Technical Evaluation Report

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ABSTRACT

This specialists' meeting brought together technical experts in net shape manufacturing to share experiences and lessons learned, obtain a better understanding of the state of the art and assess the technology readiness of competing manufacturing processes. One goal was to identify the benefits of net shape technologies for military applications in terms of cost, lead time and environmental impact. Other goals included spotlighting gaps in existing technology and identification of future military requirements with an overall objective to reduce manufacturing costs for existing and future military systems.

The scope of the meeting primarily encompassed net shape technologies applicable to metallic components with some technologies applicable to ceramic components and to a lesser extent to composite components. Processing categories included both mature powder metallurgy hot isostatic pressing (PM/HIP) and powder injection molding and relatively immature additive manufacturing (AM) deposition processes using laser or electron beams. Improved non-destructive inspection technology was identified as a major need for use of PM/HIP for critical components, and automatic processing control was cited as a key to realizing the great potential of AM deposition processes.

EXECUTIVE SUMMARY

Net shape processing can significantly impact both the unit acquisition costs and life cycle costs for military systems. Processes which manufacture components near to final dimensions, use minimal or low cost tooling and require only minor finish machining have significant advantages over conventional processing methods for cost effective manufacture and repair. Use of net shape processes can simultaneously minimize wastage of material feedstock, reduce component cost and shorten procurement lead time. A specialists' meeting was held to assess the state of the art and technical readiness of competing net shape processes.

Although some processes covered were applicable to ceramic materials and to a lesser extent to composites, the meeting was primarily focused on processes for metallic components. With few exceptions, processes could be categorized as either powder metallurgy (PM) consolidation processes or additive manufacturing (AM) processes. The PM consolidation category included both PM hot isostatic pressing (HIP) and powder injection molding (PIM). The AM category included powder bed based processes, but the predominant coverage was on fusion-based, direct deposition using laser or electron beams.

PM/HIP, the most mature type of net shape process, is extensively used for manufacturing relatively simple shapes and non-critical components for aerospace and other industrial sectors.

Advances in process modeling and tooling design have made PM/HIP viable for more complex parts involving high performance alloys. However, use of PM/HIP for critical components, particularly in aero engines, has been hampered by inability to inspect for certain defects and will require significant improvement in non-destructive inspection techniques. PIM type processes are also mature and attractive for geometrically complex parts in large batch sizes but are limited to manufacture of small parts of relatively uniform thickness using sinterable materials. PIM processes have achieved significant market penetration for ceramic casting cores, electronics/packaging and telecom. Their use is small but growing in the aerospace sector where variants using inexpensive tooling are more attractive for small batch sizes.

AM deposition processes possess enormous potential, but they are highly complex and relatively immature. They are being exploited for repair of very high value tools and components that are often unrepairable by other means. Use for original component manufacture is limited and hampered by many factors including: inapplicability of conventional design and qualification methods, inadequate understanding of process-property relationships, lack of process specifications and incomplete understanding of the application value stream. Development of automatic process control is a key to the breakdown of these barriers. A likely breakthrough is anticipated for hybrid applications where AM processes are used to add features to simplified conventionally manufactured parts. AM processes offer new freedom to design engineers to create structural shapes and forms that are not possible using conventional processes.

Enhanced awareness among the user community and integration into the design community are essential to realization of the full potential of net shape manufacturing. A lecture series is recommended to educate the wider military technical community on the benefits and state-of-the-art in net shape manufacturing. Although repair of high value tooling and components was an early application, the potential of AM processes for sustainment of aging military systems is largely unrecognized. A follow-on specialists' meeting should be planned to address the role of net shape manufacturing for sustainment and repair.

INTRODUCTION

Balancing systems capability and systems affordability presents an on-going challenge to military customers. Systems affordability requires that technology be addressed for both unit and life cycle cost improvement. At the component level the choice of materials and manufacturing processes has a critical impact on unit cost. Prevailing manufacturing processes often require high tooling costs that can only be spread over relatively few units while the service conditions for the part demand expensive materials of which more than 80% is lost as chips during machining of a final shape. A wide range of net shape manufacturing processes have been the subject of extensive research for several years particularly in the aerospace sector. These processes, some of which have achieved or are nearing production readiness, are characterized by the production of components near to final dimensions using minimal or low cost tooling and requiring only minor finish machining. Thus, employment of net shape processes can maximize the "use to buy" ratio (generally know as the fly to buy ratio in the aerospace sector), significantly reduce component cost and shorten procurement lead time. In addition to original component manufacture, net shape processes can reduce the life cycle costs of existing systems; net shape technologies offer effective capability for repair and refurbishment of components and expensive hard tooling as well as cost-effective capability for making small numbers of replacement parts for sustainment of aging systems. Clear environmental benefits can flow from exploitation of net shape technologies through more efficient use of materials resulting in both net energy efficiency and minimization of the manufacturing waste and reclamation stream.

This specialists' meeting on "Cost Effective Manufacture by Net Shape Processing" provided an opportunity for technical experts from NATO nations to share experience and lessons learned as well as to obtain a better understanding of the state of the art and the technology readiness of competing manufacturing processes. The scope of the meeting encompassed net shape technologies applicable to metallic and ceramic components with only incidental coverage of technologies for manufacture of fiber-reinforced composite components. One goal of the meeting was to identify the benefits of net shape technologies for military applications in terms of cost, lead time and environmental impact. Other goals included spotlighting gaps in existing technology and identification of future military requirements that may provide a technology pull. The overall objective was to help nations reduce manufacturing costs of existing and future military systems.

A total of 20 papers were presented at the meeting with two papers having been withdrawn. Authors represented seven NATO nations: Belgium, Canada, France, Germany, Italy, the United Kingdom, and the United States. One invited speaker was from The Laboratory of New Technologies, Russia. The meeting was well attended with a total of 65 attendees and from 30-50 participants at all sessions. In general, the papers were of good quality and stimulated spirited discussion during question and answer sessions as well as the concluding technical evaluation session.

EVALUATION

The net shape manufacturing processes covered fell into three broad categories: (1) powder metallurgy (PM) based consolidation processes, (2) additive manufacturing (AM) processes, and (3) novel processes. PM consolidation processes involve creation of a dense, near net shape preform from powder starting stock through application of heat and pressure. Distinguishing characteristics among various PM consolidation processes include the type and composition of powder starting stock, whether or not debinding and/or sintering steps are necessary, the types of molding materials and tooling employed, and the pressing method. AM processes are a form of direct manufacturing in which a part is built up in layer-by-layer fashion. The AM processes covered in this meeting involve the freeform manufacture of a solid near net shape on a substrate without the use of molds and were generally of two types: computer-controlled deposition processes and powder bed sintering processes. The novel processes comprise those that share few common characteristics and that do not easily fit in the PM or AM categories.

Among the variety of PM consolidation processes under development, two types were covered in this specialists' meeting. PM hot isostatic pressing (HIP) involves the hydrostatic compression of metal powders into a dense monolith within an evacuated, sacrificial vessel or envelope that is removed by machining or selective chemical dissolution after consolidation of the near net shape. Key elements of the process which is variously known as PM/HIP, PHIP and net shape HIP include carefully controlled powder filling to achieve a uniform packing density and computer modeling of the pre-consolidation powder envelope and the densification profile.

A second type of PM consolidation processes can be grouped under the banner of powder injection molding (PIM) which is patterned after plastic injection molding. PIM entails the pressurized injection of a mixture of fine metallic, ceramic or carbide powder with a molten polymeric binder into a mold. The polymer binder is extracted by a chemical and/or thermal debinding step leaving a loosely-packed, porous network or "green" body. A dense, solid near net shape is produced by sintering the green body to eliminate voids left behind when the binder was extracted; during sintering at a temperature below the melting point of the feedstock powder, material is diffused into the voids leading to overall part shrinkage. Variants of PIM include metal injection molding (MIM) and low pressure injection molding (LPIM). MIM uses metallic powders in the feedstock and may include a final HIP step after sintering. LPIM can be considered an adaptation of MIM using lower injection pressure that allows the use of less-expensive tooling for smaller batch production.

The AM deposition processes covered in this meeting were of the fusion-based type where a near net shape preform is built-up layer by layer through the addition of material feed stock to a moving melt pool that follows a pre-programmed path. The primary distinguishing characteristics among these AM deposition processes are the type of feedstock and the type of energy source used to maintain the melt pool. Feedstock can be metallic powder, wire or ribbon, and the energy source may be a laser, an electron beam, an electric arc or a heated plasma. The deposition head which brings together the feedstock and the energy source may be moveable or stationary, and control of the build path is accomplished through computer command of some combination of translation and rotation stages, gantry and/or robots.

The powder-bed based AM processes involve the sequential addition of a powder or paste layer followed by selective fusion of powder particles using a computer-steered laser or electron beam. Once sufficient layers have been added to achieve full thickness, the entire part may be subjected to debinding and sintering steps depending on the powder or paste composition.

KEYNOTE PAPERS

The meeting was kicked off by three keynote papers on use of net shape processing for various applications that were intended to represent the view of the user community. Two of the keynotes were on aerospace applications and are indicative of the concentration of interest for high value applications in that sector. In contrast, the other keynote offered a stimulating look at a specialized application for the ground sector utilizing unique attributes of AM processes.

Paper 1 by Wayne Voice concentrated on processes with potential for achieving high fly to buy ratios for aero-engine component applications by significantly reducing manufacturing waste. Primary emphasis was placed on PM consolidation processes, reflecting their near-term promise and relative maturity, with somewhat lesser coverage of still maturing AM processes. Progress in PM Hot isostatic pressing (HIP) of large, complex nickel-based alloy components was described, and the recently-accomplished PM/HIP of a Ti-6-4 compressor case was shown and compared favorably to cases made from conventional machined forgings. Although further cost improvements are needed, PM/HIP components were shown to have superior mechanical properties and microstructure and to require only half the lead time. Progress in metal injection molding (MIM) of nickel and titanium alloys and stainless steels was described and indicated to be attractive for small components such as stators.

Paper 2 by Benton Gady described a mobile part manufacture and repair system for use near the battlefield. Originally known as the Mobile Parts Hospital, the Rapid Manufacturing System is composed of modules that can be carried in standard shipping containers and located near the point of need. One module contains an AM machine using the Laser Engineered Net Shaping (LENS) process. A second module contains a 5-axis multitask machining center which is used to finish machine parts from near net shape preforms manufactured by the LENS machine using a 3-D CAD model of the needed part. Because of the limitations of the first LENS module including inadequate deposition rates, a second generation LENS system employing a 3 kW fiber laser has been developed with a build rate goal of 12 in^3/hr and is currently under going testing. Although the practical capability of a LENS system in the near battlefield environment has yet to be demonstrated, the potential impact of such systems to reduce vehicle repair downtime and simplify replacement parts logistics is clearly significant. Rapid repair capability will enable the battlefield commander to more effectively employ his assets and preserve the lives of his soldiers. Such mobile manufacturing capabilities have obvious applications in the air and naval forces as well.

Paper 3 by Pamela Kobyrn provided a comprehensive evaluation of AeroMat's Laser Additive Manufacturing (LAM) process for producing Ti-6Al-4V aircraft structures. LAM utilizes powder feedstock and a high-wattage CO_2 laser to build preforms layer-by-layer onto a substrate in an inert gas environment. The most emphasized application of LAM was for manufacture of rib-web components such as bulkheads, spars and ribs. Other applications such as manufacture of turbine engine cases and repair of blades and vanes were discussed. Extensive study of the economics, process-property relationships and other characteristics of LAM have led to identification of the challenges posed for realization of the enormous potential of AM processes and barriers to successful implementation for production of aerospace components. Key lessons learned which are generally applicable to similar AM processes regardless of energy source or feedstock include: immature state of AM does not allow use of conventional component design and qualification methods; adequate understanding of process-microstucture-property relationships requires improved process stability and control; development of process specifications demands more thorough characterization of mechanical properties and their uniformity within a part; full understanding of AM value steam and supply chain economics including market pressures and advances in existing technologies is required to realize expected advantages of AM in cost and schedule; pre-production process optimization activities for given part, typically trial and error, must be minimized; elimination of point design philosophy and its inherent cost and schedule detriments demands use of a broader process qualification approach.

POWDER METALLURGY CONSOLIDATION PROCESSES

In addition to the keynote paper previously discussed, six additional papers reported on PM consolidation processes. Three of these papers were either completely or partially on PM/HIP, and the other three papers were on PIM/MIM.

Paper 4, by Victor Samarov of the Laboratory of New Technologies, was an invited presentation that reviewed the state of the art in PM/HIP with a focus on application for heavily-loaded, critical components. Process maturity for relatively low complexity components was indicated by the use of PM/HIP to produce many thousands of turbine and compressor disks for auxiliary power units in the United States and jet engines in Russia. For more complex parts, PM/HIP has been shown to be a viable competitor to investment casting and machined forgings, providing typical wrought property levels at lower cost. In general, cost savings increase with the size of the component, and size is only limited by the size of available HIP furnaces. Numerous commercial applications have been found outside the aerospace sector such as in power generation and oil and gas, and materials such as Be, Al/Be alloys, Ti alloys, Ni-based alloys and Re have been employed. The primary challenge associated with achievement of complex near net shapes is the large shrinkage, 30%, that occurs during PM/HIP. This problem is being attacked by advanced process modeling to account for deformation of both powder and tooling including plastic and creep deformation and material property evolution during the HIP cycle. Improvements are also being sought in tooling design and materials, manufacturing of sacrificial and reusable tooling elements, powder and tooling out-gassing procedures, and efficient de-canning techniques.

Paper 5 by Xinhua Wu presented results from a study of manufacture of a small, cylindrical Ti-6Al-4V demonstrator engine case by PM/HIP from Plasma Rotating Electrode Process (PREP) powder and using tooling designed with advanced process modeling. Out-gassing duration was shown to have little effect on tensile properties which were comparable to those of ring-rolled Ti-6Al-4V with failure by ductile fracture. The demonstrator showed good integrity, and measured dimensions of the demonstrator compared well with computer predicted target dimensions.

Paper 6 by Michel Pierronnet reviewed the key attributes and benefits associated with PM/HIP and presented example applications for aero engines, gas turbines, rocket engines and tooling. Inherent process flexibility allows incorporation of intricate shapes and internal details such as cooling channels, production of tailored-property coatings for wear or corrosion resistance, and integration of inserts of a third material in PM/HIP consolidated components. Dimensional accuracy equal or better than that of precision casting can be achieved, and surface roughness can be controlled through choice of hardness of tooling materials. PM/HIP not only produces a homogeneous, fine-grained microstructure without segregation, but permits use of more highly alloyed grades that cannot be used in cast or wrought processing. Applications most suitable for PM/HIP were associated with high performance alloys, complex geometry, relatively large size, and batches of 100 to 500 units. Improvement of non-destructive inspection techniques was cited as a need for full exploitation of the process, and inability to inspect for certain defects was said to be a concern for low-cycle fatigue behavior and to limit PM/HIP applications to static parts or parts not subjected to fatigue loading. This latter point received considerable discussion with sharp disagreement between users and suppliers. Example applications shown included: aero engine cases made of PM Astroloy, TA 6V, and γ TiAl; an alloy 625 diffuser for an aircraft gas turbine; an Astroloy gas generator for the VULCAIN rocket engine on the ARIANE V; and an N18 super alloy hot forging die block.

Paper 7 by Eric Baril summarized the state of the art and research activities related to PIM. Components attractive for manufacture by PIM generally involve: annual production rates of more than 5,000 units, relatively high part complexity, wall thickness from 0.1 to 5.0 mm, a largest dimension from 1.5 to 137 mm and a sinterable material. Uniformity of wall thickness is highly desirable to avoid voids, internal stresses, distortion and other problems during debinding and sintering. The largest market segment for PIM is ceramic casting cores for insertion in casting cavities to form internal features such as cooling passages. Other segments with high penetration by PIM are electronics/packaging, telecom and instrumentation using materials including Fe/Ni, Kovar, W-Cu, and Mo-Cu. Although level of penetration is low, growth rate of PIM in the aerospace sector is high with R&D activities concentrated on Ni-based and Co-based superalloys and Ti alloys.

Paper 8 by Benoit Julien described research supporting development of a low pressure injection process (LPIM) for manufacture of complex-geometry Inconel 625 components for gas turbine application. LPIM is an adaptation of the MIM for economical production of smaller batches of 5,000 to 10,000 units which are typical of the aerospace industry. Low injection pressures, less than 50 psi, that permit the use of relatively inexpensive tooling, produced good quality parts. A thermal debinding treatment was developed to extract the binder in a pure Ar atmosphere and was shown to eliminate binder degradation byproducts and avoid carbon contamination. Sintering in a mixture of H_2 and Ar was shown to promote homogenization of the alloying elements and dissolution of second phase particles found in the feedstock powder while achieving 96% of theoretical density.

Paper 9 by Siegfried Sikorski discussed development of the MIM process for manufacture of superalloy jet engine components. MIM is considered attractive for relatively small parts involving high volume production such as high pressure compressor vanes made from Ni-based alloys. Complex geometrical features were molded into the green part to minimize finish machining. The debinding and sintering steps were carried out as batch operations. Because of the large shrinkage special considerations during sintering include: uniform temperature distribution, optimizing the sintering profile to achieve high density and required grain size, special setters to prevent shape deviation and distortion, and adjustment of heating and cooling rates to reduce distortion and shrinkage stress. After sintering, HIP is used to close any residual porosity for highly loaded parts, and airfoil sections are surface finished by machining and tumbling. Testing has shown MIM vanes have strength and ductility as well as high cycle fatigue strength similar to forged material. Brazed clusters of MIM processed vanes have been qualified for engine testing.

ADDITIVE MANUFACTURING PROCESSES

In addition to the three keynote papers, nine additional papers collectively provided extensive coverage of various aspects of AM processes. The preponderance of the papers involved laser based deposition processes, and one paper described an electron beam deposition process. Powder bed based processes were the subject of one paper, and another covered powder bed based and laser deposition processes. One paper described the sequential, solid state lamination of metal foil tape by ultrasonic welding.

Paper 10 by Gilles Surdon constituted a preliminary report on cooperative laser direct manufacturing research in the French aerospace industry. This project has involved both LAM and LENS processes as well as a selective laser melting process. Results presented primarily indicated the potential of these processes for short lead times, shape flexibility, and low non-recurrent cost.

Paper 11 by Johannes Vlcek described research on the properties of Ti-6Al-4V produced by direct laser deposition (laser cladding) and by two powder bed based processes, laser sintering and electron beam sintering. Observed differences in light element contamination levels and microstructural coarseness were attributed to differences in the atmosphere and heating levels inherent in the processes. Overall, laser deposited material showed the best balance of static strength and ductility. Heat treatment of laser deposited material showed a substantial improvement in fracture toughness but had little impact on high cycle fatigue response.

Paper 13 by Martin Hedges reported the state of the art for manufacture and repair of components for defense and other applications using the LENS process. Case studies were presented for manufacture of a wide variety of parts from Ti-6Al-4V and 316 stainless steel including a helicopter gas thruster, a suspension mounting bracket and a gearbox spider for F1 racing automobiles, a dual-wall turbine engine exhaust duct, and prototype satellite housings. Examples of cost effective repair, delicate structure repair and repair of otherwise unrepairable parts were presented including gas turbine engine components for the M1 tank, submarine cooling system ball valves, Inconel 718 turbine engine compressor seals and helicopter engine blisks. Near term prospects for increased use of LENS for repair applications were considered more favorable than for original equipment manufacture.

Paper 14 by Anne-Marie Clarinval described the manufacture of near net shape components using the powder bed based Optoform laser curing process. Parts are built and cured layer by layer using a spreadable paste containing resin, powder fillers and additives. Although parts such as gaskets can be made directly, supplemental debinding and sintering steps are required to produce dense metallic and ceramic parts from a green preform in a manner similar to PIM/MIM processes.

Paper 15 by Lijue Xue reported on a laser based AM process similar to LENS that employs powder feedstock that can produce parts with acceptable as-built surface finish without supplemental machining. This process can also produce very intricate, complex and thin-walled structures. Both of these advantages are attributable at least partially to a smaller melt pool and a much smaller deposition rate than with most similar processes. Good mechanical properties were demonstrated in Ni-base IN-625 and IN-738 superalloys, Ti-6Al-4V, Co-base Stellite 6 alloy and CPM-9V tool steel. Several example parts were shown with complex, thin-wall structures and excellent surface finish.

Paper 16 by Karen Taminger reported on an electron beam based AM process that employs wire feedstock. Salient features of this process are operation in vacuum, high power and feedstock efficiencies, and very high deposition rate capability. This process has been successfully used with Al, Ti, and Ni-based alloys but can theoretically use any electrically conductive material. Results presented showed that deposit microstructure was controllable through variation of processing parameters. Mechanical properties of e-beam deposited 2219 Al and Ti-6-4 were consistent over a relatively wide processing window and were comparable to wrought versions of these alloys. In addition to applications typical of other AM processes, this e-beam process is being explored for in-space fabrication.

Paper 17 by Jeff Allen presents results from an investigation to analyze and compare the cost of AM of aero engine components versus machining. Although this analysis employed many simplifying assumptions and did not include the complete process stream, it did confirm that AM is generally more attractive for components with high buy to fly ratio having complex shapes and made from expensive and/or difficult to machine materials. Early generation AM technology was deemed to be attractive for components with buy to fly ratios of 12 or higher for conventional processes, and a ratio of 3 was projected with potential AM process improvements.

Paper 18 by Phil Carroll reported on the effect of Waspaloy powder feedstock recycling on the characteristics of laser deposited parts. Because powder catchment efficiency is relatively low, 5 % for this study, large amounts of powder are available for reuse in laser deposition processes. Initial results showed that recycling powder up to 10 times did not introduce contaminants or cause the emergence of new phases in deposits, but microhardness increased and surface roughness decreased as the number of reuse cycles increased. Mechanical properties were not reported and no estimate of recycling impact on processing cost was offered.

Paper 21 by Dawn White presented a summary status of a solid state AM process that employs ultrasonic welding of metal foil tape to produce a net shape part by sequential lamination. The solid state nature of the process renders it attractive for a wide range of material combinations as well as non-equilibrium chemistries. Primary current application is rapid tooling manufacture for investment casting. Work was reported in Al alloys, metal laminates (Ti-Al, AL-Cu, Ni-Ti), SiC fiber reinforced Al composite and as well as optical fibers and shape memory alloy fibers embedded in 3003 Al.

NOVEL PROCESSES

Paper 20 by Marco Regi reported on the manufacture of complex geometrical structural components using rapid prototyping and laser sintering processes. Structures produced included flat, cylindrical and conical multigrid lattices made of polymeric composites and metallic alloys. Direct manufacturing of micro and nano particle reinforced polymer composites was demonstrated, and addition of 10% carbon micro particles by weight produced a 12% increase in Young's modulus. Direct laser sintering of bronze multigrid lattice structures was also demonstrated with post processing by shot peening, sandblasting and ultrasound to improve surface finish.

Paper 22 by Jean Savoie reported on the manufacture of hollow, axisymmetric components for aero engine applications by flow forming. This process utilizes rollers to compressively deform a preform mounted on a rotating mandrel, forcing the preform to flow and match the mandrel's shape. Results were presented for flow forming of a 410 stainless steel gas generator case at significantly lower cost and with comparable microstructure and mechanical properties as compared to a machined ring forging.

CONCLUSIONS

Net shape manufacturing offers clear potential for reduced cost, shorter delivery time and enhanced performance as compared to conventional processing. Maximum benefits are obtained for complex components made from expensive and hard to machine materials. Other benefits include significantly higher material usage efficiency and overall energy efficiency. However, full integration into the design community is essential to realization of the full potential of net shape manufacturing. Applications will increase with user experience and as confidence builds within the design community. Environmental benefits associated with net shape manufacture need to be included in life cycle cost analysis.

The net shape processes covered in this meeting varied widely in maturity and extent of application. In general the PM consolidation processes are considerably more mature than the AM processes; their process economics are better understood, the characteristics of favorable applications are well identified, and markets are being pursued aggressively.

PM/HIP, the most mature type of net shape processes, is extensively used for manufacturing relatively simple shapes and non-critical components for a variety of industrial sectors in addition to aerospace. Inherent PM/HIP process flexibility and advances in process modeling and tooling design have made it a viable competitor to conventional processes for more complex parts yielding wrought property levels at lower cost. Applications involving high performance alloys and complex geometry in batches of 100 to 500 units are considered favorable to PM/HIP, and cost savings increase with part size. Use of PM/HIP for critical components and parts subject to fatigue, has been hampered by the inability to inspect for certain defects, a particularly acute concern for aero engine applications. Full exploitation of the PM/HIP process will probably require significant improvement in non-destructive inspection techniques.

The PIM type processes are also quite mature and considered attractive for geometrically complex parts in relatively large batch sizes. However, these processes are generally limited to the manufacture of parts of relatively uniform thickness and limited size as dictated by the requirement that materials be sinterable. Significant market penetration has been achieved for ceramic casting cores, electronics/packaging and telecom. Use of PIM processes is small but growing in the aerospace sector where batches of 5,000 to 10,000 are typical. LPIM which permits use of inexpensive tooling and MIM are being explored for manufacture of Ni-based superalloy compressor vanes for gas turbines.

Although the AM deposition processes possess enormous potential, they are highly complex and relatively immature. Currently they are being exploited for repair of very high value tools and components that are often unrepairable by other means. Exploitation for component manufacture is limited and hampered by many factors including: inapplicability of conventional design and qualification methods, inadequate understanding of process-property relationships, lack of process specifications, incomplete understanding of process economics and the application value stream. A key to breakdown of these barriers is the development of automatic process controls to ensure product quality. A near term breakthrough seems most likely in hybrid applications where AM processes are used to add features and complexity to simplified performs produced by conventional processes. The freeform capabilities of the AM deposition processes allow the creation of new shapes, forms and unitized structures that have previously been impossible using conventional manufacturing processes. Exploitation of this design freedom will likely require new design and analysis methods and demands close collaboration between design and process engineers.

Powder bed based AM processes are more mature than the deposition processes but are more restricted in terms of part geometry, size and materials. These factors and a lack of compelling advantages appear to restrict their potential for wide spread use in net shape manufacturing.

RECOMMENDATIONS

Enhanced awareness of net shape manufacturing capabilities among the user community and integration with the design community were identified as important steps to more fully realize the potential of these technologies. A lecture series is recommended to educate the wider military technical community on the benefits and state-of-the-art in net shape manufacturing.

Although repair of high value tooling and components has been an early application, the potential of additive manufacturing processes for repair and sustainment of aging military systems is largely unrecognized and unexploited. A follow-on specialists' meeting or workshop should be planned to address the role of net shape manufacturing for sustainment and repair.

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