Lasers in Manufacturing Conference 2017

A fluid-dynamic numerical model for the selective laser melting of high-thickness metallic layers

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Abstract

Productivity in the Selective Laser Melting Process (SLM) is directly related with the thickness of the powder bed that is repeatedly applied, at every increment, in the growing of consolidated material in the additive manufacturing process. Although most of the relevant phenomena (limited diffusivity associated to particles contact, phase changes, gradients of surface tension associated with Marangoni convection, or even recoil pressure) are considered in the models with small bed thicknesses (roughly *20 µm – 40 µm*), in the case of larger thicknesses (between 100 µm and 200 µm) these factors strongly influence the size and shape of the fusion bath leading to a non trivial geometry of the final consolidated material. The present work proposes the use of the Arbitrary Lagrangean-Eulerian method (ALE method) to solve the thermal and Navier-Stokes equations in the frame of a free-moving discretization to predict simultaneously the space-time temperature evolution and the associated fusion bath dynamics. It allows for using a continuous domain to represent the powder bed, which, instead of a particle model approach, is advantageously compatible with realistic process parameters, where long paths are covered by the laser. The model was validated with experimental data using Inconel as working material, showing a good degree of agreement.
Keywords: SLM; ALE Method; Marangoni Convection; Fluid Dynamics

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1. Introduction

Additive manufacturing throughout the selective laser melting technology allows for the growing of 3D parts by means of a moving laser beam that melts part of the material deposited in a layer of metallic powder which is applied iteratively, after every laser sweep cycle, in order to progressively build the structure on the previously consolidated material.

The thickness of the new powder layer applied after the building of the previous consolidated ribbon will depend, in turn, of the final height of it, which generally is not coincident with the thickness of the layer from which it was grown, but, it is, nevertheless, much higher (between two-fold and five-fold), given the low thermal diffusivity of the powder which extends the fusion bath around the laser-powder interaction area, involving a considerable amount of melted material. This material tends to grow upward, acquiring a drop shape, as a consequence of its high surface tension and thanks to the freedom of movement enabled by the relatively low dynamic viscosity and density of the metallic powder which surrounds the fusion bath.

In the case of powder layers with relatively low thickness (*20 μm – 40 μm*) these phenomena can be modeled by means of some simplifications, like the activation or deactivations of finite elements in the case of FEM models, with the aim of adapting to the geometrical and physical changes of the material, like in the work of Michaleris, 2014, for the direct laser melting process or, alternatively, by providing a quantitative criterion based on temperatures to study the adhesion between the consolidated material and the substrate as it is proposed by Kruth et at., 2007.

The present contribution proposes a thermo-fluidic coupled model aiming the consideration of layer thicknesses up to *200 μm* in order to study the space-time evolution of the temperature and its consequences on the phase change and on the flow dynamics. This approach surpasses the size, and therefore the realism, of the domain that can be studied by means of particle models such as the work of Khairallah and Anderson, 2014. The most critical fluidic properties, dynamic viscosity and surface tension, have been modeled taking into account the above-mentioned phenomena for the growing of the consolidated material in a media that does not limit the moving capabilities of the fusion bath.

The Arbitrary Lagrangean-Eulerian method (Benson, 1989), permits large displacements of the discretization, and along with the automatic remeshing of the domain, constitutes a powerful tool to solve the thermal and Navier-Stokes equations in the model of a material which experiences phase change and flow dynamics, as a consequence of the different loads on the fusion bath, in a similar way to the study by Bruyere et al., 2013 about the keyhole dynamics in laser welding.

The distortion of the finite elements, as a quantitative indicator of the amount of deformation experienced by them, is presented as the most effective criterion to determine the situation in which a new discretization must be done, taking, the last deformed structure as the geometrical reference. A previous analysis based on the formation of a drop as a consequence of a phase change induced by a laser heating is presented as a procedure to adjust the index of distortion as to make a new discretization.

Results from the models are able to follow the tendencies observed in the experiments of the process, in terms of the cross section of the calculated ribbons and the experimental ones.

2. Process description

The model, at a geometrical level, consists of two domains; a first one representing the substrate on which the powder is deposited and with which the molted material must consolidate, and a second one, representing the powder layer. Fig. 1 displays a diagram of the model.

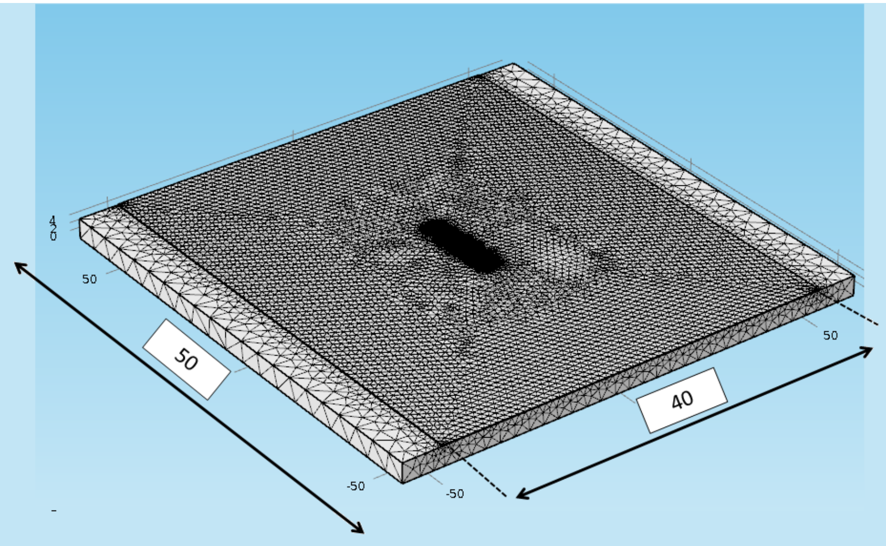

Fig. 1. Model of the powder layer deposited on the substrate

The square representing the substrate has an area of *50x50 mm*^{2}, while the surface of the powder layer is *50x40 mm*^{2}. As can be seen in Fig. 1 the size of the elements in the discretization is related with the different geometric entities. While the environs of the substrate are materialized by means of large elements, since their only mission is the final diffusion of the heat introduced into the material, the elements in the region in which the laser-powder interaction is going to happen has a maximum element size of *0.1 mm*, for a gaussian laser beam of *3 mm* diameter in all the tests presented in the present paper.

The thickness of the powder layer is *200 µm* aiming at the study processes capable of providing relatively high productivity. It lies on the basis of the domain representing the substrate with a thickness of *5 mm*, which has been determined as enough to allow the heat to diffuse.

The reason for such big dimensions in comparison with the laser beam diameter will be clarified in section 3.2, taking into account the needs of mobility and convergence for the moving mesh problem.

The experimental tests have been carried out by means of a diode laser, releasing radiation at wavelength of *900 nm*. The consolidated material has been cut and conveniently prepared for a metallographic analysis. The working material is Inconel, whose most relevant properties can be consulted at Sweet et al., 1987.

3. Model definition

The growing of a dense metal ribbon from the melting of a layer of powder by a moving laser beam is a complex phenomenon involving heat transfer in a media which, subsequently, experiences phase change, reaching fluidic-dynamic regime, after the stages of consolidation and solidification.

On the one hand, the coupling between thermal and fluidic calculations reveals the material properties and its dependence on temperature and with the material state (solid, liquid or powder), as a key factor to achieve a suitable definition of the phase change. On the other hand, the momentum imposed in the resulting fusion bath, as a consequence mainly of the gradient of surface tension, endows it with large displacements that can only be tackled by means of a moving mesh domain, making use of the Arbitrary Lagrangean-Eulerian approach. The boundary conditions of the moving mesh problem, concerning the definition of the free surface, its extension and limits, introduce no intuitive conditioning factors that determine the successful convergence of the numerical problem.

3.1. Thermo-fluidic problem

Both, heat conduction and Navier Stockes equations are solved constantly and simultaneously all along the volume of the domain. Therefore, the conception of the material when its temperature is under the melting point, as solid state, needs for the proper adjustment of those fluidic properties that allow the fluid to behave, from the dynamic point of view, like a solid, i.e., having no displacements and without any tangential effect tending to minimize its surface energy. These properties are the dynamic viscosity, that with relatively high values prevents the material from flowing under its own weight and the surface tension that ranges from *0* when the metal is solid to value form *0.51 N/m* to *2 N/m* for liquid metals.

Eq. (1) represents generically the heat transfer phenomenon for a fluid flow.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \nabla T = \nabla(\kappa \nabla T) + Q \qquad (1)$$

In Eq. (1) the C_p represents the heat capacity of the material, ρ is its density, κ represents the thermal conductivity of the material and Q accounts for all the possible heat absorptions or generations per volume unit in the domain, like the latent heats of the phase changes. The vector u symbolizes the velocity field of the liquid metal. When it is in solid state this terms turns 0, and also the second term in Eq. (1) turning it in the classic heat transfer equation.

The heat flux from the laser source is imposed as a boundary condition of the face irradiated, as expressed by Eq. (2).

$$-\vec{n}(-\kappa \nabla T) = Q_b \qquad (2)$$

In Eq. (2) Q_b represents the irradiance of the laser beam which is expressed as watts per surface unit.

Concerning the fluid flow problem Eq. (3) introduces the Navier-Stokes equation for laminar flow.

$$\rho \frac{\partial \vec{u}}{\partial t} = \nabla[-pI + \mu \nabla \vec{u} + \mu(\nabla \vec{u})^T] + F \qquad (3)$$

In Eq. (3) the term μ represents the dynamic viscosity of the material, p is the hydrostatic pressure, I is the eye matrix and F represents any force per volume unit that can affect the liquid material like the weight.

While the boundary conditions defining the walls of the liquid are presented in the following sub-section associated to the moving mesh problem, the thermo-capillary phenomenon, also known as Marangoni convection, is a major conditioning factor for the geometric definition of the fusion bath and is introduced naturally as a boundary condition from the weak formulation of Eq. (3).

The first step in the weak formulation of a partial differential equation is to integrate it on the domain studied and multiply each term by the so-called tests functions, as is shown in Eq. (4).

$$\int_{\Omega} \rho \frac{\partial \vec{u}}{\partial t} \cdot \varphi = \int_{\Omega} \nabla [-pI + \mu \nabla \vec{u} + \mu (\nabla \vec{u})^T] \cdot \varphi + \int_{\Omega} \rho \vec{g} \cdot \varphi \quad (4)$$

In Eq. (4) Ω denotes the volume in which the partial differential equation is going to be integrated, *test(u)* is the test function following the fine element method scheme and the last term, which in Eq. (3) is introduced as any external volume force, now is particularized as the specific weight of the material.

By using integration by parts the second term of Eq. (4) can be transform into the addition of a volume integral plus a surface integral, as Eq. (5) develops.

$$\int_{\Omega} \nabla [-pI + \mu \nabla \vec{u} + \mu (\nabla \vec{u})^T] \cdot \varphi = \int_{\Omega'} [-pI + \mu \nabla \vec{u} + \mu (\nabla \vec{u})^T] \cdot \varphi \cdot \vec{n} + \int_{\Omega} [-pI + \mu \nabla \vec{u} + \mu (\nabla \vec{u})^T] \cdot \varphi' \quad (5)$$

In Eq. (5) the term Ω' represents the surface integral for the fluidic problem. Marangoni convection is a tangential effect on the free surface of the liquid metal as a consequence thermal dependence of the surface tension and its subsequent surface gradient. Matching the surface integral of Eq. (5) with the temperature derivative of the surface tension, γ, and the spatial temperature derivatives at the free surface allows for taking into account the phenomenon of thermo-capillarity, including generally this effect in the model, as Eq. (6) describes.

$$\int_{\Omega'} [-pI + \mu \nabla \vec{u} + \mu (\nabla \vec{u})^T] \cdot \varphi \cdot \vec{n} = \gamma \frac{\partial T}{\partial x} \varphi_x + \gamma \frac{\partial T}{\partial y} \varphi_y \quad (6)$$

Fig. 2 left displays the surface tension, σ_{Sup}, of the working material as a function of temperature. Fig. 2 right displays the dynamic viscosity, μ, of the material as a function of temperature. Both, surface tension and dynamic viscosity functions, consider, specifically, the behavior of the phase change.

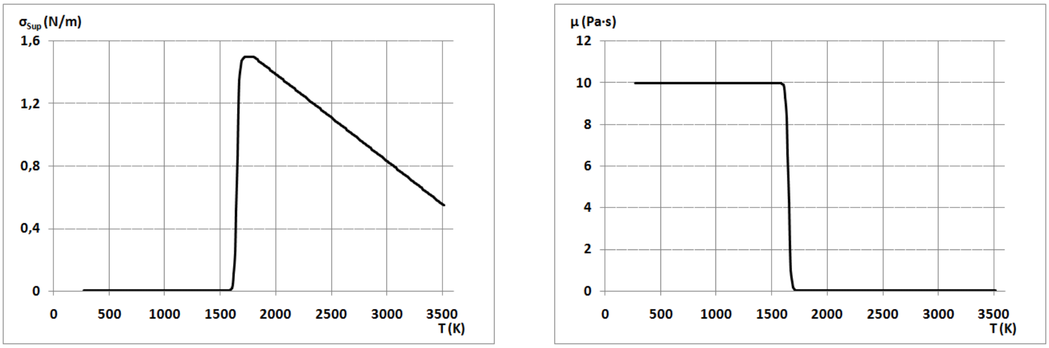

Fig. 2. Surface tension (left) and dynamic viscosity (right) as a function of temperature

From Fig. 2 it can be seen how the phase change for both, surface tension and dynamic viscosity, starting at a temperature around *1600 K*, is modeled considering a far-from-equilibrium heating, developing the transformation of the material into a liquid along an interval of *100 K* following a sigmoid function.

In the case of the surface tension, its maximum value appears after the conversion of the material into a liquid and then it decreases with a constant slope, whose value is, in turn, the temperature derivative of the surface tension, *γ*, obtained following the methodology proposed by Su and Mills, 2005. Above *3500 K* the boiling point of the material is reached and the modeling as a liquid is no longer possible.

The function proposed for the dynamic viscosity allows the material to flow as a liquid as a consequence of a low value corresponding to the liquid metal after the melting transition, while it prevents the material from flowing in correspondence to a relatively high value before the melting point. In the context of the Navier-Stokes equation, the solid state of the material is modeled, therefore, as an un-flowing fluid for the loads present in the process.

3.2. Moving mesh problem

In the case of a moving mesh study aiming to represent the movement of a fluid under the effect of internal and external loads, there are two factors which determine the complete definition of the system: the limits of the free-movement boundaries, to provide the model with stable initial conditions, and, the criterion to re-mesh the domain once it has experienced large displacements as a consequence of the representation of the movements of the fluid, preventing, the elements associated to the discretization from resulting in an inverted condition.

The stability of a domain representing a fluid where there is a free surface needs for the definition of its limits, in which the movement is not allowed, to create the vessel where the fluid is allocated, even, when the dynamic viscosity has a high value representing a solid substance, in the case of a domain for a material with phase change, since the movement of the boundaries of the vessel in which the fluid is, must be strictly zero.

The combination, in the same domain, of boundaries where the movement is prohibited with other regions where there are large displacements associated with the movement of the melted material and with the drop formation, results in a large compression of the fixed elements at the boundaries, by the mechanical transition of the movement through the intermediate elements. It leads to the local distortion of the boundaries beyond the convergence of the numerical calculations, which, additionally, cannot be solved by means of automatic remeshing, since this distortion does not imply a substantial change of the geometry. Fig. 3 left shows a plant view of the laser irradiating the powder bed (as a temperature distribution in conjunction with the color table whose unit is *K*). The circle indicates the protrusion of a boundary element as a consequence of the deformation imposed by drop formation associated with the laser acting in the vicinity of the boundary. Fig. 3 right shows a detailed view of the protrusion in the boundary, which destroys the convergence of the numerical solution because of the limited deformation capability of the elements.

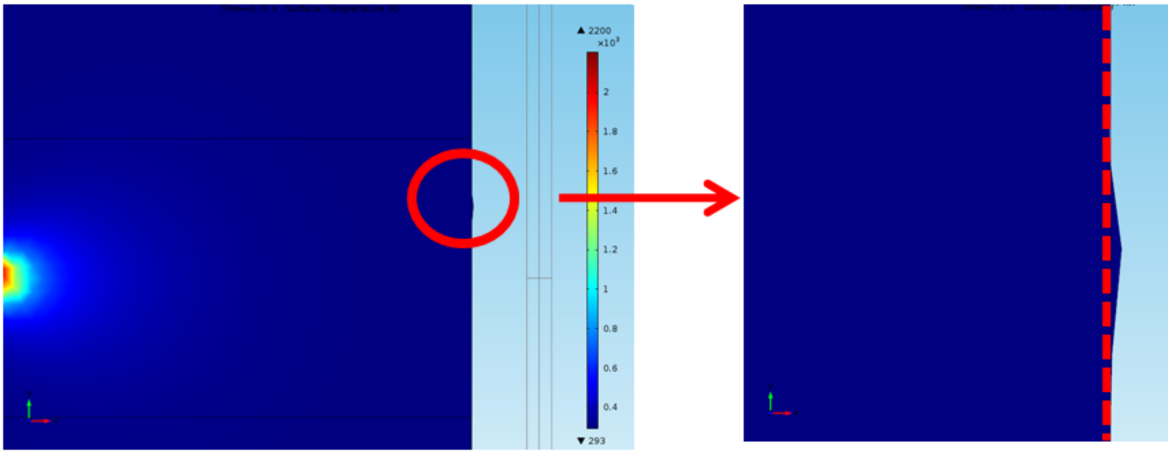

Fig. 3. Plant view (left) and detailed view (right) of the protrusion of a boundary element as a consequence of the deformation imposed by the laser heating in its vicinities.

In order to avoid the local distortion of the boundary elements, the distance between the region in which the phase change is taking place and the boundaries must be long enough to allow the intermediate elements to dissipate the small movements of the intermediate elements, preventing the boundaries from accumulating this displacement to its extreme distortion. For this reason, as can be seen in Fig. 1, the process is modeled as a relatively big squared powder bed of $40x50\ mm^2$ around the interaction area, whose dimensions can be characterized by the laser beam diameter of *3 mm*. The boundaries where the movement is not allowed are the sides of the square.

The deformations associated to the drop formation in the building of a consolidated ribbon are also significant and may imply the distortion of elements beyond the convergence of the numerical calculations. Nevertheless, unlike the case of the local distortion at the boundaries, the deformation of the mesh during the ribbon formation follows a regular pattern along a large number of elements, giving place to a smooth contour. In this case, the distortion of the elements can be controlled to build a new domain and an associated new discretization on the basis of the current deformed disposition, before it reaches such a large distortion that spoils the convergence of the numerical calculations. From a mathematical point of view, the concept of distortion measures the curvature of the elements representing the domain. It is calculated throughout a jacobian index, and it ranges from *0*, at an initial state, to any positive value. The selection of a value as a criterion to make the remeshing must be adjusted for every situation. Fig. 4 shows the four different discretizations in the formation of a drop as a consequence of a laser pulse on the modeled material. It has allowed for selecting a index of distortion of *1,25* for the simulation of the process.

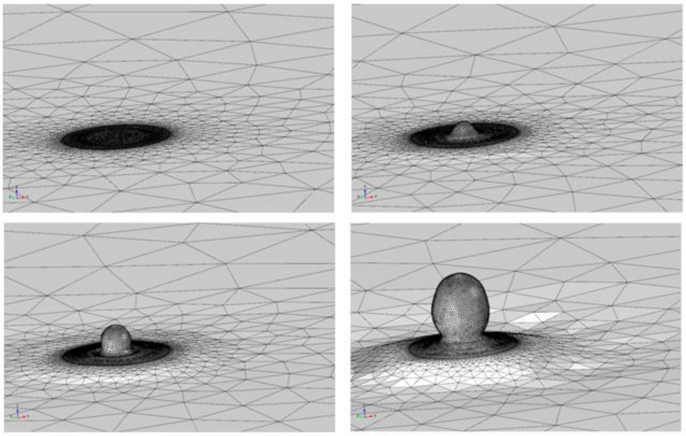

Fig. 4. Drop formation as a consequence of a phase change induced by the laser heating with a distortion index of 1,25 as a criterion for the formation of a new discretization

4. Results and discussion

The prediction of the cross section of the consolidated ribbon, considering its height, width and shape, is the main contribution of the current modeling, before the detection of defects, which requires additional considerations in further developments of the model, associated to the random distribution of the mechanical properties in the powder bed.

Fig. 5 compares the theoretical cross section obtained for a laser scanning speed of *1020 mm/min* and a power of *1000 W* with the experimental result. The calculated total height of the ribbon is around *500 µm* and its width slightly greater than *1 mm*. Both magnitudes height and width are, to some extent, larger in the experimental result than in the theoretical predictions. The predicted general shape of the ribbon, nevertheless, follows, mainly, the geometrical pattern of the experimental result.

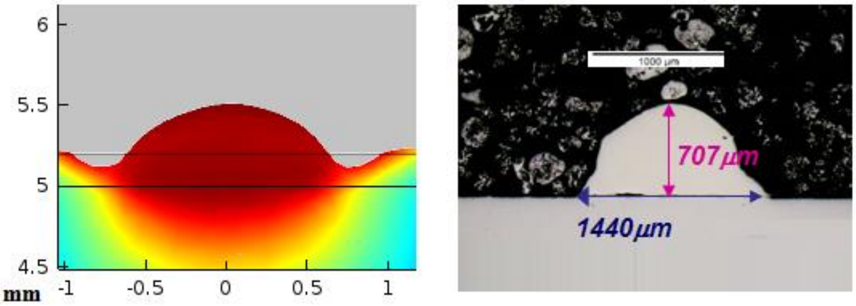

Fig. 5. Comparison between the theoretical ribbon and the experimental result for a speed of 1020 mm/min and a power of 1000 W

Fig. 6 compares the theoretical prediction and experimental result for a process made with a speed of *1020 mm/min* and a power of *2000 W*.

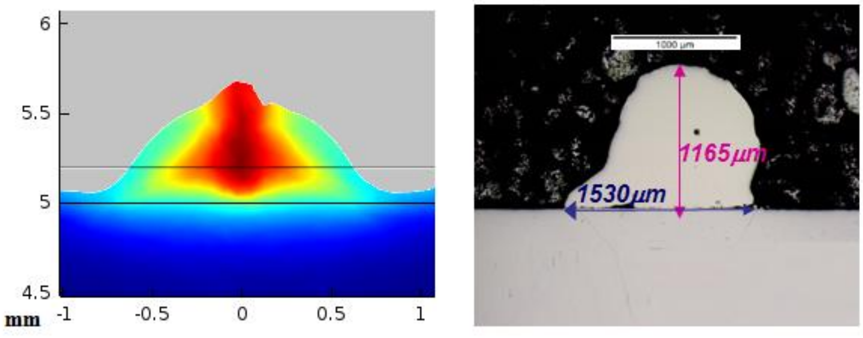

Fig. 6. Comparison between the theoretical ribbon and the experimental result for a speed of 1020 mm/min and a power of 1000 W

As in the case of the previous comparison, the predicted dimension of the cross section tends to slightly underestimate the experimental result. The increase in the consolidated area, in comparison with Fig. 5, as a consequence of the larger power, has been, however, captured.

The obtainment of shorter dimensions in the predicted results than in the experiments, in conjunction with a proper approximation between theoretical and experimental shapes is associated to the fluidic properties that determine the mass flow to the fusion bath. These values must be adjusted according to temperature to get improved results.

5. Conclusions

1. The thermo-fluidic approach has been presented as adequate for the modeling of the selective laser melting process, where the phase change and the dynamic of the fusion bath are the driving forces that determine the shape and size of the consolidated material.
2. The surface tension and the dynamic viscosity have been adjusted, under the bases of theoretical hypotheses, to represent the particular conditions of the phase change associated with the initial state of the material as a powder.
3. The Arbitrary Lagrangean-Eulerian method along with the remeshing of the domain, on the basis of the distortion of the elements, has introduced the capabilities of tackling with large displacements associated with the drop formation during the phase change.
4. The conditions to get initial stability and a successful convergence of the numerical calculations have been defined throughout the proper relation between the fixed boundaries and the region in which the phase change takes places, and, by the determination of the maximum distortion admissible as the criterion to create a new mesh.
5. The comparison between theoretical and experimental results highlights the need of continuing the improvement in the modeling of the most critical properties in the dynamic behavior of the fusion bath.

Acknowledgements

The research and development work that is the basis of the present study has been developed under the CIEN-FRACTL project funded by CDTI (Spain Project CIEN MQM-2010290).

References

Benson, D. J., 1989. An efficient, accurate, simple ALE method for nonlinear finite element programs. Computer methods in applied mechanics and engineering, 72(3), p. 305.

Bruyere, V., Touvrey, C., & Namy, P., 2013. Comparison between Phase Field and ALE Methods to model the Keyhole Digging during Spot Laser Welding. In Proceedings of the 2013 COMSOL Conference, Rotterdam.

Khairallah, S. A., & Anderson, A., 2014. Mesoscopic simulation model of selective laser melting of stainless steel powder. Journal of Materials Processing Technology, 214(11), p. 2627.

Kruth, J. P., Levy, G., Klocke, F., Childs, T. H. C., 2007. Consolidation phenomena in laser and powder-bed based layered manufacturing. CIRP Annals-Manufacturing Technology, 56(2), p. 730.

Michaleris, P. , 2014. Modeling metal deposition in heat transfer analyses of additive manufacturing processes, Finite Elements in Analysis and Design 86, p. 51.

Su, Y., Mills, K. C., & Dinsdale, A., 2005. A model to calculate surface tension of commercial alloys. Journal of materials science, 40(9), p. 2185.

Sweet, J. N., Roth, E. P., & Moss, M., 1987. Thermal conductivity of Inconel 718 and 304 stainless steel. International journal of thermophysics, 8(5), p. 593.