Hybrid Processes in Additive Manufacturing

Hybrid additive manufacturing (hybrid-AM) has described hybrid processes and machines as well as multimaterial, multistructural, and multifunctional printing. The capabilities afforded by hybrid-AM are rewriting the design rules for materials and adding a new dimension in the design for additive manufacturing (AM) paradigm. This work primarily focuses on defining hybrid-AM in relation to hybrid manufacturing (HM) and classifying hybrid-AM processes. Hybrid-AM machines, materials, structures, and function are also discussed. Hybrid-AM processes are defined as the use of AM with one or more secondary processes or energy sources that are fully coupled and synergistically affect part quality, functionality, and/or process performance. Historically, defining HM processes centered on process improvement rather than improvements to part quality or performance; however, the primary goal for the majority of hybrid-AM processes is to improve part quality and part performance rather than improve processing. Hybrid-AM processes are typically a cyclic process chain and are distinguished from postprocessing operations that do not meet the fully coupled criterion. Secondary processes and energy sources include subtractive and transformative manufacturing technologies, such as machining, remelting, peening, rolling, and friction stir processing (FSP). As interest in hybrid-AM grows, new economic and sustainability tools are needed as well as sensing technologies that better facilitate hybrid processing. Hybrid-AM has ushered in the next evolutionary step in AM and has the potential to profoundly change the way goods are manufactured. [DOI: 10.1115/1.4038644]

Keywords: hybrid processes, additive manufacturing, cyclic process chains

1 Introduction

The term “hybrid” has been widely applied to many areas of manufacturing. Naturally, that term has found a home in additive manufacturing (AM) as well [1–4]. Hybrid additive manufacturing (hybrid-AM) has been used to describe multimaterial printing, combined machines (e.g., deposition printing and milling machine center), and combined processes (e.g., printing and interlayer laser remelting). These capabilities afforded by hybrid-AM are rewriting the design rules for materials and adding a new dimension in the design for additive manufacturing paradigm. This work primarily focuses on defining hybrid-AM in relation to hybrid manufacturing (HM) and classifying hybrid-AM processes. Hybrid-AM processes are defined as the use of AM with one or more secondary processes or energy sources that are fully coupled and synergistically affect part quality, functionality, and/or process performance. By their nature, these hybrid-AM processes do not often meet the International Academy for Production Engineering’s (CIRP) definition of hybrid processes, i.e., the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on process performance [5]. Hybrid-AM processes are typically a cyclical process chain rather than simultaneous processes and rarely influence the primary manufacturing process. In fact, hybrid-AM processes are more commonly designed to enhance part performance or functionality rather than the primary build process itself. Sections 2–4 describe how this definition was derived, and examples of hybrid-AM processes are provided.

2 Hybrid Manufacturing

In order to define hybrid-AM, it is important to have a clear understanding of HM. The concept of hybrid manufacturing has been in use for many years as a solution for improving part quality and productivity via the use of two or more methodologies [6,7]. The terminology has been widely applied in literature to describe several hybrid techniques: (1) hybrid processes, (2) hybrid machines, and (3) hybrid materials, structures, or functions, see Fig. 1 [5,8,9].

Hybrid processes refer to the ever-increasing list of methods to coalesce two or more manufacturing processes. According to Kozak and Rajurkar, hybrid processes, namely machining, must make use of the combined or mutually enhanced advantages as well as avoid or reduce adverse effects the constituent processes produce when applied individually [10]. A similar interpretation is that the sum of the hybrid process is greater than the sum of the individual processes, i.e., the “1+1=3” effect [8]. The CIRP
further elaborates on the definition of hybrid processes to be the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on process performance [5]. One of the most commonly used examples is laser-assisted turning, whereby a laser simultaneously acts in conjunction with turning to ease the cutting process.

Hybrid processes are not to be confused with hybrid machines. Hybrid machines include multiple manufacturing processes in one machine platform. For example, a combined milling and turning machining center or a combined three-dimensional (3D) printer and milling machine. The salient point is that hybrid machines refer to the machine platform rather than the constituent processes.

Hybrid materials, structures, or functions are concerned with combining one or more materials to have a hybrid composition, structure, or function [11,12]. A hybrid material should result in either enhanced or completely new properties. Hybrid materials, structures, and functions have been widely investigated in literature across multiple fields of science and engineering for several decades. This work focuses namely on hybrid-AM processes, and therefore has limited discussion on hybrid materials, structures, or functions as related to additive manufacturing. Examples of hybrid materials include composite, sandwich, lattice, and segmented structures [11].

The primary objectives of this work are to define hybrid-AM and summarize hybrid-AM processes reported in literature. In order to do so, hybrid manufacturing processes will be introduced and compared to hybrid-AM processes. For completeness in defining the field of hybrid additive manufacturing, hybridization of materials, structures, function, and machines as related to additive manufacturing will be defined and briefly discussed.

3 Hybrid Manufacturing Processes

According to CIRP’s most recent classification efforts, there are two major types of HM processes: (1) assisted processes and (2) mixed or combined processes, see Fig. 2 [5]. In assisted processes, a secondary process or energy source assists the primary process for the purpose of enhancing the total process performance. Three primary assisting processes frequently found in literature include: (1) vibration-assisted machining (implements vibration to assist with material removal or byproduct/waste removal or disposal) [17,18], (2) laser-assisted machining (eases machining forces by softening the workpiece) [19–24], and (3) media-assisted manufacturing (uses a coolant or lubricant to assist the primary process) [25–28].

In mixed processes, two or more processes are combined and occur somewhat simultaneously [5]. Examples include (1) combining electrochemical machining or electrical discharge machining with grinding [5,10,29–33] or (2) combining equal channel angular pressing with extrusion [34,35].

Whether referring to assisted or mixed processes, HM processes have traditionally targeted efficiency and productivity of the process as improvement criteria. The central theme to hybrid processing is that the process performance is improved by the hybrid approach. However, the emergence of additive manufacturing to print functional parts has expanded the possibilities for a hybrid approach in
this field, where improvement is focused primarily on part quality and subsequent functionality rather than solely on the process.

4 Hybrid Additive Manufacturing

Analogous to hybrid manufacturing as described by Lauwers et al. [5], hybrid-AM is concerned with several hybrid methodologies related to processes, materials, and machines. Sections 4.1-4.3 will explore hybrid-AM processes in depth, briefly mentioning hybrid-AM materials, and present a current snapshot of commercially available hybrid-AM machines.

4.1 Hybrid-AM Processes

4.1.1 Defining Hybrid-AM Processes. In this work, hybrid-AM processes are defined as the use of AM with one or more secondary processes or energy sources that are fully coupled and synergistically affect part quality, functionality, and/or process performance. Three key features to this definition include: (a) fully coupled processes, (b) synergy, and (c) part and/or process improvement.

4.1.1.1 Fully coupled processes. The first key feature of this definition relates to the fully coupled nature of the two (or more) processes. To be precise, the secondary process cannot be decoupled from the AM process during the build. Processes that occur pre- or postprinting are not considered coupled. The intent is to separate hybrid-AM processes from those considered to be preprocessing steps prior to layer assembly and postprocessing steps once the build is complete.

An example of preprocessing that does not meet the fully coupled criterion is CIRTES Stratoconception® process [36]. In this case, individual layers called strata are precut by milling or laser cutting prior to assembly. Two common examples of post-processing after 3D printing that typically would not comply with the fully coupled criterion are hot isostatic pressing (HIP) and abrasive flow machining. Both processes are often used on 3D printed parts to reduce porosity (e.g., HIPing) or to reduce surface roughness and sealing of conformal heating and cooling passages (e.g., abrasive flow machining) [37,38].

4.1.1.2 Synergy. The second key feature to this definition relates to the synergistic nature between the two or more processes. That is, the secondary process and the AM process work together either simultaneously or as a cyclical process chain to produce an enhanced result that is unachievable by the individual processes. This is analogous to the “1 + 1 = 3” effect. An example of simultaneous process synergy would be laser-assisted plasma deposition (LAPD). A laser provides a second energy source to enhance the deposition process. A majority of hybrid-AM processes are not typically simultaneous and therefore take place in a cyclic sequence of steps, i.e., a cyclic process chain. An example of synergy using a process chain would be cyclically alternating laser shock peening (LSP) and 3D printing. The secondary LSP process imparts deep compressive residual stresses (CRSs) and is fully coupled since it occurs between printed layers. Coupling two processes results in a part with improved mechanical properties throughout the entire build volume.

4.1.1.3 Part and/or process improvement. Finally, the third key feature of this definition relates to how the hybrid-AM process affects one or more of the following: part quality, part functionality, or process performance. Traditionally, hybrid manufacturing processes benefit process performance (e.g., increase material removal rate or prolong tool life). Some hybrid processes benefit part quality and functionality as well. For example, combining equal channel angular pressing and extrusion improves strength and ductility [28,39].

In contrast to hybrid manufacturing processes, the majority of secondary processes in hybrid-AM do not assist the build process. Rather, the primary benefit is to the part or its functionality. Using the same example above, cyclically alternating LSP and AM results in a part with improved mechanical properties. In this example, the primary objective is to enhance part quality and functionality rather than the build process. Even though LSP has no effect on the build process, the two processes must be coupled in a cyclic process chain during the build in order to achieve the desired result.

There are some hybrid-AM processes where the objective is to benefit the build process rather than improving the part. An example of a secondary process improving the build process is LADP [40] and is discussed further in Sec. 4.1.5. In LADP, an assisting laser provides a secondary heat source in addition to the heat generated by the plasma arc in order to decrease melt pool diameter and improve plasma arc stability. In doing so, the primary build process was affected by the secondary manufacturing process.

These hybrid-AM processes can be classified in several ways and are a unique subset of hybrid manufacturing processes where many do not meet the consensus definition from CIRP. The most common class of hybrid-AM processes is machining, where the primary goal is usually to improve surface finish and geometrical accuracy [1]. The second most common class of hybrid-AM processes are thermal in nature and include (1) laser-assisted melting [40] and (2) surface treatments such as laser remelting or erosion [41-46]. These secondary processes employ thermal energy to improve the printing process or recondition the material properties of a previously deposited layer. Another class of secondary processes includes mechanical surface treatments such as peening [47-59] or rolling [60-71]. These processes reform the printed layer and can result in improved surface finishes, refined microstructures, minimized distortion, increased hardness, improved part density, favorable compressive residual stresses, and stress relieving. A lesser-explored class of hybrid-AM processing is solid state stirring. Combining additive manufacturing with friction stir processing (FSP) can result in enhanced mechanical properties by refining the microstructure. Sections 4.1.2-4.1.8 survey the literature on hybrid-AM processes beginning with machining. A process schematic is presented along with an analysis of each hybrid-AM process.

4.1.2 Hybrid-AM by Machining. The most common secondary process in hybrid-AM literature is machining [1,72-91]. In hybrid-AM machining, additive manufacturing is coupled with a material removal process, such as milling or turning. AM provides near net shape parts while machining in sequential layer intervals provides improved surface finish and better geometrical accuracy. The first hybrid-AM machining processes were developed in the area of welding in the early 1990s [50,87,88]. Additive processes that have been coupled to machining include selective laser welding, MIG welding, ultrasonic welding, laser melting, laser deposition, laser cladding, plasma deposition, and sheet lamination. It should be noted that machining parts after completion of the build does not meet the fully coupled criterion to be considered hybrid-AM processing. However, machining is often required between layer intervals (e.g., machining every five or ten layers) for complex geometries or internal features and would therefore be considered a hybrid-AM process since machining and printing could not be decoupled.

The most common machining process reported in literature is milling. In most cases, the objective of milling is to improve the sidewall’s surface finish on one or more layers using an end mill (Fig. 3(a)). In other cases, the objective is to face mill the top surface of a printed layer to provide a smooth, fresh surface for subsequent printing (Fig. 3(b)) [75,76,89,92,93]. Notice that when machined in a layer-by-layer manner, or multiples thereof, the two processes (printing and machining) are fully coupled but do not occur simultaneously. Furthermore, the purpose of both processes is completely different. The purpose of end milling the side surface is to improve surface finish of the final part. The purpose of milling the top of each layer is to maintain a constant layer thickness and provide a fresh surface for subsequent printing.
Layered compaction manufacturing + milling + sintering DED Powder Metal Deposition nozzle [77, 86, 88, 94–96]

Table 1 Classification of hybrid-AM machining processes

<table>
<thead>
<tr>
<th>AM process category</th>
<th>Material feedstock</th>
<th>Type of material</th>
<th>Material distribution</th>
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<tbody>
<tr>
<td>Laser welding + machining</td>
<td>DED</td>
<td>Powder Metal</td>
<td>Deposition nozzle</td>
</tr>
<tr>
<td>Laser cladding + milling</td>
<td>DED</td>
<td>Powder Metal</td>
<td>Deposition nozzle</td>
</tr>
<tr>
<td>Laser deposition + milling</td>
<td>DED</td>
<td>Powder Metal</td>
<td>Deposition nozzle</td>
</tr>
<tr>
<td>Selective laser sintering + milling</td>
<td>PBF</td>
<td>Powder Metal</td>
<td>Powder bed</td>
</tr>
<tr>
<td>Plasma/arc</td>
<td>DED</td>
<td>Wire Metal</td>
<td>Deposition nozzle</td>
</tr>
<tr>
<td>Plasma deposition + milling</td>
<td>DED</td>
<td>Powder Metal</td>
<td>Deposition nozzle</td>
</tr>
<tr>
<td>Microcasting + milling + shot peening</td>
<td>DED</td>
<td>Powder Metal</td>
<td>Deposition nozzle</td>
</tr>
<tr>
<td>Solid state fusion</td>
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<tr>
<td>Ultrasonic welding + milling</td>
<td>Sheet lamination</td>
<td>Sheet Metal</td>
<td>Sheet stack</td>
</tr>
<tr>
<td>Layered compaction manufacturing</td>
<td>PBF</td>
<td>Powder Ceramic</td>
<td>High density green compact</td>
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Usually, machining the surface is not typically associated with affecting the build process; however, Karunakaran et al. reported that face milling removed an oxidized layer that negatively impacted the build process (in this case, arc welding) [75, 92]. Removing the oxide layer provided for a more stabilized arc and consistent weld bead. This particular example is significant because it demonstrates how a nonsimultaneous secondary process can indirectly affect the primary print process.

Table 1 classifies hybrid-AM machining processes by AM energy sources and indicates the process category based on ISO/ASTM 52900:2015 terminology [104]. For metals, there are three primary AM process categories: directed energy deposition (DED), powder bed fusion (PBF), and sheet lamination. DED is the most commonly reported additive process used in hybrid-AM machining. In fact, the majority of commercially available hybrid-AM machines use DED technology. Material in the form of powder or wire is melted by a heat source and deposited on a substrate to form layers. These systems capitalize on the flexibility afforded by higher order multi-axis machine tools (e.g., five-axis or seven-axis milling machines). These higher order axis systems can deposit and machine material on nonplanar surfaces, and it is the primary reason DED systems are favored for repairing high-value critical components, such as turbine blades. An alternative to DED is PBF. In PBF, thin layers of powder are melted onto a substrate using a laser or electron beam. In contrast to DED, where powder is sprayed at high velocity, the powder in a PBF system lies stationary in a bed waiting to be sintered or melted. In the case of sheet lamination or ultrasonic welding, sheets of metal are stacked and bonded together by oscillatory shear stresses at ultrasonic frequencies. This is a solid-state fusion process where coalescence is achieved by forming a strong metallurgical bond between the surfaces. Once one or more layers have been printed, the next step is to mill the deposited layers to achieve precise dimensions.

Hybrid-AM by machining presents unique challenges related to dimensional deviation and accuracy of the machining process. Distortion caused by localized heating can make tool path planning problematic [105]. Also, frequent or excessive switching between printing and machining can become an economic burden. Liou’s group at Missouri University of Science and Technology (MS&T) investigate the use of vision and sensing techniques (e.g., stereo vision camera and a laser displacement sensor) for automated path planning. A fully automated hybrid-AM system for machining is critical for precision metal parts and improving efficiency. Frank’s group from Iowa State University is leading efforts to develop a systematic software driven system to combine additive and subtractive manufacturing allowances in the original STL file [106]. Referred to as the direct additive and subtractive hybrid manufacturing system, the goal was to create parts that are “digitally manufactured” to meet the final geometric accuracy required.

4.1.3 Hybrid-AM by Ablation or Erosion. This hybrid-AM process uses a laser or electron beam as a secondary energy source to ablate or erode the top layer of deposited material (Fig. 4). Ablation between printed layers is a fully coupled noncontact process that synergistically affects part quality and performance. Similar to hybrid-AM by machining, this subtractive process can create smooth and precise surfaces by material removal. Furthermore, this approach can be applied towards micromachining of interlayer features in additive manufacturing since the energy source erodes material.

Yasa et al. investigated hybrid-AM by ablation on AISI 316L stainless steel with the use of selective laser melting (SLM) coupled to a pulsed Q-switched Nd:YAG laser (λ = 1094 nm) for selective laser erosion [45, 107]. Using this hybrid approach, the accuracy in the build direction (z-direction) can be improved by reducing the layer thickness or removing irregularities. The authors reported that a 50% reduction in roughness was achievable.

4.1.4 Hybrid-AM by Re-Melting. Hybrid-AM by remelting uses an energy source (e.g., laser or electron beam) to remelt previously fused material (Fig. 5). Even though a laser is used, laser
powers are typically low so that vaporization does not occur. That is, no material is removed, rather it is transformed. Remelting raises previously deposited material up to the melting point to better fuse layers together. Pores formed during 3D printing fill with melted material and increase part density greater than 99%. Remelting can take place after each layer or a sequence of layers. For a given material, the mechanical, physical, and chemical changes to the remelted region depend on the laser scanning speed, scan pattern, and laser power.

The advantages of laser remelting are (1) increased part density, (2) relief of residual stresses [108], and (3) modified material properties. As a result, fatigue life and toughness are improved. The disadvantages to this process include increased processing time, since the energy beam has to make at least twice the number of scans, and the added energy input required for processing.

Yasa et al. investigated the effect of laser remelting SLM parts [43–45] on part density, microstructure, hardness, and external surface roughness (Fig. 6). Although the authors investigated improving external surface roughness, the same approach could be applied layer-by-layer (or multiples thereof) to provide a smooth layer for subsequent printing. Roughness decreased 50–75% depending on process conditions. $R_a$ was 2–8 μm after remelting. The authors also showed that remelting decreased the average porosity from 0.77% (SLM-only part) to 0.032% (remelted part) using optimal laser parameters, i.e., low laser power (85 W) and high scanning speed (100–200 mm/s). Interestingly, multiple passes for laser remelting (up to three) did not significantly decrease porosity. The microstructure changed to a lamellar pattern with a refined grain size that typically exhibited an increased microhardness if sufficient energy was applied [44].

4.1.5 Hybrid-AM by Laser Assisted Plasma Deposition. Unlike the other processes mentioned above, this hybrid-AM process employs an assisting laser during plasma deposition (Fig. 7). Plasma deposition deposits material and a laser adds a secondary energy source applied simultaneously at the same location to assist the build process and improve build quality. This hybrid-AM process is one of the few that would meet CIRP’s definition for a hybrid assist process mentioned previously. It also meets the definition of a hybrid-AM process as defined in this work. It should be noted that the laser in LAPD does not assist the build process the same way a laser assists the cutting process in laser-assisted turning. In laser-assisted turning, the laser directly benefits the cutting process by prolonging tool life or decreasing the cutting forces through work softening. In LAPD, the laser has no direct effect on the plasma deposition tool. Instead, the assisting laser adds extra energy that improves the plasma formation mechanism that improves the part build.

Qian et al. investigated the effect of using a laser as an assisting heat source in plasma-arc deposition [40]. This example demonstrates the use of an assisting energy source in additive manufacturing to improve both process performance and part quality. The laser entered the plasma arc beam to provide more thermal energy to the material being deposited.
energy. Shielding gas used in plasma arc deposition absorbed the energy and ionized gas molecules. The energy density of the plasma arc was improved, and the plasma arc diameter favorably decreased, which improved the accuracy of the part. At the same time, arc ignition became easier because of plasma induced by the laser. With more energy, the depth of the melt pool increased and improved the microstructure and decreased the porosity.

4.1.6 Hybrid-AM by Peening. Hybrid additive manufacturing using surface treatments is a widely unexplored research area. The first published activity dates back to a 1991 patent application by Prinz and Weiss titled, “Method and apparatus for fabrication of three-dimensional metal articles by weld deposition” [48]. The U.S. patent was awarded in 1993 as US5,207,371A and has since lapsed. Similar patents were filed in Europe and Canada. The inventors referred to shot peening a portion of successive layers during metal deposition. The primary objective was to relieve residual stresses produced by the deposition process that could lead to distortion and delamination [48–51].

Research activity related to surface treatments during additive manufacturing went dormant until 2012 when MTU Aero Engines GmbH, a German company, applied for a patent claiming the use of ultrasonic impact treatment, rollimetric shock treatment, and shot peening to solidify selected areas of 3D printed turbine blades [53]. Since then, other companies such as General Electric Co., United Technologies Corp., Bae Systems, and Lawrence Livermore National Security have filed similar patents between 2014 and 2016 [54–57]. In 2017, Logé’s et al. from the École Polytechnique Fédérale de Lausanne in Lausanne, Switzerland submitted another application for a patent that combines laser shock peening with SLM [59].

There exists a major knowledge gap in incorporating surface treatments in additive manufacturing. Using surface treatments, such as peening (e.g., laser, shot, ultrasonic), to print functionally gradient material properties in additive manufacturing is poorly understood and of critical importance for military, aerospace, automotive, and biomedical applications. Hybrid-AM by surface treatments allows for unprecedented advancements in materials design. Gradient mechanical, physical, and chemical properties can be designed and printed throughout the entire build volume. This will lead to the following: (1) open up new opportunities for industry adoption of AM technology by greatly expanding material properties achievable and (2) provide new insight and tools for the “manufacturing-for-design” paradigm initiated by AM technology. Sections 4.1.6.1–4.1.6.4 identify research activity related specifically to different peening surface treatments.

4.1.6.1 Laser shock peening. Hybrid-AM by LSP is the combination of any additive manufacturing process with LSP, also known as laser shot peening or laser peening. Similar to some of the previously mentioned hybrid-AM processes, the secondary peening process occurs layer-by-layer or multiples thereof as a cyclic process chain. After a layer is laser peened, another layer or set of layers is printed and the cycle repeats until completion of the build. This approach allows for functionally gradient properties throughout the build volume. Figure 8 is a schematic of hybrid-AM by LSP.

Laser shock peening is a surface treatment that dates back to the 1960s where shock waves from rapidly expanding plasma plastically deform a workpiece [109]. Plasma forms from the interaction of the workpiece with a pulsed nanosecond range laser. An ablative layer is typically used as a protective coating to prevent thermal damage from the laser on the surface of the workpiece. In this embodiment, LSP is purely mechanical in nature because the ablative layer experiences the thermal load so that the workpiece only experiences the shock wave from the expanding plasma. LSP can also occur without an ablative layer. Here, LSP becomes a thermo-mechanical phenomenon that leads to remelted or recast material in addition to the shock wave.

Sealy et al. at the University of Nebraska–Lincoln are actively investigating the use of LSP during PBF and DED processes to understand thermal and mechanical cancelation of favorable residual stress fields [47]. The objective is to print favorable mechanical properties such as compressive residual stress and increased microhardness to improve performance of AM parts. The results to date emphasized the critical role the printing process parameters have on favorable residual stress fields produced by LSP.

Logé et al. at the Laboratory of Thermomechanical Metallurgy at the École Polytechnique Fédérale de Lausanne in Switzerland are actively investigating the use of LSP in SLM to control residual stress [59]. Experimentally measured residual stress profiles using the hole drilling technique after hybrid-AM by laser shock peening are shown in Fig. 9 [59]. Austenitic SS 316L was printed using the hole drilling technique after hybrid-AM by laser shock peening occurred every one, three, or ten layers. After peening, the samples were re-introduced to the build chamber for subsequent printing. The circles in the figure indicate the approximate depth of laser peened layers. For example, 3D LSP every ten layers will have an orange circle every 0.3 mm (single layer thickness is approximately 0.03 mm). To minimize clutter on the figure, only the first 12 laser peened layers below the surface are shown for the 3D LSP every one layer samples (i.e., blue circles).

The results compared an as-built sample (without laser peening) to ones that were laser peened on the external surface (1 mm spot size with 40% and 80% overlap) and hybrid-AM samples (3D LSP layers; 1 mm spot size with 40% and 80% overlap) where laser peening occurred every one, three, or ten layers. At 40% overlap (Fig. 9(a)), the maximum CRS and depth of the CRS increased 34% and 69% on average, respectively. At 80% overlap (Fig. 9(b)), the magnitude of the CRS did not increase significantly compared to the externally peened surface; however, the depth of the CRS increased for the hybrid-AM samples and may have indicated a saturation point was reached due to the high amount of overlap. Interestingly, peening every ten layers was shown to have deeper residual stress than peening every one or three layers at 80% overlap. These results are significant because they experimentally showed that hybrid-AM by LSP can improve the properties of material by inducing favorable CRS into the layers. Also, thermal cancelation from subsequent printing did not relax away all of the favorable CRS. Since this was a PBF process, the heat affected zone was minimal compared to a DED process.

4.1.6.2 Ultrasonic peening. Hybrid-AM by ultrasonic peening (UP) applies ultrasonic energy to a workpiece using an electro-mechanical transducer layer-by-layer or multiples thereof, see Fig. 10. This mechanical/acoustic surface treatment is also known as ultrasonic impact treatment and is capable of imparting compressive residual stress, stress relief, and microstructural grain refinement. UP can improve the fatigue, corrosion, and tribological performance of AM components.
The use of UP in hybrid-AM is a low cost, quick, and simple solution to improve properties in practically any AM process. Achuthan et al. from Clarkson University investigated UP layer-by-layer to strengthen SLM parts [52]. The results showed that hybrid-AM by UP was able to increase the yield strength and refine the microstructure of Inconel and stainless steel.

4.1.6.3 Shot peening. Shot peening is a surface treatment that improves the mechanical properties of a near-surface layer by directing a stochastic stream of beads at high velocities under controlled coverage conditions. The impact of the bead on the surface induces plastic deformation that results in strain hardening and compressive residual stress. Depending on the material of interest, beads can be composed of glass, metal, or ceramic.

Shot peening external surfaces of additive parts has been investigated in academia [50,101,110–113] and widely applied in industry in order to improve the surface integrity. Intralayer shot peening as a hybrid-AM process has not been widely explored. Sangid et al. at Purdue University investigated the use of fine particle shot peening on AlSi10 Mg during a PBF process [114]. Incorporating shot peening during the build cycle as shown in Fig. 11 has several benefits and also introduces new processing challenges. For example, shot peening is a relatively low cost and quick (in terms of processing time) solution to improve surface integrity; however, bead size is often one to three orders of magnitude larger than powders used in AM processes and requires additional sifting from recycled powder and cutting chips in hybrid-AM machines. Traditional shot peening is ideally suited for directed energy deposition, sheet lamination, or material extrusion processes since particle size can be much larger and will not directly interfere with subsequent printing. In PBF, shot peening can become more problematic if a secondary material is introduced as the peening media because of part contamination issues. An alternative is to use the AM powder itself as the peening media. Current literature has indicated a minimal or negligible effect from AM powder bed peening [114]. Referred to as fine particle shot peening, the process limits the penetration depth for microhardness and compressive residual stress such that any

Fig. 9 Experimentally measured residual stress (hole drilling technique) on austenitic SS 316L after hybrid-AM by LSP using a concept M2 PBF printer: (a) 40% and (b) 80% overlap ratios. Circles indicate depth of laser peened layers. Modified from Ref. [59].

Fig. 10 Hybrid-AM using UP
favorable mechanical properties may become thermally canceled by subsequent printing [114]. Furthermore, peening soft materials with soft powders, for example aluminum alloys with an aluminum alloy powder, may not generate enough contact pressure because the limited strength and hardness of the peening media.

4.1.6.4 Pulsed laser deposition. The use of pulsed lasers as opposed to continuous lasers is continuing to grow in additive manufacturing [115]. High powered pulsed lasers have been used for many years as a method to print thin layers of material on a substrate [116,117]. The process is known as pulsed laser deposition (PLD). When a pulsed laser impinges the powder, rapid heating and vaporization occurs and is accompanied by the formation of a plasma plume (see Fig. 12). The plasma plume creates a shock wave that plastically deforms the surface during printing [118]. In fact, the principle mechanism of PLD is similar to LSP. The key distinction is that PLD combines printing and peening processes into a single laser source. Favorable compressive residual stresses are possible by PLD [119].

4.1.7 Hybrid-AM by Rolling and Burnishing. Another class of hybrid-AM processes that form (i.e., shape) and improve the workpiece are rolling and burnishing, see Fig. 13. Hybrid-AM by rolling solves two key problems in additive manufacturing. First, overlapping of beads or layers in metal additive manufacturing causes inaccuracies in the dimensions of the printed part. Although machining can eliminate these inaccuracies, wasted material in the form of cutting chips increases production costs. Rolling can alleviate some of these inaccuracies without removing material. Second, undesired residual stress from the building process warps or distorts the final workpiece. Although machining can eliminate these inaccuracies, wasted material in the form of cutting chips increases production costs. Rolling can alleviate some of these inaccuracies without removing material. Second, undesired residual stress from the building process warps or distorts the final workpiece. Although the previous peening surface treatments relieve internal stresses, rolling achieves both stress relaxation and forming for dimensional accuracy without removing material. Hybrid-AM by rolling is a desirable choice for expensive powders where rolling can effectively deform the surface or where grain refinement is needed across large cross-sectional areas.

There are two primary institutions active in hybrid-AM by rolling: (1) Williams’ and Colegrove’s groups from Cranfield University in the UK [60–66] and (2) Zhang’s group from Huazhong University of Science and Technology (HUST) in China [67–71]. The Cranfield group used wire-arc AM and applied profiled and slotted rolling tools after deposition of each layer. Results showed coupling rolling after each layer decreased distortion, enhanced grain refinement, and improved mechanical properties. Maximum strength, hardness, and elongation of hybrid-AM rolled samples were higher than the as-cast material. In addition, rolling reduced tensile stresses in the samples.

The HUST group used a metamorphic hot-rolling tool that was adaptable to rolling one, two, or three sides of a component. A metamorphic rolling tool has three rollers: one horizontal and two vertical rollers. The horizontal roller acts on the top planar surface while the vertical rollers act on the vertical faces of workpiece. Use of all three rollers is beneficial for enhancing thin wall structures. Results showed that hot rolling (rolling temperature above recrystallization temperature) resulted in a refined grain structure, increased tensile strength (approximately 33% over conventional sample), and improved dimensional accuracy.

Similar to rolling, burnishing is a surface treatment process to improve surface integrity (surface roughness, residual stress, microstructure, and hardness) of a part. Burnishing consists of a rolling/sliding tool (e.g., ball or cylinder). The tool moves on the surface of material causing plastic deformation in a thin surface layer. This plastic deformation causes material to flow such that peaks and valleys in the surface diminish. If burnishing occurs between printed layers, there is a possibility of producing functionally graded properties (similar to hybrid-AM by peening) with dimensionally accurate parts.

Book and Sangid used a variation of burnishing, referred to as sliding severe plastic deformation (SPD), on AlSi10 Mg to test the feasibility of intralayer processing [114]. SPD employs a highly negative rake angle tool that severely deforms the workpiece without generating a cutting chip. The surface is compressed in a similar manner to a ball-burnishing tool. The end result is a strain-hardened surface up to a depth of 1–2 mm that is highly plasticized and significantly rougher. If thermal cancelation can be avoided from the subsequent printing of layers, SPD may be a suitable process to generate intralayer rough surfaces with enhanced mechanical and metallurgical properties.

Surface treatments such as rolling or burnishing do not affect the AM process; however, without the use of a cyclical process chain that included rolling/burnishing, the beneficial effects for
fatigue, corrosion, or wear cannot be fully realized. Therefore, these processes must be fully coupled in hybrid additive manufacturing in order to synergistically affect part performance.

4.1.8 Hybrid-AM by Friction Stir Processing (FSP). Friction stir additive manufacturing (FSAM) is an additive process where the primary principle is based on friction stir welding (FSW) to permanently join two surfaces. In FSAM, a rotating nonconsumable tool consisting of a pin and shoulder made from refractory materials plunges into a workpiece [120]. The tool crosses the surface of the part creating heat and considerable plastic deformation that joins two layers by mixing the highly plasticized material. Similar to FSW, the workpiece does not melt to achieve coalescence. The result in metals is typically significant grain refinement and recrystallization. These improvements to metallurgical properties have translated into better mechanical and fatigue performance. In addition to metals, FSW has been successfully demonstrated on polymers and composites. The same approach could be extended to FSAM. Although FSAM is not a hybrid-AM process, friction stirring can be easily applied layer-by-layer to parts built using other additive processes (Fig. 14), such as DED or material extrusion, to improve mechanical, metallurgical, and chemical properties.

Francis et al. investigated the effect of FSP on Ti-6Al-4V parts produced by directed energy deposition [121]. The grains were refined and the hardness increased. The authors also mentioned that fatigue life would be improved based on fatigue studies of similar microstructures. Hybrid-AM by FSP is another example where the secondary process has no direct influence on the primary build process; however, a cyclic process chain is required in order to achieve the desired mechanical, chemical, and physical properties.

4.2 Hybrid-AM of Materials, Structures, or Function. Production of multimaterial or multistructural components in a single part is another exceptional capability of AM technology. Multimaterial production utilizes different materials in the fabrication of a single part. The materials can be different in color, density, composition, microstructure, etc. The development of multimaterial production has led to engineering of specially structured components such as functionally gradient and composite materials as well as porous and heterogeneous structures [11,122–128]. Multiple material parts can be produced using a variety of AM processes and with multiple classes of materials such as metals, ceramics, and plastics. The primary motivation for combining dissimilar materials is to achieve products with enhanced functionality that fulfill industry’s ever-increasing demand for better performance. Examples demonstrating hybrid-AM materials, structures, and function are shown in Fig. 15 and discussed below.

Material complexity simply includes combining two or more materials in a single build. For example, the use of a directed energy deposition process (e.g., LENS from Optomec) can easily switch materials on the fly to print a graded magnetic part, see Fig. 15(a). There are multiple examples in literature that demonstrate the advantages of AM’s multimaterial printing capabilities [124].

Structural complexity is another method to hybridize the material or shape of a component. A hybrid microstructure like the one shown in Fig. 15(b) allows for strain gradients during loading [129]. There are several manufacturing methods discussed above that can be employed to hybridize the structure of a printed part. Furthermore, hybrid structures can be hierarchical; that is, features can be designed with shape complexity across multiple size scales [115,122].

Additive parts can also have hybrid functional complexity. That is, functional devices are produced in a single build that serve multiple purposes. For example, UC Berkeley printed embedded electrical components such as resistors, inductors, and capacitors as well as wireless sensors and applied the technology as a “smart cap” to detect spoilage within a milk carton [130]. The hybrid functionality in this example is a cap that seals the carton while also detecting for spoilage, see Fig. 15(c).

4.3 Hybrid-AM Machines. Hybrid-AM machines refer strictly to the machine platforms that integrate additive manufacturing with one or more secondary processes or energy sources. The most commonly integrated platforms use directed energy deposition technology and milling [131]. Other AM technologies that have been incorporated into hybrid-AM machines include powder
bed fusion, sheet lamination, and material jetting. For peening, Sealy’s group at the University of Nebraska Lincoln have incorporated a built-in laser peening facility into a hybrid directed energy deposition system with milling from Optomec; see Fig. 16(a). As the demand for gradient and superior mechanical properties increases, there exists a growing need to have hybrid machine platforms that decrease production time and costs through multi-machine integration.

For more insight on hybrid-AM machines, the additive group in Mechanical Engineering at the University of Bath recently published a 2015 review paper in the Journal of Machine Tools and Manufacture on the past, present, and future trends on workstation for hybrid additive and subtractive processes [1]. Flynn et al. [1] reported on the commercially available hybrid-AM machines; Table 2 is an extension of that information and identifies only newer systems since 2015. Images of those systems are shown in Fig. 16.

### 4.4 Other Topics in Hybrid-AM

#### 4.4.1 Economic Challenges

As more hybrid-AM machines enter the workplace, there is a growing need to assess the economic viability of these systems for process planning. Manoharan et al. began developing an economic model to establish best practices based on batch size, machinability, material cost, part geometry, and tolerance requirements for additive and subtractive machines [132]. More economic analysis and tools are needed to be able to justify several of the previous hybrid-AM processes. Although several of the processes may have a significant short-term costs in terms of processing time or capital equipment costs, the benefits to part accuracy, mechanical properties, and performance may outweigh the cost by several orders of magnitude.

#### 4.4.2 Sensing for Hybrid-AM

Sensing is another key area of interest in hybrid-AM. The emergence of hybrid-AM has ushered in the possibility of leveraging the design and material freedom of AM and combining it with (1) the surface finish and repeatability of subtractive machining and (2) the material properties changes from forming or heat treating. Repeatability and reliability is an acknowledged impediment that hinders broad acceptance of AM technology [133]. Hence, sensing and monitoring in hybrid-AM is contingent on its success at detecting defects and material properties from both AM and the secondary process.

Sensor-based monitoring in hybrid-AM requires the combination of emerging AM monitoring technologies with well-established monitoring approaches of common secondary processes (e.g., removal/formative processes). For instance, accelerometers, force sensors, and acoustic emission sensors applied to detect variations in cutting regimes in machining can be incorporated into hybrid-AM machine platforms. Also, cameras and lasers can be used to detect surfaces in real time in order to efficiently and effectively plan machine tool paths on parts that have or are forming or heat treating. Repeatability and reliability is an acknowledged impediment that hinders broad acceptance of AM technology [133]. Hence, sensing and monitoring in hybrid-AM is contingent on its success at detecting defects and material properties from both AM and the secondary process.

In order to detect evolving process anomalies, researchers have sought to incorporate sensing techniques, such as vibration, CCD video imaging, infrared and ultraviolet imaging, pyrometers, photodiodes, ultrasonic wave generators in AM machines [134–139]. An early example (1994) presented by Melvin et al. [140] used a video-micrography apparatus bearing band pass and polarizing filters for observing the melt pool in polymer powder bed fusion. DED and PBF AM systems are evidently the most popular applications for incorporating sensors, perhaps due to the high value of laser-engineered components and also because these AM processes resemble well-known laser-based processes, such as laser welding [141]. Tapia and Elwany [142] conducted a comprehensive review of sensor-based process monitoring approaches, specifically focused on metal AM processes. More recently, Nassar et al. [143,144], Purtonen et al. [141], Everton et al. [145], Grasso et al. [146,147], and Mani et al. [148] provided excellent reviews of the status quo of sensing and monitoring focused in metal AM, particularly, DED and PBF. From these review papers, it is

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**Table 2: New hybrid-AM machines since 2015**

<table>
<thead>
<tr>
<th>Additive process</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Machining capabilities</th>
<th>Additional capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directed energy deposition</td>
<td>Optomec</td>
<td>LENS 3D metal hybrid system</td>
<td>Up to five-axis CNC machining</td>
<td>Controlled atmosphere (optional)</td>
</tr>
<tr>
<td>Powder bed fusion</td>
<td>Matsuura</td>
<td>Lumex Avance-60</td>
<td>Three-axis CNC machining</td>
<td></td>
</tr>
<tr>
<td>Material extrusion</td>
<td>nScrypt</td>
<td>3Dn + nMill</td>
<td>Three-axis CNC machining</td>
<td></td>
</tr>
<tr>
<td>Material extrusion</td>
<td>Hyrel 3D</td>
<td>Hydra 340, 640, 645</td>
<td>Three axis CNC machining and laser cutting</td>
<td></td>
</tr>
</tbody>
</table>

Note: See Flynn et al. [1] for a more complete list of all available hybrid-AM machines.
evident that researchers are actively working on sensor-based monitoring of AM processes. There is a growing need to include sensor-based monitoring in hybrid-AM processes in order to quantify the multiphysics phenomenon that results in improved processing and part performance.

5 Summary and Conclusions

Hybrid additive manufacturing is a rapidly emerging area of AM research and development. There is a growing need from academia and industry to better understand and explore the benefits afforded by hybrid-AM’s capabilities. This work defined hybrid-AM processes as the use of AM with one or more secondary processes or energy sources that are fully coupled and synergistically affect part quality, functionality, and/or process performance. The objectives of this work were to (1) establish how this definition differs from the consensus definition of hybrid manufacturing processes and (2) separate postprocessing technologies from those that cannot be decoupled from the build process. Several hybrid-AM processes were presented and discussed. For completeness in defining hybrid-AM, the hybridization of machines, materials, structures, and function in the context of additive manufacturing was also presented and briefly discussed. As more machine tool manufacturers enter the hybrid-AM landscape and industry demands greater performance at reduced costs, there is a growing need for new or refurbished economic and sustainability assessment tools specifically aimed at analyzing the full life cycle of hybrid parts and machines. Furthermore, sensing technologies will play a critical role in the evaluation and adoption of hybrid-AM technologies. The knowledge and understanding of hybrid-AM’s role in next generation manufacturing is in its infancy. There is a critical need to investigate the capabilities afforded by hybrid-AM in rewriting the design rules for materials and adding a new dimension in the design for additive manufacturing paradigm.

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References


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