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Materials in machine tool structures

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A broad variety of materials can be found in modern machine tool structures ranging from steel and cast iron to fiber reinforced composite materials. In addition, material combinations and hybrid structures are available. Furthermore, innovative intelligent and smart materials which incorporate sensory and actuator functionality enable the realization of function integrated structures. Consequently, material design and application discloses manifold degrees of freedom regarding a sophisticated layout and optimisation of machine frames and components. This keynote paper presents the current state-of-the-art with respect to materials applied in machine tool structures and reviews the correspondent scientific literature. Thus, it gives an overview and insight regarding material selection and exploitation for high performance, high precision and high efficiency machine tools.

Machine Tools, Materials, Structures, Analysis, Optimization

1. Introduction

The frame structure of a machine tool is an essential functional component inside the machining system. Main tasks of machine structures are the assurance of the geometric configuration of the machine elements even under static, dynamic and thermal loads, and the perception and guiding of forces and torques. Regarding the accuracy of a machined workpiece, the machine frame also should absorb any disturbing mechanical or thermal effects. Figure 1 shows modern structures of machining centres consisting of beds, columns, horizontal and vertical slides, Tables, main spindles, and joining guides and bearings.

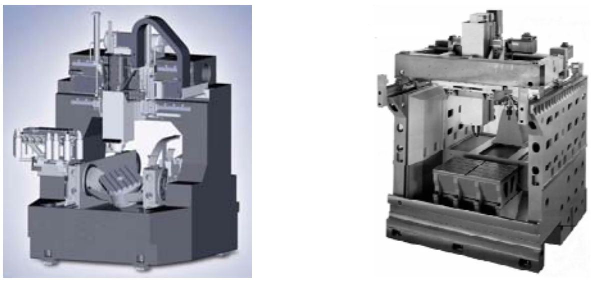

Figure 1: Modern structures of machining centres [DMGMoriSeiki]

Both, the mechanical and thermal behaviour of a machine frame are based on the elementary material properties (density, Young's modulus, shear modulus, tensile strength, material damping, heat conductivity and capacity, thermal expansion coefficient, etc.), the dimensions and cross sections of the structural components, their joining and integration into the force flow of the machining system, the foundation of the whole frame, and the applied loads.

1.1 Retrospection

The use of tools and devices is nearly as old as mankind. Figure 2 summarises material use in history.

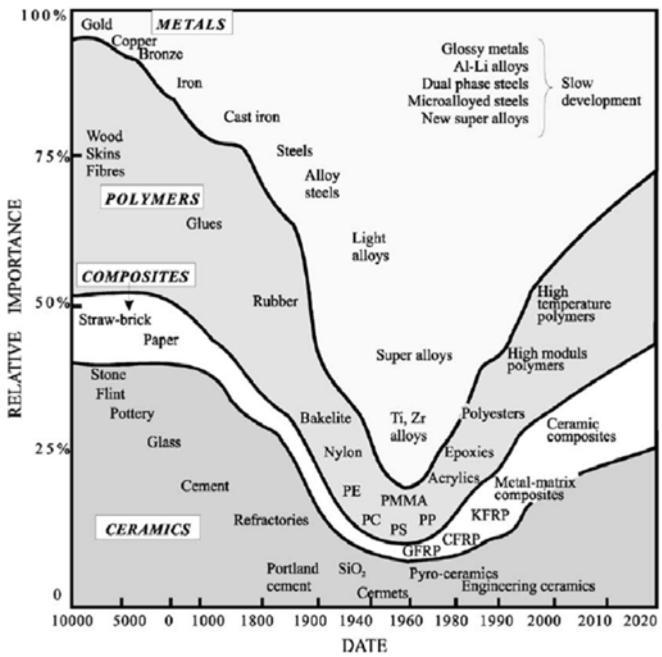

Figure 2: Material development and importance in history [74]

A historical review about the use of materials in early machine tools can be found in [175] and [54]. The improvements and diffusion of machine tools had a major impact on productivity in industry since the Industrial Revolution 1775-1830. Prior to that time, practically all machinery was made of wood. By the use of coke rather than charcoal in 1784 iron became cheap enough to be a major industrial raw material. With the use of iron and steel also metalworking machinery and machine tools appeared. In 1750 iron was used in machines only where wood or another cheaper and more easily wrought material simply would fail.

By 1830 iron was the first material considered by engineers. The provision of iron was increased when the steam engine (1775) multiplied the ironmaster's supply of power. The rapidly increasing use of steam engines in turn increased the demand for cast iron. The use of metal instead of wood was a kind of "breakthrough" in machine tool technology. Famous examples are the lathes of Henry Maudslay (Figure 3).

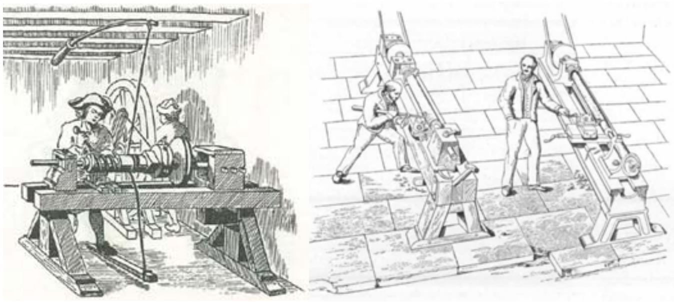

Figure 3: Lathe from 1750 (left) [175] and drawing from 1841 by James Nasmyth of a lathe with slide rest by Henry Maudslay (right) [Science Museum/SSPL]

In [138] some early design rules can be found which already emphasise the target to use the material (cast iron) as effectively as possible and to consider the process and force flow sensitively. The structural layout was depending on the experience of the designer rather than on calculations [228]. For a long time it was very difficult or said to be impossible to calculate the deformations of complex shaped structural components under load [158]. It was already understood, that closed box cross sections, welded or casted, lead to advantages with respect to stiffness and resonances (Figure 4). Koenigsberger listed some major design aspects including material properties (tensile-, compression- and impact strength, stiffness, damping, operating characteristics of sliding guideways), production limits (wall thickness accuracy, residual stresses in cast iron and heat treatment), cost effectiveness, and mass reduction.

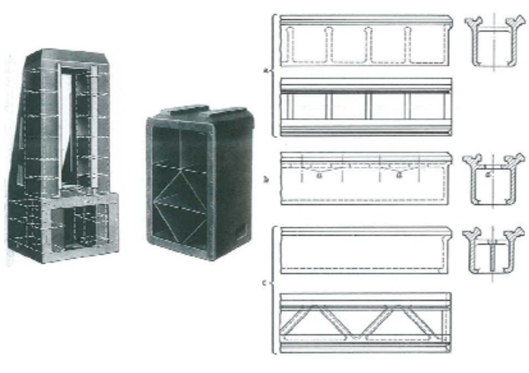

Figure 4: Cellular structure of a grinding machine (Diskus Werke, Frankfurt a. M., Germany) and different types of ribbing of a lathe bed [158, 247]

Regarding the decision between welded or casted structure, material cost were weighed up against labour cost of a welding worker which led to differences of building techniques in Germany and the US. The so-called "Peters" ribbing was found to be advantageous with respect to bending but box cross sections lead to the highest torsional stiffness. A fundamental comparison of steel and cast iron regarding the relationship between material volume, free length of a cantilever beam and bending height under load can be found in [247]. In 1917 Schlesinger tried to substitute cast iron for machine frames and slideways by cement concrete because of the lack of metal material due to the first world war [248]. The wear of the concrete slideways prohibited the success of this technology at that time. The competition of welded steel frames and cast iron structures also concerned forming machines (Figure 5). Schlesinger pointed out that if low workpiece surface quality is accepTable in a process (e.g. shear presses), steel structures can be used with the aim to exploit their strength.

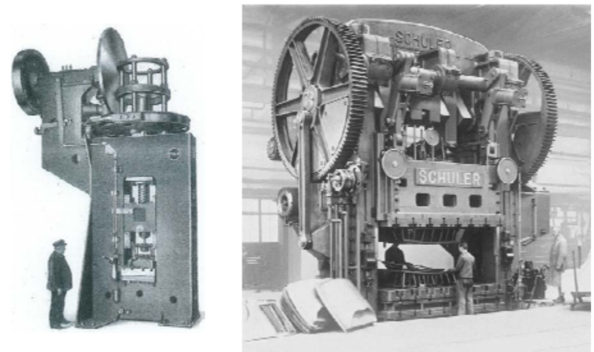

Figure 5: Friction screw press with steel frame (Henry Pels, Erfurt, Germany) [247] and SCHULER press (1928)

Figure 6 displays different base plate generations for a column stand drilling machine including stepwise improved ribbings. Welded alternatives led to a weight reduction of 32% compared to cast iron. Benjamin [33] and Fischer [87] showed further examples for casted and welded machine tool structures. Besides the stiffness improvement by supporting ribs the consideration of the chip flow can be seen. Haas presents a variety of welded constructions in [105].

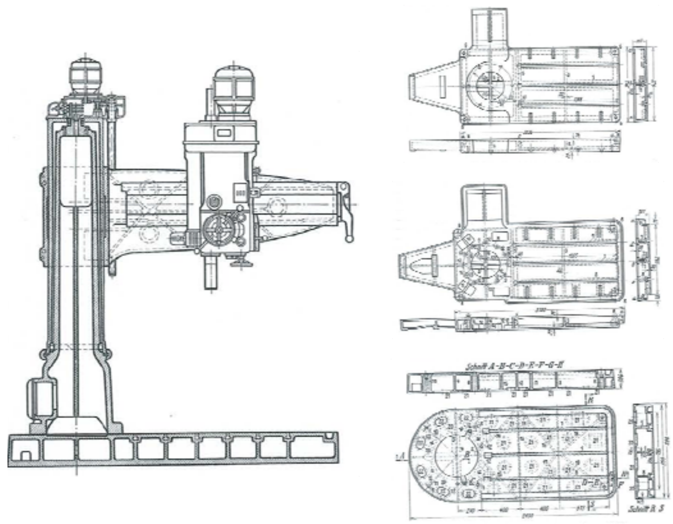

Figure 6: Different generations of the base plate of a column stand drilling machine (Raboma-Maschinenfabrik, Berlin Borsigwalde) [247]

1.2 General overview

The aspired structural characteristics (static/dynamic stiffness, fatigue strength, damping, thermal and long term stability, low weight) of a machine tool depend on the physical properties of the used materials as well as on the layout and shape of the components. Regarding the variety of available materials, basically metal, stone, ceramic, polymer concrete, porous, and reinforced composite materials can be seen in machine tools and components [197]. In addition, material combinations and hybrid structures are often applied. Research approaches also incorporate intelligent or smart materials providing inherent sensor and/or actuator capability. Figure 7 summarizes the major classes of materials with respect to density (specific weight) and stiffness (Young's modulus). Regarding lightweight design, density-specific mechanical values (such as Young's modulus divided by density) become more important.

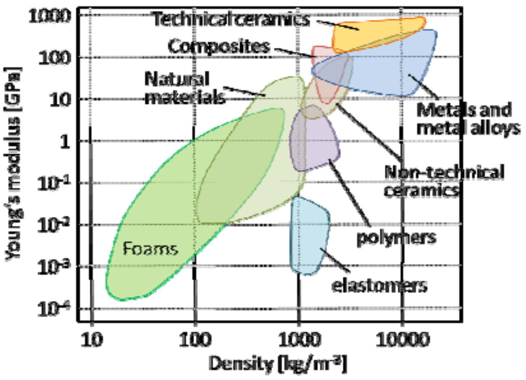

Figure 7: Double logarithmic material selection diagram [116]

Schulz discussed the requirements on machine structures and components for high speed machining in [252]. Lightweight construction is desired for moving components and high damping and stability should be provided by the machine base [277, 291]. Tlusty pointed out that even with the best strategies and most powerful drives a high cornering accuracy cannot be achieved when moving large masses. The importance of structural optimisation and lightweight design is evident [276]. For precision applications, thermal and long term stability of structures becomes essentially important [190, 246]. Today, the variety of materials and material combinations is huge. The selection of the best material for a specific machine structure is a crucial but challenging task.

As mentioned by Schellekens, DeBra equalizes "design for a high stiffness" with "designing for a minimum potential energy" [246]. This means to correctly place material in the right shape while using as little material as possible (i.e. light stiff design). A good design leads to a uniformly distributed loading. Ideally, the stress level under load should be the same for all material used. The characteristics of the processes which have to be conducted by the machine always have to be considered [39, 18, 317, 109, 70]. A structural approach to exploit materials most effectively with respect to stiffness/mass–ratio concerns parallel kinematics (PKM) [297]. However, only few PKM machine tools can be found in industry mainly due to cost and complexity. Regarding process dynamics and chatter stability, structural stiffness and damping are relevant [8]. Although extensively studied, material damping is difficult to quantify and the machine tool designer must generally rely on empirical results [246]. Material damping highly depends on alloy composition, frequency, stress level and type (tension or shear), temperature, and joint preload. Due to mechanisms of friction and micro-slip, structural joints significantly contribute to the structural damping [291, 102, 47]. The topic of joints in machine structures could probably fill an own keynote paper and is therefore left out here.

Obviously, the thermal properties of materials and structures have a significant influence on the accuracy and performance of the machines [295]. Most important are the values of thermal conductivity, specific heat capacity and thermal expansion coefficients (Table 1). In addition, thermal properties also affect the mechanical behaviour of machine tools [187].

Table 1: Thermal parameters of materials [277]

	ρ [g/cm³]	c [J/kg K]	λ [W/m·K]	a [m²/h]	α [10⁻⁶/K]
Struct. Steel	7.85	460	50	0.059	11.0
CrNi-steel	7.90	477	14.5	0.0139	-
Cast iron	7.20	450	50	0.053	9.0
Concrete, hydr.	2.10	780	0.9	0.0022	-
Polymer concr.	2.31	882	1.5	-	15
Aluminium	2.70	896	229	0.341	-
Invar	-	450	-	-	1.4
Glass	2.70	830	0.66	0.0012	-

ρ: density; c: specific heat capacity; **λ**: heat conductivity; a: temperature conductivity; **α**: thermal expansion coefficient

Optimal structural design becomes increasingly important due to limited material availability, energy efficiency and environmental impact, and technological competition, all of which demand lightweight, low-cost and high-performance structures [124, 163]. Another aspect is the carbon efficiency of machinery [81, 268]. The mining, provision and processing of the materials has to be considered [53, 74] (Figure 8).

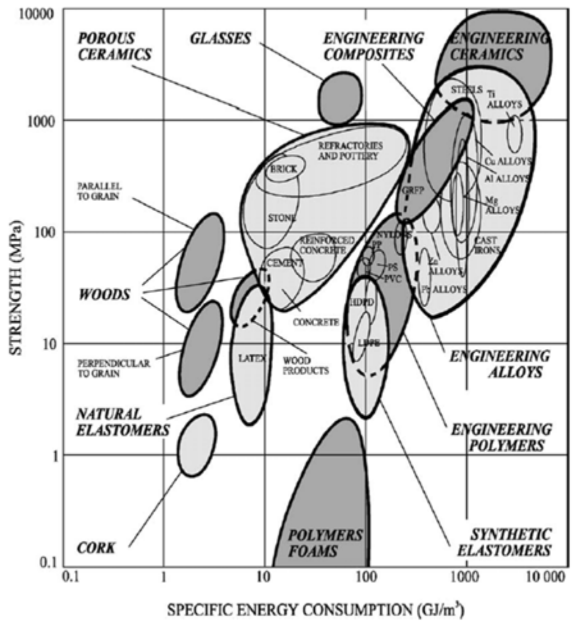

Figure 8: Strength and specific energy consumption of various materials [74]

The following chapters first introduce the materials which are mostly used in machine tool structures, their basic physical properties and exemplary applications. Subsequently, methods for structure layout and optimisation are briefly discussed. Finally, intelligent materials and structures are introduced.

2. Materials, characteristics and applications

2.1 Steel, cast iron and metal materials

Steel, cast iron and metal materials still are the mostly applied class of materials in machine tools. Metallic structures are also used for a variety of hybrid and combined material and structural solutions. Metal components are at least required for mechanical interfaces, joints, guides and bearings.

In conventional structural design, the competition between welded steel structures, steel casting and cast iron components continues. The general design rule which assigns castings to high volume production and welded structures to small batch or single piece production is often neglected by machine tool builders due to technical reasons. Whereas cast iron provides beneficial material damping characteristics, welded steel allows for material and mass savings due to the higher young's modulus. For castings, expensive moulds have to be produced which can be avoided by welded construction. On the other hand, complex ribbings and integral structures can be casted more easily.

The existing and still rapidly developing variety of steel alloys and cast iron materials can hardly be summarized in a brief but comprehensive way. In addition, heat treatment and hardening strongly influences the material properties. Figure 9 depicts a rough classification of iron materials.

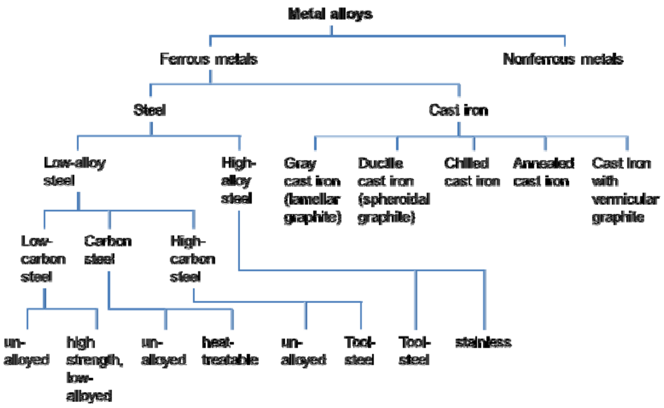

Figure 9: Classification of iron materials [245]

Table 2: Mechanical properties of different types of steel [245]

	Tensile strength R_m [MPa]	**Yield strength R_e [MPa]**	**Breaking strain [%]**	**Typical application**
Unalloyed low-carbon steel				
C10E C20D	640-780 380	≥390 205	≥13 25	Sheet metal Structural steel
High strength low alloyed steel				
S420NL S500N	500-680 560-740	320-420 ≥400	≥19 16	Constr. for low temp. Truck frames
Quenched and tempered unalloyed steel				
C40 (1.0511) G10800 (UNS) C100S (1.1274)	≥580 800-1310 1470-1670	≥320 480-980 ≥1275	≥16 24-13 ≥6	Cranks, bolts Bits, hammer Knifes, saw blades
Quenched and tempered low-alloyed steel				
G40630 (UNS) 30CrNiMo8 (1.6580) 51CrV4 (1.8159)	786-2380 1250-1450 1100-1300	710-1770 ≥1050 ≥900	24-4 ≥9 ≥9	Springs, tools Bearing bushings Shafts, pistons, gears
Austenitic stainless steel				
X2CrNiMo18-14-13 (1.4435)	500-700	≥200	≥40	Welded structures

Steel consists of ferrous metal alloys with less than 2% carbon. Depending on the alloying components and heat treatment, very different physical properties (ductile, high-strength, hardened) can be achieved (Table 2). The classification of steel grades is defined by national and international standards (e.g. DIN EN 10020, DIN EN 10027, SAE steel grades, ISO 4948).

In general, steel sheet metal parts are assembled by welding. Due to the welding heat, residual stresses, bending and distortion of the component can occur, which has to be corrected by subsequent production steps. Sheet metal parts are also assembled using bolts and screws. In this case, the resulting structural stiffness and damping behaviour depends on the surfaces and stresses of these bolted joints. With respect to the principle loads inside a steel structure, a maximum area moment of inertia in the force flux shall be achieved by the sheet metal arrangement [277, 291]. This leads to box type or ribbed structures [20]. The sheet metal parts can be breached in order to reduce the weight of the component and to improve accessibility. In [202] principle ribbing geometries for a lightweight welded steel slide are analysed. In Figure 10 the different ribbings are shown as well as normed displacements which occur if a theoretical bending load is applied. The finally assembled slide is shown in Figure 11.

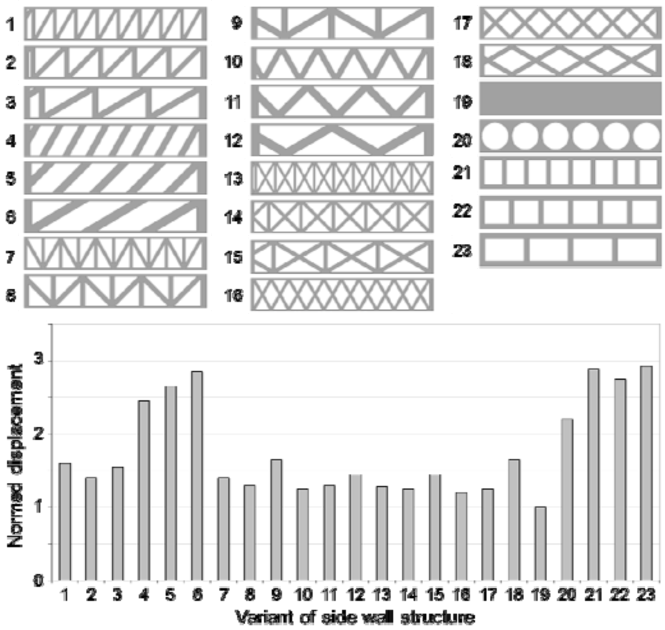

Figure 10: Different wall constructions for a slide [202]

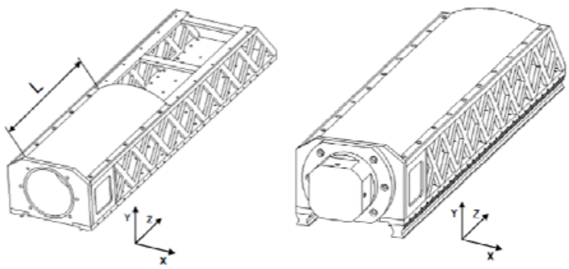

Figure 11: Welded steel slide construction[202]

Several approaches use thin walled sheet metal structures in order to achieve light but stiff components. In [257] an ultra-precision diamond turning machine with honeycomb-like bonded and sandwiched steel bed is introduced, which provides low mass and high dynamic rigidity (1st eigenmode above 1.2 kHz) with directional orientation. In [67] a welded honeycomb steel structure was applied for a gantry slide in a high speed milling machine (Figure 12). The honeycomb tubes are welded together only with a top and bottom plate in order to utilize friction between the metal sheets for damping improvement.

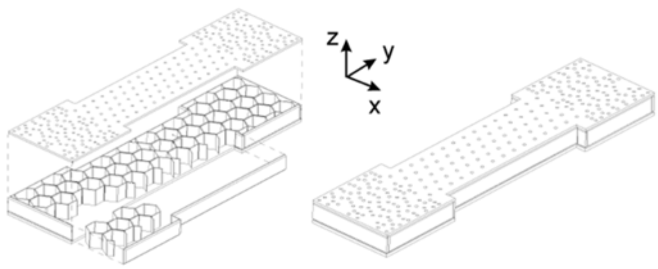

Figure 12: Honeycomb slide structure [67]

A machine for laser cutting and high speed milling consisting of lightweight sheet metal structures is introduced in [113]. Sandwich designs with various core structures (honeycomb, tube, grid) are applied (Figure 13). For the same bending stiffness, weight savings up to 40% can be achieved compared to an aluminium design.

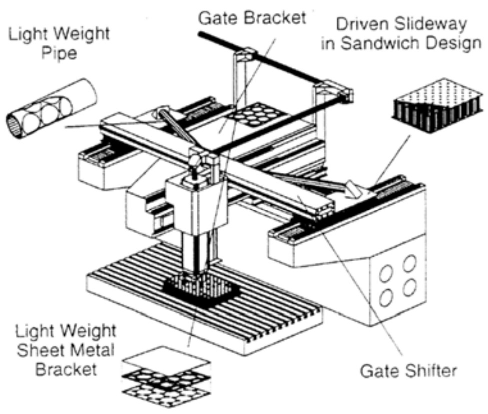

Figure 13: Lightweight sheet metal structures [113]

Welded steel structures are often used as shells for concrete and mineral casting, or filled with sand, oil or foams in order to increase structural damping. In [302] a high precision turning machine base applying a lightweight steel weldment filled with synthetic granite has been built. Cast iron rails for guideways have been bonded onto this structure by epoxy based bonding material. A similar approach was used in [303] for a large mirror grinding machine.

Cast iron compared to steel is characterised by a higher percentage of carbon. Depending on the composition and heat treatment, different types of graphite (lamellar, spheroidal, vermicular) are built inside the material (Figure 14) leading to different material properties [3]. Lamellar graphite leads to high material damping values and compressive strength but low tensile strength due to internal notch effects. Spheroidal graphite provides a lower material damping but higher tensile strength and a very high breaking strain. Basically the strength depends on the carbon content and the matrix type. Whilst for steel, the young's modulus can be indicated precisely, for cast iron areas of dispersal appear due to wall thickness and load scenarios. Cast iron with lamellar graphite shows a nonlinear relation between stress and strain. The young's modulus is derived from the initial gradient of the stress-strain-curve. A well-known method to enhance structural damping of cast iron components is to keep sand cores from the casting process inside the structure [277]. Sun et al. presented an approach to predict the loss factors of sand-filled structures in [273]. Wakasawa studied the packing of machine structures with balls [288].

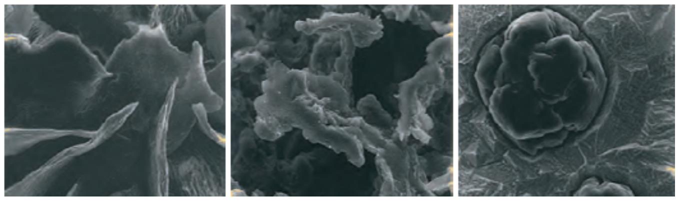

Figure 14: Lamellar (left), vermicular (middle) and spheroidal graphite (right) in cast iron [27]

A classification of cast iron can be found in DIN EN 1560-1564 whereas cast steel for general purposes is classified in DIN EN 10293. Exemplary cast iron grades for machine tool structures are GJL-300 (lamellar) and EN-GJS-400-18 (spheroidal). Cast iron materials even allow welding and hardening.

Figure 15: Milling machine frame (EN-GJS-400-18) by conpany SHW, Aalen-Wasseralfingen, Germany [27]

Even complex shaped and ribbed structural parts can be produced by casting (Figure 15). Some design rules have to be considered to avoid material accumulation, to create nodal points without stresses, and to achieve a good form filling and thus accurate geometry. A critical issue are blow holes which can occur during the casting process and which degrade the structural properties up to the initiation of breakage.

Table 3: Mechanical properties of different types of cast iron [245]

	Tensile strength R_m [MPa]	**Yield strength R_e [MPa]**	**Breaking strain [%] min.**
Cast iron with lamellar grahite			
EN-GJL-150 (0.6015)	110-135	-	-
EN-GJL-200 (0.6020)	145-180	-	-
EN-GJL-300 (0.6030)	220-270	-	-
Cast iron with spheroidal grahite			
EN-GJS-450-10 (0.7040)	450	310	10
EN-GJS-700-2 (0.7070)	600-680	370-410	1.0-2.0
EN-GJS-600-3 (0.7060)	500-580	320-360	1.0-3.0
Annealed cast iron			
EN-GJMBW-350-10	350	200	10
EN-GJMBW-450-6	450	270	6
Cast iron with vermicular graphite			
EN-GJV-300	250-300	175-210	2.0
EN-GJV-500	400-500	280-350	0.5

Due to the casting heat and subsequent cooling, residual stresses appear inside casted components. Sensitive annealing, “aging” or vibration are applied to lower these residual stresses and to achieve a better long term stability [277].

Constantly new alloys are developed which can have advantageous properties with respect to machine applications. Low melting alloys can be used for clamping of complex workpieces [13]. These materials possess solid state at room temperature but can be melted to liquid state by slight heating. High damping metal materials (HIDAMETS) are investigated for some decades [22] (Figure 16). Vandeurzen et al. analysed high damping materials ("Proteus": CuZnAl, "Gentalloy": FeCrMo, "Sonoston": MnCu, "Nitinol": TiNi, "Vacrosil": Fe-alloy) in [283]. The dynamic properties, elastic modulus and loss factor appeared to be dependent on the temperature, frequency, static and dynamic stress.

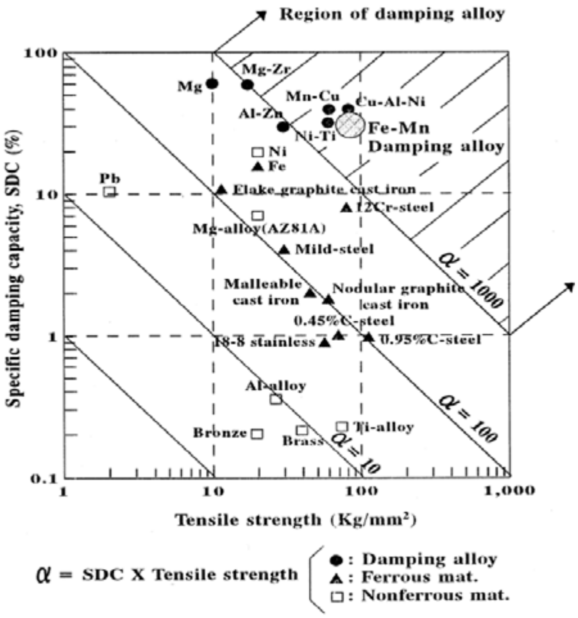

Figure 16: Tensile properties and specific damping capacities of various alloys [22]

In addition to mechanical properties, thermal issues have to be considered in machine design. Most important characteristic values of materials are the heat conductivity, specific heat capacity and coefficient of thermal expansion.

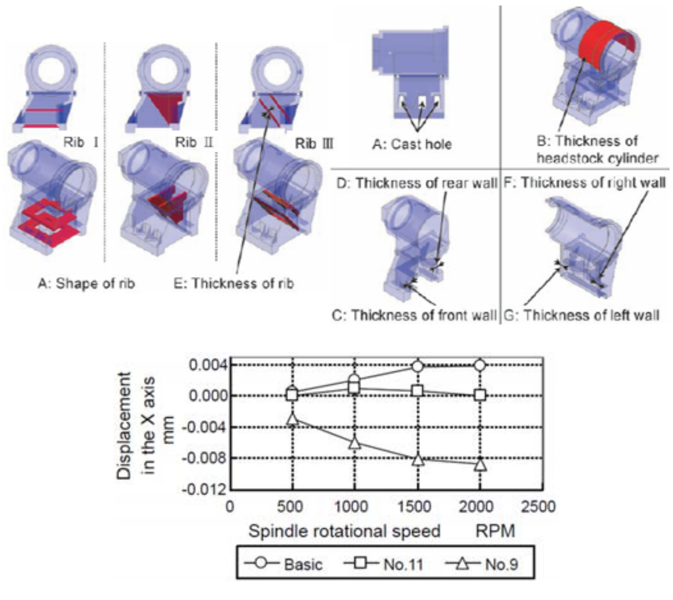

Figure 17: Features for thermal design optimization and thermal displacement in X-direction after 10 h spindle rotation [198]

In [198] the layout of ribbings, casings and structure walls with respect to thermal deformations of a lathe headstock is investigated. Figure 17 depicts the structural features for design optimization. By Taguchi method and Finite Element Analysis (FEA), the critical thermal displacement in X-direction was minimized. The influence of different wall thicknesses on the thermal behaviour of structural components of a large portal milling machine is discussed in [295]. Inasaki et al. presented an ultra-precision polishing machine which applies low thermal expansion (LTE) cast iron [130]. LTE cast iron is also discussed by Hashimoto in [109].

Besides steel and cast iron, also other metal materials are used in machine tool structures. Light metal alloys such as aluminium alloys have a significantly lower density compared to steel and cast iron. Thus, masses of moving machine components can be reduced. On the other hand, wall thicknesses can be increased in order to reduce local strain maintaining the component weight. Figure 18 shows a cross slide of a high speed machining centre by company MAP made of light metal alloy. Even in tool bodies, light metal alloys have been applied as can also be seen in Figure 18 [116]. Reducing the mass and inertia of fast rotating tools allows for shorter run-up times and energy saving.

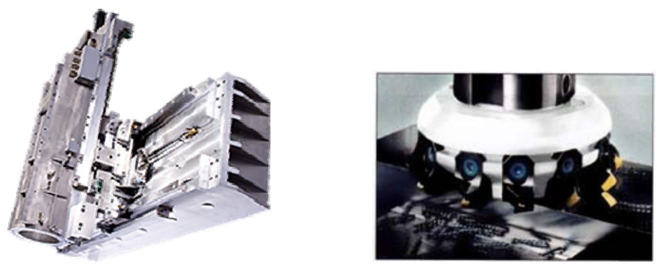

Figure 18: Light metal alloy cross slide (left) [MAP Werkzeugmaschinen GmbH, Magdeburg] and magnesium milling head (right) by company W. Fette GmbH [116]

In [284] aluminium is applied for the structure of a high precision 3D-Coordinate Measuring Machine (CMM). This material was selected because of the thermal sensitivity for gradients α/λ, which is very low due to the high thermal conductivity λ and the high thermal diffusivity $\lambda/\rho c_p$. The influence of thermal expansion is minimised by a short distance between the probe and the measuring system and mechanical thermal length compensation.

In ultra-precision machines and metrology frames materials with minimum thermal expansion are required. The frequently applied Invar (Fe-Ni alloys with typically about 64% Fe and 36% Ni, up to 1% Mn, Si, or carbon, and up to 5% Co) provides a very low or even negative thermal expansion coefficient. In [19] a frame structure of a miniature 4-axis machine tool applying Invar-36 alloy combined with a granite base is introduced. Machining tests show deviations between 0.1 and 0.52 µm. In [229] a metrology frame for a compact high-accuracy CMM is made of Invar. A volumetric standard uncertainty of 19 nm could be achieved. Inovco (63% Fe, 32% Ni, 5% Co), also called "Super Invar" provides an even lower thermal expansion coefficient of 0.72×10^{-6} K^{-1} compared to Invar-36 with 1.6×10^{-6} K^{-1} [245]. The thermal expansion of a tool holder was minimised with Super Invar by Moriwaki et al. [199] leading to significantly higher straightness in turning long workpieces.

2.2 Natural stone and ceramics

Industrially mined hard stone is used since decades in measuring plates, standards and etalons as well as structural parts of measuring and high precision production machines.

Commonly used natural stone grades are Gabbro Impala, Tarn, Fine Black, Black Galaxy or Ji Nan Black (Table 4) [133]. Granite can favourably be used as a base for prototype machines due to its high and fast availability.

Table 4: Technical values of natural stone materials [133]

	Impala (South Afrika)	**Black Galaxy** (India)	**Ji Nan Black** (China)	**Tarn** (France)
Density [kg/dm^3]	2.90	2.90	3.00	2.90
Compressive strength [N/mm^2]	300	190	250	180
Bending tensile strength [N/mm^2]	20	19	26	24
Young's modulus [kN/mm^2]	90	44	70	46
Thermal expansion coefficient [10^{-6} K^{-1}]	6.5	6.0	5.0	6.0

Natural stone materials follow Hook's law and can be analysed by linear FEA calculations. Furthermore they are antimagnetic, non-conductive, stainless and they do not generate burrs. Granite frames provide high damping, low thermal conductivity (3.2 W/m K), low thermal expansion (0.005 – 0.006 mm/m K) and high long term stability due to the absence of residual stresses [103]. Granite is a crystalline hard stone consisting of quartz, mica and feldspar. Its properties differ depending on the origin of the material. With smaller grain size, the mechanical properties increase. Fine grain granite achieves Young's moduli of 65 – 113 N/mm^2 and a pressure strength above 180 N/mm^2. Being a natural product, these values of granite scatter. Due to the high hardness (850-900 HV), abrasion resistance and homogeneous surface, granite is suiTable for aerostatic and hydrostatic bearings and guides [85]. Wegener realized an aerostatic planar guide using a granite base [298] (Figure 19).

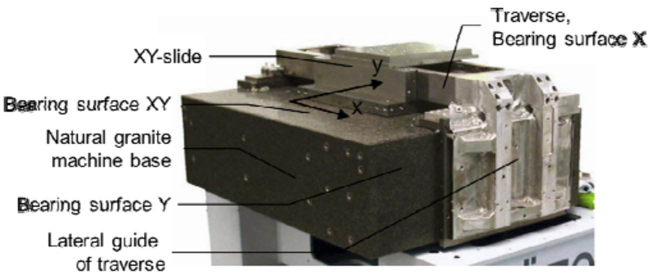

Figure 19: Planar guide with granite base [298]

In designing with granite, knowledge about stone processing is essential. Processing predominantly includes sawing, drilling and grinding. By grinding, a straightness and planarity of 5 µm/m can be achieved. Granite is often combined with glued steel inserts (bushings, T-slots) which provide mechanical interfaces. Thus a combined processing of both materials is necessary. By lapping, dimensional allowance of IT1 can be achieved. Due to the processing technology, granite frames consist of prismatic blocks. Because of its microstructure, hard stone should be loaded by pressure. The material properties regarding tensile and bending loads are much smaller. The force flow inside the structure has to be considered carefully in the design process. For machines with high accelerations, a ratio of 1:10 between moved and fixed masses should be respected. Since mostly a combination of granite with steel is applied, the thermal properties of both materials have to be taken into account in structural layout in order to avoid bending and stresses in interfaces. For the assembly of multiple granite components, screwing and conglutination are mostly applied. Since granite can absorb moisture, it is often sealed with very thin epoxy resin.

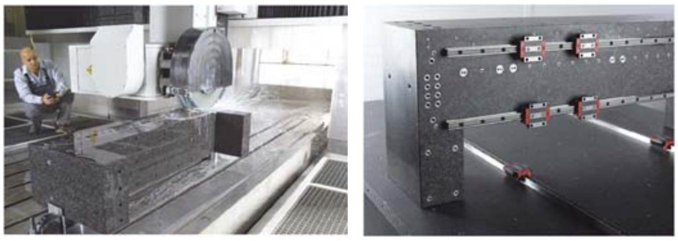

Figure 20: Grinding of granite frame (left) and linear guides and bushings in a granite frame (right) [103]

Granite is often used for high-precision and metrology applications because of its form stability. Abdin et al. and deBruin studied the dimensional stability of cast iron, granite, polymer concrete and graphite composites [1, 65]. It is pointed out that the long term stability even of granite is limited. There is a significant sensitivity with respect to the influence of moisture. However, also due to its thermal and damping characteristics, granite is the dominant material for CMMs and ultra-precision machines [76, 279, 284, 41, 43, 126]. In Figure 21 a compact five axes grinding machine based on a granite structure is shown.

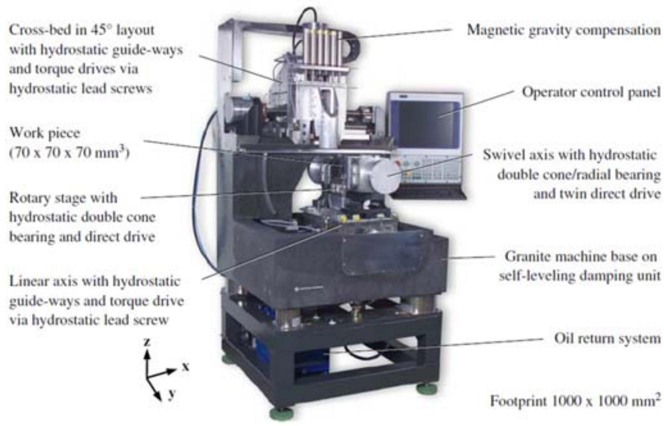

Figure 21: Compact five axes grinding machine [41, 43]

Since thermal stability, high stiffness and low masses are key issues in high and ultra-precision machine tools, also ceramics are used [189, 190, 289]. Table 5 gives an overview about characteristic values of some selected ceramic materials.

Table 5: Bending strength and Young's modulus of ceramics [245]

	Bending strength [MPa]	**Young's modulus [GPa]**	**Vickers hardness [GPa]**
Diamond	-	-	130,0
Silicon nitride (Si_3N_4)	250-1000	304	16,0
Zirconium oxide[a)] (ZrO_2)	800-1500	205	11,7
Silicon carbide (SiC)	100-820	345	25,4
Aluminium oxide (Al_2O_3)	275-700	393	26,5
Glass ceramics	247	120	
Mullite (3 Al_2O_3 – 2 SiO_2)	185	145	
Spinel ($MgAl_2O_4$)	110-245	260	
Magnesium oxide (MgO)	105[b)]	225	
Quartz glass (SiO_2)	110	73	

a) Partially stabilised by 3% Y_2O_3
b) Sintered and with approx.. 5% porosity

Ceramics are inorganic materials mostly consisting of metals and metalloids with ionic but also covalent bonding and various complex crystal structures [245]. Ceramics possess rather brittle characteristics. Due to micro cracks the tensile strength is much lower than the compressive strength. The tensile strength strongly depends on the amount of internal failures and varies among samples of the same material. The desired properties of ceramics are achieved by high temperature treatment (baking). Generally, ceramics possess low thermal expansion. A lot of ceramics exhibit a remaining porosity due to the manufacturing based on powder. For aluminium oxide (Al_2O_3) there is a non-linear decrease of Young's modulus and bending strength with higher volume share of porosity.

Technical ceramics are commonly used in applications where high resistance is required [246]. Due to the low density (3.16 g/cm^3), high Young's modulus and high hardness compared to bearing steel, silicon nitride (Si_3N_4) is used in hybrid bearings for high frequency spindles [2].

Ceramics like B_4C, SiC, Si_3N_4, Al_2O_3 have high refractory values and extremely high resistance against wear, corrosion and erosion. Ceramic parts may show considerable non-uniform shrinkage deformation. Therefore, uniform sheet thickness, relatively simple structures and the absence of sharp edges and point of line forces are essential. Vibration damping of ceramics is poor. A laminated build-up of thin ceramic tiles is preferable. A factor of 3 in mass reduction is possible compared to an aluminium or steel plate frame structure with the same stiffness. Furukawa summarized the benefits and drawbacks of using aluminium ceramics in machine structures [94]. Shinno et al. applied alumina ceramics (Al_2O_3) for a number of high precision machine components [257, 258, 259, 260, 261, 262, 263, 308]. Low thermal deformation and a lightweight but stiff construction could be achieved. In [262] an Al-ceramics Table was combined with a granite frame structure in order to achieve high thermal and dynamic stability of a 3D profile scanner. A spatial nanometer resolution was obtained with the assembled system. Yoshioka and Shinno presented an aluminium ceramics structure for a nano-pattern generator in [308] where the bed, columns, top beams and positioning systems consist of Al_2O_3 (Figure 22). A radial error during circular motion in the X-Y-plane of less than 4.5 nm appeared.

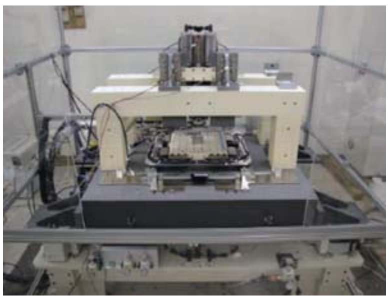

Figure 22: Advanced nano-pattern generator "ANGEL" [308]

Vermeulen introduced a single point diamond turning (SPDT) machine with ceramic slides having sub-µm accuracy and mirror surface quality [285] (Figure 23). The spindle is held in a triangular frame providing a vertical symmetry axis for thermal expansion. This frame was attached to a flat granite base plate. A horizontal granite beam serves as guideway for the cross slide. An optimisation of stiffness per mass for the slides was conducted by structural design and material selection. Multi-layer alumina ceramic laminate leads to an increase in specific stiffness by factor 3 compared to steel. The structural loss coefficient of the epoxy resin adhesive amounts to about 6% giving an overall structural loss factor of 3-4%. The ceramic laminate material offers extensive possibilities in design as compared to structural design in solid monolithic ceramics.

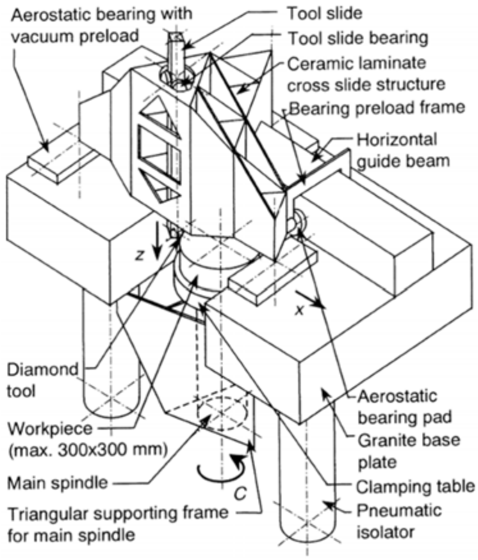

Figure 23: Schematic representation of SPDT machine [285]

Sriyotha et al. applied aluminium ceramics for the entire structure of a super precision machine an achieved a motion accuracy of 1 nm [266]. Company ZEISS applies an innovative silicon carbide ceramics for the new XENOS CMM [313] which provides around 50% lower thermal expansion, 30% higher rigidity and 20% less weight than white standard ceramics.

A fine-grain ceramics material, called NEXCERA, is introduced in [218]. The poly-crystalline oxide ceramics provides nearly zero thermal expansion by its anisotropic structure. Figure 24 depicts a comparison of NEXCERA with other materials.

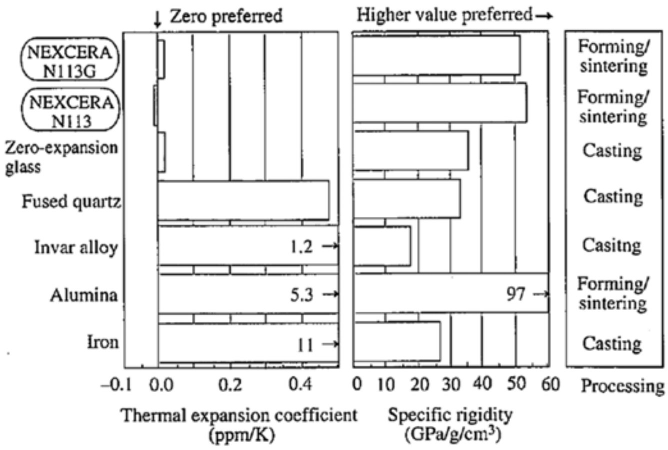

Figure 24: Comparison of NEXCERA with other materials [218]

In [302] a calibrated Zerodur reflective straight edge is used as optical reference for a plane mirror interferometer type laser transducer inside a large high precision diamond turning machine. Zerodur is a nonporous Li-Al-silicon oxide glass ceramic material with very low thermal expansion and high material homogeneity. The low expansion is achieved by a combination of a glass phase with positive and a crystal phase with negative expansion coefficient. Besides measuring devices, Zerodur is applied in metrology frames [110]. Optical industry uses low expansion materials such as Invar, super Invar, fused silica, titanium silicate glass, and glass-ceramics. Zerodur is the most famous low expansion glass-ceramics in optical use. In [192]

Zerodur is used for the guideways of a high precision linear slide. Namba introduced a spindle made of glass-ceramics (Neoceram) for an ultra-precision surface grinder in order to achieve zero thermal expansion [203].

2.3 Polymer concrete / mineral casting

A comprehensive introduction of polymer concrete, mineral casting or reactive resin concrete is given in [251, 162, 72, 131, 132, 30, 26]. DIN 51290-3 provides a standard for testing of polymer concrete for use in mechanical engineering.

In 1944 company BOEHRINGER built a first lathe bed with cement concrete. Up to now cement concrete bottom parts with cast iron upper components are combined to achieve improved system damping. In this case, the concrete part has no influence on the machine accuracy. Sugishita introduced a machining center with Portland concrete bed and column combined with cast iron plates [269]. The static stiffness was made comparable to a cast iron structure. The dynamic stiffness could be increased together with a reduction of natural frequencies. The thermal characteristics were improved by the integration of a heat pipe. The concrete structure showed a higher thermal inertia than cast iron. For this material erosion due to cutting fluid and shrinkage due to the drying process must be overcome. To avoid erosion an epoxy polymer coating can be applied. In 1983, company EMIL PRINZIG filled steel frames with hydraulic bonded concrete and improved the static, dynamic and thermal behaviour of welded steel constructions. New nano-structures nowadays allow the development of ultra-high strength concrete materials (UHPC). This material is used in machine frames without metal casing [242]. Kleiner applied UHPC for sheet metal hydroforming dies [156]. Compared to normal concrete made of cement, water and aggregates, UHPC contains additives such as microsilica and/or fly ash, as well as admixtures such as superplasticizers.

Since 1970s, cold-curing reaction resins are available which enable the production of polymer bonded mineral casting or polymer concrete for high precision machine frames. Polymer concrete or mineral casting describes a composite material that is obtained by mixing a filler material such as sand, marble, quartz, pearlite, glass, fibre, dolomite, steel, or carbon fibres with a resin such as unsaturated polyester, poly-methylmethacrylate [215], or epoxy, and by adding a catalyst or accelerant at room temperature that allows toughening through polymerization [17]. Sometimes also hydraulic bonded concrete is called mineral casting. The type and percentage of filler material and binding agent differ significantly with respect to application. In machine tool structures predominantly epoxy resin bonded mineral casting is used for bed components, frames, columns and supports. The casting process takes place at room temperature and requires sometimes complex and expensive moulds made of wood or metals. Since no external heating is necessary, the production of mineral cast components requires 20-40% less primary energy compared to cast iron or steel.

Beside high Young's modulus and damping as well as low thermal expansion, low residual stresses, minimal shrinkage and high reproducibility can be achieved. A long processing time and discharge of heat of reaction are essential. Hardening is mostly done with a curing agent. As filler materials in machine building mostly inorganic mineral fillers (quartz) and stones (granite and basalt) are used. In some cases also aluminium hydroxide, silicon carbide, iron powder or glass balls are applied. The optimal matching of filler materials with different grain sizes to a grain-size-distribution curve with high packing density allows to reduce the interspace to a minimum and to guide the loads at the final structure over the carrying grain matrix. Theoretical grain-size-distribution curves can only approximately be achieved in practice. Grain sizes reach from below 0.1 mm (rock meal) to 0,1 – 2 mm (sand) and up to 16 mm (flint). For achieving reproducible material properties, dosing of resin and curing agent as well as of the filler mixture (with up to ten grain fractions) is essential. The mass percentage of filler material is approx. 90 – 93%. Optimal bonding strongly depends on the wetting of the filler material by the epoxy resin. By rocking motion of the casted mixture, de-aeration and a decrease of porosity is achieved. The exothermic epoxy reaction leads to temperatures of up to 50°C. Curing takes usually 12 – 14 hours. The effect of moisture on the thermal and mechanical properties and curing process of polymer concrete was investigated in [107]. A significant influence could be recognized when changing the moisture content between 0% and 5%.

Regarding natural frequencies and modes, mineral casting corresponds to models for isotropic, homogeneous materials following the Hooke's law. Sahm identified slightly higher Young's moduli in compressive compared to tensile tests [243]. With high grain size (16 mm) a Young's modulus of up to 50 kN/mm^2 can be reached.

Compared to steel and cast iron, mineral casting provides lower thermal expansion coefficient, much lower heat conductivity (1 – 3 W/m K compared to 50 W/m K) but higher specific heat capacity. Thus, thermally more sTable machine frames can be produced. Due to the low heat conductivity inhomogeneous temperature fields can occur by influence of internal heat sources. On the other hand, mineral casting allows the direct integration of cooling circuits during casting [250]. In order to enable hybrid structures avoiding stresses at interfaces, the development of mineral castings with thermal expansion coefficients adapted to cast iron or steel was necessary. On the other hand, mineral cast with very low thermal expansion coefficients (7 x 10^{-6} K^{-1}) are available. Dou investigated the thermal deformation behaviour of mineral cast – metal – composite structures [77].

The application of mineral casting or polymer concrete reaches from high performance and high speed machine tools to ultra-precision machines and metrology applications. The success of mineral casting is predominantly caused by the excellent dynamic properties. In [222] it was observed that the critical damping ratio of polymer concrete can be four to seven times higher than that of cast iron. Kim analysed the influence of compaction ratio, sizes and contents of ingredients on compressive and flexural strength, thermal expansion, specific heat, thermal conductivity, Young's modulus and damping factor of epoxy resin concrete [150]. Regarding precision machine applications a significant influence of the resin content could be observed.

Haddad investigated the influence of aggregates (basalt, spodumene, fly ash, river gravel, sand and chalk) in [106]. An optimum composition, with the highest flexural strength and lowest thermal expansion coefficient, was found to be basalt, spodumene and fly ash. The resin volume fraction also showed a significant effect on the thermal expansion coefficient and flexural strength. The final optimized composition was basalt, sand and fly ash (filler 87% and resin 13%). In [182] the influence of resin, sand and fly ash contents on the compressive and flexural strength as well as split tensile strength has been investigated. It has been found that polymer concrete mortar can achieve compressive strengths in a range of 90–100 MPa. Tensile strengths were as high as 15 MPa for vinylester based polymer concrete. The results show that the polymer based filler materials are suiTable for both compression and tensile loading situations. In [234, 235] pure, fibrous and polymer impregnated ferrocement have been investigated in prototypic lathe beds by modal analysis. Ferrocement shows higher dynamic stability than cast iron. Discrete fibers with a length of 5 and 10 mm and up to 2% by volume of the matrix already improved the performance. The best results were obtained with polymer impregnation especially regarding shear loss modulus, flexural loss modulus, first resonance and damping ratio. Thus, improved process stability was assumed by calculations. In [304] polymer casting has been used for wear resistant deep drawing tools. Neugebauer presented an approach of inherent thermal error compensation of machine bed structures with layers of different thermal expansion made by mineral casting [211]. Simulations showed a significantly reduced thermal deformation. Company IFT (Magdeburg, Germany) developed sealed porous mineral cast, which enables a flow of cooling fluid (Figure 25).

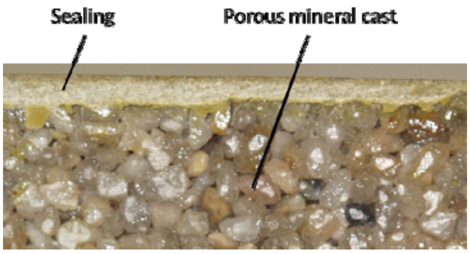

Figure 25: Porous mineral casting for active cooling [Company IFT]

Some mineral casting materials including granite as filler are called epoxy granite or synthetic granite [188]. Company STUDER creates the mineral cast GRANITAN. Guideways can directly be moulded as part of machine frames in this material. Especially because of its damping properties, synthetic granite (GRANITAN S-100) has been used for major structural parts of a large high precision diamond turning machine in [302].

Krausse and Dey developed calculation approaches for strength approximation [162, 72]. The cracking mechanism can be characterised by initial cracks between matrix and grains and subsequent brittle cracking of the grains at higher loads. The porosity of the material has a significant influence. Sahm studied the creep phenomenon and other mechanical properties of polymer concrete. Maximum values for compressive, tensile, and flexural strength were obtained using 10% epoxy resin and 8 mm particle size [243]. In [17] the rotational flexural fatigue of polymer concrete was analysed. A much lower fatigue strength compared to metals was observed which appears to be limited to 1-1.6 N/mm^2 corresponding to 10^7 loading cycles. Because of its sensitivity with respect to tensile stresses, polymer concrete is nearly not used in moved machine components so far. The cross slide shown in Figure 26 by company EMAG constitutes an exception. The casted Mineralit green body possesses a dimensional accuracy of +/- 0.1 mm so that finish machining is reduced by 80% compared to cast iron [111].

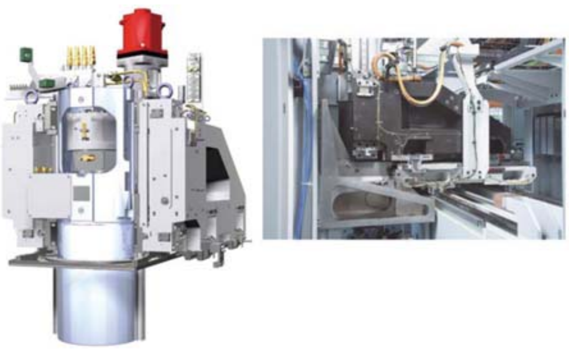

Figure 26: Polymer concrete cross slide by company EMAG [111]

Mineral casting construction types are “massive construction” of monolithic structures, “composite construction” of hybrid structures and “complete construction” (with integrated screw stays, steel rails and plates, cooling systems, service pipes, cable channels, etc.) [214]. The cost of mineral casted components predominantly depends on the level of integration, level of completeness, manufacturing principle, and weight.

Besides the use of polymer concrete and mineral casting in entire machine frame structures, there are specific applications in discrete components. Klaeger investigated the use of mineral casting in fixtures for cutting machine tools exploiting the favourable damping properties and the ability to directly integrate mechanical interfaces [155]. Rahman introduced a polymer impregnated concrete damping carriage for guideways [237]. Low-density cellular concrete impregnated with MMA polymer exhibited higher strength, elastic modulus and damping capacity compared to a steel damping carriage up to 650 Hz. Panzera investigated porous composites (high purity SiO_2 silica mixed with Portland cement) for aerostatic bearings [225]. The effects of silica size and geometry as well as compaction pressure were analysed.

The variety of polymer concrete and mineral casting materials led to specific naming of compositions by the providing companies, e.g. NMT Basaldur containing basalt and crystal quartz, UHPC-material Nanodur by company DURCRETE, UHPC-material Epudur, mineral cast Epument and ray absorbing Epuram of company EPUCRET, Baerlit of company IZM Polycast, Mineralit by company EMAG, Duropol by company MAP-Prinzing, Hydropol by company FRAMAG and many others. Jackisch concludes three major fields of development of mineral casting: the improvement of available and development of new mineral casting materials, the increase of completion, and the combination of mineral casting, adaptronics and micro technology [131].

2.4 Metal foams, porous and cellular materials

An extensive overview about the manufacturing, characterisation and application of cellular metals and metal foams is given in [25, 99, 290, 66, 119, 217, 267]. The production of metal foams is known in patent literature since the 1950s. Basically, melt metallurgic (e.g. GASARE), deposition techniques (e.g. INCO, RETIMET/CELMET) and powder metallurgic methods were developed. The foam creating process can further be distinguished by the discrete or prefabricated building of the pores. For powder metallurgic production, mostly aluminium melt is used as initial material (e.g. ALPORAS method) whereupon viscosity increasing additives (Na, Ca) and afterwards foaming agent (TiH_2) are added. Cooling of the closed-cell foam takes place in a closed die. By adding stabilizing ceramic particles (SiC or Al_2O_3) the foam can be skimmed (CYMAT or ALCAN process). Open-cell foam can be produced by ERG DUOCEL method in which open-cell plastic foam is used as a pattern. The method of Baumeister [28] is based on foaming of a compacted metal powder/foaming agent mixture by heating above the liquidus temperature of the metal. After cooling, closed-cell metal foam with 60 – 85% porosity is built. Ozan studied the influence of manufacturing parameters (NaCl ratio and particle size, compacting pressure) on the pore concentration of powder based Al-foam [223]. The manufacturing of tailor-made closed-cell metallic foams by titanium hydride decomposition is investigated in [83].

Syntactic foams are produced by embedding gas filled hollow spheres (1 -5 mm diameter Al_2O_3, mullite or TiO_2 spheres) in a matrix (e.g. magnesium, aluminium or rare-earth alloys) using infiltration technique. The mechanical properties are higher compared to aluminium foam but also the achieved density is higher [108, 233].

Since some years there are applications of aluminium foam (Al-foam) in machine tool design [204, 205, 206]. Hipke investigated characteristic design parameters such as pull out strength of joints and thermal expansion [118]. Advantages of aluminium foams in machine tool applications are the low mass and high energy absorption capability [120, 121]. Sandwiches with Al-foam core in combination with steel casings achieve an up to 40 times higher bending stiffness compared to mass equivalent steel sheets due to a higher geometrical moment of inertia. Al-foam (density approx. 0.5 g/cm^3) allows a decrease of vibration energy by its cellular structure and small deformations of internal thin walls as well as friction in cracks of pore walls. The slide of the high performance milling machine shown in Figure 27 is realised by use of Al-foam sandwiches with different cover sheet thicknesses. The mass of the slide could be reduced by 28% compared to a pure steel construction. Dynamic stiffness and damping are improved significantly.

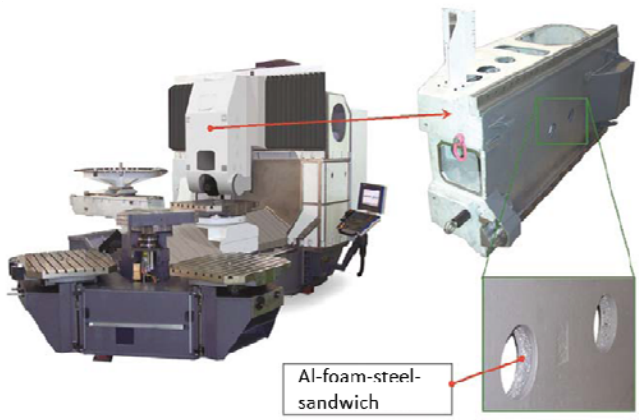

Figure 27: MIKRON HPM 1850U with universal slide applying metal foam construction [120, 121]

A specific ratio of cover sheet to foam core thickness should be maintained in order to effectively exploit lightweight engineering potential. In [207] it is shown that by the special foaming strategy using foamable pre-material a higher peeling strength can be achieved compared to aluminium bonding to steel by an adhesive layer. Smolik et al. presented a hybrid approach for a machine tool column consisting of a basic steel frame, foam cores replacing the internal ribbing in the column sides and outer steel skins [264, 265]. The hybrid column provided 64% of weight, 169%/83% of static stiffness in X-/Z-direction, and higher first natural frequencies compared to the original component within the machine assemly. Kolar discussed the filling of welded lattice steel walls with Al-foam [160]. The application of foam leads to a significant damping improvement of the structure.

Zhao reviews the thermal transport in high porosity cellular metal foams [316]. In [64] the influence of cutting methods on the thermal contact resistance of open-cell Al-foam is discussed. Aggogeri investigated sandwich structures filled with open cell metal foam which was impregnated by phase change materials [4]. The resulting structures provided high stiffness to weight ratio, good damping properties together with thermal stability.

The widespread use of Al-foam is hindered by the high production costs resulting from the expensive production process and starting materials. The idea of using aluminium chips instead of atomized powder avoiding negative influences on the macroscopic foam structure has been studied in [122] (Figure 28). Good foaming rates could be achieved by calcium carbonate as foaming agent for aluminium. Since the cost of recycled sorted aluminium chips are rather low and calcium carbonate is much cheaper than titanium oxide, a distinct price reduction for Al-foam seems to be possible.

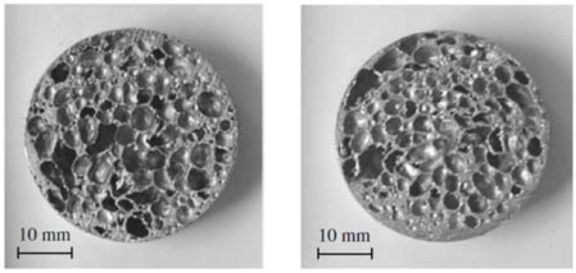

Figure 28: Al-foam based on chips (left) and powder (right) [122]

Since the foam structure influences the mechanical and thermal properties of a component, appropriate metrology for characterisation and quality inspection is needed. In [178] the use of computed tomography (CT) for obtaining statistical characteristics of open cell foam geometries is presented as well as the derivation of 3D volume elements for computational purposes.

Kashihara fabricated and analysed lotus-type porous carbon steel with respect to machine tool applications [144, 145] (Figure 29). An increase of specific rigidity, weight reduction and decreased power consumption of the machine is possible.

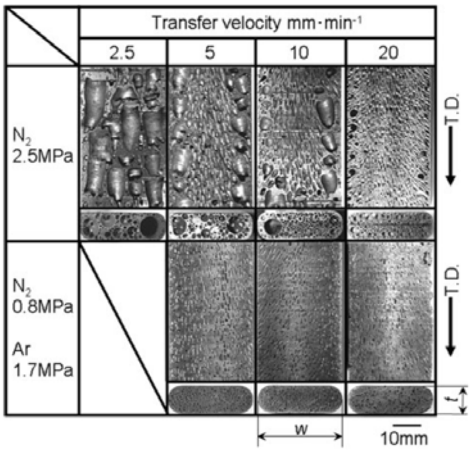

Figure 29: Cross sections parallel and perpendicular to the transfer direction (T.D.) of lotus carbon steel slabs fabricated in nitrogen and nitrogen/argon gas atmosphere (t: thickness, w: width) [144]

Another approach for light weight cellular structures applies hollow sphere composites (HSCs) [31, 194, 128, 29, 26, 286]. HSCs consist of small hollow spheres (filled with air, gas or metal powder) with a volume fraction of up to 80% and a reactive resin system. HSC materials are made from ceramics, silicates, plastics or metals. Waag and Andersen describe a spray coating process for creating metallic hollow spheres [287, 10]. The mechanical properties of sintered hollow sphere steel foam were analysed in [274]. They depend on the spherical hollow bodies (material, grain size distribution, wall thickness), the characteristics of the resin, additives, and the volume fracture and distribution of these ingredients. The thermal behaviour is mainly governed by the used epoxy resin. In [30] a combination of corundum based (0.5 – 1 mm) macro hollow spheres and aluminium silicate Fillite (5 – 300 µm) micro hollow spheres is regarded (Figure 30). Also different types of hollow spheres (10 – 2,000 µm diameter, wall thickness of 10% of diameter) in combination with cold and warm curing epoxy resin with and without fibre reinforcement have been investigated. For a comparison of mechanical properties of HSC with steel, glass fibre reinforced composite (GFRP) and carbon fibre reinforced composite (CFRP) the ratio of stiffness (Young's modulus) to density is important. HSC materials showed a higher ratio than either steel or GFRP (Table 6). HSCs show isotropic mechanical and thermal properties and beneficial damping can be achieved. In [30] applications in a robot arm and machine tool component are presented.

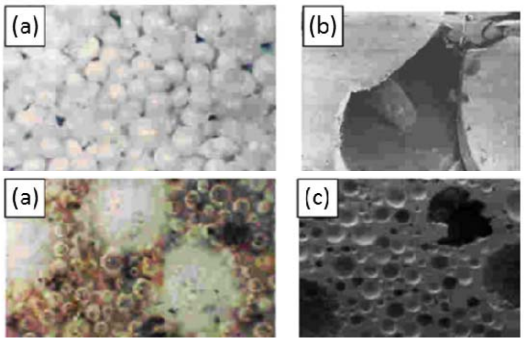

Figure 30: Hollow sphere composite (HSC); (a) bulk material of corundum, (b) interior of Fillite, (c) HSC, (d) interior of HSC [30]

Table 6: Comparison of HSC [30]

	Density ρ [g/cm³]	Young's modulus E [GPa]	$\sqrt[3]{E} / \rho$
Epoxy resin	1.15	3.5	13.2
HSC (1)	0.95	7.8	21.4
HSC (2)	0.9	6.8	21
HSC (3)	0.65	4.1	24.6
HSC (4)	1.16	8.7	18.7
Steel	7.8	210	7.6
GFRP	2.6	73	16
CFRP	1.78	235	34.5

HSC (1): 65 vol.-% Fillite + corundum
HSC (2): 78 vol.-% Fillite + corundum
HSC (3): 78 vol.-% Fillite
HSC (4): 78 vol.-% corundum (0 – 2 mm)

2.5 Fibre reinforced and composite materials

Fiber reinforced and composite materials are particularly interesting for applications in machine tool structures due to their ratio of mechanical strength to density [148, 230, 172] (Figure 31).

Liebetrau gives an overview about carbon fibre reinforced plastic materials with respect to its use in spindle casings in [177]. A deep insight into the material engineering of reinforced composites is given by [91, 92, 139, 245]. Fiber reinforced materials consist of the fiber (short or long) or particle reinforcement and a binding matrix system. Reinforcements can be whisker (graphite, silicon carbide, silicon nitride, aluminum oxide, thin mono-crystals with very high aspect ratio), fibres (polymers, ceramics or glass, aramid, glass, carbon, aluminum oxide, silicon carbide, polycrystalline or amorphous) or filaments (steel, molybdenum, tungsten). There are so-called E-glass fibres (electric isolator), S-glass fibres (with higher strength), C-glass fibres (with higher boron content and chemical resistancy), and boron-free ECR-glass fibres [116]. With respect to carbon fibres, standard high tenacity (HT), super tenacity (ST), intermediate modulus (IM), high modulus (HM), and ultrahigh modulus (UHM) fibres can be differentiated. The mechanical properties of fibres are depicted in Figure 32. Most commonly used are glass fiber reinforced plastic (GFRP) with fiber diameter 3-20 µm and carbon fibre reinforced plastic (CFRP) with fiber diameter of 4-10 µm. Other fiber materials are AFRP (aramid fiber reinforced plastics, e.g. Kevlar). The matrix consists either of polymer resin (for GFRP, polyester, vinyl ester), Epoxy (causing higher cost but providing better mechanical properties than polyester and vinyl ester and less sensitivity to moisture) and Polyimide (for high temperature applications, e.g. polyetheretherketone PEEK). In addition, there are thermoplastic resin and thermosetting resin. Matrix materials in machinery applications are predominantly epoxy resins.

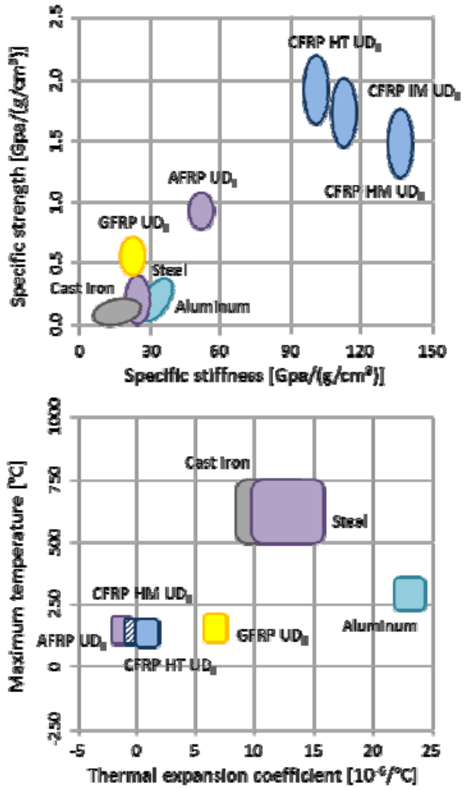

Figure 31: Comparison of mechanical and thermal properties of structural materials [Fraunhofer IWU, Chemnitz, Germany]

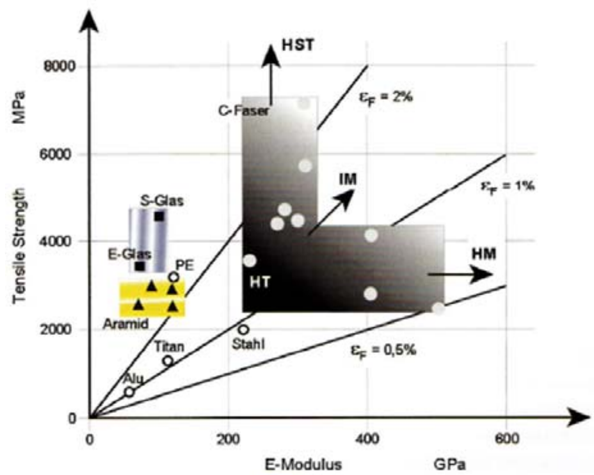

Figure 32: Properties of different fibres [116]

Responsible for the mechanical properties are the fiber strength, volumetric content of fibers and matrix, fiber orientation and layer build-up sequence, bounding surface connection with matrix as well as critical fiber length. Unidirectional (UD) fiber reinforced composites possess the highest mechanical performance in fiber direction. The fibre direction relative to the structure internal force flows has to be considered carefully during structural design [16]. In [185] the influence of the fibre orientation on a smart composite structure is analysed. In “hybrid” composites multiple different fiber types are embedded in a matrix (e.g. carbon and glass fibers in one polymer matrix). By this, anisotropic properties can be achieved. With respect to the thermal resistance of the reinforced materials, the glass transition temperature has to be taken into account at which the solid state of the matrix dissolves. In sandwich structures, covering layers enclosing a core (e.g. aluminium honeycomb core) are built. Sandwich cores can also be used to improve damping [166, 220]. Stiffnesses comparable to that of steel structures can be achieved by CFRP depending on the used fiber, combined with a mass reduction by up to 80%. With an appropriate orientation arrangement of the fibers, a thermal expansion close to zero can be provided.

For producing the fiber reinforced structural materials, several fabrication techniques are available such as draping of pre-impregnated material (known as “prepreg”) to build laminates, filament winding techniques, pultrusion, placement of dry fibers or fabrics and injection or resin transfer moulding (RTM). Figure 33 depicts a multiaxial fabric [92].

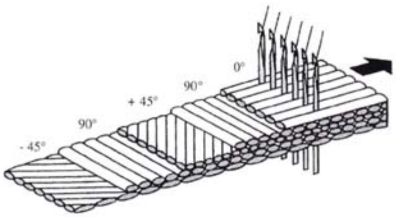

Figure 33: Schematics of a multiaxial fabric [92]

Today, the variety of machine tool applications of CFRP and GFRP is already huge and a tremendous amount of research work can be found in literature of which only a few examples can be mentioned here. Abele analysed a vertical CFRP axis and achieved a mass reduction to 60% and decreased energy consumption of 70% of the conventional design (Figure 34).

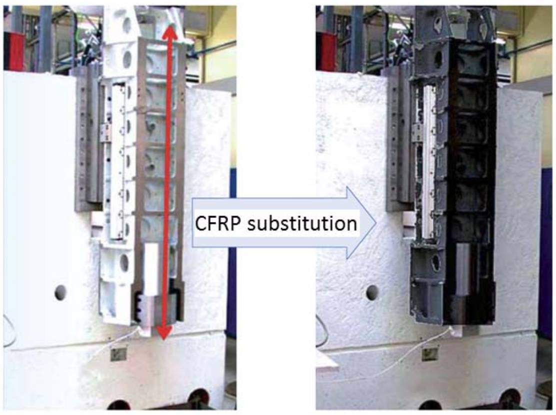

Figure 34: Substitution of conventional by CFRP structure [PTW, Darmstadt, Germany]

In 2011 a CFRP ram was presented at the EMO fair by company Roschiwal+Partner [241]. Kulisek et al. compared a thick-walled composite spindle ram with a hybrid structure composed of fiber composites with cork layers and bonded steel reinforcements [164]. For an assembly with connection interfaces, the damping ratio was increased by 70% compared to the conventional steel design. A high speed machining center with vertical CFRP z-slide has been presented by company MAP (Magdeburg, Germany) at the EMO fair in 2013 (Figure 35). Measurements of the IFQ showed that the same stiffness as with a comparable cast iron slide can be achieved.

Figure 35: Machine slide made of CFRP [source: MAP]

The integration of joints and mechanical interfaces in CFRP structures is challenging. Mechanical stability has to be achieved avoiding annihilation of the achieved mass reduction by heavy metal parts [153]. The thermal expansion of connected elements should be similar in order to prevent thermally induced stresses [307]. A design methodology for joints in laminated composites is presented in [51]. In [129] the influence of clamping effects on the dynamic characteristics of composite machine tool structures is studied and a new clamping approach using a metal core or sleeve is introduced. Peklenik studied design variations of composite plate structures with trapezoid, rectangular and circular supporting profiles for an exemplary application in a spindle box [230]. The trapezoidal showed the highest bending and torsional stiffness. Heimbs et al. studied sandwich structures with single and multiple textile-reinforced composite foldcores possessing very high weight-specific stiffness and strength [112]. Fleischer designed a CFRP slide with internal chambers which can be filled with liquids in order to control the dynamic characteristics [90, 157].

Liebetrau investigated the influence of laminate build-up and fiber type on thermal deformations in spindle casing front and back plates considering bearing power loss, heat conductivity, bearing hole diameter and position [177].

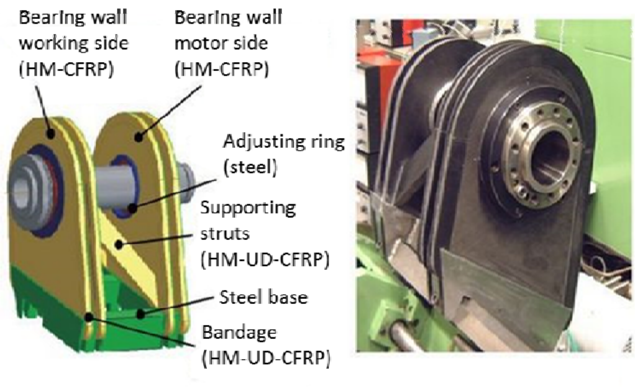

Figure 36: CFRP headstock [IWF, Berlin]

HT-CFRP appeared to be inapplicable because of inaccepTable high temperatures in the bearing casing wall which depend on the laminate build-up and thermal conductivity. Displacements could be reduced to 30% compared to a steel wall. HM fibers in an evenly distributed 0°/90°/±45° multi-axial laminate showed significantly better results. The vertical spindle bearing displacement could be reduced by 96% and temperatures were slightly lower compared to steel. With a dynamic stiffness comparable to the steel wall, the first natural frequency raised by 77% with the HM fibre and damping was higher by a factor of 3. Based on these results, prototypic headstocks for a lathe have been realized by Uhlmann at the IWF (Berlin, Germany) (Figure 36).

The potentials of low thermal expansion are also exploited for the design of modular desktop machine tools [305].

Lee and Choi introduced composite spindles [168, 61] and observed improved process stability. In order to optimize the relationship of rotational inertia, damping and natural frequencies in [24] the combination of a CFRP shaft with steel flanges for high speed air spindles was analyzed. The stacking angle of the carbon composite as well as the adherend length and thickness were taken as design variables. Centrifugal forces have to be considered in the layout of fast rotating CRFP spindle shafts. In [56] the rotor of an AC induction motor was manufactured using magnetic powder containing epoxy composite whose density is half of the conventional metal rotor. The motor shaft was made of HM carbon fiber epoxy composite. To enhance the magnetic flux of the composite rotor, a steel core was inserted. Brecher presented a carbon fibre rotor for an aerostatic spindle in [36]. The moment of inertia was reduced to one third compared to a steel rotor. The axial and radial bearing gap shrinkage is minimised since the negative thermal expansion of the CFRP offsets the positive thermal expansion of the steel nose. The material expansion due to centrifugal forces was reduced significantly.

Composite materials are also used in tooling equipment, mostly to increase damping and decrease the moment of inertia [169, 171, 278]. Lee achieved 5 times larger depth of cut with a graphite epoxy composite boring bar compared to a steel bar before the onset of chatter [169, 171]. Companies XPERION [306] and EMUGE recently presented CFRP tool extensions. The example of EMUGE has 20% of the mass of the steel component but same stiffness and strength [84]. The reduced inertia leads to energy savings. Heisel presented a modular CFRP reamer [114] (Figure 37). The weight of the tool was reduced to approx. 37% whereas the stiffness was slightly increased.

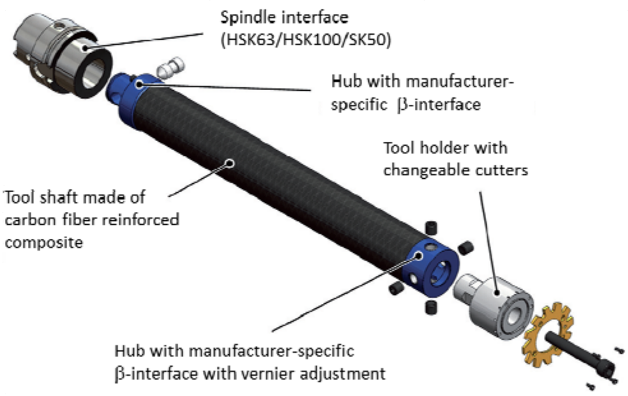

Figure 37: Modular design of CFRP reamer [114]

A kind of tentativeness regarding the use of composite materials in industrial machinery concerns the long term stability of mechanical and thermal properties under the influence of chips and coolant, as well as the complexity of internal failure mechanisms which can hardly be recognized externally but which could affect machining performance. Therefore, covering and sealing approaches as well as damage identification techniques are currently investigated. However, these materials have very high potential, especially against the background of developments in aerospace and automotive industries leading to a higher cost effectiveness. Future aspects are the further development of hybrid structures exploiting the different material potentials, a fiber related functional integration, sensor and actuator integration, and self-healing composites. Another aspect is the use of natural fiber composites for low stressed components.

2.6 Material combinations

A lot of material applications in machine tool structures actually employ material combinations leading to hybrid structures.

As mentioned before, polymer concrete is combined with metallic inserts, interfaces and joints but also with metal structures to build hybrid machine beds and columns. Steel plates for guides and interfaces are connected to the concrete material by anchors and metal reinforcements. By filling metal casings (with or without internal ribbing) with concrete material, hybrid structures are built. Compared to pure mineral casting, higher forces can be handled by thinner profiles. Since casting moulds and demoulding chamfers are not necessary, a higher flexibility regarding part shape and design changes is given, and shorter delivery times are possible. The casings provide a high resistance against abrasion and moisture. During casting of polymer concrete, functional elements (high pressure pipes, fluid tanks, active cooling systems, chip removal channels, etc.) can be integrated into the components. By use of lost cores, internal structures, material savings and light components can be realized. Hybrid steel/concrete structures (called Hydropol) are provided e.g. by company FRAMAG. The beneficial design and damping characteristics of Hydropol have been exploited for prototypic high speed machines by Denkena et al. [67, 69, 104]. Even the effect of a jerk decoupling of the linear motor axes was diminished due to the already high damping of the hybrid structure [104].

A lot of research work has been carried out with respect to hybrid metal-composite structures. Lee manufactured a hybrid column for a precision grinding machine by adhesively bonding GFRP plates to a cast iron structure [170]. The damping capacity was increased by 35% compared to the cast iron column. In [55] a hybrid headstock for a precision grinding machine was manufactured by adhesively bonding GFRP laminate to a steel structure. The stiffness increased by 12% and the loss factor by 212% compared with the steel headstock. Suh presented slides of a large CNC machine with HM-CFRP sandwiches joint with welded steel structures using adhesives and bolts [271] (Figure 38).

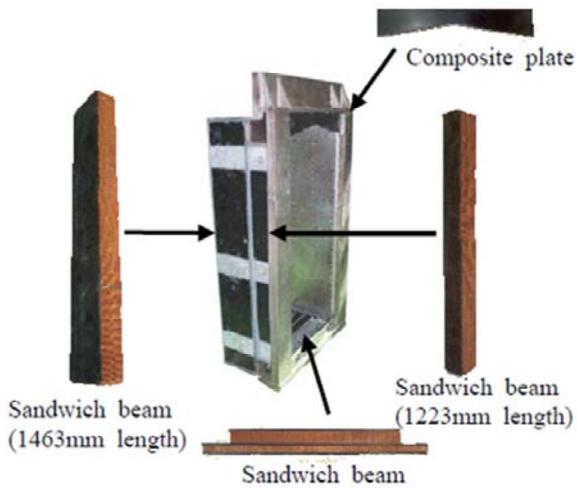

Figure 38: Section views of vertical columns of the X-slide [271]

A weight reduction of 26 to 34% and an increase of damping by factors of 1.5 to 5.7 were achieved maintaining the stiffness [173]. In [272] the reliability of the adhesive joints between the composite sandwich and the steel structure was studied in terms of strength and thermal stress induced by the heat generation of linear motors. The adhesive bonding showed acceptable performance.

In [140] a composite/aluminium hybrid beam structure with HM carbon-epoxy composites was developed for an inspecting machine of LCD glass panels. The cross-section shape, stacking sequence and thickness of composite were optimized regarding dynamic stiffness and damping. Carbon epoxy composite/aluminium hybrid structures with friction layers were used in [154] to increase structural damping. Two types of hybrid columns were proposed. The static deflection due to deadweight and the first natural frequency as a function of the stacking angle and thickness of the composites were analysed by FEA. Neugebauer presented a hybrid composite/steel ball screw, stating 10 times lower thermal expansion in comparison with a conventional metal ball screw [212]. In [270] a steel spindle cover was reinforced with CFRP in order to improve the vibration characteristics. The relationship between the loss factor and the stacking sequence was investigated. Compared to a traditional design 3-5 times higher loss factors were achieved.

A hybrid steel/composite cutting tool body was analysed with respect to material types (composite and foam), stacking angles of the composite, adhesive bonding thickness, and dimensions of the cutting tool in [151]. Heisel et al. investigated a functionally graded aluminium matrix composite (consisting of coherent aluminium matrix and ceramic reinforcement such as SiC or Al_2O_3 fibers or particles) regarding large aluminium milling cutters [115]. Machining tests revealed the improved performance of the hybrid tools regarding workpiece roughness.

Zatarain analysed bonded structures in [312]. By bonding a broad variety of materials including metals, reinforced composites and honeycomb structures can be combined (Figure 39). The mechanical properties of the used glue at the relevant temperature level have to be considered. Structural improvements could be achieved with respect to shapes, wall thicknesses and materials. A mass reduction of 40–50% was reached leading to increased natural frequencies. In some cases damping is increased by a factor of 10. Zatarain identified the material characteristics of the used glue by basic tests in order to allow modelling.

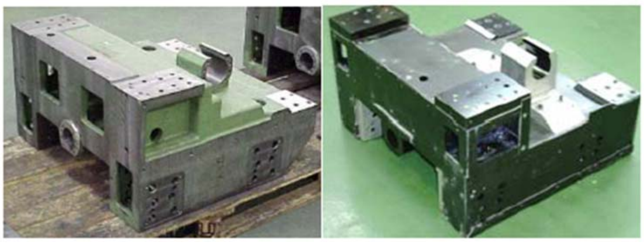

Figure 39: Bonded machine structures [312]

Combinations of fiber reinforced composites and concrete materials have also been investigated. Sandwich structures for micro-EDM machines are optimized by varying composite geometries, stacking sequence, thickness and rib geometry in [152]. The structures are composed of fibre reinforced composites for skin material and resin concrete and PVC foam for core materials. The sensitivity of design parameters like rib and composite skin thickness was examined and an optimal condition regarding structural stiffness was suggested. In [60] carbon-epoxy composite and resin concrete were combined in a Table-top machine. Several components were realized and assembled by mechanical joining and adhesive bonding. The re-designed structure provided 37% less weight, 16% increased stiffness and up to 3.64% higher loss factor. The strength in concrete can be improved by reinforcement with recycled CFRP pieces [219].

2.7 Comparative studies

Most of the developed structures and components are compared to the particular conventional ones. However, systematic comparative analyses about material solutions can rarely be found in literature. The most interesting studies assess the influences caused by the different structures and material approaches, which are relevant for the process performance and machining results.

Saljé compared grinding machine elements with polymer concrete, combined polymer concrete and cast iron, and cast iron under the influence of forces and thermal load [244]. With the polymer concrete frame, the first natural frequency raised by 50-150 Hz, the dynamic compliance decreased to 30%, and the damping was 2–6 times higher than that of the cast iron frame. Figure 40 compares the thermal activity of polymer and cast iron.

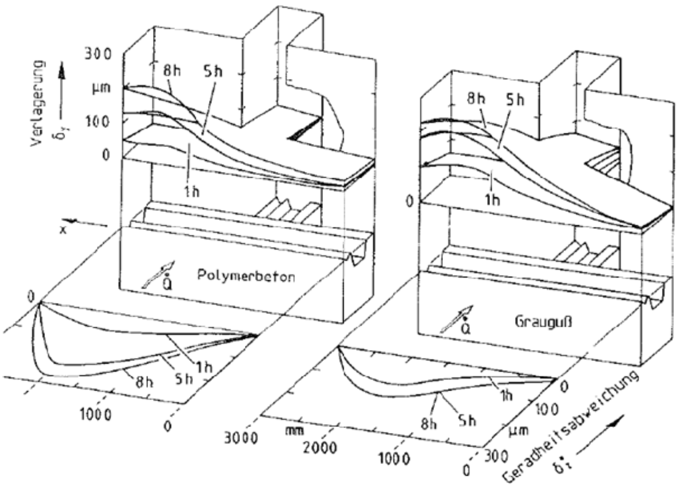

Figure 40: Thermal deformations of cast iron and polymer concrete [244]

Brecher studied the dynamics of two each differently filled test-components in [37, 38, 42] (Figure 41). The best static stiffness was achieved with a welded steel component filled with mineral casting. Advantageous dynamic stiffness is given by welded and casted components filled with cement concrete, furan resin bonded quartz sand, or sand depending on the bending or torsional mode. Cast iron with sand filling showed the shortest decay time.

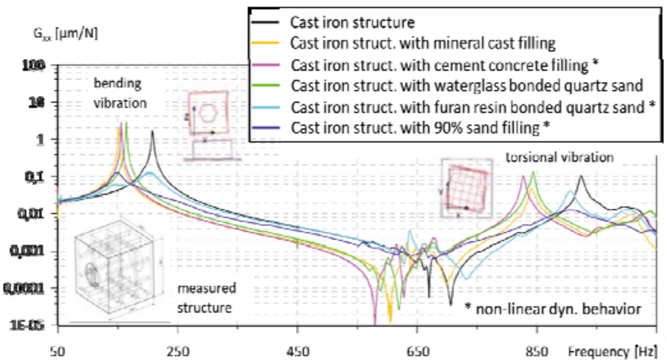

Figure 41: Comparison of filled test-components [37]

Rahman compared the chatter stability of the ferrocement bed of a lathe with a cast iron bed and observed a 50% deeper cut before chatter vibration occurs [236]. In [238] the related tool wear behaviour was compared. Lower flank wear appeared at the ferrocement bed lathe.

A comprehensive comparison of different material solutions can be found in [227] where cast iron, cast iron filled with conventional concrete, epoxy polymer concrete and a hybrid steel-concrete (Hydropol) structures have been tested (Figure 42).

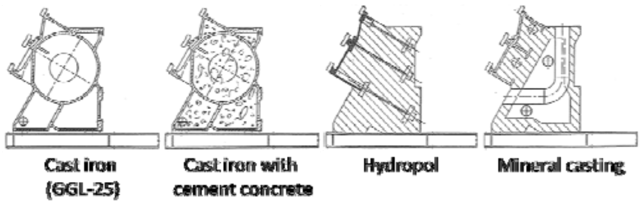

Figure 42: Comparison of lathe bed variants [227]

The lathe bed made of Hydropol showed the shortest decay time but the average tool life in cutting tests was the highest with the cast iron bed. The variation of the observed values with the cast iron and Hydropol bed was significantly higher than with the cement concrete bed. With the Hydropol bed the workpiece surface roughness was slightly improved. The advantageous decay time of Hydropol was also verified in [196].

Munirathnam designed, optimised and compared various slide structures and material applications [202] regarding the dynamic positioning behaviour of machines. An aluminium structure, a welded steel design and the application of Al-foam were considered (Figure 43).

Figure 43: Systematic comparison of slide structures [202]

Improved dynamic path accuracy was achieved by the lightweight ram structures. The structural stiffness appeared to have a significantly lower influence regarding the speed gain value optimisation compared to the mass. An increase of the speed gain by an optimized structural damping could not be verified.

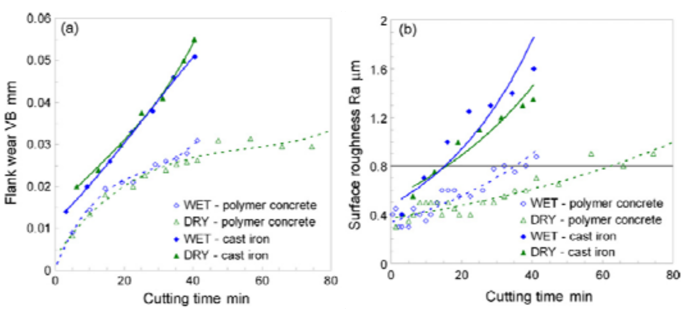

Figure 44: Influence of bed material on tool wear and surface quality [49]

Bruni et al. studied the influences of lubrication, insert technology and machine bed material in turning of AISI 420B stainless-steel and hardened 39NiCrMo3 alloy steel in [48] and [49]. The use of the polymer concrete bed leads to an improved behaviour in terms of tool wear and surface roughness compared to a similar cast iron bed (Figure 44).

3. Methods for structure layout and optimisation

For an optimised design, besides the material selection the assessment and modification of the structural performance is necessary [296]. Nowadays machine tool development can be significantly improved and shortened by the use of virtual prototypes and simulation methods [9, 141, 93]. A number of design optimisation methods has been introduced in literature [136, 100, 125, 317, 160] mainly consisting of the steps of CAD-based design, FEM-modelling and parameterization, first structural optimisation including topology and parameter optimization, first prototype realisation and experimental analysis, model updating by real parameter values, second structural optimisation applying the real parameter values, and second realisation in which the final structure is built. Multiple iterations can be carried out and for model-based optimisation different levels of detail regarding the mechatronic system can be considered [301] (Figure 45).

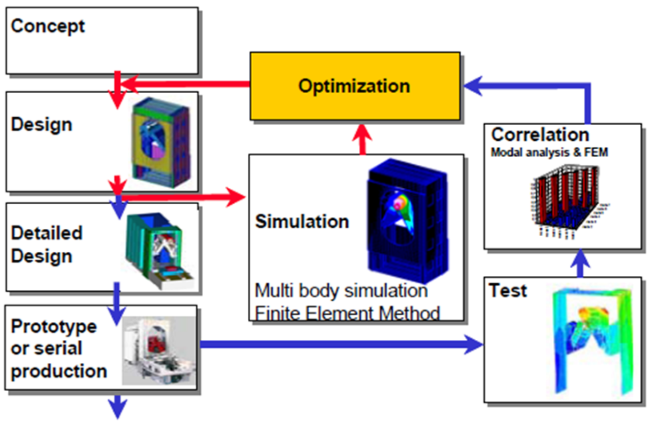

Figure 45: Structural Optimization [301]

However, up to now the essential decisions have to be performed by the design engineer. Multi-objective optimisation techniques for material selection considering partly contradictory targets and evolutionary computation in structural design can be applied [15, 149]. In [75] a framework for intelligent decision support for structural design analysis using a finite element method is discussed.

3.1 Simulation approaches

The basic simulation approaches in machine tool design including the material characteristics in order to calculate the structural behaviour apply the Finite Element Analysis (FEA) [292, 291]. Altintas summarized the different simulation approaches and FEA-types (linear/non-linear static, dynamic, thermal) in [9]. Several approaches describe the elastic behaviour of machine structures by mass-spring-damper models [52, 35], (flexible) multi-body models [32, 183, 161], transfer functions or state-space representations [34, 210] which can be derived by modal reduction from numerical calculations or obtained from experiments in order to increase computational efficiency. Jedrzejewski et al. presented a hybrid model including the finite element method (FEM) and the finite difference method for analysing the thermal, stiffness and durability aspects of machines [137]. Neugebauer et al. introduced an advanced state-space modelling approach with the aim to describe non-proportional material and structural damping such as given by fiber reinforced materials [210].The computation of composite or hybrid and combined materials requires material models at the micro level which allow to derive structure models at the macro level. For homogenisation of composite materials, representative volumetric elements (RVE) can be developed considering material properties and enabling parameterisation of FE-models [142, 143] (Figure 46). For laminated composites, layer-wise shell theory can be applied [146].

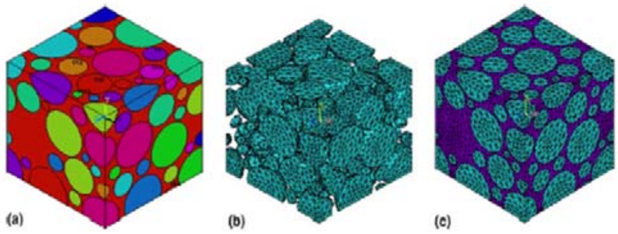

Figure 46: RVE model of randomly distributed spherical particle reinforced composites [142]

A laborious task is to consider various kinematic positions of a machine structure in order to allow a comprehensive assessment of the structural characteristics. Zatarain proposed a method using pre-calculated structures to obtain entire machine models at any position [311]. Brecher and Witt developed a model reduction and component extraction strategy [40]. Litwinski et al. presented a node swap extension for the well-known Craig-Bampton method for model reduction and compared this to FEA and flexible multi body simulation [181]. Law et al. introduced a position-dependent multi-body dynamic model of a machine tool based on reduced model sub-structural synthesis and used it for structure optimisation [167]. A method which allows to combine component dynamics models to entire structures is the receptance coupling substructure analysis (RCSA) [123, 249, 6]. In RCSA, experimental or analytic frequency response functions of individual components are used to predict the dynamic response of the final assembly.

Although sophisticated modelling approaches are available, some uncertainties have to be taken into account, predominantly originated in the unknown real stiffness and damping characteristics of joints and interfaces but also resulting from uncertainties regarding the real material properties. In [255] and [216] this aspect is studied with respect to casted machine tool components.

In order to simulate with realistic values, model updating is necessary which minimizes the differences between calculation and measurement results by modifying the mass, stiffness and damping parameters [200, 201]. Neugebauer et al. discussed the use of sensitivity-based model updating with respect to machine tools possessing a high number of parameters and introduced a cascaded-like strategy [213]. Arora et al. presented a comparative study of damped FE model updating methods in [14]. In [23] direct model updating methods are applied regarding a simple drilling machine. Esfandiari et al. proposed a finite element model updating by use of frequency response function data [86]. In [96] an updated finite element model was used to derive a state space reduced order model of a centerless grinding machine.

3.2 Modal analysis / operational modal analysis

In order to identify the dynamic parameters and characteristics of machine tool structures, experimental modal analysis techniques have been developed and used for a long time [281, 231]. Figure 47 gives an overview about the procedure for component testing and parameter identification.

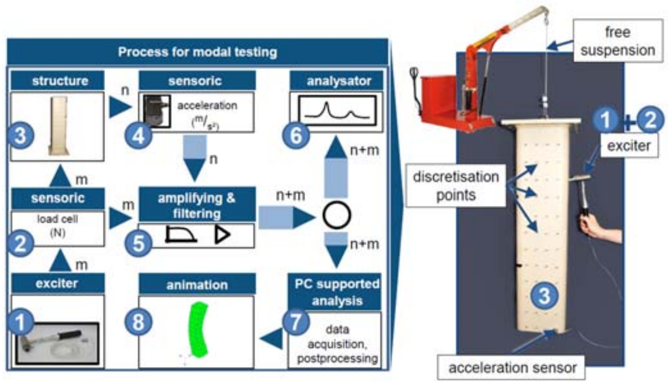

Figure 47: Test setup for dynamic analysis [IFT, TU Vienna]

In [44] an inter-laboratory comparison test regarding the use of the experimental modal analysis for assessing the compliance of machine structures under process conditions is presented. It was shown that the established and commonly applied experimental methods can only give an approximate quantification of the real behaviour due to uncertainties in the experimental procedures and measuring conditions. Furthermore, non-linear behaviour of materials and joints has to be considered. A survey about non-linear system identification in structural dynamics is given in [147].

Implementing experimental modal analysis at complex and large structures necessitates a costly procedure. A fast method for structure dynamics analysis using a tracking interferometer is presented in [45]. As an alternative to modal analysis by use of an impact hammer or controlled excitation shaker, complete machine structures can be assessed by the operational modal analysis (OMA), in which the excitation of the structure is given by the machining process [184, 310, 176].

3.3 Structural optimisation

The final objective of simulation-based and experimental assessment methods is to provide characteristic data for structural optimisation. Structural optimisation aims in design modifications applied to machine components which lead to an efficient material utilization with respect to mechanical component behaviour and performance [293]. Besides enhanced stiffness, damping and strength, material savings and lightweight structures can be achieved. The FEA-based numerical optimisation methods which are implemented in machine tool development are summarized in [9]. An accurate parameterization of material characteristic values is an essential prerequisite regarding the quality of optimisation results.

Topology optimisation can be used in an early and rough design stage to calculate an optimum material distribution with respect to internal structural loads. The resulting component topologies must be smoothed and transferred to a CAD model. In [80] topology optimisation is applied for deriving an optimum ribbing structure of large forming tools. Kolar presents an application of topology optimisation in which multiple slide positions were taken into account when calculating loads [160] (Figure 48).

Fleischer et al. coupled topology optimization with hybrid multi-body simulation in order to consider and update component loads and inertia which occur during machine operation [88, 301, 89].

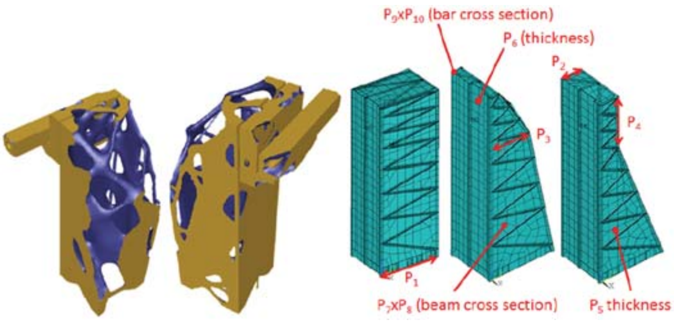

Figure 48: Topology optimization (left) and parameter optimization (right) of a machine tool column [160]

Dadalau et al. presented an optimality criteria and adaptive penalization scheme for topology optimization in [63]. Compared to the commonly used SIMP (Solid Isotropic Material with Penalization) method, better results regarding computed intermediate material densities and applicability with respect to self-weight problems could be achieved. In addition to usually considered boundary conditions such as stiffness specifications, some topology optimisation systems allow the formulation of reference stress and natural frequencies as target and restriction functions [253]. With the increasing performance of additively manufactured structures, together with topology optimisation new degrees of freedom in structural design appear [240].

Parameter optimisation aims in finding the best structural parameters (wall thicknesses, cross sections, fiber orientation) for a detailed component and machine design. Kolar conducted a parametric optimisation of a machine column by use of 10 input parameters (5 side thicknesses, 2 dimensions of ground base, variable number of internal ribs, variable section dimensions of corner bars) [160] (Figure 48). The output parameters of the simulation were the static 3D stiffness at the TCP, the first four natural frequencies and the weight of the structure. Since the sensitivity of the structural stiffness with respect to inner ribs was found to be low (by topology optimisation), a welded steel design was proposed. The column weight could be reduced to 54% (full steel construction) or 59% (hybrid construction with aluminium foam filling), respectively. The machine stiffness was increased to 102% (106%) compared to the original structure and the 1st natural frequency was lifted to 154% (166%).

In structural optimisation of fiber reinforced composite or hybrid components, the consideration of the fiber orientation is essential [294]. Depending on the laminate build-up, anisotropic material properties prevail. In order to exploit the material performance in fiber direction but to avoid structural weakness due to loads in other directions, a differential design with refined ribbing has been chosen in [163].

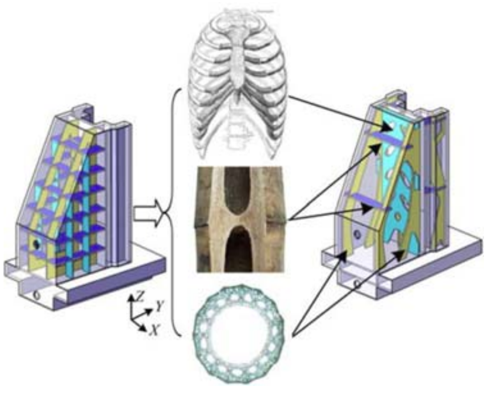

Figure 49: Bionic inspired structural optimization [314]

In recent developments bionic inspired branched structures appeared, aiming in an optimal loading in longitudinal direction of structural elements [314, 315]. In [314] a mass reduction of 2.24% and an increase of the specific stiffness by 21.10% could be achieved for a machine tool column (Figure 49).

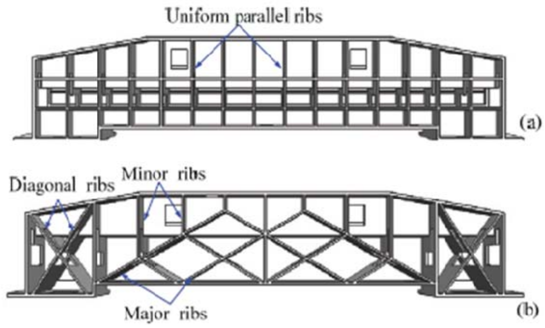

Figure 50: Bio-inspired lightweight structure design [315].

In [315] a bionic inspired crossbeam design has been investigated (Figure 50). A mass reduction of 3.31% and an increase of specific stiffness of 23.29% compared to the conventional structure could be shown with a downscaled model component.

4. Intelligent and smart materials and structures

An innovative research field deals with so-called "intelligent" or "smart" materials and structures, which contain sensory and/or actuator functionality. Actuator functionality means a change of shape, position, frequency or other mechanical properties as a function of a change of temperature, electric or magnetic fields [245]. Most commonly used smart materials for actuators are piezo-electric ceramics, shape-memory alloys, magnetostrictive materials, and electro- or magneto-rheological fluids. For sensors, optical fibers and piezo-electric materials (also some polymers) are used. Such materials can be applied for process and machine condition monitoring, active influencing of the machine dynamic and thermal behaviour as well as for improving process states and adaptive process control. An overview about materials and basic applications can be found in [127, 226]. In [208] a review of mechatronic and adaptronics systems in machine tools is presented which are in many cases based on smart materials. A distinction can be made between components which purely or predominantly consist of smart materials, and intelligent structures which combine conventional structures with smart elements such as integrated sensors or actuators.

4.1 Shape memory alloys

Shape memory alloys (SMA) are metal materials, such as Nickel-Titanium and Copper-based alloys (Cu-Zn-Al, Cu-Al-Ni), which, after deformation, reassume their initial shape with an increase of temperature [165]. The shape-memory effect is based on a transition between two different crystal structures (austenitic body-centred cubic at higher temperatures, martensitic phase when cooling down) (Figure 60). An overview about shape memory alloy research is given in [134]. Applications of SMA for tool clamping are presented in [256, 186]. In [50] SMA actuators are used for pre-stress control of ball screw drives which are actuated by the heat losses of the drive system. In [224] and [191] SMA are used in linear actuators for small machine tools.

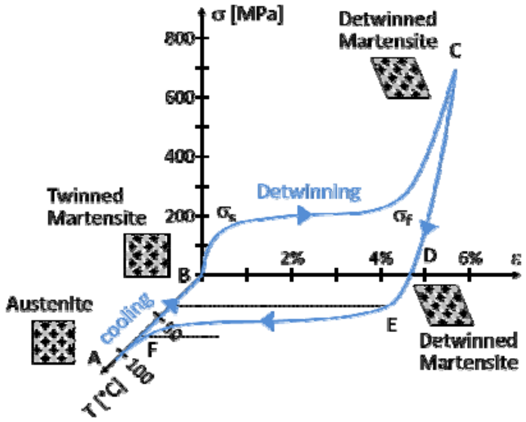

Figure 60: Stress-strain-temperature data exhibiting the shape memory effect for a typical NiTi -SMA [165]

5.2 Piezoelectric ceramics

Piezo electric ceramics react on electric potential by expansion or contraction. Contrary, they generate an electric field when they are deformed. Often used ceramic piezo materials are barium titanate ($BaTiO_3$), lead titanate ($PbTiO_3$), lead zirconate titanate also called PZT ($Pb(Zr, Ti)O_3$), and potassium niobate ($KNbO_3$) [137, 245]. Since piezo electric ceramics are the mostly used material in mechatronic and adaptronic devices for machine tools, it is hardly possible to give a comprehensive overview here. An extensive review of piezo-based mechatronic components is given by Neugebauer [208] and Hesselbach [117]. Applications of piezo actuators range from precision positioning devices [282] to active vibration control systems [5] and devices for adaptive process optimization [7, 68]. Piezo ceramics possess a low elongation to size ratio but high power density and stiffness. Furthermore, piezo ceramics can be applied in a broad dynamic bandwidth. An important aspect when applying these materials is to consider their long-term durability [95]. Figure 61 shows charge-strain curves of a piezo patch transducer specimen under cyclic fatigue testing.

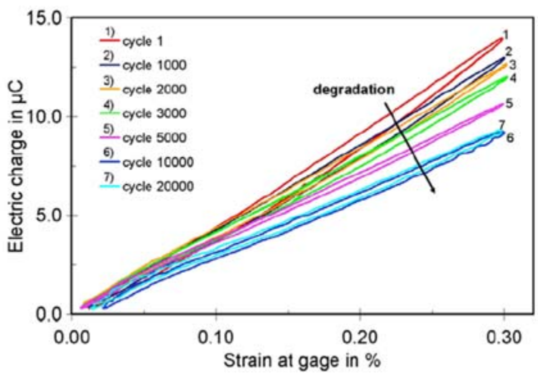

Figure 61: Charge-strain curves of piezo patch transducer specimen under cyclic fatigue testing at a maximum strain level of 0.3% ar room temperature [95]

5.3 Magnetostrictive materials

Magnetostrictive materials change their shape under the influence of an external magnetic field due to the rotation of small magnetic domains which causes internal strains in the material structure [221]. Figure 62 shows physical effects related to the magnetostrictive effect.

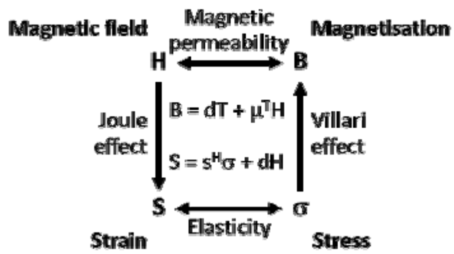

Figure 62: Magnetostrictive effects [221]

The mostly used Joule effect means the expansion of a ferromagnetic rod in relation to a longitudinal magnetic field. The elongation ratio ($\Delta L/L$) can be up to 4,000 ppm at resonance frequency. The Villari effect is based on a change of magnetic flux density when mechanical stress is imposed. This can be detected by a pickup coil and utilized in sensor applications. Further significant effects concern the change of Young's modulus as a result of a magnetic field and the Wiedemann effect leading to shear strains and torsional displacements. Table 7 compares piezoelectric, magnetostrictive and SMA materials.

Table 7 : Comparison of smart materials [221]

	PZT	Magnetostrictive material (Terfenol-D)	SMA
Elongation [%]	0.1	0.2	5
Energy density [J/m^3]	2,500	20	1
Bandwidth [kHz]	100	10	0.5
Hysteresis [%]	10	2	30

In [82] a giant magnetostrictive actuator (GMA) was manufactured and used for tool positioning in an ultra-precise machine. Yoshioka et al. presented a rotary-linear motion platform applying GMA in [309].

5.4 Electro- and magneto-rheological fluids

Electro- and magneto-rheological fluids change their viscosity significantly when an electric or magnet field is applied. This effect has been used in many systems with the aim to allow a controlled and improved damping.

Electro-rheological fluids (ERF) are suspensions which build fibrous structures when an electric field is applied. Thus, the total shear stress of the ERF is increased. Aoyama and Shinno presented ERF applications for machine tools in [11, 12, 258]. Ramkumar used an ERF core inside a composite sandwich box column and obtained an increased stiffness and natural frequency by applying an electric field [239]. With higher ERF layer thickness on the other hand the frequencies decrease.

Magneto-rheological fluids (MRF) behave similar to ERF but react on magnetic instead of electric fields. Exemplary applications are presented in [97, 280, 73]. Weinert and Biermann developed a damping system for deep-hole drilling using MRF (Figure 63). An elastic and infinitely variable torsional clamping of the drilling tool was realised, in order to dissipate the vibration energy within the damping device. Two coils control the magnetic field and hence the mechanical transmission behaviour of the damping system [299, 300].

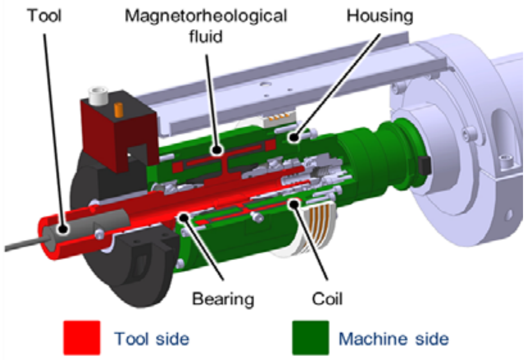

Figure 63: Damping of deep-hole drilling tools by use of magneto-rheological fluid [299, 300]

5.5 Sensor and actuator integrated materials and structures

In order to achieve "intelligent" structures, an integration of sensory and actuator functionality into the machine components is essential. Besides assemblies of conventional structures and smart devices, nowadays material and structure inherent approaches are available. Brecher studied structure integrated thermally sTable CFRP rods and optical fibers for thermal elongation measurements [46]. Fiber Bragg gratings are integrated into CFRP hybrid structures for thermal and mechanical deformation measuring in [195]. Denkena et al. developed a spindle slide with laser structured micro strain sensors [71] (Figure 64).

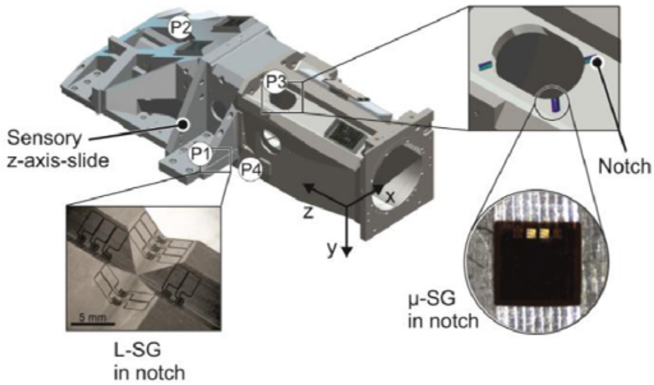

Figure 64: Intelligent spindle slide [71]

In [98] shape memory polymer composites are presented. Piezo integrated composite structures are developed in [179, 209]. Drossel et al. investigate the integration of piezo-ceramic fibres into aluminium sheets by forming processes [78, 79] (Figure 65)

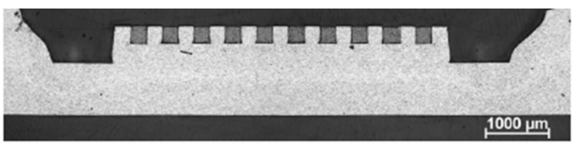

Figure 65: Piezo fibres in Al-sheet [79]

In [101] smart structure manufacturing with piezo integration by incremental forming is analysed. Leibelt introduced strain sensors which are integrated in fiber fabrics by stitching [174] (Figure 66).

Figure 66: Stitched strain sensors [174]

A high future potential of intelligent materials and structures for machine tools can be recognized. Manufacturing solutions for automation and cost reduction are currently developed.

6. Conclusion

This paper makes visible, how broad the field of research and technology regarding materials in machine tools structures already is. The material selection, particular material development, material combination, and structural design offer manifold degrees of freedom for the machine tool builder. A lot of experiences have been made with material solutions in the past and some general lessons can be learned with respect to material exploitation in specific machine tool applications. However, un-conventional and un-expected approach can be seen. Furthermore, permanently new materials are invented and investigated which can provide advantageous properties for machine tool applications (e.g. carbon nano tubes).

Simulation methods and virtual machines can nowadays be incorporated and utilized for structural layout and optimisation. Decision support systems and multi-criteria optimisation techniques as well as more comprehensive and detailed simulation models are developed and will further improve the performance of computer aided machine tool design in the future.

More efficient, accurate and reliable measuring and parameter identification approaches are necessary in order to provide the required parameters for modeling and simulation as well as for prototype assessment and comparison. The joint analysis of machine and process behaviour considering material properties and structural characteristics is increasingly important and aspired in various research initiatives.

The integration of (micro) electronic devices and the design and application of intelligent and smart materials and structures enables a high degree of functional integration. The creation of material and structure inherent sensor and actuator capability is a highly topical research field leading to sensitive and dexterous components and machines. Manufacturing solutions are investigated which allow for an industrial implementation of intelligent and smart technologies.

However, industrial machine tool building is always a matter of cost and delivery time, and this significantly influences also the material selection and structural layout. Another raising topic concerns the energy and resource efficiency and environmental impact which is associated with material application. Consequently, materials in machine tools are subject to various limiting factors, but on the other hand offer a very high technological potential.

Table 8 summarizes some relevant characteristics of materials for machine tool structures.

Table 8: Summary of some selected material characteristics [132]

	GCI	Steel	MC	UHPC	Granite	CFRP
Dispersal in industry	High	High	Middle	Low	Low	Low
Application	Bed, column, slide, table, spindle casing	Bed, column,slide, table	Bed, column, (slide), (table)	Bed, column, (slide), (table)	Bed, column, (slide), (table)	Slide, table, spindle casing, (column)
Develop. potential	++	+	++	+	+	++
Raw material	Iron	Iron	Minerals (quartz, basalt, epoxy resin)	Minerals (quartz, basalt, cement)	Natural stone	Carbon fibers, polymer matrix
Manuf.	Casting	Welding	Casting	Casting	Cutting	Laminate building
Thermal treatment	Annealing	Annealing	/	tempering	/	/
Processing temp.	1,350-1,550°C	Up to 1,000°C	45°C	60°C	20°C	20°C
Rest period before finishing	3-5 days	2-5 days	2 weeks	2 weeks	2 days	0-7 days
Finishing technology	Milling, grinding, scraping	Milling, grinding, scraping	Milling, grinding, casting, lapping	Milling, grinding, casting, lapping	Grinding, lapping	Milling, laser process., grinding
Exemplary type	GG25	St52	EPUMENT 145B	Nanodur	Gabbro Impala	EP/CFK
Density [kg/dm³]	7.15	7.85	2.40	2.45	2.90	1.40
Compr. Strength [N/mm²]	840	800	140	125	250	800
Bending tensile strength [N/mm²]	340	240	35	15	20	700
Young's modulus [kN/mm²]	115	210	45	45	65	180
Thermal expansion [10^{-6}/K]	9	12	15	11	6.5	0.1
Thermal conductivity [W/m K]	47	50	2.9	2.0	3.0	2.0
Spec. heat capacity [J/kg K]	535	360	730	750	800	1,000
Moisture absorption [mass-%]	0	0	0.03	1.0	0.3	0.1
Damping [log. decrement]	0.0045	0.0023	0.0352	0.0385	0.015	0.030

GCI: Grey Cast Iron (lamellar),
MC: Mineral Casting,
UHPC: Ultra High Strength Concrete

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