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A STUDY ON STRUCTURAL ANALYSIS BY FINITE ELEMENT METHOD ON POLYMER COMPOSITE LATHE BED

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Abstract

This paper presents the development of alternate design configuration and implementation perspectives in CNC lathe bed contexts. The static and dynamic behavior of existing Cast Iron (CI) bed was analyzed using finite element method, then the CI bed was replaced by epoxy granite material to improve the dynamic characteristics and to enhance the static rigidity of EG bed, it was reinforced with structural steel. The reinforcement was optimized using topology optimization. The optimized bed geometry was further redesigned considering manufacturing and assembly constraints. Five design configurations are numerically analyzed as per the same loading and boundary condition to that of CI bed. From the analysis it was found that the design configuration 5 meets the requirements and the same is proposed for further analysis fabrication. The static stiffness of the proposed bed is found to be 100 N/mm which is 50% higher than that of CI bed, also the results of modal analysis reveals that there was a significant shift in first five natural frequencies of the order of 10 to 15%. Hence the proposed bed was given better static rigidity and dynamic behavior, which could improve the performance of CNC lathe in terms of chatter free machining, improved surface finish on the components machined. Thermal analysis was performed to study the thermal behavior of the design configuration 5bed. The temperature distribution is observed and coolant pipe is modeled to reduce the temperature rise and again the analysis was carried out after modeling the coolant pipe and temperature distribution is observed to check the feasibility to replace the cast iron bed by the design configuration 5bed.

Keywords: Machine Tool, Stiffness Analysis, Optimization, Finite Element Method, Lathe.

1. Introduction

Machine tools are used to finish the components based on the dimensional and size requirements. The total time for the component to be machined must be as minimum as possible. This compels the machine tool to operate at high speeds. Traditionally CI and steel are the materials used for construction of structure of the machine tools due to better stiffness and damping properties, but they are limited by excessive vibration during high speed machining and at higher cutting loads, which necessitates the need of alternatives in terms of design of structure and materials etc., The vibration caused by the machine tool affects the quality of the components machined [2]. A better material and suitable damper reduces the vibration in the machine tools [1, 3]. New materials are found in these modern days and there are plenty of

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materials to reduce the vibration [4]. Researches show that composite and smart materials pave a novel initiative to reduce the vibration in machine tool structure [5]. Composite material provides better damping than the conventional materials. A stone based polymer composite material is suitable for the machine tool among other composite materials. Epoxy granite is a polymer based composite material with good properties of damping suitable for the machine tools [6]. Finite element analysis is a modern technique used by most of the researchers to analyze the structure with cost and time effective [7, 8]. The lathe bed can be modeled separately and forces can be transferred to bed and analyzed in single module method. The hybrid modeling method takes more time than single module method but the result is more consistent in hybrid modeling method [9]. Since the epoxy granite is not stiffer, reinforcement is made with high elastic modulus material and analyzed [10]. Optimization is process of arriving at the best structure and there are many algorithms to solve the optimization problem [11, 12 & 13]. Using the optimization module the steel is optimized and again the analysis continued. The machine tool structure must also be thermally stable so thermal analysis is carried out [14].

2. Alternate Material for Lathe Bed

Machine tool bed made of cast iron subjected to excessive vibration during high speed machining. Hence alternate material must be used to improve the damping characteristics. Cast iron is replaced with polymer based composite called epoxy granite [16]. Lathe bed with epoxy granite as material was modeled and analyzed. It was observed that the stiffness of the epoxy granite bed is relatively less compared to the cast iron lathe bed. Reinforcement made up of high elastic modulus is used to improve the stiffness characteristics. Steel reinforced epoxy granite was modeled and analysis was performed [15]. The model is stiffer than the epoxy granite lathe bed. The steel reinforcement in lathe bed is shown in Figure 1.

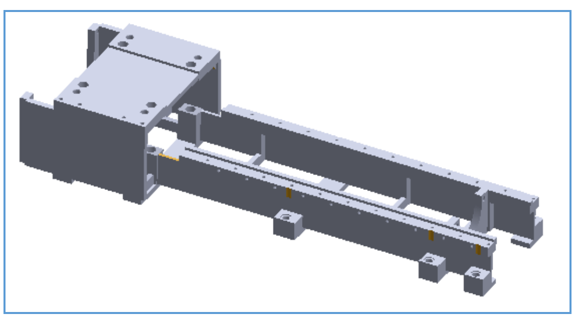

Figure1 Steel Reinforcement of the Polymer Composite Lathe Bed

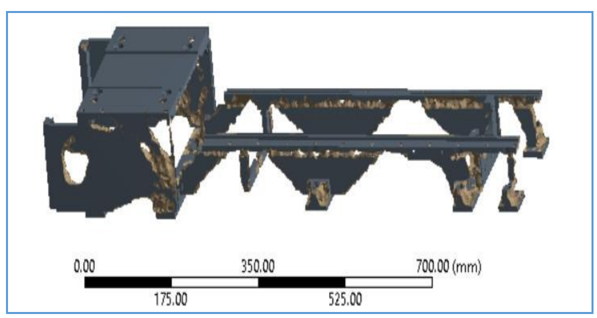

Figure 2 Optimized Structure of the Existing Steel Reinforcement

3. Topology Optimization of Steel Reinforcement

Use of steel as reinforcement in EG bed improves the static stiffness and rigidity on the other hand it reduces the dynamic characteristics because of poor material damping properties. Hence, the amount of steel reinforcement in EG composite bar to be optimized for the improved dynamic performance of SREG bed. Topology optimization paves the way to reduce the steel structure with required stiffness. Initially a static structural analysis was performed using finite

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element analysis based on worst case cutting condition. The outputs of analysis were used as input for topology optimization. Through this the zone of excess material in SREG bed was identified and the same was subtracted without affecting the structural rigidity. Figure 2 shows the optimized steel structure of the steel reinforced epoxy granite lathe bed, but it is difficult to manufacture this design without linear approximation. This structure has to be redesigned considering manufacturing aspects and structural rigidity.

4. Alternate Designs of the Reinforcement Structures

Different design configurations of steel reinforcement was proposed by approximating the optimized steel structure and all the design configurations were analyzed statically under worst case cutting condition using finite element analysis. Following the static analysis, dynamic analysis was performed to get the natural frequencies and mode shapes for all configurations.

4.1 Static analysis

All the five steel reinforced design structure were filled with EG and analyzed using finite element analysis. The structure is mounted in the whole lathe assembly. The Figure 3 shows the forces on the lathe assembly. The pad and holes are constrained to their position is given as displacement.

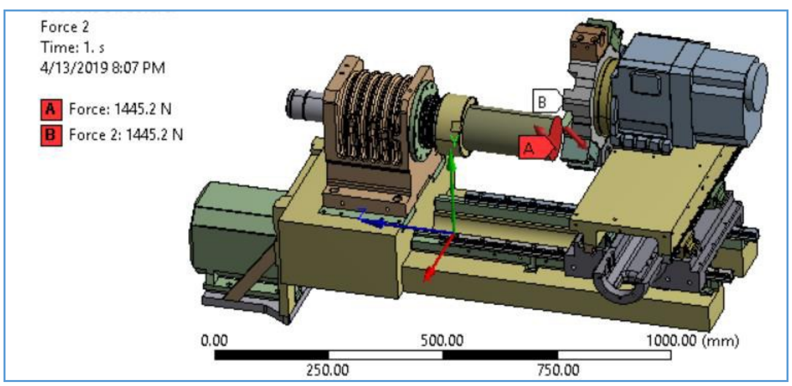

Figure 3. Forces Acting on the Lathe Assembly

The static analysis was carried on the lathe assembly under worst case cutting condition. The cutting forces acting on the work piece are 540 N, 1180 N, 540 N in X, Y and Z direction respectively and its reaction force is given on the tool tip. Design 1: From the optimized structure it is observed that the percentage of steel is more in the places of the subassemblies. Initially in this design, the steels are just placed in the places of external mountings. The deformation of this configuration is 1.36 microns, it is better than SREG lathe bed, but the connectivity between the elements has to be enhanced. The design has to be changed as the structural rigidity of the bed is affected. This steel reinforcement is shown in Figure 4.

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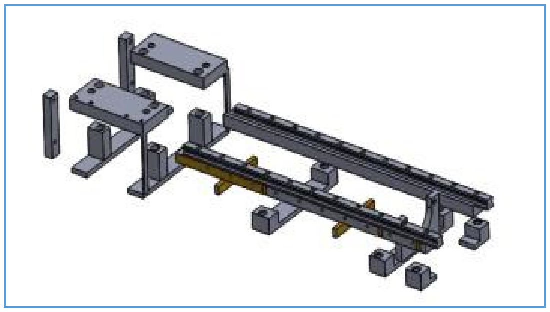

Figure 4. Design 1 Steel Configuration

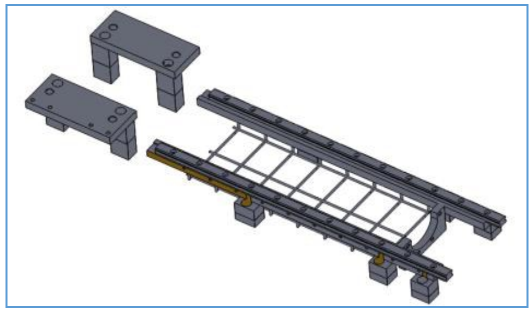

Figure 5. Design 2 Steel Configuration

Design 2: This design configuration is achieved with changes in the design 1 configuration. Here in design-2 connectivity's are made between the elements. In the headstock side the mounting pads are supported with the help of rectangular blocks. The bed rails are connected with the help of the ribs. The steel reinforcement with all the above changes is shown in Figure 5. The deformation of this configuration is 1.33 microns, similar to the previous design configuration. This design has slightly increased weight compared to design 1 and also the rib structure has to be changed.

Design 3: This design configuration is purely based on the design 2. The new design of steel reinforcement is shown in Figure 6. The deformation of this configuration is 1.16 microns. The bed rail is connected with the help of ribs but these ribs do not take torsional load and tensile load. The rib structure is changed to take these two loads. The mass of steel has been increased in above designs.

Figure 6. Design-3 Steel Configuration

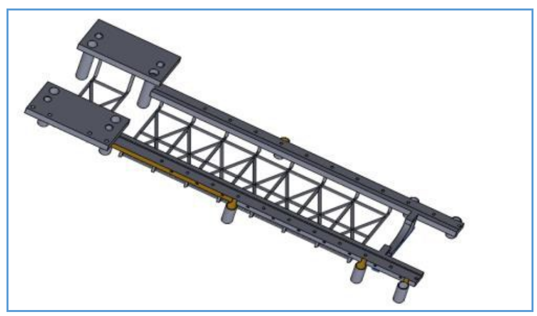

Figure 7. Design-4 Steel Configuration

Design 4: In order to reduce the mass of steel reinforcement, the rectangular blocks are changed to cylindrical blocks and the rib structure is also changed. The design 4 configuration is shown in Figure 6. The deformation of this configuration is 1.08 microns. This configuration is better theoretically but in the view of manufacturing it is difficult to connect the parts.

Design 5: Based on the manufacturing aspects and also considering the requirement like structural rigidity, the design 5 is proposed. The cylindrical blocks are again converted into rectangular blocks but this time with optimized size and placement. The design 5 configuration is shown in Figure 8. The deformation is 0.96 microns which is better than other design configurations.

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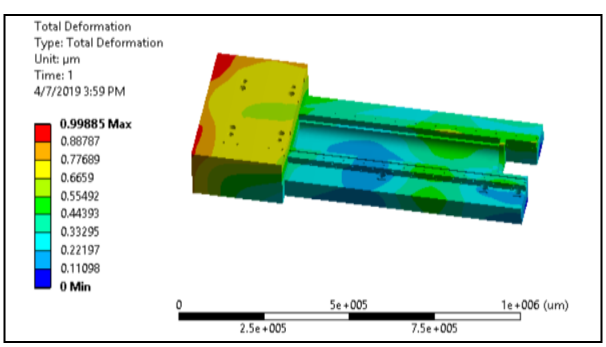
Figure 8. Design-5 Steel Configuration

The deformation plot and maximum principal stress plot was arrived for all five design configuration. The values are summarized in the Table.1. Comparatively the deformation is higher in design 1 and 2. This is due to the connectivity and load transferring issues. In all aspects such as structural rigidity and manufacturing, design 5 emerges a better design configuration.

Table 1. Static Analysis Results for Worst Case Cutting Condition

Design configurations	Total Deformation (micron)	Max. Principal Stress (MPa)
SREG	1.52	1.6
Design1	1.36	1.28
Design2	1.33	3.29
Design3	1.16	4.46
Design4	1.08	1.83
Design 5	0.96	1.58

The total deformation and maximum principal stress of design 5 are shown in Figure 9 and Figure 10 respectively. It is observed that the maximum deformation and stress occurs in the headstock side of the lathe bed. This is due to mass of headstock assembly and also the forces are transferred much in this side.



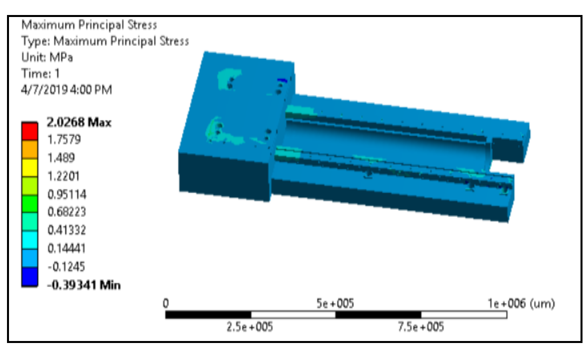


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Figure 9. Total Deformation Plot of the Proposed Design 5 Configuration

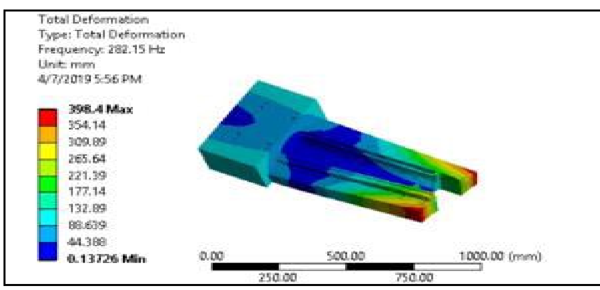
Figure 10. Maximum Principal Stress Plot of the Proposed Design 5 Configuration

4.2 Dynamic analysis

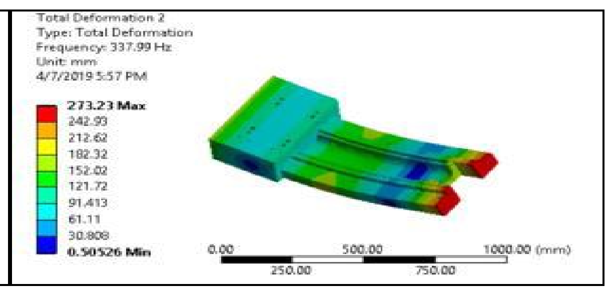
It is necessary to perform modal analysis to characterize the dynamic behaviour of the design configuration. Modal analysis was performed in the entire five design configuration under free-free boundary condition. First five natural frequencies along with their mode shapes of the given range were found for all design configurations. The natural frequencies were compared. The design 5 has higher natural frequencies; this is because the structure is stiffer with less mass. The mode shapes of the design 5 configuration are shown in Figure 11. The dynamic analysis results are summarized in the Table.2. From the above analysis it is found that the design 5 configuration is having lesser deformation and higher natural frequencies. There is a shift of order 10 to 15% increase in natural frequencies in design 5 configuration than cast iron bed. Thus design 5 is found as a better design among all other design configurations.

Table 2. Dynamic Analysis Results of Lathe Beds

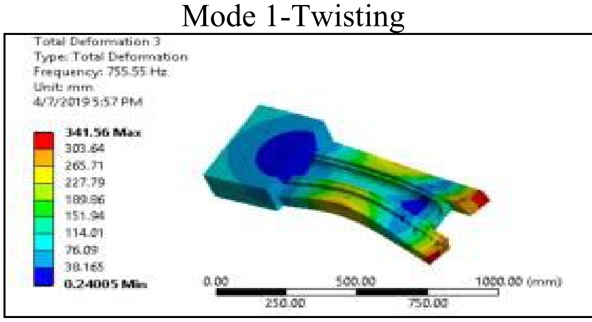
Mode No	Natural frequency (Hz)		
	CI lathe bed	SREG lathe bed	Design 5 configuration
1	262	252	283
2	302	299	340
3	643	673	757
4	699	726	774
5	761	769	867



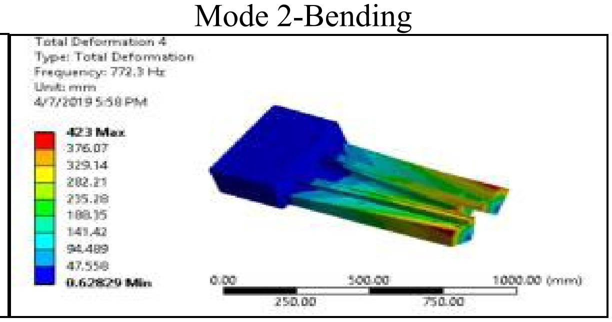
Mode 1-Twisting



Mode 2-Bending



Mode 3-Bending



Mode 4-Twisting

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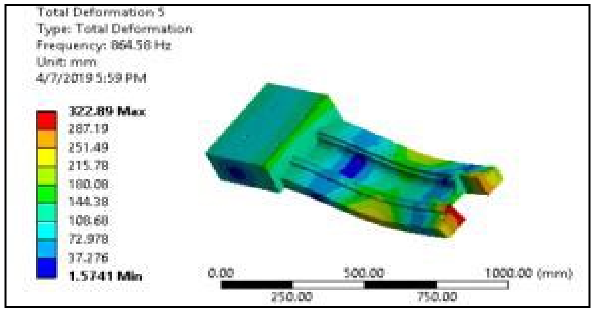

Mode 5-Bending

Figure.11 Mode Shapes For Proposed Design-5 Configuration

5. Directional Stiffness Of Proposed Design

Design 5 being better in static and dynamic analysis, it is essential to observe the deformation in all direction. The lathe bed was assembled in the whole lathe assembly and a static force of 1000N is applied on the work piece.

Table 3 Comparison of Directional Deformation of the Proposed Design and Cast Iron

Force	Direction of deformation	Cast Iron(microns)	Proposed design (microns)
X	Total	1.3	0.9
	x	1.1	0.4
	y	0.2	0.5
	z	0.7	0.5
Y	Total	0.9	0.8
	x	0.04	0.05
	Y	0.09	0.007
	z	0.6	0.5
Z	Total	1.4	1.1
	x	0.1	0.08
	y	0.09	0.08
	z	1.1	0.8

The respective directional deformation on these three axis are calculated. The directional stiffness is the ratio of force of 1000N to its respective directional deformation. The directional deformation of the design 5 is summarized in the Table.3. The directional deformation in the design 5 is less comparative to the cast iron. It emerges a better design to replace the cast iron bed.

6. Bending and Torsion Rigidity of Proposed Design

Design 5 has to undergo bending and torsional rigidity test to compare the bending and torsional stiffness with CI lathe bed. Numerical model was developed to simulate the bending and torsional rigidity test. From this analysis, bending and torsional stiffness of the lathe bed can be found.

Bending stiffness: A separate fixture was designed for the bending test. The force was applied at the centre axis of the bed so that the lathe bed undergoes pure bending. The force varies from 150N to 1500N .The deformations are taken at two places A and B at the bottom of the lathe

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bed. The deformations are taken in the direction of load. The bending stiffness was calculated by plotting the force vs. deformation graph. The slope of the graph gives the bending stiffness of the lathe bed at that point. The place where the force applied, boundary condition and the deformation measuring places are shown in Figure 12.

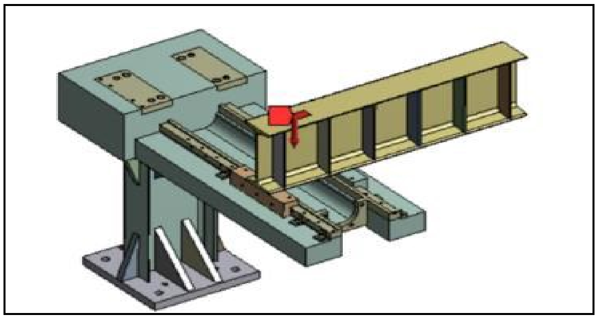

Figure 12. Numerical Model for the Test of Bending Stiffness

From the graph the bending stiffness of the proposed design lathe bed is found and it is compared with the existing cast iron lathe bed. The bending stiffness of CI lathe bed is 0.7 kg/μm and 0.4 kg/μm at two locations A and B. The bending stiffness of proposed design is 1.05 kg/μm and 0.7 kg/μm at A and B respectively. Here the values are plotted for all the forces. It is seen that the bending stiffness of the proposed lathe bed is 1.5 times higher than that of the existing cast iron lathe bed. The values are tabulated in Table 4. Torsional rigidity: The fixture used for bending test is used for the torsional rigidity test. The force is applied at a distance from the lathe bed in order to provide torsion. The load is not static the load varies from 50 N to 700N. The deformations were taken at three places at the bottom of the lathe bed. The deformations are taken in the direction of load. The torsional rigidity is calculated in the above Table.5. The torsional rigidity of the proposed design is 10 times higher than that of the existing cast iron lathe bed. This is due to the rib structure in the proposed design

7. Thermal Behaviour Of Proposed Design

The thermal property also affects the precision of the components machined. If the temperature rise is more, it would lead to thermal stress which in turn leads to thermal deformation. It is necessary to study the thermal behaviour of the lathe bed after changing the material. Heat is produced in the bearing due to the friction. The heat generation was calculated in the bearing and it is simulated in the numerical analysis. Thermal analysis was performed in the lathe bed and temperature distribution on the lathe bed was studied using finite element analysis. The heat generation was given in the front and rear bearings of the headstock. Natural convection takes place in the outer surface of the assembly. Forced convection takes place in the rotating parts. These conditions were simulated in the numerical model as shown in Figure 13. The temperature is high in the headstock mounting place and it is due to the bearing. This analysis was also performed in the epoxy granite material. Since the thermal conductivity of the epoxy granite is less the temperature rise is high in this lathe bed.

Table 5 Torsional Rigidity of Proposed Bed

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Load (N) Torque (Nm)	100 265	200 530	300 795	400 1060
Angle of deflection (arcsecs)	3.1	6.1	9.3	12.3
Torsion rigidity (Nm/ arcsecs)	85.7	85.7	85.1	85.7

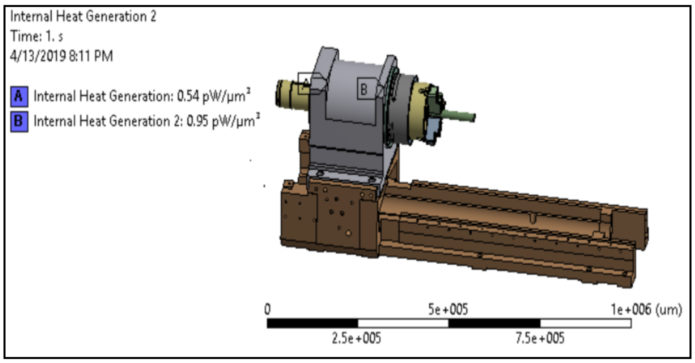

Fig.13 Numerical Model for Thermal Behaviour in Lathe Bed

Then the thermal analysis was carried out in the design 5 configuration and the temperature distribution was arrived to check its thermal behaviour. The temperature distribution is shown in Figure 14. The temperature is high in headstock side as expected. The analysis was performed and the values are summarized in the Table.6

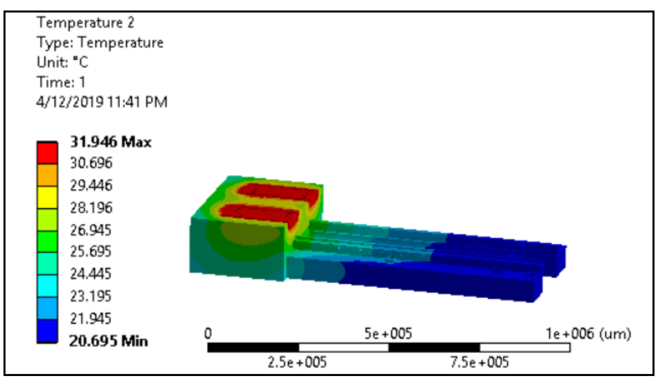

Fig.14 Temperature Distribution in Proposed Design Lathe Bed

Table 6 Comparison of Temperature Distribution in Lathe Beds

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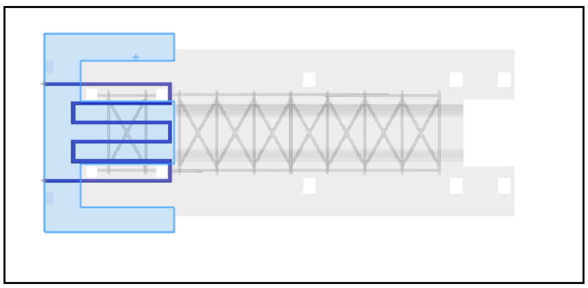
Ambient Temperature(°C)	Maximum Temperature in lathe bed(°C)		
	Castiron lathe bed	Epoxy Granite lathe bed	Proposed design lathe bed
20	29	34	32
40	48	53	51

Since the temperature is more in the design 5 than the cast iron, coolant is passed inside the headstock side of the bed. The heat is carried away by the coolant and the temperature can be reduced preventing rise in thermal stress. The coolant pipe in the lathe bed is shown in Figure 15.



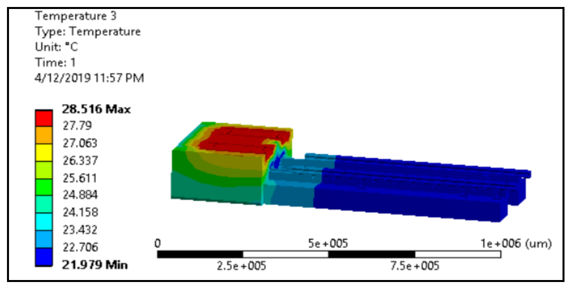


Fig.15 Coolant Pipe Design in Design Proposed Lathe Bed **Fig.16 Temperature Distribution in Proposed Lathe Bed after Coolant Passage**

Then the coolant pipe was modeled and thermal analysis was carried out and it was observed that there was drop in the temperature in the lathe bed which in turn reduces the thermal stress. The temperature distribution after the coolant design is shown in Figure 16. It is observed that after the coolant was passed due to temperature difference heat is transferred to coolant and the temperature is reduced in the headstock mounting pads. Thus the temperature rise is controlled using coolant pipe.

8. Conclusion

In this work the CI bed was analyzed statically and dynamically. The lathe bed was redesigned with different composite material named epoxy granite. Static behavior of the bed is increased by reinforcing steel in the lathe bed. The steel content was reduced without reducing its stiffness to improve damping characteristics. Hence, further it was redesigned by topology optimization. Based on manufacturing constrains, the optimized bed was approximated to linear dimensions without affecting the functional constrains. Five different reinforcement configurations in the approximated model has been designed and analyzed as per the same loading and boundary condition applied to the CI bed. It was found from the finite element analysis that the design 5 configurations are meeting the requirements from both static and dynamic perspective hence, it was proposed for further analysis and fabrication. The bending and torsion test was performed using finite element analysis and it is found that the bending and torsion is 1.5 and 10 times the

CI bed respectively. Following the structural analysis thermal analysis was performed to meet the thermal requirement. The temperature distribution is studied in both CI and design 5 and it was found that the temperature is more in design 5 due to the poor conductivity of epoxy granite. Coolant is designed and implemented and the temperature rise is reduced thus, making the lathe bed both structurally and thermally suitable for installing in machine tool.

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