Numerical calculation of technological parameters for automated layup of a thermoplastic composite construction

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Abstract. The authors of this work present the results of a research aimed to help choosing the technological parameters, such as speed, power and surface area of the heating source, for the automated layup process. These characteristics ensure bonding of thermoplastic composite layers to each other. As a result of the research, a mathematical model was developed for heating a tape of a thermoplastic composite material with a laser source. In the framework of numerical experiments, two computational cases were considered for PEEK (polyetheretherketone) and PPS (polyphenylene sulfide) materials. According to the results of numerical simulations, temperature distribution fields over the tape of thermoplastic composite materials were obtained. The technological parameters at which the process of bonding the tapes of a thermoplastic prepreg along the adjoining faces of the surface occurs were determined.

1. Introduction
In recent years, the scope of composite materials application has increased significantly. First of all, due to their wide use in civil aviation and engine building. The use of composites allows significantly reducing weight (for a number of parts in several times), improving environmental parameters and efficiency of the aircraft [1, 2]. In particular, there is an increased interest in the use of composite materials with thermoplastic matrices (TCM) in the production of a wide range of products, including critical parts of aviation equipment [3 - 5]. However, the automated layup of thermoplastic prepreg has a number of problems associated with the choice of process parameters, such as the tension force of the tape, the temperature in the area of contact of the tape with the tooling, the force of pressing the tape to the tooling, the choice of the tooling material. For this work, a research was conducted on the choice of the heating mode for the thermoplastic prepreg tape of two butt layers placed on a metal tooling. To determine the required speed of the laser source, we numerically simulated the process of heating the contacting layers of the thermoplastic prepreg to the molding temperature.

2. Numerical simulation
The object of the research is a tape of a thermoplastic composite material made of unidirectional TCM [6]. Four options for prepreg placement were simulated. For options 1 and 2, the general scheme of the geometric model is presented in Figure 1a, and for options 3 and 4 in Figure 1b. The constructed geometric models differed in the area of impact of the surface heat source. Geometrical dimensions of the tape: 7.5x900x0.15 mm. In the process of automated layup, the tape is laid over the first (support) layer of a thermoplastic located on a rectangular tooling, then next to it a second tape of a thermoplastic is laid on the support layer placed nearby. A laser beam heats the area of contact between the upper and lower layers of prepreg tapes. For options 1 and 2, the size of the contact spot was: width 7.5 mm, length...
9.375 mm. For options 3 and 4, the dimensions of the contact spot were: width 7.5 mm with the addition of 0.7 mm and on each side, the length was 9.375 mm. Simulation of the motion of a laser contact spot is carried out in a fixed coordinate system. For the simulation, several thermoplastic materials PEEK and PPS stacked on metal tooling with geometrical dimensions 360x1500x5 mm were considered. In total, four calculation options were considered. The speed of the laser source was 1 m/s. After calculations, laser transit time for each section was obtained for simulation, the transit time for each section is presented in Figure 2.

![Figure 1](image1.png)

**Figure 1.** Scheme for simulation models: 1 - tooling, 2 - prepreg tape, 3 - laser focal spot.

![Figure 2](image2.png)

**Figure 2.** The time step of the simulation with automated display.

In this research the problem of numerical calculation of the temperature fields \( T(x,y,z,t) \) in the prepreg tapes and tooling is posed. The processes are considered in a three-dimensional, non-stationary formulation, since the intensity of heat transfer between the layers of the prepreg and the tooling depends on the heating depth of the prepreg. A geometric model was developed and constructed to carry out numerical simulation of the heating of laminated CM with a thermoplastic matrix in the process of automated manufacturing (Figure 3).

![Figure 3](image3.png)
The mathematical formulation of the problem includes the nonstationary heat conduction equation for anisotropic bodies \[7\].

\[
C_p \rho \frac{\partial T(x)}{\partial t} = \lambda_{11} \left( \frac{\partial T}{\partial x} \right)^2 + \lambda_{22} \left( \frac{\partial T}{\partial y} \right)^2 + \lambda_{33} \left( \frac{\partial T}{\partial z} \right)^2 + \left( \lambda_{23} + \lambda_{32} \right) \frac{\partial T}{\partial y} \frac{\partial T}{\partial z} + \left( \lambda_{31} + \lambda_{13} \right) \frac{\partial T}{\partial z} \frac{\partial T}{\partial x} + \left( \lambda_{12} + \lambda_{21} \right) \frac{\partial T}{\partial x} \frac{\partial T}{\partial y} \quad (1)
\]

where \(T(x)\) is the value of the temperature field; \(\lambda_{11}, \lambda_{22}, \lambda_{33}, \lambda_{23}, \lambda_{32}, \lambda_{31}, \lambda_{13}, \lambda_{12}, \lambda_{21}\) are the thermal conductivity of the material in the \(x,y,z\) directions; \(t\) is for time; \(C_p\) is the specific heat capacity of the material; \(\rho\) is the density of the material.

As initial conditions, the value of the temperature of the thermoplastic, tooling and external environment was set \(T(x,y,z,0)=22^\circ C\). At the place of contact of the layers and in the interaction area of the lower layer and the tooling, boundary conditions of the fourth kind were assigned \(2\). Between the lower edge of the upper layer and the upper edge of the lower layer of thermoplastic there is a contact spot with a constant heating temperature \(T(x,y,z,t)=420^\circ C\) for the PEEK material and \(T(x,y,z,t)=280^\circ C\) for the PPS material. In the area of contact of the prepreg layers and the tooling with the external environment, the boundary conditions of the third kind were assigned \(3\).

\[
\lambda_1 \frac{\partial T_i(t)}{\partial n} = \lambda_2 \frac{\partial T_s(t)}{\partial n} - I_n, \quad (2)
\]

where \(\lambda_1, \lambda_2\) are the thermal conductivity coefficients of the first and second body; \(T_i, T_s\) - the temperature of the first and second bodies on the border of their contact; \(I_n\) is the vector of normal to the surface of the body.

\[
\lambda \frac{\partial T}{\partial n} = h(T_a(M,t) - T_{oc}), \quad (3)
\]

where \(T_a\) - the temperature of the thermoplastic layer; \(T_{oc}\) - the value of the external environment temperature; \(h\) is the coefficient of heat transfer between the external environment and the surface of the body; \(M\) is the point belonging to the surface; \(I_n\) is the normal vector to the surface of the body.

While constructing and local grinding of the mesh, no sharp differences in the geometric dimensions of the neighboring elements were allowed (sharp differences are understood to be more than 2 times). The mesh was adapted in the areas of high temperature gradients, namely, on the contact surface of the laser spot and the prepreg tape. The maximum element size for prepreg tape was 1 mm, for tooling - 2
mm. (Figure 4). The total number of finite elements was 2000 thousand elements. The final elements of the tooling are hexagonal in shape. The elements of prepreg tape represent the ethereal form.

Figure 4. General view of the finite element model of a layered blank placed side by side on a flat metal tooling during automated fabrication

In the numerical experiments, the process of automated calculation of thermoplastic PEEK and PPS materials was simulated. During the processing, the prepreg tape was laid on a metal tooling. A moving laser beam heated the area of contact between the upper and lower layers of prepreg tapes. The thermo physical properties of anisotropic thermoplastic prepregs were determined analytically from the properties and relationships presented in [8, 9]. In the modeling process, it was assumed that one heat source should be considered as two layers of thermoplastic, neglecting the convection between the layers in the areas of laser spot impact, because the contact between the bodies is considered as perfect.

To implement the sequential layout of prepreg tapes, taking into account interlayer heat transfer, an algorithm and a software module integrated into the ANSYS engineering analysis system have been developed and implemented. The algorithm provides the transfer of data obtained as a result of the solution at the previous step for a new geometric model.

According to the results of numerical simulations, temperature distribution fields were obtained, for the convenience in determining the degree of the layers’ heating, the temperature diagrams for the layers of thermoplastic tape were constructed. For the TCM with the PEEK matrix, the diagrams are shown in Figure 5. Figure 6 shows the temperature distribution diagrams for the TCM with the PPS matrix.
Figure 5. Temperature distribution epures and diagrams for temperature dependence on the height, length, and width for a PEEK material, a - along the height of two layers at a point close to the junction of the two layers placed side by side; b, d - on the border of the layers placed side by side on the surface of the first layer; b, e - the intersection of the width of two layers placed side by side on the surface of the first layer.

Figure 6. Temperature distribution epures and diagrams for temperature dependence on the height, length, and width for a PPS material, a - along the height of two layers at a point close to the junction of the two layers placed side by side; b, d - on the border of the layers placed side by side on the surface of the first layer; b, e - the intersection of the width of two layers placed side by side on the surface of the first layer.
The analysis of the plotted temperature distribution epures along the height of the TCM layer revealed that for model 1, heating to the molding temperature in the area of the contact spot reaches 12.5% for the PEEK material and 12.91% for the PPS material. For model 2, the values are 17.08% and 14.58% for the PEEK and PPS materials, respectively. Thus, we can conclude that increasing the width of the contact spot by 18.6% leads to the layers bonding together along the side faces, while simultaneously increasing the heating depth of the material. It should be noted that the use of thermal insulation coating is recommended to prevent overheating of the support layer. To ensure the recommended temperature processing and control overheating requires the use of thermal imaging control on the surface of the tape and tooling. According to the results of the conducted research, it was revealed that the speed of the laser source movement of 1 m/s is sufficient for heating the layers in the contact spot area for PEEK and PPS materials. This value was determined based on the speed of movement of the laser head of the equipment used for laying the composite tapes.

Thus, in the framework of the research, a mathematical model has been developed that describes the non-stationary processes of heating the tapes of a thermoplastic prepreg in the process of automated layup. The speed of the laser source was selected, to provide the temperature needed for molding of the considered materials. The conducted researched revealed, that a heating contact spot when having a large heating area leads to bonding of the first and second layers when arranging layers on each other and to bonding on the lower face of the second layer. Metal tooling has a greater heat capacity, it contributes to heating the thickness of the tooling, while carbon fiber tooling, in turn, removes heat better, thus preventing the material from heating. Interlayer bonding depends on the speed of the source and its power.

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