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A review on epoxy granite reinforced polymer composites in machine tool structures – Static, dynamic and thermal characteristics

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Abstract

Machine tool structures produced with Epoxy Granite reinforced polymer composites (EGPCs) have gained prominence in recent years and have replaced conventional cast iron materials and other metals due to its remarkable damping characteristics. However, machine tool structures manufactured with EGPCs tends to exhibit limited strength, stiffness and stability. Such challenges in EGPCs are resolved by incorporation of steel as additional reinforcement and enhanced mechanical properties are observed in these hybrid machine-tool structures. Hybrid epoxy granite machine tool structures with enhanced mechanical performance are prone to thermal errors resulting in machining inaccuracies and limited performance. Thermal errors induced in machine tool structures could be attributed due to effect of temperature distribution and displacements at the Tool Center Point (TCP). This review work carried out focuses predominantly on design methods adopted in resolving the challenges identified in development of machine tool structures and further analyses results of several polymer concrete-based machine tool structures with regard to static, dynamic and thermal characteristics. Several review works conducted earlier have discussed the results of static and dynamic characteristics, whereas this review work provides additional information on thermal based errors induced and discusses the methods adopted in compensation of thermal errors. In this review paper, research studies pertaining to static and dynamic characteristics of different machine tool structures performed in last three decades have been discussed and a wholistic information is provided in relation with static, dynamic and thermal characteristics and properties toward developing a machine tool structure with a novel, newer class or alternative materials.

KEYWORDS

damping, epoxy granite, machine tool, mechanical characteristics, polymer concrete, thermal error

1 | INTRODUCTION AND PRESENT SCENARIO

With the advancements in technology and further based on the dynamic variations in consumer's preferences have led to the invention of several new products in wide range of industrial sectors. Consumer's preferences and interest have dramatically led to the innovations in design and development of machine tool structures.[1] Such technological advancements enabled with the intelligence resources and mechatronic system have witnessed a significant development in the machine tool industries.[2] Conventional machine tool structures for several down-to-earth applications have been replaced by advanced machines like vertical machining centers (VMC's) and other higher precision machine tool structures. Since the inception of this century, such VMC's and high precision machine tool structures have gained huge prominence and are highly preferred due to its precision and accuracy in operation enabled with the presence of mechatronic systems and intelligence sources embedded within the structures. In addition to conventional and other form of alternate materials, a fewer section of sustainable materials derived from renewable resources can also be employed in development of machine tool structures. Such materials derived from renewable and other form of biological resources are eco-friendly, sustainable, non-hazardous and can be identified as a potential reinforcement in cleaner production of machine tool structures. Several varieties of natural fibers derived from plants and animals are identified, characterization studies were performed and evaluated for suitable reinforcement in polymer resins and other bio-resins like soy protein, green epoxy for sustainable and cleaner production of machine tool structures. Several research investigations have been performed in the recent years in evaluation of natural fibers as a potential reinforcement for several industrial applications.[3–5]

In this millennium, Bio-composites and other bio-based constituents have gained attraction among everyone and are being used in several industrial and other commercial applications in the different domains of automotive, manufacturing, defense, marine, aviation and other industries. Even, governments and public firms of different countries have taken several initiatives, provides tax exemptions, incentives and attracted the utilization of natural fibers and other bio-based constituents in the reduction of greenhouse gas emissions in the cleaner production of components. These bio-based reinforcement material proves to be critical in enhancing the strength and functionality of the machine tool structures. The percent weight fraction of reinforcing material plays a significant role in development of such polymeric composites. Recent research works on natural fibers as a potential reinforcement in polymer composites, provides reliable information on the selection of appropriate percent weight fraction of reinforcement along with epoxy binding agent and other polymers in manufacturing of composite materials in manufacturing of machine tool structures.

Weight reduction is a critical factor that plays a major role in manufacturing of machine tool structures. In concrete material reinforced polymer composites, addition of nano particles enhances the mechanical properties of the composites, provides better bonding with a remarkable performance and functionality of the developed machine tool structures.[6,7] Nano particles have a high surface area to contact ratio and provides higher chemical reactivity. Nano particles range in size from sub nanometer to 100 nano meters. Addition of nano particles as filler materials shows that, the volume occupied by 3 microparticles is equivalent to 3 million nanoparticles.[8,9] This could be due to the very smaller size; higher number of nano particles allow significant interaction between the polymer matrix. Several research studies have performed in addition of nano particles as filler materials in concrete reinforced polymer composites and its effects on the mechanical properties and performance. Nano particles as fillers increases the compressive, flexural strength and thermal stability of the composites. The most commonly used nano particles as filler materials are, nano clay, alumina nano particles, nano TiO_2, nano SiO_2, agricultural and other solid wastes derived from bio resources.[10,11] Addition of such nano particles improves the bond strength of the composites and is found to be higher by up to 40%–60% than the polymer composites manufactured without any nano fillers. Polymer composites produced with the addition of nano particles enables creating a new class of polymer composites with a remarkable ductility, thermal stability and fracture resistance.[12]

However, machine tool structures developed with the advances in technology, innovations in design strategies, produced with the use of novel composites and other conventional materials are prone to errors, and exhibits certain contradictory behavior resulting in inaccuracy of the machined components.[13–15] Such errors induced in machine tool structures can be categorized based on these sources such as geometric errors, kinematic errors, thermal sources, cutting forces like thrust and tangential components of forces, self-induced vibrations like chattering and few secondary sources of errors, which are induced due to cutting tool motion and assembly of structures.[16,17]

The need for such highly accurate machines has driven the machine tool research community involving several researchers and scientists across diverse states of the globe to conduct investigations on errors.[18] Among these different errors identified in the machine tool structures, thermal errors are the primary source, which significantly affects the accuracy of the machined components.[19] In this century, several research investigations carried out in the domain of errors in machine tool structures reveal that, among the total error thermal error accounts for nearly 40%–70%.[20] Thermal errors induced in machine tool structures are caused by the heating and temperature rise either from internal or external sources resulting in deformation or distortion of the machine structures. Thermal errors induced by means of internal sources could be attributed by several factors such as due to the heat generation during cutting process, heat source from friction in spindles, gearboxes, guides and ball screws, heat identified from motor and other systems.[21] Simultaneously external heat sources could be attributed due to the heat from environmental temperature, ambient conditions and from solar and other forms of radiations. In the entire machine tool structures, spindle is a critical component that dissipates a greater intensity of heat than any other components during high-speed operating conditions. This review focusses mainly on the thermal errors induced in the spindles of machine tool structures. Such thermal errors induce a negative effect on the accuracy of the machined components and further affects the performance and functionality of machine tool structures. The thermal errors induced in machine tool spindles can be eliminated by means of certain design strategies employed by few researchers in the earlier years.[22–25] Such design strategies proposed by researchers is categorized into three different methods and they are thermal error avoidance, thermal error control and compensation.[26] Thermal error avoidance strategy reduces the heat generation or deformation due to thermal sources in the spindle system. Thermal error in machine tool structures can be avoided by replacement of conventional metals with the usage of advanced and novel materials like carbon fiber reinforced plastics (CFRP) and another polymer concrete reinforced composites.[27–30] Compared with these metallic structures, CFRP and other composites exhibits lower coefficient of thermal expansion and are insensitive to changes in thermal conditions.[31] Typical example in case of thermal avoidance is that the metal bearings are replaced with hybrid bearings having ceramic balls, which exhibits lesser heat generation due to friction.[32] Thermal error control strategy minimizes the thermal error by control of heat-transferred amount in the spindle housing or eliminates the generation of non-uniform temperature distribution. Incorporation of cooling jackets around the spindle bearings enhances the heat dissipation, which leads to lesser heat left in the spindle.[33,34] Alternative approach in thermal error control is that the machine tool structures are optimized by employing heat pipes and thermal actuators over the spindle system, which equalizes the temperature distribution. Thermal error compensation essentially involves modification of position of the cutting tool and work specimen in the machine tool structures.[35,36] Among the three different design strategies for reduction of thermal error, thermal error compensation methods are highly efficient and cost effective and this could be attributed due to its ease in implementation at any stages of machine tool design or assembly and also does not requires any additional hardware such as heat pipes and other advanced materials.[37–39] In a real time, thermal error compensation, there are various aspects such as analysis, testing, modeling and implementation.[17,40,41] A typical machine tool system incorporated with sensors, actuators and other mechatronics devices for thermal error measurement is shown in Figure 1.

With regard to illustrate the entire aspects in the design of machine tool structures in terms of performance, functionality, properties and further aid the researchers and scientists in this domain with a clear ideology, this review work is divided into seven sections. In section 2, the results comprising static analysis of different machine tool structures and the design methodology adopted for each research work is summarized. The dynamic analysis, methodology adopted and the results of different machine tool structures are analyzed and summarized in section 3. In section 4, the thermal error, temperature and its measurement set up is discussed in detail. Section 5 discusses the thermal error computation methods and provides the relationship between the

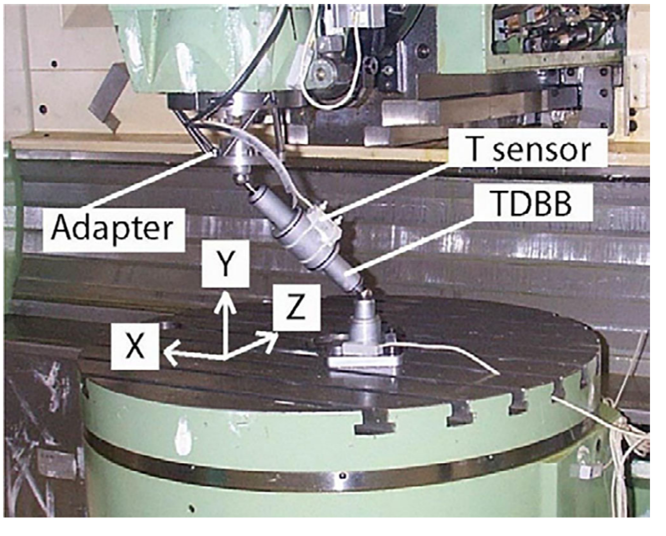

FIGURE 1 Experimental set up of five-axis machine tool structure embedded with mechatronics system for thermal error measurement (Reproduced with permission from Elsevier, License Number: 5161731098697) Ref. [13]

thermal errors and temperature. In section 6, the different challenges that exist in development of machine tool structures and the suitable techniques employed in resolving such challenges are discussed. Finally, in section 7 the thermal analysis pertaining to the research investigations on various machine tool structures comprising the results involving thermal error, thermal expansion and deformation are summarized. The summary of static, dynamic and thermal analysis comprises essentially results pertaining to research investigations of 70 different machine tool structures until the year 2020 involving conventional materials, polymer concrete materials and other novel composites. The results that are listed and summarized in Tables 1, 2 and 3 provides a wholistic information on the existing research on machine tool structures and its development in terms of design methods adopted, performance and its properties.

Bryan and co-authors in 1990,[22] Weck and their research group in 1995[23] and Ramesh et al. in 2000[25] have published few keynote papers in the domain of thermal errors. This review paper provides a complete update on the research investigations in the domain of thermal errors and discusses the strategies employed in resolving challenges and elimination of errors with regard to achieve the thermally stable machine tool structures. The keynote papers published in the earlier decades provides information only with regard to the thermal based errors. Whereas, this review work provides an additional information on static and dynamic properties of different machine tool structures and lists the summary of up-to-date results pertaining to the static, dynamic and thermal characteristics of different machine tool structures till the year 2020. ArunRamnath in his research investigations reviewed and experimentally investigated the machining performance of various composite materials for determination of suitable optimization technique and ideal machining parameter combinations with regard to the selection of ideal machining parameters in end milling epoxy granite composites.[42–51] With a similar research methodology, the results of static, dynamic and thermal characteristics of research investigations of 70 different machine tool structures are identified and summarized and further the design methodologies employed are analyzed with the objective of enhanced performance and functionality of machine tool structures. This review work performed provides a clear ideology on machine tool structures and aids researchers, scientists and metallurgists in development of machine tool structures by epoxy granite composites and other polymer concrete reinforced composites with the objective of minimization of thermal errors without any trade-off among static and dynamic properties.

2 | STATIC ANALYSIS OF MACHINE TOOL STRUCTURES

Static analysis of machine tool structures is performed in order to provide an in-depth knowledge of these structures with regard to strength, stiffness and stability. Several different machine tool structures are identified and its performance is studied based on the material and the binding element chosen, design methodology employed, properties determined and its most suitable industrial application. This section discusses the research investigation on static analysis of different machine tool structures and it is presented in Table 1.[52–81]

3 | DYNAMIC ANALYSIS OF MACHINE TOOL STRUCTURES

Dynamic analysis of machine tool structures is carried out in order to provide an in-depth knowledge of these structures with regard to damping capacity and dynamic stiffness, dynamic stability and the modal frequencies. Several different machine tool structures are identified and its performance is studied based on the material and the binding element chosen, design methodology employed, properties determined and its most suitable industrial application. This section discusses the research investigation on dynamic analysis of different machine tool structures and it is listed in Table 2.[82–95]

4 | THERMAL ERRORS AND MEASUREMENT

The numerical methods and the analytical models provide much more information on the thermal characteristics and properties of the spindles in machine tools. However, the results obtained from these methods are not highly accurate and sufficient experimental validations are required to ensure the reliability and consistency of the solutions determined. Analytical methods are simplified mathematical models derived based on certain assumptions and the thermal analysis results determined are not accurate in relation to the three-dimensional spindle with complex and intricate shapes. Similarly, the thermal analysis results determined from numerical methods is limited in terms of accuracy and reliability since the results vary depending on the power of heat sources and boundary conditions (heat transfer coefficient and ambient temperature conditions) considered. With regard to overcome such limitations of these methods, thermal errors and temperature of machine tool structures are determined by prior experimental investigations.[96,97] Experimental tests reveal the original and reliable information of

TABLE 1 Static analysis of machine tool structures

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
N Mahendrakumar[52]	Nettle fiber reinforced composites	Polyester	Micro lathe bed	Form design modification was employed for the enhanced stiffness of micro lathe bed	Tensile strength, bending and torsional stiffness	The fabricated nettle polyester micro lathe bed exhibits a 20% reduction in weight than cast iron lathe bed without any trade-off among the stiffness values. The tensile strength was found to be 30 MPa with a total deformation limiting up to 29 microns.
Joel D'Mello[53]	Granite particulate reinforced composite	Epoxy resin	Precision machine structures	Composites were fabricated based on higher weight percentage of granite particles with regard to the epoxy matrix	Compressive strength and flexural strength	Experimental results reveal that the highest magnitudes of strength and stiffness were obtained for granite particulate epoxy composites with a weight fraction of 80:20 ratio. The maximum values are compressive strength 111 MPa; Flexural strength 41.3 MPa and Modulus of elasticity 14.811GPa.
Maria Luzia PM Gomes[54]	Artificial granitic stone	Epoxy resin	Precision machine structures and construction industries	Development of Artificial Granitic Stone (AGS) with a proportion of 85% mass of granite agglutinated by 15% mass of epoxy resin by vacuum assisted compression process	Three-point flexural strength	Experimental results reveal that the developed AGS exhibits a highest mechanical resistance with a maximum flexural strength up to 32 MPa. Abrasive wear tests conducted on AGS material displays a minimum thickness and indicates that it can be used in flooring for highly dense traffic areas.
Seung-Wan Son[55]	Polymer concrete filled with Methacrylic acid (MAA)	Acrylic resin	Lower temperature applications	Addition of Methacrylic acid (MAA) as a filler material for the enhanced mechanical	Compressive strength, Modulus of elasticity, Poisson's ratio and flexural strength	Incorporation of MAA proved to be highly effective resulting in enhanced mechanical properties such

(Continues)

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
				properties of acrylic polymer concrete		as compressive strength, flexural strength, Modulus of elasticity and Poisson's ratio. Addition of MAA more than 15 phr proved to be ineffective with a decline in properties other than Modulus of elasticity and Poisson's ratio.
Byung-Wan Jo[56]	Polymer concrete	Unsaturated polyester resin from recycled Polyethylene Terephthalate (PET)	Pre-cast components and transportation related components for higher durability	Aggregate material reinforced with proper formulation of unsaturated polyester resin with recycled PET for higher mechanical properties and durability	Compressive strength, flexural strength, split tensile strength and elastic modulus	Research investigations on these concrete materials reinforced with unsaturated polyester resin cured for 7 days exhibits: compressive strength 73.7 MPa; flexural strength 22.4 MPa; split tensile strength 7.85 MPa and Modulus of elasticity 27.9 GPa.
Prabhu Raja Venugopal[57]	Epoxy granite composites filled with glass fibers	Epoxy resin	Vertical Machining Center Base	Steel reinforcement incorporated in epoxy granite composites with seven different design configurations in order to attain the enhanced structural static stiffness	Deformation and strength	Optimum reinforcement of 80% granite particles bonded with 20% epoxy resin displayed a higher strength and stiffness values. Design configuration 7 proves to be the ideal combination and aided with steel reinforcement there is a reduction in total deformation by 56% and 36% for drilling and milling operations.
Prabhu Raja Venugopal[58]	Epoxy granite composites filled with glass fibers	Epoxy resin	Column of machine tool structures	Optimization of structural design among nine different design configurations	Structural stiffness	The ninth design configuration with standard steel sections proved to be an ideal choice and exhibits a structural

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
				by employing steel reinforcement in epoxy granite composites with regard to obtain enhanced structural stiffness and stability		stiffness equivalent to that of cast iron machine tool column.
Tsung-Chia Chen[59]	Artificial granite	Synthetic resin	High-precision milling machine	Optimization of design configurations were performed without any trade-off among static and dynamic stiffness	Static stiffness and dynamic stiffness	Numerical analysis together with experimental validation reveal that the static stiffness of the granite material reinforced machine tool column is enhanced up to 8% whereas granite exhibits a superior dynamic stiffness about 1.3 times higher than the conventional cast iron.
M Rahman[60]	Polymer impregnated ferrocement composites	Synthetic resin	Micro lathe bed	Advanced ferrocement materials filled in with discrete fibers have been adopted in this research study for enhanced performance	Deformation	Static test results conclude that the deformation of less than 1 mm was observed with regard to an operating load of 15 KN whereas ultimate failure occurs at a load of 140 KN.
H Sugishita[61]	Portland cement concrete composites	Synthetic resin	Machining center	Composites were developed by Portland cement type due to its superior structural properties and thermal resistance	Compressive strength, tensile strength and Modulus of elasticity	The mechanical properties of the composites made of Portland cement are observed as with compressive strength 58.1 MPa; tensile strength 4.6 MPa and modulus of elasticity 35 GPa.
Atanu Ranjan Ojha[62]	Palm stalk fiber reinforced composites filled with granite aggregates	Epoxy resin	Structural applications	Palm stalk fibers were chemically treated with alkaline solutions for enhanced mechanical properties	Tensile strength, flexural strength and modulus of elasticity	Experimental results reveal that the addition of granite aggregates have a significant influence with regard to the strength and stiffness of

(Continues)

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
						these composites. Higher tensile and flexural strength of magnitudes 54.6 MPa and 50.2 MPa were observed without any addition of granite particles, while higher stiffness of 956 MPa was observed with an addition of 15% granite aggregates. Modification of palm stalk fibers by alkaline solutions resulted in enhanced mechanical properties.
Jung Do Suh[63]	Polymer concrete composite with welded steel structure	Epoxy and Polyester resin	Machine tool bed	Sandwich structures of welded steel faces were incorporated in addition with the polymer concrete for the enhanced strength and stability of structure	Structural stiffness	Numerical results predict that the stiffness of the developed machine tool structures are highly dependent on the plate thickness in the X-direction. Steel weld plate thickness in the Y-direction does not have any influence toward the stiffness values.
Header Haddad[64]	Six different concrete materials basalt, fly ash, river gravel, sand, spodumene and chalk	Unsaturated polyester resin	Precision machine tool base	Composition of resin volume fraction was optimized which has a higher influence on the flexural strength of the composite	Flexural strength	Research studies reveal that for an optimized combination of 87% of concrete filler and 13% resin content, these composites (basalt, sand and fly ash) displays a maximum flexural strength and minimum values of thermal expansion. This optimum combination proves to be highly cost effective and displays a minimum deformation across the rail bases.

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
Fareed Mahdi[65]	Polymer concrete	Recycled Polyethylene Terephthalate (PET) resin to glycol ratio of 1:1 and 2:1	Construction industries	The optimized combinations of PET to glycol ratio have been employed to attain the enhanced mechanical properties	Compressive strength, Flexural strength and Modulus of elasticity	Polymer concrete reinforced with PET and glycol ratio of 1:1 displays superior mechanical characteristic s with regard to strength. MEKP as initiator proves to be highly efficient than BPO as an initiator in terms of with the highest values of modulus of elasticity 3.33 GPa and modulus of rupture 9.31 MPa.
Baotong Li[66]	Polymer concrete	Synthetic resin	Machine tool structures	Biologically inspired topology optimization methodology	Strength and stiffness determined by numerical approach	Based on the inspiration from nature, a venation growth algorithm derived from the plant veins has been employed as a topology optimizer for the stiffener layout and design. Leaf venation concepts applied in re-design of grinding machine column displays enhanced performance when numerically analyzed and proves to be a good choice in stiffener layout design in machine column.
A.M. Badiea[67]	Portland cement filled in with glass powder	Polyurethane (PU) resin	Construction industries	Finely graded glass powder ranging over a size of 600 microns were added as a filler material for least moisture absorption and higher strength	Compressive strength, split tensile strength and flexural strength	Results reveal that, glass fillers at a ratio of 10% by weight displays superior values of mechanical properties as compressive strength 52.43 MPa; flexural strength 6.8 MPa; modulus of elasticity 30 GPa and split tensile strength 5.8 Mpa.

(Continues)

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
						Addition of glass powder beyond 15% by weight proves to be inefficient with negative results.
S Murugan[68]	Pebble stone reinforced composites	Epoxy resin	Machine tool structures	Taguchi's experimental design were employed and the composites were fabricated with composition of 85:15 with regard to pebble stones and epoxy resin	Water absorption and porosity	Experimental results reveal that, the void content and moisture absorption characteristics of pebble epoxy reinforced composites are inter-dependent on each other and is being influenced by curing time and aggregate size. For the composition of pebble: epoxy in the 85:15 ratio a minimal moisture absorption and void content is observed in the composites.
A Ghiami Bajgirani[69]	Concrete reinforced polymer composites	Polyester resin	Application in construction industries and building materials	Polymer concrete composites were fabricated with different weight percent of polyester resin ranging from 18-22% and the optimal combination of resin content as chosen for superior characteristic	Compressive strength and modulus of elasticity	Mechanical tests conducted over these cubic and cylindrical specimens reveal that, for an 18% weight content of polyester resin these composites display a superior value of strength and stiffness. The magnitudes of compressive strength and modulus of elasticity for 18% weight content of polyester resin were found to be 74.1 MPa and 1424 MPa.
C Vipulanandan[70]	Concrete composites reinforced with epoxy and polyester resin	Epoxy and polyester type resin	Construction industries and repair of highways and other structures	Two different methodologies such as vibration method and compaction method	Compressive strength, flexural strength and split tensile strength at different temperatures	Experimental investigations conducted reveal that the compaction method of composites fabrication

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
	and filled in with glass fibers up to 4% weight			were employed in preparation of composites and the mechanical characteristics are determined with regard to temperature		proves to be highly effective with the maximum magnitudes of strength and stiffness. Additionally, it can be observed that the experiments conducted at a temperature of 110°C exhibits excellent properties of strength and stiffness. Glass fibers as filler material significantly influences the strength values and strength values increases in proportion with regard to the volume fraction of glass fibers.
Jicai Yin[71]	Granite aggregates reinforced with fly ash	Epoxy resin	Precision machine tool structures	Effective resin content in weight percent is optimized in order to attain the overall enhanced performance of the granite aggregate reinforced composite	Compressive strength, flexural strength and void content	Results reveal that compressive strength tends to decrease with an increase in weight percent of epoxy resin content whereas flexural strength exhibits an opposite trend with a proportionate increase with regard to the effective resin content. Additionally, fractal dimension of granite aggregates tends to influence the magnitudes of strength and the void content of composites. Air voids in composites are found with the presence of higher size of granite aggregates and such voids are eliminated with the addition of effective resin content.

(Continues)

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
Kailas V. Gurav[72]	Indian origin black granite	Epoxy resin	Metrological and precision machine manufacturing	Compaction technique is employed in development of epoxy granite composites for higher strength and load carrying capacity	Density and flexural strength	Results conclude that, the Indian origin black granite composites display superior mechanical characteristics with maximum density and higher flexural strength. Among different combinations of epoxy resin, 16% weight content of epoxy resin proves to be an ideal choice with higher density and strength.
Sung-Kyum Cho[73]	Polymer concrete filled in with carbon fibers and reinforced with stainless steel back plate	Epoxy resin	Table-top machine tool structure	Machine tool structures are redesigned and further numerical analysis and vibration tests were performed with regard to attain the enhanced structural stiffness	Structural stiffness	Numerical analysis of the re-designed machine tool structure reveal that the, structural stiffness was enhanced by 16% with a reduction in weight of the structure by 36.8%.
Juturi Saidaiah[74]	Granite aggregates	Epoxy resin	Lathe bed	Weight optimization of lathe bed by design modification techniques and numerical analyses	Deformation and von-mises stress	Results determined from numerical analyses reveal that, the lathe bed based on weight optimization and re-design techniques has drastically reduced up to 39.469 kg, which is 62.7% times less than the base model weight. Lathe bed with a reduction in weight proves to be effective without any trade-off among damping stresses and deformation.
A Selvakumar[75]	Granite aggregates	Epoxy resin	Machine tool structures	Epoxy resin content with a weight fraction		Experimental results convey that, the desired mechanical

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
				ranging from 10%–18% is applied in the composites and the optimum composition is determined for the enhanced mechanical properties	Compressive strength, tensile strength and Young's modulus	properties are obtained for a weight fraction of epoxy resin ranging between 12%–14%. Excellent mechanical properties such as tensile strength 5.4 MPa, compressive strength 30.88 MPa and Young's modulus 15 GPa were obtained for the weight fraction of 12% epoxy resin content.
Khashayar Jafari[76]	Aggregates of concrete with grain sizes ranging from 4.75–9.5 mm and 9.5–19 mm were used	Epoxy resin	Construction applications	Destructive and non-destructive testing methods under various temperature conditions were employed in estimation of mechanical properties and the concrete mixes were optimized based on Taguchi's methodology	Compressive strength, split tensile strength and flexural strength	Desired strength and stiffness obtained at an optimized weight content of 14% epoxy resin content and aggregate sizes of 9.5–19 mm with higher values of compressive strength, flexural and split tensile strength. Good mechanical properties is found for the operating temperatures decreasing in the range from 25°C to −15°C rather than increase in temperatures from 25°C to 65°C and such effects could be attributed due to the effects of higher energy absorption for the lower temperature conditions of -15°C. ANOVA results conclude that temperature is a most significant parameter, which influences the magnitudes of

(Continues)

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
						split tensile and flexural strengths.
Xu Ping[77]	Steel-fiber polymer concrete (SFPC)	Synthetic resin	Machine tool bed	Addition of steel as a reinforcement material in machine tool bed for the enhanced strength and stiffness	Compressive strength and Young's modulus	Reinforcement of steel in polymer concrete composites exhibits an enhanced value of strength, stiffness, and damping and thermal expansion properties in relation with polymer composites without any reinforcement materials. The properties of SFPC are found to be as: compressive strength 84.8 MPa, Young's modulus 78.96 GPa, damping ratio 0.044, co-efficient of liner thermal expansion 5.9×10^{-6}/K.
Ying Li[78]	Particulate reinforced polymer composites	Synthetic resin	Construction industry appliances	Temperature dependent tensile strength model was formulated with combined effects of temperature, particle volume fraction, particle radius, interfacial bonding strength and polymer matrix strength and further validated by experimental tests	Temperature dependent tensile strength	Theoretical model formulated for prediction of temperature dependent tensile strength are highly accurate and agree well with the experimental results.
M M Shokrieh[79]	Foundry sand filled in with chopped glass fibers	Epoxy resin	Construction industries	Experimental design of Taguchi's orthogonal array is employed and	Compressive, bending and interfacial shear strength	Three variables: aggregate sizes, weight percent of resin and glass fiber content

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
				additionally experiments were performed at three various freeze/thaw thermal cycles		significantly influences the magnitudes of the mechanical strengths. Additionally, the mechanical strengths predicted from statistical techniques and experimental measurements agree well with each other. With regard to the freeze/thaw cycles, cycle B with an operating temperature ranging from 25°C to 75°C exhibits deteriorating effect toward compressive, flexural and interfacial shear strength. Such reduction in strength values when specimens are exposed toward cycle B could be the effect of thermo-mechanical behavior of polymer matrix and its intrinsic properties, which changes proportionately in relation to the increase in temperature up to HDT point. Cycle A and C have a negligible effect on the strength values and it is proposed for the utilization of such composites in lower temperature environments (up to −30°C) with enhanced mechanical strength.
Harun Tanyildizi[80]		Vinyl acetate polymers	Building materials	Taguchi's orthogonal array with L_{25} was	Split tensile strength	Taguchi's single objective methodology of optimization

(Continues)

TABLE 1 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced static performance	Mechanical properties determined	Inferences
	CEM I 42.5 R cement filled in with phosphazene			employed for experimental design and optimum combinations were determined		reveals that the maximum split tensile strength values for variable combinations such as: specimens cured for 365 days, further carbonated for 14 days, with a phosphazene content of 3% by weight combined with cement with a weight ratio of 450Kg/m^3. Statistical investigations reveal that, cement content have a highest impact toward the values of split tensile strength.
Wahid Ferdous[81]	Angular limestone filled in with fire retardant filler (FRF), hollow micro spheres (HM) and fly ash (FA)	Epoxy resin	Construction appliances	Employed effects of resin-to-filler ratio and matrix-to-aggregate ratio toward mechanical characteristics in order to optimize the mix design	Compressive, tensile and flexural strength	The optimal resin-to-filler ratio is determined as 70:30 for layered composite material and 60:40 for homogeneous material while matrix-to-aggregate ratio is 1:1.35 without any trade-off between performance and cost. Homogeneous structures were obtained in the entire depth if there is a filler material of minimum 40% by weight and it is feasible due to the reduction of flow ability of epoxy matrix. Mechanical strength of these composites is directly proportional to the matrix-to-aggregate ratio and it is highly dependent on the resin content of the concrete.

TABLE 2 Dynamic analysis of machine tool structures

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
A Selvakumar[82]	Granite aggregates	Epoxy resin	Micro lathe bed	Numerical analysis of lathe bed made of epoxy granite composites were analyzed and investigated in order to obtain the reduction in weight of lathe bed for the same stiffness to that of cast iron	Damping ratio	Research investigations reveal that the damping ratio of epoxy granite lathe bed were found to be 2.2 times higher than the cast iron counterparts. In addition to the numerical analyses, the fabricated epoxy granite lathe bed exhibits a weight reduction by 38.64% than the cast iron counterparts for the same stiffness.
Harshad Sonawane[83]	Granite aggregates filled in with steel reinforcement	Epoxy resin	Machine tool column	Combined methodology of similitude theory, numerical analysis and the results are further validated experimentally in order to attain enhanced dynamic performance	Damping ratio	Research studies on such filled in composite structures convey that, this combined methodology for the enhancement of dynamic performance reduces the complexity associated with implementation of conventional scaled down modeling approach. Further, with regard to this combined methodology, the dynamic properties of filled in machine tool structures are increased by 20-30 times than the unfilled structures.
Francesco Aggogeri[84]	Al foam sandwiches (AFS), Al corrugated sandwiches (ACS) and carbon fiber reinforced polymer (CFRP) composites	Epoxy resin in CFRP	Movable parts of milling machine	Finite element simulations combined with experimental validations were employed in enhanced dynamic characteristics	Damping ratio	Research studies reveal that, the moving parts such as RAM produced by AFS displays a damping capacity, which is almost 20 times higher than the other counterparts and conventional materials like steel and cast iron. The RAM produced by AFS material is

(Continues)

TABLE 2 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
						most widely applied in machine tool structures involved in high-speed finishing operations. RAM manufactured by CFRP material offers higher structural stiffness and is widely applied in structures involved in roughing operations.
S Syath Abuthakeer[85]	Red granite aggregates filled with glass fibers	Epoxy resin	Micro lathe bed	Numerically analysis and experimental validations were adopted with the aid of LabVIEW interfacing software	Damping ratio	Experimental results reveal that the filler material E-glass fibers tends to enhance the structural stiffness without any trade-off among damping characteristics. Limited variation in experimental results were observed when compared with numerical results and the percentage deviation is within 10%.
Hyun Surk Kim[86]	Pebble and sand aggregates	Epoxy resin	CNC grinding machine bed	Compaction method is employed in preparation of composites which highly influences the dynamic characteristics of composites	Damping ratio	Experimental results convey that, the damping ratio of pebble and sand reinforced epoxy composites is 30 times higher than the conventional cast iron material. Better dynamic characteristics were obtained with the combination of different aggregate sizes and with a weight fraction of 50% of pebble aggregates.
F Haase[87]	Cast iron structure	No binding agent	3-axis milling machine	New model of accelerometer is employed and positioned along the three axes during cutting process for	Modal frequencies	It can be concluded that, forced vibrations are induced due to rotary motion of tool and spindle motor. Self-induced

TABLE 2 (Continued)

Author(s)	Work material	Binding agent/ resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
				controlling self-induced vibrations		vibrations called chattering are excited due to the milling process at a critical value of depth of cut and the frequency values displays a poor surface finish on the machined components.
N Kepczak[88]	Hybrid structure- Cast iron and minerals cast in it	No information provided	Machine tool structure	Numerical analysis was applied in determination of modal frequency and dynamic stiffness	Dynamic stiffness	Simulation results conclude that the hybrid machine tool structure proves to be an ideal choice than the conventionally made cast iron structure due to its enhanced dynamic stiffness and damping ratio.
Frederik Birk[89]	Hybrid structure- Mineral cast and CFRP reinforced in it	Epoxy resin	Machine tool structure	Two different manufacturing methodologies such as glued approach and direct encasting of CFRP pipe are employed for design of lightweight structures with regard to obtain enhanced dynamic characteristics	Damping ratio	Research studies conclude that the hybrid lightweight structures manufactured by two different methods offers its unique advantages. However, cast in method of hybrid structures comprising CFRP and mineral cast proves to be highly efficient in terms of operational stability and remarkable damping characteristics.
A A Dyakonov[90]	Cast Iron	No resin	16K20 NC Lathe bed	Mathcad simulations and experimental validations were employed for reliable and prompt estimation of dynamic rigidity and dynamic properties	Damping decrement	Based on the experimental results and from the eigen frequency of the vibrations, the damping decrement for frame is 2.2-2.8 for the frame and 2.7-5.7 for the spindle chuck. Spindle chuck highly contributes toward the source of vibration with its rigidity

(Continues)

TABLE 2 (Continued)

Author(s)	Work material	Binding agent/ resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
						greater than the frame by up to 76%.
Pawel Dunaj[91]	Steel-Polymer concrete	Synthetic resin	Machine tool frames	Computational models were developed by posteriori approach in modeling steel-polymer concrete structures and verified experimentally	Natural frequency	Research findings from this study is that the natural frequencies of experimental and computation for an unconstrained frame differ only by up to 4% whereas in case of constrained steel-polymer concrete frame the variation is up to a maximum of 9%. The proposed model by posteriori approach proves to be highly consistent with experimental results providing reliable evaluation of the dynamic properties.
Mihai Simon[92]	Polymer concrete	Synthetic resin	CNC machine tool spindle carriage	Impact test method with accelerometer and rowing hammer approach employed in determination of natural frequency and rigidity	Natural frequency	Graphical results reveal that, abnormal peaks were found which indicates the frequency response thereby resulting in limited dynamic stability of the structures. Inference from this study is that, sufficient redesign of structures can be carried with regard to obtain a rigid structure with enhanced damping characteristics.
Dai Gil Lee[93]	Hybrid structure- Cast iron reinforced with glass fibers	Epoxy resin	Grinding machine tool column	Damping capacity of hybrid machine tool column were estimated with regard to fiber orientation and thickness of the composites by Ross-Kerwin-Ungar (R.K.U) method	Damping ratio	Results reveal that the composite laminates with 90^0 stacking sequence and 15 mm thickness was preferred than stacking sequence with 45° orientations.

TABLE 2 (Continued)

Author(s)	Work material	Binding agent/ resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
						Damping ratio predicted by R.K.U. method reveals a 30% increase in damping ratio for a hybrid column whereas the experimental results reveal a 35% increase in damping ratio when compared with the conventional cast iron column. Such an increase in damping ratio from experiments could be attributed due to the effect of inter laminar shearing in the laminates and the adhesive joining area.
Ralph Kussmaul[94]	CFRP composites	Synthetic resin	Multi Axial Testing Machine (MATM)	Optimized CFRP MATM was compared with regard to the state-of-the-art aluminum design of MATM in terms of cost, inertia, stiffness and frequency characteristics	Natural frequency	CFRP structures proves to be a valuable asset and an ideal choice in design of high design of MATM. Selection of CFRP based design could be attributed to the structural rigidity with a 77% increase in natural frequency; reduction in inertia by 31.7% and cost effectiveness, which is 7.9% lower than aluminum reference system.
Selvam Rangasamy[95]	Carbon and glass fiber reinforced composites	Epoxy resin	Machine tool bed	Experimental and numerical investigations were carried with the aid of ANSYS12 and DEWESoft software on the hybrid composite laminates with regard to the damping ratio, strength and stiffness	Damping ratio and natural frequencies	Experimental results reveal that the natural frequency of the hybrid composite laminate is 1372 Hz, which is 37.06% times higher than the frequency of conventional cast iron (1001 Hz). Such a higher value of frequency exhibits an excellent structural rigidity with

(Continues)

TABLE 2 (Continued)

Author(s)	Work material	Binding agent/ resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
						accurate metal cutting operation. The damping ratio of hybrid composites shows an increase in magnitudes with 3–5 times higher than the cast iron.
N Mahendrakumar[52]	Nettle fiber reinforced composites	Polyester	Micro lathe bed	Form design modification was employed for the enhanced dynamic characteristics	Damping ratio	Experimental modal analysis performed conclude that the damping ratio of nettle polyester reinforced composites were 4 times higher than cast iron lathe bed and such a superior damping characteristic could be attributed to the structural form design of bed and inherent damping properties of the composites reinforced with nettle fibers.
Prabhu Raja Venugopal[57]	Epoxy granite composites filled with glass fibers	Epoxy resin	Vertical machining center base	Steel reinforcement incorporated in epoxy granite composites with seven different design configurations in order to attain the enhanced dynamic properties	Natural frequency	Proposed design configuration number 7 displays higher structural rigidity with a higher magnitude of natural frequency than compared with the cast iron base of a machining center. The frequency values were found be 948 Hz for proposed design configuration 7 and such higher frequencies could be the enhanced stiffness in both bending and torsion modes.
Prabhu Raja Venugopal[58]	Epoxy granite composites filled with glass fibers	Epoxy resin	Column of machine tool structures	Optimization of structural design among nine different design configurations by employing steel	Natural frequency	The proposed design configuration number 9 displays a static stiffness equivalent to that of cast iron

TABLE 2 (Continued)

Author(s)	Work material	Binding agent/ resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
				reinforcement in epoxy granite composites with regard to obtain enhanced structural stiffness and stability		and a structural rigidity higher than cast iron structures with a natural frequency 12-20% higher than cast iron. Such higher values of natural frequency could be the reduction in mass of the machine tool column by about 118 kg.
Joel D'Mello[53]	Granite particulate reinforced composite	Epoxy resin	Precision machine structures	Composites were fabricated based on higher weight percentage of granite particles with regard to the epoxy matrix	Damping ratio	Experimental results reveal that the highest magnitudes of damping ratio were obtained for granite particulate epoxy composites with a weight fraction of 80:20 ratio. The maximum value of damping ratio is found to be 0.0218 and it is higher than cast iron (0.018) normally used in precision machine tool structures.
M Rahman[60]	Polymer impregnated ferrocement composites	Synthetic resin	Micro lathe bed	Advanced ferrocement materials filled in with discrete fibers have been adopted in this research study for enhanced structural stability	Damping ratio	Dynamic test results conclude that the damping ratio and the natural frequency of ferrocement lathe beds are quite higher than the cast iron bed. Such better performance of ferrocement beds are the impregnation of polymers into the ferrocement aggregates thereby produces excellent dynamic properties.
Jicai Yin[71]	Granite aggregates reinforced with fly ash	Epoxy resin	Precision machine tool structures	Effective resin content in weight percent is optimized in order to attain the overall enhanced performance of the	Damping ratio	Results reveal that damping ratio tends to increase in proportion with an increase in weight percent of epoxy

(Continues)

TABLE 2 (Continued)

Author(s)	Work material	Binding agent/ resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
				granite aggregate reinforced composite		resin content. Additionally, fractal dimension of granite aggregates tends to influence the magnitudes of damping ratio of the composites. Overall, the structural rigidity of these composites are directly influenced by the effective resin content.
H Sugishita[61]	Portland cement concrete composites	Synthetic resin	Machining center	Composites were developed by Portland cement type due to its superior structural properties, damping capacity	Damping ratio	The damping ratio of these portland cement reinforced concretes is superior to that of cast iron structures. With regard to the measured natural frequencies, the natural frequency values of these concrete beds are lesser than the frequencies of cast iron bed for the same frequency range.
Sung-Kyum Cho[73]	Polymer concrete filled in with carbon fibers and reinforced with stainless steel back plate	Epoxy resin	Table-top machine tool structure	Machine tool structures are redesigned and further numerical analysis and vibration tests were performed with regard to attain the enhanced damping capacity	Damping capacity	Modal analysis of the re-designed machine tool displays higher damping capacity than the original structure with a loss factor ranging from 2.82% to 3.64%. The re-designed machine tool structure exhibits superior dynamic characteristics with a reduction in weight by up to 36.8% without any trade-off among strength and stiffness.

TABLE 2 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced dynamic performance	Dynamic properties determined	Inferences
Jung Do Suh[63]	Polymer concrete composite with welded steel structure	Epoxy and Polyester resin	Machine tool bed	Sandwich structures of welded steel faces were incorporated along with the polymer concrete for the enhanced structural stability of structure	Damping ratio	Impact hammer tests reveals that, for a wide range of frequency hybrid machine tool structures displays large magnitudes of damping factors. Based on the measured natural frequency, the damping capacity ranges from 2.93%–5.69% that are larger than the conventional machine tool structures ranging from 0.2%–0.3%.

TABLE 3 Cooling fluids and its mode of heat transfer

Cooling fluids	Type of convective heat transfer	Heat transfer coefficient (W/m^2K)
Air	Free	2
Water	Free	100
Air	Forced	30
Water	Forced	10
Oil	Forced	2000

the thermal characteristics of the spindle, which can be, used a data in thermal error modeling and compensation. Based on the experimental results the boundary conditions in numerical analysis could be altered and can be chosen judiciously with the view of accuracy of the results.[98,99] Experimental investigations on thermal analysis have gained significant importance everywhere and the different methods are employed for temperature measurement, thermal key point selection and thermal error measurement.

4.1 | Measurement of temperature

Temperature measurement essentially comprises incorporation of temperature sensors in the spindle of the machine tool structures.[15,24] The temperature sensors normally employed for temperature measurement are thermometers, thermocouples, negative temperature coefficient (NTC) thermistors, positive temperature coefficient (PTC) thermistors and other semiconductor thermal elements. The temperature sensors smaller in size are contact based measuring instruments and it is placed in the spindle of the machine tool structures for identification of heat source and its temperature.[13] The factor that limits the utilization of such temperature sensors is that the wires embedded interrupts the spindle system during operation conditions thereby affecting the machining performance. Such limitations are overcome with the development of non-contact type thermal cameras. Thermal cameras work based on the principle of infrared imaging and provides information on the surface temperature and thermal field patterns over the entire structure. Infrared imaging provides information on the thermal images that can be recorded and further processed in determination of temperature over the specific regions or points. In running conditions of the spindle, thermal camera proves to be a safer and ideal option in temperature measurement.[100,101] Temperature measurement in a spindle system with the aid of thermal camera is presented in Figure 2.

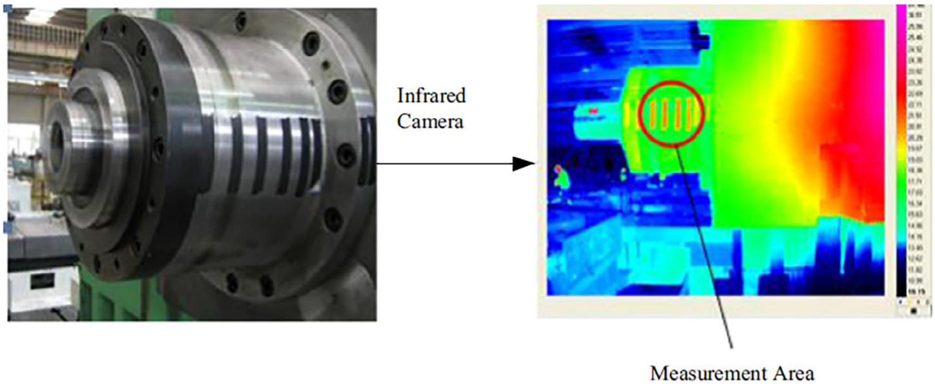

FIGURE 2 Temperature measurement in spindle system with thermal camera (Reproduced with permission from Elsevier License Number: 5161750318819) Ref. [15]

Non-contact type temperature measurement with thermal camera proves to be a safer approach in temperature measurement than the utilization of temperature sensors.[102] However, the degree of testing accuracy in contact-based temperature measurements is much higher than compared with the non-contact measurements and the radiation from other heat sources are negligible in contact type measurements. Infrared images provide only the information on surface temperature and fails to reveal the temperature of the elements in the internal components in the spindle system.[103,104] Based on the degree of accuracy and much more specific information of temperature of the elements in spindle, the suitable contact or non-contact mode of temperature measurement is employed.

4.2 | Thermal key points and its selection

Temperature measurement by contact type sensors is performed by taking into consideration of certain key aspects. Such sensors cannot be chosen and positioned in random manner for measurement. More number of sensors placed in spindle system significantly influences the temperature measurement and thermal error modeling.[105,106] Incorporation of temperature sensors in spindle system is carried out depending on the optimal number of sensors to be placed and the determination of ideal location of heat sources for temperature measurement. The number of sensors and its location is directly proportional to the accuracy of the developed thermal error model.[107] In certain circumstances where higher proportion of sensors placed in machine tool spindles and further the measured data are applied in modeling, the thermal error model accuracy is lesser and the model proves to be highly inconsistent. Hence, selection of optimal key points and the quantum of sensors required proves to be a critical task in thermal error modeling and temperature measurement. The points at which the temperature sensors are placed are termed as thermal key points or simply thermal susceptible points. These optimal point's exhibits higher influence toward the degree of thermal error in spindle system for changes in temperature. Thermal error model formulated from the measured data from these optimal key points are highly accurate. The optimal key points are chosen based on certain requirements as: the temperature sensors need to be placed at nearest proximity to the main heat sources, temperature field patterns of the spindle are based on the temperature of the optimal key points and the temperature change at the optimal key points influences the intensity and direction of spindle thermal error in a machine tool system.[108,109] From the above-mentioned aspects the optimal key points are identified for temperature measurement and thermal error modeling.

4.3 | Measurement of thermal error

Thermal error measurement and testing is carried out with the aid of displacement sensors such as capacitance sensors, eddy current sensors and proximity sensors. These displacement sensors listed are the widely preferred and utilized sensors in thermal error measurement and testing. Thermal error testing is performed in a spindle system with the aid of these sensors and the experimental set up arranged is unique and depends on the other available instruments in the machine tool structure. This section discusses the various experimental arrangement for thermal error measurement of a spindle system in the machine tool structure based on the different displacement sensors. Figure 3 illustrates the experimental set up comprising master ball and capacitance sensor for thermal error measurement in machine tool spindle.[110]

In this experimental arrangement, the capacitance sensors are placed over the table and the master ball is inserted in the spindle. The entire spindle system incorporated with the sensors is interfaced with the Data

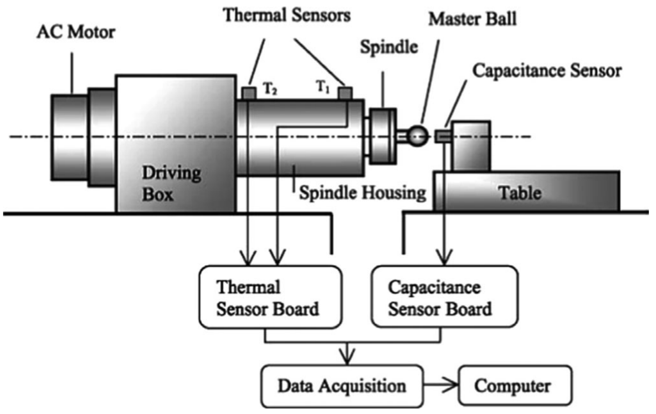

FIGURE 3 Experimental arrangement for thermal error measurement in machine tool spindle using capacitance sensors (Reproduced with permission from Elsevier, License Number: 5161750591218) Ref. [110]

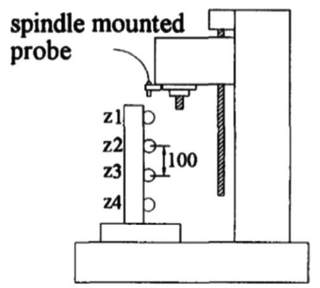

FIGURE 4 Experimental arrangement for thermal error measurement in machine tool spindle using touch probe (Reproduced with permission from Elsevier, License Number: 5161760238704) Ref. [112]

Acquisition (DAQ) system and the thermal error measurements are done virtually with the aid of personal computer.[111] The table is considered to be in non-deformable state, since it is positioned away from the heat sources. In the operating conditions of the spindle, deformation is observed and this could be attributed due to the rise in temperature induced by the heat sources. These heat sources are identified to be originated from the bearings and the drive box. Such rotary motion of the spindle exhibits a change in relative displacement among the master ball and the capacitive sensors. These changes in relative displacement of the sensors, indicates the spindle thermal error and is measured with DAQ system.

Thermal error evaluation can also be performed with contact measuring methods. The touch probe is one such device employed in determination of thermal error of machine tool spindles. Thermal error evaluation by contact-based touch probe and its experimental set up is shown in Figure 4.[112]

The touch probes were placed over the spindle while the spherical balls were placed over the table surface. The thermal error of the spindle is evaluated based on the difference between the coordinate's position of the balls when the spindle is in stationary or cold condition and the coordinates position where there is a change in temperature during operating conditions. In this experimental arrangement, the principle of measurement is based on the displacement of probe in relation with the temperature change displayed by the balls mounted in the table.[113,114] Thermal error testing and evaluation in machine tool spindles is performed with the aid of ball bar device.[115] The ball bar device comprises four magnetic sockets where one socket is mounted with the spindle system and it is termed as tool socket whereas the other three sockets were fixed to the table and are termed as base

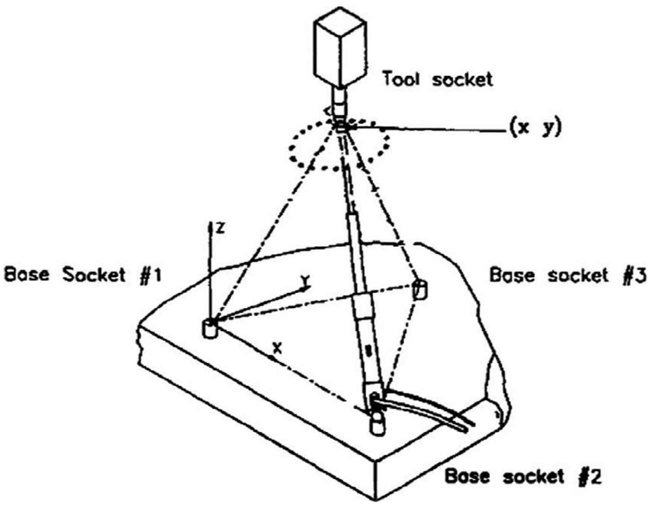

FIGURE 5 Experimental arrangement for thermal error measurement in machine tool spindle using ball bar (Reproduced with permission from Elsevier, License Number: 5161760437674) Ref. [116]

sockets. The experimental arrangement for ball bar test is shown in Figure 5.[116]

The arrangement of these four sockets depicts the shape of a tetrahedron. During operating conditions, the spindle traces the path of a circle and further based on the coordinates of points of the circle the spindle axes and its center position were determined. The thermal error is computed based on the differences between the initial orientation of the spindle with regard to its axes and center position and to that of the position and orientation of the spindle during operating conditions. These experimental investigations illustrated provides the correlation between change in temperature and thermal error and could be analyzed which further serves as a basis for formulation of thermal error models.

Experimental investigations on thermal errors are highly time consuming, involves huge quantum of sensors and other devices incorporated over the spindle system. However, such experimental method of thermal errors measurement is direct, effective and highly accurate method of determination of thermal behavior of machine tool spindles.[117–119] From the measured thermal errors, thermal error models are formulated and further the thermal error compensation can be implemented. It can be concluded that the experimental investigations on thermal error measurement is highly effective and proves to be a more reliable and effective approach than numerical and analytical methods and completely reveals the entire information on thermal behavior of machine tool spindle.

5 | MODELING OF THERMAL ERROR

The primary objective is determination of ideal methodology for establishing thermal error model with higher accuracy and consistency and as such, the model influences the effectiveness of the thermal error compensation.[120,121] Several thermal error models formulated earlier have considered the following parameters such as temperature and thermal deformation of spindle while in recent years few models formulated have considered additionally the parameters such as spindle speed, power of the motor and other factors as the input conditions.[122–124] In this section the different methodologies that are normally employed in thermal error modeling of machine tool spindles is discussed in an elaborate way. The different methodologies discussed in this review work is listed as least squares method, neural network, support vector machine (SVM) and other hybrid models.

5.1 | Least squares method

Least squares method is the most simple and consistent approach and it is widely preferred in thermal error modeling in spindle system. This method of thermal error modeling determines the best-fit line in correlation with the measured experimental data. The generalized equation for the least square's method is expressed as,

$$y = a_1 f_1(x) + a_2 f_2(x) + \ldots\ldots\ldots\ldots + a_k f_k(x) \qquad (1)$$

Where a_1 to a_k denotes the constants.[125] The primary objective of least squares method is the determination of these constants, which thereby minimizes the deviation between the experimentally measured and the computed values of y as expressed in equation (1).[126] Several researchers have employed least squares method in formulation of thermal error models with regard to the temperature and measured thermal errors. Li et al.[127] established a relationship among temperature and axial thermal errors by formulation of thermal error model for machine tool spindle and the established thermal error model proved highly effective with minimum deviations among the measured and computed values of temperatures. Yang proposed an online-based modified method based on the principle of least squares method for development of thermal error models with regard to temperatures and thermal errors.[128] The online methodology proposed comprises several recursive equations, which thereby aids the model in modification recursively based on the newer input data. Such changes in the developed thermal error model enhances the accuracy and robustness with the minimal deviation among measured and computed values of temperature.

5.2 | Neural networks

The Artificial neural networks (ANN) method is the most valuable methods in formulation of functional relationships between thermal errors and temperatures with regard to the machine tool spindle. This method provides the relations among multivariable inputs and output variables.[129,130] This method exhibits a good performance in formulation of models for non-linear functions and it is widely preferred in several research domains.[131] In thermal error modeling of machine tool spindles by ANN method, the input and output parameters were considered as temperatures and thermal errors.[132] The structure of an ANN model is presented in Figure 6.

In this model the input and output vectors are denoted by p and a.[133] The limitations in modeling of thermal errors for machine tool spindles have been overcome with the ANN method, since the thermal error modeling of spindles in multiple directions is performed with only one neural network as it has multiple

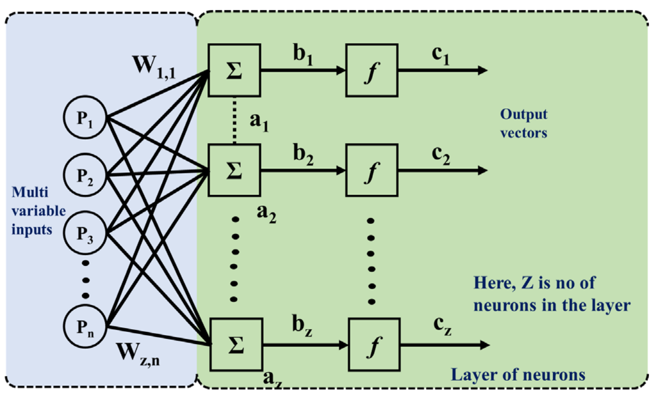

FIGURE 6 Structure of artificial neural network (ANN)

outputs.[134,135] This principle of modeling based on ANN methods reduces the complications in thermal error modeling. ANN models can be classified as static and dynamic models depending on the flow of information within the network.[136] The static models of ANN are back propagation (BP) network and radial basis function (RBF) network while integrated recurrent neural network (IRNN) comes under the category of dynamic networks. The static and dynamic models of ANN in thermal error modeling is discussed below.

Back Propagation (BP) network employed in thermal error modeling exhibits remarkable performance with good robustness for longer periods and further proves to be versatile with its application in modeling for different machine tool structures. In BP network, the information flows in only one direction and it is termed as feed forward network. However, the limiting factor in employing BP networks is the slower rate of convergence and tends to fail in a local minimum value.[137] Such limitations in BP network are overcome with the development of thermal error models based on a hybrid methodology comprising optimization techniques embedded with the BP networks for a better convergence rate with higher accuracy. Huang and Hao in their research investigations proposed a hybrid methodology in the development of thermal error models by using the BP network with the genetic algorithm (GA) and the thermal error models developed proved to be efficient with higher accuracy and enhanced convergence rate.[138,139]

Radial basis function (RBF) network, also termed as feed forward network comprises three layers such as input, hidden layer and the output layer. In feed forward network, the flow of information exists in one mode namely forward where the information flows from the input neurons to the output neurons through the hidden layer.[137] In thermal error modeling of machine tool spindles, RBF network is preferred than BP network due to its higher speed of training with a better convergence rate without any trade-off in terms of the prediction accuracy of the developed thermal error model.

Integrated recurrent neural network (IRNN) comes under the category of dynamic neuron network models, where the information flows in the network with a feedback loop. This network of modeling exhibits a remarkable robustness in modeling thermal errors of spindles subjected to, dynamic variations in temperature with non-linear changes in thermo-elastic process under different working conditions.[139] Yang in his research investigations developed an IRNN model for thermal error modeling in a machine tool spindle.[110] The thermal error model developed comprises a feedback loop and the structure of a neural network with a feedback loop is shown in Figure 7.

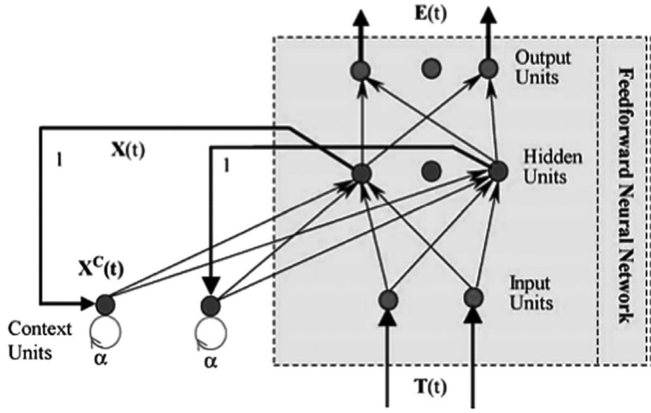

FIGURE 7 Recurrent neural network with feedback loop (Reproduced with permission from Elsevier, License Number: 5161760633182) Ref. [111]

In this feedback loop, the earlier outputs of the context layer are transferred to the input layer where the information is propagated forward and other directions vice-versa.[140] The thermal error models of machine tool spindles developed by IRNN methods with a unique aspects of feedback loop proved efficient than compared with the thermal error models developed from other static networks such as BP and RBF.

5.3 | Support vector machine (SVM)

Support vector machine method of modeling thermal errors have gained prominence in recent years and have drawn much attention similar to that of neural networks. This SVM method is based on the principle of structural risk minimization (SRM) and the principle adopted is quite superior to that of empirical risk minimization (ERM) principle applied in neural network.[141,142] SVM method is preferred widely in thermal error modeling of spindles, since it minimizes the upper bound on the errors thereby reducing the complications in resolving real time problems.[24,143–145] Miao et al in their research investigations revealed that the temperatures were tested at various spindle speeds, and further inferred that lesser data for modeling influences the prediction accuracy and robustness of the MRA model.[145] Further, upon application of SVM method in thermal error modeling, the model displayed a higher prediction accuracy with the dynamic variations in the working conditions. Ramesh et al analyzed the performance of SVM based model with the aid of root mean square criterion and further performed a comparison of the model in relation with the ANN based model.[144] Comparison studies reveal that the thermal error models developed by ANN and SVM methods exhibits similar performances in case of train-and-test and the model developed by SVM is relatively quicker with a higher accuracy than the model developed with ANN.

5.4 | Hybrid models

Modeling of thermal errors in a machine tool spindle is complex and intriguing, non-linear and variations is observed with regard to the dynamic changes in the working conditions. Hence, development of a unique and a comprehensive thermal error model by employing a single methodology with a consistency in terms of performance and accuracy is a complicated task. Such limitations in modeling thermal errors of a machine tool spindle by a simple method can be overcome by incorporation of two different methods with a hybrid approach of modeling thermal errors. The uniqueness of employing hybrid methods is that it combines the salient aspects and advantages of two different approach in a single methodology with the objective of achieving enhanced accuracy and performance. Several researchers have employed such hybrid models with a combined methodology in thermal error modeling of machine tool spindles.

Lin and co-authors in their research investigation employed a hybrid methodology with the combination of SVM and neural network (NN) in development of thermal error model of spindle.[145] In addition to the hybrid model, comparative studies were performed with regard to the determination of superior thermal error models developed based on SVM and NN. The machining investigations were performed at a cutting condition of 2000 rpm. Results conclude that the predictive error control is within 0.5 microns, and the hybrid model proved to be effective with a percentage error up to 1.95% and it is relatively lesser than that of SVM and NN and it is found to be 2.74% and 2.63%. Zhang[146] proposed a hybrid methodology named Gray neural network (GNN) in thermal error modeling of spindles with the aid of gray system theory and neural network. Experimental investigations in a five-axis machining center and the axial spindle thermal error model reveal that the GNN model exhibits good performance with a higher prediction accuracy and higher robustness than the thermal error models developed by gray model or by neural network. Ramesh et al[24] developed a thermal error model with a combined methodology of SVM and Bayesian network (BN) based on the working conditions. This hybrid SVM-BN model of thermal error exhibits a higher accuracy in prediction of thermal errors for dynamic variations in working conditions. The hybrid models developed establishes a functional relationship among the temperatures measured and the thermal errors determined either by experiments or by computations.

Such limitations in modeling spindle thermal errors with single methods is overcome with a combined methodology of a hybrid thermal error model. However, the hybrid thermal error models developed exhibits a good performance in terms of higher prediction accuracy and consistency in relation to the unique models such as NN, BN and SVM and so forth. The different thermal error models formulated exhibits a difference in performance and prediction accuracy and this could be attributed due to the operating conditions and the principles of methods adopted in developing such models. However, a globally accepted universal thermal error model for machine tool spindles with higher accuracy and robustness is yet to be developed and implemented successfully for varying operating conditions and much more efforts are required in developing such models. Several researchers have developed spindle thermal error models and such models developed are subject to display a variation in performance with regard to the dynamic changes in operating conditions. The discussion on thermal error modeling and formulation of relationship between thermal errors and temperatures in this section provides a clear ideology for several researchers and scientists in the domain of machine tool spindles for prediction and analysis of thermal characteristics in terms of performance, functionality and properties.

6 | RESOLVING CHALLENGES IN DEVELOPMENT OF POLYMER COMPOSITE MACHINE TOOL STRUCTURES

Machine tool structures manufactured by means of polymer concrete reinforced composites and other alternate materials exhibits superior performances in relation to that of conventional cast iron machine tool structures. However, such polymer concrete reinforced machine tool structures cannot be manufactured as such and there are certain challenges associated with it.[17,42] The major concern in machine tool structures is the limited static and dynamic characteristics to possess the desired strength, stiffness and stability and in addition the thermal deformation and errors developed during operating conditions. Heat generation developed during running conditions of machine tool spindles is another critical factor and such factors could be overcome by embedment of cooling system in machine tool structures. Such challenges in development of machine tool structure can be resolved with incorporation of thermal actuators and other mechatronic systems for determination of temperatures and other form of thermal errors, incorporation of cooling systems, utilization of advanced and hybrid materials with an optimized proportion of aggregates to obtain the desired strength and stiffness and thermal error compensation strategies for elimination of thermal errors.[2] Henceforth, with a view to provide clear ideology in development of polymer concrete reinforced machine tool structures this section discusses the various methodologies implemented in resolving the challenges for manufacturing machine tool structures.

6.1 | Different form designs and embedment of hybrid materials

Light weight design and machine tool structures with minimal weight are preferred significantly due to its limited cost and energy savings. With regard to the design of lightweight materials, fibers derived from natural resources exhibits superior advantages than the man-made synthetic fibers since they are available in abundance, cost effective and eco-friendly with limited greenhouse gas emissions. Desired static and dynamic characteristics of machine tool structures are achieved by alternate form designs and the ideal form designs are selected based on the desired strength and stiffness displayed by them. N Mahendrakumar[37] in his research investigations designed and developed a micro lathe bed based on natural fiber reinforced composite materials with different form design strategies. The research work essentially comprises development of micro lathe bed by nettle fiber reinforced polymer composites with 20 different form designs with various cross sections. Among the 20 different form designs, form designs six and seven displayed enhanced bending and torsional stiffness and are ranked as 1 and 2 respectively. With regard to the rankings the form design six with a cross section of hollow hexagon with a longitudinal and transverse vertical rib is chosen as the ideal cross section for the design, development and fabrication of nettle fiber reinforced polymer composite micro lathe bed to achieve the desired strength, stiffness and dynamic characteristics. Experimental results reveal that the nettle polymer micro lathe bed exhibits the desired stiffness and strength values for a 20% weight reduction in the entire structure. Similarly, experimental modal analysis convey that the damping ratio was found to be 4 times higher than cast iron micro lathe bed. Nettle polymer composites with alternate form design proved to be an efficient strategy in enhancing the dynamic characteristics of micro lathe bed without any trade-off among stiffness. With the inspiration from the concepts of biology and nature, several researchers across the globe have employed suitable form design strategies in development of machine tool structure with an objective of enhancing the static and dynamic characteristics.

Incorporation of steel and other metallic structures as an additional reinforcement in the development of polymer concrete reinforced machine tool structures proves to be a highly consistent approach with regard to achieve the maximum stiffness and rigidity of the structures without any trade-off among the magnitude of damping ratio. Prabhu Raja Venugopal et al.[81,82] in their research investigations designed, developed and fabricated machine tool structures such as lathe bed and column made up of epoxy granite composites with steel as an additional reinforcement. Lathe bed and column produced by glass fiber reinforced epoxy granite composites with an optimized proportion of 80% finely crushed granite aggregates and 20% epoxy resin exhibits superior damping characteristics with a limited magnitude of mechanical characteristics such as strength and stiffness. Such a minimal value of mechanical characteristics exhibits a limited performance life and leads to failure of the structure during operating conditions. With an objective to produce epoxy granite machine tool structures with a remarkable dynamic characteristic and further without any trade-off among stiffness and rigidity, steel material is incorporated as an additional reinforcement in epoxy granite machine tool structures. Incorporation of steel as an additional reinforcement with nine different design configurations were proposed and further designed and fabricated. Numerical results combined with experimental validations of this research investigation conclude that the, ninth configuration (standard steel sections with column wall thickness 60 mm and two 20 mm plates for lead screws) proposed exhibits a static stiffness and rigidity equivalent to that of cast iron structures with an increase in natural frequencies by 12%–20% higher than cast iron structures. Thus, in order to obtain the superior performances of machine tool structures, hybrid materials (in the form of two or multiple materials combined together) are preferred to achieve the desired properties and further proves to be an ideal strategy in development of machine tool structures.

6.2 | Utilization of advanced materials for thermal error compensation

Selection of suitable materials in development of machine tool structures plays a critical role and further influences the product quality and the production processes. Thermal displacements induced in machine tool structures is an undesired phenomenon and can be controlled with an application of ideal material as a bandage in development of such machine tool structures. Such thermally induced displacements and errors can be possibly limited by incorporation of carbon fiber reinforced plastics (CFRP) as a bandage over the periphery of the machine tool structures.[147] CFRP materials displays a negative thermal coefficient of expansion and limits or compensates the thermal displacements generated from the machine tool spindle housings. In case of machine tool spindles made by aluminum materials (positive linear expansion coefficient), the thermal displacements generated are reduced or compensated by generation of thermal strains in the opposite directions by CFRP materials with an inherent properties of negative linear expansion coefficients. Embedment of CFRP materials as bandage exhibits a reduction in thermal displacements by up to 70% in the machine tool spindles with relation to that of the monolithic aluminum-based machine tool spindle housings.[148] Such compensation strategies limit the values of thermal displacements at the bearing points which thereby induces a reduction in angular displacements at the tool center point (TCP) resulting in enhanced accuracy of the machining processes. The compensation strategies employed in thermal displacements reduction with the application of CFRP bandage in machine tool structures is shown in Figure 8.[149]

Apart from CFRP materials several other fiber materials tend to exhibit a negative linear expansion coefficient and such fibers are chosen based on the anisotropy of the material. The inherent characteristics of negative linear thermal expansion exists only in the fiber direction.[150,151] In case of aramid fibers, the ratio of linear thermal expansion across the direction of fiber to that of the linear thermal expansion in the fiber direction is found to be 35, while the magnitude of expansion in the fiber direction is negative and the thermal expansion magnitude across the fiber is positive. There are different wide range of carbon fibers that exist with negative thermal expansion coefficients. The compensation strategy for reduction in thermal displacements with different materials and its linear thermal expansion is shown in Figure 9.[152]

6.3 | Cooling system embedment in machine tool structure

Heat generated during the running conditions of machine tool structures is an undesired phenomenon and it needs to be compensated or reduced. Utilization of coolants, machine tool structures operated at ambient temperature conditions and several other temperature control techniques and strategies can be employed in controlling the thermal characteristics of machine tool structures.[153] Cooling fluids is the primary method in controlling the thermal behavior of machine tool structures.[154] In case of more precise machine tool structures, it is proved that conventional coolants limit the thermal error. However, utilization of cutting fluids and further with minimum quantity lubrication (MQL) approach do not take into account of machining accuracy and hence affects the performance and quality of the product with a trade-off among the desired characteristics and its functionality.[155,156] An alternatively effective technique in control of temperature gradients in the structure and the

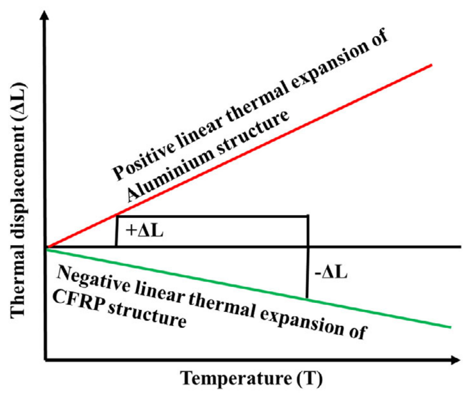

FIGURE 9 Compensation principles for thermal displacements with advanced materials

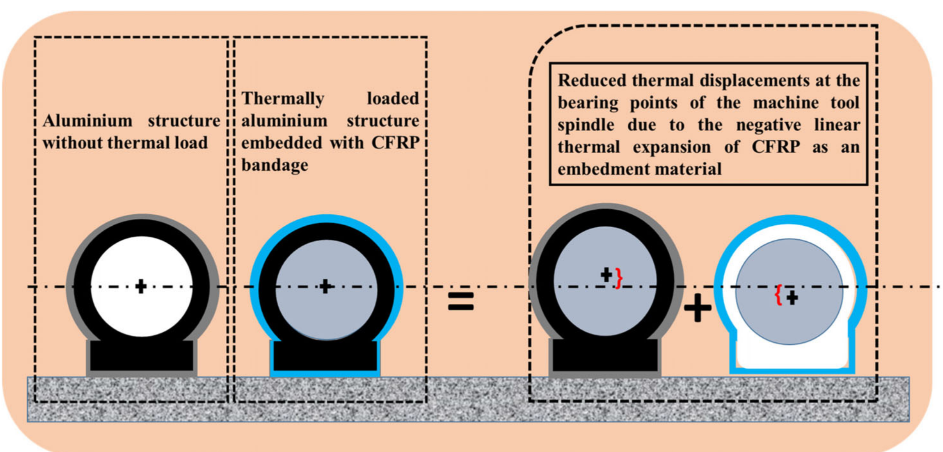

FIGURE 8 Compensation strategy for thermal displacements with CFRP bandages

thermal errors is possible by means of convective heat transfer using cooling fluids which thereby eliminates the internal heat generated in the structure to the maximum extent. Forced convective mode of heat transfer with the aid of external sources significantly controls the temperature and heat generated within the machine structures. The efficiency of heat removed in the machine tool structures is influenced by the convective heat transfer coefficient, fluid film thickness, viscosity, specific heat, thermal conductivity and velocity over the surfaces[157–159]. Cooling fluids with forced convection mode of heat transfer with external sources (like powerful fans and other form of air regulators) exhibits an enhanced cooling performance in relation to that of free mode of convective heat transfer.[160] The most commonly preferred cooling fluids with the mode of heat transfer and the magnitude of heat transfer coefficients is shown in Table 3.

Heat transfer coefficient values from Table 3 reveals that, an enhanced cooling performance is observed in the machine tool structures is with an increase in velocity of cooling fluids on the surfaces of the machine structure. The increase in order of heat transfer coefficients conclude that, forced convective mode of heat transfer proves to be an ideal strategy in temperature control and further exhibits an improved cooling performance and a higher thermal stability in machine tool structures. Such a higher thermal stability in machine structures can only be obtained with air circulation at higher velocities ranging up to 150 m/min which incurs powerful fans and other source of air supply.[160] Incorporation of such external source of devices adds up the cost and additional arrangement in the entire cooling system and proves to be ineffective with regard to the cost. Forced convective mode of heat transfer proves to be highly effective in terms of thermal stability and temperature control of machine structures with a trade-off in terms of cost and incorporation of additional instruments in the system.

Such limitations in forced convection of cooling fluids is overcome by high-precision machine tools with temperature control enclosures within the machine with regard to enhance the thermal stability. In such temperature control enclosures, the cold air is mixed with the air from the machine enclosures and further heated to maintain a uniform temperature in the machining zone. With this approach of temperature control enclosures, a temperature stability of +/−0.1°C is achieved in the machine tool structures. For a wide range of precision applications, machine enclosures with even higher temperature control are needed. Since the earlier decade, several research investigations have been carried out for heat removal from machine tool structures with a highly cost-effective technique. Fundamental heat transfer studies provide a functional relationship between Nusselt number (Nu) and Reynolds

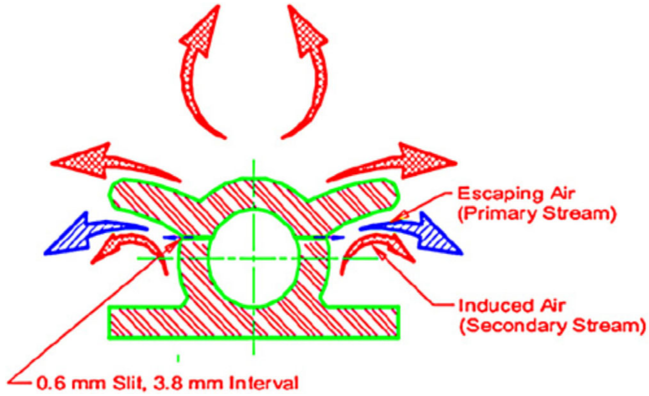

FIGURE 10 Sectional view of Coanda-effect tubing for thermal stability in machine tools (Reproduced with permission from Elsevier, License Number: 5161761109934) Ref. [35]

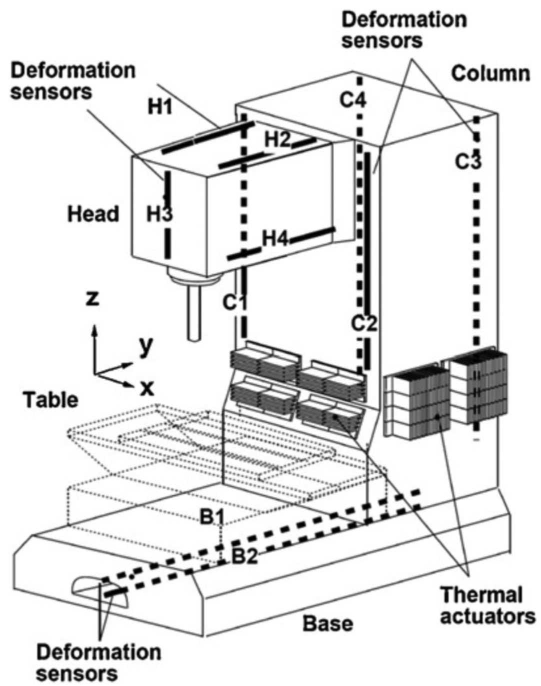

FIGURE 11 Intelligent machine tool structure embedded with sensors and actuators for thermal error compensation (Reproduced with permission from Elsevier, License Number: 5161761307618) Ref. [163]

number (Re) which thereby reveal that the turbulent flow enhances the heat transfer rate of liquids.[161] Such conceptual approach from heat transfer is employed in obtaining superior thermal stability with the incorporation of Coanda-effect cooling devices with silicon tubes in the machine tool structures. The sectional view of Coanda-effect tubing for temperature control in a machine tool spindle is shown in Figure 10.[35,162]

Silicon tubes when pressurized by air, the air gets discharged through small slits and further induces

TABLE 4 Thermal analysis of machine tool structures

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
Shuming Yang[164]	Cast iron	No such resin is employed	Machine tool structures	Finite element analysis techniques were applied for different oil film thickness	Temperature variation	Numerical studies conducted for an oil film thickness ranging from 20 to 40 microns reveal that, for an oil film thickness of 30 microns the strain deformation and temperature difference are within the minimum magnitudes. Mathematical relations formulated indicate that there is a negative correlation of temperature with regard to oil film thickness.
Kiho Kim[165]	Aggregate particles of boron nitride (BN)	Epoxy resin	Packaging materials in electronics industries	BN were chemically surface treated with sodium hydroxide (NaOH) prior to the fabrication of composites without voids	Thermal conductivity	Experimental studies reveal that, the BN composites with a weight fraction of 70:30 exhibits superior magnitudes of thermal conductivity and this could be attributed to the effects of maximum formation of conductive networks coupled minimized heat resistance over the flow path.
Yong Hu[166]	Al_2O_3 composites	Epoxy resin	Packaging materials in electronics industries	Al_2O_3 composites were developed by a new processing technique which comprises gel casting, sintering and vacuum infiltration methods	Thermal conductivity and flexural strength	Experimental investigations conclude that, for Al_2O_3 loading up to 70% volume the higher values of thermal conductivity and flexural strength were observed and it is found to be 13.46 W/m K and 305 MPa. This novel processing technique employed in this research

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
						work proved to be highly effective for electronics industries.
Christian Brecher[167]	Carbon fiber reinforced polymers (CFRP)	Synthetic resin	Machine tool column	Novel mechatronic system comprising Integral deformation sensors (IDS) were employed for the measurement of thermally induced deformations	Thermal deformations and thermal expansion coefficient (TEC)	From the experimental results the IDS enhance the positioning accuracy under thermal loading up to 89% with minimum thermal deformations. The accuracy of such IDS is higher by 46% and the thermal loading is applied only on the linear axes of the machine.
Jung Do Suh[168]	Hybrid composites reinforced with steel and glass/ carbon fiber	Epoxy resin	CNC milling machine	The machine tool structures were welded by steel structures and its thermal characteristics were investigated by experimental and numerical techniques	Thermal deformation	Thermal properties determined from experiments and further validated numerically convey that the thermal deformation of X-slide occurs mainly in the vertical column, with higher values up to 0.2 mm with a deformed shape at its center.
Geon-Woong Lee,[169,170]	Aluminum nitride (AlN), silicon carbide (SiC), whisker, boron nitride (BN) and wollastonite filler materials reinforced with polymer matrix	High density polyethylene	Packaging materials in electronics industries	Surface modification of filler materials by titanate coupling agent at 80°C for 2 h was employed to achieve enhanced interfacial adhesion among filler material and polymer matrix	Thermal conductivity	Hybrid fillers proved to be effective with an increased thermal conductivity and this could be due to the improved connectivity offered by the filler material with a higher aspect ratio. Surface treatment of such filler material displays a reduction in coefficient of thermal expansion. Optimal composition of

(Continues)

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
						hybrid fillers is determined by packaging principle with a maximum packing fraction based on material simulation and analysis.
Wenlong Feng,[170,171]	Conventional metal structures	No synthetic resin is employed	Commercial vertical machining center 850E	Thermally induced errors were controlled by a novel compensation approach where thermal expansion of screw shaft due to friction heat is analyzed theoretically and mathematically with regard to time and further validated by experiments	Thermal deformation	Research studies reveal that, the screw shaft is divided into several evenly distributed heat zones and a model is established and fit for each region. Further, a synthetic model is formulated by superposition of all models in the heat zones. Experimental validations were performed by machining six different test specimens and it can be concluded that the synthetic model of the complete screw shaft is highly effective in terms of accuracy of machine tools.
Yuan-Xiang Fu[171]	Eight different fillers- natural graphite, copper, aluminum, zinc oxide, boron nitride, aluminum oxide, diamond and silver powders with various sizes were filled as reinforcements	Epoxy resin	Electronic devices	Filler materials with better dispersion were facilitated by surface treatment with ethanol solution and deionized water	Thermal conductivity	Among the eight different fillers, natural graphite-epoxy adhesives prove to be an ideal choice with a highest thermal conductivity of 1.68 W/m K for a weight of 44.3% graphite. Among different sizes of filler material, layer shaped fillers is preferable and efficient than ball shaped filler material.

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
Kuo Liu[172]	Conventional metal structures	No synthetic resin is employed	Vertical machining center	Radial thermal drift error (RTDE) along X and Y directions were tested under different rotating speeds and further modeled based on compensation strategy	Thermal deformation and temperature	Results reveal that the predicted accuracy and robustness of the proposed model based on compensation strategy was found to be good. Compensation models proposed for this machine tool application is effective and controls the RTDE of spindles.
Ikuo Tanabe[173]	Portland cement concrete	Epoxy resin	Precision internal grinding machine bed	Thermal behavior of portland cements reinforced concrete beds are analyzed under fluctuating ambient temperature conditions by FEM and further compared with cast iron bed	Thermal deformation	Concrete beds when subjected to the fluctuating ambient temperature conditions displays a thermal deformation, which is much smaller in magnitude in relation with cast iron beds. The thermal conductivity of concrete bed is very smaller than in comparison with cast iron bed.
ChengXin Zhang[174]	Conventional metal structures	No synthetic resin is employed	Machine tool structures	Thermal error transfer function models were employed in thermal error modeling	Thermal deformation	The thermal error transfer function of the entire machine is formulated with regard to the structural characteristics of machine tool structures. Thermal error transfer function parameters are identified by environmental temperature measurement and thermal error data and finally analyzes the thermal characteristics and

(Continues)

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
						implements the desired thermal error model.
V Prabhu Raja[175]	Conventional metal structures	No synthetic resin is employed	Spindle system of CNC lathe	Employed transient thermal analysis by finite element model for the resulting thermal deformation and temperature distribution	Thermal deformation	Numerical investigations reveal that, spindle displacement is highly influenced by the deformation of bed due to heat flow from head stock assembly. Spindle displacement along X-axis, directly influences the geometrical accuracy of machined component and is found to be 13 microns, which is lesser in relation with Y and Z-axes of displacement.
Chao Jin[176]	Conventional metal structures	No synthetic resin is employed	High speed CNC feed system	Development of comprehensive model/ generic method for determination of thermal characteristics in a ball screw CNC feed for varying operating conditions	Temperature	Results convey that, pre load of ball screw is a critical factor which affects the rise in temperature of bearings; simultaneously the rise in temperature of ball screw nut is highly influenced by speed, feed rate and cutting forces. WNN-NARMAL2 model developed predicts the temperature rise of heat source under varying operating conditions while machining and this model is highly effective in control of thermal positioning errors.
Zeji Ge[29]	Carbon fiber reinforced plastics (CFRP)	Epoxy resin		Thermal error control system (TECS) is developed with	Thermal deformation	Numerical analysis and experimental results reveal

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
			High speed motorized spindle of machine tool structures	regard to minimization of thermal deformation of high-speed motorized spindle system		that, based on thermal deformation balance principle the developed TECS achieves close to zero thermal error of motorized spindle, which thereby indicates the efficiency of the developed structure. TECS principle developed is highly effective in control of thermal errors.
Ryo Kondo[177]	Carbon fiber reinforced plastics (CFRP)	Epoxy resin	Machine tool spindle shafts	CFRP spindle shafts were developed by filament winding method and a relative comparison is performed with regard to the thermal characteristics of steel spindle for the same geometry	Axial thermal displacement and dynamic stiffness	Numerical results validated with experimental tests conclude that, the CFRP spindle shafts are thermally stable than its steel counterparts and thermal deformation is found to be only one-third of steel spindles. Compliance of CFRP spindles were smaller than steel spindles by 80%.
Daisuke Kono[178]	Hybrid structure – CFRP reinforced with steel	Epoxy resin	Machine tool spindle shafts	Hybrid structure of steel and CFRP is proposed to achieve minimum thermal expansion without any trade-off among static stiffness	Thermal expansion	Research study reveal that the proposed hybrid structure exhibits a minimal value of thermal expansion without any trade-off among static stiffness in comparison with steel spindles. With regard to the proposed hybrid design, the thermal expansion was reduced by 39% whereas the bending and torsional stiffness

(Continues)

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
						were found to be 80% of the steel spindles. For an optimum design of the hybrid structure, the volume fraction of steel in the front and taper bearing were in the ratio of 40% and 10%.
A Selvakumar[179]	Granite aggregates	Epoxy resin	Machine tool structures	Investigations were performed based on Transient plane source (TPS) method for eight samples with epoxy resin content varying from 10-24%	Thermal conductivity	Results reveal that, thermal conductivity decreases with increase in epoxy resin content in the composites and this is due to the interfacial resistance of the epoxy matrix. The effective thermal conductivity values are found to be 2-3 W/m K and such values are obtained for an epoxy resin content ranging from 12%–14%. TPS method proves to be a reliable method in measurement of thermal conductivity of composite materials.
Sun-Kyu Lee,[180,181]	Conventional metal structures	No synthetic resin is employed	Slide guides for precision motion applications	Linear motion of slide guide with respect to thermal deformation and external load were investigated numerical by and experimental techniques	Thermal deformation	Numerical investigations reveal that the thermal deformation of the slide guide induces linear change of motion followed with pitching and yawing motion changes. Experimental validations conclude that there is a 30% reduction in friction force due to non-uniform

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
						contact between table and guide surface.
J F Zhang[181]	Conventional metal structures	No synthetic resin is employed	Machine tool headstock	Employed numerical techniques and structural design optimization of headstock with regard to thermal performance	Thermal deformation	Numerical studies reveal that based on the multiple simulation runs with regard to the response factors such as headstock structure and cooling trough layout, the machine tool structure has witnessed a significant rise in thermal performance with limited thermal deformation. Thermal structural optimization of headstock structures proves to be highly efficient and displays an enhanced machining accuracy with controlled temperature.
Xian sheng Gao[182]	Carbon fiber reinforced plastics (CFRP)	Epoxy resin	Ball screws	Novel adaptive method was proposed to reduce thermal deformation and further analyzed by numerical methods and compared with experimental validations	Thermal deformation	Adaptive method of design proposed is highly effective which exhibits a reduction in thermal deformation by up to 70.1% and a limited temperature of the ball screw is observed. Experimental validations carried out reveal that the thermal deformation is determined as 198 microns, which is higher than adaptive method (161 microns). Temperature rise observed in adaptive method is significantly lesser than

(Continues)

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
						experimental tests and lies in the range of 7.52–9.25°C.
Zhang Dexian[183]	Conventional metal structures	No synthetic resin is employed	Machine tool structures	Employed thermal excitation method for measurement of temperature points with regard to minimize of thermal error	Thermal deformation	Results conclude that, thermal error compensation was achieved based on the position identification of thermal susceptible points and neural network model. Among 40 different points of thermal sources, points such as 2, 5, 9, 17, 18, 20, 31 and 32 are determined as the thermal sources which exhibits minimized thermal error.
Yu-Chi Liu[184]	Conventional metal structures	No synthetic resin is employed	Machine tool structures	Combined methodology comprising key temperature point selection algorithm and Long short-term memory (LSTM) modeling method was employed in prediction of spindle thermal displacement	Thermal error	Results conclude that the proposed combined methodology is experimentally validated for spindle speeds of 3000, 6000 and 9000 rpm and spindle thermal displacement measured lies within the range of 0.6 microns. The largest root mean square errors (RMSE) of the proposed methodology agree well with the experimental results and this hybrid methodology proves to be highly efficient in prediction of spindle thermal displacement.

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
Jong-Jin Kim[20]	Conventional metal structures	No synthetic resin is employed	Linear motors of machine tool	Numerical analysis is employed in determination of temperature and its variation, heat sources and thermal deformation	Thermal deformation	Numerical results reveal that, the thermal error induced in the machine tool structures are significantly influenced by heat loss in linear motor, frictional heat in the LM block and ambient temperature. Thermal deformation is induced in the linear motor and this could be attributed to the conduction source of heat generated in the machine tool structure without any cooling system.
Moritz Wiessner[185]	Conventional metal structures	No synthetic resin is employed	5 axis machine tools	Thermal test piece after machining is employed in evaluation of thermal errors of machine tools	Thermal error	Results reveal that thermal errors induced in a thermal test piece is compared with CMM measurements and R-test measurements. The results agree well with CMM measurements and proves to be an efficient method in an industrial application. Thermal behavior of machine tool structures is predicted based on thermal test piece and such test pieces proves to be an efficient option in an industrial application.
Yi Zhang[186]	Conventional metal structures	No synthetic resin is employed	Machine tool structures	Employed a novel methodology termed gray neural network (GNN)	Thermal error	Results of this study convey such as the SGNN and PGNN prediction models

(Continues)

TABLE 4 (Continued)

Author(s)	Work material	Binding agent/resin	Industrial application	Methodology employed for enhanced thermal characteristics	Thermal properties determined	Inferences
				model for determination of thermal error		are highly effective in terms of accuracy and robustness with limited learning samples. Experimental validations performed over a five axis-machining center reveal that, hybrid prediction models perform relatively efficient than traditional gray and ANN models and it is most suited in prediction and evaluation of thermal errors.
Zhao Haitao[98]	Conventional metal structures	No synthetic resin is employed	CNC machine tool spindle	Numerical analysis was performed in evaluation of convection heat transfer and a robust error model is formulated for prediction of thermal error	Thermal error	Numerical investigations were performed with regard to thermal deformation and further the results are compared with experimental validations. It can be concluded that, simulation results are highly accurate than the experimental tests and has a greater significance in reduction of design costs without any trade-off in terms of efficiency.

secondary air flow thereby resulting in improved cooling performance. The thermal stability and cooling performance achieved in machine tool structures is quite effective by Coanda-effect and it is almost equivalent to that of forced convection by air fans. The flexible silicon cooling tubes involves ease in installation in wide areas of hard-to-reach zones near the heat sources and it is much more cost effective than the forced convective heat transfer. Additionally, for the similar levels of thermal stability achieved, the Coanda effect requires a power of about 0.6 kW power whereas in forced convective heat transfer with the aid of high velocity air flow the machine incurs a power consumption of up to 40 kW.[35] The Coanda effect with silicon tubing proves to be cost effective, requires lesser energy consumption to achieve the desired thermal stability and proves to be an ideal strategy or technique in embedment of cooling system in machine tool structures.

6.4 | Embedment of mechatronic devices in machine tool structures

Thermally induced angular displacements and thermal errors is compensated by embedment of advanced materials like CFRP in the main spindle housings. Thermal displacements in the spindle of machine tool housings are compensated by negative linear thermal expansion coefficient of CFRP bandages and structures in the mechatronic system.[150–152] The mechatronics system is designed and embedded within the machine tool structures and it essentially aids in temperature control through actuators and limits the thermal error. The mechatronics system essentially comprises the temperature sensors and other form of displacement and proximity sensors, controllers and CFRP actuators which thereby heats the filaments and other peltier elements for uniform temperatures in the laminate. Figure 11 presents an intelligent machine tool structure embedded with the mechatronic system comprising deformation sensors and other thermal sensors and actuators for thermal displacement compensation and thermal error reduction.[163]

7 | THERMAL ANALYSIS OF MACHINE TOOL STRUCTURES

Thermal analysis of machine tool structures is performed in order to provide an in-depth knowledge of these structures with regard to temperature, thermal displacement and some form of thermal errors. Several different machine tool structures are identified and its performance is studied based on the material and the binding element chosen, design methodology employed, properties determined and its most suitable industrial application. This section discusses the research investigation on thermal analysis of different machine tool structures and it is presented in Table 4.[20,29,98,164–186]

8 | CONCLUSIONS

This review paper presents itself as a summary of the research investigations performed since the inception of this century and explores the different aspects and challenges in the development of machine tool structures by polymer concrete reinforced composites and other hybrid composites and advanced materials. The performance of a machine tool structure with regard to static, dynamic and thermal characteristics for a wide range of materials and further employed in a specific industrial application have been analyzed and henceforth this review work provides an in-depth knowledge for several researchers and scientists in development of machine tool structures using Epoxy granite polymer composites (EGPCs). Research investigations pertaining to the machine tool structures such as lathe bed, column and other forms of micro lathe bed developed and produced by EGPCs are only in its incipient stages and have focused on the performance and the functionality of such structures mainly on static and dynamic characteristics namely strength, stiffness and rigidity and the range of natural frequencies. Numerical results combined with experimental validations discussed in sections 2 and 3 convey that the EGPCs reinforced with steel as a filler material in the optimum range of proportion exhibits an equivalent stiffness and strength to that of cast iron with a superior magnitude of damping ratio. Additionally, it can be concluded that the machine tools manufactured by hybrid materials and other advanced materials displays a superior performance than compared with the conventional metallic structures. However, 70% of the error in machining any product is influenced by thermal errors and displacements and therefore reduction in thermal displacements and thermal error control strategies needs to be adopted. Henceforth, sections 4 and 5 discuss in detail the different thermal error modeling and measurement techniques. However, studies on thermal characteristics and other form of thermal error modeling and compensation strategies for EGPCs have not been attempted earlier and this review work provides scope for researchers to explore the thermal performance and characteristics of EGPCs. The key note papers published in the years in 1995, 2000 and 2012 provides the reliable information of the machine tool structures with regard to its development and performance only based on thermal performance and thermal error reduction techniques. This review paper provides a detailed information and knowledge in the machine tool domain and serves as a guideway toward the research and development of machine tool structures with respect to static, dynamic and thermal characteristics and further provides an overview of existing challenges in machine tool industries and elaborates in detail the techniques or strategies employed in resolving such challenges.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

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CONSENT TO PARTICIPATE

All authors have been personally and actively involved in substantial work leading to the paper, and will take public interest for its content.

CONSENT FOR PUBLICATION

The author(s) and co-authors agreed for publication.

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