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Modeling of Thermal Processes in DED Using SolidWorks Simulation

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Abstract: The study analyzes software products for numerical modeling of additive processes performed using SLM and DED technologies. Determining temperature fields in DMD processes is an important and complex task. Based on previously determined experimental data on the volume of molten material added during cladding, the thermal processes during laser cladding of powder materials were modeled in the SolidWorks system. This allowed determining the distribution of temperature fields on the substrate and in the cladded material over time.

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1 Introduction

The creation of various structures of new equipment from metals and alloys with high strength, physical, and mechanical properties, operating in aggressive environments at various temperatures and loads, is most relevant in the rocket and space industry, nuclear energy, aviation, and automotive industries. Particular attention is paid to the manufacturability of the product and ensuring minimal labor intensity in its manufacturing.

The rapid production of new products considering consumer or customer requirements is ensured by using additive technologies that enable the creation of functional products. One of the promising methods of rapid shaping of workpieces is volumetric (3D) synthesis with coaxial laser cladding of metal powders. This technology allows creating parts by depositing material layer by layer on a substrate. The cladding process is quite complex as the stability of the dimensions and defect-free nature of the cladded bead and the entire product are influenced by many factors.

The purpose of this work is to model the process of direct deposition of metal powders with a coaxial nozzle.

Currently, the most in-demand technologies are: selective laser melting (SLM); selective electron beam melting (EBM); and direct laser metal deposition (DLMD).

2 Analysis of software products for simulation of additive processes

Selective laser and electron beam melting technologies are based on the selective melting of powder spread in a layer on a platform (substrate) in the area of laser or electron beam impact. There are more than 130 technological parameters affecting the processes of selective laser and electron beam melting. A feature of the SLM process is the high scanning speed of the powder layer, which allows the use of a rapidly moving or instantaneous heat source for modeling the melting processes. This assumption significantly simplifies the mathematical model of the thermal effect of laser radiation on the melting powder layer and the product. Using calculated temperature fields, one can predict heating and cooling cycles, structure, and thermal stresses during the product's construction and after cooling. The considered method of modeling the SLM additive process is used in almost all software products intended for analyzing additive processes by the powder layer in industrial synthesis conditions. Currently, the following systems for numerical modeling of the SLM process have been developed: Amphyon from Additive Works; SimufactAdditive; Netfabb by Autodesk; the FLOW-3D package; products by ANSYS - Additive Suite; applications from Dassault Systems - Functional Generative Design, Additive Manufacturing Programmer, Additive Manufacturing Researcher, and Reverse Shape Optimizer; COMSOL Multiphysics [1].

The direct laser metal deposition technology is based on using laser radiation and coaxial (or side) powder feed onto the substrate, with the powder flow and laser radiation focused into a single point. The part construction is performed on 5-axis equipment without supporting structures. The cladding process is carried out at relatively low speeds, and for the mathematical description, it is necessary to consider the speed of the heat source movement, the distribution of thermal energy density in the impact zone, the sequential addition of a certain volume of material, and other related phenomena. It is also necessary to analyze gas-dynamic phenomena in the coaxial nozzle when forming a gas-powder jet with the required concentration and velocity parameters of powder particles. The initial calculated data for modeling the laser cladding process is also the temperature field, based on which one can determine the structural and stress-strain state parameters of the product during construction and cooling.

2.1 Mathematical modeling of laser cladding

Mathematical modeling of phenomena during laser cladding of powder materials is a more complex task than analyzing SLM processes. Only a few companies offer software products for solving DED-technology tasks: the FLOW-3D package; applications from Dassault Systems; COMSOL Multiphysics. It should be noted that using these programs and applications requires special knowledge of the interconnected processes and phenomena occurring in DED-technology and significant time to master the software tools [2-4].

The main goal of all software products is to ensure reliable simulation. However, the results of numerical modeling depend on many factors and may differ significantly from the actual values of controlled parameters. Developers believe that the discrepancies may be due to insufficient understanding of the features of their software by users, lack of reliable data on materials, or insufficient understanding of the process physics [5]. Therefore, the simulation process of additive synthesis of parts needs to be adjusted considering experimental data for specific equipment and production conditions.

Determining temperature fields in DMD processes is an important and complex task because material addition and heat source impact occur simultaneously and locally in a limited zone. Moreover, the cladding process speed is low. Therefore, when modeling, it is necessary to determine the method of applying thermal impact: thermal flux or the temperature of the melted powder under the laser beam impact and the method of simulating a moving heat source [5].

Analyzing physical processes occurring when powder moves in the laser beam showed that a layer of molten material is deposited on the substrate, with its temperature potentially reaching boiling point. Also, depending on the overlap coefficient, laser radiation may impact the substrate. The most unfavorable conditions for forming the melt pool on the substrate occur when the overlap coefficient $\mu1=1$, and the formation of the bead's bond with the substrate or previous layers will depend on the melted powder's temperature.

The most reliable modeling would be in the treatment zone of two heat sources: one directly on the substrate as a moving thermal flux from laser radiation considering the overlap coefficient, and the second – thermal impact $T = T_{boil}$ in the volume of the added material fragment. Modeling a moving heat source requires additional software developments or modules and is quite labor-intensive. It is necessary to ensure coordinated impact of this source over time and space with the application of thermal load $T = T_{boil}$ on the added material fragment.

The geometric parameters of the added volume of molten material are determined based on the assumed treatment diameter corresponding to the beam diameter $D_{beam} = 2R$, the layer height H, and the cladding speed Vs or experimental and theoretical values of the cross-sectional area of the cladded layer. The process is non-stationary, and the characteristic time of thermal load impact for each added volume is determined by the formula

$$t = \frac{D_{beam}}{Vs} \tag{1}$$

Also, for modeling the cladding process of a solid part, a path for adding elemental volumes of material is required. The trajectory of adding material volumes is formed based on the part construction strategy and represents a file in the G-code language.

It is most advisable to consider temperature fields under the most unfavorable cladding conditions, i.e., $\mu_1=1$, and a volume of material with a temperature T = Tboil is deposited on the substrate. Each elemental volume is a cube with a side $a = D_{beam}$.

Modeling the cladding of Inconel 718 powder onto a steel 45 substrate was conducted in the SolidWorks Simulation software package.

The initial data for the calculations were taken according to experimental data under stable cladding conditions:

- elemental volume – length and width a = D_{beam} = 1×10^{-3} m;

- elemental volume height – 0.25 mm;

- number of added elemental volumes – 5 pieces;

- thermal load – temperature applied to the elemental volume T_{boil} = 3000 K (boiling point of Inconel 718 alloy).

- time of thermal impact at cladding speed V_s = 6×10^{-3} m.s^{-1} is t = 0.17 s.

According to analytical calculations, the specified geometric parameters of the cladded layer correspond to $K_{\text{powder utilization coefficient}}$ = 0.2 and an overlap coefficient μ_1 = 0.14.

3 Results and discussion

The calculation results showed that the temperature in the contact zone of the cladded material and the substrate at the initial moment of time 0.02 s is higher than the melting temperature of steel and Inconel 718 alloy, ensuring sufficient penetration of the substrate to a depth of 0.132 × 103 m (0.132 mm) and firm attachment of the part to the substrate (Figure 1).

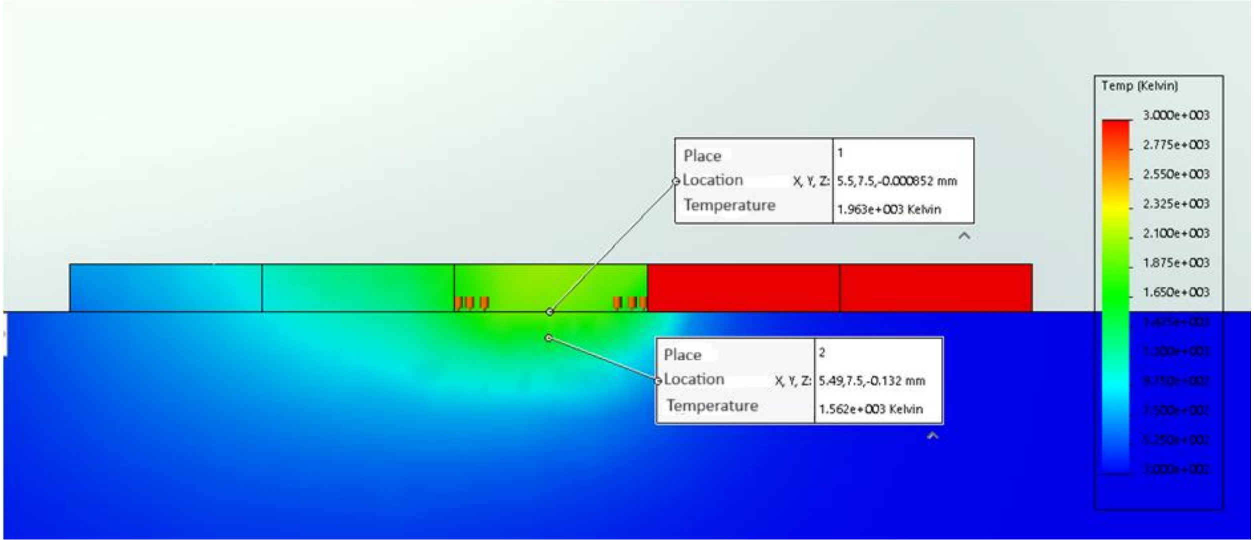

Figure 1 Temperature distribution in the contact zone of the deposited material and the substrate

With increasing time to the characteristic value of 0.17 s, the temperature in the contact zone and the penetration depth increase respectively to 2017 K and 0.208 × 103 m (0.202 mm) (Figure 2).

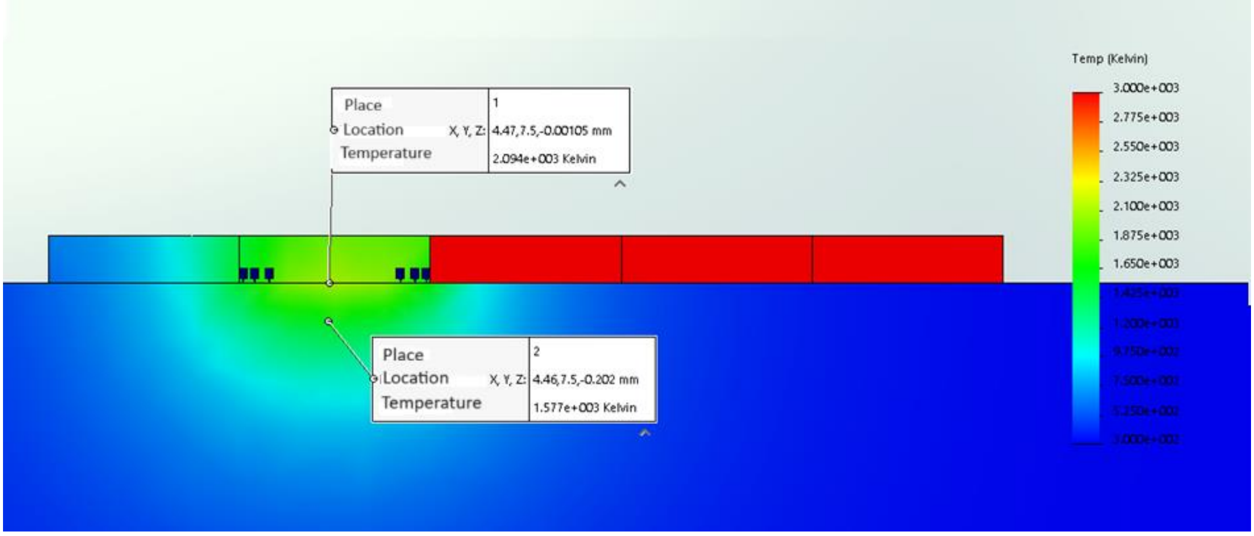

Figure 2 Temperature distribution in the contact zone of the deposited material and the substrate

The temperature field on the substrate is distributed along the cladding direction. The cooling of the cladded material to a temperature of 413 K occurs in a short time of 0.85 s.

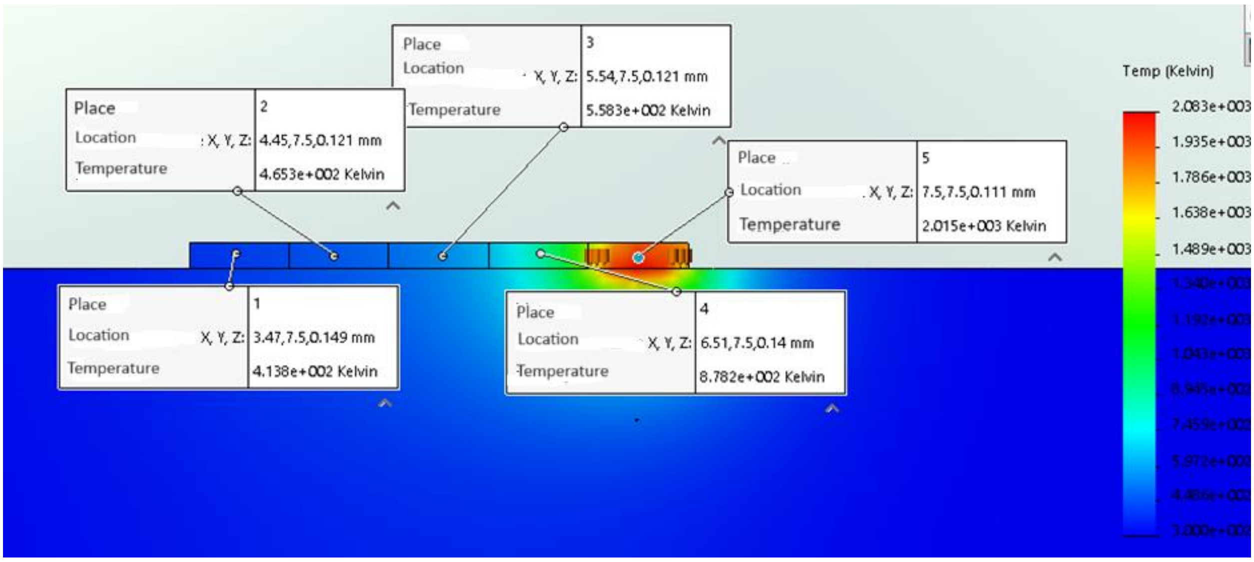

Figure 3 Temperature distribution along the direction of deposition

An increase in temperature in the contact zone and penetration depth occurs due to the thermal flux on the substrate, the value of which is quite large at 188 × 108 W.m^{-2} with low values of coefficients K $_{\text{powder utilization coefficient}}$ = 0.2 and μ_1 = 0.14.

4 Conclusion

Modeling of thermal processes during laser cladding of powder materials in the SolidWorks system allowed determining the temperature field distribution on the substrate and in the cladded material over time. The modeling was applied to steel 45 substrate materials and Inconel 718 powder.

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