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Simulation of the thermomechanical behavior of 30ХГСН2А steel during pulsed laser cladding of wire materials

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This study focuses on the numerical simulation of thermomechanical processes occurring during pulsed laser cladding of wire filler materials onto 30ХГСН2А steel. The relevance of this study stems from the need to minimize defects in the clad zone and reduce residual stresses. A three-dimensional finite element model was developed using the Ansys Mechanical APDL software package to analyze the non-stationary temperature fields and the stress-strain state. The model accounts for the temperature dependence of the material's thermophysical and mechanical properties, as well as its plastic behavior described by a bilinear isotropic hardening model (BISO). The cladding process is simulated using the sequential activation of elements representing the deposited bead, accompanied by the application of a laser heat flux. The martensitic transformation of austenite upon cooling is described with the Koistinen-Marburger equation, which enables the description of additional strains from phase transitions. The developed model facilitates the prediction of residual stress distribution and can optimize technological parameters in order to minimize defects during pulsed laser cladding of 30ХГСН2А steel with wire filler material.

Keywords: laser cladding, finite element modeling, thermomechanical behavior, residual stresses, Ansys.

Работа посвящена численному моделированию термомеханических процессов, возникающих при импульсной лазерной наплавке проволочных присадочных материалов на сталь 30ХГСН2А. Актуальность работы обусловлена необходимостью минимизации дефектов в зоне наплавки и остаточных напряжений. Для анализа нестационарных температурных полей и напряженно-деформированного состояния разработана трехмерная конечно-элементная модель в программном комплексе Ansys Mechanical APDL. Модель учитывает температурную зависимость теплофизических и механических свойств материала, а также пластическое поведение по билинейной модели изотропного упрочнения (BISO). Процесс наплавки моделируется последовательной активацией элементов, соответствующих наплавляемому валику, с приложением теплового потока от лазера. В работе учет мартенситного превращения аустенита при охлаждении осуществляется с помощью уравнения Койстинена-Марбургера, что позволяет описать дополнительные деформации от фазовых переходов. Разработанная модель позволяет прогнозировать распределение остаточных напряжений и может быть использована для оптимизации технологических режимов с целью минимизации дефектов при импульсной лазерной наплавке стали 30ХГСН2А присадкой в виде проволоки.

Ключевые слова: лазерная наплавка, конечно-элементное моделирование, термомеханическое поведение, остаточные напряжения, Ansys.

Introduction. Currently, various methods are employed to achieve the desired surface properties of materials, including electron beam treatment, ion treatment, flame treatment, laser treatment, etc. When processing machine-building components, laser technologies are particularly effective, distinguished by their productivity, flexibility, and the ability to process parts of virtually any size and geometry. The implementation of laser cladding is highly efficient in attaining the desired properties of the surface layers of products. This method is characterized by high adhesion strength between the deposited layer and the substrate, as well as a minimal heat-affected zone [1]–[2]. However, the use of laser cladding is occasionally associated with crack formation. This is due to the fact that the laser cladding process of steels involves complex thermomechanical phenomena that lead to the formation of residual stresses. The mechanism of their occurrence is determined by the incompatibility of inelastic deformations, primarily thermal shrinkage strains during cooling, structural shrinkage resulting from phase transformations, and the differing deformation history of various regions of the material [3]–[5].

To address this issue, it is advisable to use pulsed laser radiation and wire filler materials. Pulsed laser cladding, through the variation of processing parameters, enables precise control over the heating and cooling rates of the deposited metal and the substrate. This consequently provides the opportunity to reduce residual deformations and stresses [2]–[3].

Finite element modeling of the pulsed laser cladding process using wire filler materials is an important step for optimizing the corresponding technological parameters that ensure the minimization of defects and residual stresses. Studies [6]–[10] present finite element modeling of the wire material melting process performed in the Marc, Mentat, and Ansys software packages, considering the thermal and deformation processes occurring in the samples.

Previously, the authors in [6]–[7] performed optimization of pulsed laser cladding of 30ХГСН2А structural steel with wire filler material using a genetic algorithm and neural network modeling. In that surrogate model of pulsed laser cladding of steel, only temperature values in the processing zone were used as responses, neglecting the thermomechanical behavior of the steel. This research examines the characteristics of thermomechanical modeling during the pulsed laser cladding process of 30ХГСН2А steel with wire filler material using the element birth technique in the Ansys software.

Finite element modeling of pulsed laser cladding. A three-dimensional finite element model was developed using the Ansys Mechanical APDL software package to explore the thermomechanical processes involved in the pulsed laser cladding of wire materials. The model is designed to calculate non-stationary temperature fields, determine changes in the stress-strain state, and evaluate residual stresses within the «substrate – deposited layer» system. The base material and the filler material consist of 30ХГСН2А structural steel. The simulation incorporated the temperature dependence of thermal conductivity, specific heat capacity, density, elastic modulus, Poisson’s ratio, and the coefficient of thermal expansion [3], [11]. Plastic behavior was described using a bilinear isotropic hardening model (BISO) with temperature-dependent yield strength and hardening modulus (see Figure 1 in [5]).

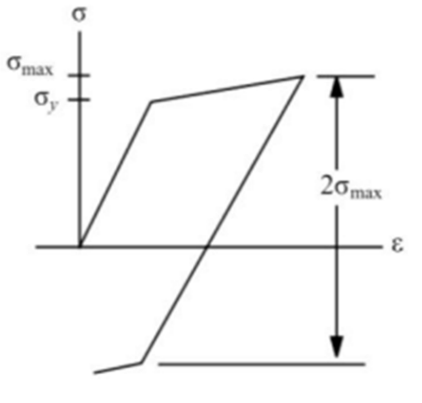

Figure 1 – σ – ε diagram for the bilinear isotropic hardening model (BISO)

The computational model considers the formation of a single deposited bead on the surface of a metal substrate (see Figure 2).

The model geometry comprises the substrate and the deposited layer: a metal substrate in the form of a rectangular parallelepiped with dimensions of 8 × 8 × 3 mm and a deposited layer with dimensions of 3 × 0,5 × 0,2 mm. To ensure the required accuracy while reducing computational costs, the finite element mesh was refined in the cladding region (see Figure 3). The element size in the deposited layer and the adjacent part of the substrate was 0,05 mm. Twenty-node SOLID90 elements were used for thermal analysis, whereas SOLID186 elements were utilized for mechanical analysis. The total number of elements was 17,131.

The initial temperature of the sample and the ambient environment was assumed to be 20° C. Heat transfer with the surroundings via convection was considered on the external surfaces of the computational domain.

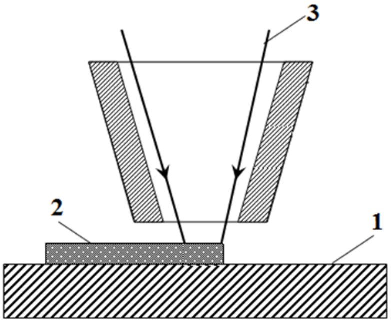

Figure 2 – Arrangement of the base metal and filler material relative to the laser beam: 1 – base metal; 2 – filler material; 3 – laser beam

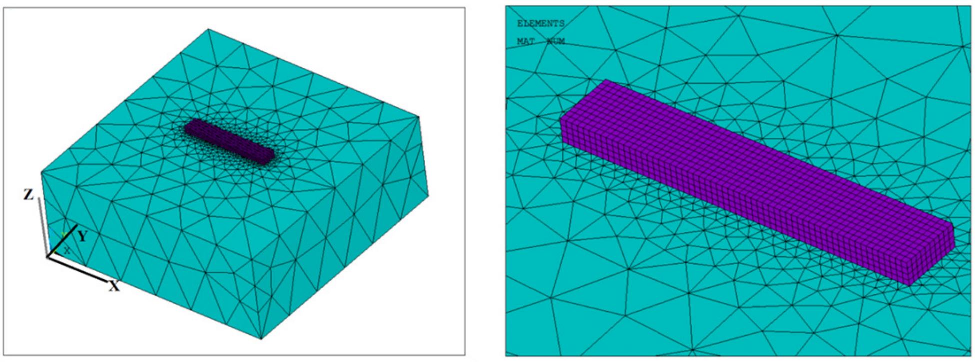

Figure 3 – Finite element mesh of the model

The parameters for the pulsed laser radiation utilized in the cladding simulation were as follows: pulse energy E = 5 J, pulse duration τ = 5 ms, repetition rate f = 5 Hz, and laser spot radius R = 0,25 mm. The spot overlap was 50 %, which corresponds to a laser translation step between pulses of Δx = 0,25 mm. The absorbed laser power was specified as a surface heat flux with a uniform distribution over the spot.

The problem was divided into two uncoupled problems: transient heat conduction and quasi-static thermomechanics of the stress-strain state. This approach aligns with the methodology described in [4]–[5] and allows for a significant reduction in computational costs.

Numerical simulation of pulsed laser cladding of wire materials onto 30KhGSA steel was implemented using the element «birth» and «death» technique. With this technique, all elements corresponding to the as-yet-unclad material are physically present in the finite element model from the very beginning of the calculation, but are excluded from the solution by assigning them degraded thermophysical and mechanical properties. This approach avoids mesh reconstruction and renumbering of nodes throughout the solution procedure. In practice, to ensure numerical stability, values several orders of magnitude lower than the original ones are used rather than strictly zero values. Upon element activation, their properties are restored to their original values. An important feature is that the activated elements inherit the existing deformed state of the structure. Thus, the initial strains for the newly activated material are assumed to be equal to the strains corresponding to the moment of its emergence, which is inherently considered in the constitutive relations.

The beginning of the simulation involved the deactivation of all elements corresponding to the deposited layer. This was followed by a loop over the heating steps representing successive laser positions. The number of heating steps was determined by the cladding length and the translation step.

For each position of the laser beam center, the following steps were performed:

– activation of the cladding elements whose location coincided with the laser beam irradiation zone;

– application of a heat flux to the nodes on the top surface of the active elements within the laser beam irradiation zone;

– solution of the heat conduction problem over a time interval equal to the pulse duration τ;

– removal of the heat flux and solution of the heat conduction problem over the pause interval $1/f\text{-}\tau = 0{,}195$ s;

– saving the current time instant and the coordinates of the laser beam center for subsequent mechanical analysis;

– upon completing the cladding cycle, a sample cooling stage was implemented.

After obtaining the complete thermal history, we calculated the stress-strain state. The element type was switched to the structural SOLID186. At this stage, element activation was redefined in the same sequence as in the thermal analysis. For each time instant, the corresponding temperature field was derived from the thermal analysis results file and applied as a nodal load. Subsequently, the stress-strain state of the material was computed. The displacement boundary conditions simulated rigid fixation of the bottom surface of the substrate. The mechanical properties of deactivated elements were modified in a manner similar to the thermal analysis. The activation of elements was accompanied by the restoration of their original properties, with the initial strains assumed to be equal to the strains accumulated in the structure by the time of activation.

In pulsed laser cladding of steels, the formation of residual stresses is determined not only by the evolution of temperature fields but also by phase transformations occurring during the cooling of the molten metal. The high cooling rates characteristic of laser technologies lead to the formation of a predominantly martensitic structure. Accordingly, the developed finite element model accounted for the martensitic transformation of austenite upon cooling. The martensite fraction was calculated using the Koistinen-Marburger equation [12]. The austenite-to-martensite transformation is accompanied by an increase in the volume of the crystal lattice. This results in an additional phase transformation strain, which influences the formation of residual stresses during pulsed laser cladding of 30ХГСН2А steel. The phase transformation strain was introduced into the finite element model as an additional plastic strain.

The results of numerical simulation regarding the thermomechanical behavior of 30ХГСН2А steel during pulsed laser cladding are illustrated in Figures 4–6.

Figure 4 shows the distribution of temperature and von Mises equivalent stresses within the processed plate at the moment of completion of the sixth laser pulse. At this moment, a localized zone of intense heating is generated in the region of laser irradiation. The maximum temperature values are observed directly in the laser irradiation zone. Moving away from the irradiation zone, the temperature decreases rapidly. The high heterogeneity of the temperature field induces an intense stress state in the material. The analysis of the von Mises equivalent stress distribution reveals that the regions of the highest stress intensity are also localized in the direct laser irradiation zone and in the adjacent area of the substrate.

Figure 5 depicts the temperature and von Mises equivalent stress distribution after the completion of the pause between the sixth and subsequent laser pulses. During the pause, the heated metal cools down, which is accompanied by a decrease in maximum temperatures and a more uniform temperature distribution within the sample volume. The evolution of the temperature field is accompanied by a redistribution of the stress state. The von Mises equivalent stress distribution reveals a shift in the regions of the highest stress intensity and their partial reduction compared to the moment of laser pulse action. The main areas of increased stress intensity remain in the region of the deposited layer.

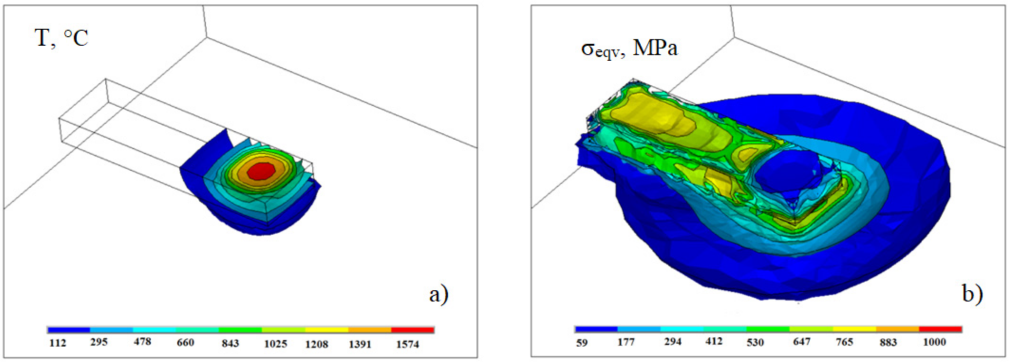

Figure 4 – Temperature and von Mises equivalent stress distribution within the processed plate at the moment of completion of the sixth laser pulse

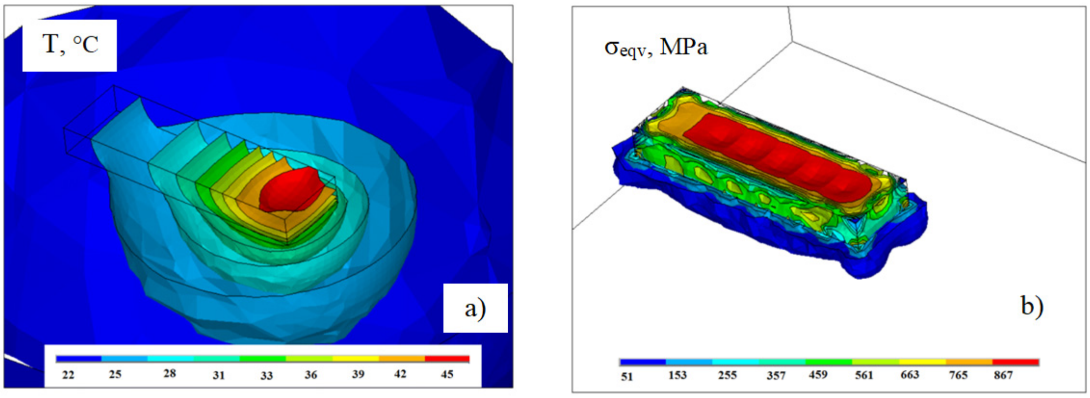

Figure 5 – Temperature and von Mises equivalent stress distribution within the processed plate at the moment of completion of the pause after the sixth laser pulse

Following the cladding process and cooling of the sample to ambient temperature, a residual stress state is established, the distribution of which is illustrated in Figure 6. The illustration presents the distributions of von Mises equivalent stresses alongside the stress components σ_x, σ_y, and σ_z within the volume of the processed plate.

The analysis of the von Mises equivalent stress distribution reveals that the regions of the highest stress intensity are concentrated predominantly in the deposited layer. This phenomenon is explained by the observation that in these regions the material undergoes the most intense heating and cooling cycles, accompanied by significant temperature gradients and plastic deformations. The distribution of the stress components σ_x, σ_y, and σ_z allows for a more detailed assessment of the material's stress state. The most significant stress values are observed near the cladding zone, where the most intense thermomechanical processes occur.

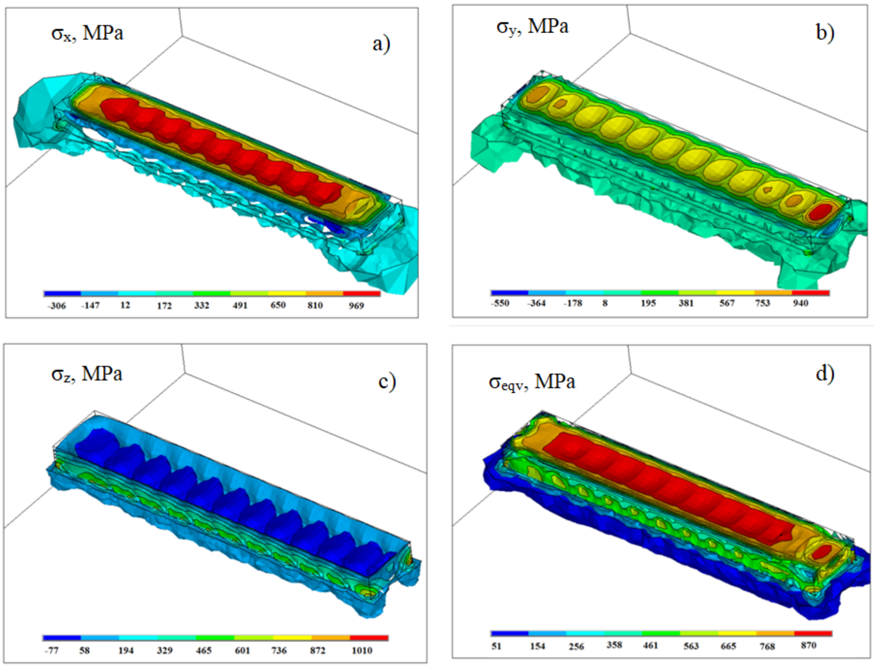

Figure 6 – Residual stress distribution in the processed plate after cladding and cooling to 20° C

Conclusion. The authors have developed a finite element model for pulsed laser cladding of 30ХГСН2А steel, incorporating thermal, mechanical, and structural changes in the material. The model enables simulation of the thermomechanical behavior of the substrate–deposited layer system and prediction of residual stress formation. The key factors determining the stress-strain state are the localization and cyclicity of heat input, together with phase transformations during cooling. Ac-

counting for the martensitic transformation modifies the residual stress distribution. The regions of maximum stresses are concentrated in the deposited layer and the adjacent heat-affected zone, which correlates with the experimental data. The proposed modeling approach provides a mechanism for optimizing processing parameters to minimize residual stresses and enhance product quality.

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