

ADDITIVE MANUFACTURING REPAIR METHODS FOR METALLIC COMPONENTS

Kenneth M. Sabo
Concurrent Technologies
Corporation
Johnstown, PA

Brock T. Golesich
Concurrent Technologies
Corporation
Johnstown, PA

Michael L. Tims
Concurrent Technologies Corporation
Johnstown, PA

ABSTRACT

As metallic parts are used, wear, fracture, galling, warpage, and other forms of obsolescence occur. When these issues progress beyond a predefined level, the parts are either replaced or repaired. Replacement leads to undesirable logistics requirements, especially for those parts requiring difficult-to-source, expensive and/or long-lead-time materials. Repair options are often limited due to strict performance requirements of the parts or concern over the quality of the repair. Two relatively new additive manufacturing (AM) process options exist to complete repairs, including repairs required in theater. Hybrid repair via metal AM followed by precision machining within a single setup offers unique repair options not previously available. Though somewhat limited with respect to the number of alloys currently tested, hybrid AM via directed energy deposition (i.e., powder sprayed into a laser-heated liquid metal pool) offers the possibility to quickly, economically and accurately repair metallic components without the side effects associated with more common methods including traditional weld repair.

Another repair method gaining acceptance in the DoD community is cold spray. Here a metal powder is accelerated to supersonic speeds and aimed at a metal substrate forming craters that help the newly added metal to adhere. In addition, atomic diffusion occurs between added particles resulting in further adhesion of the added metal.

These AM processes generally lack qualification standards for use in repair of DoD applications. But, the nature of repair and the buildup of material(s) should be much faster to reach qualification status, even if it's on a part-by-part, or application-specific basis.

This paper defines hybrid AM and cold-spray technologies relative to repair of metallic components of interest to the DoD. The state of the art is discussed and several examples of the use of the equipment are presented. Hybrid builds of Inconel 718 features onto preexisting substrates are discussed.

Mechanical properties of the build material are presented. Finally, a plan for use of these technologies by the DoD is defined.

INTRODUCTION

Hybridized additive/subtractive/inspection technologies are ideal for metallic component repair since they enable addition of new metal, machining to desired geometry and surface finish, and inspection in a single part setup resulting in quick, thorough and accurate repairs of components. With a directed energy deposition additive manufacturing (DED AM) machine, small weld beads (of the order of 0.02–0.03 up to 0.12 inch width) can be placed on material yielding a small heat affected zone and minimal distortion and acceptable mechanical properties. Worn parts typically can be dimensionally restored without the lengthy and costly logistics associated with completing each production step at a separate remanufacturing station. Although alloy selection is currently limited for DED AM processes, those currently in use are commonly used by the Department of Defense (DoD): alloys of titanium, nickel (including Inconel¹), stainless steel, and aluminum are available.

Another repair method gaining acceptance in the DoD community is cold spray. Here a metal powder is accelerated to supersonic speeds and aimed at a metal substrate to achieve a solid-state build-up (with no powder melting). Due to the extreme pressures and kinetic energy through the acceleration process, the powders plastically deform and create a mechanical bond with the substrate and previously added material via craters formed upon impact of the powder material. These craters help the newly added metal to adhere. Although the powder particles do not melt, atomic diffusion occurs between added particles resulting in further adhesion of the added metal. Material selection for cold spray is very broad and includes metallic alloys, metal or ceramic matrix composites, and other multi-component systems.

In both of these new AM processes, the component size is limited by the dimensions of the chamber in which the repair is being made. Some hybrid systems can support large working envelopes, such as the one at Concurrent Technologies Corporation (CTC), which can repair workpieces up to 120 inches by 40 inches by 30 inches. One of the largest cold spray units is at Ellsworth Air Force Base (AFB), where a unit exists that can accept parts over 10 feet by 10 feet by 6 feet.

However, these AM processes generally lack qualification standards for use in DoD applications. Since weld repairs are currently made on many metallic components and since the region to be repaired is typically small relative to the entire component volume, AM repair technology may be faster to qualify for repair of DoD parts compared to parts fabricated as a whole by AM processes. The acceptance criteria will still need to be determined, and suitable parts, materials, and procedures must be implemented for either of these technologies. The nature of repair and the buildup of material(s) should be much faster to reach qualification status, even if it is on a part-by-part, or application-specific basis.

HYBRID DED AM SYSTEMS

Benefits and Attributes of Hybrid DED AM Systems

Several benefits of a hybrid manufacturing approach (i.e., combining multiple processes into a single machine) are apparent. Cycle time is greatly reduced since the part requires a single setup from which multiple process steps can be completed. That contrasts with conventional manufacturing process routes where limited-purpose machines are used to successively convert the workpiece into a finished product. Eliminating the transit time between the machines used to complete the various process steps reduces the total production time. In addition, many of the labor hours required to reset workpieces are

¹ Inconel is a registered trademark of Special Metals Corporation, Huntington, WV.

eliminated. For example, hybrid additive/subtractive/inspection machines allow repair of a component to be initially machined to remove damaged material, then new metal to be added, final machining to be completed, and intermediate and final geometric inspection to be completed in a single setup. An additional benefit from a single setup is an improvement in part-to-part consistency.

As a result of reduced part movement, parts that may require a week or more to repair can often be refurbished in a day; for some components, turnaround time may be as quick as 1–3 hrs. The geometric complexity, accessibility to the repair site, amount of material addition needed, and required finishing tolerances and surface finish are important factors in establishing actual turnaround time. Current build rates for laser DED machines are of the order of 0.1 kg/hr to 2.5 kg/hr depending upon the application head size and required deposit accuracy. In addition, up to twice or three times the volume of metal is applied to account for the irregular surface developed by the DED additive process. Excess metal is machined off as a final (or intermediate) production process.

Unlike powder bed processes, DED allows for adding material in a non-planer manner. Therefore, repair of metallic parts is more easily accomplished with DED AM methods. In the DED process, metal is sprayed into the molten pool via a carrier gas – typically argon. The hybrid equipment available at CTC has a stationary print head, which fits into a standard milling machine spindle while the workpiece articulates three dimensionally beneath the print head. Therefore, assuming the region to be built up is accessible to the print head (see Figure 1); metal can be built on existing structure. By manipulating the workpiece underneath the print head, one can add features onto complex curved surfaces. Undocking the powder metal delivery system and laser, one can quickly place a common machine cutting tool, like those shown in Figure 1, into the spindle and machine metal. Similarly, any

of several inspection probes (touch for dimensional validation or eddy current for determination of surface or near-surface anomalies) can be used. This design allows for modification of existing machine tooling equipment to accept this DED AM technology as an upgrade to existing machine tool functionality. Swapping among the AM hardware, cutting tools, and inspection heads is automated. Therefore, the working volume of a component is dictated by the working envelop of the machine tool. Furthermore, the workpiece may be manipulated (3-axis, 4-axis or 5-axis equipment) in the same manner as machining a workpiece. When not used as a DED AM tool, the equipment may still be employed to machine metallic components. This option is not readily available for laser powder bed fusion machines.



Photo courtesy of Hybrid Manufacturing Technologies
Figure 1: Typical DED AM print head among a series of cutting tools.

Properties of Inconel 718 DED AM Builds

Tensile and hardness properties for Inconel 718 builds versus hot-rolled bar (with no subsequent thermal treatment) are shown in Table 1. Strength of the deposited material from Yamazaki [1] is comparable to that of wrought material that has not been thermally post processed. Elongation, however, was lower for the AM material. The CTC results showed significantly higher yield

stress (at 0.2% offset), but significantly lower elongation than the as-hot-rolled Inconel 718. Presumably, all three materials would tend to have more similar properties after post thermal treatment. The bond strength between the added material and the substrate was comparable to the ultimate tensile strength listed.

Table 1: Tensile and hardness values for Inconel 718

	Reference [1]	Testing at CTC	As-Hot-Rolled Bar [1]
Yield Stress (N/mm ²)	587	768	591
Ultimate Tensile Strength (N/mm ²)	931	990	965
Elongation (%)	31.7	14	46
Reduction of Area (%)	31.2	20	58
Hardness (HRC)	23	N/A	23

Examples of Build Features Made by DED AM

Figure 2 shows Inconel 718 material added to a 1.0-inch-diameter Inconel 625 tube. Specifically four features were added via DED AM to the substrate tube: aerodynamically curved cooling fins of 0.10-inch thickness, bosses (0.25-inch diameter and 0.25-inch height with a 0.12-inch diameter through hole), a flange (2.0-inch outside diameter and 0.2-inch thickness) and an end plug. These results demonstrate the ability to add metal to existing substrates and machine back to desired feature forms. A similar approach could be applied to repair of metallic components. No surface-connected voids were found in any of these added features. The results of die-penetrant testing of the flange are shown in Figure 2. In each case, the geometry was first defined in a computer-aided design (CAD) file, computer-numerical controlled (CNC) G-code developed to define the laser path along the curved surface of the tube and previous build material, and intermediate and final CNC G-code developed to define metal removal to achieve the final feature shape and surface finish. The flange was added with the aid of a 4-axis trunnion, which allowed

the part to rotate and translate under the metal application head. Although this build was part of a developmental effort and proof of concept, production of a 4.0-foot-long tube with a flange, end cap, 12 cooling fins, and 12 bosses was estimated to be less than 16 hours.

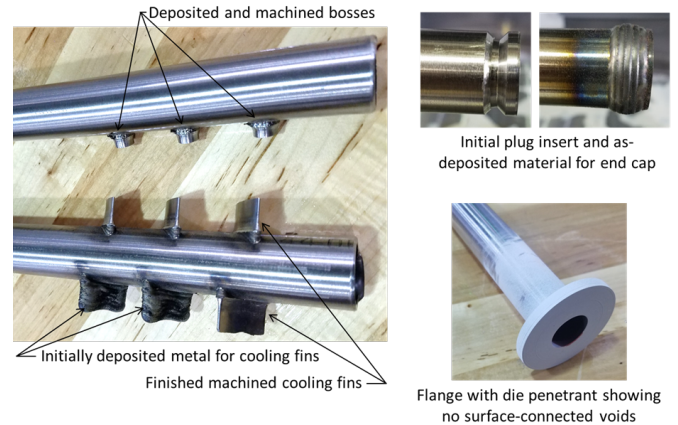
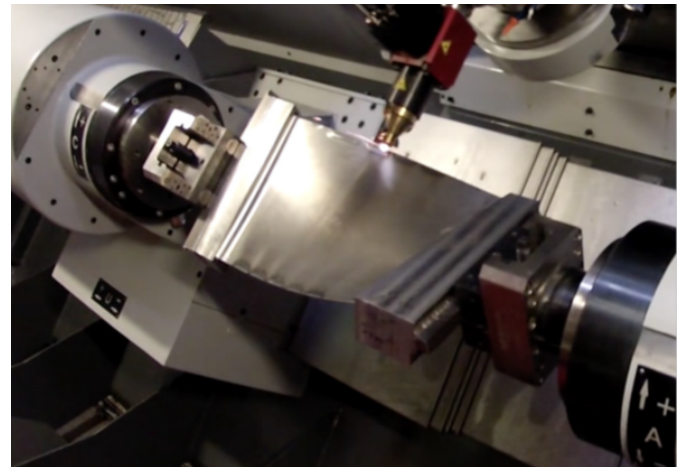


Figure 2: Representative build features via DED AM.

Hybrid DED AM Repair Examples

This machine-build-machine-inspect methodology has been proven with the proposed AMBIT™² system on turbine and impeller blades for GE, Alstom, Cummins and other premiere engine manufacturers (see Figure 3). A hybrid repair methodology for a variety of GE blade models is now certified (a world first).



² AMBIT is a trademark of Hybrid Manufacturing Technologies.

Figure 3: Single set-up repair of a gas turbine blade edge with AMBIT system integrated into a 5-axis milling machine.

COLD SPRAY

Principles of Cold Spray

In the cold spray process shown in Figure 4, micro-sized metal particles are supersonically accelerated toward a substrate, where collision results in significant plastic deformation, mechanical interlocking, and metallurgical bonding of the particles to the substrate and/or previously deposited layers of particles. During the process, the metal particles never reach melting temperatures, but are fused through kinetic energy transfer and adiabatic shearing processes, therefore substrate heating is minimized, dimensional stability is maintained, and unwanted thermal effects (heat affected zone, thermal stresses, dilution layer formation, etc.) are avoided. Figure 5 shows a cold spray system that can be controlled very accurately with the use of a robot. Hand-held operation is also possible; however, at a reduced level of application fidelity. Figure 6 shows a close-up of a nozzle, which is typically made of a high-temperature plastic.

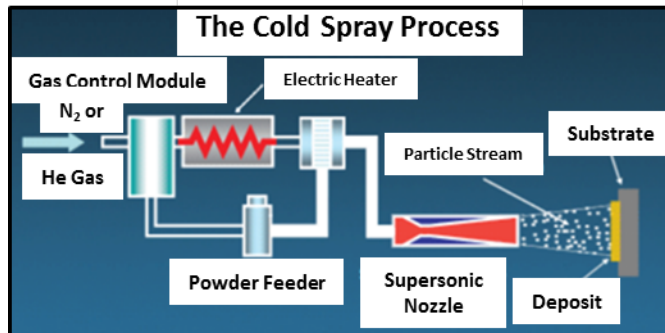


Figure 4: Schematic of a high-pressure cold spray process.

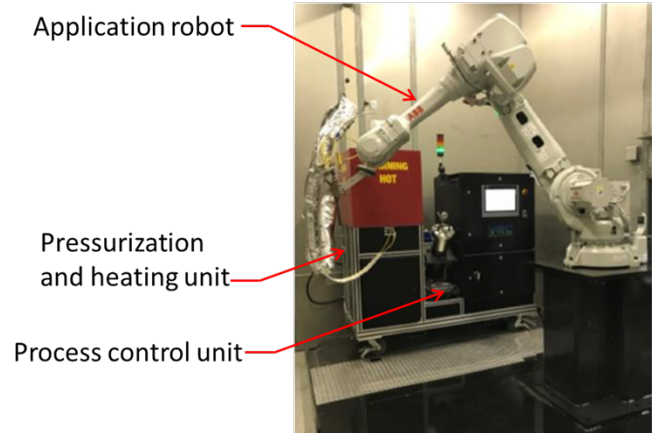


Figure 5: Robot-assisted cold-spray system.



Figure 6: Typical cold-spray nozzle.

Cold spray deposited metals exhibit low porosity (< 1%), and exceptional mechanical strength (> 60 ksi) and adhesion (> 10 ksi), where grain size and structure can generally be maintained from the powdered state to the as-deposited condition. Another benefit of this technology is that it produces a high density, high hardness, and cold-worked microstructure with beneficial compressive residual stresses, which retard crack propagation and improves the corrosion fatigue resistance similar to shot peening.

In the past few years, significant advancements have been made in the field of cold-spray technology, which have led to very high-strength deposits. For example, the use of high-pressure cold spray (> 500 psi) has been shown to be capable of producing coatings of superior mechanical strength and adhesion, making it suitable for some structural applications [2]. Furthermore, the cold-spray technique has the ability to spray a wide variety of materials, and can even include ceramics to create in-situ metal matrix composites for wear resistance. The

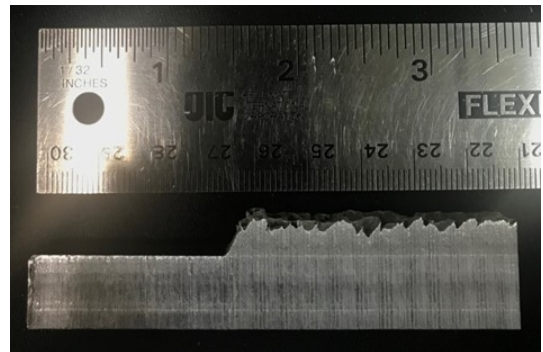
composition of the coating can also be specifically tailored to meet the corrosion requirements of the components, through an understanding of the corrosion potentials of the substrate and coating. In this way, coatings of a neutral, anodic, or even a cathodic nature can be designed and applied [3].

The cold-spray deposition process has significant advantages over conventional thermal spray technology especially in terms of preventing undesirable phase formation, avoiding oxidation and retaining properties of original material. Another benefit of this technology is that it produces a high density, high hardness and cold-worked microstructure with compressive residual stresses present in the deposition, instead of the tensile residual stresses typically associated with thermal spray processes. Exceptionally high bond strengths can be achieved with cold spray and metallurgical bonding can be achieved because of mutual deformation and adiabatic shearing processes between the coating material and substrate on impact [4, 5]. Regions of recrystallization with preferential grain orientation and regions of high dislocation densities were also observed at the interface of cold-sprayed depositions [6, 7]. Since the particles are bonded in the solid state, the resulting coating is also highly cold-worked, which increases the hardness when compared to parent material.

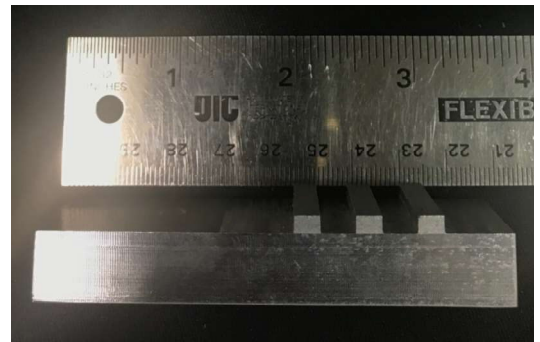
Cold-Spray Repair Examples

Currently fielded examples of cold-spray repairs for DoD and commercial parts include mostly aluminum and magnesium components such as transmission and other housings, various panels, actuators, pump casings, power shafts and a few tube structures. These repairs include addition of material in high-wear areas such as fastener attachment locations. As with DED AM discussed above, cold spray repairs require excess metal be applied as the final build mass is not controlled to feature tolerances commonly needed for most finished components. Final machining is required to achieve the desired tolerances and surface finish

for the majority of applications to which cold-sprayed metal is applied, as shown in a cold spray test sample in Figures 7 and 8.



(a) As sprayed



(b) As machined

Figure 7: Thick cold-spray build.

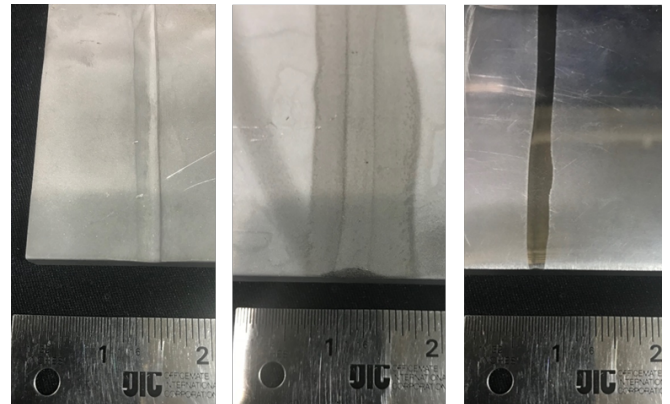


Figure 8: Divot repair cold-spray trial before/after machining.

While cold spray can be used for applying a wide range of materials, a primary thrust area for cold spray is in aluminum alloy applications. Efforts involving 6000 and 7000 series aluminum alloys

for aircraft component repair are continually being developed and optimized for non-structural component repairs with more recent developments leading to potential use for structural component repairs.

LIMITATION OF LASER POWDER BED FUSION (L-PBF) REPAIRS

Severe limitations exist with applying the L-PBF AM process to repair of metallic components. Repair surfaces must be flat, parallel to the build plate surface, and at the extreme location of the part so as not to interfere with the recoating mechanism. Illustrating this approach, CTC prepared fracture toughness and fatigue crack growth rate (FCGR) specimens to measure through-thickness crack behavior of a thin metallic layer of Inconel 625 clad onto a steel substrate. To complete the test specimens, material needed to be added to the top of the cladding where the load application holes are located, as illustrated in Figure 9. These test specimens were first welded to a L-PBF build plate, and the top surfaces of all specimens were then machined flat and parallel to the surface of the build plate. Laser scanning provided a point cloud from which a solid model was prepared for definition of the laser path during L-PBF addition of metal on top of the cladding. The method provided useful test samples, thus permitting meaningful crack characterization in the thickness direction of fracture toughness and FCGR specimens.

A similar process could be followed for parts requiring repair or metal addition by the L-PBF process. Because of the limitations of this AM repair method, no further discussion is provided for this method in the present paper.

SUMMARY OF VIABLE METALLIC REPAIR METHODOLOGIES VIA AM

Table 2 summarizes several factors to consider when considering the use of AM for repair of metallic components. As the technology matures in the next several years, additional viable processes may be added and the table updated with then-current information.

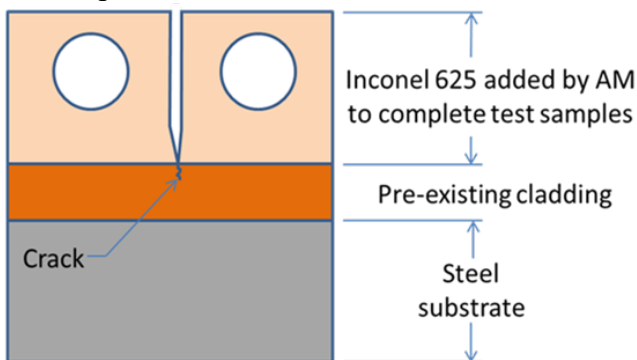


Figure 9: Fracture toughness or FCGR test specimen completed via L-PBF AM processing.

Table 2: Comparison of Hybrid DED AM and Cold Spray Repair

Factor	Hybrid DED AM	Cold Spray
Current alloys available	nickel, stainless steel, cobalt, bronze, tool steel, copper, metal matrix composites (aluminum and titanium under protective environments)	aluminum, magnesium, titanium, nickel, copper, steel, zinc, tin, metal matrix composites
Bond strength	similar to parent material	typically 10–30 ksi
Metal application rate	0.1–2.5 kg/hr [8]	Up to 42 kg/hr [9]
Typical carrier gas	argon	helium, nitrogen, air
Comments	build volume limited by size of CNC working volume, laser-safe enclosure required, line of sight process, allows machining independently of AM; system may be used for laser welding, marking or drilling	systems may be portable, < 1.0% porosity is common, highly deformed particles, solid-state process, requires ductile substrate, builds have low ductility in sprayed condition, high cost of carrier gas, ear protection required, line of sight process, dedicated process equipment

VISION FOR REPAIR OF DOD ASSETS VIA AM PROCESSES

The following four-phased approach is envisioned for application of AM processes to repair DoD assets.

Phase 1: Identify parts that would benefit from repair by AM processes

Phase 2: Develop process conditions that meet performance requirement for each associated alloy

Phase 3: Qualify the process for use as a repair technology

Phase 4: Plan and execute the repair

Although some effort has been expended by the Army Research Laboratory to identify potential applications for cold-spray repair of metallic components [10], little has been done to the authors’ knowledge to identify a comprehensive list of DoD repair applications for DED AM. When identifying the potential list of parts amenable for repair by DED AM or cold spray, one must classify components according to several criteria including alloy, overall size, common repair requirements, required properties, accessibility for repair by the given technologies, mission criticality and other requirements. Application of DED AM requires removal of the component from the weapon system for treatment in the DED AM work cell. On the other hand, in some cases, portable cold-spray equipment may be brought to the location of the part to be repaired. However, one must consider other factors associated with cold spray such as the excessive noise caused by cold spray, overspray, finished machining and their impacts to neighboring system components.

Although large repair systems were emphasized in this paper, small components (less than 4.0 inches on any side) may also be repaired by either of the two processes. Finally, any list of potential components will likely need to be periodically updated as AM technologies continue to mature and expand. Reliance on currently available information on properties, repeatability and costs must be used. Guidelines for determining whether a part should be replaced or repaired must also be developed.

Phase 2 efforts must go beyond merely adding metal and testing the mechanical properties of the bulk material and the bond strength with substrate materials. Post processing, which may include stress-relief, hot isostatic pressing (to heal porosity), heat treatment and surfacing, will be required for many components to meet all of their performance requirements. Surface cleanliness requirements, acceptable cutting fluids (especially during the initial surface preparation step prior to

metal addition) must be defined and acceptable environmental conditions specified.

Clearly, any repair process must demonstrate its ability to consistently meet defined performance requirements, which includes several mechanical properties such as tensile strength, fracture toughness, fatigue resistance and others. Some applications require repairs to meet certain physical properties such as thermal conductivity, pressure tightness or magnetic permeability among others. In many DoD applications, qualification does not merely apply to a process, but to specific components as well. Phase 3 qualification requirements, including estimated costs to complete qualification, should be included in the information collected in Phase 1. In addition, limitation on the size and location of acceptable repairs must be identified.

Once a qualified process is defined and a part is ready to be repaired in Phase 4, a repair procedure/plan is required. If a computer solid model is available, it should be used as the basis for identifying a datum, the amount and location of material to be removed to create a known high-quality surface upon which to build, a plan for addition of metal, and all final and intermediate machining operations required. Ideally, each component would be scanned and fit to the CAD solid model to determine a precise location for metal removal and addition. Masking to shield other surfaces from overspray or machining debris may also have to be incorporated into the repair plan. Finally, intermediate and final inspection must be planned to ensure the repair is progressing successfully. Any post processing may then be applied and the part returned to active use.

CONCLUSIONS

1. Hybrid DED AM is useful for repair of many metallic components.
2. Cold spray has been successfully applied to the repair of several metallic components for the DoD.

3. L-PBF has limited practical use for repair of metallic components.
4. Prior to wider application of AM repair technologies in the DoD, qualification for specific alloys, and in some instances for specific components, must be completed.
5. As AM processes continue to mature, expect an increase in the number of parts repaired by AM processes for both DoD and civilian applications.

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