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ЧИСЛОВЕ МОДЕЛЮВАННЯ НАПРУЖЕНОГО СТАНУ У ПРОСТОРОВИХ ВИРОБАХ СКЛАДНОЇ ГЕОМЕТРИЧНОЇ ФОРМИ З КРЕМНІЄВОЇ БРОНЗИ ПІД ЧАС АДИТИВНОГО WAAM ПРОЦЕСУ

Анотація. Для моделі рівнобічної тригранної призми, яка виготовлена з кремнієвої бронзи CuSi3Mn1 за допомогою адитивної технології GMAW, методом скінченних елементів розв'язана нестаціонарна задача термопружнопластичності, результатом якої є розподіл еквівалентних напружень у призмі після кожного з 10 наплавлених шарів. Результати моделювання напруженого стану можуть бути використані для оцінки вірогідності утворення тріщин.
Ключові слова: GMAW, WAAM, напружений стан, адитивні технології, кремнієва бронза CuSi3Mn1, пошарове наплавлення

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NUMERICAL MODELING OF THE STRESSED STATE IN SPATIAL PRODUCTS OF SPATIAL GEOMETRIC SHAPE MADE OF SILICON BRONZE DURING THE WIRE ARC ADDITIVE MANUFACTURING

Abstract. For a model of an equilateral triangular prism made from silicon bronze CuSi3Mn1 with the use of additive GMAW technology, a nonstationary thermalelastoplasticity problem was solved by the finite element method, which resulted in the distribution of equivalent stresses in the prism after each of the 10 deposited layers. The results of the stress state modeling can be used to estimate the probability of crack occurrence.
Keywords: GMAW, WAAM, stress state, additive technologies, silicon bronze CuSi3Mn1, layer-by-layer deposition.

The widespread use of non-ferrous metals based on copper alloys, such as CuSi3Mn1 silicon bronzes, in industry, due to their high cost and high expenses for manufacturing of the final product, has led to a strong push and development of Wire Arc Additive Manufacturing (WAAM) technologies for the creation of print-welded metal products by the layer-by-layer arc deposition method.

Previous studies on the practical application of silicon bronze CuSi3Mn1 in additive manufacturing indicate problems associated with the occurrence of cracks during layer-by-layer deposition of samples.

First of all, this is related with the high heat input of one of the methods of applying WAAM technology - deposition using filler wire in shielding gases Gas Metal Arc Welding (GMAW).

In addition, such material as CuSi3Mn1 is characterized by fluidity, high coefficient of thermal expansion, and peculiarities of crystallization process that cause the formation of an anisotropic structure and heterogeneity of mechanical properties in the longitudinal and transverse directions of the deposited metal, which, together with shrinkage during crystallization and the stress level from the deposited layers in the product, can cause cracking.

Taking into account the above-mentioned problems, which are caused by thermodeformation processes and structural transformations in silicon bronze CuSi3Mn1 during additive deposition of bulk products, the study of the stress state is an actual scientific and practical task.

Since the study of the stress state of print-welded products by experimental methods is complicated due to the complex geometric shape of the finished products, it was decided to perform finite element modeling of layer-by-layer deposition and cooling process to solve this problem.

The experimental sample and the finite element model (FEM) that was created on its basis have the form of an equilateral triangular prism with a side length of 50 mm, the total number of deposited layers is 10, and the height of each layer is 1.3 mm. The layers were deposited by GMAW using a 3-axis CNC machine on a 6 mm thick triangular substrate made from stainless steel E304L. For deposition of the sample, filler wire ERCuSiA with a diameter of 1.2 mm was used. The parameters registered during the deposition of 10 layers were used for finite element modeling.

The verification of the developed FEM was performed by comparison of the thermal cycles obtained during the deposition of the sample and as a result of solving the temperature problem for the model by the finite element method.

Experimentally, thermal cycles were measured at three points of the substrate (one point on each of the three straight segments of the depositing trajectory). The deviation between the results of the temperature simulation and data registered during the experiment amounted to 10...15% for the maximum temperature values.

During the experiment, the formation of through going cracks was observed in the silicon bronze CuSi3Mn1 sample in 1...2 and 5...10 layers in the area of junction of the beginning and end of the deposited layer, as well as in the places of sharp change in the deposition trajectory, which necessitated further analysis of the stress fields in the sample model.

Fig. 1 shows the fields of equivalent stresses for the model of the test sample after deposition of each of the 10 layers, and in the residual state after complete cooling. Since the deposition of each layer occurred with a time delay, the stress fields presented correspond to the quasi-residual state of each layer (the state before the next layer was deposited).

From Fig. 1 it can be seen that the stress level in the deposited layers corresponds to the range of 164...187 MPa, which does not exceed the tensile strength of the material (Fig. 2) at the actual temperature of the layer at this point in time. Therefore, it can be concluded that the appearance of cracks in the sample during deposition does not occur in the quasi-residual state after deposition of each layer and not in the residual state after deposition of all layers. In this regard, the stress state of the prism will be analyzed at a specific time point – the completion of deposition of the selected layer.

Fig. 3 shows the distribution of temperatures and equivalent stresses at the time of completion of deposition of the 5th layer: in the cross-section of the deposited layers, it can be seen that at this point the equivalent stresses in the 1st layer reach 144 MPa, which is 0.96 of the tensile strength (~150 MPa) at the actual temperature of the 1st layer of 550 °C (Fig. 2), while the temperature in the other layers (2..5) exceeds 700 °C, and therefore the material is in a weakened state.

Since the determination of the stress state during the sequential deposition of each layer was performed without taking into account the material fracture model, the obtained numerical values of equivalent stresses cannot exceed the tensile strength of the material. At the same time, it can be seen from Fig. 2 and Fig. 3 that the values of the equivalent stresses in the corresponding layers of the model almost reached the tensile strength for the material under study, which suggests the possibility of crack formation in this particular location.

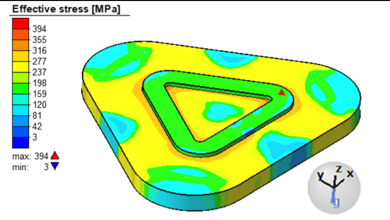
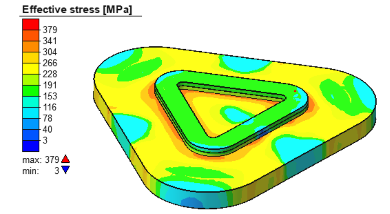
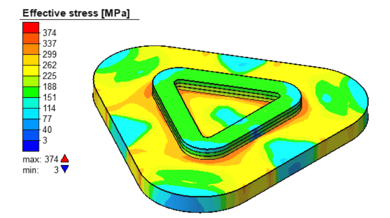
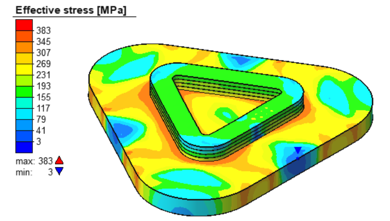
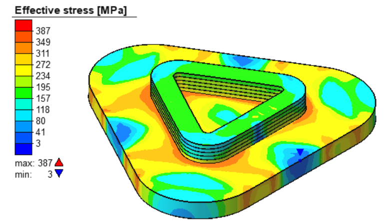
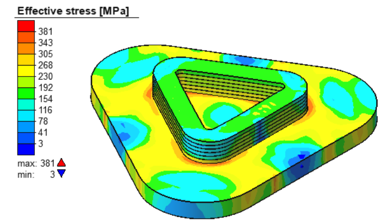
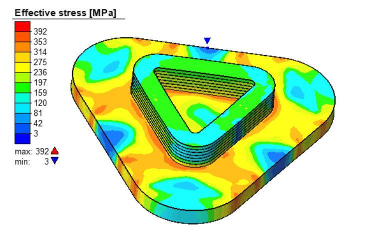
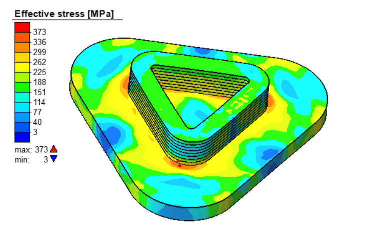
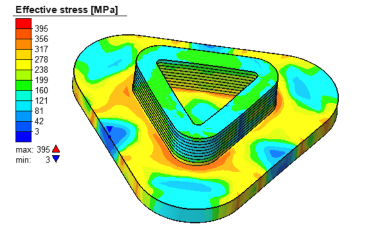
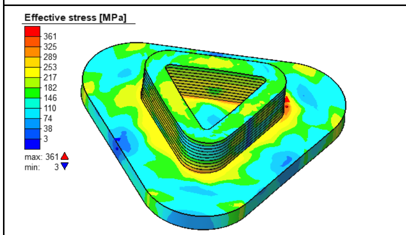
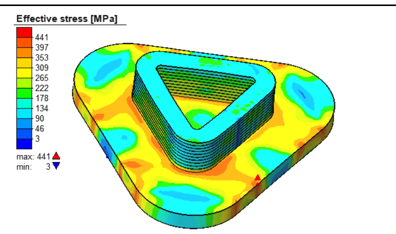
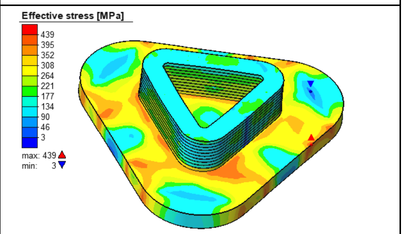
 1st layer, 84.375 s, 78 ^{o}C, 178,5 MPa	 2nd layer, 147.35 s, 132 ^{o}C, 180 MPa	 3rd layer, 209.225 s, 156 ^{o}C, 172 MPa
 4th layer, 298.9 s, 119 ^{o}C., 164 MPa	 5th layer, 378.376 s, 127 ^{o}C, 180 MPa	 6th layer, 447.351 s, 143 ^{o}C, 179 MPa
 7th layer, 555.326 s, 99 ^{o}C, 182 MPa	 8th layer, 628.501 s, 132 ^{o}C, 169 MPa	 9th layer, 731.276 s, 109 ^{o}C, 180 MPa
 10th layer, 799.652 s, 147 ^{o}C, 187 MPa	 10 layers, 1009.652 s, 35 ^{o}C, 177 MPa	 10 layers, 1343.95 s, 21 ^{o}C, 180 MPa

Fig. 1. Equivalent stress fields in the triangular prism model after deposition of each layer and after deposition of all 10 layers

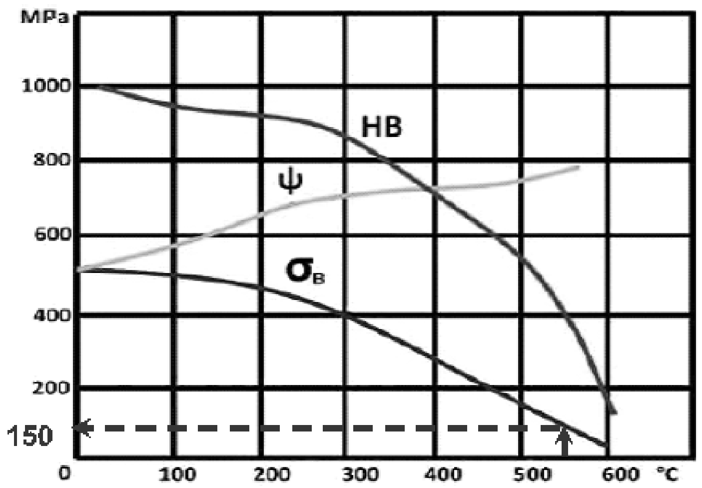
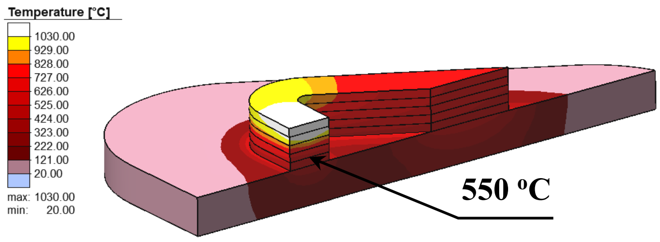
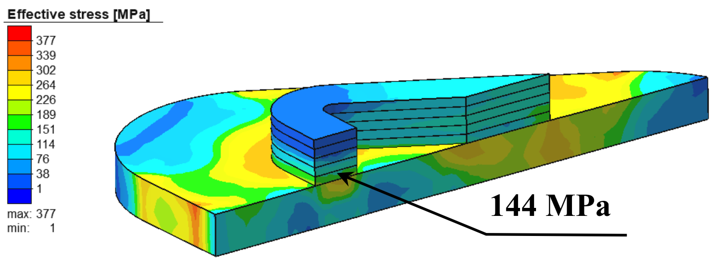


Fig. 2. Dependence of mechanical properties of CuSi3Mn1 on temperature



(a)



(b)

Fig. 3. Stress state in the triangular prism model during deposition of the 5th layer: temperature distribution - (a); equivalent stresses - (b)

Thus, the developed finite element model of a three-dimensional geometric shape that was layer-by-layer deposited by the GMAW method allows, based on a numerical solution of the coupled thermoelastoplasticity problem, to determine the stress state and the probability of crack formation at any moment of heating and cooling stages, with taking into account the chemical composition of the substrate and welding wire materials, changes in the thermal, physical and mechanical properties of materials with temperature, and the sequence of layers deposition.