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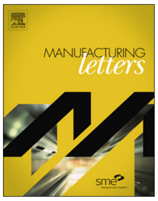

Rethinking production of machine tool bases: Polymer additive manufacturing and concrete

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ABSTRACT

Cast iron and steel weldments are the most common machine tool base elements. However, both construction methods have associated disadvantages for domestic machine tool manufacturers. This paper documents the investigation of an alternative method for machine tool base production using concrete to fill an additively manufactured polymer mold, where the motion components are attached to the concrete base after the initial concrete curing. Modal testing results for a three-axis, vertical spindle prototype indicate high damping and stiffness can be achieved using the concrete base construction. Advantages are reduced cost and lead time compared to traditional methods.

1. Introduction[1]

Machine tools are critical for the consumer and defense industrial base. They are the foundation of the supply chain for nearly all manufactured products. In 2018, the US was the 2nd largest consumer, but the 5th largest producer of machine tools [1]. Traditionally, machine tool bases are produced via casting or as weldments [2]. However, the number of US cast iron facilities declined by over 50% in the period from 1987 to 2018, resulting in a shift toward imports [3,4], primarily from China, Taiwan, and Korea [5,6].

Compared to castings, bases designed as weldments are characterized by high stiffness with low damping, high production cost, and long lead times [7,8]. Disruptions to the global supply chain, such as the COVID-19 pandemic, emphasize the importance of reliable domestic sources for machine tools that can adapt to changing needs.

This paper describes a concrete machine tool base manufactured by leveraging polymer big area additive manufacturing (BAAM) [9]. The result is a rapid and adaptable production method for machine tool bases. Additive manufacturing of base molds expands the design space to non-traditional geometries while dramatically reducing the time from design to production.

A polymer mold for a three-axis, gantry style machine base was designed, printed, and filled with high-strength, fiber-reinforced concrete. The high rail gantry configuration puts the base in compression, with loads supported by the two vertical columns. Concrete improves dynamic stiffness (the product of stiffness and damping ratio) compared to cast iron [7], and enables elements such as sensors and cooling channels to be incorporated, and is approximately 15 times less expensive per pound than cast iron. This additive-mold, concrete-casting technique was used to produce a machine tool base in less than two weeks. A metal casting of similar size would take between two months and one year depending on complexity and source; a month or more is required for shipping alone when sourced from an overseas supplier. The dramatic reduction in lead time and 15000, with increased design flexibility, provides an economical method for custom machine tool production with minimal equipment and the ability to use local resources.

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2. Material and methods

The mold was designed to maximize printability and minimize deflection due to the concrete's hydrostatic pressure during casting. It was printed on a Cincinnati BAAM system using a 20% carbon fiber ABS polymer. Polymer additively manufactured (AM) components produced using filament or pellet extrusion have highly anisotropic material properties. The tensile strength along the print direction is approximately 4.5x higher than in the perpendicular (layer boundary) direction [10].

All design calculations used the worst-case tensile strength and modulus determined through previous testing at Oak Ridge National Laboratory (ORNL) [10]. The maximum pressure at the bottom of the mold, assuming a concrete density of 2400 kg/m^3, was 37.6 kPa. The interlaminar strength of the printed material was 16.38 MPa [10]. The material has sufficient interlaminar strength for a single bead width wall to not fail from the hydrostatic pressure of the concrete, but lacks the stiffness to maintain the mold shape. To minimize the mold deflection, the nominal wall thickness of the mold was 34.5 mm (four bead widths), reinforcement ribs were added to the inside walls, and a sacrificial structural wall was added between the gantry columns as shown in Fig. 1. The mold print orientation was rotated 90° from the final machine configuration, with the front face of the machine located at the bottom of the print. This reduced the number of mold components and simplified the print and concrete pour. It took approximately 31 h and 795 kg of polymer to print the 1.6 m × 2.2 m × 1.6 m mold.

A welded #4 rebar cage was placed inside the mold after printing. Spacers printed in the bottom located and fixed the reinforcement structure. Accelerometers, temperature sensors, and coolant pipes were secured to the reinforcement cage before the pour. To protect them from the high moisture content and impact of the pour, the temperature sensors and accelerometers were mounted inside waterproof boxes and secured at five locations within the base. A single unprotected accelerometer was attached directly to the reinforcement cage near the center of the base.

Four cubic yards of commercially available, high strength (48 MPa) concrete mix with 0.04% (by mass) F-70 fiber fill and maximum aggregate size of 19 mm was used as the base material. The concrete was poured at approximately 150 mm intervals and vibrated to remove air bubbles and settle the mix. A plastic tarp was secured over the top of the mold to retain moisture during curing. Once a day for seven days the tarp was removed, and the (top) exposed surface of the concrete was sprayed with water and the tarp replaced. The base was left to cure for 20 days before being rotated 90° to the functional machine orientation.

As a final preparation step for the base, the sacrificial wall and several sections of the mold were removed to expose the concrete surfaces where machine components were mounted. Note that linear motion components were not mounted directly to the concrete surfaces.

3. Results and discussion

After the removal of the polymer mold from the printer, two cracks approximately 250 mm long and 1.5 mm wide formed between mold layers approximately halfway up the print. These cracks were attributed to long layer times resulting in localized incomplete adhesion between layers. As the mold cooled, residual stresses resulted in cracks at these weaker interfaces. Prior to the pour, the cracks were filled with epoxy and reinforced with aluminum plates. During the pour, minimal weeping occurred through these cracks, and no crack propagation was observed.

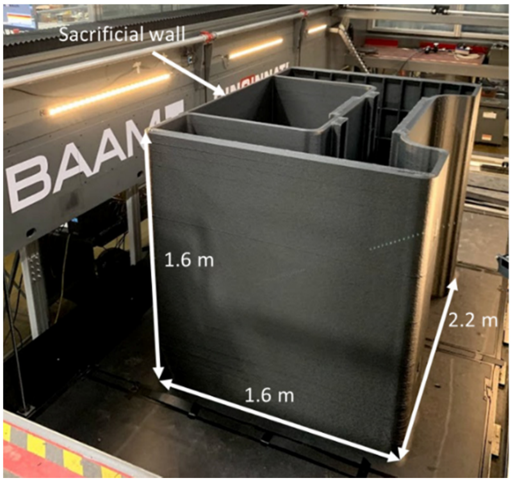

Fig. 1. Polymer mold in the print-and-pour orientation. The front face of the machine is the bottom of the mold as shown.

The temperature profile during curing was monitored by the five sensors located within the base. These results are provided in Fig. 2. The maximum internal temperature of 68.7 °C was reached 17 h after the pour start due to the exothermic chemical reaction during curing. Following this peak, temperature decreased and followed the ambient diurnal cycle with a lag. After curing, these sensors give the thermal state of the base and temperature gradients that effect the base geometry.

After curing, the dynamic response of the base was evaluated by impact testing, where an instrumented modal hammer and accelerometer are used to measure the frequency response function (FRF). Each measurement consists of between eight and ten impacts and responses. Direct FRF measurements were completed at the same location on the right and left columns of the base; see Fig. 3. The first measurements were made 15 days into the cure when the concrete reached 90% strength, with the base in the as-printed orientation shown in Fig. 1. The second measurements were made after the base was in the final upright configuration, 20 days after the pour as shown in Fig. 3.

To reduce the effect of interactions at the interface between the cured concrete structure and the polymer mold on the dynamic measurements, a small circular section of the mold was removed on either side of the column using a hole saw. A PCB 352C68 accelerometer was attached directly to the concrete on one side of the column and a PCB 086D20 short-sledge impulse hammer was used to excite the structure on the opposing side as shown in Fig. 3.

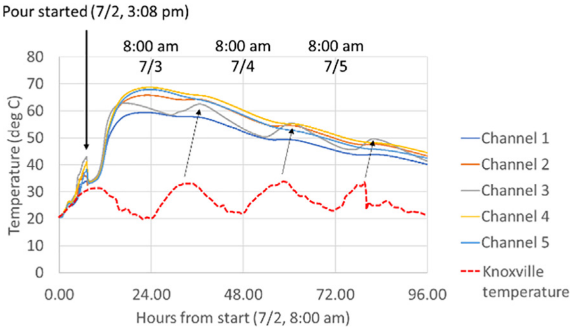

Fig. 2. Temperature data was collected at five locations within the base during the concrete pour and the first four days of curing [11].

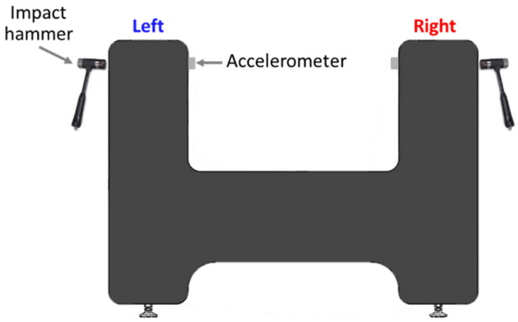

Fig. 3. Direct frequency response function measured at the same spatial location on the left and right columns of the concrete base (upright orientation).

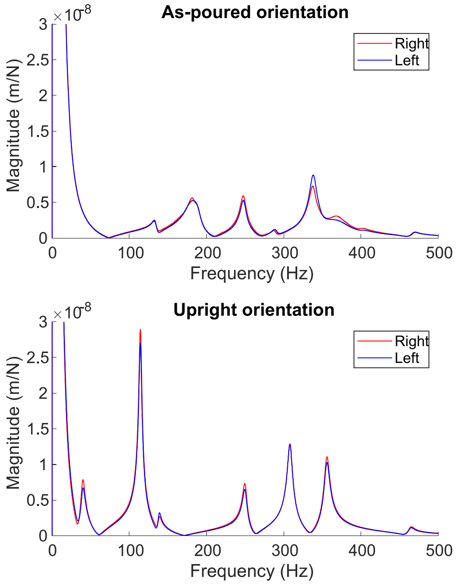

Fig. 4. FRF for the Fig. 2 locations in the as-poured and upright orientations.

The dynamic response was evaluated for the first five vibration modes. Each mode is indicated by a peak in the magnitude plots shown in Fig. 4. The natural frequency and modal damping ratio for each mode were extracted by peak picking [12]; results are listed in Table 1.

The FRF magnitudes for the left and right measurement locations on both the as-poured and upright configurations are displayed in Fig. 4. Because the left and right FRFs both before and after re-orientation of the base are similar, it was inferred that no significant cracking occurred during movement of the base from the pour to testing locations. The change in the FRFs between the two orientations is due to the change in boundary conditions. For the as-poured orientation, the column faces were in direct contact with the floor. In the upright orientation, the base is resting on four leveling feet.

Betters *et al.* found the average damping ratio of a cast iron tombstone to be approximately 0.25% [7]. Initial measurements of the concrete base indicate more than a 4x increase in damping ratio compared to a cast iron construction. These findings suggest that concrete has desirable characteristics and can be used to produce machine tool bases with similar or better dynamic performance than cast iron.

Table 1
Natural frequency, f_n, and modal damping ratio, ζ, for first five modes of the concrete base in the upright orientation.

	Right		Left	
Mode	f_n (Hz)	ζ (%)	f_n (Hz)	ζ (%)
1	39.6	6.2	39.6	6.0
2	114.3	1.7	114.3	1.7
3	138.4	1.2	138.4	1.3
4	250.0	1.2	250.1	1.2
5	308.3	1.1	308.3	1.1

4. Conclusions

A machine tool base was produced by integrating 21st century advancements in additive manufacturing with established concrete technology. Tandem use of these processes resulted in a structure with dynamic performance exceeding that of traditional cast iron structures. A proof-of-concept for the viability of an additively produced polymer mold-Portland cement concrete machine tool base was described. The ease of mold production using AM reduces the barrier for design changes; additionally, reduction of lead time using domestically available materials illustrates this construction method as an enabling technology for US machine tool production. Future work investigating the effects concrete blends on structural dynamics and long-term dimensional stability is needed for a better understanding of concrete as a machine base material.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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