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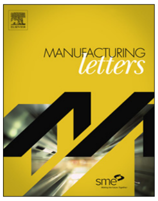

Letters

Hybrid manufactured dynamometer for cutting force measurement

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ABSTRACT

This paper describes a two-step (additive + subtractive) hybrid manufacturing approach for a laser powder bed fusion 316L stainless steel constrained-motion cutting force dynamometer (PBF CMD). The purpose of the research is to produce a near-net shape metallic dynamometer via additive manufacturing (AM) with post-processing by machining and wire-EDM to achieve the desired surface finish and performance. A cutting force comparison is presented with a commercially-available dynamometer.

1. Introduction

In manufacturing research, metal cutting mechanics have been studied for more than a century [1–3]. Due to the complexity of material removal processes, the modeling of cutting mechanics remains an area of academic and industrial interest. The cutting force signal is fundamental to the understanding, modeling, and evaluation of machining processes. The force signal can be used for process optimization, such as: 1) adaptive feed rate control to maintain the applied force at a predetermined level [1–4]; 2) chatter detection [1–2,4–10]; 3) tool wear evaluation [8–10]; and 4) detection of tool breakage in milling [8–10]. Multi-axis piezoelectric dynamometers are a popular choice for cutting force measurement. These dynamometers rely on specific piezoelectric transducer arrangements and the structural dynamics of the system, while stiff, are not rigid. Although these systems offer a large measuring range, high sensitivity, and fast response time, the systematic errors caused by their complex structural dynamics must generally be compensated using advanced post-processing techniques [11–13]. This research builds upon the concepts introduced by [14], where the dynamometer structural dynamics are a principle component in the mechanical design and are easily altered with material selection and flexure element geometry and arrangement. It was reported that the constrained-motion cutting force dynamometer (CMD) achieved a high-resolution force response within a prescribed measurement bandwidth using a structural deconvolution procedure [14,15] at a significantly lower cost than traditional piezoelectric dynamometers. The integration of the CMD on the machine table lowers the influence of transmissibility behavior which may occur if the machining point is sufficiently far away from the measuring system [5].

In this paper, the development and verification of a CMD manufactured by powder bed fusion (PBF) and machining is presented. The intent is to produce a near-net shape metallic dynamometer via PBF with post-processing by machining to achieve the desired surface finish and performance. While prior research efforts have focused on alternative dynamometer designs and cutting force signal compensation for existing piezoelectric systems, to date, the development of a cutting force dynamometer produced by a hybrid manufacturing approach has not been reported. This novel approach offers design freedom, customization, and part count reduction compared to traditional cutting force dynamometers [16,17].

2. Hybrid manufacturing process description

A monolithic PBF CMD is constructed to measure milling forces in two directions. The design includes four leaf-type flexure

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Table 1
Hybrid manufacturing detail for the PBF CMD.

Operation	Machine	Tool details	Description	Operation time
PBF (316L SS)	Farsoon FS271M	Spherical powder with 15–45 μm diameter. Laser power of 300 W with a 1000 mm/s scan velocity. Laser spot size of 133 μm with a layer thickness of 40 μm.	Generation of the near-net additive preform.	20 h
Face and peripheral milling (bottom)	Haas TM-1P vertical milling machine	5-flute solid carbide endmill (19.05 mm diameter)	Removal of the rough PBF surface on the base of the additive preform	20 min
Wire-EDM	Sodick AQ750LH wire-EDM machine	Brass wire (0.254 mm diameter)	Removal of the additive preform from build plate	4 h
Face and peripheral milling (top)	Makino A51nx horizontal milling machine	5-flute solid carbide endmill (19.05 mm diameter)	Removal of support material, rough PBF and wire-EDM surfaces	5 min
Helical milling		2-flute solid carbide endmill (4.0 mm diameter)	Removal of excess material in printed holes for thread milling	15 min
Thread milling		3-flute solid carbide single point thread mill (2.5 mm diameter)	Removal and generation of threads required for workpiece mounting	15 min

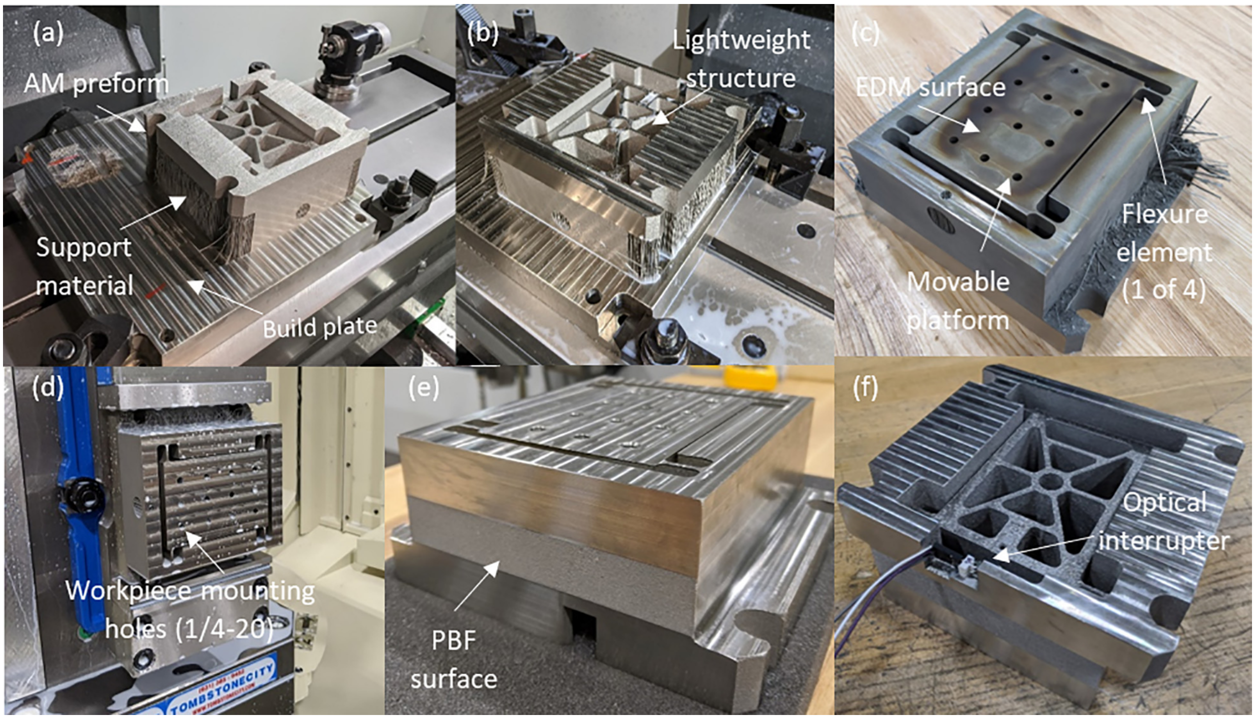

Fig. 1. PBF CMD additive preform on the build plate (a), detail of the additive preform after a reference datum was machined on the base (b), rough surface resulting from wire-EDM operation (c), setup for the generation of functional threads by a combination of helical and thread milling operations (d), hybrid manufactured PBF CMD top view (e) and bottom view (f) showing the optical interrupter placement on the base of the dynamometer.

elements in a symmetric dual four-bar linkage arrangement which guides the movable platform. The CMD design and corresponding flexure leaf geometry are analogous to the CMD presented in [14]; the purpose of this paper is to augment the design procedure, outlined previously, to add a hybrid manufacturing approach using an additively produced metallic alloy. The additive preform was produced using a Farsoon FS271M PBF printer with a Yb fiber laser (500 W). The printing details and steps required for the hybrid manufacturing process are provided in Table 1 and the additive preform is shown in Fig. 1(a–f). For force measurement, displacement is inferred from the optical interrupter, identified in Fig. 1 (f). In this approach, a knife edge is attached to the movable platform and partially blocks the optical beam during motion caused by the milling force. This low-cost sensor has the added benefit of a compact footprint and fast response time (10 μs) without the need for a supplementary amplifier.

3. Results and discussion

To complete the structural deconvolution procedure, the frequency response function (FRF) for the PBF CMD is required. Since clamping (boundary) conditions can affect the dynamic response, the PBF CMD was bolted to the machine table with the guided

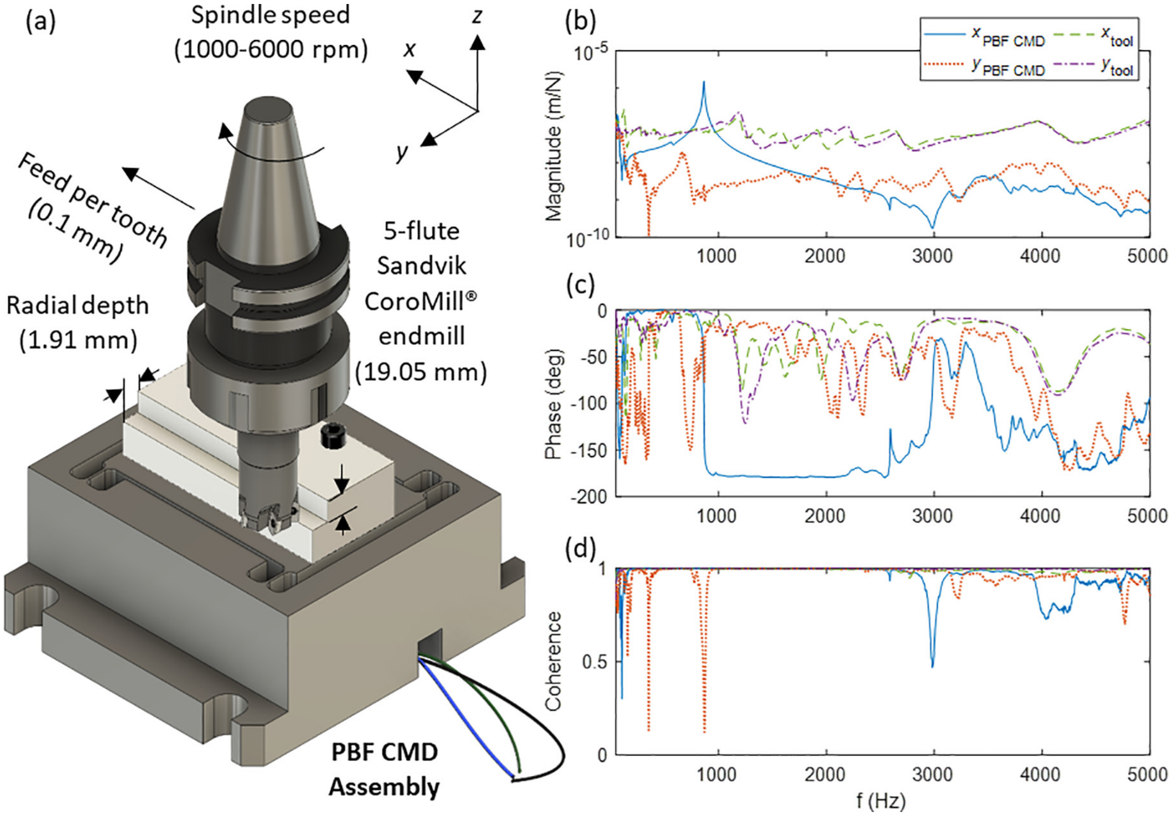

Fig. 2. Experimental setup and cutting conditions for milling force measurement (a). Direct frequency response function (FRF) measurement results for the endmill and PBF CMD under clamped (bolted) boundary conditions with a mounted workpiece; semi-logarithmic magnitude (b), phase (c), and coherence (d) are presented. The results are an average of 10 measurements.

motion occurring in the *x*-direction; see Fig. 2(a). To measure the FRFs, modal impact tests were performed on the PBF CMD in the experimental configuration; the measured FRFs are displayed in Fig. 2(b–d). The estimated static stiffness for the *x*- and *y*-directions were 6.47×10^7N/m and 2.28×10^8N/m, respectively.

To compare the PBF CMD with a piezoelectric dynamometer (Kistler 9257B), independent cutting tests were completed on a Haas TM-1P vertical milling machine. The cutting performance was evaluated using the same cutting tool inserts (Sandvik Coromant® 390R-070204E-MM) on nominally identical workpieces with identical cutting and clamping conditions. With reference to Fig. 2(a), the *x*- and *y*-direction force measurements were realized by adjusting the table feed direction to *x* and *y*, respectively. This procedure allows for the *x*- and *y*-direction force components to be measured separately without the need for an additional optical knife edge sensor.

Once the FRF is obtained, the structural deconvolution procedure proceeds by converting the time-domain displacement (scaled voltage from the optical interrupter) to the frequency domain using the discrete Fourier transform (DFT). Next, the frequency-domain displacement is converted to frequency-domain force using the inverted PBF CMD FRF; see Eq. (1) [14,15].

$$F(\omega) = \left[\frac{X}{F}(\omega)\right]^{-1} \cdot X(\omega) \tag{1}$$

A lowpass digital filter (3rd order Butterworth) is convolved with the inverted FRF to attenuate high frequency noise in the displacement signal. In this case, the filter corner frequency was set at the dynamometer's natural frequency (866 Hz from Fig. 3(b)) [14,15]. The inverse DFT is then applied to the Eq. (1) result to convert the force to the time domain.

To enable direct comparison between the PBF CMD and piezoelectric dynamometer, a compensation technique based on inverse transmissibility filtering was used to truncate the unwanted frequency content in the cutting forces measured by the piezoelectric dynamometer [18–20]; see Fig. 3(a–e). Good agreement is observed between the CMD and piezoelectric dynamometer at three different spindle speed (tooth passing frequency) values. The measured time-dependent cutting force profiles from both dynamometers is dependent on the runout in the endmill teeth as mounted in the holder and spindle. This is because spindle axis rotation errors, offsets between the holder centerline and spindle axis of rotation, and offsets between the tool centerline and holder centerline can lead to differences in chip thickness [1]. The tool-holder-spindle system runout inherently appears in the measured force record at all spindle speeds. For this study, the PBF CMD was capable of accurately measuring cutting forces within a bandwidth of approximately 2.5 kHz.

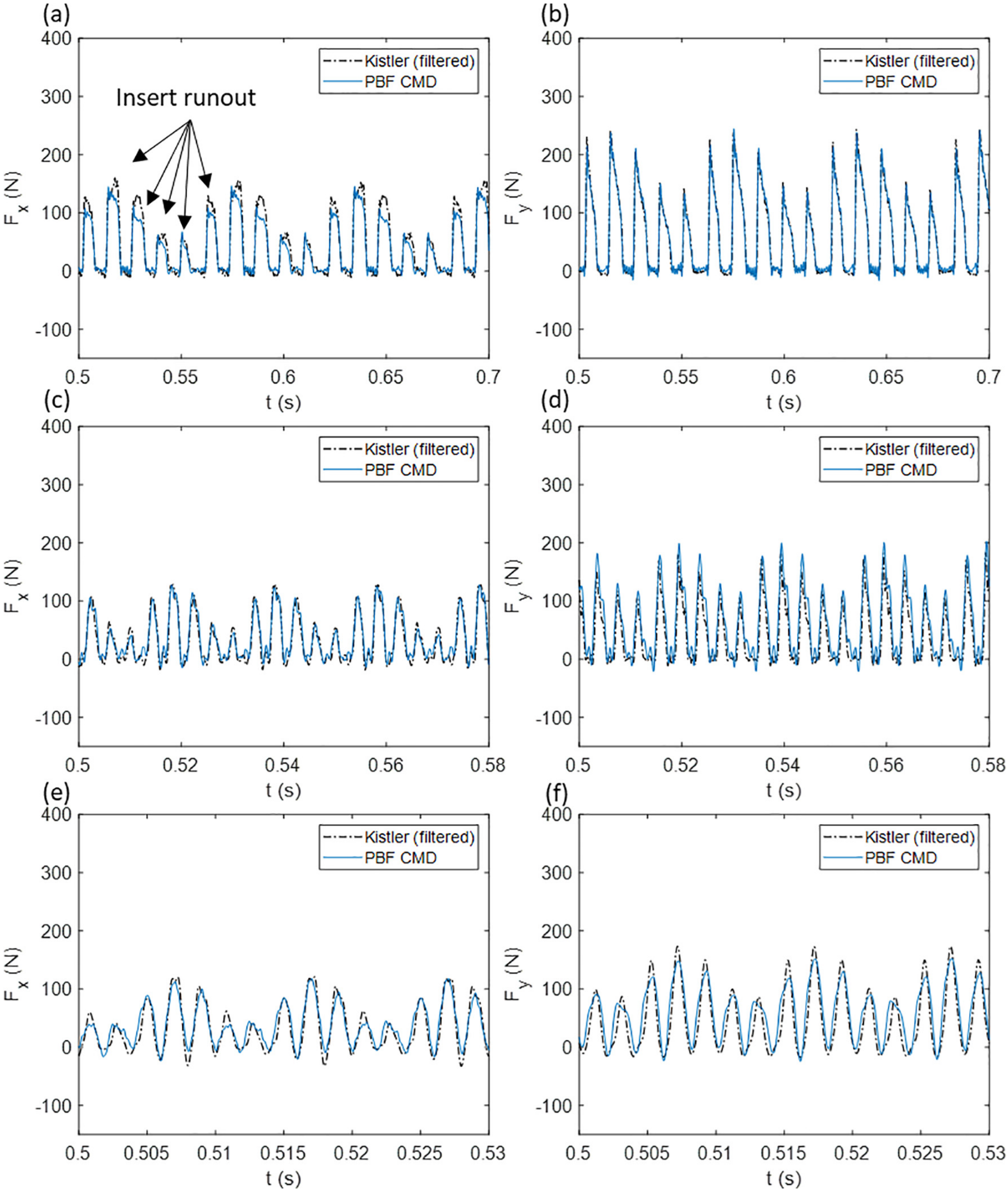

Fig. 3. Comparison of the PBF CMD (blue solid line) and filtered piezoelectric dynamometer (black dash-dot line) cutting forces for the *x*-direction (left column) and *y*-direction (right column) at 1000 rpm (a-b), 3000 rpm (c-d), and 6000 rpm (e-f). The fundamental tooth passing frequency for the presented results are 83.3 Hz, 250 Hz, and 500 Hz, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

The limited setup and machining time, coupled with monolithic design concepts, enable rapid development and iteration for a cutting force dynamometer manufactured using PBF and machining. The concepts introduced can be adopted for alternative CMDs which leverage the design freedom afforded by the hybrid manufacturing approach. Experimental results were presented which validate the PBF CMD against a piezoelectric, industry-standard dynamometer. Future efforts will be targeted at new designs and advanced filtering techniques to advance this technology.

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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