Producing Titanium Aerospace Components from Powder Using Laser Forming

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Titanium is an attractive choice for many components in the aerospace industry; however, its inherently high cost often negates its use. A cost-effective, near-net shape, laser forming approach to producing large and complex parts has been developed and is being commercialized.

INTRODUCTION

The excellent combination of specific mechanical properties (i.e., normalized to density) exhibited by titanium alloys such as Ti-6Al-4V are very attractive for aerospace applications.[1–3] However, the high cost of the final components, resulting from the high cost of producing raw titanium and processing and machining difficulties combined with buy-to-fly ratios that average 5:1 and can often be greater than 20:1, result in titanium being used only when it is the only material that can meet design requirements. There is generally a direct relationship between material cost and volume of use; consumption decreases with increasing cost. Thus, any process that can reduce the cost of titanium components is attractive to the aerospace industry.

One such process is the near-net shape Lasform[SM] process[4–8] being commercialized by the AeroMet Corporation of Eden Prairie, Minnesota. This process, shown schematically in Figure 1, is a laser additive manufacturing (LAM) process that combines high-power laser cladding technology with advanced rapid prototyping to directly manufacture complex, fully dense, three-dimensional components directly from computer-aided design images. The process fabricates shapes from titanium powder and target plates and is performed without the cost of molds or dies. The major advantages of Lasforming are near-net shape components, dramatically reduced delivery times, greatly reduced machining requirements, enhanced design flexibility, the ability to produce grade chemistries, repair capability of broken or worn components, feature addition capability, rapid prototyping, and rapid design modifications.

Development of the basic concept began more than 20 years ago, and technical feasibility and scale-up were demonstrated as part of an R&D program funded by the U.S. Defense Advanced Research Projects Agency, with the Office of Naval Research serving as the technical agent.[4] This work, led by Johns Hopkins University, was conducted over a three-year period with Pennsylvania State University and MTS Systems Corporation, AeroMet's parent company, serving as subcontractors. The program demonstrated the viability of rapid prototyping of titanium-alloy parts and the production of cost-effective components very close to net shape (requiring only a final machining operation) with chemistry, microstructure, and mechanical properties meeting stringent aerospace requirements.

MTS Systems Corporation designed and fabricated the full-scale commercial Lasform system currently located at AeroMet's Eden Prairie facility (Figure 2). The system is being operated in collaboration with the U.S. Army Research Laboratory's Aberdeen Proving Ground, Maryland, as part of a three-year cooperative research and development agreement program to further develop, evaluate, and validate the Lasform process for defense applications in a semi-commercial mode. Independent investor resources have supported the continued development of the process to the point of full commercialization.

THE LASFORMING PROCESS

A schematic of the process is shown in Figure 1, in which titanium powder is fed in a controlled fashion to the workpiece, where it is melted by the CO_2 laser, progressively building up a structure one layer at a time. Thus, for example, complex ribs and flanges can be built up on a starting plate, dramatically decreasing material loss (to machine chips). Typical laser-formed structures are designed to be 0.762–5.08 mm oversize. These built-up structures can be angled as much as 60° from the vertical. The deposition rate can be controlled based on heat-balance effects, so that metallurgically sound interfaces are formed between each fused powder layer. Normally, fully dense parts are produced at a deposition rate of 0.90–4.5 kg per hour. Typical lasformed parts after final machining are shown in Figure 3.

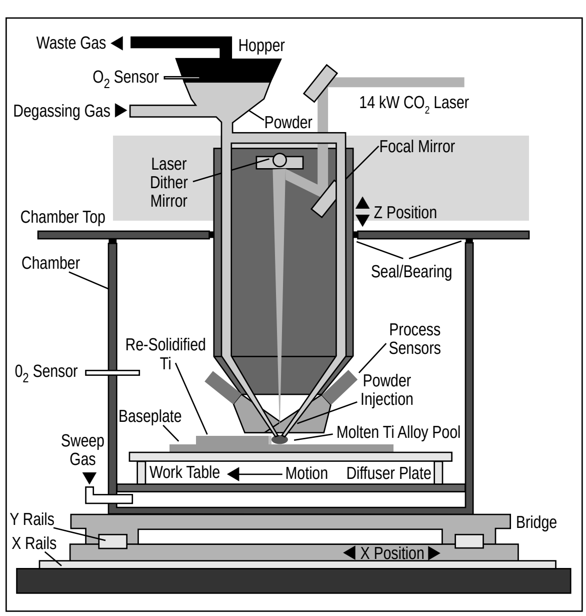

Figure 1. A schematic of the Lasform process.

At least four types of precursor titanium powders[9,10] have been successfully used to date, all in the –40 +325 mesh range: blended elemental (commercially pure titanium powder plus Al/V master alloy), gas-atomized, plasma-rotating electrode processed, and hydride-dehydride prealloyed powder. Good flow characteristics to the workpiece are required. Alloys produced include Ti-6Al-4V, Ti-5Al-2.5Sn, Ti-6Al-2Sn-4Zr-2Mo-0.1Si, and Ti-6Al-2Sn-2Zr-2Cr-2Mo-0.25Si.

The major advantage of the Lasform process is producing complex, laser-formed, near-net shapes (referred to as machining preforms) requiring only final machining and heat treatment.

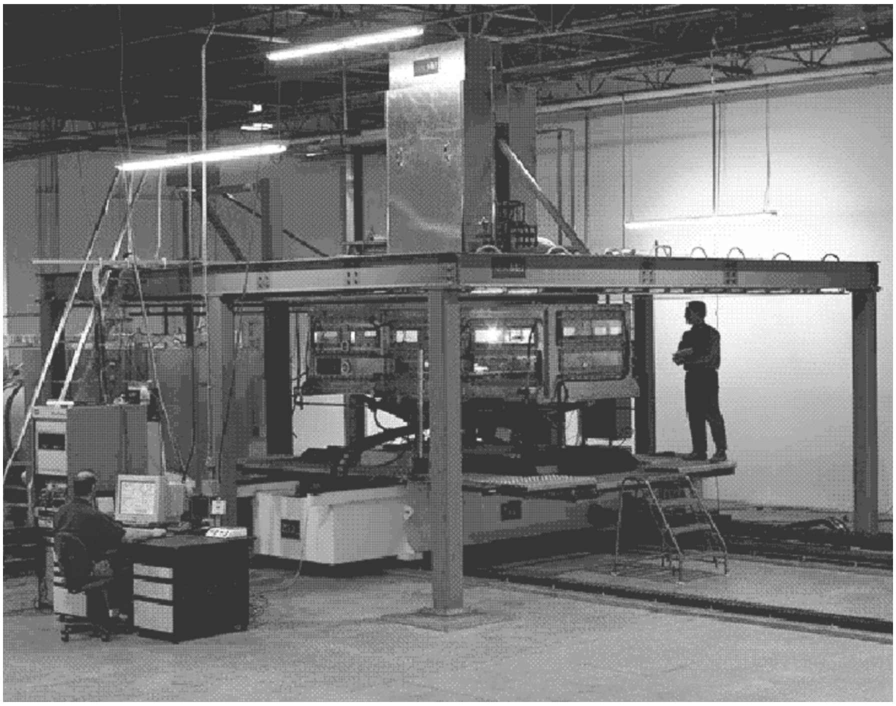

Figure 2. The current AeroMet Corporation/ARL Lasform commercial-scale system.

Conventionally, these parts are produced by forging, which requires expensive tooling and extensive machining or a hog-out from a large slab or plate of hot-rolled material. The cost for relatively short production runs (up to 500 parts) is decreased, and design changes once a production run is underway can be achieved much easier. Delivery times are about 30–60 days as compared to as much as 15 months for the forge plus machine approach.

Post-laser-forming part inspection includes coordinate measuring machine verification of the dimensions, witness samples for mechanical property testing, and chemical analysis as well as ultrasonic inspection and x-ray radiography. After final machining, die-penetrant inspection can also be carried out.

The Lasform process can also be used as a feature addition technique in which lugs or extensions are added to forgings, castings, or extrusions. This allows simpler and economical dies and tools to be used and provides more efficient material utilization. There is also the possibility of repairing broken, mismachined, or worn sections of a component.

LASFORMED COMPONENT CHARACTERISTICS

The microstructure of lasformed Ti-6Al-4V consists of relatively fine prior beta grains that are about the same size as those in thin casting. These prior beta grains, which can be columnar or equiaxed, depending on the laser-system forming perameters used, transform during cooling to produce relatively thin and discontinuous grain-boundary alpha and transgranular alpha (Figure 4).

The mechanical properties of lasformed Ti-6Al-4V (post laser-form sub beta transus anneal and age) include 839 MPa yield strength, 900 MPa ultimate tensile strength, 12.3% elongation, a 23.5% reduction in area, and 104 MPa $\sqrt{m}$ KIC. As would be expected,[1–3] these are equivalent to the mechanical properties typical of Ti-6Al-4V cast and wrought (ingot metallurgy) material.

The integrity of the lasformed parts produced has been found to be as good as or better than that of cast and wrought products, and these latter are not typically 100% defect free. For example, the powder-metallurgy approach to producing components from superalloys and titanium for demanding applications suffers from at least the perception that defects that will degrade mechanical properties can be present. Hence, even though superalloy Rene 95 parts have never exhibited a problem in T700 helicopter engine parts, near-net shapes are not allowed; instead, a quality-assurance forging step is included in final part fabrication.

Fatigue initiation properties are very sensitive to the presence of inclusions. Thus, the data shown in Figure 5 are very encouraging. Here, the smooth S-N fatigue data for lasformed Ti-6Al-4V are at the high end of cast data, albeit the lower portion of the cast and wrought scatterband.[1–3] This is probably at the lower end of the ingot data because of the nature of the microstructure of the lasformed material. A finer, more equiaxed microstructure would raise the data toward the upper part of the cast and wrought scatterband. More recent data show this improved S-N performance.

THE NEXT STEP

The current AeroMet/Army Research Laboratory production system is operating at 18–19 kW and allows parts 2.5 m long × 1 m wide × 1 m in height (up to nine tonnes in weight) to be produced with ±0.076 cm reproducibility. A second planned unit (scheduled for commissioning in October) with a 30 kW CO_2 laser will allow parts up to 3.6 m × 3.6 m × 1.2 m to be produced at projected deposition rates of 5–7 kg per hour or greater. A third planned unit, which could be the same size or bigger than the second unit, will result in a total plant capacity of greater than 45–60 t/y depo-

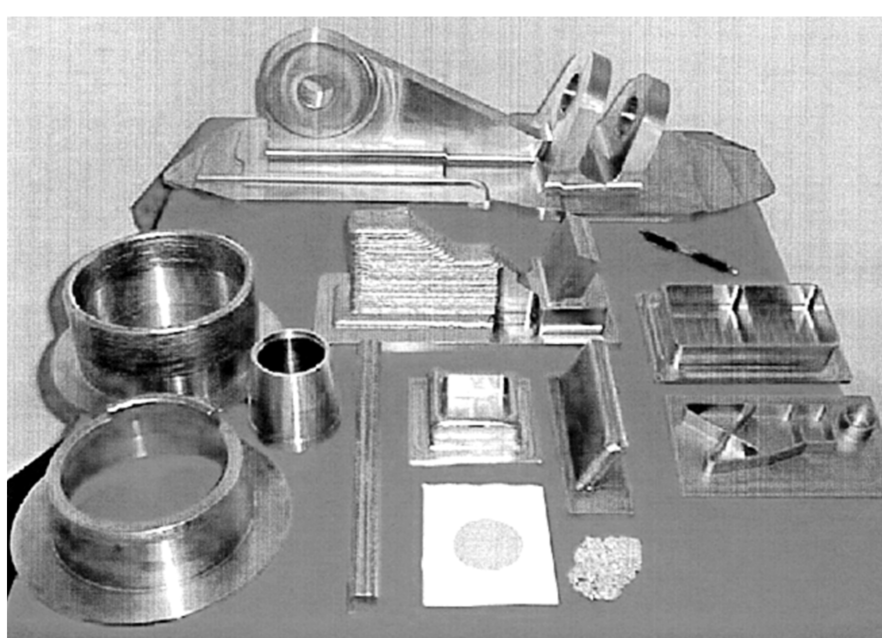

Figure 3. Typical lasformed and machined components.

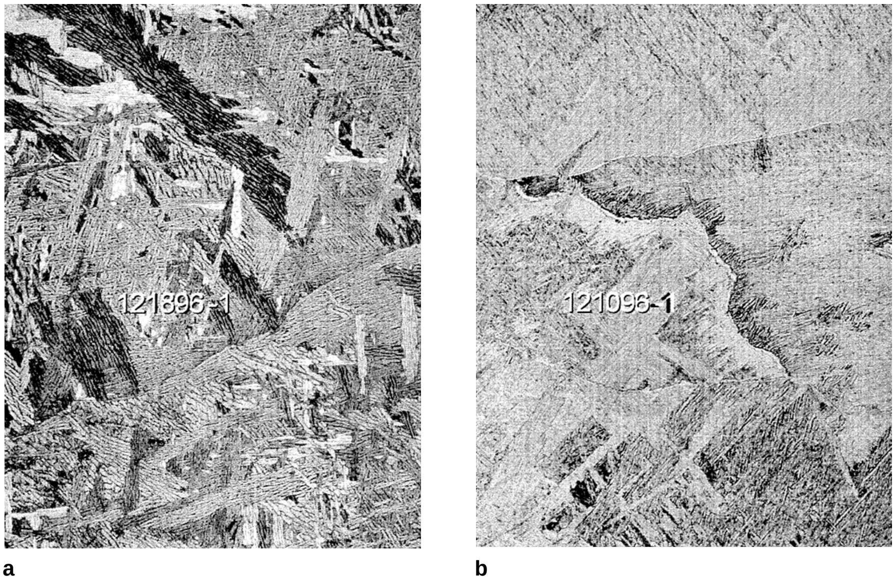

Figure 4. The microstructure of lasformed material, vacuum-mill annealed at 788°C for 2 h, argon cooled Ti-6Al-4V.

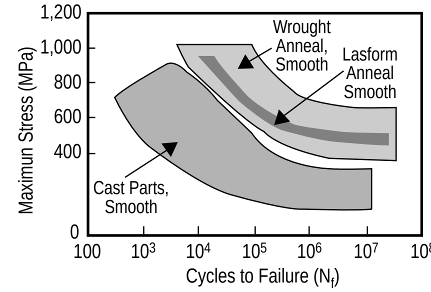

Figure 5. S-N fatigue data for lasformed Ti-6AL-4V, indicating a data scatter-band at the high end of cast material (coarse microstructure) and the low end of cast-and-wrought (ingot) material (fine microstructure).[11]

sition, offering total integrated part weights considerably beyond this when the weight of the starting plate is added in. Various full-scale subsections of integral reinforced rib on web and cylindrical parts (e.g., rings, cones, and flanges) formed by the Lasform process with Ti-6Al-4V are shown in Figure 3. AeroMet is currently preparing for an ISO9000 audit to receive quality-assurance certification.

Cost savings as compared to conventional approaches are projected to be generally 15–30%. Under an Office of Naval Research Dual Use Science and Technology program, four wing components for the F/A-18E/F will be fabricated using laser forming—the inner wing-splice fittings and the wing-fold fittings.[12] Based on a purchase of 400 aircraft, a cost savings of $50 million is estimated. The prime contractors, Boeing and Northrop-Grumman, estimate that laser forming will result in a 75% reduction in delivery time and more than than 20% cost savings.

The project's near-term thrust is to produce titanium parts for full component testing, demonstrating cost savings and reduced delivery times at mechanical property levels equivalent to cast and wrought levels. Production orders are expected to follow. In the future, new concepts will be explored, such as built-up structures (unitized structures eliminating fasteners) and structures with functionally graded compositions (e.g., a disc with optimized low-cycle fatigue behavior in bore areas and maximized creep performance in the rim locations). The lasforming of components from other base materials, such as niobium, rhenium, inconel, and stainless steel, is also planned.

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