MINERAL CASTING AS MATERIAL FOR MACHINE BASE-FRAMES OF PRECISION MACHINES

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OVERVIEW OF BASE-FRAME MATERIALS
In precision engineering the importance of the base-frame on the precision of the machines is often underestimated. Machine base-frames define the position of subsystems like drive systems, measuring systems or machining devices to each other and are often the most expensive single part of a positioning machine. The aim is to achieve low-cost, highly integrated base-frames.

In this article materials for machine base-frames of precision machines are compared and design guidelines for mineral cast are derived. In ultra-precise measuring and machining the base-frame has to guarantee the stable position of all subsystems with high rigidity against static and dynamically changing thermal loads and mechanical forces and torques. The long-term stability is a crucial issue of the base-frame as well.

MINERAL CAST IN MECHANICAL ENGINEERING
Commonly used materials for base-frames are natural stone, cast iron, steel and ceramics. An alternative to these materials is polymer concrete. In this article the compound material will be comprehended as polymer concrete. The machine base-frame made of polymer concrete is called mineral cast. Mineral cast is used as base-frame in e. g. grinding machines or machining centres. However, it is not used commonly in precision positioning machines. The aim of this research is to prove the possibility of the appliance of mineral casting in ultra-precise positioning and measuring.

Composition of polymer concrete
Polymer concrete is a composite material of non-metallic fillers like silica minerals with well-defined grain size and distribution bound in an epoxy resin. The size of the mineral fillers varies from 0.25 mm up to 32 mm [1]. The mechanical properties result from the high-density network of the fillers with direct mineral grain contacts, which is shown in Figure 1 as draft.

FIGURE 1. Draft of the filler-network with different grain sizes
The epoxy resin is an interlayer, which holds the filler material together. Its volumetric percentage is in applications in mechanical engineering below 12 % [2]. Depending on the chosen resin the chemical reaction of binding takes times from minutes to hours [3]. Several additives are mixed in a low weight percentage to the resin and filler network in order to
- diminish viscosity,
- initiate the polymerisation,
- accelerate/slow down the polymerisation.

Manufacturing of mineral cast
Polymer concrete has to be prepared thoroughly. Filler material has to be dried properly. Grain size fractions of stochiometrical quantities of mineral fillers are mixed with resin and additives. Aim is to achieve full moistening of the mineral fillers and high packing density. To avoid air bubbles in mineral cast, it is possible to mix polymer concrete in vacuum-chambers or to heat the moulding form.

Manufacturing of mineral cast parts is comparable to the technology of iron casting, although curing is based on polyaddition of the resin instead of cooling. During the casting process onto the appropriate moulding form the so called pot-life is of importance. It takes two to six hours in dependence of the complexity of the moulding form [2].
In order to reduce pores and eliminate air from the compound it is densified on shaker plates. For applications in submicrometer-range, during the curing of the resin the moulding form is heated or insulated to receive evenly distributed temperature in the mould and small temperature gradients. Shrinkage during polyaddition is not significant, these factors lead to a low intrinsic tension-level of the mineral casting part.

Depending on the requirements of the achieved precision, tolerances and surface quality of the mineral cast base-frame and the number of castings the utilized moulding forms are made of wood, plastic, steel or cast iron and its combinations. For the use in micrometer-range only cast iron or steel moulding forms are applicable. Nonporous surfaces (functional surfaces) are produced at the bottom of the moulding form.

**Function integration in mineral cast**

It is possible to integrate other subfunctions than support of measuring or driving subsystems into the mineral cast base-frame by inlets. Figure 2 shows some common inserts with form fit: thread anchors, drilling bars and transport aids. The integration of further functions like lost cores to reduce weight, electrical conductors, channels, heating/cooling pipes with form closure facilitate highly integrated mineral cast base-frames. For applications in precision engineering – to receive better distribution of forces – end-to-end prestressing anchors are used. Monolithical integration of functional surfaces and guideways eliminate or diminish post-processing: up to $10 \mu m$-resolution it is possible to create functional surfaces with tight tolerances with replication.

**Properties of mineral cast**

Corresponding to the literature [2, 5] mineral cast has favourable properties:

- outstanding material damping (Figure 3 shows damping curve of mineral casting),
- high thermal capacity,
- low heat conduction,
- low density,
- non-corrosive,
- electrical insulator,
- non-magnetic,
- low water absorption,
- mineral cast is considered as a lightweight construction material.

**FIGURE 2. Examples of typical inlets [4]**

Characterising mineral cast has many difficulties: different fill factors, grain-size distributions and materials, used resins and additives, distributions of natural products influence the properties of the resulting compound. Achieving comparable qualities of different charges is only possible with process control of the applied technology from preparation of the materials until cooling. Anyhow, properties of mineral cast can only be defined in value ranges.

**FIGURE 3. Comparison of damping curves of mineral cast (top) and cast iron (bottom) [4]**
TABLE 1. Comparison of the properties of mineral casting, cast iron and natural stone

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Mineral cast</th>
<th>Cast iron (GG30)</th>
<th>Natural stone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal capacity</td>
<td>[J/kgK]</td>
<td>0,9-1,1</td>
<td>0,5</td>
<td>0,85</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>[W/mK]</td>
<td>1,5-2</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>[10^-6 K]</td>
<td>13-14</td>
<td>9,2-11,8</td>
<td>2,1-9,1</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>[kN/mm²]</td>
<td>15</td>
<td>137</td>
<td>60-90</td>
</tr>
<tr>
<td>Density</td>
<td>[g/cm³]</td>
<td>2,3-2,4</td>
<td>7,25</td>
<td>2,8-3</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>[N/mm²]</td>
<td>≤10</td>
<td>410-560</td>
<td>34</td>
</tr>
<tr>
<td>Compression strength</td>
<td>[N/mm²]</td>
<td>≤100</td>
<td>600-1000</td>
<td>&gt;250</td>
</tr>
</tbody>
</table>

Mechanical properties and dependencies
The following list gives an overview of the mechanical properties relevant in precision engineering.

- Mineral cast has, similarly to cast iron, different strength values on compression and tension. Independent from the used resin the ratio of compression strength to tensile strength is about 9:1 [6].
- Specific stiffness of mineral cast is smaller than the specific stiffness of natural stone but greater than cast iron.
- Mechanical material properties of mineral cast are temperature-dependent. Raising the temperature from 20°C to 80°C decreases the compression strength by 50%.
- The fatigue endurance limit of mineral cast is at about 50% of the static load. Fatigue of mineral cast begins at 50% of the nominal compression strength.
- Creeping in submicrometer-range occurs, when mineral cast is exposed to compressive loads ≥ 20% of the nominal compressive strength of the polymer concrete.

Thermal properties and dependencies
The relevant thermal properties of mineral cast for applications in submicrometer-range are listed:

- Thermal conductivity of mineral cast is one order below the level of steel or cast iron and comparable to natural stone.
- Thermal capacity of mineral cast is about two times greater than steel or cast iron.
- Thermal expansion is greater than of natural stone, its value is comparable to steel and cast iron.
- The thermal expansion of mineral cast is (in limits) variable in dependence of the resin and its volumetric part.

Conclusions of the properties of mineral cast
The advantage of polymer concrete is the freedom of adjusting thermal expansion at the composition of the compound material. Thermic inertia and the bad thermal conductivity of mineral cast results in comparable values to natural stone. Because high thermal capacity is linked with bad thermal conductivity, the temperature-distribution is not even in mineral cast parts, which leads to hot-spots.

According to the absolute and specific mechanical strength of mineral cast it is not a lightweight construction material in comparison to steel and cast iron. Based on temperature-dependence and creeping, mineral-cast parts are not applicable in base-frames for machines in submicrometer-range.

DESIGN GUIDELINES OF MINERAL CAST IN PRECISION ENGINEERING
Aim of the designing engineer is to create long-term stable base-frames of highly precise measuring machines. Considering the properties of polymer concrete and mineral cast, design guidelines are compiled with special respect of cost-effectiveness, technology and applications. The most important guidelines are listed:

- Technology of mineral casting is similar to iron casting.
- Wall thickness of the moulding form depends on the biggest grains of the grain distribution. Generally the use of wall thickness five to eight times of the largest grain is recommended. Application of smaller fractions result in thinner walls, a multi-mould with differing filler fractions is possible.
- Differing wall thickness in a mineral cast part is due to the low level of intrinsic tension possible, though notching effects have to be considered.
- Mould inclines of approx. 5 degrees is necessary to extract the mineral cast from the moulding form.
• Undercuts are possible. The only restrictions are filling the moulding form and air elimination. Lost cores or filling the moulding form in more steps from multiple directions allow the usage of polymer concrete.

• Inlets should have a wall thickness of three to four times of the largest grain size. Pull-out tension is estimated as 1 MPa.

• Simple and shallow mould form leads to better air elimination and homogenous mineral cast.

• Symmetric design with adequate wall thickness accentuate the positive thermal damping property of mineral cast, though the thermal inertia of the system has to be considered.

• To control the tight tolerated cast-in parts they should be clamped on one (preferably bottom) part.

• Complex geometrical contours of moulding forms are to be avoided.

• Tight tolerances are possible with the use of precise, reuseable steel moulding forms. In a two-step moulding into a second layer of fine-grained material guideways are replicated. Another possibility is the machining of the functional surface.

• With monolithically integrated functional surfaces grinding and post-processing costs are diminished.

• The designer has to aim at a simple and massive form-design without complicated contours, whereas integration of functions in the mineral cast leads to a complex, function-integrated base-frame.

• Machining of the mineral cast base-frame is challenging in dependency of the mineral fillers.

• Grinding surfaces should be parallel and geometrically separated from other surfaces.

• The designer has to leave enough space between the cast-in parts to permit polymer concrete to fill the room.

• Inlets are always applied form-fitted.

• Casting of defined, tolerated surfaces is cheaper than post-processing (e.g. grinding).

• Use of a safety factor greater four is in dynamically utilised base-frames recommended.

• To avoid creeping in submicrometer-range in shape (after 1000 hours), only 1% of the bending strength is useable.

• Tensile stress and bending strain is to avoid in mineral cast parts, where loads should be transmitted not punctually.

CONCLUSIONS
Polymer concrete is an adequate base-frame material for highly-integrated base-frames produced in series. To diminish production costs replication technology is recommended.

The properties of mineral cast spread statistically. Another issue is creeping under load. They have to be taken into account by the designer with process control and overdimensioned parts with large safety factors. The excellent damping properties of mineral cast are not relevant in measuring machines because dynamic forces and resulting bending and torsion are significant smaller than machining forces with solid-borne vibrations.

To sum up: mineral cast is recommended as base-frame for precision machines with precision $\geq 10 \mu m$, it is applicable for precision $\geq 1 \mu m$ and not applicable in submicrometer-range due to uncertain long-term stability.

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REFERENCES


