

Polymer Concretes for Machine Tool Structures – A Review

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ABSTRACT: Structural material in machine tool plays important role in deciding the machine tool precision. It shares a major part in dampening the vibration generated during machining. Hence, for precision machine tools, vibration damping of structural material has become an important property along with stiffness and strength for designing the structure. Recent trend in research shows that polymer composites are replacing cast iron and steel as they provide improved damping accompanied with comparable stiffness and strength. Among all the polymer composites, polymer concrete has found to be the promising material. This study presents a literature survey on polymer concrete for machine tool structural application. Cast iron, steel and other conventional materials are compared with polymer concrete. The review summarizes the research findings reported by different authors by using polymer concrete in different types of machine tool structures. Different varieties of particulate reinforcement, matrix and other fillers, reported in literatures are studied as to understand their influence on final properties of polymer concrete for machine tool structures.

KEYWORDS: Polymer Concrete, Machine tool Vibration, Structural damping, Polymer Composites\

I. INTRODUCTION

Machine tools form the most important and critical aspect of manufacturing of mechanical components. Machining of certain components require high precision and good surface finish especially in aerospace, automobile and mold making industries. Also, there has been an intense competition among manufacturing industries to increase productivity and reduce cost of machining. The components that are fabricated by casting has to undergo a series of machining operations such as milling, grinding and various super-finishing operations to attain the required precision and surface finish. This causes increase in production time and also cost of manufacturing [1]. Currently machine tools utilize only 30% of their time in actual machining of the parts while the remaining time is spent of traversing and tool changing. Therefore the productivity can be increased by reducing the traverse speed of machine structures of machine tools by reducing the weight of the massive structures [2].

The precision of the machine tool is generally affected by the static and dynamic properties of the machine tool structures. These properties play an important role in vibration of structures during machining because vibration affects the quality of the end product [3]. The static and dynamic properties of structures can be improved by using materials of higher elastic modulus and higher damping characteristics. Thus materials used in the structures determine the quality of the product.

Conventional materials such as Cast iron, steel are commonly used in machine tool structures. Cast iron has lower density, higher damping and is suitable for large scale manufacturing. However, the fabrication of ribs and closed structures using casting is difficult and decreases the static stiffness of the structure. Steel has higher young's modulus and hence static stiffness but lower damping characteristics. Thus, theses advantages have led the researches to look for alternative materials which offer higher stiffness against bending, improved dynamic properties and dimensional stability [4].

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There have been efforts by various research groups globally, to replace conventional materials using synthetic granite, ferrocement [5], hydraulic cement, fiber reinforced cement [6], polymer concrete [7] and fiber reinforced polymer composites [8].

Polymer concrete is a composite mixture of particulate reinforcements and polymeric matrix. There have been recent works reporting the use of polymer concrete for machine tool structures due to its excellent mechanical properties [9-10].

The properties of polymer concrete depend on the composition of concrete, thus many factors affect the mechanical and damping properties and careful investigations are required to obtain the desired set of properties. In this paper, reviews of the current work done on polymer concrete are discussed and its application to machine tool structures as alternative materials are evaluated. Finally, the method of formulation of polymer concrete is discussed based on the literature review.

II. MATERIALS FOR MACHINE TOOL STRUCTURES

The structural materials used in machine tool plays a vital role in functional operation of machine tools. The mechanical and thermal properties of the structural frame depends significantly on the material properties such as damping ratio, elastic modulus, shear modulus, tensile and bending strength. The main requirements of machine tool structures are high stiffness, high damping ratio, good dimensional stability, low coefficient of expansion and low density. The commonly used structural materials in machine tools are discussed below.

A. GREY CAST IRON

Grey cast iron is the most commonly used material in machine tool structures due to ease in large scale fabrication and better damping characteristics. Grey cast iron is considered as a two phase material with matrix material (pearlite or ferritic) and graphite precipitates. The damping characteristics can be attributed to the internal friction mechanism that takes place in the graphite planes [29]. The elastic modulus is influenced by the matrix material and has insignificant influence on the damping properties [30]. Hence it is possible to engineer the two phases and develop different grades of grey cast iron that exhibit simultaneously high damping ratio and elastic modulus that is suitable for machine tool structures. However the main disadvantage of grey cast iron is the high manufacturing cost involved in casting large intricate sized structures [31].

B. WELDED STEEL

Welded steels structures have higher stiffness and lower density as compared to cast iron. Welded structures are used because of ease of fabrication of intricate structures and in a short production time. However the main disadvantages of welded steel are the lower damping characteristics and residual stresses and distortions inherent with welding process [32].

These limitations have led research to look for alternative materials which can either supplement or completely replace the conventional materials in machine tool structures.

III. COMPARATIVE STUDY BETWEEN POLYMER CONCRETE AND EXISTING MATERIALS

Polymer concrete in comparison to cast iron exhibits superior vibration damping but has lower elastic modulus. Properties of polymer concrete are dependent on various factors such as resin mass fraction, particulate size etc. Damping ratio is an extensive property unlike other mechanical properties such as elastic modulus and compression strength and it is dependent on frequency of vibration. Therefore since there are several factors involved in determining the damping ratio other than composition of polymer concrete, it is a challenge to predict the values of damping ratio. Table 1 summarizes the polymer concrete and cast iron values represented by various authors. Increase in damping ratio of polymer concrete in comparison to cast iron is 1.22 times to 30times as shown in the table. But decrease in elastic modulus of polymer concrete in comparison to cast iron is predictable, which is being nearly 30% of that of cast iron.

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Table 1: Comparison of damping ratio, elastic modulus of polymer concrete(PC) and cast iron(CI)

Author	Composition- Particulate size range, resin mass fraction, resin type	Frequency range(Hz)	Damping ratio (ξ_{PC}/ξ_{CI})	Elastic modulus (E_{PC}/E_{CI})
A. Selvakumar et al.[1]	<4mm,12%,Epoxy	80-1200	1.22	0.3
Jung Do Suh et al.[2]	<23mm,10%,Polyester resin	150-900	18-12	0.25
SezanOrak[3]	<8mm,20%, Polyester resin	-	6.84	-
Hyun Surk Kim et al.[4]	<23mm,7.5%, epoxy	600-830	30	0.25
SubramanyaSwamy et al.[5]	<20mm,14%,epoxy	600-900	11	0.28

Table 2 compares other mechanical properties such as density, compression strength and coefficient of thermal expansion (CTE) between polymer concrete, cast iron and steel. Polymer concrete is lighter in comparison to cast iron and steel with density being 4 times lower. It exhibits 8 times lower compression strength, 6 times lower flexural strength in comparison to cast iron. Comparison of coefficient of thermal expansion reveals that the polymer concrete has the CTE value close to that of cast iron. CTE of polymer concrete is determined by mass fraction of its particulate reinforcement as it has low CTE (Marble – $6 \times 10^{-6}/C$) and resin matrix has high CTE (Epoxy- $30 \times 10^{-6}/C$). Therefore the resulting polymer concrete can be made to have minimum CTE by using maximum mass fraction of particulate reinforcement. Polymer concrete produces less dimensional change due to temperature variation when used in machine tool structures as it has high specific heat (0.9 kJ/kgK) compared to CI (0.45kJ/kgK).

Table 2: Comparison of other properties of polymer concrete, cast iron and steel

Properties	Cast Iron	Alloy Steel	Polymer Concrete
Order of damping ratio	10^{-3}	10^{-3}	10^{-2}
Elastic modulus (N/mm ²)	80-120	180-210	25-30
Density (g/cc)	7.2-7.8	7-7.8	2.2-2.8
Compression Strength (N/mm ²)	600	-	70-130
Flexural Strength (N/mm ²)	150	-	25-40
Coefficient of Thermal Expansion(CTE X $10^{-6}/C$)	12	12	17
Specific Heat (kJ/kg.K)	0.46	0.46	0.92
Thermal conductivity (W/m.K)	53.5	53.5	1.9

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IV. EFFECT OF COMPOSITION ON POLYMER CONCRETE PROPERTIES

A. COMPOSITION OF POLYMER CONCRETE

Fig. 1 shows the composition of polymer concrete with particulate reinforcement dispersed in polymeric resin matrix. Fibers and microfillers are mixed with particulate reinforcement to enhance the properties. The properties required for machine tool structures such as high stiffness, compressive strength, damping ratio and good thermal properties are dependent on following elements [9] :

1. Particulate reinforcement
2. Resin matrix
3. Fiber reinforcement, fillers and additives

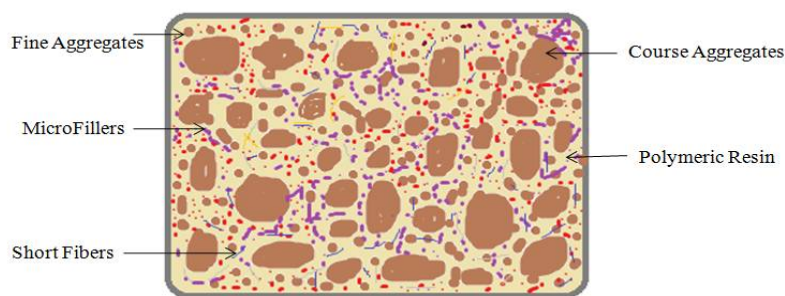


Figure 1: Polymer concrete model

B. PARTICULATE REINFORCEMENT

Properties of the polymer concrete are dependent on grain size and packing density of the particulate reinforcement [4]. Highest packing density is achieved by mixing appropriate mass fraction of course and fine particles. The mass fraction is determined by the range of sizes or grading chosen for the reinforcing particles. It was found that the grading of particle size determines the resulting properties of the polymer concrete, ease of workability, handling and surface finish characteristics of polymer concrete [9]. Mechanical properties such as elastic modulus and compressive strength etc. are determined by packing density. Increasing packing density and hence reducing the void content increases the elastic modulus, compression strength due to contact mechanism [4]. However the damping ratio dependence is in contrast to that of compression strength and elastic modulus as found in conventional materials. The damping ratio is highest at minimum elastic modulus and compression strength [4, 10]. The composition of polymer concrete at highest packing density has shown maximum elastic modulus and least damping ratio whereas the composition at lower damping ratio has shown highest elastic modulus and compression strength. In most of the studies, the range of particles size used for reinforcement was upto 23mm. Wenfeng et al. reported highest damping ratio when maximum mass fraction of fine sized particles were used [10]. However, Subramanyaswamy et al. reported highest value of damping ratio for the composition with maximum mass fraction of course sized particles [5]. Table 3 summarizes the studies conducted on particulate size and its influence on the properties. It indicates that voids play a major role in vibration damping mechanism. As the fine and course sized particles are mixed together and hence the packing density is maximized, the compression strength and elastic modulus increased considerably.

Table1: Particulate size influence

Author	Range of particulate size	Grading	Variation in properties
Hyun Surk Kim et al.[4]	0-25.4mm	Less than 3.36mm-sand, more than 3.36mm-pebble	Pebble content was varied from 0-50% keeping the overall particulate reinforcement mass fraction constant. With addition of 50% of pebble, compression strength and elastic modulus increased by 2.5 and 1.6 times respectively.
Wenfeng Bai et al.[10]	0-10mm	-	Damping ratio reduced by 45% as coarse sized particles were mixed in fine sized particles
Subramanyswamy et al.[5]	0-10mm	More than 4.75-course,less than 4.75-fine	Compression strength and elastic modulus increased by 9% and 20% as the mass fraction of coarse sized particles are increased from 0 to 50%

There are many research works carried out on polymer concrete for precision machine tool application with different types of reinforcing particles. Natural sand[11,12], Foundry sand [13,14] Crushed Stone [15,16] , quartz , granite [17] and gravel are some of the types of aggregates reported by authors. Hardness of particles influences the damping and other mechanical properties of polymer concrete [3]. A clear shift in usage of type of aggregate material from sand to granite can be found after 2008. This can be attributed to several advantages of granite, especially in rendering the required characteristics to polymer concrete by varying the size and shape of granite powders. Granite is a fine grained, dense and hard rock having very low thermal conductivity and coefficient of thermal expansion (8×10^{-8} m/mdegreeC) in addition to good compression strength. There is a lack of work which can compare the different types of aggregates for better mechanical properties.

C. RESINS

Resin mass fraction used as matrix in polymer concrete has a major influence on its mechanical and dynamic properties. The variation of resin was limited to a maximum mass fraction of 20%. Hyun Surk Kim et al varied the mass fraction upto 10% and found increase in elastic modulus, compression strength and damping ratio with resin amount [4]. However, the rate of increase became lower as the mass percentage of resin approached 10%.Wenfeng Bai et al. found increase in damping ratio with increase in resin mass fraction upto 16% [10]. The result was similar to that reported by Hyun Surk Kim. The increase in damping ratio became slower from 10-12% mass fraction of resin, increased from 12-14%, again reduced between 14-16%. However, the increase in damping ratio was linear with resin mass fraction upto 14% as reported by SubramanyaSwamy et al [5].

Polymer resins that are commonly used in polymer concrete are Methacrylate, Polyester resin, Epoxy resin, Vinyl ester resin and Furan resins. Among these, unsaturated polyester resins are most commonly used owing to their better mechanical properties and easy availability [18]. Polymer concrete made of polyesters is hard, stiff and has better mechanical properties. However few types of polyester resins such as unsaturated isophthalic polyester shows a risk of cracking with thick block moulding due to the internal stresses related to shrinkage of resin. Hence in many instances epoxy resins are preferred over polyester resin because of their better mechanical properties and chemical resistance

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and durability when subjected to harsh environmental factors. However polyester properties can be enhanced to the same level as that of epoxy resins by employing microfillers and silane coupling agents [19].

D. FLEXIBILIZER & FILLERS

In order to improve the impact strength of epoxy resin, authors have reported the use of flexibilizer with epoxy resin in polymer concrete. W. Bai et. al reported improvement in damping ratio of the polymer concrete by adding upto 13% by mass of Dibutylephthalate (DBP) as flexibilizer. Further increase beyond 13% reduced the damping ratio. DBP addition was harmful to other mechanical properties, chemical resistance and thermo-resistance because of its chemical reactivity[10].

Several research works involved reinforcement of fillers such as flyash, cast iron powder and fibers to improve the mechanical properties for machine tool structural application. Microfillers are added to polymer concrete mix to reduce the void content and thereby improve the mechanical properties. Microfiller is the powder with particle size less than 80 μ m. Application of flyash, calcium carbonate and silica fume as microfillers has been reported in literatures [9]. Flyash, a byproduct of coal burning has been used by many researchers to enhance the workability, surface finish and mechanical properties in polymer concrete. It is found that addition of 15% of flyash improves the compressive strength of polymer concrete upto 30% [20]. Addition of 15% of Cast Iron powder of size less than 0.075micron has imparted around 14% increase in damping ratio [8].

Reinforcement of fibers was found to enhance the mechanical properties of polymer concrete. Steel fibers, glass fibers, nylon and polypropylene fibers were used to improve the required properties [10, 21-25]. W. Bai et al. studied the influence of short glass fibers (5-25mm length) upto 5% mass fraction on damping ratio of polymer concrete for machine tool application. The author reported increase in damping ratio with increase in fiber mass fraction and length. As the glass fiber length increased, damping ratio first increased and then decreased [10]. The maximum damping ratio was obtained when the glass fiber length was 20mm.

There are many other researchers who have reinforced different types of fibers to enhance mechanical properties in polymer concrete. Broniewski et.al. has reported 40% increase in flexural strength with addition of 35% steel fibers in polymer concrete reinforced with sand aggregates in epoxy resin matrix [21]. Few authors have added nylon, glass, aramid and steel fibers of length 12.7 to 38.1 mm and found the considerable increase in compression and flexural strength [22-25].

Application of a coating around the particles and other fillers such as glass fiber improves adhesion between the polymeric matrix and solid particles or other reinforcements and hence improves the mechanical properties. It is found that compressive strength and flexural strength of silane coupling coated polymer concrete is 15% to 20% higher than those of un-modified polymer concrete [10].

V. METHOD OF MANUFACTURING POLYMER CONCRETE BED

General Method of manufacturing polymer concrete bed starts with mixing of polymeric resin with particulates of required mass fraction with microfillers and short fibers if needed. The particles can be treated with coupling agents to enhance the bonding with resin. The mixture is poured on to a mould of required shape. In order to remove air voids and ensure better compaction and uniform mixing of particles with resin, the mould is vibrated at a certain frequency on a vibrator. It is coated with a mould release agent to facilitate easy removal of the final cured structure from the mould. Cured bed of polymer concrete is removed and finishing operations are performed as depicted in fig.2 [4]

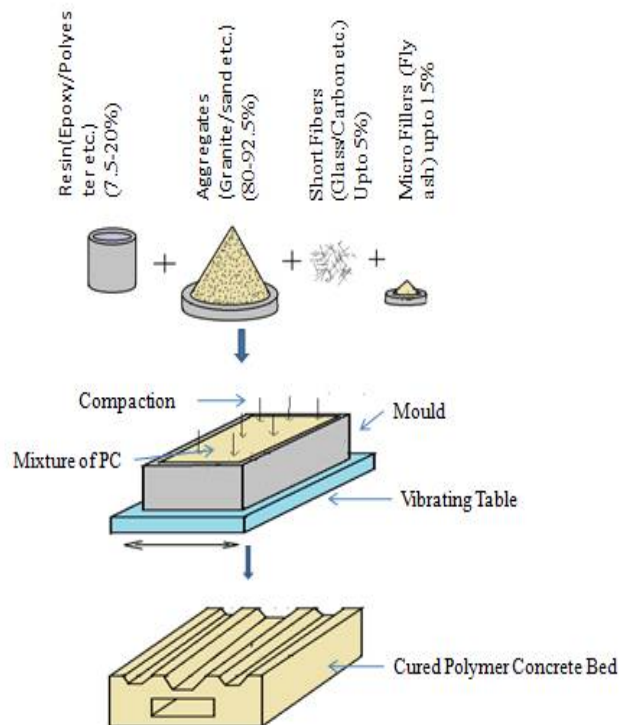


Figure 2: Polymer concrete machine bed manufacturing steps

VI. APPLICATION OF POLYMER CONCRETE TO MACHINE TOOL STRUCTURES

Since polymer concrete is poor in stiffness in comparison to cast iron and steel but has superior vibration damping, it was employed in machine tool structures in different ways as summarized in table 4. Few authors have replaced the entire machine tool bed by polymer concrete by enlarging the volume to keep the stiffness same whereas few others have used it as hybrid structure along with high stiffness conventional materials such as steel and carbon fiber-epoxy composite to enhance the vibration damping and reduce the structural mass without increasing volume. It was also used as damping carriage for linear guideways in machine tools. Limited work is reported on the performance characteristics such as surface finish and tool wear of machine tool with polymer concrete structures. C. Bruni et al. reported enhancement in surface finish and reduction in tool flank wear with polymer concrete bed [26]. Finish turning performed on the machine tool equipped with polymer concrete bed provided Ra values lower than ones given by the same operations carried out on the turning centre equipped with the cast iron bed [26].

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Table 2: Application of polymer concrete on machine tool structures by different authors

Author name	Mass fraction of reinforcement(%)	Polymeric resin	Application into machine tool structure	Improvement
C. Bruni et al.[26]	92	Epoxy	CNC turning center bed	Tool flank wear was reduced and surface finish of the machined part improved
Hyun Surk Kim et al.[4]	92.5	Epoxy	Ultra-precision mirror surface finish grinding bed	-
M Weck et al.[27]	-	-	Milling machine column and bed	Resonance frequency increased
Jung Do Suh et al.[28]	90	Polyester	Hybrid polymer concrete-welded steel bed for high-speed gantry type milling machine	Vibration damping improved by 10-20 times

VII. CONCLUSION

In comparison to cast iron and steel, polymer concrete shows superior vibration damping and comparable stiffness and strength. Researchers have found improved surface finish and reduced tool wear rate by employing polymer concrete bed. It is a promising material to replace cast iron and steel for machine tool structural application as it has high damping ratio, moderate elastic modulus and strength, low density and it is simpler to manufacture in comparison to cast iron. Polymer concrete properties can be tailored to meet the requirement by varying particulate types, sizes, matrix type and proportions. Microfillers such as flyash, flexibilizers and different fibers can be reinforced to control the properties.

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