Rapid Laser Forming of Titanium Near Shape Articles: LaserCast™

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ABSTRACT

An ongoing collaborative program sponsored by the DoD Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR) continues to show promising results in the development of a new laser based manufacturing process. The program's goals are to develop and demonstrate a laser based, rapid manufacturing system (LaserCast™) for titanium and its alloys. Economical precursor powders are being laser formed into integral, 100% dense, near-shape articles by sequentially fusing multiple metal-powder layers in a controlled environment. A CO_2 continuous wave (CW) high energy laser has been used to form commercially pure (CP) titanium, Ti-6Al-4V, and Ti-5Al-2.5Sn in varied geometries from 1-inch square bars to a 4-inch diameter (1-inch wall) cylinder. Materials characterization tests, revealing excellent chemistry control and mechanical properties, are presented. Large near-shape structures may be formed directly from metal powders, without using molds or dies, by direct download and post-processing from a Computer Aided Design (CAD) database. Economic projections indicate significant reductions in manufacturing costs and "time to market" production cycles when the LaserCast process is used instead of conventional casting and forging processes.

INTRODUCTION

Previous work in the laser based rapid prototyping of titanium metals and alloys has been reported[1,2,3,4]. The conventional routes to titanium which include the double, and triple, vacuum consumable arc remelt of consolidated Kroll sponge to drive off magnesium, chlorine, hydrogen and other more volatile processing constituents, and the subsequent forging, casting, or deep machining processes necessary to obtain titanium (alloy) structurals for aerospace and marine applications, may be by-passed by the laser based rapid prototyping process being developed in this program. As an example, present practice to deliver a 330-pound forged titanium bulkhead for a hypersonic aircraft requires starting with a 6,000-pound ingot and working the metal through a series of forging blocker dies, heat treatments, and a final machining[5]. This poor fly-to-buy ratio is also impacted by sometimes lengthy delays in forging or casting schedules. An economic analysis shows that substituting the present manufacturing process with the LaserCast™ flexible manufacturing process could decrease the cost of the bulkhead by 60% and decrease manufacturing time by 50% or more. A second example is the manufacture of pump components for cryogenic fluids. These components have been made from Ti-5Al-2.5Sn extra-low interstitial (ELI) alloy. This alloy is no longer commercially available at reasonable prices or schedules; the demand for

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this specialized alloy has diminished to only a few low volume customers. As a result, these customers may have difficulty meeting delivery schedules. A new process to rapid prototype in titanium and its alloys is also of interest because it would facilitate the interests of the DoD in agile manufacturing, the virtual factory, and the ability to fabricate metallic parts and structures directly from electronic drawings without molds or dies[6]. Thus, electronic drawings may be forwarded to a laser based rapid prototyping site, and the drawings may be processed by slicing codes, and post-processed into computer numerical control (CNC) instructions to direct the laser in constructing the required part by controlled layer-by-layer fusion of the metal powder into the desired geometry. The term LaserCast™ will be used below to describe the product of this laser forming process.

DEVELOPMENT EFFORTS

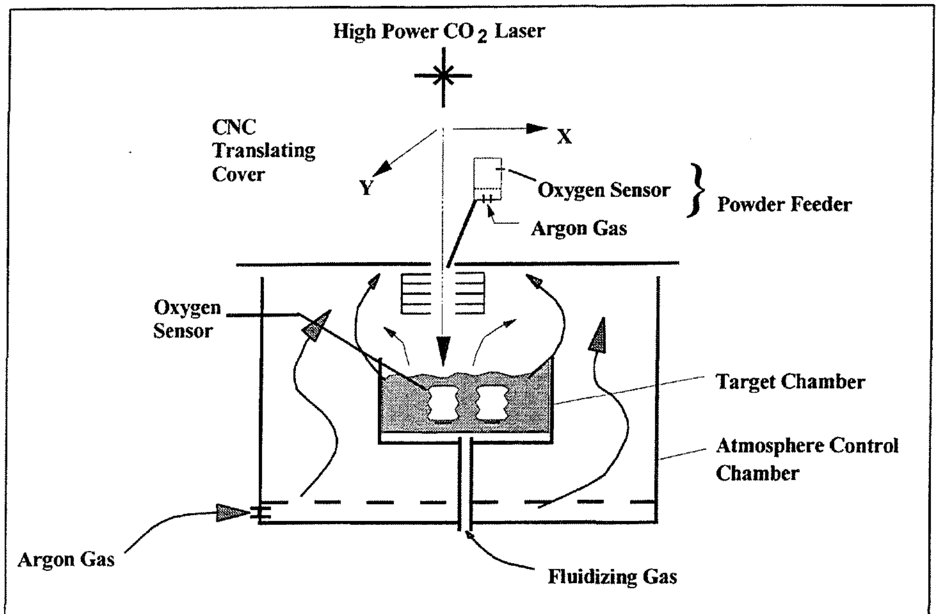
Program efforts, thus far, have been primarily directed at development of process parameters specific to laser fusion of titanium powders, qualification of inexpensive precursor titanium and alloying powders, and qualification of the resulting LaserCast material. Qualification of the powders and LaserCast material has been governed by industry standard test and analysis specifications. The specification and design of a production system is pacing the continuing development efforts. A functional requirements specification (FRS) coupled with a preliminary conceptual design has been completed. Additionally, detailed design efforts targeting specific equipment and control objectives are in progress.

Laser and Environmental Control Apparatus - Development System

A Convergent Energy (formerly United Technologies Industrial Lasers) 14 kW CO_2 CW (Model SM14 Mod 1) laser operating at 10.6-µm is used for all experiments. The laser beam mode is best characterized as a mechanically generated multi-mode 01* configuration. The beam is delivered to the work piece via a series of mirrors. The laser beam is focused by a parabolic mirror with an f-number of 16. The laser beam can be oscillated in one direction (i.e., linear dither) using a Spawr Industries Type 252 scanner. Alternatively, an omni-directional laser dithering mechanism has been fabricated and integrated into the development LaserCast system. Beam motion is accomplished through a 3-axis gantry controlled by an Aerotech Unidex CNC controller. Other laser functions controlled by the CNC are laser shutter and relays for support equipment and gas.

The metal target and powder are contained in a specially designed atmosphere control apparatus that consists of two boxes fabricated from stainless steel. Each box has a porous floor covering a plenum. The plenums are pressurized using high purity argon gas creating a uniform up-sweep of argon. The outer box provides atmosphere control and supports a lid. The plenum in the inner (target) box supports the metal target and powder. Zero grade argon (guaranteed minimum purity 99.998%) is used for all laser operations. Oxygen levels are continuously monitored in the target chamber (at the powder fusion point) and in the powder feeder using a Delta F Model FA35550A oxygen probe.

A vision system consisting of a closed circuit television camera (CCTV) with strobe illumination is installed on the lid. Signal output is displayed real time on a TV screen and captured on SVHS tape for subsequent evaluation. This visual feedback is used by the developers to access *in situ* process integrity and make adjustments to process parameters for subsequent laser runs. This information will also provide valuable information for the development of real-time process control sensors for next generation LaserCast systems. A schematic of the current research system is shown in Figure 1.



Titanium Powder Fluidized Bed in the Atmosphere Control Chamber

Figure 1. Schematic of LaserCast Development System[1]

Control of the processing parameters and conditions are established to minimize the possibility of unacceptable levels of contamination. All processing parameters are controlled, monitored, and documented. The major processing steps for producing a titanium near-shape are given in Table 1.

The authors have adopted the term 'ingot' to describe the resulting product. To date, two ingot shapes have been produced under this program as shown in Figure 2. These are:

- Linear ingots approximately 6-inches long by 1-inch wide by 2-inches high.
- Cylindrical ingots approximately 4-inches O.D. by 2-inches I.D. by 2-inches high.

Target Material

Two basic types of targets have been used. The first is a simple plate target which was found to bow extensively during processing. A box beam starter target was subsequently used. The box beam target provides additional rigidity which significantly reduces target bowing. All starter targets are CP certified to ASTM B-265-93 Grade 2.

Table 1. Major Processing Steps to LaserCast a Shape: Development System

Step Number	Description
1	Load target into target chamber and purge with argon to 50-ppm oxygen or less and maintain
2	Load powder de-gas chamber, heat and purge with argon to 50-ppm oxygen or less and maintain
3	Align laser to target
4	Monitor oxygen level, initiate laser run
5	Charge target chamber with powder from de-gas chamber
6	Fluidize powder using target chamber gas (deposits powder on target)
7	Level powder on target
8	Run laser over the target in a pre-defined path
9	Repeat steps 6-9 until the desired shape is completed
10	Cool under argon and remove from box

Mechanical Testing and Chemical Analyses

Mechanical testing and chemical analyses have been performed on LaserCast CP titanium and Ti-6Al-4V alloy materials. All mechanical testing is performed in accordance with applicable ASTM specifications [7]. Chemical analyses of precursor powders and LaserCast products was performed by more than one laboratory, using industry standardized LECO and inductively coupled plasma/mass spectrometry (ICP/MS) techniques, to obtain multiple independent analyses. The results of the testing and analyses were compared to the applicable sections of ASTM B 367-93[8]. Test results on the LaserCast Ti-5Al-2.5Sn ingots will soon be available.

RESULTS

Results of dimensional stability, chemical analyses, and mechanical testing are presented in this section. The results of each test are shown in comparison to a commercial specification where applicable.

Dimensional Stability

Distortion of a flat, unsupported starter target during laser processing can be significant. Initial ingots were formed on simple 0.25-inch thick plates. These plates bowed extensively due to the thermal cycling and the resulting residual stresses caused by laser processing. As the ingot is built the amount of restraint created by adding material increases and distortion effectively stops after approximately 0.50-inch of build-up.

Hollow box beam starter targets have been implemented to alleviate the extensive bowing. These targets are welded from 0.25-inch thick plate and have exterior cross section dimensions of 1.25-inch x 1.25-inch. The additional rigidity of the box beam targets significantly reduces bowing.

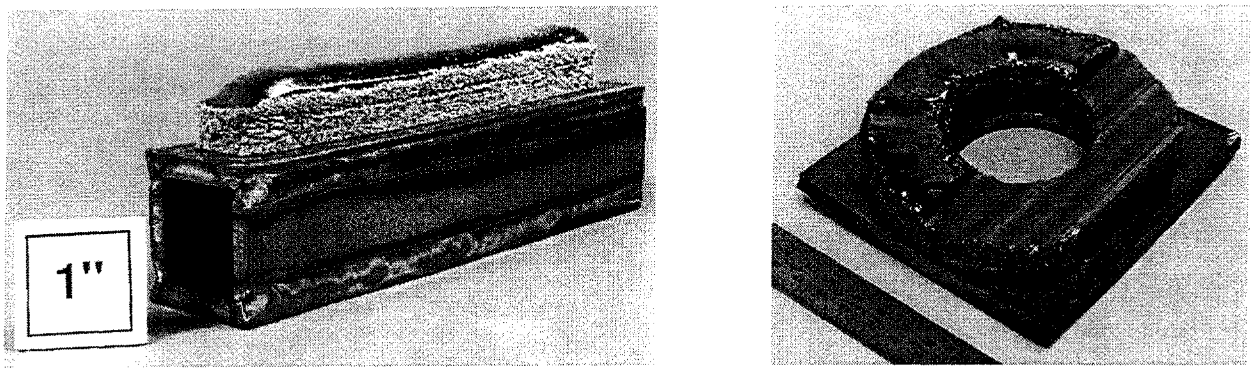


Figure 2. Typical LaserCast Ingot Research Shapes

Chemical Analyses of Ingots

Table 2 shows the results of chemical analyses performed on ingots of CP titanium and Ti-6Al-4V. Results are in the post mill-annealed condition as previously described. The results are compared to ASTM B367 grade C2 and grade C5 respectively.

Table 2. Chemical Analysis of LaserCast Ingots: CP titanium(C2) and Ti-6Al-4V (C5)

Elements	ASTM B367 C2 (wt.%)	LaserCast Ingot C2 (wt.%)	ASTM B367 C5 (wt.%)	LaserCast Ingot C5 (wt.%)
Oxygen	0.40 max	0.25	0.25 max	0.25
Nitrogen	0.05 max	0.13	0.05 max	0.04
Aluminum	N/A	-	5.5-6.75	5.79-5.95
Vanadium	N/A	-	3.5-4.5	3.75-3.85

Oxygen pick-up in the ingot material is a primary indicator of process integrity. Oxygen pick-up during ingot formation is held to less than 200-ppm [4]. Similarly, nitrogen pick-up was also held to less than 100-ppm. This is a result of maintaining a good working argon environment, free of atmospheric gases.

Mechanical Testing

Mechanical qualification of LaserCast ingots has consisted of multiple room temperature tensile tests and hardness testing of the respective tensile specimens. Results are in the post mill-annealed condition as previously described. Table 3 lists the results.

Table 3. Mechanical Property Results of LaserCast Ingots

Test	ASTM B367, C2	LaserCast Ingot C2 (wt.%)	ASTM B367, C5	LaserCast Ingot C5 (wt.%)
Hardness (max)	96 HRB (17 HRC)	30 HRC	39 HRC	37
UTS - ksi (min)	50	116	130	143
YS - ksi (min)	40	130	120	126
% Elongation 1-inch gage length (min)	15	<<15	6	6.2
No. of Tensile Specimens	N/A	2	N/A	6

Hardness values are listed as maximums. UTS, YS, and % Elongation values are listed as minimums.

The C5, Ti-6Al-4V, ingot's yield strengths exceeded ASTM requirements while maintaining acceptable levels of hardness and ductility. It is noted that, while the oxygen levels are near the upper limits of the specification, the nitrogen levels are well below specified maximums. These mechanical properties are supported by post test examination of the fractured surfaces which display a uniformly dimpled ductile failure [4].

The excessively high hardness and strength of the C2, CP titanium, ingots and the corresponding low ductility are a result of the high concentrations of oxygen and nitrogen in the titanium precursor powder [9]. This hardening effect is also present in C5, Ti-6Al-4V, ingots produced using this titanium precursor powder [4]. The material properties listed in Table 3 for C5, Ti-6Al-4V, material were obtained by using precursor powders with acceptable levels of interstitial oxygen and nitrogen. The LaserCast process yields grain structure that is significantly more refined than conventionally cast thick sections.

PRODUCTION SYSTEM DEVELOPMENT

Figure 3 contains an overall functional block diagram of the LaserCast system design which shows its major components; the LaserCast Workcell and Controller. Supporting components include a 14 kW Laser Generator and a workstation (used for CAD to CNC database translation).

The LaserCast workcell, shown in Figure 4, contains a number of integrated mechanical subsystems consisting of a process chamber, chamber lid and laser positioner, laser beam delivery and oscillation, powder delivery, gas delivery, and water cooling. Some notable characteristics of the workcell are:

- The size of the chamber can vary depending on customer requirements. Present scale-up designs are for a maximum 10-foot x 16-foot (plan-area) LaserCast structure.
- The modular design facilitates streamlined subsystem improvements (e.g., change in chamber size, laser technology).
- The design provides flexibility to use higher power lasers for increased build rates. Smaller fiberoptic lasers can also be incorporated without major re-design.

- The environment is maintained via a simple sliding lid seal and a turbulator orifice for the laser beam. The turbulator is designed to break up the backflow of atmospheric gases into the chamber as hot chamber gases are exhausted.
- Present scale-up designs are for build rates in excess of 12-in^3/hour for titanium.

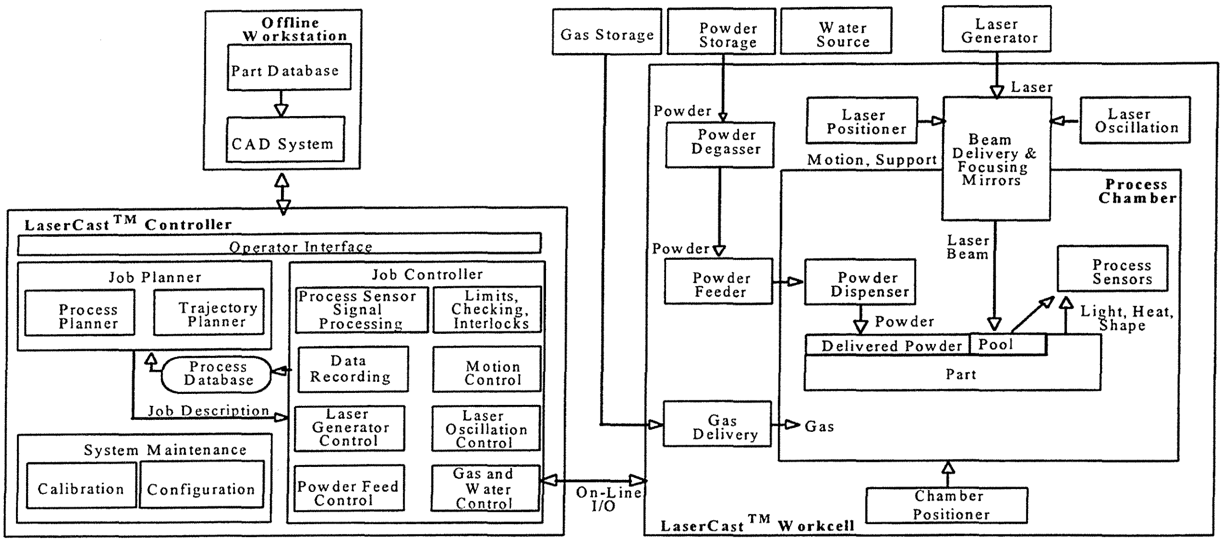


Figure 3. Functional Block Diagram of a Production LaserCast System

The LaserCast controller has a user interface that allows the operator to plan and program the specific processing parameters and paths for the LaserCast workcell. In addition, workcell sensor feedback will assist the operator in calibration and maintenance planning and execution. The LaserCast controller is being designed to accept input from Rapid Prototyping (RP) industry standardized file formats such as STL. This allows the LaserCast system to be used with the numerous 3D CAD and other third party CAD translation programs that can output solid model geometry in STL format.

The decision to use the STL file format enables the use of commercial STL post-processing software such as slicing software and automatic support structure generation. This has benefits in operator familiarity and in economics-of-scale issues such as bug fixes and acquisition costs.

The controller will use sophisticated process sensing and feedback strategies to maintain process quality. Process variables include gas rates and composition, powder feed rates, laser power, laser/target relative motion, dithering rates and fill patterns, and melt-puddle shape and size. Monitoring these variables and adjusting the process to maintain desired characteristics is a complex but necessary task. For example, the build-up rate of the ingot is dependent on precursor powder geometry and feed rates (which affects pre-fusing density). Therefore, the CAD description of the part will need to be sliced in real time based on the current ingot height in the LaserCast cell.

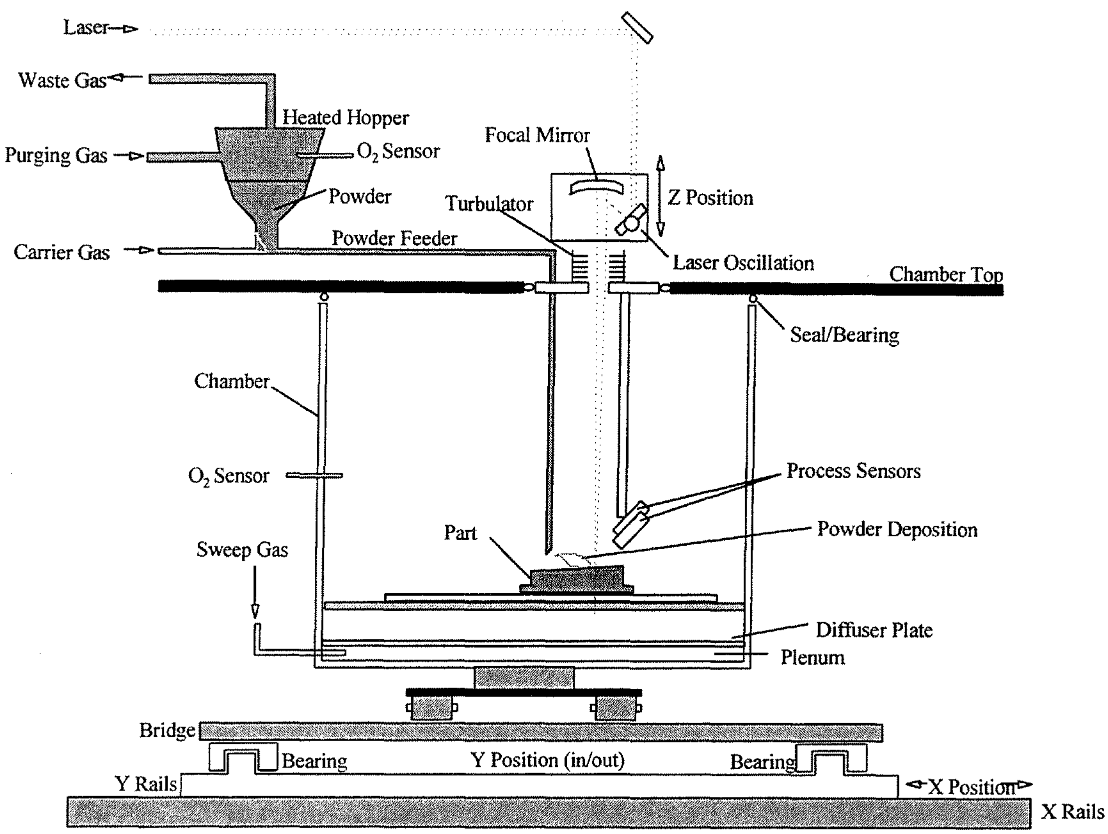


Figure 4. Conceptual Drawing of Production LaserCast Workcell

CONCLUSIONS

Results of experiments to date are very encouraging. Production of structurally useful, 100% dense, titanium alloy material has been demonstrated using this unique LaserCast process. The CP titanium and Ti-6Al-4V material produced under this program exceeds commercial ASTM B367 casting specification in ultimate strength, yield strength, elongation, and chemical constituency requirements. Oxygen pick-up in the ingot material is consistently held below 200-ppm, and nitrogen pick-up is below 100-ppm. It is anticipated that when ELI titanium powder is used (0.040 wt % O_2, 0.006 wt % N_2), the LaserCast process will be able to produce alloys such as Ti-5Al-2.5Sn ELI for cryogenic applications. This process is capable of rapid prototyping large titanium structures with a variety of alloying elements and in CNC directed flexible geometries. Direct use in replacement of castings, or as quick delivery forging pre-forms, is projected.

Selection of quality precursor titanium and alloying powders is critical to the success of the process. Titanium powder from different suppliers and manufactured using different techniques has been investigated and the results published [4]. The wide variation in powder chemistries requires the user to be especially selective when procuring powders for the LaserCast process.

The processed near-shape titanium articles fabricated by this process require additional manufacturing to obtain net shape and surface quality requirements. For some applications machining may suffice. The near-shape LaserCast articles should provide a quality forging and hot isostatic press (HIP) pre-form for larger articles and where application requirements require additional metallurgical refinement. This process is especially favorable to producing large forging pre-forms where tooling costs are often prohibitive. A near-shape forging pre-form can be produced by this process in a few weeks that will eliminate the need for many of the initial forging blocker die and heat treatment operations. This will offer a significant savings in cost as well as time to market.

A preliminary evaluation of the economics of titanium parts production from a dedicated LaserCast manufacturing cell cost center was explored. Results indicate that titanium parts can be delivered at 50% or less of the present cost of similar forged, HIP'd, or conventionally cast structures. Time to market can also be significantly reduced by 50% or more.

FUTURE WORK

Further work is planned to perform additional material qualification tests on Ti-6Al-4V and ELI Ti-5Al-2.5Sn ELI alloy ingots. Additionally, plans include the fabrication of two prototype structures with guidance from two aerospace-defense contractor companies and delivery of these structures for their evaluation. Refined economic projections for metallic parts produced by a commercial system, and the detailed design of that system, are also planned.

Process refinement is continuing with several key system hardware improvements planned. An enhanced processing chamber is being developed that will facilitate production of larger articles measuring 30-inches x 30-inches in plan view cross section and up to 12-inches thick with a maximum weight of 500-pounds. A unique circular dithering laser beam (to supersede the current linear dither) has recently been added to the system to provide flexibility in forming complex geometries. Continuous laser processing will be supported by the addition of a unique powder feeder, to provide continuous deposition of powder, and active cooling on critical heat affected components.

The production system development is in progress. Detailed design efforts for the production system have been initiated based on a completed FRS and a preliminary conceptual design. Key components of the production system have been identified and their design accelerated to allow for prototyping. These key components include a unique powder feeding system (including the capability to change powder constituents on-the-fly to make graded-composition alloys) and process feedback sensing subsystems. A potential customer for the first production system has also been identified.

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