Chapter 50
Enhancement of Static and Dynamic Characteristics on Micro-lathe Bed by the Use of Alternate Form Design and Composite Materials

N. Mahendrakumar, P. R. Thyla, P. V. Mohanram, M. Ramu, V. Prabhu Raja, C. Raja Kumaran, K. N. Manojkumar and A. Siddarth

Abstract Machine tools are operated at higher speeds vibrations are generated between workpiece and tool, results dimensional variation and poor surface finish on machined components. Hence, machine tools are developed with high dynamic stiffness by using high stiffness and damping composite material to reduce such effects and to achieve better dimensional accuracy with good surface finish on machined components. The machine tool structure considered in this study is a cast iron (CI) micro-lathe bed. The numerical model of the reference cast iron micro-lathe bed taken up for study was developed and experimental validation of the same was done. Static finite element analysis of the validated numerical model with worst-case cutting forces and moments was carried out for three different materials, namely gray cast iron, epoxy granite, and nettle polyester, and the results were compared, and the need for form design was justified. Static characteristics are improved through the use of cross sections and rib configurations with higher bending and torsional stiffness. Dynamic characteristics are improved through the use of stone- and fiber-based composite materials with higher specific stiffness and damping properties. The improvements in static and dynamic characteristics of the newly developed structures are investigated.

Keywords Composite · Form design · Micro-lathe bed · Finite element analysis

---

N. Mahendrakumar (✉) · P. R. Thyla · V. Prabhu Raja · C. Raja Kumaran · K. N. Manojkumar · A. Siddarth
Department of Mechanical Engineering, PSG College of Technology, Coimbatore 641004, India
e-mail: nmahendranet@gmail.com

P. V. Mohanram
Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore 641062, India

M. Ramu
Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham University, Coimbatore 641112, India

M. S. Shunmugam and M. Kanthababu (eds.), *Advances in Simulation, Product Design and Development*, Lecture Notes on Multidisciplinary Industrial Engineering,
https://doi.org/10.1007/978-981-32-9487-5_50

50.1 Introduction

High structural stiffness and damping are desired properties in machine tool applications, as they lead to higher cutting speeds which improve productivity (by reducing the cycle time). The high operating speed generates more vibration at the joints and interfaces of the machine tool elements [1]. It affects dimensional accuracy and shows poor surface finish on machined parts. It is desirable that the challenges due to vibration in machine tools are brought to a minimum level. In general, cutting machine tool industries develop machines using cast iron and steel as materials to build structures for material removal process through cutting action. Further, traditional machine tool materials exhibit either static stiffness or damping and vice versa [2]. To improve the static and dynamic performance of machine tools, alternate materials and new design concepts with enhanced stiffness and better damping properties are needed. Composite materials show promise as alternate materials for machine tools. Composite materials consist of two materials—one material, responsible for stiffness and another responsible for damping and so the composite exhibits both improved modulus and damping properties owing to which composite materials are increasingly used in the manufacture of machine tools. Ferrocement, as the name implies, consists of steel and cement, and this material offers three to four times higher damping ratio than CI [3]. Polymer concrete materials exhibit improved dynamic stability in machine tools due to higher damping ratio (four to seven times) than that of cast iron. Mineral casting materials consisting of granite as filler, called epoxy granite, this also enhance both damping ratio four to seven times and thermal stability two times than that of CI machine tool structure [4].

The requirement of high specific stiffness combined with high damping can be satisfied by employing fiber-reinforced polymer composite materials [5]. The commonly used fiber-reinforced polymer matrix composites are carbon-epoxy, glass-epoxy, glass-polyester composites and hybrid composites (sandwich structure composed of e-glass fiber faces and CI column core, and carbon-epoxy faces joined with welded steel structures using adhesives and bolts). Sandwich structures contain steel faces, inserts, aluminum rings, and castiron columns for improvement in the structural stiffness of the composite. The realization of new fiber-reinforced composite material (CFR) structures improves static, dynamic, and thermal properties of precision machine tool that can produce precise products [6]. The mass reduction potential for sandwich structures such as CI and steel structure filled with polymer concrete, e-glass fiber faces, and CI column core, is typically about 20% including better damping, whereas CFR can reach 60% mass reduction without sacrificing on stiffness and damping of the structural components.

Mostly in current research, synthetic fibers like glass, carbon, and aramid are used in fiber-reinforced composite. However, synthetic fibers are hazardous to human health and environment. The manufacturing cost of the above fibers is also high. In order to overcome the above problems, natural fibers can be used for making the composite. Natural fibers have a greater edge over synthetic fibers in that they are readily available, environmentally friendly, and cost-effective. Plenty of research works are being carried out on natural fibers because of their inherent higher specific mechanical properties, lightweight and higher performance to weight ratio [7, 8]. Hence, they find new applications in automotive, aerospace, packaging, building, marine, electronics, and other engineering fields [9]. The principle of light weight material selection and form design can satisfy requirements of machine tool structures such as higher stiffness and damping [5].

In this study, static and dynamic characteristics of machine tool structures are enhanced by the use of alternate form designs and composite materials. Using constant area/volume approach, best cross section from a set of selected cross sections is determined. Finite element method is employed to identify the best rib configuration among the available standard rib configurations. Using constant stiffness approach, taking the cast iron bed as reference, composite lathe beds are developed for equal stiffness. Numerical model of the cast iron lathe bed was developed, and experimental validation was carried out. The cutting forces at the worst operating condition are evaluated and the same are used to perform finite element analysis on the developed numerical model for the evaluation of deformation, maximum stress, and factor of safety. Numerical models of composite lathe beds are also developed, and finite element analysis was carried out for the worst-case cutting forces. The results of cast iron and composite late beds are compared and the improvements in static and dynamic characteristics are recorded.

50.2 Development of Numerical Model of CI Lathe Bed

50.2.1 Static Analysis on CI Bed

To validate the numerical model of CI bed, experimental static deflection and modal analysis was carried out. Further, the results are compared with numerical results. Figure 50.1 shows reference CI bed, solid model, boundary condition, and deformation model.

Static performance of the reference CI micro-lathe bed was carried out using strain gauges, dial indicator, NI data acquisition (DAQ) system with LabVIEW software as shown in Fig. 50.2. Deflection and strain values are noted for incremental loads of 10–300 N.

ANSYS Workbench software was used to carry out numerical static deflection analysis on the lathe bed. Loads in the range 10–300 N were used for the analysis. Figure 50.1 shows the cast iron lathe bed model with boundary conditions and deformation results. Comparison of static test deflection and strain results obtained from experimental and FEA shows that a good correlation was observed with a maximum deviation of 10% between the experimental and numerical analysis.

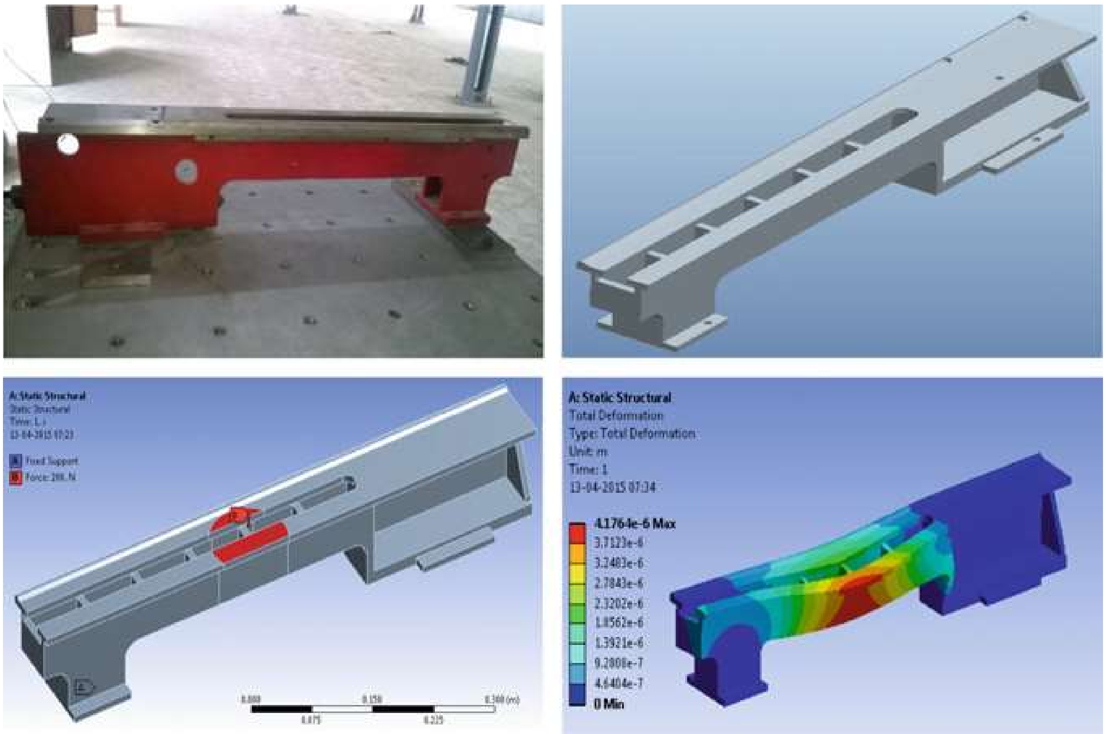


Fig. 50.1 Cast iron micro-lathe bed physical and FEA model

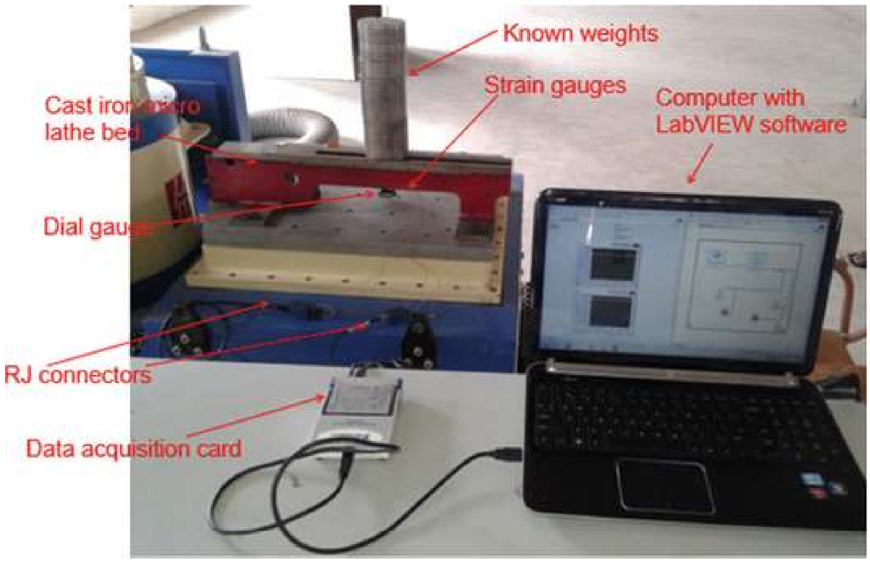


Fig. 50.2 Experimental static deflection test setup

50.2.2 Dynamic Analysis of CI Bed

Dynamic analysis of reference CI micro-lathe bed was carried out using impact hammer, accelerometer, NI DAQ with LabVIEW software. The experimental setup is shown in Fig. 50.3.

The first six natural frequencies and the corresponding mode shapes are evaluated and are shown in Fig. 50.4. The fundamental natural frequency determined by the finite element method was found to have close correlation with experimental value, with a deviation of 3.8%. Hence, the numerical model developed is deemed to be a reliable model and can be used for further analysis.

Fig. 50.3 Experimental modal analysis test setup

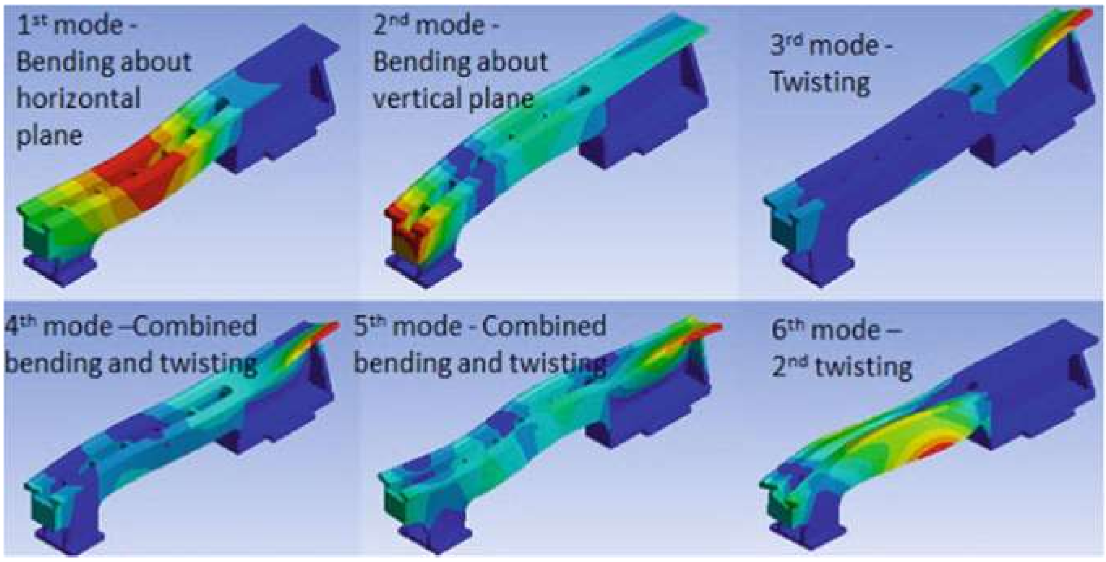


Fig. 50.4 First six mode shapes of cast iron lathe bed

Table 50.1 Properties of materials

Material	Gray cast iron	Epoxy granite (12:88) [4]	Nettle polyester (40:60) [10]
Young's modulus (GPa)	110	30	3
Poisson's ratio	0.3	0.25	0.22
Tensile strength (MPa)	130–400	20–45	20–40
Compressive strength (MPa)	500–1200	65–150	98–120
Damping ratio	0.017	0.032	0.036
Density (kg/m^3)	7200	2250	1188

50.2.3 Alternate Materials

The main aim of this work is to improve the dynamic properties (natural frequency and damping) of machine tool structures without affecting stiffness. Composite materials help to achieve improved dynamic properties in structures. In this study, two different composite materials are used, namely epoxy granite and nettle polyester. Table 50.1 shows the properties of alternate materials chosen for this study. Both epoxy granite and nettle polyester have higher damping ratio and lower density than gray cast iron material.

50.3 Design of Composite Lathe Bed

Finite element analysis (FEA) of the micro lathe bed model under the worst-case cutting forces and moments of CI bed and composite materials were also carried out as shown in Fig. 50.5 and the comparison of results are shown in Table 50.2.

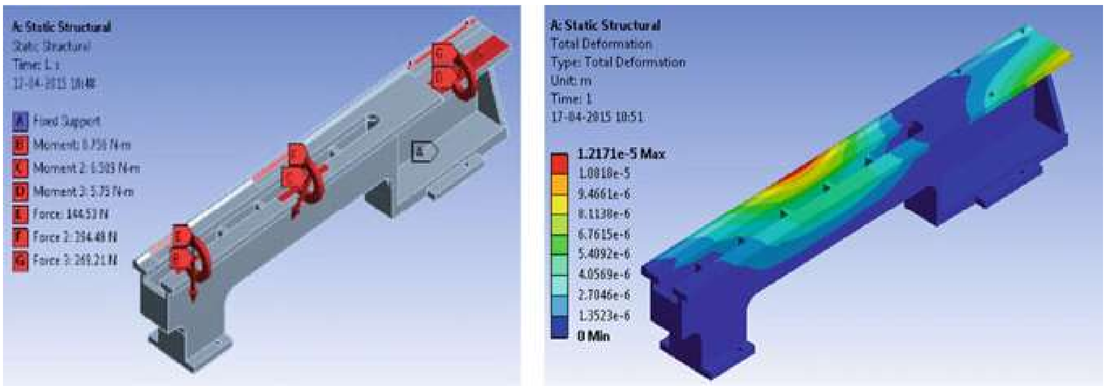


Fig. 50.5 CI micro-lathe bed FEA BCs and deformation plot

Table 50.2 Comparison of FEA results of CI, EG, and NP lathe beds for standard 'I' section

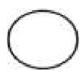
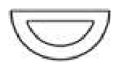
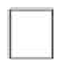
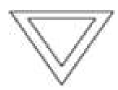
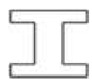
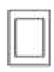
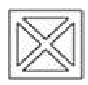
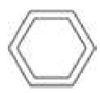
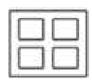
Sl. No.	Lathe bed material	Mass (kg)	Relative weight	Total deformation (μ)	Maximum principal stress (MPa)
1	Cast iron	11.39	1	12.2	3.5
2	Epoxy granite (12:88)	3.56	0.31	44.5	3.5
3	Nettle polyester (40:60)	1.88	0.17	443.1	3.4

From the table, it is evident that the maximum deflection in composite lathe beds for the same geometrical dimensions is quite high compared to cast iron micro-lathe bed. This is because of the lower value of Young's modulus of the identified composite materials and hence there is a need for form design.

50.3.1 Identification of Best Form

To improve static performance of the newly designed micro lathe bed, through form design principle "hollow hexagonal" as shown in Table 50.3, was found better torsional and bending stiffness than other forms and the same form has adopted to design lathe beds.

Table 50.3 Identification of best rib configuration

Form number	Form design	Form number	Form design
1		6	
2		7	
3		8	
4		9	
5		10	

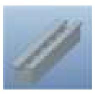
50.3.2 Identification of Best Rib Configuration

In order to study the effect of various rib configurations, the cast iron micro-lathe bed with straight transverse ribs (existing rib configuration) is considered as reference and other values are normalized based on it. Six different possible rib configurations were developed, and finite element analysis was carried out. Based on analysis, lathe bed with the combination of longitudinal and transverse stiffeners (rib configuration 3 in Table 50.4) is identified the best rib configuration with improved bending and torsional stiffness.

50.4 Design and Analysis of Lathe Bed for Constant Stiffness

The proposed CI, EG and NP lathe beds were subjected to worst case cutting forces and moments, based on FEA results the hollow hexagonal cross section with combined longitudinal and transverse vertical ribs designed composite EG and NP lathe beds provides enhanced bending and torsional stiffness. Figure 50.6a, b shows the improvements in static and dynamic characteristics were evaluated.

Table 50.4 Comparison of rib configurations

Sl. No.	Rib configuration	Form design	Relative weight	Relative bending stiffness	Relative torsional stiffness
1	Existing transverse vertical ribs		1	1	1
2	1		1.022	1.00	1.05
3	2		1.116	1.03	1.31
4	3		1.217	1.32	1.49

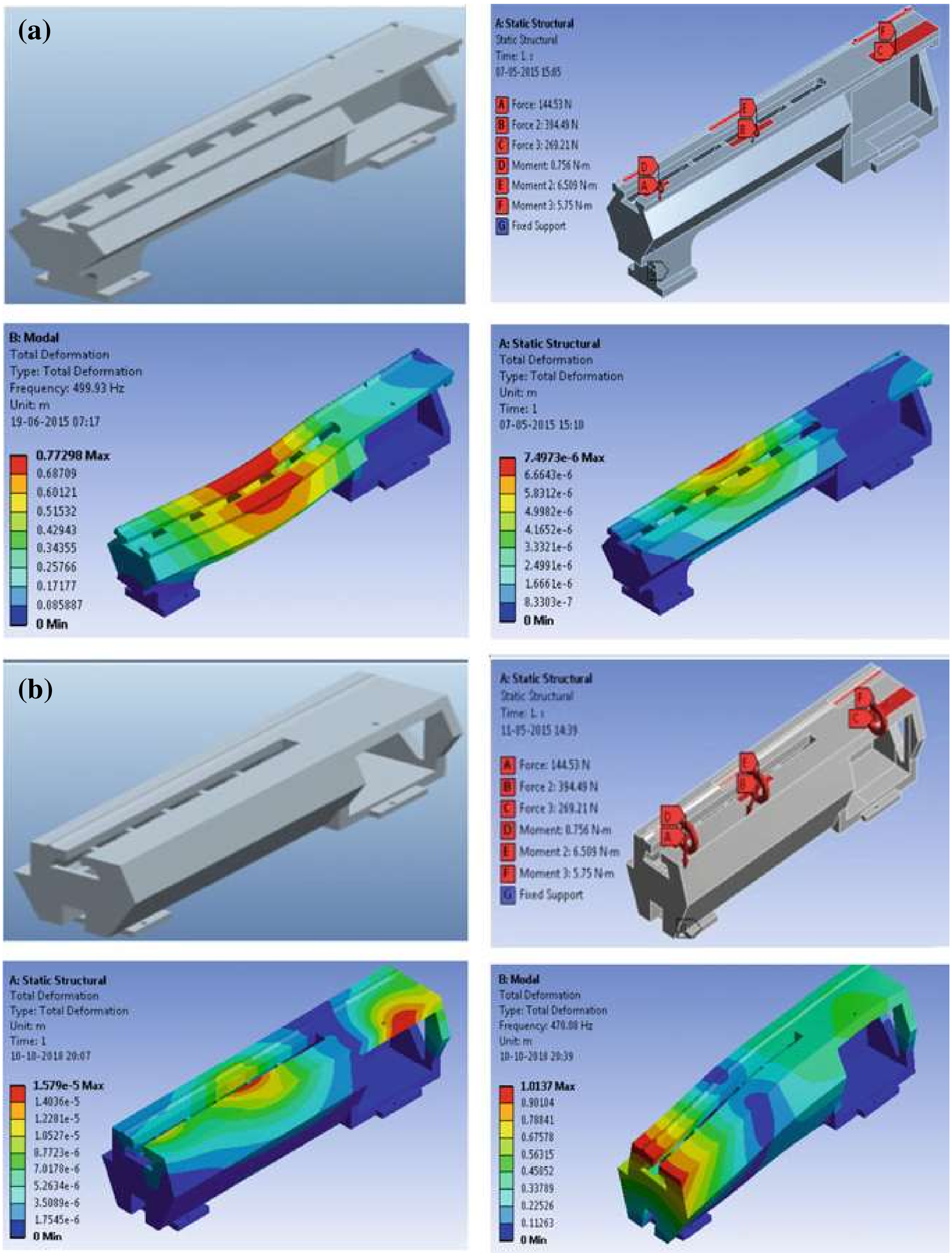


Fig. 50.6 Composite micro-lathe beds static and dynamic response FEA plots

Table 50.5 Comparison of FEA results of CI and composite lathe beds for "Hexagonal" section

Sl. No.	Lathe bed material	Relative weight	Total deformation (mm)	Maximum principal stress (MPa)
1	Cast iron	1.00	12.20	3.5
2	Epoxy granite (12:88)	0.70	7.50	1.0
3	Nettle polyester (40:60)	0.80	15.80	0.5

50.5 Results and Discussion

Table 50.5 shows the comparison of FEA results of CI, EG, and NP lathe beds. The newly designed EG and NP composite micro-lathe beds showed 33 and 6% weight reduction without affecting the stiffness of the micro-lathe bed structure by the use of form design principle. Further, the fundamental natural frequencies were found to be higher for composite lathe beds. The studies indicated that EG and NP composites could be considered as a suitable alternate to cast iron structures in machine tools.

50.6 Conclusions

In this work, epoxy granite (12:88) and nettle polyester (40:60) were identified as alternate materials owing to their high damping characteristics, low density and comparable strength to weight ratio. The static and dynamic characteristics of the micro-lathe beds are improved through the use of modified cross section and rib configuration with higher bending and torsional stiffness. Also, with the use of composite materials, weight reduction was achieved without affecting the stiffness. Hence, composite lathe beds could be used as a suitable replacement for cast iron lathe beds.

References

1. Rivin, E.I., Kang, H.: Enhancement of dynamic stability of cantilever tooling structures. Int. J. Mach. Tools Manuf. **32**(4), 539–561 (1992). https://doi.org/10.1016/0890-6955(92)90044-h
2. Rahman, M., Abdul Mansur, M., Bazlul Karim, M.: Non-conventional materials for machine tool structures. JSME Int. J. Ser. C **44**, 1–11 (2001). https://doi.org/10.1299/jsmec.44.1
3. Rahman, M., Mansur, A., Chu, K.H.: Evaluation of advanced cementitious composites for machine-tool structures. **37**(1), 373–376 (1988). https://doi.org/10.1016/s0007-8506(07)61657-6
4. Selvakumar, A., Mohanram, P.V.: Analysis of effective thermal conductivity for mineral cast material structures with varying epoxy content using TPS method. Mater. Res. **16**(2), 315–321 (2013). https://doi.org/10.1590/S1516-14392012005000184

5. Suh, J.D., Lee, D.G.: Design and manufacturing of hybrid polymer concrete bed for high-speed CNC milling machine. Int. J. Mech. Mater. Des. **4**, 113–121 (2008). https://doi.org/10.1007/s10999-007-9033-3
6. Kroll, L., Blau, P., Wabner, M., Frieß, U., Eulitz, J., Klarner, M.: Lightweight components for energy-efficient machine tools. CIRP J. Manuf. Sci. Technol. **4**, 148–160 (2011). https://doi.org/10.1016/j.cirpj.2011.04.002
7. John, M.J., Anandjiwala, R.D.: Recent developments in chemical modification and characterization of natural fiber-reinforced composites. Polym. Compos. **29**, 187–207 (2008). https://doi.org/10.1002/pc.20461
8. Bledzki, A.K., Reihmane, S., Gassan, J.: Thermoplastics reinforced with wood fillers: a literature review. Polym. Plast. Technol. Eng. **37**(4), 451–468 (1999). https://doi.org/10.1080/03602559808001373
9. Anandjiwala, D.: The role of research and development in the global competitiveness of natural fiber products. Compos. Sci. Technol. **65**, 805–881 (2006)
10. Mahendrakumar, N., Thyla, P.R., Mohanram, P.V., Sabareeswaran, A., Manas, R.B., Srivatsan, S.: Mechanical and dynamic properties of nettle-polyester composite. Mater. Expr. **5**(6), 505–517 (2015). https://doi.org/10.1166/mex.2015.1263