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Materials in machine tool structures

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A R T I C L E I N F O

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A B S T R A C T

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 sensor 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 optimization 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.

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, as well as the absorption and guiding of forces and torques. Regarding the accuracy of a machined workpiece, the machine frame also should absorb any disturbing effects. Fig. 1 shows modern structures of machining centers including beds, columns, slides, tables, main spindles, joining guides and bearings.

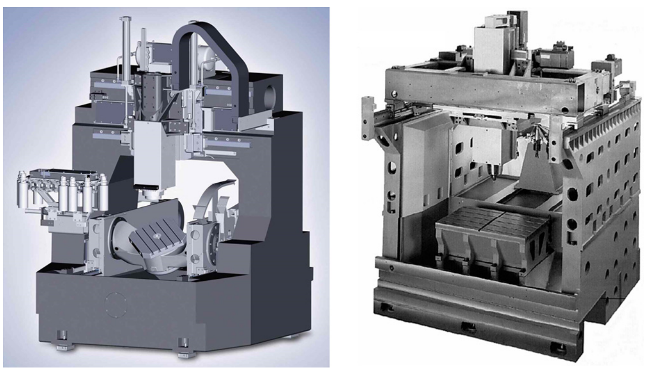

Fig. 1. Modern structures of machining centers [DMG Mori Seiki].

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The mechanical and thermal behavior of a machine frame depends on the elementary material properties (Young's modulus, shear modulus, bending and tensile strength, material damping, density, heat conductivity and capacity, thermal expansion coefficient), 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 general importance of materials was discussed in Ref. [70]. Fig. 2 summarizes the use of materials in history. A historical review about the application of materials in early machine tools can be found in Refs. [54,170]. The improvements and diffusion of machine tools had a major impact on the productivity in industry since the Industrial Revolution 1775–1830.

Prior to that time, almost 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 would fail.

By 1830, iron was the mostly preferred material. The delivery of iron was increased with the introduction and exploitation of the steam engine (1775). The rapidly increasing use of steam engines in turn increased the demand for cast iron. The use of metal instead of wood was a "breakthrough" in machine tool technology in terms of machine performance. Famous examples are the lathes of Henry Maudslay (Fig. 3).

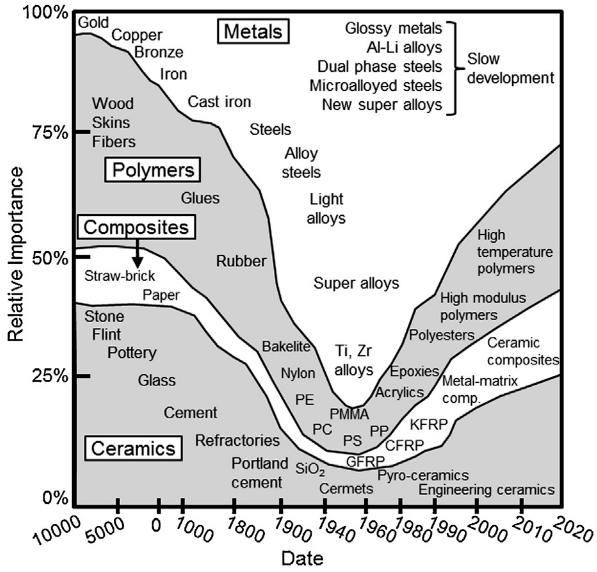

Fig. 2. Material development and importance in history [70].

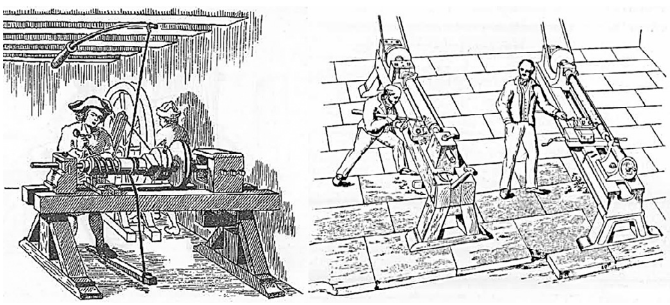

Fig. 3. Picture of a lathe from 1750 (left) [170] and drawing from 1841 by James Nasmyth of a lathe with slide rest by Henry Maudslay (right) [Science Museum/SSPL].

Early design rules were presented in Ref. [267], which already emphasized the target to use the material (cast iron) effectively and to consider the process and force flow sensitively. The structural layout was depending on the experience of the designer rather than on calculations [222]. In 1961, Koenigsberger mentioned that a precise calculation of deformations of complex shaped structural components under load is very difficult or even impossible [153]. This situation changed significantly with the availability and usability of Finite Element (FE) software packages [58,286].

It was early understood that closed box cross sections, welded or casted, lead to advantages with respect to stiffness and resonances (Fig. 4). The so-called "Peters" ribbing was found to be advantageous with respect to bending but box cross sections lead to the highest torsional stiffness. Koenigsberger listed some major design aspects including material properties (tensile, compression and impact strength, stiffness, damping, operating

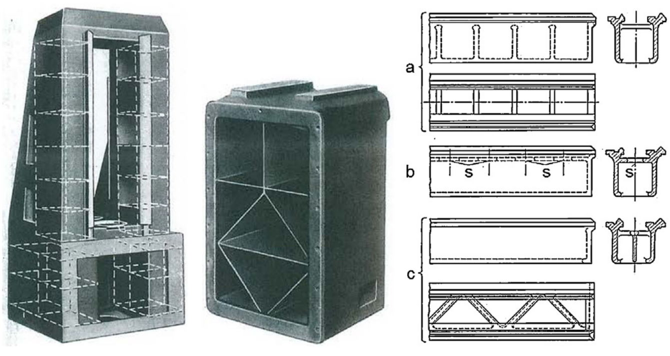

Fig. 4. Cellular structure of a grinding machine (Diskus Werke, Frankfurt a.M. (a) M., Germany) and different types of ribbing of a lathe bed ((a) vertical cross walls, (b) horizontal cross walls with chip holes (s), (c) Peters ribbing) [153,240].

characteristics of sliding guideways), production limits (wall thickness accuracy, residual stresses in cast iron and heat treatment), cost effectiveness and mass reduction [153].

Regarding the use of welded or casted structures, material costs were weighed up against labor costs of a welding worker. This led to different building techniques in Germany and the US. 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 Ref. [240]. 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 [241]. The wear of the concrete slideways prohibited the success of this technology at that time. Fig. 5 shows different generations of base plates for a column stand drilling machine including stepwise improved ribbings. Welded alternatives led to a weight reduction of 32% compared to cast iron [240]. Benjamin [33] and Fischer [83] showed further examples for casted and welded machine tool structures. Besides the stiffness improvement by supporting ribs the consideration of the chip flow affects the machine design. Haas presented a variety of welded constructions in Ref. [102].

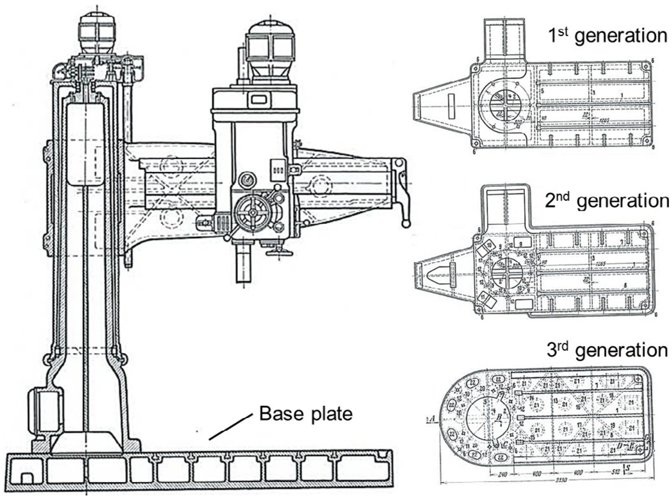

Fig. 5. Different generations of the base plate of a column stand drilling machine (Raboma-Maschinenfabrik, Berlin Borsigwalde) [240].

1.2. General aspects regarding materials in machine structures

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 [191]. In addition, material combinations and hybrid material structures are often applied.

Research approaches also incorporate intelligent or smart materials providing inherent sensor and/or actuator capability. Fig. 6 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. Fig. 7 shows a trade-off plot by Ashby for a performance metrics regarding specific stiffness and damping characteristics of various materials which can be used for optimum material selection [15].

The material selection and structural layout strongly depend on the targeted application of the machine tool. The characteristics of the processes which have to be conducted by the machine have to be considered [18,39,66,106]. Uriarte et al. mentioned relevant aspects with respect to large machine tools [274]. High stiffness and damping as well as low thermal expansion are particularly

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