Temperature Field Simulation of Polymeric Materials During Laser Machining Using COSMOS / M Software

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Abstract: - The parametric temperature field analysis was realized by the finite element method. The analysis was run in COSMOS/M software solver. A thermal module HSTAR makes it possible to realize cases of the temperature dependences on the material properties. Material data can be entered as a function of a temperature. The thermal and physical characteristics of the polymeric materials change significantly. The output of the analysis was described by colourful spectrograms with temperature field distribution of various materials.

Key-Words: - Polymeric Materials**,** Laser, Micro-machining, Temperature Field Simulation

1 Introduction

LASER stands for Light Amplification by the Stimulated Emission of Radiation. In 1917 Albert Einstein calculated the conditions necessary for stimulated emission, but, it was only much later, in 1960, that the first visible LASER was demonstrate by T. Maiman. However, a MASER, a similar device that emitted energy in the microwave region was the first to be developed.

The task of the laser micro-machining has very extensive usage in industrial applications. The system development and introduction of these technologies is very attractive. Micro-machining belongs to the group of production processes, in which undersized products are made. Production specifications trend to continual minimization of product's dimensions. The laser is optimal tool for its features in this development. Results of the laser micro-machining – surface quality of product and its utility in specific application – depend on the laser parameters and the polymer material type [2], [4].

2 Problem Formulation

2.1 The laser beam effect on material

Concentration of power – electromagnetic radiation visible of light – on the small surface of product is principle of this cutting way. The place of impact warms up on temperature considerably exceeding melting temperature of machined material by the transformation of power this radiation visible light on thermal power. The material melts and vaporizes in a place of impact. The part of beam reflects, the part absorbs, the part passes through material after the impact of beam on the material. Absorbed beams share in heating of material. The quantity of reflected beams depends on material reflectance. Absorption A [%] of luminous radiation implicates the heating of surface layer. Reflectance and absorption are complex events, following relation shows their correlation:

$$\mathrm{R} + \mathrm{A} = 100\% \qquad (1)$$

Absorption of luminous radiation and followed heating depend on thermal conductivity of material. Heat convection from the laser to the material is complicated effect. Today true theory for formulation of thermal conductivity and temperature calculation does not exist because heat transfer is very quick. The process propounded by Carslaw-Jaeger is used for formulation of heat transfer for mobile source with speed in (m/s). The process presents solution partial differential equation for heat convection from the source with dimension of focused beam to surface layer and in material at definite marginal conditions. It goes from simplified hypothesis that material of product is isotropic and heat transfer can describe by equation of diffusion:

$$\frac{\partial T}{\partial t} = \alpha \Delta_L T \qquad (2)$$

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where T is absolute temperature (K), t is time (s), ΔL specific elongation, α thermo diffusion given by relation:

$$\alpha = \frac{k}{\rho \cdot c} \qquad (3)$$

where k is thermal conductivity coefficient (W·m-1·K-1), ρ is density of material (kg·m-3), c is specific heat (J·kg-1·K-1) of solid material [1],[2],[4],[5].

2.2 Temperature field simulation

After heat, which does not expend at the material evaporation in place action of laser beam, radiates to material rest. It is possible proceed according to several methods at the temperature field simulation:

1. Change of phases, change of radiation absorption, structural change of material (depolymerisation …) and change of geometry take into consideration at action of laser beam. Physical quantities of machined material take in dependence on these changes variable in the time (they are variable during acting of thermal energy).
2. The change of phases is taken as constant. Although this model do not correspond to fact it is possible his in view of temperature course speed in place cutting use for temperature field analysis.
3. Temperature field is solved without reference to evaporated material – the model is takes into consideration only as heating of specimen by concentrate energy on surface of laser beam action.

The making of model is the biggest problem at using the first method which respects change of physical properties and material behaviour at heating and change of phases. The specific heat capacity c_p which is in dependence on temperature from 0,585 kJ/kgK (at -173°C) till 2,5 kJ/kgK (at 300°C) is changed with change of temperature and phase. The thermal conductivity is also changed at change of temperature and it is from 0,20 W/mK (at 25°C) till 0,16 W/mK (at 150°C). It is necessary to reckon with change of cutting profile at the making of model. The beam does not evaporate the material by all surface of cut at the feed. This material is heated at the feed of the beam above non machined part of the material and it is evaporated after the giving sufficiency energy.

The second method does not take into consideration change of phases and cut geometry but takes into consideration the material evaporation at the cutting. It is necessary consider with sequential stock removal by influence of laser beam action at this model. It is possible consider simply that the beam cuts part of material corresponding to surface of beam and set power at limited time intervals [3],[5].

3 Temperature Field Simulation During Laser Machining

3.1 Models Creation in COSMOS/M Programme

The assembled model is a compromise as it does not take into account the changing phases and interfaces (overheating of the material is so fast that the change of phases does not affect the accuracy of the results) and the material structure of the material. It solves only the heat transfer in the solid phase of the material as the heating of the sample by concentrated energy applied to the surface of the laser beam effect. However, the change of physical quantities (namely the specific heat and thermal conductivity) depending on the temperature (that is changing with temperature) was taken into account, because COSMOS / M programme enables to solve cases of temperature-dependent material properties, since the material characteristics can be defined as a function of temperature by the so-called temperature curves.

As a vaporized material and therefore the change of phases and the interface were not taken in to account, it could be presumed that the temperature field character in any section of the material during its interaction with the laser beam was identical; it allowed the solution simulation (modelling) in the plane without the use of 3D geometry. The result is a model showing the temperature penetration and its distribution (temperature field) within the material section (i.e. inside). For the possibility of creating a 2D model it was also necessary to assume that the temperature profile spreads equally in the material.

According to another assumption, all the energy of laser radiation supplied into the material converts into heat immediately. Therefore, the laser beam energy is implemented as heat flux of a certain value entering into the material surface. Furthermore, it was assumed that the solid part of the material in the section (the change of phases has been neglected), which does not evaporate due to the laser beam effect is defined by the temperature of the thermal decomposition, which is obviously dependent on the polymer type. For this purpose, a heat flux, the maximum value of which was defined as a variable parameter using the so-called time

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curve, was entered into the individual nodes (nodal points of individual elements) with the overall scatter corresponding to the total width (the laser beam diameter is 0.2 mm); thus a repeated change of heat flux value and the subsequent calculation of the temperature field after the specified time steps was achieved. Evaluation of temperature field results was based on the values of the heat flux, i.e. of a time step when the temperature of the solid phase of the material reached the above mentioned point of decomposition. Using COSMOS/M programme, the initial temperature condition was set out across the cross-sectional area of the material. The initial temperature was imposed at 20°C. The Gaussian distribution of density of laser beam energy was neglected during the simulation. Its maximum power is located in the centre of the laser beam. The modelling was based on the fact that the density of laser beam energy is invariable across its diameter; proving that during the simulation a heat flux, whose value in all nodes was the same, was entered into every node (nodal points of elements) with the overall scatter corresponding to the laser beam diameter [4], [5].

3.2 The dimension of the specimen (mm) and finite element mesh

During machining of polymeric materials there are significant effects and thus impact to the material near the laser beam interaction with the material. Therefore, it was not necessary to choose the total dimensions of the material cross-section during 2D simulation; only one specific element was chosen allowing us to solve modelling as an isolated system (i.e. without affecting the surrounding environment). Final model dimension were 10x5 mm and symmetry was used for their creation. Firstly, a surface 5x5 mm was created; secondly, the above mentioned symmetry was used after mashing.

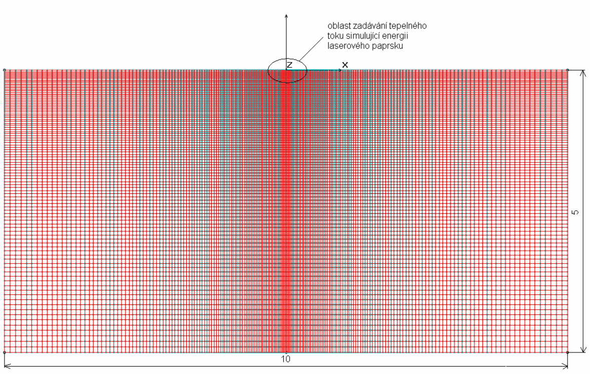

Fig.1. Created and meshed surface of the models

The value of the entered heat flux was random in essence since it was set out according to the previous choice of a time step solution (so-called time-curve) as a variable parameter; it resulted in repeated changes of the heat flux values and the subsequent calculation of the temperature field in the specified time increments. In Figure 2 we can see a part of the created model; attention was paid to details on the nodes into which the heat flow was entered.

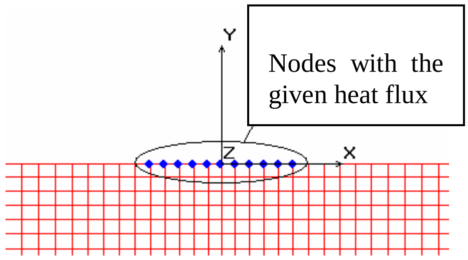

Fig. 2. Detail of the model

3.3 2D Models

The following figures show real spread of heat inside material within binding conditions.

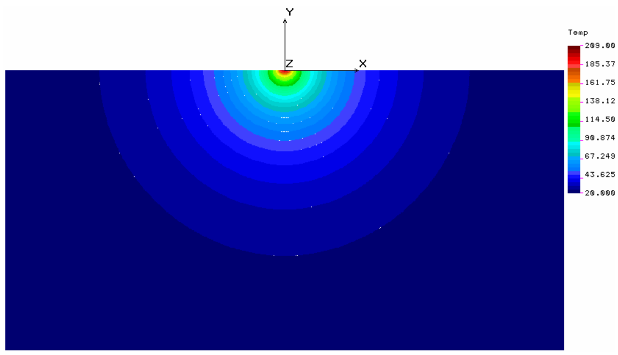

Fig.3. A temperature field of PVC

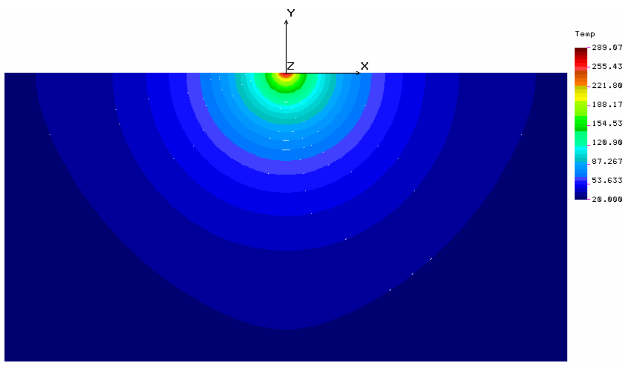

Fig.4. A temperature field of PS

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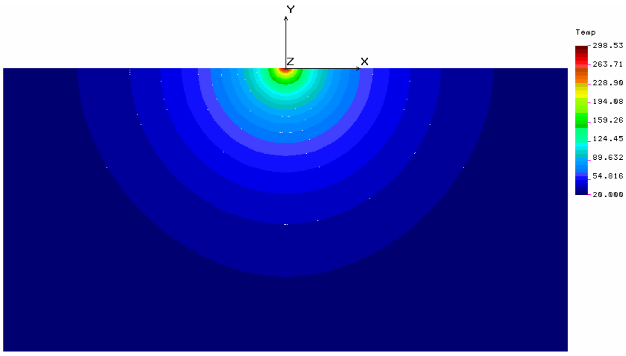

Fig. 5. A temperature field of PMMA

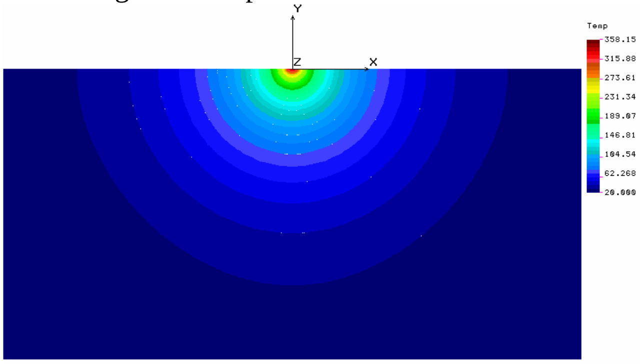

Fig.6. A temperature field of PC

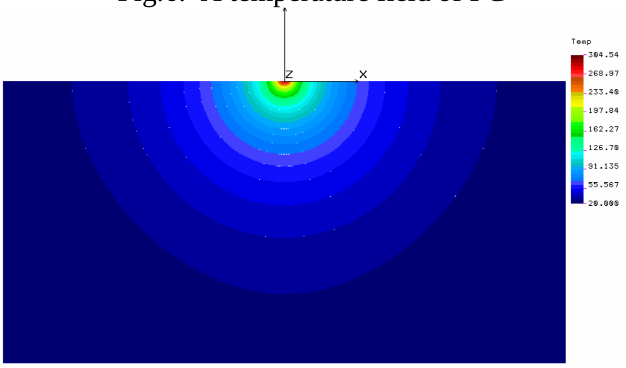

Fig.7. A temperature field of PA 6

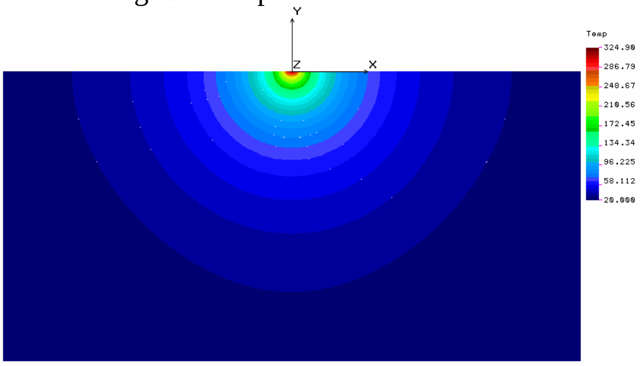

Fig.8. A temperature field of PA 66

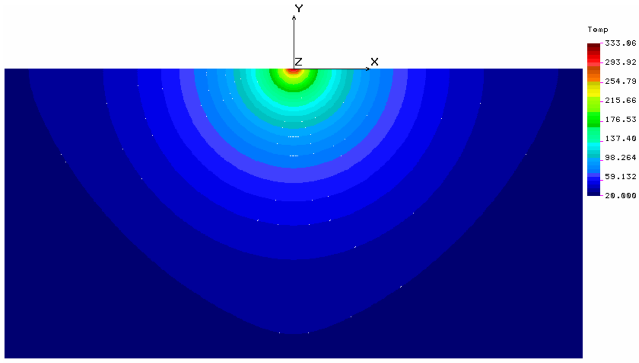

Fig. 9. A temperature field of POM

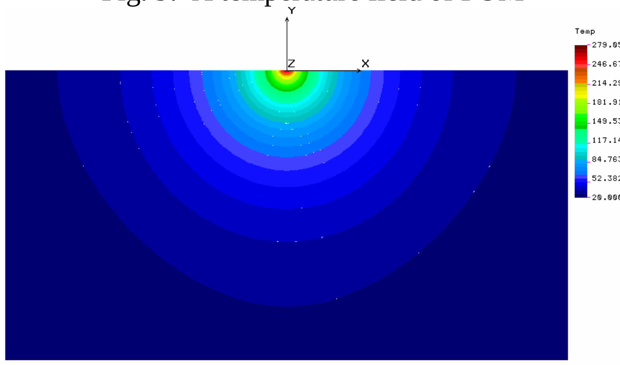

Fig. 10. A temperature field of ABS

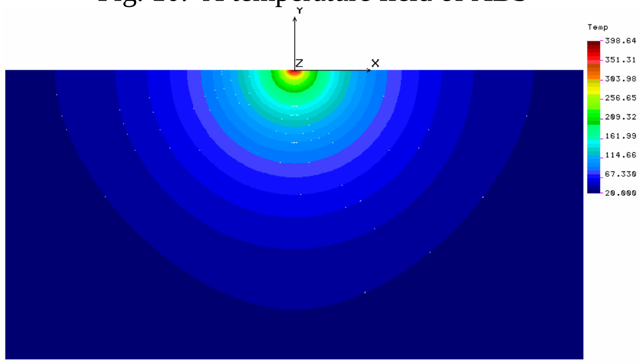

Fig. 11. A temperature field of PTFE

4 Conclusion

The results of analysis of various types of polymers confirm the assumption that there are significant effects, i.e. significant heat impact on the material, during the material processing only near the laser beam interaction with the material as none of the material types was affected across the whole model section with dimensions 10 x 5 mm.

The values of temperatures which could lead to phase changes in the material were found in all types of amorphous materials (PVC, PMMA, ABS, PS, and PC) in the fifth of the model maximally, i.e. up to a distance of 1 mm from the place where the heat flow was set.

Concerning crystalline polymers (PA66, PA6, POM, PTFE) the distance was at about the half value, corresponding to a tenth of the model, which represents a distance of 0.5 mm.
The simulations also show that the area in which depolymerisation and destruction of various materials could occur is very small and reaches a maximum depth of 0.07 mm (= 70 µm).
There is similarity evident in the character, particularly in the shape, size, layout and distribution of temperature field for the given types of polymeric materials. This similarity is probably the result of a small variance in the values of thermal conductivity of different types of polymers. Impact on the course and size of the temperature field is therefore mainly defined by temperature of thermal decomposition of polymers.
In the end it is possible to state that the model of LASER interaction with the thermoplastic material is possible. The influenced area of high temperature gradient is narrow when the LASER ray after passes through. At the near proximity the high temperature gradients induce as high short time value of transient thermal stress as residual tension.
Providing linear-elastic behaviour of specimen, the thermal tension responds thermal state in the time „t“. Level of these tensions is proportional to the temperature gradient. The linear-elastic tensile relaxes after equalization of temperature in the specimen [4], [5].

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