PROJECT PROPOSAL UNDER CONTRIBUTION TO ALMA MATER PROJECT

Name of Project: Laser Additive Manufacturing of Aerospace Components

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Project Objectives: The key goals and objectives of the project are:

- Through computational modeling provide a fundamental understanding on the effect of process variables (laser power, scan speed, preheating temperature, raster pattern) on build conditions, residual stress and microstructure during Laser Direct Metal Deposition (LDMD) and Laser Powder Bed Fusion (LPBF) of IN625 components.

- To provide a fundamental understanding between the changes in build conditions (melt pool length and depth) on the magnitude and distribution of residual stresses, solidification cooling rates and thermal gradients during laser additive manufacturing of IN625 components.

- To provide simulation-based tools ("process maps") which will provide direct feedback on how changes in process parameters to optimize build conditions will simultaneously affect the control of residual stress buildup and component microstructure in laser additive manufacturing of IN625 components.

Key Deliverables/Outcomes

Although the proposed research is fundamental in approach, the ultimate goal is to provide LAM developers and users with an engineering base for LAM process development . he following key deliverables are anticipated following the project completion:

- The proposed research is expected to provide guidelines on the use of computational modeling (analytical and numerical) approaches for simultaneous control of melt pool size, residual stress and microstructure thereby providing a basis for true process optimization of LAM processes especially for deposition of IN625 components.

- The proposed research emphasizes on the use of simulation-based methods for materials development which offers the potential of reduced cost and accelerated introduction of next generation materials.

- The proposed research is expected to answer the key fundamental questions
    - How can deposition knowledge for an LAM process at one scale be applied to processes at other scales?

- How can deposition knowledge from one material system be applied to other material systems?

- The publication of several journal and conference papers detailing the results of this work.

- Students involved in this project will develop a combined manufacturing, solid mechanics, heat transfer and materials background that will make them highly valuable in industry and academics. Subsequent to graduation these students will represent a valuable asset to the technology base of India.

- The principal investigator (PI) intends to develop a laboratory entitled “Modeling and Simulation Laboratory” at NITK. This laboratory will be a high-tech computing facility for conducting simulation-based research that will involve numerically intensive computations.

Estimated Cost

S.No	Equipment Details	Cost
1	High Performance Computing Workstation	Rs. 5,00,000
	Total Cost	Rs. 5,00,000

Justification for Equipment:

1. A High Performance Computing Workstation is required for carrying out computational modeling of Laser Additive Manufacturing processes.

TECHNICAL DETAILS

1. Background

1.1 Description of problem:

The methodology underlying Laser Additive Manufacturing (LAM) processes is to slice a 3-D CAD model of the object to be fabricated into 2-D cross-sectional layers, and then use a laser to build the layers one by one to form the object. ((e.g., the Laser Engineered Net Shaping (LENS) process of Fig. 1) [1].). The laser additive manufacturing processes have evolved from Rapid Prototyping (RP) and have been developed over the past two decades for fabricating complex parts additively in a fast, flexible and automatic manner, without the need for tooling [2]. LAM techniques such as Laser Direct Metal Deposition (LDMD) which is a powder fed technique and Laser Powder Bed Fusion (LPBF) which is a powder bed technique are promising technologies for the manufacturing of aerospace components because they can substantially reduce both the buy-to-fly ratio and production lead time compared with conventional manufacturing methods [3]. Moreover, such processes will potentially enable the direct manufacture of advanced aerospace components made of multiple or functionally graded materials, or "smart" structures containing embedded sensors or electronic components [4].

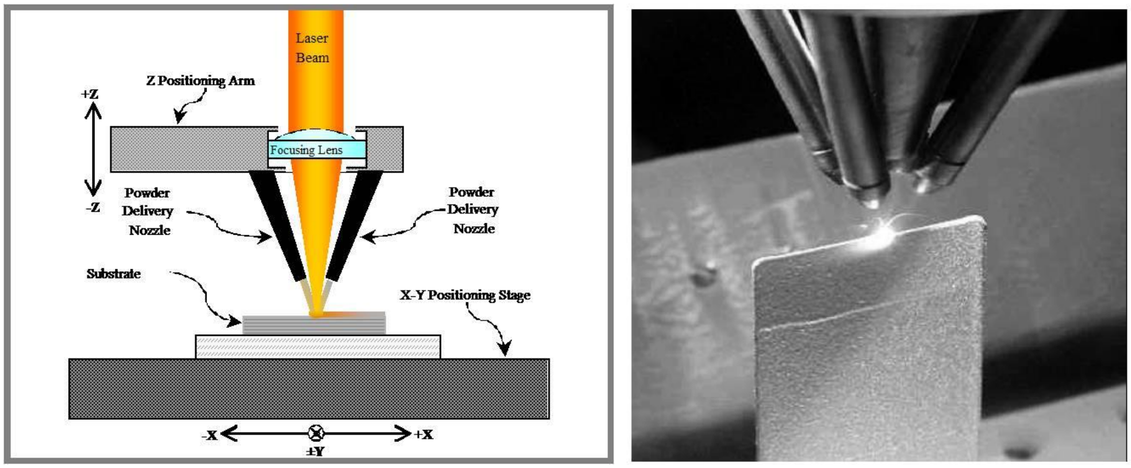

Figure 1. The LENS^{TM} Additive Manufacturing Process
(Source: Photograph from cover of JOM, Vol.51, No.7, July 1999)

Right from the time of their initial development, laser additive manufacturing processes have proved beyond doubt that they can be useful manufacturing techniques for short run or low-volume component fabrication, repairing components, addition of detailed elements to generic components and fabricating functionally graded materials [4]. However, the primary obstacles to the widespread commercialization of these processes include the control of melt pool size (for consistent build conditions), residual stress (to avoid tolerance loss and decreased reliability) and microstructure (to obtain consistent mechanical properties). The control of melt pool size and residual stress and microstructure in these processes have been addressed in the literature [5-18].

As stated earlier, the three key process characteristics that must be understood and controlled in laser additive manufacturing processes are build conditions, residual stress-induced tolerance loss, and microstructure. Of these three process characteristics, the control of melt pool size assumes the highest priority within the manufacturing community [9]. This is because a consistent melt pool size is needed to allow a specific feature to be built using these laser-based material deposition processes. An understanding of melt pool size control is needed for both steady state conditions (e.g., determining nominal melt pool sizes for two different power levels) and for transient conditions (e.g., determining the melt pool size as a function of time due to a step change in power) [10]. Insights into steady-state conditions are of value in overall process design. Transient response must be understood to build an effective system for feedback control of melt pool size, which is a major goal for commercial laser additive manufacturing processes.

Residual stresses are an inherent consequence of the thermal deposition processes used in LAM. In addition to affecting the failure resistance (strength or life) of mechanical parts, residual stresses can lead to unacceptable losses in dimensional tolerance. For LAM deposited structures, it is often the stresses induced in the top portion of the existing component (as opposed to stresses in the added feature itself) that can lead to significant tolerance loss from warping. Moreover, because warping deflections scale with distance, the effects of residual stress-induced distortion can be seen far away from the location where a feature is added. Thus, a fundamental understanding of how residual stress magnitudes relate to LAM process variables is needed to identify strategies for minimizing losses in both failure resistance and dimensional tolerance in aerospace components.

The control of microstructure is critical, when these laser deposition processes are used for the fabrication or repair of aerospace components, because of the strict guidelines that aerospace applications have on microstructure and mechanical properties.

While the control of melt pool size, residual stress and solidification microstructure have been addressed individually in the literature, their interconnection is yet to be investigated. In particular, it is not known how changing process variables to control melt pool size might simultaneously affect the magnitude and distribution of residual stress and also cooling rates and thermal gradients which ultimately control microstructure.

Inconel 625 (IN625) is a Nickel-base superalloy which is known for its excellent high temperature strength and creep resistance. Similarly, IN625 exhibits outstanding oxidation and corrosion resistance at high temperatures [19]. Applications of IN625 include aircraft ducting systems, engine exhaust systems, turbine shroud rings, propeller blades for motor patrol gunboats, exhaust ducts for navy utility boats, electrical cable connectors, fasteners, flexure devices, and oceanographic instrument components etc. Machining and shaping IN625 can be difficult due to high hardness, low thermal conductivity and rapid work hardening. Hence LAM processes are currently under consideration for fabrication of IN625 components for aerospace applications [20-22].

1.2 Rationale for taking up the project

A substantial void exists in understanding the effect of controlling build conditions on both the magnitude and distribution of residual stress and also the resulting microstructure in laser additive manufacturing processes. This void if not overcome will represent a significant barrier to the wide-spread application of this emerging manufacturing method. Unfortunately, laser additive manufacturing processes are so complex that the cost of extensive experimental only programs needed to advance them is a major inhibitor to their further development.

The proposed research will address this above void through the use of computational modeling for simultaneous control of melt pool size, residual stress and microstructure thereby providing a basis for true process optimization of LAM processes especially for deposition of IN625 components. In addition, to providing a more basic scientific understanding of laser-based material deposition, the proposed research will be of direct and immediate use to members of the manufacturing community.

1.3 Relevance of Proposed Research

The proposed research will play a vital role in the transition of laser additive manufacturing processes from functional prototyping to production level manufacturing processes. If successful, such processes will provide substantial cost advantages for aerospace components (decrease in both the buy-to-fly ratio and production lead time compared to conventional manufacturing methods), and will enable the direct manufacture of complex, multi-material, functionally graded or smart components which cannot be produced by conventional methods. Thus, the proposed research will help pave the way for the application of other emerging technologies to aerospace components. Further, the proposed research will emphasize the use of simulation-based methods in materials development, which offers the potential of reduced cost and accelerated introduction of next generation materials.

2. Science & Technology (S&T) component in the project.

- The proposed research will highlight the use of simulation-based methods for materials development which offers the potential for reduced cost and accelerated maturation of materials.

- The process map approach is not only unique and based on mechanics fundamentals, but it also offers a means for process engineers to effectively use the results from large numbers of simulations. Thus the impact of this research on the industrial development and use of laser additive manufacturing processes will be immediate and substantial.

- The proposed research will provide a unique educational opportunity for the students involved, who will develop a multi-disciplinary background in mechanics, materials heat transfer and manufacturing science.

3. Methodology

The goal of this research is to use computational modeling approaches (analytical and numerical) for simultaneous control of melt pool size, residual stress and microstructure thereby providing a basis for true process optimization of LAM processes especially for deposition of IN625 components. In particular, the effect of controlling build conditions on residual stress and microstructure in laser-deposited IN625 will be investigated. The big picture idea is to investigate how much controlling melt pool size affects both the control of residual stress and also the microstructure in laser additive manufacturing processes.

Computational Modeling of Laser Additive Manufacturing Processes: The primary objective of computational modeling is to develop a complete understanding between the deposition process variables on the build conditions, magnitude and distribution of thermally induced residual stresses and solidification cooling rates and thermal gradient (and thereby on the resulting microstructure). In this work, two basic geometries will be considered: (a) The 2-D thin-walled structures of **Fig. 2 (a) and** 3-D Plate geometry of **Fig. 2 (b)**. It is believed that understanding the effects of process variables on the magnitude and distribution of residual stresses in these fundamental geometries will form the basis for understanding residual stress control issues in the building of complex shapes.

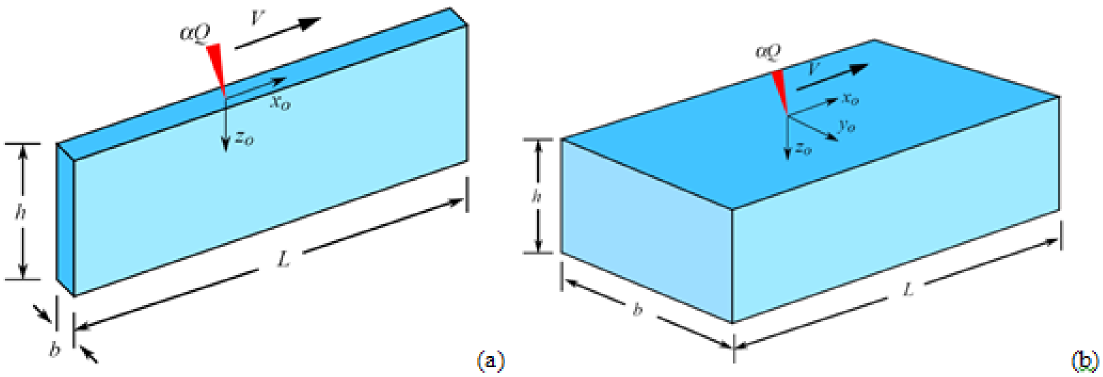

Fig. 2 Geometries being considered in this Study (a) 2-D Thin-wall geometry, (b) 3-D plate geometry.

Modeling Procedure: Numerical modeling of the LAM processes will be carried out using the commercial finite element software package ANSYS and the various add-on's available with it. ANSYS has an add-on entitled "ANSYS Additive Suite and Print" for Selective Laser Melting (SLM) which is a powder-bed based Additive Manufacturing process. In the proposed research, this add-on suite will be used for the simulation of SLM process.

In order to determine thermally induced residual stress, a sequentially coupled transient thermomechanical simulation will be carried out. Firstly, a transient thermal finite element analysis of the LAM process will be carried out to obtain the time and space dependent temperature solution. For the transient thermal simulations, temperature dependent thermo-physical properties (Density, Specific heat and Thermal conductivity) and latent heat of IN625 are taken into consideration. In order to simulate the repair process, a single laser pass deposition of IN625 will be carried out. In order to simulate the feature addition, multiple laser pass deposition of IN625 will be carried out. Simulations will be carried out modeling the laser as a heat source with a Gaussian power distribution. The addition of material (for simulating feature addition in either multi-track or multi-layer depositions) will be taken into account by using the element birth and death feature in ANSYS. In element birth/activation technique the elements of the entire geometry are initially considered inactive or dead. As the heat source moves over the elements, they are activated or 'made alive' to simulate the deposition of material layer upon layer. Upon completion of a single laser pass for repair or the building of the specified number of layers for feature addition, the geometry will be allowed to cool down to the room temperature.

Following the transient thermal simulation, the mechanical simulation will be carried out. For the mechanical simulation, the history of the time and space dependent temperature solution at every node of the geometry will be read as input. The material properties needed for the mechanical simulation include temperature-dependent Elastic modulus, coefficient of thermal expansion and yield stress. The solution of the mechanical simulation provides information regarding the thermally induced residual stress.

4. Likely Impact

- Although the proposed research is fundamental in approach, the ultimate goal is to provide laser additive manufacturing users with an engineering base for process development. A complete base does not exist currently. The results of this research will also have applications to a wide range of other, similar manufacturing processes, including Electron Beam Freeform Fabrication and other laser processing operations such as laser surface alloying, laser cladding and laser welding. It is expected that results from this research will be used directly by manufacturing engineers at the companies working on these processes.

- Insights into deposition of different alloy systems are expected to strongly impact the additive manufacturing industry. Currently process knowledge on one alloy system is not readily transferable to other alloys. Although some experimentation may still be needed to develop expertise in depositing new material systems, it is expected that results from this work will be used by process engineers to key combinations of process variables they should consider, substantially reducing testing time and costs. The value of this knowledge to process developers and their customers will be immense.

5. Suggested Post Project Activities:

- Presentation of the conducted research work by PI and postgraduate students at various national and international conferences.
- The publication of several journal and conference papers detailing the results of this work.
- Application of the concepts developed in the research to other material systems of interest to both aerospace and automotive sectors.

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