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INTELLIGENT HYBRID MATERIAL SLIDE COMPONENT FOR MACHINE TOOLS

In mid-scale and large five axis overhead gantry type milling machines, the vertical z-slide (ram) often constitutes one of the most sensitive and critical components regarding stiffness, structural vibrations and thermal influences. During machining, the z-slide is loaded by (quasi-) static process and drive forces, transient acceleration forces, periodic excitations by the tool engagement, as well as by thermal effects resulting from altering ambient conditions, heated chips, cooling lubricant and power losses in drives, guides and bearings. Deflections, thermal deformations and vibrations of the z-slide lead to geometric machining errors and inacceptable surface location errors at the workpieces. Furthermore, instable cutting conditions and regenerative chatter limit applicable material removal rates and, thus, productivity. In this work, a newly developed hybrid material structure for an exemplary z-slide, involving metal parts and mineral cast, is introduced. Structural optimization methods as well as process simulation techniques were applied in order to derive the final design solution. The integration of active cooling circuits for thermal stabilization is investigated and the use of fibre optical strain sensors is analysed with respect to a state monitoring of the machine tool component.

1. INTRODUCTION

Five axis overhead gantry type milling machines provide essential advantages in machining of mid-scale and large parts which necessitate a workspace of several cubic meters. Since the workpiece is not moved during the milling operations, the dynamics of the feed axes can be optimized without the requirement to consider influences and disturbances due to inertia forces of the different workpieces. As a result, high traverse path velocities and high surface qualities can be achieved even at complex workpiece geometries. In this work, the exemplary machine tool ENDURA 700 linear, produced by company FOOKE, is regarded. This machine tool and its principle structure are depicted in Fig. 1.

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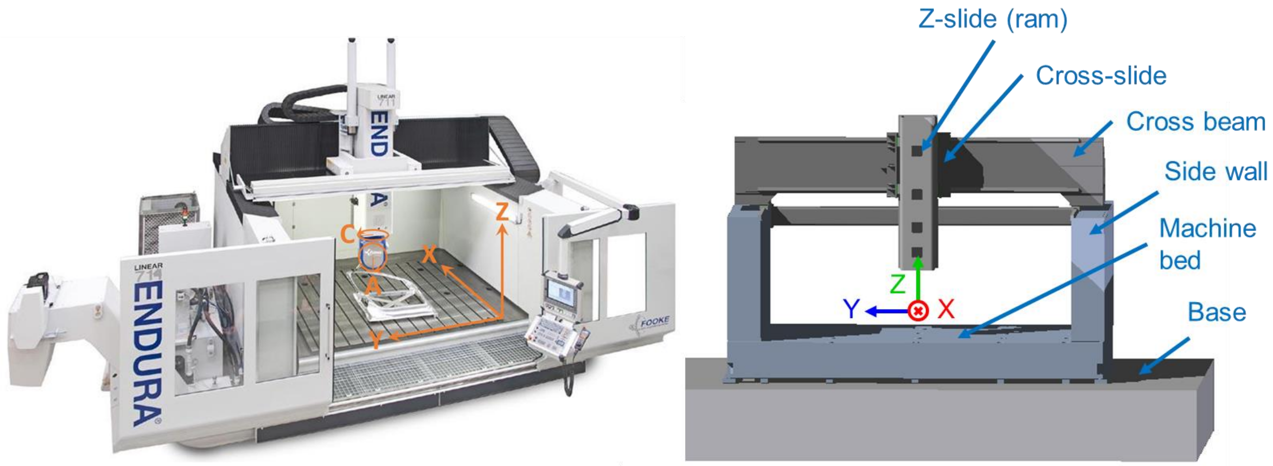


Fig. 1. Exemplary five axis overhead gantry type milling machine ENDURA 700 linear

The kinematics structure of overhead gantry type milling machines mainly consists of a cross beam which moves along the side walls on a machine bed and which carries a vertically moving z-slide (often called “ram”) via a cross-slide (Fig. 1). Various milling heads can be attached to the z-slide so that the machine can be configured with respect to the processing tasks. As a result of the kinematics principle and functional requirements, the z-slide usually consists of a long and slender hollow body. In terms of the mechanical and thermal behaviour, the z-slide can be compared to a vertical cantilever beam with an attached mass. Basically, a light-weight but stiff design is aspired in order to enhance the dynamics characteristics of the machine.

Due to accelerations of the machine axes and by dynamic process forces, the z-slide is excited severely during machining operations. Consequently, structural vibrations occur which affect the traverse path accuracy and which lead to inacceptable surface location errors at the workpiece. In addition, because of limited dynamic stiffness and damping properties, instable cutting conditions and regenerative chatter arise that constrain the implementation of high material removal rates [1],[7].

Furthermore, as a result of changing boundary conditions and ambient temperatures, and due to heat losses in drives, guides and bearings as well as thermal loads by heated chips and cooling lubricant, thermal deformations of the z-slide occur which have a significant influence on the geometric and kinematic accuracy of the machine tool [9],[18], [12],[13],[15],[24]. Thermal effects also have an influence on the dynamics properties of machine tools and, thus, on the chatter stability characteristics [2].

In order to achieve light but dynamically stiff and thermally stable z-slide structural components, various approaches were investigated in recent years. Several design concepts, including aluminium structures, differently ribbed welded steel structures as well as the use of aluminium foam were analysed by Munirathnam [21]. The application of sandwich structures filled with aluminium foam was investigated by Hipke and Neugebauer et al. [11], [22]. A comprehensive overview of material application and structural optimization is given in [19]. In [5] and [6] active elements for the improvement of stiffness and damping properties of rams are introduced and analysed. Regarding thermal stabilisation, basically passive approaches by means of structural materials with low thermal expansion coefficients [19], model-based error compensation strategies [4] and actively controlled cooling methods [10],[25],[26] can be implemented. For the realisation of adaptive compensation strategies based on actual machine states, sensor integration into the structural component is necessary, leading to “intelligent” machine elements [14],[8],[20].

However, the combination of hybrid material structures (i.e. the integrated application of multiple materials in one component) active cooling and embedded sensors in order to achieve an improved dynamic and thermal stability as well as state monitoring capability was not investigated sufficiently in the past.

2. PRINCIPLE APPROACH OF HYBRID MATERIAL STRUCTURE

The principle structural design approach followed here utilizes a hybrid material combination of metal parts (cast iron or welded steel) and mineral cast (Fig. 2). Due to the relatively low density of the mineral cast material, a reinforcement of the metal component that provokes only a comparably low increase of the overall weight is possible. As a result of the enhanced geometrical moment of inertia, an increased bending stiffness of the hybrid component can be achieved.

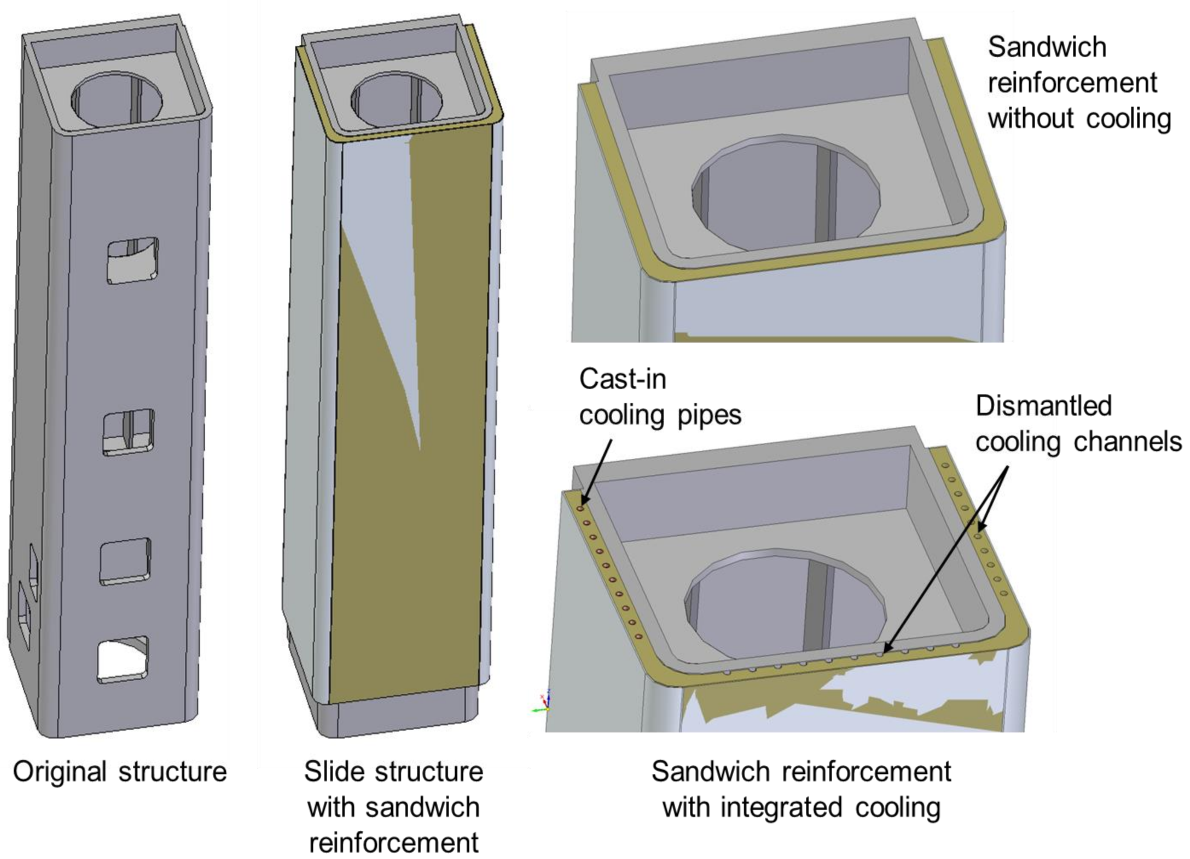


Fig. 2. Principle approach of sandwich reinforcement with integrated active cooling

Furthermore, the advantageous material damping of the mineral cast leads to an improved structural damping of the slide. In addition, during the casting process of the mineral cast material, an easy integration of cooling pipes or channels can be implemented. Since this process takes place at low temperatures (normally below 60°C) copper or even plastic pipes can be built in. The cooling channels can also be realised directly within the mineral cast substructure by means of lost cores during the casting process and an appropriate sealing of the inner surfaces of the remaining channels. As a result, a laminar cooling can be achieved by distributed pipes or channels.

In order to enable a direct measurement of the temperature distribution inside the hybrid material component, thermal sensors can be integrated also during casting. This sensor integration allows thermal state monitoring and an adapted active temperature control. Furthermore, an integration of strain sensors is possible. Thus, thermal deformations as well as mechanical distortions can be identified. The sensors (temperature and strain) are finally covered by the mineral cast sandwich layer and protected against damages by external impact.

In principle, the sandwich reinforcement can be applied outside (Fig. 2) or inside the metal structure. Since the metal material provides the higher Young's modulus and tensile strength compared to the mineral cast material, structural optimisation has to be conducted in order to arrange the material combination properly. This structural optimisation also includes the configuration of ribbings and the layout of wall-thicknesses.

3. INVESTIGATION OF ACTIVE COOLING

In order to analyse the characteristics and capability of the integrated active cooling, experimental investigations were carried out using the test setup shown in Fig. 3. A hollow profile made of structural steel with dimensions 200 x 200 x 800 mm and a wall thickness of 12 mm was reinforced by an internal layer of mineral cast with a layer thickness of 20 mm. Twelve copper pipes with a diameter of 12 mm were built in during the casting process. For internal temperature measurements, twelve thermal sensors (Pt100) were integrated between the steel component and the mineral cast layer. An additional thermal sensor was applied for measuring the ambient temperature. In order to measure thermal strains, six strain gauges (three of them mounted directly on the steel test structure; additional three mounted via an intermediate steel plate which was screwed at the steel test structure) as well as one fibre optic Bragg sensor were attached to the test component (Fig. 4). Furthermore, thermal distortions were observed by means of eight inductive touch probes that were mounted at a CFRP reference measuring structure with low thermal expansion. During the experiments, the test component was actively cooled down by a reflux water chiller to different temperature set values in sequential steps. Fig. 5 depicts measurement results for a cooling to set values of 15°C and 10°C, respectively.

The measurement results in Fig. 5 show that the temperatures inside the test component react sensitively and fast to the active cooling. Apart from some minor calibration deviations, a homogeneous cooling can be observed.

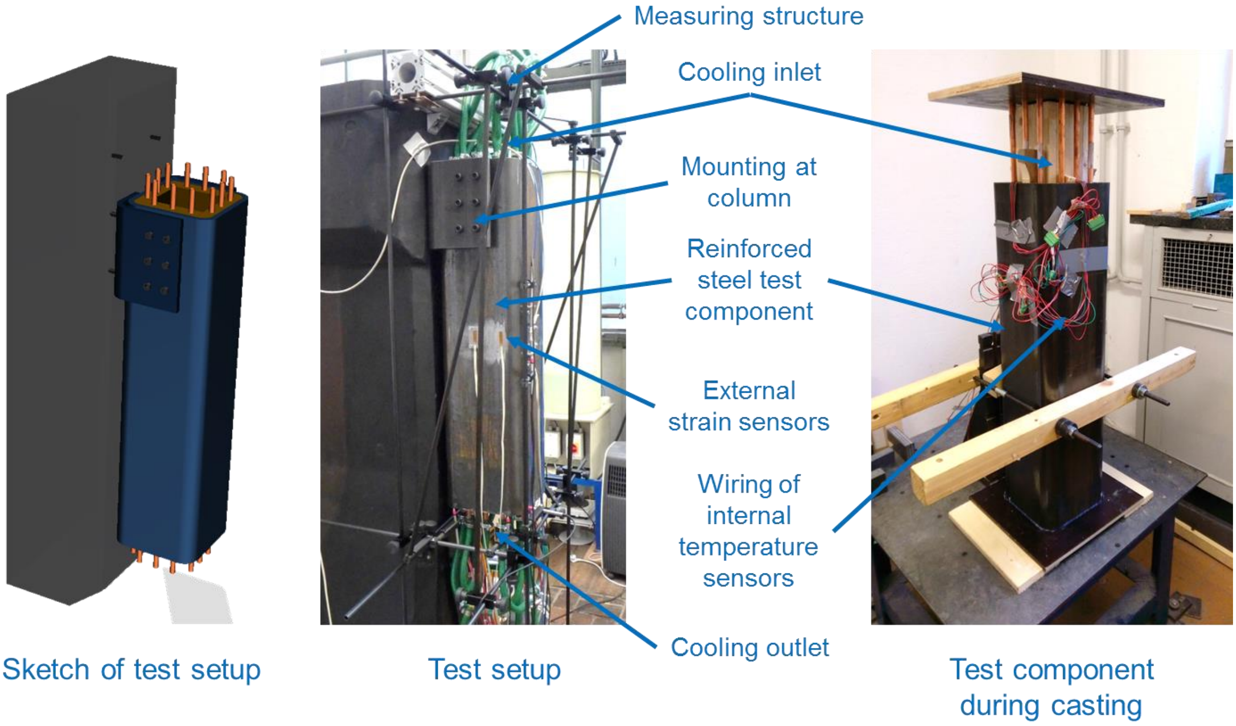


Fig. 3. Test setup for active cooling experiments

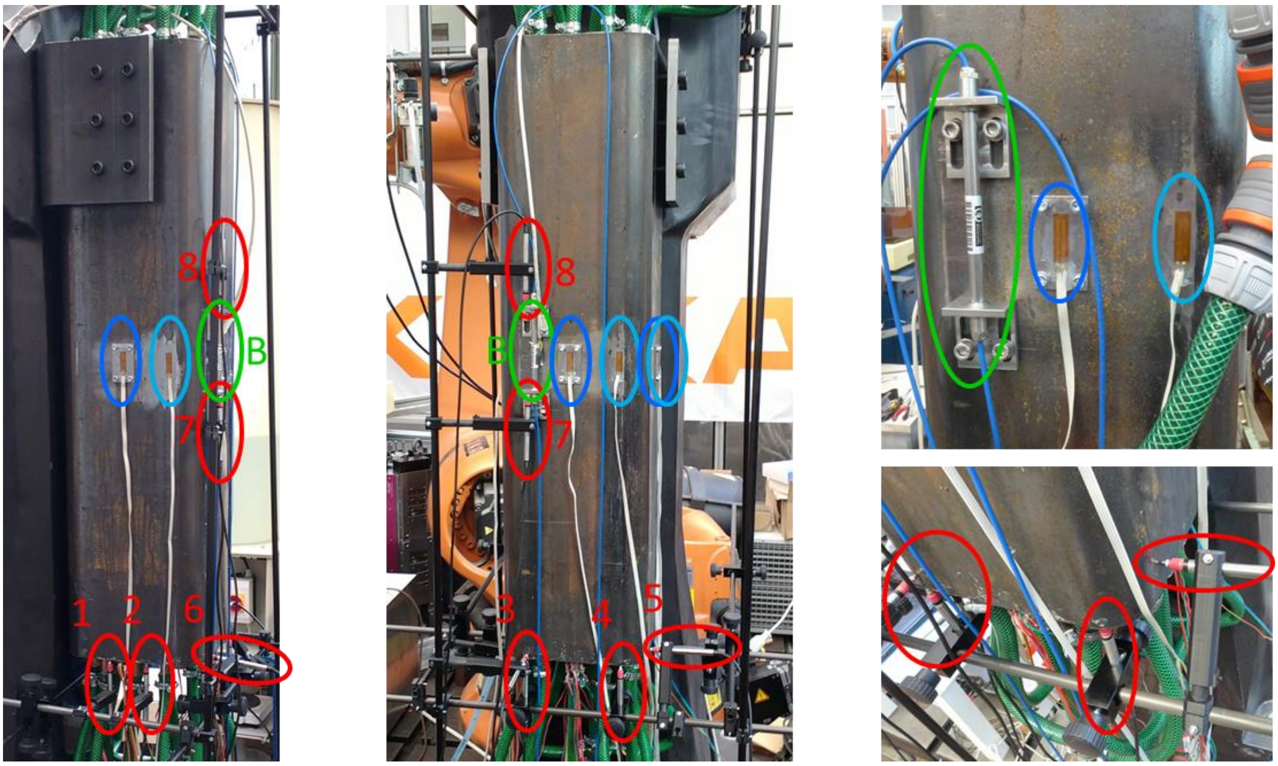


Fig. 4. Arrangement of external strain and displacement sensors (light blue: directly mounted strain gauges, blue: indirectly mounted strain gauges, green: fibre optic Bragg sensor, red: displacement sensors)

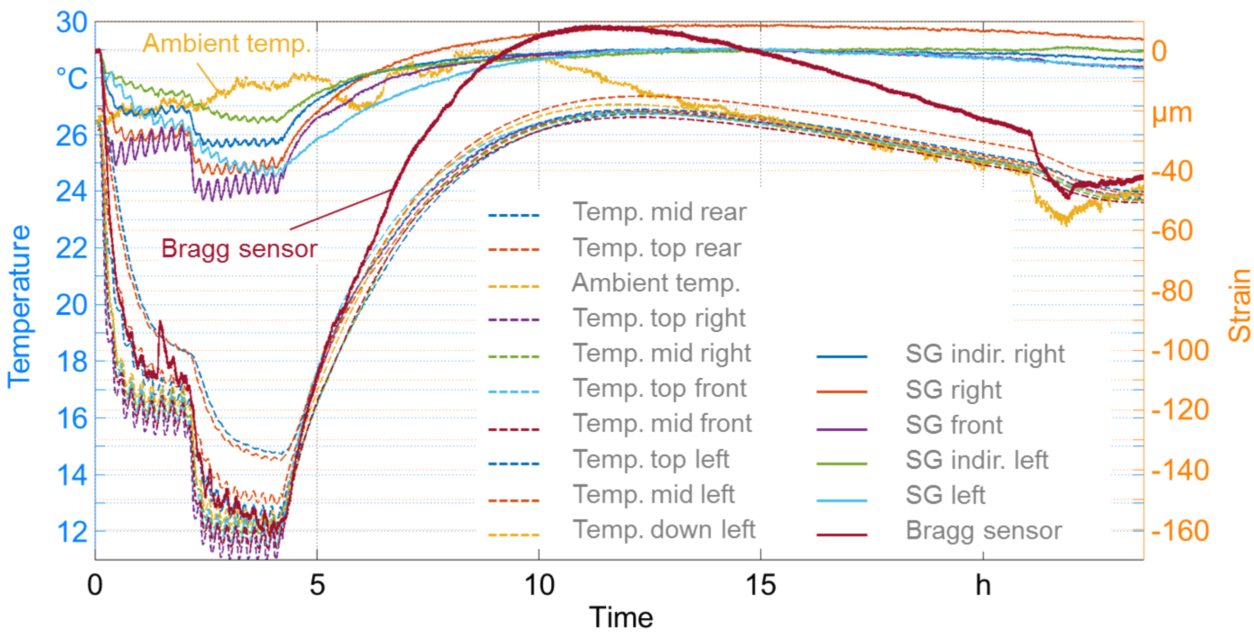


Fig. 5. Results of measurements with active cooling of the hybrid material test component (SG: strain gauge)

Furthermore, the applied strain gauges reveal thermal strains due to the changing temperatures of the component. The fibre optic Bragg sensor provides much more sensitive strain information than the strain gauges. But it has to be mentioned that the signal of the Bragg sensor is also influenced by the ambient temperature directly as can be recognized e.g. at a measurement time of approx. 22 hours. This direct temperature influence has to be corrected by an appropriate sensor arrangement of a Bragg sensor combined with a thermal sensor.

4. STRUCTURAL OPTIMISATION

In order to derive an optimised hybrid material structure, in a first step, topology optimisation of a simplified initial slide body was carried out. Within the Finite Element Analysis (FEA), the initial slide body was connected to linear guide rails that were supported by four fixed carriages. Different loads (forces in x-, y- and z-direction as well as torques about the x-, y- and z-axis) were considered and applied at the front edge of the inner bore hole (representing the mounting interface of the milling head). The results of the topology optimisation are presented in Fig. 6. The material that could be reduced is marked in red. The results show, that a significant amount of material can be saved especially in the upper rear part of the slide which is located above the supporting carriages. Furthermore, a breached and ribbed design of the side walls of the slide component appears to be feasible in order to further decrease the portion of steel within the aspired hybrid material solution.

Assuming a sandwich type combination of an outer steel frame with an inner mineral cast reinforcement, another aspect in structural optimisation concerns the wall thicknesses of the outer and inner substructure, respectively. This aspect was investigated by theoretical analysis of an abstract sandwich type hollow profile with similar dimensions compared to the original machine tool slide (Fig. 7). This sandwich profile includes an outer steel part with cross section A_1, the mineral cast reinforcement with cross section A_2 and an additional inner steel part with cross section A_3. The length of the profile amounts to 2,000 mm.

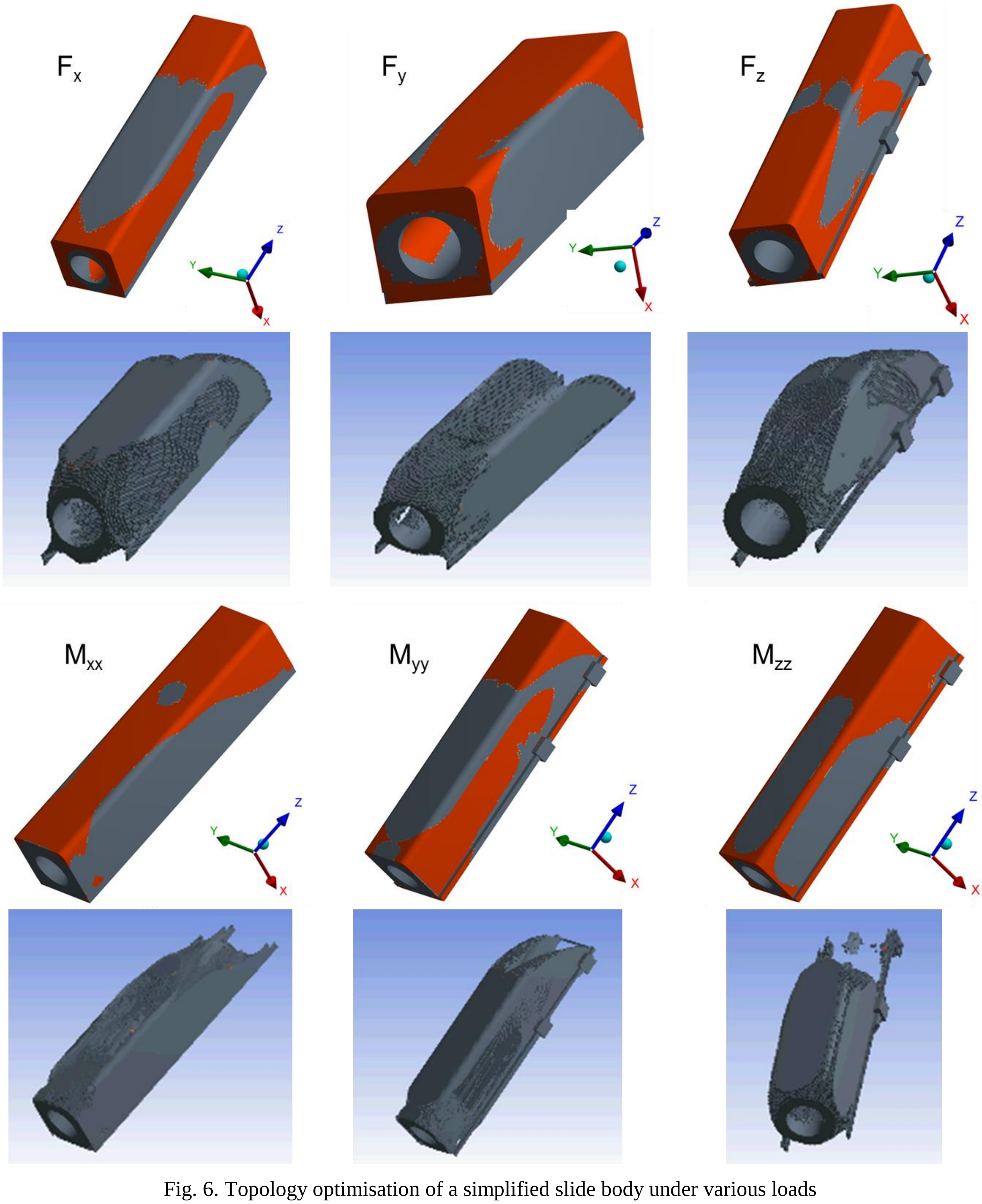


Fig. 6. Topology optimisation of a simplified slide body under various loads

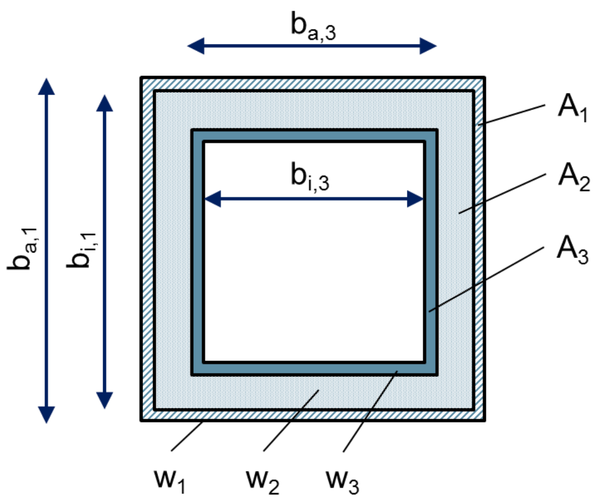


Fig. 7. Cross section of an abstract sandwich type hollow profile with three layers

The outer dimension $b_{a,1}$ was set to 480 mm. The inner dimension $b_{i,3}$ was varied from 270 to 384 mm in steps of 2 mm (denoted by control variable k = 1…58). The wall thicknesses w_1 and w_3 were also varied in a range of 2 up to 24 mm. The wall thickness w_2 of the mineral cast layer results from the combination of the wall thicknesses w_1 and w_3 of the steel parts and the inner dimension $b_{i,3}$. Furthermore, the material densities (7,850 kg/m³ for steel and 2,300 kg/m³ for mineral cast), Young's moduli (210 kN/mm² for steel and 41 kN/mm² for mineral cast) and shear moduli (85 kN/mm² for steel and 17 kN/mm² for mineral cast) were considered. Based on these parameters, the mass, bending spring constant and torsional spring constant of the different sandwich profile variants were calculated. In addition, the "specific" spring constants were derived by dividing the spring constants by the mass values (Fig. 8). Considering a desired minimum wall thickness of the mineral cast layer of 50 mm (due to material and casting requirements) and an aspired mass of 700 kg of the abstract profile, an optimised set of design parameters can be found. Here $w_{1,opt}$ was chosen to 17 mm and $w_{3,opt}$ was chosen to 5 mm.

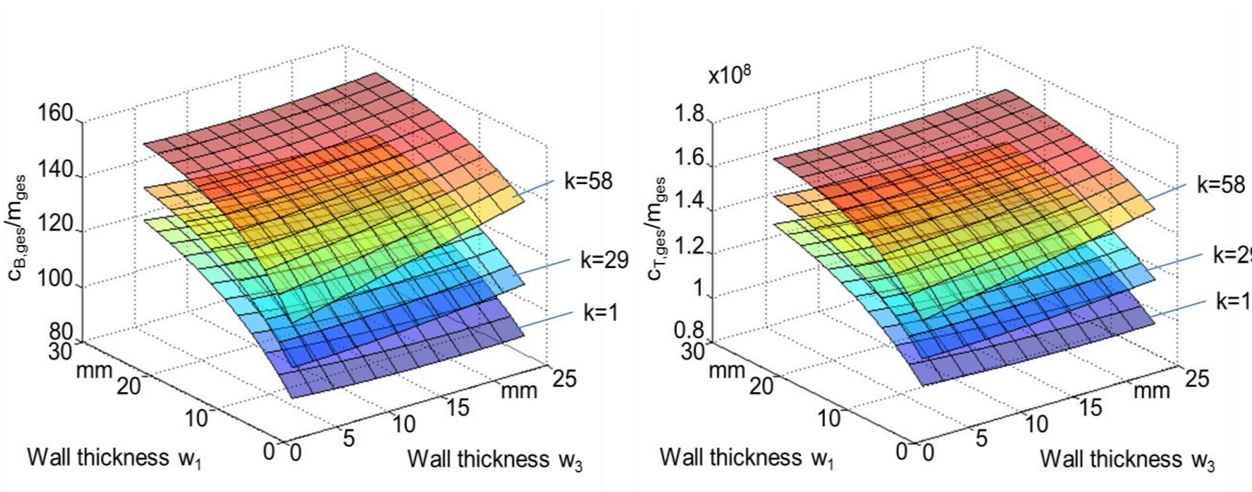
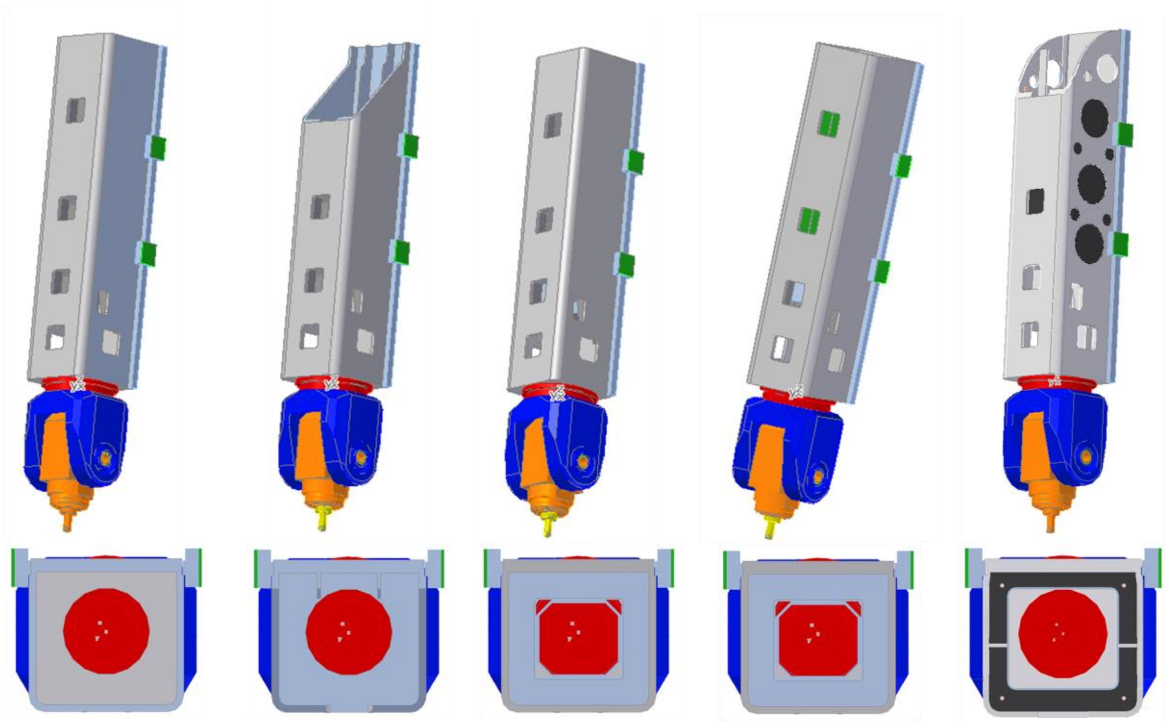


Fig. 8. Specific bending (left) and torsional (right) spring constants of sandwich profile variants

5. ANALYSIS OF THE DYNAMIC CHARACTERISTICS

Based on the above described ideas, several variations of hybrid material slide components were designed and compared to the original structure with respect to the dynamic behaviour. In this paper, 4 variants (out of 16) are introduced (Fig. 9).



Variant 0 (original) m_{slide} = 788 kg | Variant 1 m_{slide} = 700 kg | Variant 4 m_{slide} = 963 kg | Variant 5 m_{slide} = 1114 kg | Variant „VF" m_{slide} = 856 kg

Fig. 9. Selected design variants of the z-slide (position P1)

The original slide (variant 0) consists of a monolithic metal part with internal ribbings and stiffening plates which is supported by two linear guide rails and four carriages. A simplified milling head is attached to the slide component via a rotational bearing. For FEA modelling, the material properties of the carriages, the rotational bearing of the milling head and the bearings of the swivelling axis of the milling head were parameterized according the measured dynamic characteristics of the real component. Thus, the influence of the stiffness and damping of the guides and bearings is considered. The mass of the milling head as well as its centre of gravity were also adjusted to the real system by the material properties of the model. The position P1 of the carriages is chosen with respect to an exemplary position of the z-slide within the kinematics structure of the machine tool. For the original slide, in addition, an extreme position was analysed in which the upper carriages are located close to the end of the linear guide rails. The cross section of the original slide is characterised by an inner bore hole with a diameter of 270 mm.

The variant 1 differs from the original slide in terms of the reduction of material at the upper part of the metal component. In the variant 4 the circular inner bore hole is replaced by a rectangular clearance. A first rectangular steel hollow profile is inserted into this clearance and a second octagon steel hollow profile is mounted in the first profile. The space between the first inner profile and the main structure of the slide is filled with mineral cast material in variant 5. The variant "VF" consists of an optimised and breached metal main body with modified ribbings, an inner rectangular steel hollow profile and a mineral cast filling with four integrated cooling pipes. All variants were investigated by means of FEA-based harmonic analyses in which forces in x- and y-directions were applied (Fig. 10).

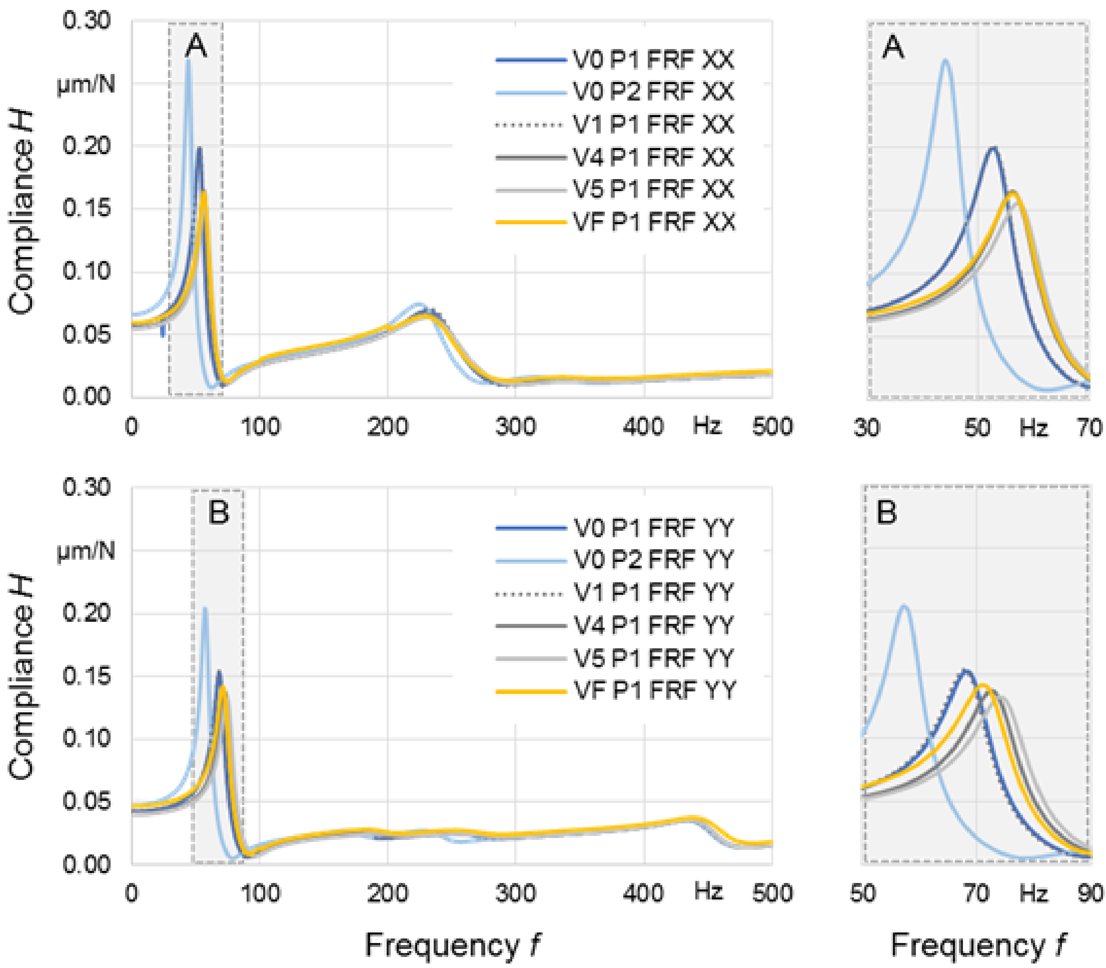


Fig. 10. Frequency Response Functions (FRFs) for the variants in X- and Y-direction.

Compared to the original slide (V0) the modified variants provide higher natural frequencies and structural damping. The most significant effect is achieved by variant 5 (V5). However, this variant also possesses the highest mass of the slide (Fig. 9). The optimised solution (variant VF) also shows a promising improvement compared to the original slide and provides a relatively minor mass increase.

6. ANALYSIS OF THE PROCESS STABILITY

Due to the fact, that the development of an optimized z-slide component is on an early stage, an experimental analysis of the structure is not possible. Therefore, stability diagrams were calculated for the evaluation of the simulated dynamic properties of different z-slide designs under process conditions. The applied time-domain simulation system, which is developed at the Institute of Machining Technology (ISF), uses geometric models for the description of the tool and workpiece side as well as the engagement conditions. By analysing the intersection between the tool and the workpiece, the uncut chip shape and the resulting forces can be predicted. The process forces are determined with an empirical model, based on the analysis of the uncut chip thickness [23]. The cutting forces lead to quasi-static and dynamic deflections of the compliant tool, machine and workpiece, which effect the uncut chip thickness and, thus, the process forces respectively. In this way, the regenerative effect and chatter vibrations are modelled and stable or instable process conditions can be predicted. For this purpose the dynamic behaviour of the machine and tool at the tool centre point (TCP) and the workpiece at the contact position is represented by damped harmonic oscillators for each mode. These uncoupled harmonic oscillators are excited by the calculated cutting forces and exhibit deflections [16]. A detailed description of the simulation systems functionality and its capabilities is given by Kersting [17]. For modelling the dynamic behaviour of a machine structure, the variation of the FRFs at the TCP in different machine poses have to be taken into account [3].

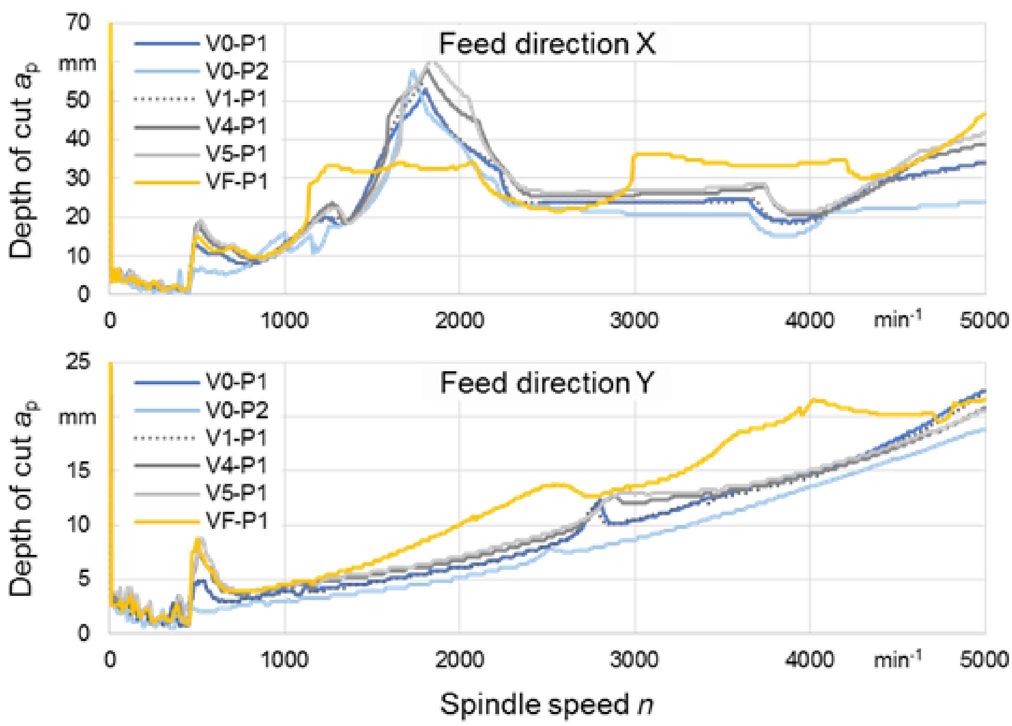


Fig. 11. Stability charts for the slide variants with feed directions in X and Y

The simulated stability charts (Fig. 11) are based on a down milling process with a constant width of cut of $a_e = 26$ mm and a feed per tooth of $f_z = 0.2$ mm. The tool is modelled as a cylindrical cutter with a diameter of $d = 52$ mm and $z = 7$ teeth. The empirical force model uses parameter values, which were determined for St2312 steel. The spindle speed is varied from $n_{min} = 1$ min^{-1} to $n_{max} = 5{,}000$ min^{-1} and, thus, covers the relevant cutting speed ranges for St2312 steel.

The process stability exhibits higher stability boundaries when the feed direction is X. In this case, the stability prediction for the optimized variant (VF) provides a higher average level, but a lower absolute maximum at about $n = 1{,}800$ min^{-1}. This means that the optimized variant provides advantages for most spindle speeds, but not such a high optimization potential at specific spindle speeds as, e.g., for the initial variant (V0) at about 1800 min^{-1}. For a feed speed in Y-direction, the optimized structure provides the highest stability for almost every spindle speed.

To allow an evaluation of the structural optimization success, the light blue stability boundary represents the initial z-slide variant (V0) in the lowest, and, thus, most compliant position (P2). It can be seen that the effect of the structural optimization is higher than the position-dependent effect on the dynamic properties of the structure.

7. CONCLUSION

This paper presents the development and analysis of a hybrid material intelligent z-slide for mid-scale or large overhead gantry type machine tools. Metal slide bodies are combined with mineral cast fillers in order to exploit the potentials of both materials.

Topology and structural optimisation were implemented aiming to achieve an optimum compromise between the mass of the component and its dynamic stiffness characteristics.

Active cooling of a hybrid material test component was investigated in experiments. The results show, that a fast reacting thermal control is possible. Integrated thermal sensors show the required sensitivity with respect to monitoring and adaptive control purposes. Furthermore, built-in strain sensors are capable to observe thermal distortions. A fibre optic Bragg sensor provides a significantly higher sensitivity compared to strain gauges.

The structural dynamic characteristics of multiple design variants were analysed by means of FEA. In addition, process stability simulations were conducted which allow an assessment of the predicted machining performance in terms of applicable material removal rates. Thus, the benefits of the novel design approach could be evaluated.

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