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Letters

Smart manufacturing multiplex

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A B S T R A C T

This letter introduces a concept smart manufacturing multiplex (SMM) capable of executing multiple process chains and thermodynamic pathways to control the geometric, morphological as well as microstructural integrity of custom components. A proof-of-concept based on hybrid machine tools consisting of additive and subtractive processes integrated with high resolution sensors via a novel sensor wrapper to track the spatiotemporal evolution of the process states is implemented. The value of SMM to discrete part manufacturing in realizing low-volume, high variety parts and its ability to handle multiple processing pathways in a single machine is discussed.

1. Introduction

1.1. Background and state of the art

The growing trend towards custom and personalized products is fuelling a rethink of the current manufacturing systems. While conventional manufacturing flow lines are not easily reconfigurable to meet the soaring demand for low-volume and high variety components, traditional cells and job-shops become highly inefficient to execute a variety of process plans and workflows to create one-off products with complex shapes, textures and functionalities. Additive manufacturing (AM) alleviates a few of these limitations. It has an advantage over conventional machining in its ability to create near-net shape components with complex geometry, and modify the material's composition and microstructure. However, the control of morphology and surface finish remains a bottleneck. AM products often undergo elaborate finishing operations, extending their cycle times by 20–70% before they can be deployed for use.

Recent advances in hybrid machines (HM) [1–3] offer an interesting possibility to fabricate complex, custom products to their near-net shapes via AM, and then control the final shape via subsequent subtractive manufacturing processes. Most of the efforts so far have focused on enhancing geometric precision and surface finish in freeform components based on integrating a CNC machining center with a laser head [4–6] or an wire-arc welding head [7–9]. Multiple commercial HM platforms, including INTEGRIX series from Mazak, LASERTECH from GMG, GSTM series from Reinchenbacjer, Optomec MTS 500, and Hybrid Technologies AMBIT, have been introduced in recent years incorporating these capabilities. Innovations in process plans for HM platforms to improve the finish or to carryout part repairs have also been reported [10]. Few efforts have focused on controlling the thermo-mechanics through the process chain, and the microstructure in HM platforms. For example, Daehn *et al.*'s [11] metamorphic manufacturing is one such concept which includes metal forming techniques ("robotic blacksmith") to modify the shape and grain structure in incremental steps. We conceptualize a smart manufacturing multiplex (SMM) that builds on these efforts as follows.

1.2. Overview of the SMM

The current concept of SMM is implemented on a hybrid machine tool LENS MTS 500 from Optomec. It consists of a directed energy deposition (DED) laser head for printing near-net shape components and a vertical rotating spindle to perform machining, grinding and polishing processes (see Fig. 1). This implementation allows the control of not just the geometric dimensions, but also of the morphology (via grinding and polishing), and, to a limited extent, the material composition and microstructure by adjusting the laser heat-treatment parameters, all using the same datum in a machine tool. The infusion of sensor technologies and data science/AI algorithms transforms HM into a *smart manufacturing multiplex* (SMM) which can not only execute process chains that traverse the material and process parameter space, but also enable tracking across various processes.

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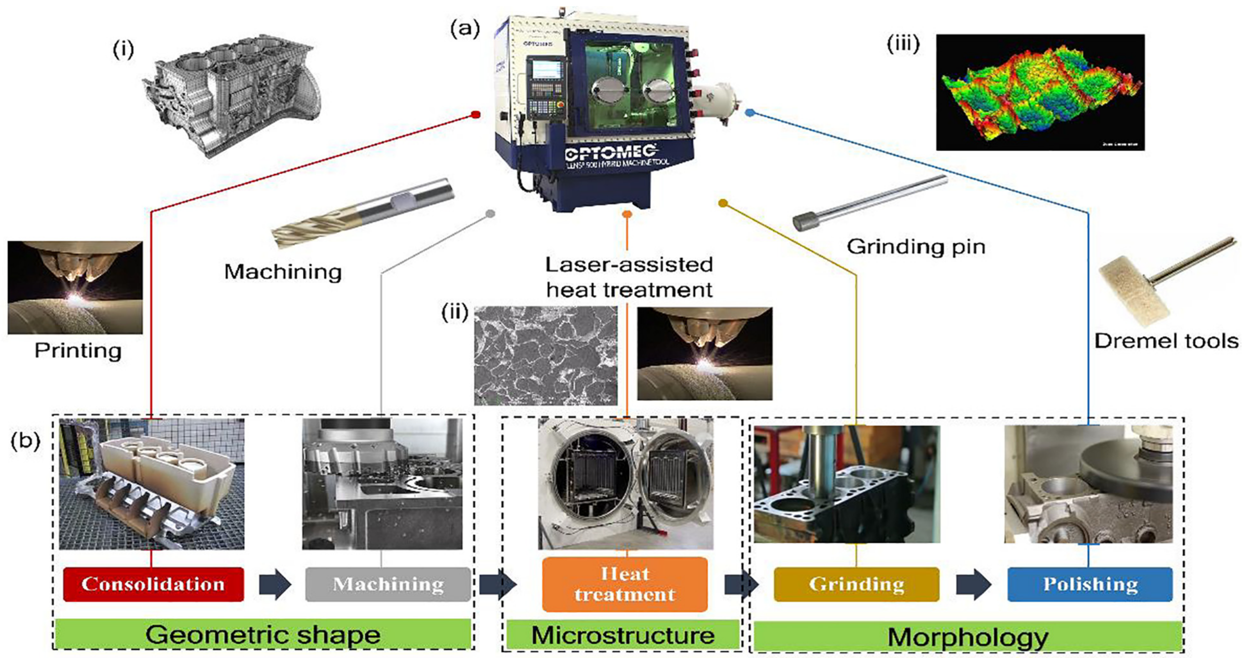

Fig. 1. Contrasting the workflows in a traditional job-shop vs. an SMM to realize a specified geometric shape, microstructure and morphology (a) Hybrid manufacturing pathway with printing and machining to create (i) net geometric shape, laser assisted heat treatment to vary (ii) microstructure and a diamond grinding pin and Dremel tools to change (iii) morphology (b) Conventional manufacturing process chain to realize the same output using five different machines/equipment like a sand cast for consolidation of material, milling machine to create a rough finish, heat treatment furnaces to vary microstructure and grinding and polishing machines to impart final mirror-like finish.

1.3. Outline of specific capabilities

The single platform execution not only allows multiple process chains (see Section 2.1) but also improves over conventional approaches in terms of enhancing forensics and traceability through the process chain, and thereby guaranteeing high levels of provenance. There is a wealth of information which a manufacturing process leaves as a complex trail in the form of the product, consumables, and various sensor signals. This data gathered across various stages of a process chain allows investigations into what happened in the process to trace back and understand the cause-effect from a process standpoint. In this context, we use a judiciously chosen set of sensors, along with sensor fusion and AI methods, collectively specified as a *sensor wrapper* [12], for quality assurance and traceability. The set of sensors provide spatial and temporal tracking across multiple process, allowing us to identify problems, suggest possible corrections, and enable manufacturing forensics, as discussed further in Section 2.2.

An SMM also opens the ability to cleverly manipulate the energy input and thereby modify the thermodynamic pathways for materials processing through a combinatorial use of multiple processes. Also, the different fabrication methods and post-process heat treatments afforded in an SMM can take the material through time-temperature cycles that can significantly alter the properties of the fabricated part, all of which can be tracked using the temperature sensor and machining forces provided by the sensor wrapper. This aspect of laser assisted heat treatment in a HM has not received much attention to date. Our preliminary investigations (see Section 2.3) have yielded encouraging results to demonstrate this capability.

2. Architecture of smart manufacturing multiplex

This section presents the architecture of an SMM and an initial demonstration of the following capabilities: (1) execution of multiple process chains to improve productivity, (2) integration of a sensor wrapper into the process workflow to track process state and enhance quality assurance, and (3) manipulation of energy input to an HM machine tool to reduce machining forces. A summary of the implementation challenges and limitations of the SMM and a note on future directions to continue the present work is discussed.

2.1. Efficient execution of multiple processes and process chains

For the current SMM implementation, Optomec MTS 500 hybrid machine tool with the capability for metal powder deposition and a machining spindle was used. Fig. 1 contrasts the manufacturing workflow of a custom part on the SMM (Fig. 1(a)) versus in a traditional job-shop (Fig. 1(b)). Traditionally, a sample or a workpiece from a near-net shaping process has to be removed from the platen on which it was fabricated and is followed by machining to meet the geometric (tolerance) specifications. The part is subsequently heat treated to impart the desired microstructure and polished to control the surface finish and morphology. Each individual step is usually executed on a separate machine tool, and it incurs significant time to setup tooling and fixtures, to determine the datum planes for measurements, as well as to transport between machines. On the contrary, the ability to use the same datum to execute various operations and process chains in a HM can simplify the work-holding and material handling needs, and dramatically reduce the setup and processing times, and costs for realizing complex custom parts.

Towards an initial demonstration this capability, a stainless steel SS316L cube with dimensions 10 mm $\times$ 10 mm $\times$ 10 mm was fabricated to a mirror finish (See Fig. 2) on an SMM from ϕ 40m metallic powders. The first stage of the process chain employed a DED process with a hatch speed of 0.12 m/min and a laser power of 450 W to fabricate the 10 mm $\times$ 10 mm $\times$ 10 mm cube. The part was built in 21 stacked layers using a cross-hatch pattern. The part was subsequently milled using a six flute carbide coated cutter of ϕ8.25 mm and at 2500 RPM spindle speed. A 30% overlap was maintained for each pass and the depth

Fig. 2. (a) Surface morphology and average surface (Sa) and profile (Ra) values for different processes in the workflow.

Table 1
Comparison of process times in a conventional job-shop and a SMM showing approximately 40% reduction in overall process cycle time.

Process	Conventional job-shop	Smart manufacturing multiplex
Fabrication/Printing	20 min	20 min
Datum setup	10 min	<1 min
Machining	5 min	5 min
Datum setup	10 min	<1 min
Grinding	10 min	10 min
Datum setup	20 min	<1 min
Polishing	20 min	20 min
Total time	95 min	60 min

of cut and feed rate were fixed at 2 mm and 0.5 mm/s, respectively. The surface was finished using a surface grinding diamond tool with a diameter of 6.35 mm with a depth of cut of 0.025 mm per pass and a total depth of 0.1 mm at the end of grinding. The other parameters of the grinding cycle were the same as that in the milling stage. Next, a Dremel wool felt pad with a polishing compound was used to polish the surface. The tool was maintained at a constant depth of 0.5 mm from the top surface for 20 min to realize a final finish Sa of 39 nm. We compared the fabrication cycle time on the SMM with that in a conventional job-shop setting, where each stage of a process chain is executed on a separate machine. Here, the processing time for each step of the process chain, namely, fabrication, machining, grinding and polishing in a conventional job-shop is taken to be the same as in the SMM workflow (see Table 1). For instance, the processing time for milling a 10 mm $\times$ 10 mm cube on a CNC machine was set to be the same as in the SMM. As summarized in Table 1, the cycle time to realize a mirror finish is approximately 40% lower on the SMM compared to in a traditional job-shop setting (see Fig. 2). The value addition with SMM was shown to result from the reduced time taken to setup and create the datum, even discounting the times to perform material handling steps in and between each stage.

2.2. Integration of sensor wrapper and demonstration of manufacturing forensics

As shown in Fig. 3, the current setup is equipped with the following sensing elements: a tri-axis dynamometer, an accelerometer and acoustic emission (AE) sensor along with National Instruments (NI) data acquisition systems with acquisition rates up to 1 MHz. The thermal sensing element used is a high speed monochrome camera from Photron (Photron Mini AX100) with a Micro-Nikkor VR lens. The camera is used to capture high-speed footage of the printing and machining process as and when desired. The camera can be used to capture the melt-pool dynamics and spatter using visible and near infra-red (VNIR) light and the light intensity readings from IR range can be calibrated to find the temperature variations of the melt-pool and capture the sputter signatures from a DED process [13].

The assortment of sensors mentioned above are specified using a sensor wrapper [12] (see Fig. 3). Essentially, a sensor wrapper includes sensor fusion methods (reported in the manufacturing literature) along with observability considerations so that the sensing needs can be systematically mapped to sensors, data acquisition and processing settings. The selected sensor signals contain complementary information to allow for reconstruction of the process state, making it easy to track the process from data obtained. The sensor wrapper implementation provides an additional framework which can gather all sources of data using a plug-and-play type of functionality using a single LabVIEW VI. The force sensor can capture minute changes in the forces during milling, grinding and polishing of the sample which can be used for obtaining bulk physical properties of the material such as toughness, hardness, Young's modulus and machinability [14]. Accelerometers complement the force sensor by capturing the dynamic interactions between the process and the machine tool. AE signatures can be used to capture variations in material microstructures and phases. A high speed camera is a staple in most AM monitoring research as capturing the melt pool dynamics sheds light on the material defects arising during the printing process and the sputter signatures are used to study the rheology of the melt-pool. Variation in heat imparted can cause non-equilibrium microstructures which change material properties significantly and hence accurate temperature sensing (with suitable spatial and time resolution) assists in tracking these changes in the material properties.

The sensor wrapper also has a major advantage when used with an SMM. Here, surface defects such as key-hole defects, balling effect and gas-induced porosity can be captured using a thermal camera. Sensors which capture machining dynamics can differentiate these defective components produced with AM. Also, the use of a single datum in an SMM allows spatio-temporal tracking of these defects based on fusing the different sources of information.

Sensor qualification study, showing the effectiveness of the sensor wrapper, along with a multi-sensor fusion model which is able to track micro-structural changes during milling experiments has been demonstrated elsewhere [15]. Efforts are underway to extend

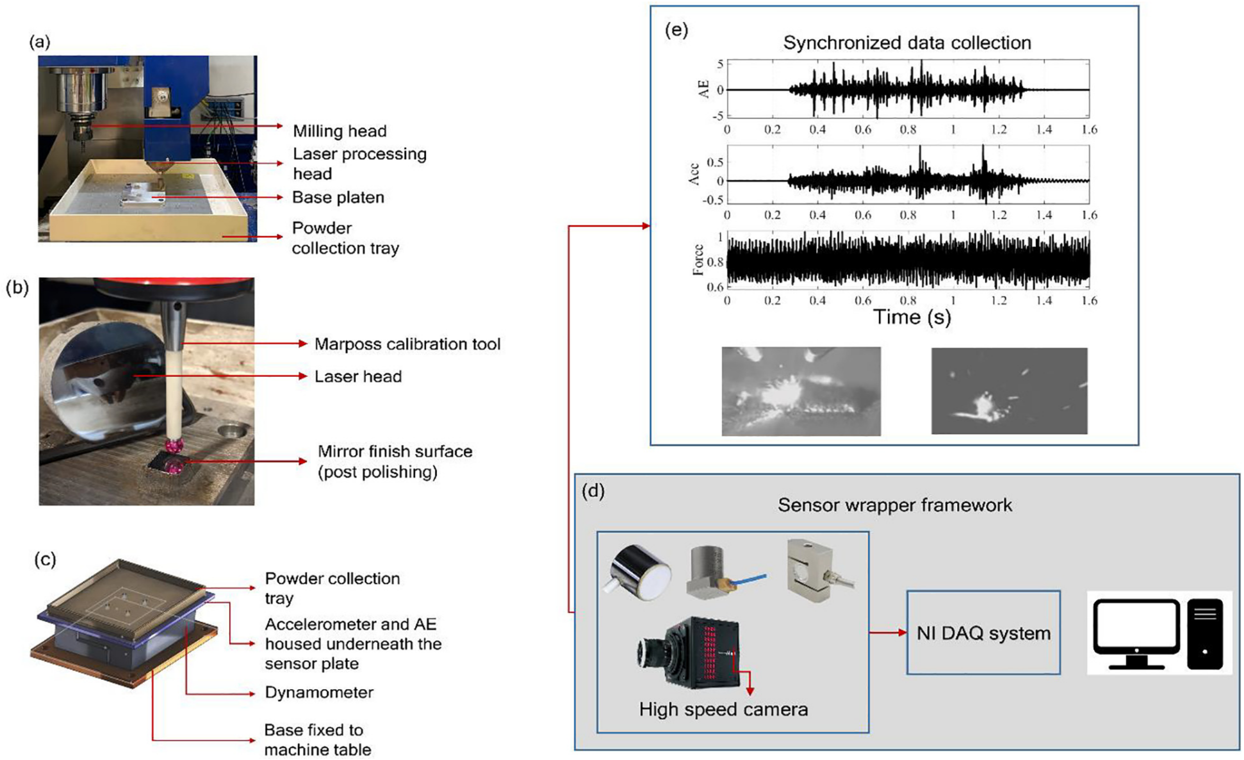

Fig. 3. (a) A snapshot of the SMM with additive and subtractive head, (b) Snapshot of the mirror polished surface in the SMM, (c) 3D model showing the placement of sensors under a plate to shield them from the stray, unused powders in the chamber heat due to laser deposition as well as to provide mechanical coupling to reduce transmission of vibrations and AE from the base plate during additive and subtractive processes, respectively, (d) Sensor wrapper implementation showing the sensors and DAQ systems, (e) Synchronized data collection from all sensors.

this work to allow for faster *in situ* characterization and discovery of materials using SMM.

2.3. Demonstration of improved machinability in an SMM

The SMM architecture, including the relative positions of the laser head and the machining spindle, as well as the use of a single datum and a sensor-wrapper enables the harnessing the residual energy of the laser heat input during the DED process as well as subsequent heat treatment to improve machinability of a custom manufactured part. The features extracted from accelerometer signals gathered during a machining process can be used to adjust the machine parameters, specifically the laser power and the table speed in the SMM, to assess the machinability of the printed 316L component. The improved machinability in this higher temperature machining regime is summarized in Fig. 4. Here, Milling cycle 1 was conducted on the as-printed component with a laser power of 450 W. The part was milled using a six flute carbide coated milling tool of 8.25 mm diameter and with a spindle speed kept constant at 2500 rpm. A 30% overlap was maintained for each pass (11 passes in total) and the depth of cut and in-feed rate were fixed at 2 mm and 0.5 mm/s, respectively. Milling cycle 2 was conducted at the same machining settings as cycle 1 but the as-printed component was subjected to an additional heat treatment cycle at a laser power 1000 W following the same hatch pattern as the initial print. The parameters of the milling cycle were same for the first and second milling cycle. It is observed that the vibration energy (signal variance) across all the machining passes is decreased by about 50% as a result of thermal softening. Reduction of cutting forces can lead to better tool life and lower energy foot-print, especially while machining hard-to-process materials compared to machining an as-printed component.

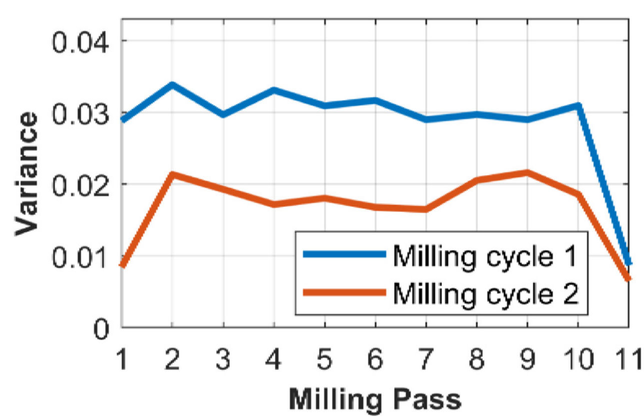

Fig. 4. Variation of the vibration signal variance for eleven milling passes on a DED printed part (Milling cycle 1), and after a laser heat treatment (Milling cycle 2).

3. Summary, limitations and future work

A smart manufacturing multiplex (SMM), based on combining a hybrid machine tool with advanced sensor fusion and AI boosts current thrusts in custom manufacturing. An SMM can improve the agility in terms of allowing multiple processes to be executed on a single machine with the same datum, thereby reducing the cycle times, and radically compressing the entire job-shop into a single machine tool. It can also allow thermodynamic pathways heretofore not considered in prior materials process approaches to realize custom shape and morphology along with a control over material composition and microstructure to optimally meet the desired functionality. The integration of sensors and AI methods for sensor fusion over different data streams and through multiple process chains enables manufacturing forensics with improved traceability of the defects and anomalies, as well as guaranteeing of provenance performance. An initial implementation of an SMM demonstrates some of these capabilities.

Nonetheless, various current limitations noted during the current implementation should to be addressed to realize the full potential of an SMM. In HM machine tools, the distance between the centers of the milling and laser head are known but are not explicitly programmed in many commercial controllers. In addition, when compared to a traditional machine tool, the execution of a process chain in an SMM might cause heat-induced variations and defects such as bending, warping and irregular expansion in a few regions of the printed block. This causes the part geometry to deviate significantly from the design specifications [9]. This issue makes integration of an SMM with traditional CAD/CAM systems highly cumbersome.

Additionally, as with any HM platform, the part is braze-welded to a platen as it is printed. The strength of the brazed joint is often weaker compared the gripping strengths of conventional work holding fixtures. This condition can cause the part to detach from the platen during a subsequent machining operation, especially at high transverse and in-feed settings. Also, the heat treatment process in an SMM is mostly restricted to achieve surface modification. This might not control or guarantee a uniform microstructure throughout the bulk of the material. Due to the design constraints of the machine, the spindle and the laser head are separated at a fixed distance. This causes a delay in terms of when the heat is imparted on to the surface versus when the part is machined. This limits the laser-assisted machining (LAM) capability of an SMM. In contrast, in conventional LAM implementations, the heat source is located in close proximity to where the cutting is performed. However, as heat inputs are in orders of magnitude higher compared to conventional LAM implementations, thermal effects can still be leveraged to enhance machinability. Another limitation of the SMM is that the part dimensions are restricted by 0.35×0.35 m^2 and it has only two powder hoppers to deliver powders for printing functionally-graded materials. However, the machine allows installation of up to a maximum of four powder hoppers.

It may also be noted that the various capabilities of an SMM, such as process monitoring via sensor fusion, usage of a common datum, and the ability to achieve a sub-micro meter finish were discussed individually in many works. In the present implementation SMM, we had attempted to integrate all these functionalities into a single platform, and thereby extract certain synergies. The ongoing efforts are focused on expanding the sensor-based approaches beyond *in situ* monitoring of the process to establish control loops to make necessary adjustments in process parameters. Also, efforts are underway to understand process signatures across all sensors to understand the effect of laser heat-treatment on DED-printed components.

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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