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Technical Proposal

Lightweight Additive Manufacturing of Beta-Ti Alloys

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National Additive Manufacturing Innovation Institute

The National Center for Defense Manufacturing & Machining (NCDMM)

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1 Executive Summary

When an engineer looks to utilize the full capabilities of additive manufacturing they are extremely handicapped because almost all engineering alloy compositions are typically optimized for mill products (i.e., sheet, plate, extrusions and forgings) or metal casting processes. Additive manufacturing as an industry accepted process is still in its infancy and as a result there is no ***established*** open sourced materials knowledge. In fact, many additive equipment manufacturers will only guarantee build performance and properties with their custom materials. This places OEMs in a sole source position (***Value Chain***) which is ultimately unsustainable in a free market. Further compounding the issue is that there has been limited involvement of material suppliers to enter into the arena of additive manufacturing due to the still relatively low amounts of materials being consumed. The work currently being done is typically done on existing alloy compositions which severely limits the knowledge of feedstock material requirements that can be exploited to enhance the overall mechanical properties of a material (***Materials***). One such example is that of titanium beta alloys which have been utilized since the 1950's and typically have better mechanical properties than that of the better known Ti-6-4 (alpha+beta) alloy. Despite having the potential of a more favorable process for additive manufacturing no comprehensive work has been done to develop a robust procedure that incorporates the design and use of Ti Beta alloys in structural applications (***AM Genome***). For traditional manufacturing approaches the use of Ti-6-4 over Beta-Ti alloys has been a result of the lower costs but when costs are not a main factor Beta-Ti (i.e. high strength low weight requirements) alloys are preferred. The highly alloyed metastable Ti-beta has long offered an improved alternative to the alpha-beta alloys because of their increased heat treatability, deep hardening potential, and inherent ductility attributable to its body centered cubic structure. Typically beta alloys when compared with alpha-beta titanium alloys also have superior fracture toughness, especially at higher strength levels. Therefore the goal of this project is to showcase that with the proper approach a low-cost Ti-beta alloy can be developed that is additive manufacturing friendly and capable of outperforming current standards achievable with traditional components (as cast, or forged).

This type of project requires a multi-disciplinary effort in order to succeed. As such Northern Illinois University as the lead with its capability in AM process monitoring for LENS has teamed up with the following partners, Northwestern University with its modeling & simulation capabilities, Cristal Global as a supplier of CP Ti and Ti alloys, Siemens with its software integration capabilities and Product Development & Analysis (PDA) as the end user. Northern Illinois University currently works closely with Northwestern as a result of their $2.5 Million NIST MSAM program in which they are developing the tools (experimental & numerical) that will be utilized in this project for qualification and certification of the current and newly developed alloys. Therefore by combining these efforts the main objective for this project will be to take advantage of the unique qualities of Ti-Beta alloys which is its ability to hold a wide range of mechanical properties by simply controlling the thermal gradients during processing. As example the literature shows that Ti-10-2-3, can have yield strengths that range from 180 MPa up to 1500 MPa, depending upon the heat treatments. This is possible by controlling the alpha precipitates in the alloys. As such, the finest grain sizes are obtained by low hot working temperatures relative to the B-transus and by solution treating very close to the B-transus temperature; this prevents dynamic recrystallization, provides a high driving force for subsequent recrystallization (thus forcing recrystallization despite the pinning effect of the up during the sub- transus Solution treatment), and then prevents the recrystallized grains from growing rapidly.

The program intends to provide a comprehensive solution that will address the following America Makes priority areas: Materials (detailed thermal history analysis of Ti-beta alloys and its correlation to material properties), Value Chain (focus on certification and material qualification-pre and post build), and AM Genome (integrating several physics based models to provide holistic view of material from end to end). More specifically within these categories the focus will be on, material property characterization (looking at current beta-Ti that are favorable to AM), advanced sensing and detection methods (quantifying energy going into AM process to define boundary conditions), model assisted property prediction and physics based modeling & simulation (looking at multi-scale physics models and ensuring all relevant information is available to perform the analysis).

For TIMET 10-2-3 Titanium Alloy (Ti-10V-2Fe-3Al), Aged Billet/Bar per ASTM 4986 which is typically used for landing gear applications has an ultimate tensile strength of 1170 MPa and 12% elongation. A general structure that will resemble in loading conditions of a landing gear will be agreed upon by our industrial advisory board which consists of several aerospace companies (UTAS and SVSC). All relevant data pertaining to existing 10-2-3 alloy will undergo a through modeling and simulation analysis by QuesTek and Northwestern University. This analysis will then yield a series of guideline processing parameters that must be followed to achieve the potential characteristics as defined by the traditional methods. NIU will perform the builds of the structural tests components and monitor the energy density and general shape of the components to ensure all requirements are satisfied. The samples will then be mechanically tested and compared to the historical data. This information will then be fed into the modeling and simulation tools developed during the project, combining software contributions by Northwestern, into Siemens NX software tool. This comprehensive AM process simulation will then be used to investigate a new set of processing parameters for the modified alloy and to characterize the effect of raw material input and process parameters on quality metrics. NIU will then perform the second round of builds with the modified alloy and the data captured and compared to the baseline obtained in the previous round.

Northern Illinois University has an outstanding track record in engagement by providing high value cutting edge technology to the northern Illinois manufacturing industry as a result of large federally funded programs. An example is the development of an automated laser cladding cell for repair and refurbishment of naval components (DOD Contract: **SP0700-97D-4005**). This technology now resides with Spider Inc. (located in Rockford IL) and enables them to bid on providing more than refurbished components; but new parts for the stationary power turbine industry. A second example was developing an integrated solution for laser assisted machining of ceramics (TARDEC Contract: **W56HZV-04-C-0783**), this technology now resides with Reliance Tool and Manufacturing (Elgin IL) and has allowed them to successfully machine complex ceramic parts for the automotive and energy industry. NIU has been further strengthened in the area of tech transition and education and workforce training with the recent addition of the **EIGERlab** which is focused to assist start up, early stage growth and expanding existing businesses. **EIGERlab** serves as a one-stop resource for both new and existing entrepreneurs and innovators to commercialize new ideas, increase revenues and profits, participate in peer groups, access business services, utilize design engineering and art-to-part rapid prototyping services, meet with dedicated mentors, link to qualified investors and receive assistance in selling to the government or executing global market expansions.

2 Problem Statement and America Makes Relevance

It is very difficult today to utilize the full capabilities of additive manufacturing because almost all engineering alloy compositions are typically optimized for mill products (i.e., sheet, plate, extrusions and forgings) or metal casting processes. Additive manufacturing as an industry accepted process is still in its infancy and as a result there is no *established* open sourced materials knowledge. The need here is to understand the mechanical properties of Ti-beta alloys that can be achieved via AM with current feedstock materials, then to expand the scope to slightly modified AM friendly Ti-beta alloys to take advantage of their unique capabilities. This specifically relates to the "Materials" swim lane and looks at adding value to the materials property characterization and next-gen materials. For this need this proposal will specifically focus on adding value to America Makes by: 1) establishing what are potential standardized feedstock materials for making AM friendly Ti-beta alloys , there is currently no information with regards to AM so this will be the first attempt at creating a database on feedstock variability the advantage here is working with a CP-Ti supplier which can provide best practices for the alloy development 2) by benchmarking current Ti-beta alloys with regards to UTS and elongation for AM vs. standard processing methods (i.e. casting/forging) the hope would be to at a minimum match the current values and then starting with a slightly modified Ti-beta alloy that is AM friendly and see if an improvement of 25% in UTS can be achieved without sacrificing ductility (must stay same) , 3) understanding what energy density may be required during the AM build to reduce the growth of alpha-precipitates, no data available so it will be necessary to provide a benchmark to which it will be possible to compare against for modified Ti-beta alloys 4) to define the supra-transus "processing window" as a function of temperature through which the alloy can be taken to result in a final fine equiaxed beta grain structure. This "processing window" is relatively wide for the lean metastable beta alloys and for heavy amounts of deformation. However it is much more constricted for the richer alloys and for lighter amounts of deformation and 5) develop the processing guidelines and specifications for creating this AM friendly Ti-beta alloy.

Another problem this project will address is related to the “Value Chain” swim lane specifically with regards to rapid qualification/certification methods via advanced sensing and detection methods. As stated previously despite the well-known mechanical advantages Ti-beta alloys have over traditional alpha-beta alloys no work has been done to characterize/quantify the thermal processing conditions required in AM to fully take advantage of them. It is understood that there are various processing conditions (i.e. P-V maps) that can influence the final microstructure and that they are inherently controlled by the thermal history. An approach that is currently utilized by NIU for its NIST MSAM project is looking at the measured energy density via calorimetry. Direct measurements of the energy absorbed during processing of 316L shows that if the same processing path is taken the parameters will have little influence on the final mechanical properties. This type of insight is required for providing a realistic metric for process improvement which then can be related to costs (i.e. material, processing, quality control, productivity, etc…). The aim as such will be to look at the energy requirements for the traditional methods (i.e. casting/forging) and see how this compares with the measured energy of the AM process which would then provide a potential cost justification for achieving improved mechanical properties that are at least 25% better than the average.

The final problem this project will address is related to the “AM Genome” swim lane specifically with regards to the creation of physics based models. The current predictive models are often driven by empirical data obtained from existing materials. These tools do not have the ability to predict properties of materials across multiple spatial and temporal scales. Researchers at Northwestern (Dr. Liu) have established a rigorous mathematical framework for integrating spatial and temporal scales with multi-physics phenomena. They have implemented their multi-scale simulation framework into the commercial finite-element code, LS-DYNA® [1]. To overcome the current roadblock in computation time, they have successfully parallelized their code, which brings the benefit of being able to utilize an industry standard library of routines (MPI) that passes data and task coordination information between independently executing copies of the code. For this project, they will build on the work being carried out for the NIST MSAM project and implement the physics-based material models developed by Dr. Olson of NU with the multi-physics additive manufacturing processes to predict mechanical properties, for example, crack growth and fracture toughness of these Ti-beta alloy AM parts. It is anticipated that integrating these various tools together will give a reduction in computation time of 20% over empirically based models utilized today.

This project identifies key challenges in three of the swim lanes defined by America Makes which are related to first establishing a need for defining AM friendly materials (Materials) specifically related to Ti-beta alloys, then quantifying the energy requirements to build these AM friendly materials into structural components that can be tested and evaluated against their traditional counterparts (Value Chain) and finally modifying these materials and carrying out advanced physics based modeling and simulation programs (AM Genome) that will help streamline the development process (Value Chain) to create tailor made Ti-beta alloys that are AM friendly (Materials).

This project has garnered interest from several companies and organizations such as UTAS Aerospace located in Rockford Illinois, GPI prototyping also in Illinois which is a full service metal additive manufacturing company that supplies the aerospace and medical industry as well as the Silicon Valley Space Center (SVSC) which provides business acceleration, strategic direction and angel level funding for startup companies within the growing New Space industry. QuesTek computationally designed and developed three castable titanium alloys under U.S. Army-funded SBIR Phase I and II programs to incorporate lower-cost raw materials and exhibit greater strength and/or ductility than Ti-6-4. The new alloys are tentatively named QT-Ti-1A, QT-Ti-2A, and QT-Ti-2B.). Their aim would be to help us in future work to develop AM friendly Ti-beta alloys. They have all written letters of support and will serve as advisory board members to this project. While they will not have access to the data or specifics they will help guide and support as much as possible to ensure that our developments are relevant to industry. They have also indicated interest in future projects through America Makes and beyond as they see a critical need for development of AM friendly Ti-beta alloys for the aerospace industry.

3 Technical Approach and Methodology

The challenge as stated in the previous section is to take an existing alloy (Ti-Beta) characterize it for AM processing and ensure that it can at the very least meet current values of wrought and or cast product but more importantly find a way to enhance it beyond that point. In order to do this you first need to not only have a good understanding of the powders available but then how you may process them to ensure you meet all the criteria required for a high quality build. Then you need to have physics based modeling tools that can go across several platforms from thermal conditions to microstructural behavior to mechanical properties as it relates to the available AM processing parameters so that you can streamline the DOE for actual builds for validation. This also requires having the necessary AM system with all the sensors that can capture the data and ensure the builds are carried out according to plan. This section highlights all the capabilities of the key contributors in this proposal that will deliver such a model. Some of this work has come from previous collaborations through the NIST MSAM program and DARPA open manufacturing program which will be leveraged and reduce the amount of development time needed to analyze this particular alloy. At this stage we are not aware of such a diverse and multifunctional team that is looking to tackle this problem of maximizing the capabilities of Ti-Beta alloy. This will be a great value add for the America Makes membership because anyone will be able to follow this approach to obtain the same results. Furthermore, the Gantt chart provided in section 4.1 clearly provides all the deliverables of this project as a result of the task work described here in the proceeding sections.

3.1 Thermal Modeling of the Deposition Process

High intensity and localized heating combined with extremely rapid cooling rates, all of which take place in a cyclic manner, make it very difficult to experimentally monitor the historical response taking place in AM processes. However, these effects are of great importance in understanding the local microstructural and material properties which accumulate to give the final product performance of additively manufactured components (see Figure 1). This is the primary driver necessitating simulation-based methods for predicting the outcome of AM processing. In process modeling, the ultimate goal is to determine what the final state of a material will be given a set of process parameters. This task will focus on four primary task areas:

1. Optimize in-house thermal process modeling techniques, for AM processes that are capable of providing higher resolution thermal history during processing,
2. Develop model calibration procedures and corresponding experimental techniques with collaborators at NIU,
3. Develop and integrate material science-based microstructure evolution laws within the in-house code set in order to predict final product performance after processing and process parameter optimization,
4. Verification and validation of the developed modeling procedures.

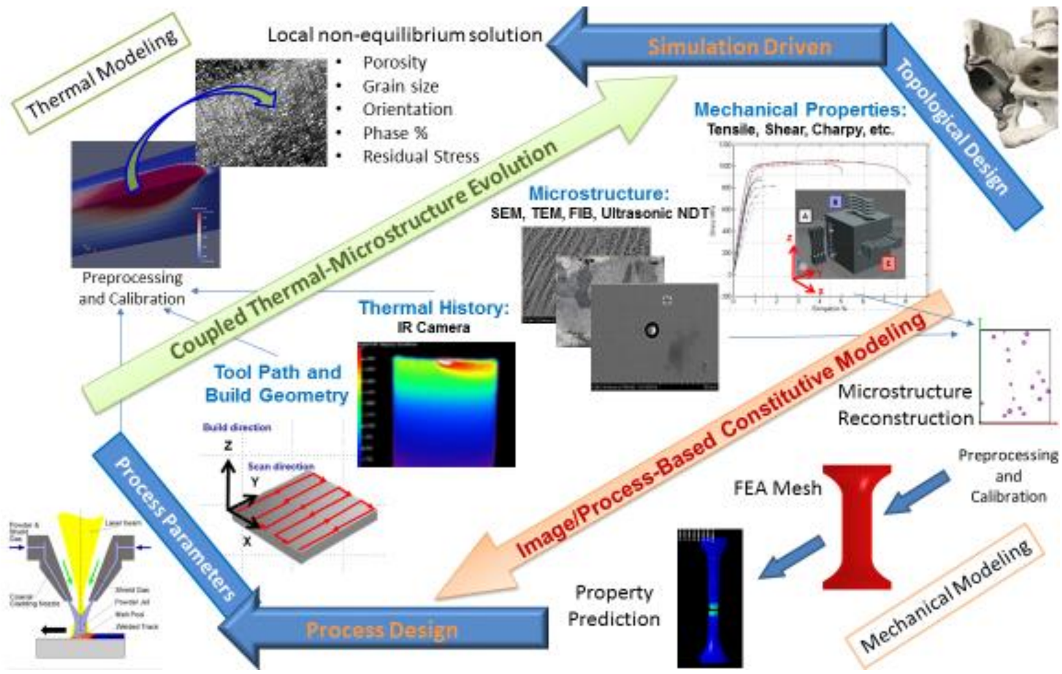

Figure 1. Simulation driven product performance based on thermal history and microstructure evolution

3.1.1 Optimize In-House AM Thermal Process Models

The cyclic, localized, and high intensity thermal loading of AM processes tremendously increase the level of complexity in obtaining accurate numerical predictions of the thermal behavior for a given set of process parameters. To date, commercial software, e.g., ABAQUS, has been the standard in attempting to analyze AM processes and final product performance via simplified models which are based on previously developed welding models. Although welding is similar to AM processes in principle, it has been experimentally proven that the cyclic nature of AM processes, which is not a factor in welding, makes them strongly history dependent and therefore simplified models can only give a very limited amount of useful analysis which may not be characteristic of the final product [2]. However, simply extending these models to simulate the entire process is utterly infeasible due to the fact that commercial software is directed at general use applications, i.e., it is not optimized for the specific characteristics of AM processes. As a result, commercial software can be used for only short time spans with a limited spatial resolution before the memory requirements and computation time will because a major handicap.

The combined research groups at Northwestern Dr. Liu and Dr. Cao have been developing in-house finite element codes which are optimized for simulation of large-scale AM processes for nearly two years through the NIST MSAM program. These codes have proven to be drastically more efficient than commercial software. This was integrated with an additional set of parallelized preprocessing codes developed within the aforementioned research groups which minimizes simulation setup time (this is typically one of the largest consumptions of time in FEA from start to finish), see Figure 2. This previous work will be further developed in the present research to improve efficiency and to incorporate additional physical phenomena, as the code is currently for thermal analysis only, such as thermo-elastic analysis for prediction of thermal expansion and residual stresses in the final product. As will be discussed in Task 1.3 (see section 3.1.3), this code will also be used as the foundation for integrated analysis of thermo-elastic behavior and microstructure evolution in order to allow process parameter optimization.

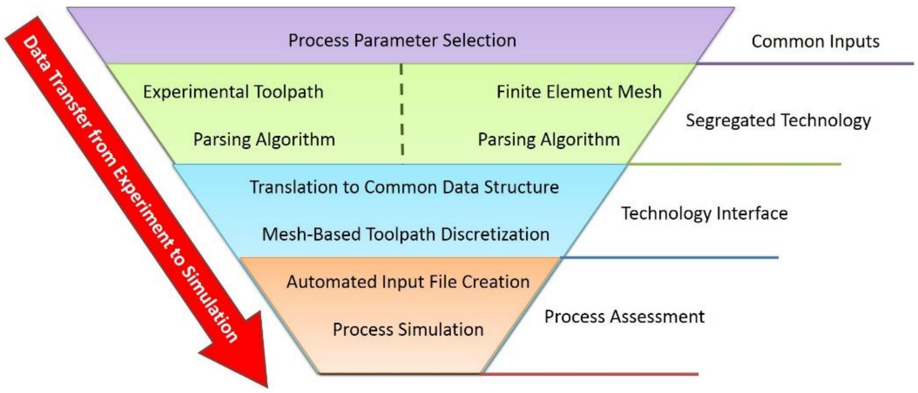

Figure 2. Automated translation of experimental and simulation data for rapid preprocessing and accurate process history prediction

3.1.2 Develop Thermal Model Calibration Procedure and Data Collection

Model calibration is essential for any modeling procedure to be successful, particularly for a predictive model. However, the extremely high temperatures, thermal gradients, and heat/cooling rates seen in AM processes necessitate the development of novel model calibration procedures. Dr. Liu will work with both experimental groups from NU and NIU in order to develop model calibration techniques. The latest thermal imaging hardware and software along with calorimetric energy measurements, through experimental methods developed in previous collaborative work between NU and NIU through the NIST MSAM program, will be utilized for this task. Collaboration between Dr. Liu and Dr. Olson and Dr. Xiong will be utilized to incorporate the temperature dependent material properties, e.g., heat capacity and thermal conductivity, resulting from fine-scale simulations using CALPHAD-ICME database generated from Thermo-Calc and DICTRA simulations [3]. The high level of resolution in the temperature dependent material properties will allow better representation of the thermal history in the process and will in turn improve the microstructure evolution prediction developed in Task 1.3 (see section 3.1.3).

3.1.3 Develop Microstructure Evolution Law for In-House Thermal Model

AM processes are unique amongst other manufacturing methods in that the local microstructure, which may have a sub-grain characteristic length scale orders of magnitude smaller than the characteristic length scale of the component being manufactured, of a product can be adjusted by simply altering the process parameters in that area. Adjustment of the local microstructure will in turn have an effect on the local properties of the component and this of course can extend to the overall final product performance [4]. This provides AM processes with a tremendous advantage but also challenge over other processing methods and the number of controllable process parameters, e.g., laser power, laser velocity, laser diameter, particle size, and particle element ratio, yield a vast number of possible outcomes of the process. This task will be directed at integrating material science informed microstructure evolution laws within the in-house process modeling code set in order to predict the final microstructure and final product performance and AM produced parts, see Figure 3. Using microstructure reconstruction and morphological analysis, a series of thermally driven microstructure evolution laws taking into account non-equilibrium phase transition effects will be created and integrated with the thermal process modeling code developed for AM.

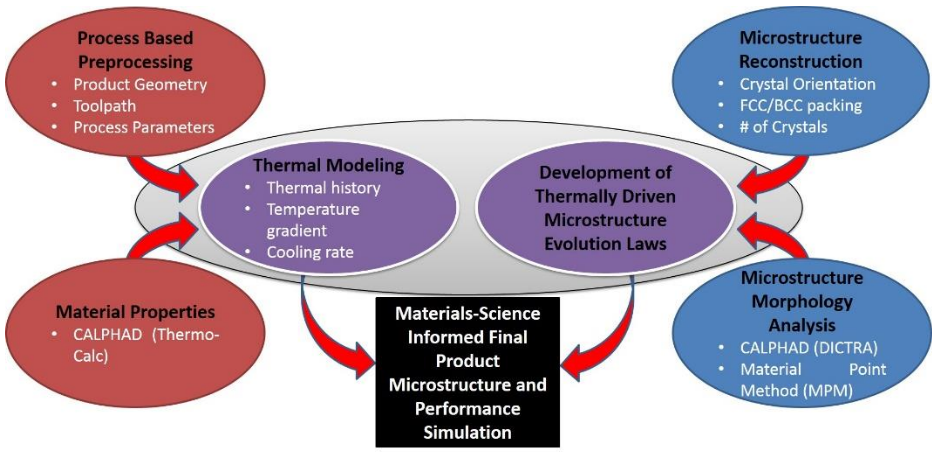

Figure 3. Coupling strategy for thermally-driven, materials-science informed, final product microstructure and performance prediction model

3.1.4 Model Verification/Validation Studies and Optimal Process Parameter Prediction

The final task of AM process modeling will be to conduct model verification and validation studies. A series of models will be developed to verify and validate the in-house process model implementation on its ability to predict thermal history, residual stress, and final microstructure within AM processes. This task will require development of experimental metrics which will be defined and measured for comparison with the model predictions. The validation study of the process model implementation and theory will be conducted as part of the developed calibration procedure and through the experimental metrics defined for comparison. The calibration procedure will be used to ensure that the model implementation is correct while the experimental metrics can be used to test how well the developed microstructure evolution laws predict the principle microstructure variables. The verification study will be based on testing the models ability to predict both the thermal history and the microstructure metrics to within a reasonable accuracy for various process parameter sets.

3.2 Modeling for Materials Process Design

Integrated Computational Materials Engineering (ICME) methodologies are effective tools to reconfigure the materials development process and accelerate implementation of new higher performance alloys into demanding applications. New alloys, meeting specific desired property goals, can be designed much more quickly and at less cost than empirical trial and error methods.

In this task, Northwestern University will simulate thermal history during the LENS processing of legacy β-Ti alloys with the resultant microstructure evolution through computational thermodynamics. This includes simulations of microstructure evolution during LENS processing, and application of computational modeling to the optimization of post-build processing. With refined predictions of the behavior of baseline alloys this will be utilized for future alloy development work.

3.2.1 CALPHAD Modeling For Powder Composition Design

Utilizing a number of ICME modeling tools to facilitate process development, based on the CALPHAD (CALculation of PHAse Diagrams) framework. CALPHAD is a well-established computational thermodynamics and diffusivity framework for phase equilibria and diffusion-related calculations, and

NU has extensive experience in applying CALPHAD techniques to the design/optimization process condition (including additive manufacturing). Examples of particular interest to additive manufacturing is the thermodynamics-based prediction of solidification behavior during the complex thermal conditions of laser deposition, and phase evolution during post-build processing (hot isostatic pressing, heat treatment, etc.).

3.2.2 Kinetic Modeling for Homogenization Process

Evolution of microstructure during rapid solidification can be modeled with equilibrium or nonequilibrium thermodynamics using various material models implemented in the ThermoCalc® software platform with appropriate thermodynamic and kinetic databases. Other relevant material models include prediction of solid-liquid interfacial energy, free energy, latent heat and heat capacity, all relevant inputs into build process models. Evolution of microstructure during in-process thermal cycling and post-build processing includes predictions of phase equilibria and kinetics of formation, and multicomponent precipitation modeling (using the TC-Prisma® module of ThermoCalc®) to simulate second-phase formation (e.g. alpha precipitation).

3.3 Modeling for Mechanical Behavior

3.3.1 Experimental Material Characterization - Microstructure and Mechanical Behavior

The objective of this subtask is to characterize the mechanical properties and microstructure of the LENS-processed titanium alloys, which have inherent anisotropy and porosity due to large thermal gradients. Specimens that follow a set of design of experiments will undergo mechanical testing (i.e. tensile).

3.3.2 Develop Process Parameter-Based Phenomenological Mechanical Behavior/Fracture Model for LENS Manufactured Products

The mechanical response of AM manufactured materials is an effect of the compositions of elements used in the powder, the solidification behavior during processing, and the volume fraction of phases and defects in the final product microstructure (See Figure 4). Process parameters (e.g., laser intensity, laser velocity, powder feed rate) are the key to controlling these drivers of the mechanical response. Slight variations of process parameters can yield drastic changes in the material anisotropy and the tensile properties [5]. In the proposed research, the research group of Co-PI Cao will develop process parameter-based phenomenological constitutive laws through investigation of the mechanical testing conducted in Task 3.1 (section 3.3.1). Using design of experiments as a guideline for spanning the process parameter space, several samples will be created using AM and will be analyzed for both the attributes of the mechanical behavior and the morpohology of the final microstructure. Proper spanning of the process parameter space will ensure that information obtained for development of the process-based phenomenological constitutive laws is of the highest quality and robustness achievable. The newly developed constitutive laws can then be applied in analysis to assist in the design of both process and product simultaneously in order to reduce both product-to-market time and material waste by eliminating ad hoc and guess-and-check style experiments.

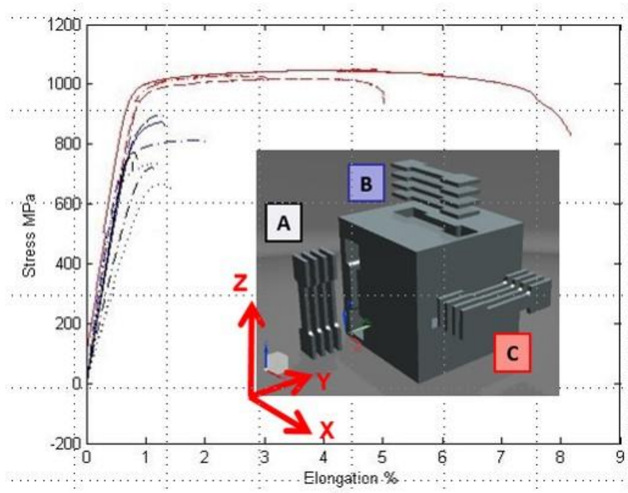

Figure 4. Process parameter-dependent anisotropic material response

3.3.3 Model Verification/Validation

As with the thermal modeling, verification and validation of the process parameter-based constitutive laws is a primary initiative that is essential to success of the present research. A series of experiments will be conducted in order to calibrate the constitutive laws. The verification study will recreate what is observed experimentally to the highest level of accuracy possible. Following calibration and verification, the constitutive laws will be validated using a design case study which is targeted at simultaneous design of a product and its corresponding AM process. In this design case study, the constitutive laws will be applied in finite element analysis on a component which is to be developed using AM in order to perform a particular function (e.g., a load bearing strut). The flowchart for the design case study is in Figure 5.

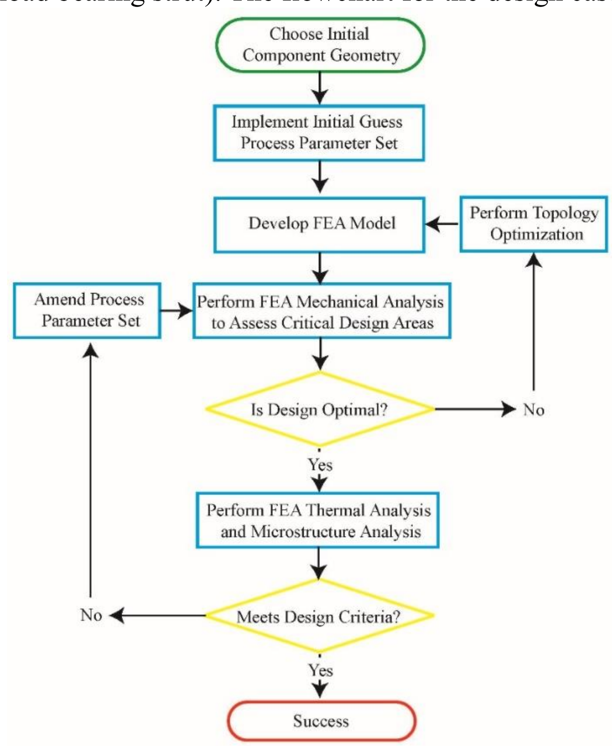

Figure 5. Verification flowchart for simultaneous process and product design

3.4 LENS Trials with Energy Density Measurement

One of the most sought after aspects of additive manufacturing is the ability to produce repeatable mechanical properties when building components. In order to produce components with repeatable properties it is critical to measure and control your process in situ. Typically measurement is done in the form of looking at the melt pool during the build process and controlling the size of the melt pool by changing the processing parameters. The problem with this approach is that there is never a real understanding of the amount of energy that is actually going into to building the component. Typically research will focus on the processing parameters such as power and travel speed to try and control the process. Again the problem with this is that there is no clear understanding of how these processing parameters influence the overall energy going into the process during the build.

Thermal energy input is the fundamental parameter that defines the mechanical properties as well as the thermo-mechanical behavior for all AM components. Understanding how much energy is required and its temporal and spatial distribution are critical to ensure an AM produced component meets the application requirements. To date, there has not been a comprehensive approach to measure the amount of energy required that will ensure the proper material properties. Most often researchers will measure the <u>surface temperature</u> (using thermal imaging) during AM builds and empirically correlate that to properties as processing parameters are changed. This approach gives partial information. In order to reach a high level of confidence in energy absorption by the part during additive manufacturing, a systematic, fundamental and complete understanding of <u>thermal energy input</u> is required. The amount of energy absorbed per unit inch for the AM process is defined as thermal energy input (**H**). In order to determine **H**, two variables must be known: the net power of the laser heat source ($\mathbf{P_{net}}$) and the travel speed of the heat source or part (**S**):

$$H = P_{net} / S \tag{1}$$

If input power (P_{in}) is the power generated by the laser, (measured by power meter), then, P_{net} is the portion of input power that is transferred into the substrate. The remaining energy is lost due to radiation and reflection. At a constant travel speed, P_{net} (rather than P_{in}) is directly responsible for all physical and metallurgical changes in the parts being built, including expansion and contraction of the part, defect generation by loss of component integrity, metallurgical phase changes (grain growth, allotropic phase transformations) and mechanical property variations caused by thermal processing.

Despite the importance of P_{net} this variable has never been used in industry and often times P_{in} is used in its place. This has been due to the lack of technology available to accurately measure P_{net} that is cost efficient and robust. Measurement of P_{in} is common via electrical power input such as amps and is often sufficient for standard electricity-based fusion welding processes. When considering very critical components (i.e. biomedical components) or melting using lasers, these electrical measurements are not sufficient. Researchers have developed laboratory devices (e.g. calorimeters) to determine P_{net}. The ratio P_{net}/P_{in} is equal to the thermal efficiency factor of the heat source, k. Reported data for thermal efficiency 'k' of GTA welding obtained via calorimetery over the last 5 decades varies from 21 – 80% as summarized in [6]. Similar variability can be found in other applications where lasers are used as a heat source [7]. Data for current laser processing systems, such as Ytterbium fiber and direct diode lasers, is largely unknown.

Without an accurate and robust calorimeter, P_{net} assumptions are made from measuring P_{in} despite the fact that the relationship between them is non-linear and not well known in many applications (as in AM). This effect is well documented in welding research [8-9] where the heat transfer efficiency decreases from 75% to 67% when P_{in} is increased from 1.38 to 2.30 kW. This shows the difficulty of trying to relate P_{in} to P_{net} and why it is critical to measure P_{net} over a strategic range of parameter schedules. Further work carried out in [10] shows capability to measure P_{net} for laser cladding. Precision measurement and understanding P_{net} by the Northern Illinois University provides critical baseline data for the modeling constitutive equations to be developed by Northwestern University.

3.4.1 Characterization Beta-Ti –A

For the characterization work Cristal Global will follow Metal Powder Industries Federation's (MPIF) standards and guidance to measure powder characteristics. These measurements include dry sieve analysis of granular metal powders per MPIF Standard 05, determining the apparent density of non-free-flowing metal powders MPIF Standard 28 and tap density of powders per MPIF Standard 28. Furthermore, Cristal Metals, Inc. will analyze the chemical content of the powders in accordance to ASTM E 120 – Chemical Analysis of Titanium and Titanium Alloys standard. Leico TCH 600 chemical analysis instrument will be used for oxygen, hydrogen and nitrogen analysis. The carbon content will be analyzed with a Leico C 230 while ICP instrument will be used for rest of the chemical elements. Addition to the chemical content, characterization work by Cristal Metals, Inc. will also include Scanning Electron Microscopy (SEM) imaging for powder morphology observation as well as Energy-dispersive X-ray Spectroscopy
(EDS).

3.4.2 Single Bead Analysis Beta-Ti-A with Energy Density DOE

A full factorial design of experiment will be implemented that will enable us to have a rapid characterization of processing parameters. Individual beads are made using different processing parameters, then specific outputs are measured. These include bead dimensions: bead width, bead height, bead contact angle with substrate, aesthetic appearance/surface roughness, and porosity. The beads that pass these analysis filters are made into partial builds, at which point dimensional analysis of the build will be measured, as well as aesthetic appearance/surface roughness, porosity, and microstructure. In addition to this the calorimetry data will provide a guideline of amount of energy absorbed in the process and so a comparative analysis between these values and the other key attributes will be compared.

The builds that pass those analysis filters will then be ranked by hardness and microstructure. A schematic which illustrates hatch spacing determination as well as the analysis filters is shown in Figure 6. Table 1 shows the factors and levels that will be varied. By testing different global energy densities, we can quantify the effect that process parameter modifications have on mechanical properties.

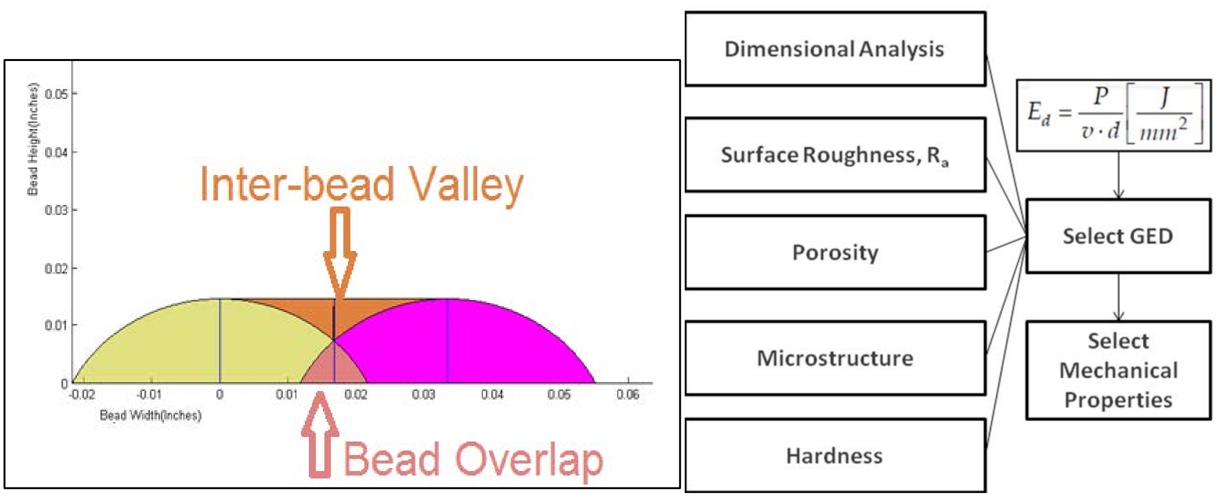

Figure 6. Basis for parameter optimization program. Hatch spacing is 0.033 inches.

Table 1. Full factorial design of experiment with factors and levels shown. The constants in the analysis consisted of hatch orientation (90, 270), pressure of regulator (50 psi), and flow rate for center purge (25 l/min). A total of 64 different parameter sets will be tested followed by a replicate set.

Factors	Levels, +/-			
P_{Lens}, W	475	560	645	725
Travel Speed, ipm	15	20	25	30
Powder Feed, RPM	4	6	8	10

This data can then be used to monitor during the builds of parts later in the program.

3.4.3 Analysis Energy Density

With the information obtained in the previous section we plan on developing an understanding between the net heat input and the global energy density as it pertains to mechanical properties. Another important factor will be how the geometry will influence the results from the calorimeter which will provide the measured energy density. Similar work was done on the NIST MSAM project where there was a good linear trend between the net heat input and the GED of Ti-6-4 alloys that were built and analyzed. Furthermore it was shown that larger thin samples retained heat much longer and the energy values lent themselves to generating a more uniform structure throughout the component.

3.4.4 Build qualification coupons

Samples will be built according to specifications set forth by ISO/ASTM52921 – 13, Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies. As shown in Figure 7 the samples will be built on a base plate of the Ti-Beta as produced by wrought process. Each panel will deliver several orientations to define isotropy of the printed builds

3.5 Validation Testing

3.5.1 Design AM Property QA Artifact

While there many investigators[1,2], including NIST, explored the development of additive manufacturing "artifact", the focus of these studies address the dimensional capabilities of the build equipment. More recently, the need for an AM mechanical property artifact was recognized[3]. Not only is the geometry defined, but also the build path at the thermal history will play an important role to retain the beta phase in solution during the build. To illustrate the cruciform concept, Figure 7, sample that may be modified with different wall thickness for each leg.

[1] J. Kranz, D. Herzog, and C. Emmelmann, *Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4*, **J. Laser Appl**., Vol. 27, No. S1, February 2015, p. S14001-1-15.

[2] Shawn Moylan, John Slotwinski, April Cooke, Kevin Jurrens, and M. Alkan Donmez, *An Additive Manufacturing Test Artifact*, **Journal of Research of the National Institute of Standards and Technology**, Volume 119 (2014), http://dx.doi.org/10.6028/jres.119.017 .

[3] Beth E. Carroll, Todd A. Palmera, and Allison M. Beesea, *Anisotropic tensile behavior of Ti–6Al–4V components fabricated with directed energy deposition additive manufacturing*, **Acta Materialia**, 87 (2015) p. 309–320.

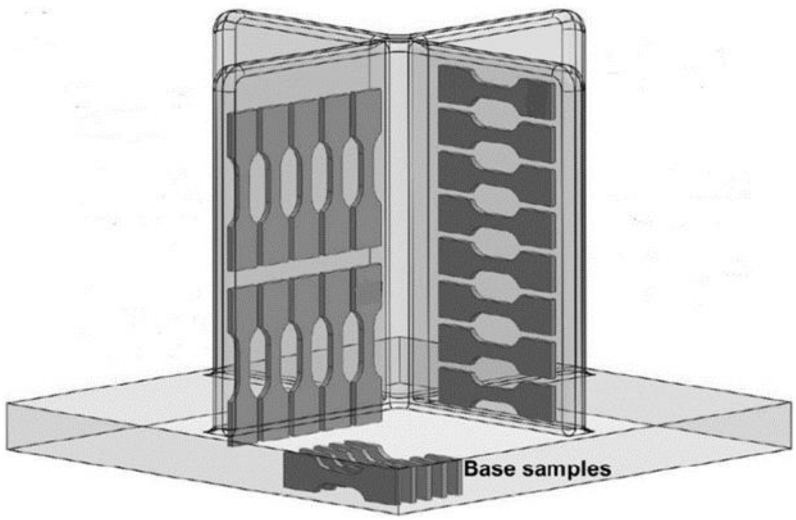

Figure 7. Exemplar AM property validation test artifact

The bottom plate provides a calorimeter baseline with near 100% conduction. As the cruciform height increases the parsing of the conduction, radiation and convection contributions will change based, in part, on the wall thickness as well as build path (local thermal history). The cruciform sample that may be modified with different wall thickness for each leg. Above several wall thicknesses, a steady state parsing of the three different heat flow mechanisms may occur with a constant cross section. This task will assess NIST and other publicly AM artifacts as well as those from our Industry Advisory Board. Based on this review a concept design will be prepared for a review during the bi-monthly status review meeting. Both modeling and LENS capability perspectives will be used to assess utility. Once the concept is ratified, a detailed design will be produced. Modelers will use this STL file to explore the impact of different build strategies to understand the potential impact on the microstructure.

3.5.2 Build tool Path Design for AM QA Artifact

The build tool path design task will take the NX interface to the thermal model of the direct energy deposition AM (LENS) process and explore processing space with the goal of distilling build path rules by establishing the sensitivity of the tool path on the microstructure. This includes the layer height and trace overlap percentages for different build laser cross sections and geometric transition points. This is similar to welding best practices for different joint configurations. The knowledge gleaned from these trial will become design rule that would eventually become embedded in an NX DED AM tool, once validated. Several build criteria to be explored include minimizing residual stress (based on heuristic insight from welding technology), validated measurement of surface finish, and avoiding beta-phase precipitation caused by heat affected zones between layers and adjacent traces within a build layer.

3.5.3 NX Tool Sensitivity Assessment

The baseline validation work will focus on beta-titanium alloy. This ally will have a digital or virtual existence in terms of the constitutive equations that describes the time dependent behavior of its thermos-physical properties like specific heat, thermal conductivity, etc. Data bases are frequently a module available for commercial CAM software distributors as well as the NIST. Not all thermos physical properties need to be known with equal precision for the model to make useful predications which have trends that match the observed trends. The purpose of the task is to explore the sensitivity of the key thermo-physical properties to the prediction of the microstructure. This study will identify which properties is require high accuracy in order to accurately predict the correct trends for the microstructure evolution (precipitation of the beta-phase). This will identify where the greatest return on investment will be achieved for the creation of a digital (virtual) beta-titanium, and other, alloys defined by the constitutive equations of its thermo-physical properties.

3.6 Model Integration with Siemens NX and Virtual Process Characterization

3.6.1 Software integration with Siemens NX

The software tools described in sections 3.1, 3.2 and 3.3 will be combined in an integrated framework, connected with Siemens NX, which will also provide an entry point at the CAD level, to design the part to be built, and CAM capabilities for seamless integration with the production environment.
The software integration task will be achieved by developing an add-on software prototype using the public Application Program Interface (API) of Siemens NX (NXOpen[4]). This add-on will allow the user to select the part to be manufactured, the material properties, the machine configuration and the process parameters. Then it will transfer this information to the software tool described in section 3.1, to simulate material deposition and thermal behavior during the process. During the process simulation, the output of the thermal model, together with the initial user input, will be then transferred to the software tool described in section 3.2, for material property prediction, and the modified material properties, information will be broadcasted to the other software components (developed in tasks 1 and 3). An additional integration step will be performed to output the results of the process simulation at the last stage of the manufacturing process and pass them as input to the software at point 3.3, for the mechanical properties and microstructural behavior estimation. The process parameters used in the simulation will then be input in NX CAM, together with the machine information, to provide the CAM plan to be used by the additive manufacturing machine. Additional details on the integrated software development are provided in section 4.

3.6.2 NX AM Calibration and Validation

Since each of the three software components has been already tested and validated in the previous tasks, the validation of this part of the project will simply consist in comparing the final results predicted by the software tool (in terms of mechanical properties and microstructural behavior), with the acquired benchmark data obtained experimentally using material input with the same properties and the same machine and process parameters as in the user input to the simulation. Any needed model calibration will be performed at the single tool level, with the only exception of tuning the frequency of data exchange between components 1 and 2 during the process simulation.

3.6.3 Global Energy Density Characterization with NX AM

The developed integrated software prototype will be used to perform a virtual analysis on the effect of process parameters on the Global Energy Density (GED), with varying raw input material and considering various health status levels of the additive manufacturing machine (wear and tear).
The following approach will be pursued, utilizing CAD models of standard shapes of different sizes and complexity as starting point:

1. A selection of possible raw materials will be made by the project team and their properties provided as input to the software tool.
2. Different machine health conditions will be modeled by prescribing variations on the machine parameters, such as laser power and feed rate. Variations on these parameters will be determined at the project stage to simulate different levels of machine degradation, based on information acquired from the operation, maintenance and service stages and on the interactions with the project team.
3. A matrix of combinations of materials at step 1 with machine health conditions at step 2 will be developed. For each matrix element, the critical points in the build-path, in terms of high GED,

[4] http://m.plm.automation.siemens.com/en_us/Images/4988_tcm1224-4564.pdf

will be automatically identified, displayed to the user and stored in a library of that connects constitutive material and machine process parameters to the corresponding GED and critical points.

4. Optionally, the path can be modified locally to avoid critical situations with high values of GED. Examples of these modifications may include avoiding sharp turns in the build tool path, where the longer residence time of the tool would increase the amount of energy released, if the power is not properly reduced.

This approach has the goal of developing the knowledge base to allow the user to compensate for lot-to-lot materials variation and machine health condition. The same approach can be used to create a library to account for variability between machines. It also opens the door to more sophisticated but time-consuming approaches in which the build tool path or other controllable parameters can be optimized stochastically to achieve quality metrics (e.g. GED) within specified bounds around the expected value, accounting for possible unknown perturbation in input raw material characteristics and machine conditions.

4 Technology Transition and Pervasive Impact

4.1 Technology Transition Plan

The technical and business expertise of the key personnel of the project team are described in detail in the **Project Team Appendix**. The team assembled includes capabilities to deliver project results to industry, via Siemens Corporation – Corporate Technology, with expertise on development of add-on components to **Siemens NX** software, an integrated product for design, engineering and manufacturing solution that helps deliver better products faster and more efficiently. In the course of this project, process-specific applications in NX for simulating the manufacturing processes will be developed, to provide a complete solution for predicting the mechanical properties and material quality of the part to be manufactured. This will be achieved by integrating software components from Northwestern University with existing Siemens NX capabilities. The outcome of this effort will be an add-on for Siemens NX, for process simulation of the LENS additive manufacturing process. Figure 8 shows a schematic of the team's program effort.

Figure 8. Development team and their role for beta-titanium alloy for AM

Northern Illinois University (NIU) has worked with **Northwestern University** (NU) for the last 18 months on a NIST funded program on the *Measurement Science for Additive Manufacturing*. During the course of this work, NU has developed a seven times faster algorithm to compute the thermal history, while NIU has prepared three invention disclosures on calorimeter sensor head design, non-contact powder mass flow rate measurement, and optimized overlap determination. If required these tools will be made available as part of the integrated solution for development of AM friendly Ti-beta alloy.

Cristal is a global supplier of high quality titanium-containing products including ore, titanium chemicals, titanium dioxide and titanium metal powder. In 2008, Cristal Metals (formerly ITP) was acquired by Cristal US, Inc. (a wholly owned subsidiary of Cristal Global). Cristal Metals manufactures high quality titanium powders using the patented Armstrong Process® with the ability to produce both commercially pure and alloy powders. The Armstrong Process® technology has been developed to provide powders for efficient powder metallurgy processes to facilitate the production and to lower the production costs of titanium components. The Armstrong Process® technology eliminates the need to process sponge, thereby reducing supply chain cycle time, energy consumption, manufacturing costs and environmental impact. Cristal owns all rights to the Armstrong Process® technology, which can be used for production of a wide range of metals, alloys and ceramics.

The Ti-Beta alloy team plans to produce an alpha release of the processing-structure-properties additive manufacturing interface for delivery to the industry. This seamless package permits AM process planning to virtually explore the impact of the AM build history on the resulting microstructure and the resulting properties. This permits an OEM to explore the manufacturing feasibility to determine the design sensitivity to routinely produce a component with consistent properties. This provides a systems approach whereby the proposed alloy, the build orientation and the build tool path can be optimized for both build speed and a generous manufacturing process window.

With the virtual AM suite, a quality assurance module provides a tool for a custom additive manufacturing manufacturer to build their own library of constitutive material and machine process parameters to compensate for lot-to-lot materials variation, machine-to-machine variability, and machine wear with a standard build geometry by measuring the global energy density (GED). This can be part of a lot release package depending on the quality requirements.

High-value components requiring extreme reliability such as found on space systems are ideal candidates for such a level of scrutiny and are chosen for this demonstration. Siemens NX PLM already has a manufacturing suite which includes machining, welding and fiber lay-up. The addition of AM is a logical next step.

This project team includes the entire breath of the supply chain from an Illinois titanium powder producer (Cristal Global), an international computer aided manufacturing (CAM) software manufacturer and distributor (Siemens NX), and end user (PDA). In addition NIU has recruited an industrial advisory board of an AM manufacturer, a west coast (SVSC) and Mid-west (EIGERlab) business acceleration and angel level funding for startup companies, and an aerospace-defense end user (UTAS). Each of these companies have a letter of commitment or a letter of interest in Exhibit III. The IAB is the external "Board of Directors" that will serve as strategic sounding board and sanity check. Members of SVSC and UTAS can also provide actual metrics that we can measure our progress against that will provide value to industry and America Makes membership.

A user interface and the hand shake between the process, microstructure, and properties tools will be primary responsibility of Siemens NX. The interface can begin after each tool input and output parameters are defined. The handshake will have an elastic structure so the number of I/O can be changed without loss of connectivity with each block or step in the algorithm. This mapping of I/O to each calculation step permits future refinement with minimal disruption. Several "wild card" I/Os will be associated with each tool (process, microstructure, and properties). The tools integration will be connected to up-to-date version Siemens NX, to harness CAD, CAE and CAM existing capabilities.

The NIU partners and IAB will exercise the alpha-release to establish if the user interface is user friendly and try different build conditions and build sequences to determine potential calculation instability that prevent convergence to a solution. These results will be compiled during a review meeting and form the basis of producing the beta-version at the end of the program. The NIU team will be made available at a beta-version AM Module user's virtual kick-off meeting to provide an overview of how to get started as this documentation may be sketchy at this stage of its development. America Makes will announce the beta AM module and NIU team will choose a reasonable number among these volunteer members.

Once a beta AM process module version is prepared, it would be released to a selected number of AM members in good standing that have expressed interest in exercising the module and willing to share the results of their experience with the Siemens NX development team. The beta module will have an expiration date and is expected to be released at the end of the program. The beta AM module will not be released to other CAM vendors for competitive reasons. The distributed module will only have data for the developed beta titanium alloy. If other alloys are to be modeled, the beta site will need to import the required data and will need to consult with Siemens NX on the best way to proceed.

The Gantt chart below identifies the tasks, time frame, and notes for milestones and deliverables [numbered notes in square brackets-also shown just below]. The numbers are months from the start of the program (July 10, 2015). NIU experience with other process models for melting and solidification, suggest that the alpha-version of each tool may not be completely perfected and that additional refinement to correlate with validation test data may be required. While a multi-physics model is the goal, some calculation steps may be sufficiently complex that an empirical approach may be required to develop a first generation tool within a limit time (15 months) to produce an alpha-version AM module complete with a user interface.

Notes [Deliverables & Milestones]

1- Complete sub-awards for NU, Siemens, PDA, and Cristal Global
2- Alpha thermal process released to Siemens & PDA
3- Beta thermal process released to Siemens & PDA
4- NU work with PDA & NIU
5- Conceptual approach reviewed with partners prior to detailed code implementation
6- Release implementation of process law w/ recommendations for improvement
7- Scope of LENS process space review & DOE
8- Release preliminary model LENS process sensitivity analysis
9- Recommendations for substitutional modification to commercial Ti-beta (i.e Ti-10-2-3)
10- LENS process limits for beta-phase suppression
11- Recommended LENS DOE for locating beta-phase formation
12- Preliminary LENS process boundaries for beta-phase suppression
13- Preliminary empirical LENS DOE based on Ti-10-2-3 AM knowledge
14- Review the microstructure based failure criteria for static properties
15- Review the microstructure based failure criteria for dynamic properties
16- Use QA sample for statistically significant results
17- Use QA geometry
18- Assess NIST & other AM artifacts before concept design
19- Review, detailed design & STL for digital model studies
20- Build tool path sensitivity (NX inter face NU thermal model)
21- Existing innovation focus groups tapped for AM appetite
22- Business development calls on a minimum of twelve companies
23- Record and document best practices of companies currently utilizing metal additive manufacturing resources
24- Schedule, market and deliver workshops and presentations on metal AM
25- Recommend tool practice for residual stress, surface finish, minimum re-heat
26- Document constitutive parameter sensitivity to microstructure prediction
27- Conceptual approach reviewed with partners prior to detailed code implementation
28- Use GED virtual characterization tool to build a library of GED maps based on input data
29- Perform validation of integrated tool with benchmark data
30- Release integrated software tool in prototype quality

AM β-Titanium Alloy Components Tasks, Timeframe, Milestone and Deliverables

Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1.0 Thermal modeling of the deposition process																		
1.1 Develop in-house AM thermal process models	[1]							[2]				[3]						
1.2 Develop & implement model calibration procedure						[4]												
1.3 Develop microstructure evolution law								[5]						[6]				
1.4 Model sensitivity exploration and process parameter optimization												[7]				[8]		
2.0 Modeling for materials process design																		
2.1 CALPHAD modeling for powder composition design	[1]					[9]												
2.2 Kinetic modeling for homogenization process								[10]				[11]						
2.3 Precipitation simulation for 2nd particle strengthening														[12]				
3.0 **Modeling for mechanical behavior**																		
3.1 Experimental microstructure & mechanical behavior		[13]																
3.2 Develop LENS parameter mechanical properties model								[14]		[15]								
3.3 LENS model validation																[16]		
4.0 **LENS trials with Energy Density measurement**																		
4.1 Select & Characterize Beta-Ti alloy	[1]	[13]																
4.2 Single bead Energy Density DOE						[9]												
4.3 Build qualification coupons												[17]						
5.0 Validation testing	[1]																	
5.1 Design AM Property QA Artifact				[18]				[19]										
5.2 Build Path Design for AM QA Artifact										[20]		[25]						
5.3 NX AM tool sensitivity assessment																		[26]
6.0 Model integration with Siemens NX																		
6.1 Integrate Task (1-3) tools into NX AM	[1]							[27]									[24]	[30]
6.2 NX AM calibration and validation (NIST MSAM)												[29]						
6.3 Global Energy Density characterization with NX AM																[28]		
7.0 Ed & Wkforce Training (EWT)																		
7.1 Additive Manufacturing Focus Group									[21]									
7.2 Small Business Potential											[22]							
7.3 Best Practices												[23]						
7.4 Workshops and Presentations															[24, 26]			
8.0 Project Management																		
7.1 Bi-Monthly Partner Status Review		✍		✍		✍		✍		✍		✍		✍		✍		
7.2 Quarterly report			🗀			🗀			🗀			🗀			🗀			
7.3 Industry Advisory Board Update			🔔			🔔			🔔			🔔			🔔			
7.4 AM Project reviews (PMR)						⚐						⚐						⚐
7.5 Final report																		📖

4.2 Economic Development Plan (EDP)

For this proposal, NIU contacted a number of end users for letters of intent to judge the depth of the interest for additively manufactured beta titanium alloys. ALL the end users contacted expressed interest as documented in Exhibit 3. The reason for the interest in beta-titanium alloys is that they can deposit as a single-phase (suppress alpha-phase and omega-phase formation, “AM friendly”). Then strengthened by precipitating alpha-phase during post-processing. The single phase, with a lower yield strength, offers the possibility of lower residual stresses responsible for distortion. By requiring a post-build heat treatment, the alpha-phase precipitation provides a strengthening mechanism. If the post-build heat treatment is done in a HIP unit, any potential micro-porosity would be eliminated (as done for titanium engineered shaped castings). This provides a higher quality threshold (for medical and space applications) than a typical atmosphere heat treatment. The need for this material is evident and the vehicle to deliver it will be developed by this team and then disseminated to the America Makes membership.

The NIU team includes a titanium alloy powder supplier that will help define a general guideline for materials analysis, a small business devoted to virtual manufacturing that will create special AM tools for this alloy, and a CAM software developer and distributor that will integrate the developments into a beta version for release to AM membership. The assumption here is that this market will be the same if compared to small and medium size manufactures whether in metalcasting or sheet metal forming, because they generally lack the economic usage rate to afford process simulation software. Thus, the business model dictates the virtual manufacturing nodes of small businesses affiliated with an industry (medical, defense and aerospace, nuclear energy, sea-based wind turbines) so as to have a consistent work load to sustain regular software upgrades. This is an extension of the business model that has slowly emerged over the last five years in the metalcasting industry. If mergers and acquisitions continue, this may change in the distant future. It is imperative then to have some base open source software like NX that can provide the requisite tools to meet standard requirements as set by the AM community.

For example, the software would have a module to codify the taking of calorimetry data from some known machine and then be able to calibrate individual machines. The approach is to use standard shapes (possibly more than one, based on the geometric complexity and envelope of the part being produced) with defined build paths. This approach qualifies both equipment and lots of raw materials so small adjustments in the build strategy can accommodate normal perturbations among different lots of powder materials and accommodate machine wear and tear. This software calibration tool would accelerate the definition and promulgation of ASTM standards. This is defined in Task 6 and will be led by Simens.

The long term goal (as part of another program) is to work with the accomplished global leaders in Integrated Computational Materials Engineering (ICME) to develop metal alloys tailored for the manufacturing process. This is leader is QuesTek which has provided a letter of interest and will look into developing future Ti-beta blends that will be AM friendly. We know this will be successful because, **QuesTek** computationally designed and developed three castable titanium alloys under U.S. Army-funded SBIR Phase I and II programs to incorporate lower-cost raw materials and exhibit greater strength and/or ductility than Ti-6-4. The new alloys are tentatively named QT-Ti-1A, QT-Ti-2A, and QT-Ti-2B.). One alloy, QT-Ti-1A utilizes a refined, interweaving α/β microstructure which can be achieved at cooling rates representative of conventional commercial processes. This microstructure yields higher strength/toughness characteristics than the parallel α laths found in Ti-6-4.

5 Sustainability

NIU has an institute for the study of the Environment, Sustainability and Energy. The energy studies emphasis combines courses in the colleges of Liberal Arts and Sciences and Engineering and Engineering Technology which introduces students to the world of green technology and energy related issues. The focus of the emphasis includes, but is not limited to, green concepts in power production, processing, manufacturing, ecologically friendly materials, and transportation. Students take courses on the humanities and social sciences to better understand the role that energy plays in society. We will engage one of the courses starting in the fall to have students measure the impact of the processing we are carrying out from powder development to final print production of the component and compare this to the traditional methods of Ti-Beta alloy development and post production of parts. This will then be given in the form of an energy report providing a comprehensive understanding of the requirements for such an operation. This economic analysis will be added as a deliverable to America Makes membership.

6 Education and Workforce Training

NIU EIGERlab serves as a regional resource for entrepreneurs, SME's and innovators to commercialize new ideas, increase revenues and profits, participate in peer groups, access business coaching, contract for product development services, design engineering and art-to-part rapid prototyping services, meet with dedicated mentors and link to qualified investors.

Collaboration regarding regional innovation and economic development has long been a core competency of EIGERlab. Delivering regional resources and connections as a conduit for economic growth is an important key to its mission. NIU EIGERlab will serve on the Industrial Advisory Board for the project and provide feedback on how to accelerate progress and/or discover new opportunities.

Rockford is the third largest city in Illinois and home of the NIU EIGERlab. NIU has long history of engagement and outreach in the Rockford area, where the College of Engineering & Engineering Technology has helped facilitate more than $20 million in federal funding for manufacturing projects over the last decade. Most recently, NIU has led a collaborative focused on strengthening the area's thriving aerospace cluster. NIU continue to work closely with the EIGERlab, the Rockford area business incubator/accelerator, where NIU's manufacturing training, consultation and outreach was centered for the last decade. Consequently, EIGERlab was chosen as a beta site for Digital Manufacturing and Design Innovation Institute (DMDII).

The Midwest is home to both aerospace and medical Tier 1 and OEM (like Woodward and United Technologies Aerospace Systems, Baxter, Stryker, and DePuy) with a significant supply chain that includes materials suppliers (like International Titanium Powder and PRAXAIR), and small manufactures (like SPX, Spider Inc., Superior Joining and Technology, and Met-L-Flo), to name a few). Both aerospace and medical applications have business cases which will make them early adopters of additive manufacturing. These industries need to economically produce increasing complex (number of features, dimensional tolerances, and surface finishes) components that are becoming more difficult to produce with consistently high standards by conventional machining. This need is punctuated by the retirement of traditional 3D machinist of the baby-boomer generation in the coming decade. These industries are already multi-national and provide a natural conduit to migrate the lessons learned across international standards bodies at the speed of business. NIU proposes to transfer the program knowledge through a range of four outreach activities: additive manufacturing focus group, small business potential, best practices, and workshops and presentations.

6.1 Additive Manufacturing Focus Group

NIU EIGERlab will specifically reach out to regional companies (in Winnebago, Boone, McHenry, Stephenson, Ogle and DeKalb Counties) thru their newly formed innovation focus groups and specifically gather information on their interest in metal alloy additive manufacturing interest and opportunities. Focus Groups will enhance and build upon our existing strengths while also developing strategic new directions. The primary objective of the focus group is to explore and identify critical technical, operational and sustainability challenges facing the successful implementation of additive manufacturing systems.

6.2 Small Business Potential

NIU EIGERlab will make business development calls on a minimum of twelve companies in the region to discuss and evaluate how metals in general, and specifically titanium additive manufacturing would assist and leverage their current and future customer needs. Customized focus group that addresses immediate pain points and provides a short-term action plan, or to expand your markets and customer base, NIU EIGERlab business accelerator tools are designed to develop and grow businesses.

The Additive Manufacturing has become an evolutionary process of designers, developers, with tooling shops for engineered metal casters and metal forming manufacturers finding more efficient ways to transform ideas into three-dimensional physical objects. How additive manufacturing functions align supports this view. Three different program developers (Altair, Click2Cast, and HBM nCode) and one of the principal suppliers of additive manufacturing systems (VoxelJet) are collaborating to introduce a new design and manufacturing process that combines established production methods with simulation-driven design and product verification into a packaged mold making capability whether it be for casting or metal forming. Nearly all these anticipated customers are small businesses.

6.3 Best Practices

NIU EIGERlab will record and document best practices by companies in the region that are currently utilizing metal additive manufacturing resources. By disclosing strategies for everyday operation, empirical the internal expertise acquired overtime copes with the lack of standards within the additive manufacturing industry. Some issues to be survey include process planning, materials and costs. Questions range from general additive manufacturing perceptions to specific production criteria like: layer thicknesses, laser power, and quality assurance methods, ease-of-use of specific AM machines, its dimensional accuracy, build speed, and surface finish quality of the fabricated part. The support model, training offerings, and services portfolio provided by the equipment manufacturer are critical in the reduction of staffing levels. The need for specific additive manufacturing standards previously identified in the America Makes road map like material recycling, process planning and costs assignment will be validated and potential new needs discovered.

6.4 Workshops and Presentations

NIU previously developed *Cladding Technician Multimedia Training Program* (an on-line course developed with nearly $1 million in NSF funding) to help community colleges around the US educate Associate Degree students in the earliest form of metal additive manufacturing process (cladding) to include an overview of AM technologies and their relationship to the process control technologies taught in the course. Currently this template is being extended as an on-line multimedia community college training course for *Wind Turbine Technician Training* under NSF Advanced Technology Education funding.

NIU has already prepared two modules und its NIST funded *Measurement Science for Additive Manufacturing* program. These will be updated and form the core curriculum contingent upon the input received through the additive manufacturing focus group and the best practices tasks explained above. Activities to be undertaken as part of course module development will include the following: 1) survey of materials currently available (coordinate with AM), 2) consultation with industry representatives regarding content (coordinate with AM), 3) integration of materials from previous NSF laser cladding project, 4) lesson outline development, 5) production of video, animations, narration, and other media , 6) construction and validation of skill assessments, 7) testing and review of course materials, and 8) delivery of the online materials.

NIU EIGERlab will schedule, market and deliver a series of workshops and presentations on metals additive manufacturing and include EOS and/or Trumpf to overview current technologies and capabilities. NIU EIGER will deliver this series to REV3 in Naperville, Catalyze in Chicago, NIU-Hoffman Estates, NIU-Rockford and NIU-DeKalb.

In addition, the project team will prepare material (documentation and test cases) and will provide effort to train a selected audience on the capabilities and the usage of the software prototype developed in the project for additive manufacturing process simulation. Two training workshops are planned, expected to have a 2- and 5-days duration respectively.

The first workshop will serve to educate the AM members selected to exercise the developed software prototype. The focus of this first workshop is on the usage of the software tool. At the end of the workshop, the participants will be able to use each developed functionality, to generate results and to compare them with benchmark data, in order to identify any potential problem. The material for this workshop will be mainly provided by Siemens.

The second workshop will provide information on how to use the software (provided by Siemens), as in the previous workshop, but will mostly focus on the technical approaches adopted in the simulation tools development (provided by all the models/software developers in the team). This second workshop will target, graduate students from the academic partners (Northern Illinois and Northwestern University), to enable them to build on the research conducted in this project and leverage it to advance even further the state of the art of additive manufacturing process and mechanical and microstructural performance simulation, in the scope of their research projects. Additional longer training sessions will be considered if needs arise during the project.

7 Project Management Approach

Northern Illinois University will coordinate overall program direction and conduct LENS trials. Prof. Federico Sciammarella serves as PI with Dr. Joseph Santner will be Co-PI. The technical lead for **NU** is Prof Jian Cao and will address modeling mechanical behavior of materials as well as thermal modeling the deposition process. Dr. Lucia Mirabella technical lead for **Siemen NX** responsible for model integration. Dr. Jiten Shah leads **Product Development and Analysis** will build on past components to validate with AM process. Kamal Akhtar the lead for **Cristal Metals, Inc**. will provide characterized Armstrong-based titanium alloys. Each of these individuals are experienced program managers in their own right and detailed in greater depth in the *Project Team Appendix*. Their role, and other key personnel, are tabulated at the end of this section.

The Gantt chart shows *bi-monthly partner status meetings*, will be used to coordinate project activity. The first bi-monthly meeting will be after all the sub-awardees are under contract. NIU will be in contact with the respective technical and business leads for each partner. The inaugural bi-monthly meeting is anticipated to occur before the scheduled three months once the partner agreements are established to assure that the work plans are synchronized. NIU will prepare briefing charts that will be shared with the other PIs and key people. Subsequently, bi-monthly review, coordination and synchronizations meeting will be held to identify issues and identify remedial actions to adequately address and measure the efficacy of the program. Some of these meetings may occur as satellite meetings at national or regional meetings sponsored by AM, SME, FMA, ASM or ASTM. NIU has allocated travel funds to coordinate with its association partners.

Technical and financial quarterly reports will be issued to America Makes for program management. Quarterly written status reports will capture the technical accomplishments of the prior three months, plans for the coming quarter, and identify of issues with recommend actions for resolution. Furthermore, NIU will participate at the semi-annual America Makes project review meetings (PRM).

NIU has solicited and received Letters of Interest from several companies within the AM supply chain (Silicon Valley Supply Chain, UTC Aerospace Systems, and GPI Prototype & Manufacturing Services, Inc.) interested in titanium additive manufacturing to serve on an *industrial advisory board*. The purpose of this board is to provide continuing engagement with the titanium AM technology, motivation to join AM, and confidence in a business case for their projected role in the additive manufacturing supply chain during the course of the program.

Key Personnel and Their Roles

Key Personnel	Expertise	Role
Federico M. Sciammarella PhD Materials, IIT	Laser materials processing such as cladding, heat treating and surface cleaning	PI
Mathew J Gonser PhD Welding, Ohio State	Materials processing, solidification, materials selection, mechanical behavior and microstructure	Laser Processing Specialist
Joseph S. Santner PhD MS&E, NU	Metal processing and technology development and technology transfer	Co-PI, Tech Transition & Impact
Jian Cao PhD ME, MIT	Laser processes; forming mechanics; process control; instability analysis; uncertainty analysis; mechanics-based tool path generation	Inventor of deterministic Tool Path generation now applied to beam path generation
Wing K. Liu PhD, Calif. Institute of Technology	Computational mechanics; multi-scale analysis and design; multi-physics computational modeling; reproducing kernel particle and wavelets methods	Integrating spatial and temporal scales into commercial multi-physics FEA modules
Gregory B Olson ScD Materials, MIT	Dynamic multilevel structure; systems design of materials	Inventor of "Materials by Design"™
Wei Xiong PhD MS&E, KTH Royal Institute of Technology	Materials and processing design for additive manufacturing Ti and ferrous alloys	Develop microstructure evolution law for in-house thermal model
Sanjeev Srivastava PhD, Texas A&M	Software development, optimization algorithms	Software integration with NX and process qualification/optimization
Suraj Musuvathy PhD, University of Utah	Software development, design optimization for additive manufacturing	Software integration with NX and process qualification/optimization
Lucia Mirabella PhD Math Eng, Politecnico di Milano	Software development, process simulation for additive manufacturing	Software integration with NX and process qualification/optimization
Erhan Arisoy PhD ME CMU	Software development, design optimization for additive manufacturing	Software integration with NX and process qualification/optimization
Edward Slavin MS CS PSU	Software development, design for additive manufacturing, rendering	Software integration with NX and process qualification/optimization
Michael Colbert	EIGERlab Assistant Director and Center for Product Development lead	AM focus group and best practices
Sherry Pritz	Marketing coordinator and business development	Small business potential, workshops and presentations
Kerem Araci	Titanium alloy powder property development and powder conversion	Supply and characterize Ti powder produced by Armstrong process
Jiten Shah PhD ME, IIT	Concurrent product and process design using CAE tools, experience and knowledge	Validation testing (SME)

8 References

(1) Tang, S., Kopacz, A. M., Chan, S., Olson, G. B., and Liu, W. K., 2013, "Concurrent Multiresolution Finite Element: Formulation and Algorithmic Aspects," conditional acceptance in Computational Mechanics.

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(3) G.B. Olson, C.J. Kuehmann, Materials genomics: From CALPHAD to flight, *Scripta Materialia*, **70**:1 25-30, 2014.
(4) Fencheng Liu, Xin Lin, Gaolin Yang, Menghua Song, Jing Chen, Weidong Huang, Microstructure and residual stress of laser rapid formed Inconel 718 nickel-base superalloy, *Optics & Laser Technology*, **43**:1, 208-213, 2011.
(5) Tabernero, A. Lamikiz, S. MartÃnez, E. Ukar, J. Figueras, Evaluation of the mechanical properties of Inconel 718 components built by laser cladding, *International Journal of Machine Tools and Manufacture*, **51**:6, 465-470,2011.
(6) Giedt, W. T., Tallerico, L. N. and Fuershbach, R.W. 1989. GTA welding efficiency: Calorimetric and temperature field measurements. Welding Journal, 68 (1), 28-32.
(7) Fuerschbach, P. W. 1996. Measurement and prediction of energy transfer efficiency in laser beam welding. Welding Journal, 75 (1), pp 24-34.
(8) Malin, V. E. 1969. A study of thermal characteristics of constricted alternate-current arc. Svarochnoe Proizvodstvo (Welding Production), No. 9, pp 3-5.
(9) Smartt, H. B., Stuart, J. A. and Einerson, C. J.1986. Heat transfer efficiency in gas tungsten arc welding, ASM Metals/Materials Technology Series, No 8511- 011, pp 1-14
(10) Malin V, Sciammarella F, "Controlling Heat Input by Measuring Net Power", Welding Journal, July 2006, 44-50.

Exhibit I. Identification of Background Intellectual Property

Project Title	Lightweight Additive Manufacturing of Beta-Ti Alloys
Organization	Northern Illinois University
Principal Investigator	Federico Sciammarella

List all known background intellectual property to be used in the conduct of this project or for which access may be required to implement project results:

Inventor / Owner	**Title**	**Patent or Disclosure I.D.**
Federico M Sciammarella, Joseph S. Santner, Mathew J. Gonser, Justin Whiting, Daniel Nikolov	Uniform Chilling Thermal Reservoir Chamber	ID dated 20 Jan 2015
Federico M Sciammarella, Mathew J. Gonser, Justin Whiting, Adam Springer,	Active Powder Mass Flow Monitoring	ID dated 22 Jan 2015
Federico M Sciammarella, Justin Whiting, Adam Springer, Dan Nikolov	LENS Parameter Optimization	White Paper 8 October 2014

■ **If controlled by a project participant, I understand that a "good faith" commitment to enter into negotiations for a license of this background intellectual property to America Makes or the project partners may be required.**

OR

☐ **I am unaware of any background intellectual property to be used in the conduct of this project or that may be required for implementation of project results.**

Intellectual Property Rights Policy & Confidentiality Statement

As the Principal Investigator at Northern Illinois University (Member) participating in this project, I agree to accept and abide by the Intellectual Property Rights Requirements of the America Makes Membership Agreement, as approved by the Governance Board, dated 12/21/2012. I understand that I may be the recipient from time to time of information of a confidential and proprietary nature belonging to another America Makes participating organization. I have read and explicitly agree to abide by the provisions Section 5 of the America Makes Membership Agreement with respect to proprietary information.

I further agree to assist the project participants in their obligation of implementing America Makes' intellectual property requirements for funded projects. I will do this by encouraging the timely submission of invention disclosures by project participants to their appropriate Intellectual Property Office, clearly identifying such disclosures as relating to this project, and by providing any supporting documentation and information that may be requested from time to time for the purpose of filing patent applications under America Makes and/or the Inventing Organization(s).

Principal Investigator

Signature	
Printed Name	Federico M. Sciammarella **DATE:** April 20, 2015

Exhibit I. Identification of Background Intellectual Property

Project Title	Lightweight Additive Manufacturing Beta Titanium Structures
Organization	Northwestern University
Principal Investigator	Wing Kam Liu

List all known background intellectual property to be used in the conduct of this project or for which access may be required to implement project results:

Inventor / Owner	Title	Patent or Disclosure I.D.
Gregory Olson/Northwestern	A computationally-designed transformation-toughened near-alpha titanium alloy	62/043,897
Jakob Smith/Northwestern	Optimized Numerical Analysis Tool for Additive Manufacturing Applications	NU:01-14-2015

Exhibit I. Identification of Background Intellectual Property

Project Title	Lightweight Additive Manufacturing Beta Titanium Structures
Organization	Cristal Metals, Inc.
Principal Investigator	Kerem Araci

List all known background intellectual property to be used in the conduct of this project or for which access may be required to implement project results:

Inventor / Owner	Title	Patent or Disclosure I.D.
Donn Reynolds Armstrong, Stanley R. Borys, Richard P. Anderson	Titanium and Titanium Alloys	7,445,658
Donn Reynolds Armstrong, Stanley R. Borys, Richard P. Anderson	Elemental Material and Alloy	7,435,282
Donn Reynolds Armstrong, Richard Paul Anderson, Lance E. Jacobsen	Preparation of Alloys by the Armstrong Method	7,041,150
Donn Reynolds Armstrong, Richard Paul Anderson, Lance E. Jacobsen	Method and Apparatus for Controlling the Size of Powder Produced by the Armstrong Process	7,501,089
Donn Reynolds Armstrong, Richard Paul Anderson, Lance E. Jacobsen	Injecting, reduction halide vapor into liquid metal; controlling temperature	7,351,272
Richard P. Anderson, Donn Armstrong, Jacobsen Lance	System and Method of Producing Metals and Alloys	7,621,977

☑ **If controlled by a project participant, I understand that a "good faith" commitment to enter into negotiations for a license of this background intellectual property to America Makes or the project partners may be required.**

OR

☐ **I am unaware of any background intellectual property to be used in the conduct of this project or that may be required for implementation of project results.**

Intellectual Property Rights Policy & Confidentiality Statement

As the Principal Investigator at Cristal Metals, Inc. participating in this project, I agree to accept and abide by the Intellectual Property Rights Requirements of the America Makes Membership Agreement, as approved by the Governance Board. I understand that I may be the recipient from time to time of information of a confidential and proprietary nature belonging to another America Makes participating organization. I have read and explicitly agree to abide by the provisions Section 5 of the America Makes Membership Agreement with respect to proprietary information.

I further agree to assist the project participants in their obligation of implementing America Makes' intellectual property requirements for funded projects. I will do this by encouraging the timely submission of invention disclosures by project participants to their appropriate Intellectual Property Office, clearly identifying such disclosures as relating to this project, and by providing any supporting documentation and information that may be requested from time to time for the purpose of filing patent applications under America Makes and/or the Inventing Organization(s).

Principal Investigator

Signature		
Printed Name	Kerem Araci	**DATE:** April 20, 2015

6.2 Exhibit II. Multiple Submissions Summary

America Makes recognizes that projects may be submitted to multiple sources of funding.

America Makes must be informed if other funding is secured and will work with the Principle Investigator (PI) to modify this project scope, as appropriate.

List all planned or submitted requests for additional funding of work in this project area from sources other than America Makes.

Date Submitted or Planned Submittal Date	Organization	Decision Date
NA	NA	NA

Principal Investigator

Signature	Federico sciammarella
Printed Name	Federico Sciammarella
Date	04/29/2015

Northern Illinois University

Office of Sponsored Projects
DeKalb, Illinois 60115-2874
815-753-1581
Fax 815-753-1631
www.niu.edu/osp

April 30, 2015

John Wilczynski
America Makes Deputy Director, Technology Development
National Center for Defense Manufacturing and Machining

To Whom It May Concern:

I am pleased to submit, on behalf of Northern Illinois University, a proposal entitled "LIGHTWEIGHT ADDITIVE MANUFACTURING BETA TITANIUM ALLOYS" under the direction of Dr. Federico Sciammarella (815-753-1288, sciammarella@niu.edu). This proposal is submitted to the America Makes Project Call. This proposal covers the project period of 07/10/15-01/10/2017 with the proposed award amount to NIU being $ 877,286.

NIU and its team will address the following America Makes priority areas: Materials (detailed thermal history analysis of Ti-beta alloys and its correlation to material properties), Value Chain (focus on testing, certification and material qualification-pre and post build), and AM Genome (integrating several physics based models to provide holistic view of material from end to end). More specifically within these categories the focus will be on, material property characterization (looking at current beta-Ti that are favorable to AM), advanced sensing and detection methods (quantifying energy going into AM process to define boundary conditions), model assisted property prediction and physics-based modeling & simulation (looking at multi-scale physics models and ensuring all relevant information is available to perform the analysis).

To explain and document NIU's portion of the cost-sharing requirements, we are administratively committed to providing $ 877,484 in cost share. These funds are available and dedicated to the project, should the grant be awarded. Specifically, we have committed $ 83,131 in salary across the 18 months of the project; these funds will come from College of Engineering and Engineering Technology and Division of Research and Innovation Partnerships. Further, we have committed $ 93,121 in unrecovered Facilities and Administrative costs; these funds are committed at the University level rather than the department level. An additional $ 26,132 in tuition remission for two Graduate Research Assistants is committed by the Division of Research and Innovation Partnerships. And funds of $675,100 from the third parties are committed to this project, should the proposal be funded.

Please contact us if you require additional information about any of these materials. We would appreciate being advised as developments occur regarding this proposal.

Sincerely,

Dara Little

Director, Office of Sponsored Projects

CRISTAL

John Wilczynski
America Makes Deputy Director, Technology Development
National Center for Defense Manufacturing and Machining

April 17, 2015

America Makes Project Call Proposal: Lightweight Additive Manufacturing Beta Titanium Structures

This is to indicate Cristal Metals, Inc's willingness to collaborate with Northern Illinois University (NIU) on an AM project entitled, "**Lightweight Additive Manufacturing Beta Titanium Structures**" with a cost-share amount of $25,000. Should this proposal be funded, it is Cristal's intention to participate as a subcontractor under the leadership of Mr. Kerem Araci (815-221-2276, kerem.araci@cristal.com).

This proposal is submitted to the America Makes Project Call. This proposal covers the project period of 07/10/15-01/10/2017. NIU will take the lead in this project to showcase that with the proper approach a low-cost Ti-beta alloy can be developed that is additive manufacturing friendly and capable of outperforming current standards achievable with traditional components (as cast, or forged). Cristal Metals, Inc. will partner as a supplier of CP-Ti and Ti alloys.

To explain and document Cristal Metals Inc.'s portion of the cost-sharing requirements, we as a sub-recipient of the project are administratively committed to providing $25,000.00 in cost share. These funds are available and dedicated to the project, should the grant be awarded. We have committed $22,400 in materials and 2,600.00 in fringe benefits. In addition, funding for $10,000 in salary and $15,000 in equipment costs will be required across the 18 months of the project.

Please contact us if you require additional information about any of these materials, referencing the proposal name shown above. We would appreciate being advised as developments occur regarding this proposal.

Yours sincerely,

Kamal Akhtar
Director of Technology and Quality
kamal.akhtar@cristal.com

SIEMENS

Siemens Corporation, Corporate Technology

April 24, 2015

John Wilczynski
America Makes Deputy Director, Technology Development
National Center for Defense Manufacturing and Machining
236 West Boardman Street
Youngstown, OH 44503

Subject: Proposal from Northern Illinois University in response to the Project Call to Members of the NAMI Institute for applied research projects;

Dear John Wilczynski,

Siemens Corporation, Corporate Technology (SC CT) is pleased to support the proposal from Northern Illinois University titled "Lightweight Additive Manufacturing Beta Titanium". SC CT contribution will include the development of a software interface to build a multiscale simulation tool for the additive manufacturing process, integrated with the NX software suite. This will be achieved combining existing software tools from the project partners. In addition, SCCT will participate in the software validation and will lead the process characterization/optimization component using the validated simulation tool, to achieve satisfactory material and mechanical properties of the resulting part.

If funded, we are committed to supporting this project by offering our technical expertise on additive manufacturing process modeling and software development. We will support the project task "Technology Transfer" (#6), including multi-scale models integration and overall virtual process characterization and optimization. This task will be performed by Siemens Corporation, Corporate Technology over a period of 18 months. The value of SC CT's participation in this project is $600,000, including $350,000 cost share in the form of NX software licences provided by Siemens PLM Software, Inc. The Principal Investigator for this work at SC CT will be Dr. Lucia Mirabella (609-734-3529 / lucia.mirabella@siemens.com).

Located in Princeton, New Jersey, SC CT is one of several world-class central research and development labs within Siemens Corporate Technology. Our hundreds of research scientists and software engineers provide technological solutions to the global family of Siemens' businesses. We also work closely with Siemens' customers, government agencies, universities, and other organizations.

We view the goals of this proposed project as critical in improving the knowledge base on additive manufacturing technology, and in ultimately making a significant contribution towards its widespread usage in the manufacturing industry. We look forward to collaborating with you in this important research.

Sincerely,

Silvano Dall'Asta

Terry Heath
Sr. Vice President
Corporate Technology

Silvano Dall'Asta
Head of Business Administration
Corporate Technology

OSR **Office for Sponsored Research**
Northwestern University
1801 Maple Avenue, Suite 2410
Evanston, Illinois 60201-3149

Phone 847 491-3003
Fax 847 491-4800

NORTHWESTERN UNIVERSITY

April 27, 2015

To whom it may concern:

This is to indicate Northwestern University's willingness to collaborate with Northern Illinois University (NIU) on the project "Materials and Process Design Based on Predictive Models and Advanced Characterization for Titanium Beta Alloys in Additive Manufacturing". This proposal is submitted to NIU to ultimately submit a proposal in response to the current America Makes Project Call. It is Northwestern's intention to participate as a subcontractor under the leadership of Professor Wing Kam Liu, who will serve as the Northwestern Principal Investigator.

Support is requested for an estimated project period of 7/10/15-1/09/17 for a total budget of $275,000 in sponsor funding and $275,000 in cost sharing. Northwestern has provided cost sharing in the form of effort inclusive of salaries and fringe benefits, as well as waived and unrecovered F&A, or indirect costs.

It is our understanding that the scope of work to be performed by Northwestern will at all times concern fundamental research as defined under export control regulations. It is the policy of Northwestern University that instruction, research, and services will be accomplished openly and will lead to the publication and dissemination of the results of academic and research activities. Also, Northwestern is not in a position to accept controls on foreign national access to the university research project or its results. Should the proposal be funded, Northwestern reserves the right to negotiate the resultant subcontract.

This application has been administratively approved by Northwestern University. Questions regarding the technical aspects of this proposal should be directed to the Principal Investigator. Should you have questions or need additional information of a contractual or administrative nature, please contact me via phone (847/467-3283) or email (kellym@northwestern.edu).

Sincerely,

Kelly Morrison
Associate Director, Evanston Campus
Office for Sponsored Research
Northwestern University

Product Development & Analysis LLC
PROVIDING ENGINEERING & MANUFACTURING SOLUTIONS

Letter of Commitment

April 24, 2015

John Wilczynski
America Makes Deputy Director, Technology Development
National Center for Defense Manufacturing and Machining

To Whom It May Concern,

This is to indicate Product Development & analysis (PDA) LLC's willingness to collaborate with Northern Illinois University on an AM project entitled "**Lightweight Additive Manufacturing Beta Titanium Structures**" with a request of $25,075. Should this proposal be funded, it is PDA's intention to participate as a subcontractor under the leadership of Mr. Jiten Shah (PDA PI's phone number: 630 505 8801 and email address: info@pda-llc.com).

PDA will provide primarily the process modeling domain expertise and support and facilitate with the workforce development and enabler transition through benchmarking Siemens's proposed modeling enabler development, working with SMEs.

To explain and document PDA's portion of the cost-sharing requirements, we are committed to providing $ 25,175 in total cost share, out of which $ 2,400 towards travel related expenses; $2700 towards travel and meeting related time and $20,000 value derived from Siemens committing to providing a full license of NX software during the entire project execution.

Please contact us if you required additional information about any of these materials, referencing the proposal number shown above. We would appreciate being advised as developments occur regarding this proposal.

Sincerely,

Jiten Shah

Jiten Shah
President,
PDA LLC.

1776 Legacy Cir. Suite#115, Naperville, IL 60563
Phone #: 630-973 0576   Fax #: 630-585 3006   E-mail: info@PDA-LLC.com

GPI PROTOTYPE & MANUFACTURING SERVICES™

Galloway Plastics, Inc. • GPI Prototype & Manufacturing Services, Inc.

April 20, 2015

John Wilczynski
America Makes Deputy Director, Technology Development
National Center for Defense Manufacturing and Machining
236 West Boardman Street
Youngstown, OH 44503

RE: Letter of Interest – *Additive Manufacturing Beta Titanium Alloy Components*

Dear Mr. Wilcynski:

GPI has been providing Direct Metal Laser Melting (DMLM) services since 2008. As one of the first Metal Additive Manufacturing (3D Printing) service providers in the country, GPI produces prototypes and end-use parts with complex geometries not possible with traditional machining in a variety of metals, including titanium, for clients ranging from college students in the lab to Fortune 500 companies in the medical, aerospace and defense industries.

Our specific interest in this program is related to open source materials knowledge and value chain. GPI plans to serve as an industrial advisory board member to ensure industrial relevance. While details need to be worked out and approved, we are committed to work through those issues and work with the NIU team to provide guidance and feedback based on our internal experts, experience, and relevant information such as manufacture, installation, operating conditions, and service failures/repairs. We understand that the NIU team of materials, manufacturing, and business experts will use this information to develop and recommend best practices across the supply chain for using beta titanium alloys for additively manufactured parts.

GPI Prototype & Manufacturing Services Inc. is pleased to support the beta titanium proposal and certainly affirm the need. We wish the America Makes "Lightweight Additive Manufacturing Beta Titanium Structures" program under the direction of Dr. Federico Sciammarella success in accelerating the maturation of the infrastructure and supply chain to routinely produce high-strength titanium-friendly additive manufacturing parts. Based on the results we may pursue ancillary programs with NIU in the future.

Please feel free to contact me for clarifications.

Sincerely,

Kate O'Boyle Kummerer
New Business Development
katek@gpiprototype.com

QuesTek
INNOVATIONS LLC

April 27, 2015

John Wilczynski
America Makes Deputy Director, Technology Development
National Center for Defense Manufacturing and Machining
236 West Boardman Street
Youngstown, OH 44503

RE: Letter of Interest – *Additive Manufacturing Beta Titanium Alloy Components*

Dear Mr. Wilcynski:

QuesTek invents, designs, develops and qualifies engineered materials for demanding applications to reduce capital, processing, operating or maintenance costs, or to improve environmental protection, competitive supply or competitive advantage. QuesTek exemplifies a successful model of mutual support that can strengthen the economic competitiveness of local innovative businesses and enable universities to compete more effectively for federal funding, which is increasingly tied to commercialization goals.

Our specific interest in this program is related to Beta titanium alloys optimized for additive manufacturing to reduce residual build stress and provide higher strength than available from the Alpha-Beta titanium work horse, Ti-6-4. QuesTek plan to serve as an industrial advisory board member to ensure industrial relevance. While details need to be worked out and approved, we are committed to work through those issues and work with the NIU team to provide guidance and feedback based on our internal experts, experience, and relevant information such as manufacture, installation, operating conditions, and service failures/repairs. We understand that the NIU team of materials, manufacturing, and business experts will use this information to develop and recommend best practices across the supply chain for using beta titanium alloys for additively manufactured parts.

QuesTek is pleased to support the beta titanium proposal and certainly affirm the need. We wish the America Makes "Lightweight Additive Manufacturing Beta Titanium Structures" program under the direction of Dr. Federico Sciammarella success in accelerating the maturation of the infrastructure and supply chain to routinely produce high-strength titanium-friendly additive manufacturing parts. Based on the results we may pursue ancillary programs with NIU in the future.

Please feel free to contact me for clarifications.

Sincerely,

Jason Sebastian
Manager of Technology and Product Development

Business Confidential – for America Makes internal use in evaluation of NIU proposal.

Silicon Valley Space Center
"Launching New Space Entrepreneurs in Silicon Valley"

www.siliconvalleyspacecenter.org

Mr. John Wilczynski
America Makes Deputy Director, Technology Development
National Center for Defense Manufacturing and Machining
236 West Boardman Street
Youngstown, OH 44503

April 21, 2015

RE: Letter of Interest – Additive Manufacturing Beta Titanium Alloy Components

Dear Mr. Wilcynski:

Silicon Valley Space Center (SVSC) provides business acceleration, strategic direction and angel level funding for startup companies within the growing NewSpace industry. Events and workshops bring together the vast array of entrepreneurs, scientists, engineers, and investors who share a passion for shaping the market potential of spaceflight. Our center features monthly tech talks in partnership with the local chapter of the AIAA on the topics of propulsion, small satellites, ground stations, and commercial programs for low-earth orbit, the lunar surface, and beyond. Current list of companies within the center include Vital Space, Positron Dynamics, Alanax software, Integrated Spaceflight Services, and SpaceVR.

Our specific interest in additive manufacturing is related to the development and certification of powdered alloys for aerospace applications. This would include propulsion and support structures along with multi-function structures. As managing director of the center, I plan to serve as an industrial advisory board member to ensure industrial relevance for bay area aerospace companies. While details need to be worked out and approved, we are committed to work through those issues and work with the NIU team to provide guidance and feedback based on our internal experts, experience, and relevant information such as manufacture, installation, operating conditions, and service failures/repairs. We understand that the NIU team of materials, manufacturing, and business experts will use this information to develop and recommend best practices across the supply chain for using beta titanium alloys for additively manufactured parts.

Silicon Valley Space Center is pleased to support the beta titanium proposal and certainly affirm the need for continued research and development in this area. Several bay area aerospace firms have expressed interest in the topics presented by the NIU team and are eager to see the results of the titanium based studies proposed. I wish the America Makes "Lightweight Additive Manufacturing Beta Titanium Structures" program under the direction of Dr. Federico Sciammarella success in accelerating the maturation of the infrastructure and supply chain to routinely produce high-strength titanium-friendly additive manufacturing parts.

Based on the results anticipated, our center expects to pursue ancillary programs with NIU in the future.

Please feel free to contact me for clarifications.

Sincerely,

Sean C. Casey, PhD, MBA
Managing Director,
Silicon Valley Space Center
sean.casey@siliconvalleyspacecenter.org

UTC Aerospace Systems
4747 Harrison Avenue
Rockford, IL 61125 USA

UTC Aerospace Systems

April 30, 2015

John Wilczynski
America Makes Deputy Director, Technology Development
National Center for Defense Manufacturing and Machining
236 West Boardman Street
Youngstown, OH 44503

RE: Letter of Interest – *Additive Manufacturing Beta Titanium Alloy Components*

Dear Mr. Wilcynski:

UTC Aerospace Systems is among the largest suppliers of technologically advanced aerospace and defense products. We design, manufacture and service systems and components for commercial, regional, business and military aircraft, helicopters and international space programs. Innovative designs require advanced manufacturing technology like additive manufacturing to change art into parts.

Our specific interest in this program is actually achieving the desired static and dynamic properties for a beta titanium alloy that we are interested in using. We plan to serve as an industrial advisory board member to ensure industrial relevance. While details need to be worked out and approved, we are committed to work through those issues and work with the NIU team to provide guidance and feedback based on our internal experts, experience, and relevant information such as manufacture, installation, operating conditions, and service failures/repairs. We understand that the NIU team of materials, manufacturing, and business experts will use this information to develop and recommend best practices across the supply chain for using beta titanium alloys for additively manufactured parts.

UTC Aerospace Systems is pleased to support the beta titanium proposal and certainly affirm the need. We wish the America Makes "Lightweight Additive Manufacturing Beta Titanium Structures" program under the direction of Dr. Federico Sciammarella success in accelerating the maturation of the infrastructure and supply chain to routinely produce high-strength titanium-friendly additive manufacturing parts. Based on the results we may pursue ancillary programs with NIU in the future.

Please feel free to contact me for clarifications.

Sincerely,

William Wentland

William Wentland
Fellow - Materials/Special Processes

Business Confidential – for America Makes internal use in evaluation of NIU proposal.

This document does not contain export controlled technology or technical data.

6.4 Exhibit IV. Acknowledgement of Consortium-developed Intellectual Property and Disclosure of Planned Publications

☒ As the Principal Investigator at Northern Illinois University (Member), I agree that results from this project will be considered consortium-developed intellectual property (CDIP) and will be shared amongst the membership according to the consortium-developed intellectual property (CDIP) structure in the Membership Agreement, with exceptions made for any ITAR/Export Control information.

☐ As the Principal Investigator at ____________________ (Member) participating in a funded Project, I project the following publications of the results from this project. In addition, I agree that all publications will be approved through the AFRL Technical POC 45 days prior to public dissemination.

Summary of Planned Publications from Project Team

Principal Investigator

Signature	Federico sciammarella		
Printed Name	Federico Sciammarella	**DATE:**	04/29/2015

6.5 Exhibit V. Identification of Project Deliverables

List all project deliverables that will be delivered at the end of this project:

Organization Name/Responsible Party	Deliverable	ITAR Restricted (yes/no)
NIU/NU	Deliver workshops and presentations on Ti-beta AM	no
NU/Siemens	Recommend tool practice for residual stress, surface finish, minimum re-heat	no
NU	Document constitutive parameter sensitivity to microstructure prediction	no
NIU/Siemens	Use GED virtual characterization tool to build a library of GED maps based on input data	no
Siemens/PDA	Perform validation of integrated tool with benchmark data	no
Siemens/NU/NIU	Release integrated software tool in prototype quality	no
Cristal	Best practices for material characterization of Ti-Beta	no

Principal Investigator

Signature	Federico sciammarella
Printed Name	Federico Sciammarella
Date	04/29/2015