Abstract—Laser Direct Metal Deposition (LDMD) uses a laser beam to form a melt pool deposit of metal powders that is fusion bonded to the substrate. The required geometry can then be built up layer by layer. This paper presents a brief overview of finite element (FE) simulation and analysis of LMD. Thereafter, results from 3-d FE modeling and analysis (FEA) conducted to numerically simulate transient heat transfer in stainless steel (SS316) deposit on carbon steel 45 substrate and coupled-thermal phenomena in SS304 are presented. The FEA software ANSYS-14 was used and codes were generated using Ansys Parametric Design Language (APDL) to investigate the influence of various parameters including temperature dependent physical properties on the thermal history and validation with published literature. The influence of thermal loading on the model distortion was also studied.

Keywords—Heat transfer, Finite Element Analysis, Laser Additive Manufacturing, Simulation

I. INTRODUCTION

With Additive Manufacturing (AM) parts can be built by melting of thin layers of metal powders. The material is added instead of being removed, as is the case in traditional machining. Each layer is melted to the exact geometry defined by a CAD model to build complex geometry parts without the use of complicated tooling and fixtures and without producing any waste material. It is a fast production route from CAD to a physical part with high material utilization and without the need of expensive castings or forgings as inventory stock. In addition to design freedom and cost-efficiency, AM is also an energy-efficient and environmentally friendly manufacturing process and can be customized for parts on the fly and deposition of novel materials [1].

Laser Direct Metal Deposition

The laser-aided direct metal deposition (DMD) technique, also known as the laser engineered net shaping (LENS), allows one to fabricate large sized real life components direct from CAD data using layered deposition, through a sequence of melting–solidification of powders, projected from a nozzle usually coaxial to a moving laser beam. During the LDMD process, a laser irradiation creates a molten region on the substrate surface. A stream of metal powders is fed into the laser-induced melt pool to layer wise form a 3d part (Fig. 1) [2]. LDMD also allows other applications such as surface treatment via cladding and components repair.

![Fig. 1 Schematic of the LDMD process](image)

Although, LMD is a viable process but it has been underutilized until recently. One of the problems in this process could be the residual stresses induced by uneven heating and cooling phenomenon that may prove to be significant in high-precision processes e.g. turbine blade repair. Its other disadvantages include - size limitation, imperfections and high cost. However, higher-power lasers integrated into robust machine tools, decreased capital investment and operating costs of the laser device have lead it to growing popularity. Use of higher-performance materials to fabricate functional parts rapidly, has forced many to rethink the use of the LMD process for production of new components or repair used ones particularly in aerospace, automobile manufacturing, offshore drilling, and tool and mould making applications.
II. LITERATURE REVIEW

In the typical multi-physical LDMD process a large number of variables are involved and experimental investigation tends to become expensive and time consuming. Usually laser power, scanning speed and spot size govern the temperature field, temperature gradient and cooling rate of the melt pool which in turn decides the morphology and crack susceptibility. An improvement in the process by observation and following up the change in process parameters is also unlikely. Hence, the most effective and productive approach to obtain most of the necessary information is by modeling and analysis, primarily using available finite element analysis (FEA) tools.

The distribution and variation of temperature field has an important influence on microstructure, quality, formation of cracks etc. Song et al. [3] using FEM studied the temperature-time history curves, temperature field distribution, cooling rate and the temperature gradient of the laser cladding forming process. Influence of laser power and scanning speed on the temperature gradient and cooling rate of the cladding layers have been studied, which provided an explanation of the microstructure formation mechanism, cracking sensitivity and parameter selection. In this work 316L stainless steel powder was used as the cladding material and common carbon steel 45 was used as the substrate.

Peak temperature and thermal cycle experienced by each layer influence the final mechanical properties and dimensional accuracy of the part. An understanding and quantitative knowledge of the peak temperature, melt pool dimensions, and thermal cycles experienced in the deposited layers are essential for a priori selection of the process parameters in the LENS technique. Neela and De numerically simulated heat transfer phenomenon in the LENS process considering deposition of SS316 powder on a substrate of the same material [4].

Yang et al. [5] described the thermal dynamics behaviour in direct laser fabrication. A FEM model was developed based on global model and sub-model pattern. The global model exhibits the heat conduction characteristics of parts in the whole thermal history according to scanning path planning. Contact pairs and gap elements, which consider the effect of the temperature and porosity dependent thermal conduction, are designed in the model to explain powder-to-solid intrinsic transition. The influence of non-linear behaviour of thermal properties in pure nickel on the temperature distribution is estimated as well. Adopting the thermal physical parameters with solid–liquid phase change makes the melt pool temperature higher than that where the solid–liquid phase change parameters are not considered.

Zhang et al. [6] deposited SS410 using the LDMD process on a SS316 substrate. The influence of thermal history on the microstructure and properties of a multilayer (200) SS410 thin wall was investigated experimentally and numerically. Simulated and measured thermal history indicated that the absorption and heat loss tended to be close to equilibrium when the deposited material reached a certain height during LDMD. Different microstructure regions were formed due to the different thermal history the material experienced.

Zhang et al. [7] defined a critical temperature specific to thermal history and discussed its distribution in the part. The simulation results indicated that the critical temperature can make the property analysis from thermal history easier. Thermal history of all the deposited materials was found to be similar. It was also concluded that process parameters needed to be time-varying according to the real-time temperature field during the process. The process parameters dependent thermal history of the deposited materials has significant influence on the geometric precision and mechanical properties of the final part. Thus better properties can be obtained by maintaining a predetermined steady melt pool temperature field, which requires time-varying process parameters according to the real-time temperature feedback.

Kumar et al. [8] simulated the temperature distribution and single track geometry in Laser Rapid Manufacturing using a 2d model, and calculated the excess enthalpy above the melting point. Laser beam size and profile, scan speed, powder feed rate and powder stream diameter with flow distribution is taken as user input. The results of the developed algorithm were demonstrated by depositing single track on SS316L work piece using Inconel 625 at simulated process parameters.

Manavatkar et al. [9] computed values of cooling rate during solidification to estimate variation in cell spacing of solidified structure. Numerical prediction of the influence of the process parameters on thermal cycle, residual stress, microstructure, micro hardness in deposits of SS304, SS316 and various tool steels was also reported.

Zhu et al. [10] discussed the effect of curvature change and accumulation of layers on the temperature field distribution as investigated by thin walled rings with different curvatures. They concluded that the temperature of the thin wall increases with layer number and its curvature. The rules for changing the laser power with number of layers and curvature in the processing of thin walled blade can be obtained by simulation when keeping the molten pool temperature stable.

Fig. 2 Trend of laser power change with layer number [35]
Labudovic et al. [11] created an FEM model to calculate the transient temperature profiles, dimensions of fusion zone and residual stresses. Model simulations are compared with experimental results acquired on line using an ultra-high shutter speed camera which is able to acquire well contrasted images of the molten pool, and off line using metallographic and x-ray diffraction analysis in the deposition of MONEL 400 alloy on AISI 1006 steel. Both numerical and analytic model were developed for thermal history. Results from heat transfer analysis were then used as loads for FE analysis of residual stress and the results were compared with x-ray diffraction technique.

A three-step analytical and numerical approach using multi-physics COMSOL software was presented by Peyre et al. [12] to predict the shapes of manufactured structures and thermal loadings induced by the DMD process. First, the powder temperature was calculated using an analytical model, then the geometry of walls was predicted by a combined numerical + analytical modeling, finally thermal behaviour during DMD of a titanium alloy was described. The thermal model takes into account the moving interface during metal deposition allowing the conductivity front to move simultaneously with the moving laser source (with an appropriate spatial energy distribution), thus representing rather precisely the DMD process.

Liu et al. [13] presented a thermo-mechanical FE model to predict residual stress and deformations. The thermal distribution, thermal stress field, geometry deformation and effect of deposition parameters on residual stress and deflections are explained.

Verma and Shukla presented LMD thermal analysis using Ansys Parametric Design Language (APDL) based FEM to simulate a moving heat source for SS316 and Ni [14]. The overall conclusions derived from an in-depth literature review are listed in [15].

Following these works, our objective in this paper was to conduct FE modeling to simulate and analyse the thermal fields during LMD process of stainless steel (SS316) and carbon steel 45 and the final geometries in SS304.

### III. FINITE ELEMENT MODELING AND ANALYSIS

The commercial FEA software ANSYS - 14 was used in this work for APDL coding to model the laser beam path in movement and the temperature dependent thermo-physical properties.

#### Transient Heat Transfer Analysis

Dimensions of the substrate were taken to be 0.058 x 0.035 x 0.035 m and the dimensions of the cladding were taken as 0.058 x 0.024 x 0.008 m. Meshing was done with SOLID 278 brick element and coarse meshing was done in the lower areas of the substrate and fine meshing was done on the deposited part at the top. A half model was considered in this case due to model symmetry and aiming to reduce the computational time (Fig. 3a).

Two different materials, 316L stainless steel as the cladding material and common carbon steel 45 as the substrate were used in this analysis. A rectangular laser beam profile is taken instead of the usual circular. For C45 steel a thermal conductivity of 45 W/m-C, density of 7850 kg/m$^3$ and specific heat of 480 J/kg-K were taken. For 316L stainless steel, Table I shows the thermal conductivity and enthalpy of the material.

An initial temperature of 20 C and heat transfer convection coefficient of 10 W/m$^2$ K$^{-1}$ was taken. Fig. 3b shows the surfaces assisting in convective heat loss. The laser power is varied from 1500 to 3000 W and the scanning speed from 50 to 250 mm/min. The rectangular laser spot was taken of dimensions 0.00283 x 0.004 m.

| Table I: Material properties of 316L stainless steel [5] |
|----------------------|----------------------|----------------------|
| Sl. No. | Temperature (C) | Enthalpy (10$^{10}$ J/m$^3$) | Thermal Conductivity (W/m-K) |
| 1. | 20 | 0 | 15 |
| 2. | 1420 | 1.1787 | 22 |
| 3. | 1460 | 1.213 | 22 |
| 4. | 3000 | 2.5294 | 22 |
| 5. | 6000 | 5.095 | 22 |
| 6. | 1200 | 10.225 | 22 |

Fig. 3 (a) Meshed half model, (b) Convective surfaces and (c) Temperature distribution

#### Coupled-thermal Analysis

In the coupled-thermal analysis, the base plate is fixed at one end and the laser beam is incident on the powder deposit at the middle part of the plate. Due to the thermal loading in the middle, the deformation at the free end has been found out. The dimensions of the base part were taken as 50.8 x 12.6 x 3.175 mm and for the deposit it was 2.5 x 7.4 x 1.5 mm [13]. Meshing was done with eight nodded SOLID278 brick elements of size 0.3175 x 0.2 x 0.2 mm (Fig. 4). The element type gets changed when switching is done from...
thermal to structural module, and it is done by etchg.tts command and SOLID 278 get converted to SOLID 185.

The thermal properties in Ansys Heat Transfer module were taken is shown in Table II and for the Structural module the modulus of elasticity was taken as $10^5$ GPa, Poisson's ratio as 0.34 and coefficient of thermal expansion was taken as 2.1e-5 [13]. Heat transfer loss through convection was assumed, with convective coefficient of 200 J/m$^2$-K. The initial temperature was set at 273K, laser power at 607 W, laser travel speed at 250 mm/min, absorption coefficient at 0.4 and the rectangular spot was taken with dimensions 2.6 x 0.7 mm. After completing the heat transfer analysis, structural analysis was performed.

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**TABLE II**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Temperature (K)</th>
<th>Density ($10^3$ kg/m$^3$)</th>
<th>Specific Heat (J/kg-K)</th>
<th>Thermal Conductivity (W/m-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
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<td>510</td>
<td>15</td>
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<td>2.</td>
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<td>18</td>
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<tr>
<td>7.</td>
<td>4000</td>
<td>5000</td>
<td>800</td>
<td>30</td>
</tr>
</tbody>
</table>

**IV. RESULTS AND DISCUSSION**

**Transient Heat Transfer Analysis**

The thermal gradient increases with laser power and in the vertical z direction the gradient is maximum, followed by x and y directions (Fig. 5). In the present FEA results the thermal gradient in x direction is obtained on the lower side as compared with that in Ref. [13], therefore the difference between the total value and value in the z direction is small.

**Fig. 5** Variation of simulated thermal gradient with laser power

A similar behaviour is observed in Fig. 6 when the influence of scanning speed on thermal gradient is investigated. The thermal gradient is obviously reducing with an increase in the scanning speed.

**Fig. 6** Variation of simulated thermal gradient with scanning speed

**Coupled-thermal Analysis**

Fig. 7 presents the nodal displacements after 5.4 seconds of laser exposure.
were given. This issue is still being researched.

Further, after a length of time the whole of the material recovered the deflection as only elastic properties. The present simulation is limited to elastic region with only elastic properties of the material being used as against elasto-plastic properties. Since LMD is a multi-physics manufacturing process, hence real-time simulation should address modeling issues like thermo-capillary action, radiation modeling, phase change modeling during melting and solidification, fluid-structure interaction (FSI) and laser-material interaction (LMI) to name a few. Additive manufacturing or 3d printing based on lasers are potentially the most powerful technologies (LMI) to name a few. Additive manufacturing or 3d printing based on lasers are potentially the most powerful technologies. Additive manufacturing or 3d printing based on lasers are potentially the most powerful technologies.

**V. CONCLUSIONS**

From FE simulation we could establish that the LMD process parameters significantly impact the final structure of the deposited layers. A close matching of thermal history with published literature was obtained but coupled-thermal needs more studies. Since LMD is a multi-physics manufacturing process, hence real-time simulation should address modeling issues like thermo-capillary action, radiation modeling, phase change modeling during melting and solidification, fluid-structure interaction (FSI) and laser-material interaction (LMI) to name a few. Additive manufacturing or 3d printing based on lasers are potentially the most powerful technologies for the future.

**REFERENCES**