. Cylinder liner	Sliding, guiding, retention	0.3 - 10.5 µm

Figure 4: Selected function surfaces based on the example of a large combustion engine

Grey cast iron (GJL, GJV and GJS) is one of the most important crankcase materials for large combustion engines. In particular the usage of lamellar grey cast iron offers advantages in relation to the low material costs and the good machining properties. Due to the different graphite structures as well as the material properties of grey cast iron materials, the following tribotechnological application areas can be defined: cast iron with lamellar graphite (GJL) has been proven particularly for functional surfaces with sliding loads. Machine tool guides, brake discs or cylinder linings in combustion engines are preferably made of lamellar grey cast iron. For functional surfaces subject to scoring loads high alloyed cast iron types with carbide embedding are used. Fundamentally, the high wear resistance of the so-called chilled cast iron types results from a graphite-free structure with special embedded carbides. Cast irons with spheroidal graphite (GJS) are particularly suitable for functional surfaces with rolling loads. In comparison to cast iron with lamellar graphite, the wear rate slows with the usage of spheroidal graphite cast iron due to its higher ductility reserves [10].

Another positive feature of grey cast iron materials is the low tendency to deformation in the area of the cylinder linings and the main bearings. Because grey cast iron materials can also be used for cylinder linings with high tribological loads, some process steps are not required, Cutting materials and tool concepts for machining functional surfaces by cutting

for instance the thermal spray coating of cylinder linings in crankcases made of aluminium. Cast iron with vermicular graphite, on the other hand, is suitable for higher thermo-mechanical loads, but as mentioned at the start has significantly poorer machinability. As a consequence cast iron with vermicular graphite is currently only used for supercharged diesel engines [11].

The manufacturing processes widely used for the manufacture of functional surfaces on cylinder linings and crankshafts are honing, laser structuring and deep rolling. For instance, multidirectional surface structures can be achieved on roller bearing shells using a kinematically modulated transverse-peripheral external grinding process. In this way the elastohydrodynamic lubricating film properties can be specifically adjusted and changed in relation to the functional surface topography [10].

Tool concepts for the manufacture of functional surfaces

Tool concepts for the manufacture of functional surfaces

Machining methods with a geometrically defined or geometrically undefined cutting edge are mostly used to manufacture functional surfaces. Examples of processes with a geometrically undefined cutting edge are honing, grinding or also lapping. During the fine machining of cast iron materials with a geometrically undefined cutting edge, the so-called superficial effect represents a significant problem during the manufacture of functional surfaces. The term superficial effect describes in general a plastic material deformation on the surface of the part that can be caused by, for example, blunt honing bars or the deep rolling method. Material compression and flaking on the machined surfaces of the part fill the honing grooves and smear the graphite lamellae so that the dry-running properties of the functional surfaces are minimised [12].

For the fine machining of functional surfaces with a geometrically defined cutting edge, for instance fine boring or reaming, there exists a very wide range of tool concepts (see on this topic Figure 5). Suitable tool concepts are selected based on the specific boundary conditions as well as taking into account the cost-effectiveness. Tools with indexable inserts (1), (2) offer advantages due to low tool circulation costs, fine boring tools (2) guarantee very high shape and position accuracies and multi-bladed reamers (3) impress due to short cycle times and high output. The various tool bodies can be tipped with different cutting materials for this purpose.

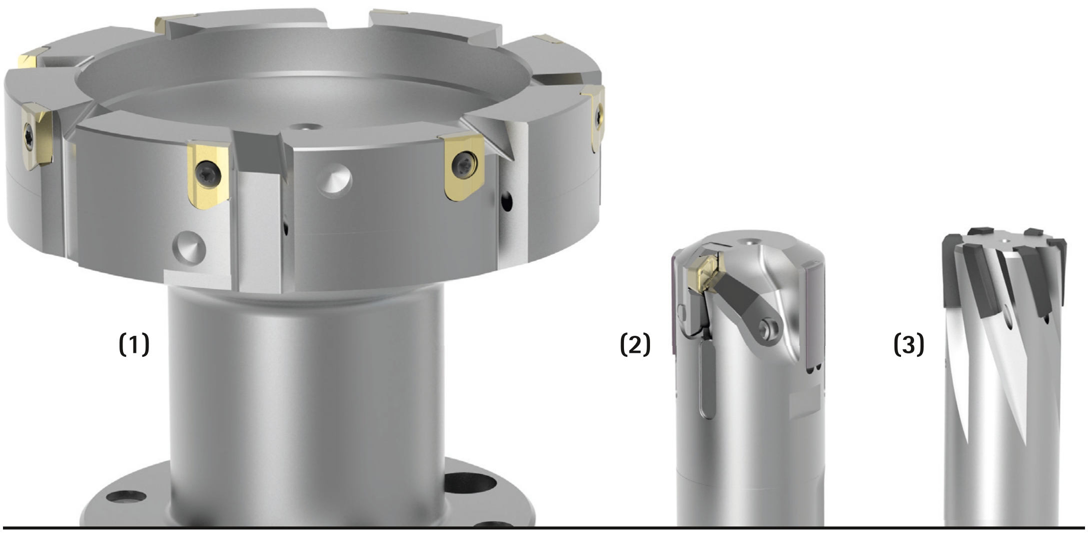


Figure 5: Tool concepts for fine bore machining using a geometrically defined cutting edge

Tool concepts for the manufacture of functional surfaces

Along with the cutting methods, forming manufacturing methods such as smooth rolling, deep rolling or finish rolling are used to achieve certain part functions. During rolling, the surface of the part is formed using one or more balls or using rollers, in this way hardening as well as a higher compressive stress component in the parts outer layer can be achieved. It is also possible to achieve a low roughness and also excellent surface quality using these forming methods. All materials with high ultimate strain that can be formed plastically are suitable for fine machining by forming. Brittle cast iron materials often tend, on the other hand, towards craking in areas close to the surface on the usage of these methods and are therefore only of limited suitability for these machining methods.

Cutting materials for machining grey cast iron materials

Cutting materials for machining grey cast iron materials

In general, primarily coated carbides (HC) and PcBN cutting materials are used for the fine machining of cast iron materials. For finishing cast iron with vermicular graphite (GJV), however, carbide cutting materials in cutting material group K are used in particular. Carbide cutting materials in application group K10 in combination with matched cutting tool design and edge rounding greater than 50 µm without additional chip forming geometry offer very good tool life behaviour during fine boring processes with a continuous cut. During the machining of vermicular cast iron, a cutting speed increase has the greatest effect on the tool usage behaviour compared to an increase in the feed and material removal rate (see Figure 3).

In particular during the machining of cast iron with lamellar graphite, often the extremely hard cutting material boron nitride (PcBN) is used, and in special cases also polycrystalline diamond (PCD), HC and cermet. The stated cutting material types are used here depending on the type of graphite precipitation in the cast iron and the specific machining task. With the exception of PcBN, the cutting speed for the fine machining of cast iron materials should be chosen between 80 m/min and 220 m/min. For cutting materials made of boron nitride, on the other hand, significantly higher cutting speeds of up to 1,200 m/min apply, see table 1.

	Cutting speed v_c [m/min]				
	Coated carbide	Cermet	Coated cermet	PcBN	PCD
GJL	80 - 120	90 - 120	110 - 220	600 - 1,200	50 - 110
GJS	80 - 120	90 - 120	110 - 220		
GJV	80 - 110	80 - 100	100 - 180		

Table 1: Cutting speeds for the fine machining of grey cast iron

In addition, in the latter case the machining by cutting should be undertaken dry so that the wear-minimising maganese-sulphide layer can form on the tool cutting edge due the elevated machining temperatures, see Figure 3 (b). On the other hand, process conditioning using cryogenic CO_2 snow cooling is recommended for finishing vermicular grey cast iron so that the thermal load on the tool due to the lack of the manganese-sulphide protective layer can be reduced [1].

Machining example: Fine machining of cylinder linings

Machining example: Fine machining of cylinder linings

The cylinder lining is manufactured using a multi-stage process chain comprising a fine machining method and a precision machining method. Each cylinder bore is initially given the required macro-geometry (cylindrical form and position) using the fine boring machining method (method with a geometrically defined cutting edge).

Cylinder block with grey cast iron liners	
Material:	GG26Cr
Cylinder bore:	Ø = 92.9 mm
Machining time:	3 s

Cutting data for the multi-bladed fine boring tool	
Cutting material:	PcBN
Cutting speed:	v_c = 1,000 m/min
Feed rate:	v_f = 3,083 mm/min
Spindle speed:	n = 3,430 rpm
Number of teeth:	z = 5
Cutting depth:	a_p = 0.3 mm
Feed:	f = 0.9 mm

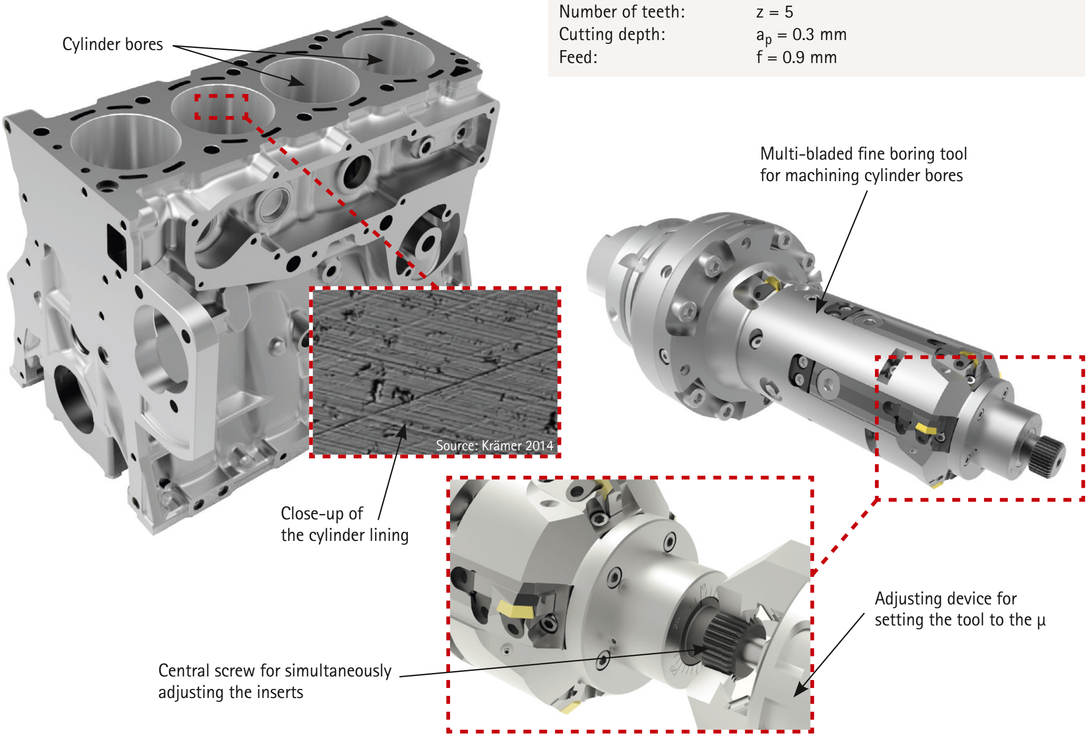


Figure 6: Fine boring cylinder linings on a grey cast iron crankcase with depiction of the tool concept, cutting parameters and a section of the functional surface

Actuating tools with a fine adjustment feature are used for the fine boring operations. The low material removal and the high cutting speeds are characteristic. Mostly pull/push rod mechanisms or coolant pressure are used for adjusting the cutting edge, as is the case on the tool shown in Figure 6. The cutting edges are initially positioned at the machining diameter set by controlling the coolant pressure (approx. 50-60 bar) and the cylinder bore is machined. On completion of the machining, the coolant pressure is switched off, the adjustable arms with the finishing blades lift off the workpiece and the tool can be retracted from the bore without scoring. Furthermore, via a central screw positioned on the end of the tool the cutting edges can be re-adjusted to the µ, either manually using an assembly tool or automatically using an adjusting mechanism mounted in the machining centre, to compensate for the cutting edge wear.

A defined surface profile is required for the subsequent honing process; this profile can be produced using fine boring operations. The requirement in relation to the average roughness depth R_z is 8 to 16 µm (see Figure 7).

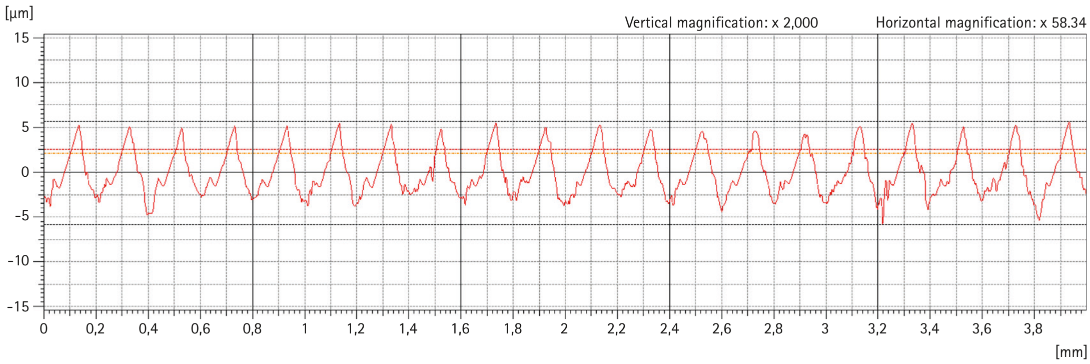


Figure 7: Defined surface profile before honing

Machining example: Fine machining of cylinder linings

The functional properties of the cylinder bore are produced in a second process step by using a honing tool (method with a geometrically undefined cutting edge). The resulting microgeometry defines the functional properties of a completely honed surface that includes the tribological states „adhesion" and „sliding" as well as „guiding". The deviation on the cylindricity after the honing should be less than 6 µm. A key advantage of the material grey cast iron when used for a crankcase is the dry-running properties due to the exposure of the graphite inclusions. The cross-hatch groove structure is a typical surface structure due to the honing and in combination with the exposed graphite produces excellent tribological sliding properties (see Figure 6). A release of graphite also results in the formation of voids that act as lubricant reservoirs.

Machining example: Brake calliper with a multi-bladed reamer

Machining example: Brake calliper with a multi-bladed reamer

During the machining of a brake calliper, several machining steps are necessary in particular for the manufacture of the closely toleranced functional surfaces. The machining of the channels and the connection bores is fundamental for the further process steps. Then the piston bore is roughed with subsequent fine machining of the grooves and clearances with the aid of actuating tools. The functional surfaces in the area of the piston bore are then finished (see Figure 8). This finishing action is divided into the following three machining steps that take place simultaneously:

- Fine machining of face surface and stepped connection bore (incl. chamfers)
- Fine machining of the face surface (close to the connection bore incl. chamfers)
- Fine machining of the main bore

Machining example:
Brake calliper with a multi-bladed reamer

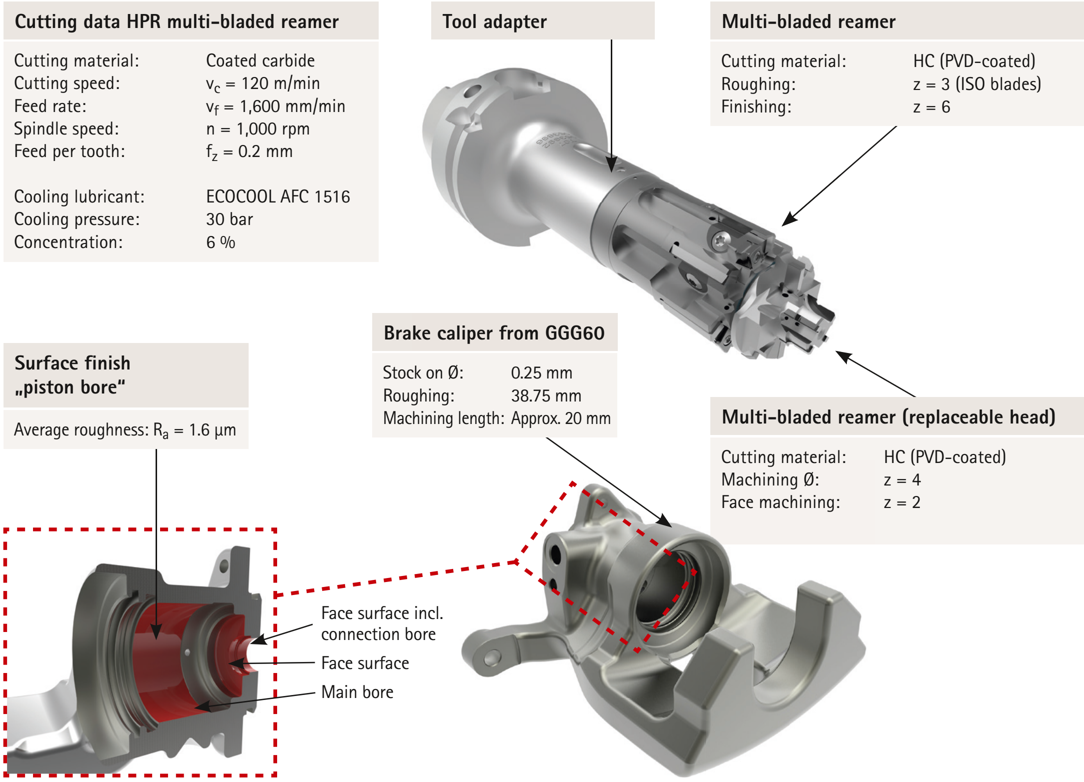


Figure 8: Functional surface machining on a brake calliper made of GGG60 – presentation of tool concept, technology parameters and surface quality achieved

Due to the different machining paths, tolerance requirements (Ø of main bore + 8 µm and Ø of connection bore ± 15 µm) and cutting speeds, the tool lives of the front and rear machining steps on the multi-bladed reamer used are different. In particular the cutting edges on the replaceable head achieve two to three-times the tool life of the cutting edges used on the main bore tool due to the differences and the application conditions stated above. For this reason, multiple piece tool concepts are mostly used for the fine machining of functional surfaces on the brake calliper. These offer the possibility of reconditioning to increase the cost-effectiveness of the tool used.

Summary

Summary

To fulfil the function of highly complex assemblies, ever higher requirements are placed on the machining in relation to the macrogeometric part properties such as dimensional, shape and position accuracy as well as microgeometric part properties such as the surface finish. Compliance with the required tolerances necessitates the usage of fine machining methods and precision machining methods; special tools and cutting materials adapted to the machining task are also needed. In addition, increasingly cast iron materials with improved mechanical and thermal properties are used; as a consequence machinability is made more difficult due to embedded carbides as well as higher strength pearlite phases. The general requirement for the more productive machining of cast iron parts therefore requires the holistic consideration of the process. The requirement for higher machining speeds necessitates an increase in the cutting parameters. These increases are achieved by means of optimisation of the cutting geometry, the cutting material and the cutting material coating. In addition, the development of innovative concepts for the reduction of the tool setting time and tool changing time is essential to improve the productivity during the fine machining of functional surfaces on cast iron materials and in the end to reduce the tool stock at the customer. Due to new innovative tool technologies, in future it will be possible to realise both more productive and also more cost-effective machining processes on cast iron parts.

Literature

Literature

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