COMPARISON OF DYNAMIC STIFFNESS IN TOMBSTONE MATERIALS

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ABSTRACT

The pre-process selection of stable cutting conditions in milling requires knowledge of the structural dynamics. An important metric for describing the dynamic response of a system is the dynamic stiffness, or product of modal stiffness and damping ratio for each vibration mode, for both the cutting tool (as reflected at the tool point) and workholding setup. A common workholding method in horizontal machining centers is a tombstone. Traditionally, these tombstones are cast iron or steel weldments; however, there are potential dynamic stiffness and cost benefits to the use of different materials. In this work, impact testing was used to measure the frequency response functions for cast iron, aluminum, steel, epoxy-mineral, and concrete tombstones. Improved dynamic characteristics were observed in the epoxy-mineral and concrete tombstones when compared to traditional cast iron.

Keywords: Dynamic stiffness, damping, workholding

INTRODUCTION

Tombstones are fixturing blocks that generally have between two and eight surfaces used for mounting parts to be machined on a horizontal milling machine. Often, they are used in production environments to fixture and machine many parts on each surface. They enable shops to increase their capacity and implement automation. The stiffness and damping characteristics of the tombstone directly impact the quality of components that can be manufactured and the productivity of the machine tool. Traditionally, tombstones are either cast iron or a steel weldment and can be solid or hollow, where steel tombstones offered higher stiffness with low damping and cast iron provides slightly more damping and less stiffness. A useful way capture both the stiffness and damping characteristics is dynamic stiffness, or the product of the stiffness and damping. Maximizing the dynamic stiffness in a tombstone increases the maximum metal removal rate and productivity of the setup [1].

A material with the potential to provide greatly increased damping is concrete. Concrete has been used by machine tool manufacturers as a damping material or as the primary base material for decades. For example, Studer began using a polymer concrete as the base for their grinding machines as early as 1971 [2]. Hardinge Inc. has a patent for the use of polymer concrete to decrease the influence of machine tool vibration on part accuracy and increase in thermal stability of composite or cast-iron lathe bases [3]. As with the machine base, the tombstone is part of the structural loop connecting the workpiece and spindle. Increasing the damping of the tombstone should result in an improvement in material removal.

In this paper, results are presented for frequency response function measurements, and the corresponding damping ratios, of five different tombstone materials including cast iron, welded steel, aluminum, epoxy-mineral, and a contractor grade, fiber-reinforced concrete mix. Comparisons are made between the material-dependent damping values.

SETUP AND EXPERIMENTATION

To evaluate the variation in dynamic response of potential workholding materials, frequency response function measurements of commercially-available cast iron (hollow), welded steel (hollow), aluminum (hollow), and epoxy-mineral (solid) tombstones (see Fig. 1) were compared to a concrete tombstone (solid) with nominally the same dimensions (508 mm × 203 mm × 711 mm, or 20" × 8" × 28") manufactured at Oak Ridge National Laboratory. The concrete tombstone was cast in an additively manufactured polymer composite mold produced using the Big Area Additive Manufacturing (BAAM) system. A 48 MPa (7 ksi) compressive strength concrete mix with 0.0375% fiber fill by mass and a maximum aggregate size of

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19.1 mm (0.75”) was used. The pour was allowed to cure for 35 days prior to testing.

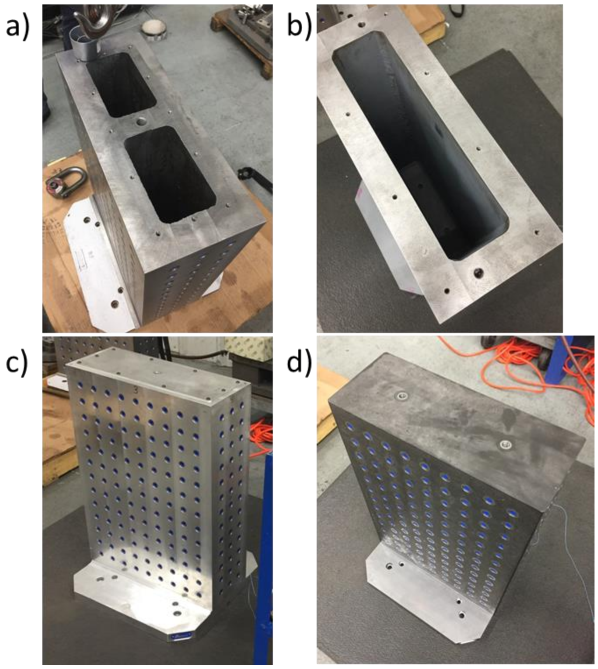

FIGURE 1. a) Hollow cast iron tombstone (no top cap)
b) Hollow steel tombstone (no top cap, no center rib)
c) Hollow aluminum tombstone (with top cap)
d) Solid epoxy-mineral tombstone.

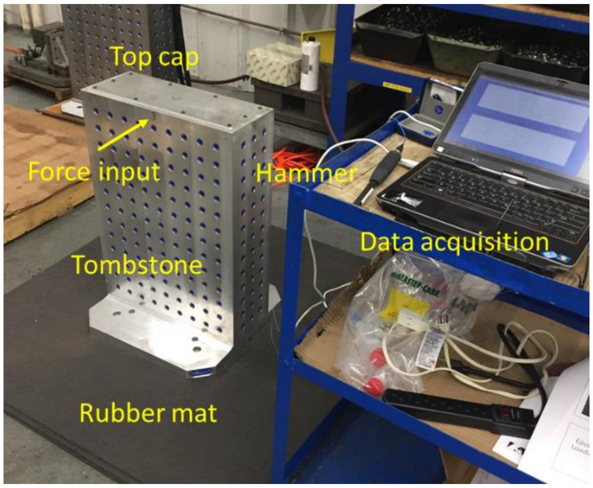

FIGURE 2. Experimental setup for frequency response function measurement.

The frequency response functions were measured by impact testing, where an instrumented modal hammer is used to excite the structure and low mass accelerometer is used to measure the vibration response. Measurements were completed on all tombstones in a free-free condition, where the boundary condition was approximated by setting the tombstones on a soft rubber mat. The direct frequency response function was measured at the top center of each tombstone; see Fig. 2. For the aluminum, steel, and cast iron tombstones, testing was completed with no top cap. For the concrete tombstone, a section of the mold was removed from the concrete on either side, as shown in Fig. 3, so that the measurement was not influenced by the interface between the cured concrete and polymer mold.

The three most flexible modes were used to evaluate the dynamic response for each tombstone. The natural frequency and damping ratio for the three modes were extracted from the frequency response function by peak picking. The results are provided in Table 1 [4].

FIGURE 3. Section of mold removed to allow for direct measurement on concrete.

RESULTS AND DISCUSSION

The measured frequency response functions for each of the five tombstones are displayed in Figs. 5-9.Only the magnitude is shown for brevity; note that the scales are identical for direct visual comparison. As seen in Fig. 1b, the welded steel tombstone did not have an internal rib. The absence of this stiffening feature accounts for the additional modes observed in Fig. 7. The large response magnitude at low frequencies observed in each figure is due to rigid body modes associated with the free-free boundary condition.

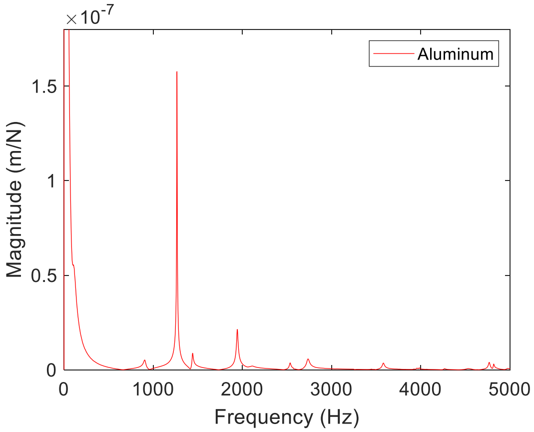

FIGURE 4. Frequency response function for aluminum tombstone with no cap in free-free condition.

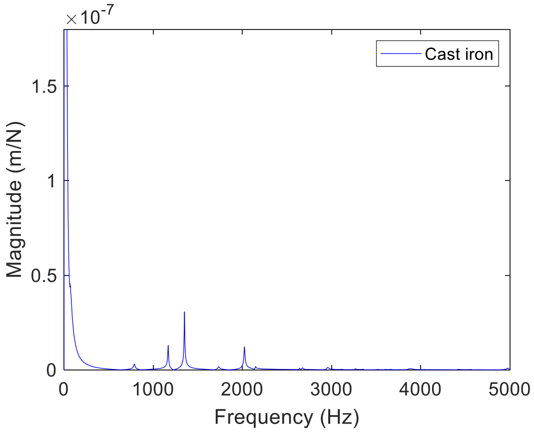

FIGURE 5. Frequency response function for cast iron tombstone with no cap in free-free condition.

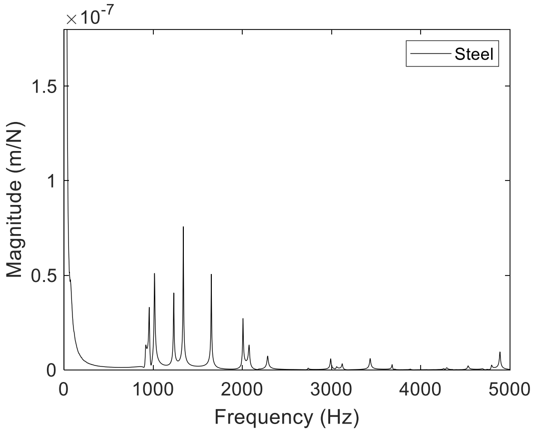

FIGURE 6. Frequency response function for welded steel tombstone with no cap in free-free condition.

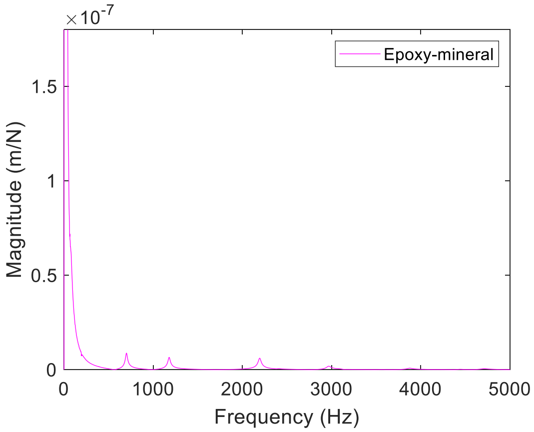

FIGURE 7. Frequency response function for epoxy-mineral tombstone in free-free condition.

Table 1: Modal parameters for three most flexible modes.

Mode	Modal parameter	Cast iron	Steel	Aluminum	Epoxy	Concrete
1	Natural frequency, Hz	1167.7	1229.9	1266.4	699.7	1477.9
	Damping ratio, %	0.33	0.26	0.19	1.48	1.30
2	Natural frequency, Hz	1350.0	1651.4	1441.8	1177.2	2541.3
	Damping ratio, %	0.23	0.16	0.40	1.06	0.59
3	Natural frequency, Hz	2022.6	2075.2	1943.8	2192.5	2918.4
	Damping ratio, %	0.25	0.3	0.41	0.73	1.04
Avg	Damping ratio, %	0.27	0.24	0.33	1.09	0.98

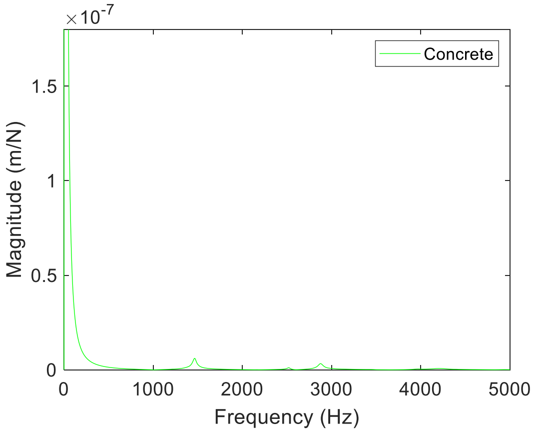

FIGURE 8. Frequency response function for concrete tombstone in free-free condition.

The frequency response function magnitude for the aluminum tombstone shown in Fig. 4 is much larger than other tested materials. this indicates a lower dynamic stiffness and decreased machining performance in comparison. The magnitudes for the concrete and epoxy-mineral tombstones are similar, as displayed in Fig. 10, indicating a similar dynamic stiffness.

The damping ratios for the three most flexible modes for each material are listed in Table 1. The average damping ratio for the epoxy-mineral tombstone is the largest, followed closely by the concrete. This suggests that a contractor grade concrete has material properties which could enable it to function as a viable and improved workholding material versus traditional cast iron. Additionally, its cost is much less than the epoxy-mineral material.

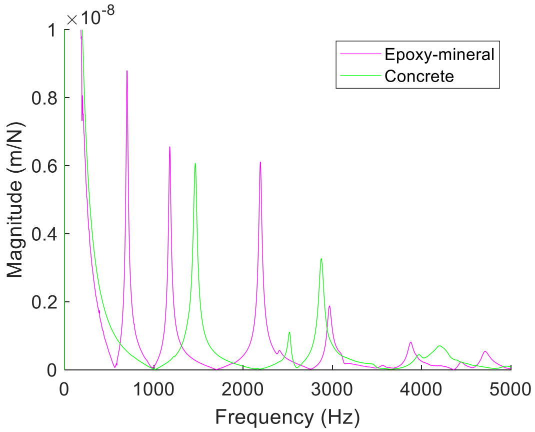

FIGURE 9. Comparison of epoxy-mineral and concrete tombstone frequency responses

It has been demonstrated that the structural properties of concrete change throughout its lifetime [5]. While this study is a relatively new effort, measurements have been taken at several stages of the cure, and dynamic changes have been observed. Further analysis and discussion will be presented in follow-on studies.

CONCLUSIONS

The optimized cutting parameters in a milling or turning application are a function of the structural dynamics of both the tool/spindle and workpiece/workholding combinations. While cast iron or steel weldments have been the traditional choices for tombstone materials, manufacturers also provide aluminum options, which offer a weight advantage and is often used as a sacrificial surface, and epoxy-mineral tombstones, which boast improved damping, but at increased cost. Both increased stiffness and damping enable higher material removal rates.

In this study, it was shown that an epoxy-mineral tombstone provided significantly higher damping than steel weldment and aluminum tombstones. However, comparable damping was measured between tombstones with a similar geometry made from epoxy-mineral and a contractor grade, fiber-reinforced concrete (48 MPa/7 ksi compressive strength). This offers the potential for a similarly high performing workholding system at a fraction of the material price. The improvement in damping also demonstrates the capability of concrete construction for use in machine tools as an alternative to castings and traditional manufacturing methods.

Future work will focus on the changing dynamic parameters of concrete as it continues to cure over time, and the implementation of low-cost concrete construction for machine tools and their components.

ACKNOWLEDGEMENTS

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