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Accelerating Industrial Adoption of Metal Additive Manufacturing Technology

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While metal additive manufacturing (AM) technology has clear benefits, there are still factors preventing its adoption by industry. These factors include the high cost of metal AM systems, the difficulty for machinists to learn and operate metal AM machines, the long approval process for part qualification/certification, and the need for better process controls; however, the high AM system cost is the main barrier deterring adoption. In this paper, we will discuss an America Makes-funded program to reduce AM system cost by combining metal AM technology with conventional computerized numerical controlled (CNC) machine tools. Information will be provided on how an Optomec-led team retrofitted a legacy CNC vertical mill with laser engineered net shaping (LENS®—LENS is a registered trademark of Sandia National Labs) AM technology, dramatically lowering deployment cost. The upgraded system, dubbed LENS Hybrid Vertical Mill, enables metal additive and subtractive operations to be performed on the same machine tool and even on the same part. Information on the LENS Hybrid system architecture, learnings from initial system deployment and continuing development work will also be provided to help guide further development activities within the materials community.

AM ADOPTION BARRIERS

This paper is intended to provide an industrial example of where the additive manufacturing (AM) industry is headed in order to guide further development activities in the materials community. There is a trend emerging in the machine tool industry that holds the promise of accelerating industrial adoption of metal AM technology. A number of computerized numerical control (CNC) machine tool suppliers are now offering AM capabilities as another metal working tool within their subtractive machining centers.[1] This movement is further supported by AM equipment suppliers such as Optomec, who now offer their AM technology in a modular print engine form for integration into new or existing subtractive CNC machine tools.

The synergy of these two technologies integrated in one machine tool platform offers a number of advantages to the metal working industry. First, subtractive CNC machines cost less to manufacture because they are sold in much higher quantity than AM machines. In 2014, an estimated 543 metal AM machines were sold worldwide compared to hundreds of thousands of subtractive CNC machine tools.[2,3] USA and European suppliers sold metal AM machines with build volumes of 1 cubic foot or larger for prices ranging from US$700,000 to over US$1,000,000.[2] By leveraging the lower cost subtractive CNC automation platform, additive systems can be sold at a lower price. Secondly, the integrated additive/subtractive system, called Hybrid, can be operated from a common human machine interface (HMI) already familiar to a CNC machine tool operator, thus lowering training time. Third, many in-service subtractive CNC machine tools can be upgraded with AM capabilities allowing customers to leverage existing capital assets to deploy AM technology. And fourth, combining metal additive and metal subtractive technology into a Hybrid CNC machine enables capabilities not possible with either technology alone. For example, Hybrid CNC machines enable the production of net shape 3 dimensional metal parts and allow processing of larger metal components than is possible on standard metal AM systems. Currently, suppliers of

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AM systems offer a limited choice of machine sizes. AM systems with larger build volumes can be developed to meet custom requirements at a higher cost. Hybrid CNC machines can also speed production of complex parts by using each process where best suited. So combining additive and subtractive metal working capabilities into one machine tool seems logical and promising, but how did this idea evolve and what are the current capabilities of Hybrid machine tools?

BACKGROUND ON METAL AM TECHNOLOGY

Laser-based AM technology was invented in the 1980s and the two most commonly known methods available for commercial use today are powder bed fusion (PBF) and powder fed directed energy deposition (DED) systems. As shown in Fig. 1, PBF systems use a laser to selectively melt a bed of metallic powder layer by layer to build up the physical part. After the first layer is spread and sintered, the bed is filled again with a second layer of powder and selectively sintered. This process is repeated until the part is fully formed. The end result is buried in the powder cake and is not visible until the excess powder is removed. As shown in Fig. 2, powder fed DED systems continuously blow powder through nozzles directed at the focal point of a high-powered laser. The resultant molten pool of metal is then moved using a motion control system and the part is built up in free space. The entire process is visible as the part is grown layer by layer. Each process has its advantages.

The PBF method is better at building smaller, more complex-shaped parts, and produces a better surface finish. The powder fed DED method is better at adding material to existing parts (as in repair or Hybrid manufacturing) and building larger parts. In general, powder fed DED technology produces fully-dense material that has mechanical properties at least equal to or better than cast material, and in many cases very similar to forged or wrought material. For building small metal components, PBF machines can be used in many cases, except if a functionally graded material is required, or if the desired material is one not commonly processed by PBF systems. For building large parts or repairing worn or defective metal components, powder fed DED machines, such as LENS machines offered by Optomec, are stronger candidates.

AMERICA MAKES PROJECT

America Makes, the National Additive Manufacturing Innovation Institute, issued a project call in 2013 to lower adoption barriers for laser metal AM technology. Optomec responded with a proposal to package its LENS technology into a modular print engine, which could be integrated with other metal working platforms, such as CNC mills, lathes, robots, custom gantries, or even laser cutting and welding systems. In January 2014, Optomec was awarded an America Makes contract to package LENS technology into a modular print engine and to prove the concept by upgrading a legacy Fadal Vertical Mill into a Hybrid CNC machine tool.

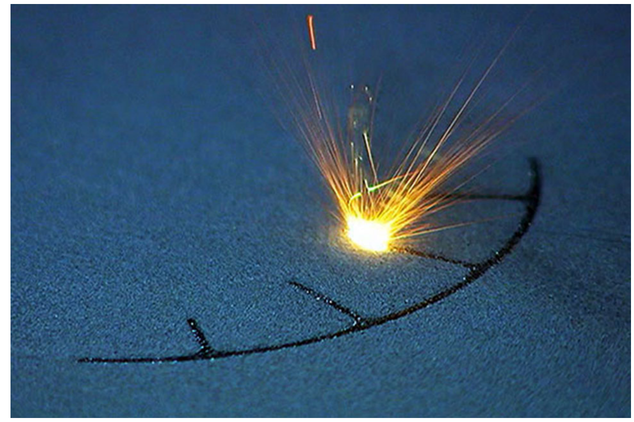

Fig. 1. A laser fuses metal powder to form one of many successive layers that will form the final manufactured part. Courtesy of GE Oil & Gas.

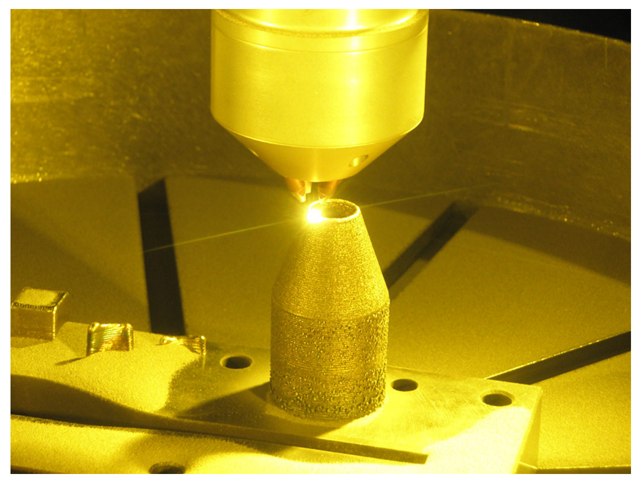

Fig. 2. Metal powder is blown through nozzles to the focal point of a laser forming a molten pool which is moved to form the part layer by layer. Courtesy of Balmar.

Figure 3 shows the modular components of the LENS print engine: a processing head with collimator and focusing lenses for delivering laser energy to the deposition zone; print head nozzles for delivering metal powder and purge gas to the deposition zone; powder feeders for delivering a variety of commercially available powders to the deposition zone, software for slicing CAD models and creating tool paths to drive the CNC motion control system; and a high power fiber laser.

The CNC machine tool must first be upgraded for safety, which includes a Class I Laser enclosure and a laser safety window for viewing the process. The access doors and ports are interlocked to prevent

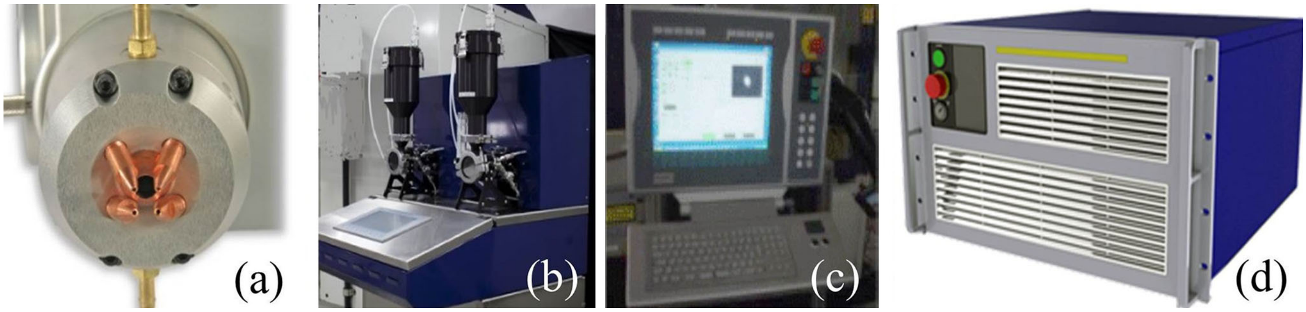

Fig. 3. LENS print engine components: (a) LENS processing head with print head nozzles, (b) cart with dual powder feeders, (c) tool path generation software, and (d) IPG Photonics fiber laser.

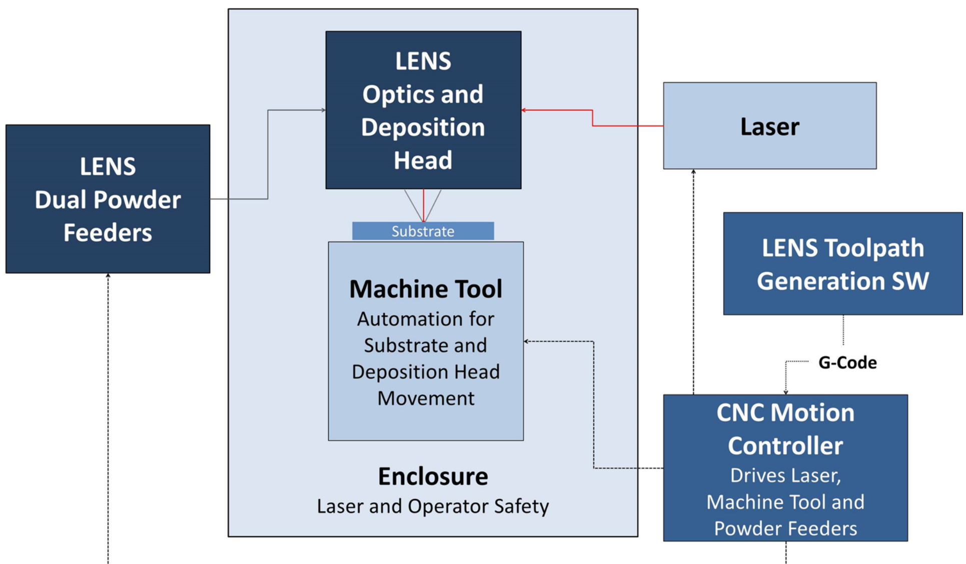

Fig. 4. Schematic of LENS print engine integrated into a CNC machine tool.

possible exposure to the high-power laser beam during normal operations. The laser and powder feeders are integrated into the system through the CNC motion controller. The LENS tool path generation software creates G-code commands to drive the laser, powder feeders and motion control system for additive operations. Figure 4 shows a schematic diagram of the LENS print engine components integrated into a CNC machine tool.

In addition, the LENS print engine can include a closed loop control that monitors and adjusts key process parameters during the build to help ensure metal parts with consistent qualities. As the AM build progresses, heat build-up in the part can affect the size of the melt pool, which in turn can affect the microstructural properties and dimensional accuracy of the printed metal. The closed loop control consists of special focusing optics and a melt pool sensor, which are housed within the LENS print engine deposition head. The sensor monitors the build process, and control software automatically adjusts laser power to keep the area of melt pool constant. Numerous studies have demonstrated that closed loop systems are effective in controlling heat input and cooling rate, and thus promote microstructural uniformity that defines the mechanical properties of the printed metal.[4,5] Maintaining melt pool size also ensures the geometric and dimensional integrity of the final part. In actual operation, the closed loop control dramatically reduces laser power from the first layer to the end of the build.

PROJECT RESULTS AND DISCUSSION

An Optomec-led team consisting of experts in CNC motion control, machine tool process optimization, and users from the Aerospace/Defense industries participated in an 18-month project to develop, integrate, and test the LENS print engine. In April 2015, Optomec delivered a Hybrid Fadal Vertical Mill shown in Fig. 5 to TechSolve, a company with expertise in process improvement and CNC machining. TechSolve's task was to evaluate the capabilities and manufacturing readiness level (MRL) of the LENS Hybrid CNC system. The LENS Hybrid

Fig. 5. Legacy Fadal Vertical Mill upgraded with LENS print engine AM technology and Class I laser safety enhancements.

system was installed in 1 day and the TechSolve machinist, who had no prior 3D printing experience, was building parts the same day. This fast learning curve was possible because the LENS Hybrid system utilizes a custom interface that integrates innovative 3D printing protocols with traditional CNC programming and control protocols such as G codes, a language already familiar to most machinists.

The LENS Hybrid system was fully functional and could operate in subtractive mode as it did prior to the upgrade, or in additive mode building a complete 3D part, or could operate in Hybrid mode switching back and forth between additive and subtractive operations on the same component. In May 2015, the LENS Hybrid system was unveiled at TechSolve and a live demonstration was conducted showing the machine operating in Hybrid mode. The jaws of a stainless steel crescent wrench shown in Fig. 6 were cut off with the Hybrid machine and then grown back using the integrated LENS print engine. Then, the internal cavity of the new jaws was finished and machined using the Hybrid machine's milling capabilities. This of course is a simple example of Hybrid operations, but brings home the concept of repairing parts and selective finish machining based on functional requirements.

The metal housing shown in Fig. 7 with thin wall structures is another example of the unique capabilities of Hybrid processing. The thin wall structures on this component would be very difficult to machine out of a billet, and the base hub structure (approximately 450 mm in diameter) would be very time consuming to build using AM technology. However, machining the base from a billet and

Fig. 6. Stainless steel crescent wrench repaired with the LENS Hybrid CNC Vertical Mill.

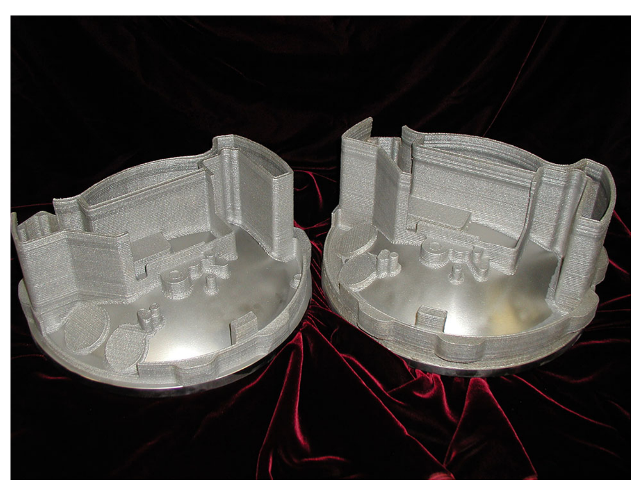

Fig. 7. Metal housing built with Hybrid manufacturing process. Base hub structure machined from billet and thin walls built with LENS AM process.

then building the thin walls with AM would take advantage of what each process does best. In fact, the thin walls could be finished net shape by partially building the structure, then machining it and continuing in this fashion until the thin walls were completely fabricated.

The LENS Hybrid machine has been evaluated by TechSolve to be at MRL 6/7, the highest rating possible by a non-production entity. On-going evaluation includes analysis of energy and cost savings by operating in an open air environment and utilizing local inert shielding techniques. While this condition is not ideal for processing high-performance materials for the most demanding aerospace requirements, such as flight critical titanium alloy components, it does enable application of additive and Hybrid techniques for a wide range of structural materials at a significantly lower cost. Traditional LENS systems, which operate in a high quality (O_2 <5 ppm) argon glovebox chamber and are capable of processing large parts, cost over US$1,000,000. Other additive Hybrid machine tools currently on the market cost even more. A LENS print engine can be integrated with an existing CNC platform for less than half that amount.

A second LENS Hybrid machine was delivered to the Golisano Institute for Sustainability at the Rochester Institute of Technology. Here, the system will be used to develop repair and remanufacturing processes for the automotive and aerospace industries. A third LENS print engine is currently being integrated on a custom gantry to apply wear resistant coatings on injection molding dies. Other applications of the LENS print engine for the repair of aerospace and power generation equipment are also in progress.

CONCLUSION

It is still in its early days, but the market reception for a low cost metal AM capability is encouraging. Some of the remaining subtle, but complex, additive Hybrid issues which remain to be evaluated and resolved relate to the interrupted processing steps involved in the Hybrid concept. Material microstructural integrity and consistency is highly susceptible in an interrupted thermal deposition process that can involve variable cooling rates, even quenching that can result from the use of machining coolants on a hot, recently deposited feature. Much more sophisticated modeling and simulation tools will need to be developed to predict the possible distortion and microstructure results of utilizing the Hybrid concept.

"Dry" machining techniques involving evaporative cooling or other non-liquid (aqueous or solvent) tool wear enhancements will need to be refined in order to avoid the rapid cooling and surface contamination issues involved with traditional methods. In addition, the metal powder and chip recovery management and mechanical wear issues need to be examined as they relate to traditional CNC machine tool designs and tooling coolant methods using additive Hybrid concepts.

These challenges will ultimately be overcome as early adopters and the material community move the technology forward. A lower cost and more flexible pathway for development and transition to production will accelerate adoption of both additive and Hybrid fabrication methods.

ACKNOWLEDGEMENTS

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