Study of Alternative Structural Materials for Machine Tools

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Abstract

Precision machine tools are required to produce precise products at high machining speeds. Hence, the machine tool structures must possess high damping and high structural stiffness along with dimensional and geometrical stability. A great deal of research and development is in progress on non-conventional materials for machine tool structures. Composite materials such as ferrocement, polymer concrete, epoxy granite and cementitious composites are replacing the traditional cast iron as machine tool structure material. This study makes an attempt to evaluate different composite materials used in machine tool structures in respect of the major requisite attributes namely tensile and compressive strength, high stiffness and damping. It is shown that, of the various composite materials under research, epoxy granite and fiber reinforced polymer matrix composite are predominant materials for the modern precision machine tool structures. The compositions of epoxy granite used in machine tool structures and the processing techniques for manufacturing of both epoxy-granite composite and fiber reinforced polymer matrix composite are discussed.

Key words: Machine tool structure, Epoxy granite, Fiber reinforced polymer matrix composite, processing technique.

1 Introduction

Machine tools need to be operated at high speeds without vibration, to meet high customer demands by maximizing the productivity without sacrificing precision on products. The high operating speed generates more vibration on the joints and interfaces of the machine tool elements. It reduces structural dimensional accuracy and shows poor surface finish on machined parts. Further, it causes resonant condition when the machining operation frequency matches with the natural frequency of the machine tool structure. Therefore the main requirements of machine tool structures are high static stiffness against bending and torsion high specific stiffness (stiffness-to-mass ratio) against torsional stiffness, high dynamic characteristics (natural frequency, damping ratio), high dimensional stability, low coefficient of expansion, low cost and less weight Emmanuil Kushnir et al. (2001).

Gray cast iron and steel weldments are the main conventional machine tool structural materials used in modern machine tool industries due to their manufacturing flexibility, low cost and better material damping and static stiffness which reduces the influence of dynamic loads. However, the intricate shapes and large size of the castings require high initial cost for making the pattern and molds Rao (1997) and also the foundry process is the potential source of air pollutants such as a) effluents from dust producing operations within the plant, b) odors and gaseous compounds, c) effluents from furnace operation Herbert Weber (1961). It affects human health, animals, buildings and vegetation. Further, traditional machine tool materials exhibited either static stiffness or damping vice versa Satoshi Ema and Etso Marui (2000). For Example cast iron has more damping capability than steel, but steel had more stiffness capability than cast iron. To improve the static and dynamic performance of machine tools, alternative materials and new design concepts with both enhanced stiffness and better damping properties are needed. Composite materials play an important role to enhance both static and dynamic properties. They consist of two materials, one material, responsible for stiffness and another responsible for damping and so the composite exhibits both improved modulus and damping properties. High strength-to-weight ratio, high specific stiffness, damping and resistance to corrosion properties which influence the composite materials, are increasingly used in the manufacture of machine tools.

In this paper, through literature survey, the currently researched alternative materials of stone and fiber based reinforced polymer matrix composite’s static and dynamic properties (tensile, compressive strength, stiffness and damping ratio) were reviewed and reported.
suitable for machine tool applications. The sequence of study is as follows: At first the stone and fiber based alternative polymer composite materials were evaluated for machine tool applications by comparing their mechanical properties. This was followed by an identification of the optimal chemical composition of stone and fiber based composite. Finally the processing sequences of epoxy granite and fiber reinforced-epoxy matrix composite were proposed based on the literature survey conducted.

2 Alternative materials for machine tool applications
2.1 Stone based polymer matrix composites

The machine tool structure performance is directly related to the mechanical and physical properties of the material used to build it. Hence the materials and their static and dynamic properties were investigated and their results were compared with the conventional material (cast iron). This included stone based alternative materials; ferrocement, polymer concrete, epoxy granite, hybrid composites (granite aggregates filled in mild steel weldments structures and fiber reinforced polymer matrix composite bolted and adhesively joined structures).

Rahman et al. (1988) designed and fabricated prototype beds for a typical lathe machine using ferrocement and its static and dynamic properties were compared with cast iron beds. The fabricated legs contained, sand: cement: water with the mixing ratio of (2:1:0.45). The fine wire mesh with steel skeleton reinforcement cage was used in ferrocement beds. From the static test a maximum deflection of 0.49 mm for ferrocement bed and 0.5 mm for cast iron bed was found. The natural frequency and damping ratio of the ferrocement were (280 Hz and 1.79%) almost twice of those of cast iron (125 Hz, and 1.275%).

Rahman et al. (1990) designed and fabricated supporting legs (columns) for a center lathe using ferrocement and its static and dynamic properties were compared with cast iron legs. The fabricated legs contains, sand: cement: water with the mixing ratio of (2:1:0.45). The fine wire mesh with steel skeleton reinforcement cage was used for ferrocement legs. The static test results revealed ferrocement head-end and tail-end had 0.040 mm/KN, 0.58 mm/KN deflection respectively. The corresponding values for the cast iron were 0.20 mm/KN, 0.21 mm/KN respectively. The damping ratio of ferrocement was found to be significantly higher than cast iron.

Rahman et al. (1993) were inspired from their previous study, as evident from the improved results of ferrocement bed in comparison with the parent cast iron bed under both static and dynamic loadings. They aimed to assemble the whole lathe machine tool with a ferrocement bed and investigate its dynamic performance through cutting test. The results showed that the new lathe offered an approximately 50 % deeper cut than a conventional lathe before chatter vibration initiates. And also the dynamic results indicated that the new ferrocement lathe had higher natural frequency and damping ratio (320 Hz, 1.83%), than a conventional lathe (230 Hz, 1.35%) respectively.

Rahman et al. have made several attempts either to supplement or to completely replace cast metals using ferrocement and polymer concrete, followed by (Hawlader et al. (1990), Kane (1991), Kobischek (1991) and Ow (1993)) who made an elaborate study on the tool wear comparison of both the ferrocement bed and the cast iron lathe bed to evaluate their relative performance. The results showed ferrocement bed had better dynamic properties than cast iron material.

Vitor Ducatti et al.(2004) [12] designed and developed twelve lathe bed prototypes in actual scale; with the following materials cast iron, cast steel, fiber-reinforced mortar, polymer mortar, reinforced-polymer mortar and ferrocement. And the static results revealed that ferrocement, polymer mortar and reinforced-polymer mortar had improved flexural strength, stiffness and from the dynamic behavior cast steel had higher natural frequency and other alternative materials had increased damping property.

Mani et al. (1987) presented comparative results on mechanical properties of cement concrete (1:1.6:2.4 by weight) cement : sand : aggregate, water cement ratio (0.55) with two different types of polymer concretes, prepared with two different types of binders (epoxy and polyester resin) with same aggregates (crushed quartzite and silica sand. The aggregates: binder ratio (88:12 by weight) was used. The coarse aggregates comprised of crushed quartzite of sizes ranging from 10 mm to 2.36 mm. The fine aggregates comprised siliceous sand of sizes ranging from 1.18 mm to 150 µm. And also the samples contained CaCo3 microfiller (94:6) with in the (88%) of aggregates proportion by weight. Two types of polymeric binder were used; Epoxy resin (GY-257) added in polyamide hardener (HY-840) and the resin: hardener ratio was (1:0.5). Polyester resin was (Crystic-196 general purpose resin) added to a catalyst (50 % solution of dimethyl pthalate in methyl ethyl ketene peroxide), and the accelerator (1 % solution of cobalt naphthanate in styrene). Both the catalyst and accelerator were added to (2 % by weight of resin). The analysis revealed that polymer concrete gave higher compressive, split-tensile and flexural strength by a factor of 2-4 and 3-6 than cement concrete. And the author concluded that the effect of microfiller was more pronounced in the case of epoxy- concrete than the polyester-concrete.
Antonio Piratelli et al. (2008) presented the study of polymer composite samples, prepared using epoxy resin (15-20 %) with granite particles of size < 500 µm and (85 %) by weight, and found the compressive strength (114.23 MPa) value to be close to that of the literature.

Jung Do Suh et al. (2008) have designed and developed hybrid polymer concrete machine tool bed that consist of sandwich structures of welded steel faces and polymer concrete core for gantry type milling machine. The polymer concrete consisted of granite aggregates and unsaturated polyester matrix. The study concluded from the impulse dynamic test, that hybrid machine tool bed had large damping ratio over a wide range of frequencies (5.69 %, 155 Hz), which were larger than those steel or cast iron bed structures (0.2 - 0.3 %).

2.2 Fiber based polymer matrix composites

Dai Gil Lee et al. (1998) designed and developed a precision mirror surface grinding machine tool column using adhesively bonded glass fiber reinforced epoxy composite plates, which were attached to a cast iron (C.I) column-(hybrid composite) to improve damping capacity of the column. The damping capacity of the hybrid column was calculated with respect to the fiber orientation and thickness of the composite laminate plate. The study reveals that the hybrid column had a maximum damping ratio of 0.0165 at a frequency of 434 Hz. This was 35 % than that of C.I column. (0.0086 at 409 Hz). They concluded that stacking sequence highly influenced the damping ratio (it was maximum at 45 degree stacking sequence).

Dai Gil Lee et al. (2004) designed and developed the light weight vertical and horizontal slides of CNC milling machine by joining carbon-fiber epoxy composite in welded steel structure using adhesive and bolts and compare the masses and dynamic properties of hybrid and conventional materials. The weight of the vertical and horizontal slides was reduced by 34 % and 26 %, respectively. And also the damping was increased by 1.5–5.7 times without sacrificing the stiffness. The positional accuracy of ± 5 µm per 300 mm of the slide displacement also was obtained. And also the authors concluded the damping ratios at higher frequencies were higher for hybrid X- slide (357 Hz, 0.8 %) compared to conventional X-slide (308 Hz, 0.14 %). At the same time reduction of mass by 30 % and higher damping ratio at higher frequencies influenced acceleration of the hybrid slide as it increased to (14 m/s²) when compared to conventional slide acceleration (2.1 m/s²).

Sung Kyum Cho et al. (2011) studied a table-top machine tool structure; and also designed and fabricated it using carbon/epoxy prepreg composites and resin concrete, to reduce the weight of the structure, and enhance the structural stiffness and damping capacity.

The results showed that the re-designed structure was 36.8 % lighter, the structural stiffness was increased by 16%, and the damping ratio increased by (2.82–3.64 %). FEA analysis was carried out to determine natural frequency for both hybrid and conventional material. From the analysis it was found that the natural frequency of hybrid was higher by 16 % (342 Hz-conventional), (396 Hz-Hybrid). Further the structures were also compared whether the experimented results were in line with the analysis.

The following section presents mechanical properties such as Young’s modulus, density, tensile strength, compressive strength, coefficient of thermal expansion and damping ratio of the stone and fiber based alternative materials used in machine tool structures were compared with conventional material such as cast iron as shown in Table 1 and Table 2.

Table 1 Comparison of mechanical properties of conventional and stone based alternative materials used in machine tool structures. [Literature survey]

<table>
<thead>
<tr>
<th>Property</th>
<th>Cast Iron</th>
<th>Cement Concrete</th>
<th>Polymer Concrete</th>
<th>Epoxy granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(GPa)</td>
<td>80-120</td>
<td>20-30</td>
<td>30-40</td>
<td>60-80</td>
</tr>
<tr>
<td>σ_{FS} (MPa)</td>
<td>150</td>
<td>3-5</td>
<td>25-40</td>
<td>25-40</td>
</tr>
<tr>
<td>σ_{CS} (MPa)</td>
<td>600</td>
<td>20-40</td>
<td>70-130</td>
<td>65-150</td>
</tr>
<tr>
<td>α (10^3/K)</td>
<td>10</td>
<td>10</td>
<td>11.5-14</td>
<td>8</td>
</tr>
<tr>
<td>ρ (kg/m³)</td>
<td>7150</td>
<td>2300</td>
<td>2260</td>
<td>2850</td>
</tr>
<tr>
<td>Order of ζ</td>
<td>10³</td>
<td>10³</td>
<td>10³</td>
<td>10⁻²</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties of fiber based alternative materials used in machine tool structures [Literature survey]

<table>
<thead>
<tr>
<th>Property</th>
<th>E-glass epoxy</th>
<th>E-glass polyester</th>
<th>Kevlar epoxy</th>
<th>Carbon Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(GPa)</td>
<td>45</td>
<td>37.9</td>
<td>75.8</td>
<td>142</td>
</tr>
<tr>
<td>σ_{TS} (MPa)</td>
<td>1020</td>
<td>903</td>
<td>1380</td>
<td>1830</td>
</tr>
<tr>
<td>σ_{CS} (MPa)</td>
<td>620</td>
<td>357</td>
<td>586</td>
<td>1096</td>
</tr>
<tr>
<td>α (10^3/K)</td>
<td>30</td>
<td>22</td>
<td>60</td>
<td>27</td>
</tr>
<tr>
<td>ρ (kg/m³)</td>
<td>2076</td>
<td>1850</td>
<td>1380</td>
<td>1580</td>
</tr>
<tr>
<td>Order of ζ</td>
<td>10⁻³</td>
<td>10⁻³</td>
<td>10⁻²</td>
<td>10⁻²</td>
</tr>
</tbody>
</table>

Compared to other polymer concrete materials, the cement concrete exhibits inferior strength and other mechanical properties. The epoxy granite discussed, is a particular type of polymer concrete prepared with fine granular particles of granite material as the filler and the
epoxy resin as binder. The epoxy granite exhibits excellent mechanical properties such as high damping and compressive strength as compared to polymer concrete materials. The granular size of the material ensures more ductility and the use of epoxy resin with good adhesive properties ensures high strength and reduced deformation due to creep. Considering the benefits, irrespective of its high cost, the epoxy granite is emerging as a promising alternative material for precision machine tool structures. Based on literature survey, polymer concrete, carbon-epoxy and glass-epoxy fiber composite sandwich structures (Hybrid Composites) are being developed for high speed machine tool and other structural applications. Sandwich structures contain steel faces, inserts, aluminum rings, and C.I columns for improvement in the structural stiffness of the composite. Mostly in current researches, synthetic fibers are used. However synthetic fibers are hazardous to human health and environment. In order to overcome the above problem, natural fiber can be used for making the composite. Thus natural fibers can be considered as potential materials for making machine tools structures in the future. The following two sections discuss the proposed processing sequence for epoxy granite and fiber reinforced epoxy matrix composites.

3 Epoxy granite composite processing sequence

Based on the above literatures survey, conclude that the epoxy granite composite can be used as an alternative material for machine tool structural applications. Better material properties can be achieved by varying the mixing ratio (weight fraction) of granite aggregates and epoxy resin binder used in the composite. Based on the study, the different compositions of epoxy granite structure that can be used for advanced machine tool structures have been summarized in Table 3.Epoxy granite is defined as a hot curing mixture of a reactable epoxy resin-hardener system (binder) and a graded aggregate system of granite (filler), which can be poured into mould and then vibrated for a few minutes for compaction. The process is repeated till the mould is completely filled up. It is then cured for about 24 hours at room temperatures. The major manufacturing sequences and equipments can be used for epoxy-granite are the following:

a. Granit slabs crushing into aggregates (stone crusher),
b. Sieve analysis of aggregates (ASTM standard sieves),
c. Mixing of aggregates, epoxy resin and hardener (muller),
d. Mould layout preparation (steel dies with inserts),
e. Mould filling and horizontal shaking for mould compaction (horizontal shaker) and f. Curing after mould making (autoclave).

The details of processing sequence are shown in Figure 1 and explained in the following section.

The granite slabs is crushed into required size using stone crusher. Big and small particles are separated by means of sieves analysis (ASTM standard), the smaller ones filling the spaces among the big ones. The following weight balance is planned for aggregates 1mm, 0.5 mm and 50 µm (50:30:20).The epoxy resin to hardener ratio is to be maintained at 10:1 parts by weight. In the epoxy granite; aggregates and epoxy content weight balance is (80:20). The above proportions mixed thoroughly using muller machine before pouring into mould. The required shape and size of the mould cavity prepared with steel dies and also mounting and other lifting accessories like screws and eye bolts fitted into mould cavity as an insert. Now the mould is filled and then using horizontal shaker unit the entire mould unit is horizontally shacked for mould compaction, after compaction the mould curing process is carried out in an autoclave unit up to 24 hours time duration.

4 Fiber reinforced epoxy matrix composite processing sequence

Fiber reinforced epoxy matrix composite is defined as a hard thermost material composed of fiber and matrix mixture of a reactable epoxy resin-hardener system (binder). Figure 2 shows the processing sequence of fiber reinforced – epoxy matrix composite. The required amount of fiber and epoxy are weighed and kept in a tray. The fiber:epoxy mixing ratio (60:40 by weight %) are mixed with epoxy; hardener at the mixing ratio of (10:1 by weight %). Then the mold release agents are applied to the mold surfaces for easy removal of composite. Now the matrix and fiber are stacked over the mould surface in a layer by layer sequence. The process is repeated till the mould is completely filled up. It is then cured for about 24 hours at room temperatures to form hard thermost composite material.

5 Conclusions

In this study, the composite materials were studied as alternate materials to existing materials (cast iron) used in precision machine tool structures. The use of cement-concrete, polymer-concrete and epoxy-granite to replace the supporting structure of an existing machine tool were analyzed based on their strength, damping properties, Young’s modulus and weight. It was observed that the epoxy granite material was found to exhibit good mechanical properties such as high compressive strength and damping ratio as compared to other composite materials. It can be concluded that the epoxy granite material (consisting of granite aggregates (80-90 %) in the range with epoxy and hardener in the range (10-20%) of total weight), and fiber–epoxy composite (consisting of fiber (60%) with epoxy and hardener (40%) of total weight) exhibited suitable properties for machine tool and other structural applications.
Figure 1: Processing systems for epoxy granite composite

Figure 2: Processing sequence of fiber reinforced–epoxy matrix composite

Table 3: Epoxy granite material compositions for machine tool structures [Literature survey]

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
<th>Size</th>
<th>E</th>
<th>$\nu/\zeta^*$</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$\sigma_{T,S}/\sigma_{I,S}^*$</th>
<th>$\sigma_{C,S}/\sigma_{F,S}^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy granite</td>
<td>80% filler: Feldspar &amp; quartz minerals</td>
<td>&gt; 5mm</td>
<td>60-80 GPa</td>
<td>0.25</td>
<td>2600</td>
<td>23 MPa</td>
<td>65-150 MPa</td>
</tr>
</tbody>
</table>
| Antonio Piratelli-Filho and Frank Shimabukuro (2008) | 1. 20% Epoxy resin by weight: (YD 128, Bisphenol A based) of total weight of the filler (i.e., epoxy granite)  
2. Epoxy resin composition: 60% curing agent (i.e., Ancamide 805) by weight of the resin, 40% liquid resin YD128 by weight. Gel time: 65 minutes. |
| Epoxy granite powder composites                     | (80-85% by weight) Granite powder | 45, 106 µm, and 500 µm | 0.014*     |             |                  |                               |                               |
| Antonio Piratelli-Filho and Flamínio Levy-Neto (2010)| 1. 15-20% Epoxy resin by weight: (YD 128),  
2. 1% Hardener: Ancamide 805, 60 phr (parts per hundred parts of resin) |
| Epoxy granite powder composites                     | 80% Granite by weight (Coarse 40%: Fine 60%) | Coarse 40%: (10-475mm)Fine 60%:(4.75-2.36 mm10%+2.36-1.18mm10% + 18-0.60mm10%+0.6-0.30mm6%+0.3-0.15mm 4%+ 0.15-0.075mm10%) | 28GPa* | 120.00MPa |
| Subrahmanya swamy et al. (2014)                     | 1. 12% Epoxy resin, 2. 1% Hardener |
| Epoxy concrete                                      | 90% Granite: Coarse 50% (0.5-3.3-5 and 5-8mm), Fine 50%<0.5mm | Coarse 50% (0.5-3.3-5 and 5-8mm), Fine 50%<0.5mm | 92.20MPa/ | 24.46MPa* |
| Deepak et al. (2013)                                | 1.10% Epoxy resin: Araldite 103, 2. 1% Hardener :Hy 951 | Araldite 103, 2. 1% Hardener :Hy 951 | 92.20MPa/ | 24.46MPa* |
REFERENCES


