The Transient Temperature Field Simulation of Polymeric Materials During Laser Machining

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Abstract — The paper deals with possibilities of using the laser in technologies. 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.

Keywords — Polymeric Materials, Laser, Micro-machining, Temperature Field Simulation.

I. 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 term „laser“ tells us that a simplified description of the lasing process could be „opposite of absorption”. At the heart of the lasing phenomenon is the ability of photons to stimulate the emission of other photons, each having the same wavelength and direction of travel as the original.

According to quantum theory, atoms and molecules have discrete energy levels, and can change from one level to another in discontinuous jumps. Under normal conditions, most atoms or molecules remain quiescent at their lowest energy level, or ground state. But if these particles are exited into higher energy states-by an intensive flash of light, an electrical charge, or other means-they will, in dropping back to the normal ground state, emit incoherent light in the process. In a laser cavity, such emitted photons are trapped between highly polished and parallel mirrors. Whenever a photon passes close to another excited particle of the same wavelength, the second particle will also be stimulated to emit a photon that is identical in wavelength, phase, too, become part of the growing wave between mirrors. Lasing begins when enough photons are present, and if one of the mirrors is partially transparent, a highly disciplined, intense, and now, coherent beam is emitted.

A typical laser beam is about 1/5th of a millimeter in width and has an intensity of 100 to 2000 watts. Most laser cutting machines are integrated into a CAD/CAM system that helps the user design the end product on a computer before implementing it on the work piece.

Laser cutting devices are proving beneficial in a wide array of industries. The plastic industry is no exception. These optic powered devices are used to cut precise shapes into plastic or acrylic sheets. The lasers can be used to cut plastics of varying thickness by simply altering the intensity of the beam. Lasers are not only used to cut through plastics but also help engrave on various surfaces.

Laser plastic cutting machines bring precision and accuracy to the entire process. Since most machines are fully automated, they can perform complex cutting operations at high-speeds. The laser plastic cutting machines can also be used to cut polymers, polycarbonates and other synthetic materials such as polyesters and rubbers.

The laser cutting method uses a non-contact approach when cutting the material. Due to this, the wear and tear associated with conventional methods is absent, preventing the product from any damage and deformation. The laser process also delivers a finish quality unmatched by any other process.

When using laser plastic cutting machines, care should be taken to avoid the use of flammable plastics such as PVCs. These materials cannot cope with the heat generated by the laser and get damaged easily.

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].

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II. PROBLEM FORMULATION

A. *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:

$$R + A = 100\% \tag{1}$$

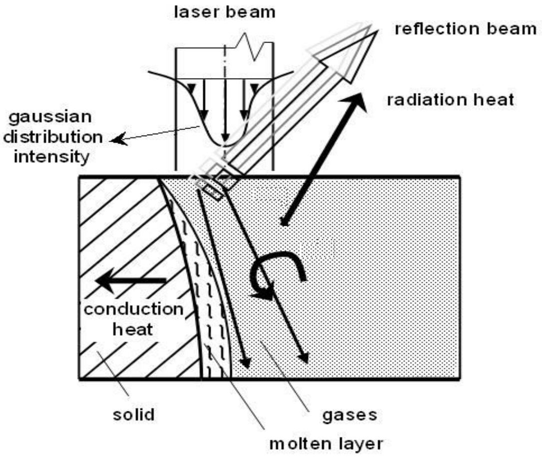

Fig. 1 The laser beam effect on material

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:

$$\frac{\partial T}{\partial t} = \alpha \Delta_L T \tag{2}$$

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

$$\alpha = \frac{k}{\rho \cdot c} \tag{3}$$

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].

B. *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 etc.) 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 [6], [7].

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].

III. METHODOLOGY

A. *The laser beam effect on material*

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 (modeling) 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 [8]-[10].

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 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 [8] - [10].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 modeling 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].

B. 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 modeling 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.

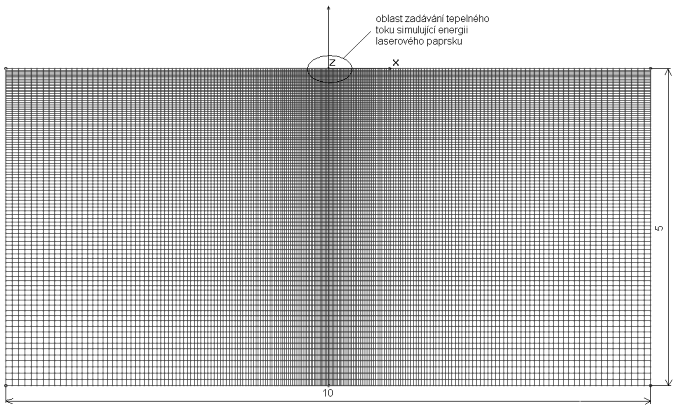

Fig. 2 Created and meshed surface of the models

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.

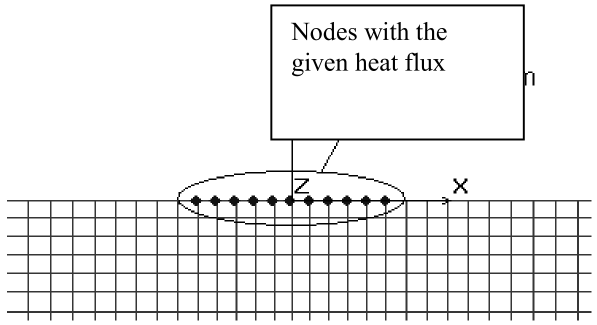

Fig. 3 Detail of the model

IV. RESULTS AND DISCUSSION

A. 2D Models

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

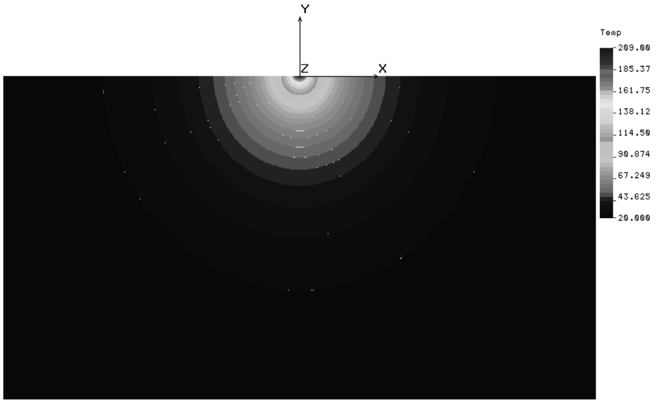

Fig. 4 A temperature field of PVC

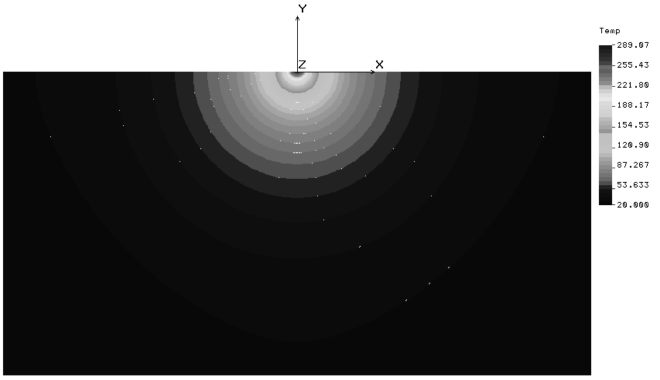

Fig. 5 A temperature field of PS

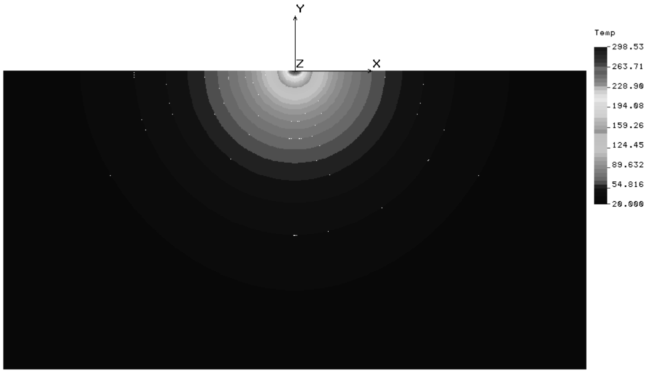

Fig. 6 A temperature field of PMMA

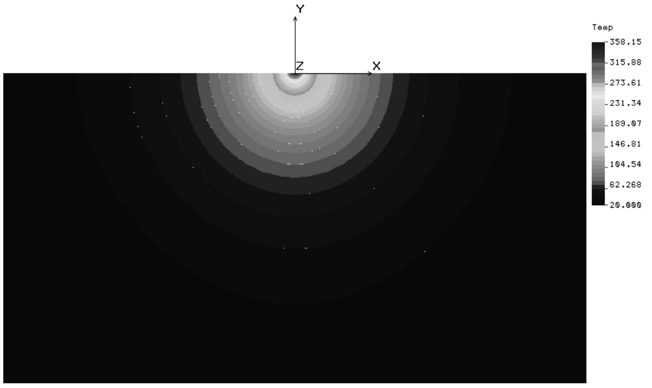

Fig. 7 A temperature field of PC

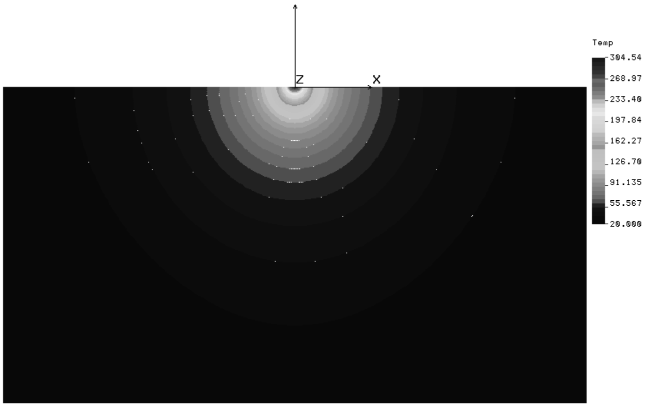

Fig. 8 A temperature field of PA 6

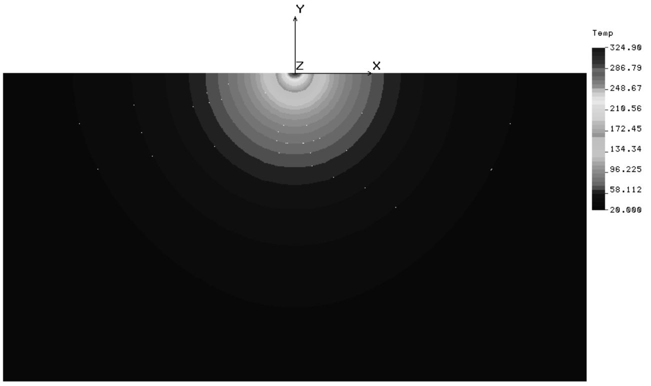

Fig. 9 A temperature field of PA 66

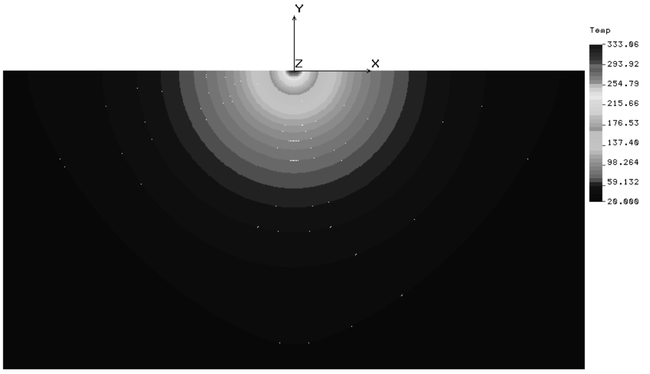

Fig. 10 A temperature field of POM

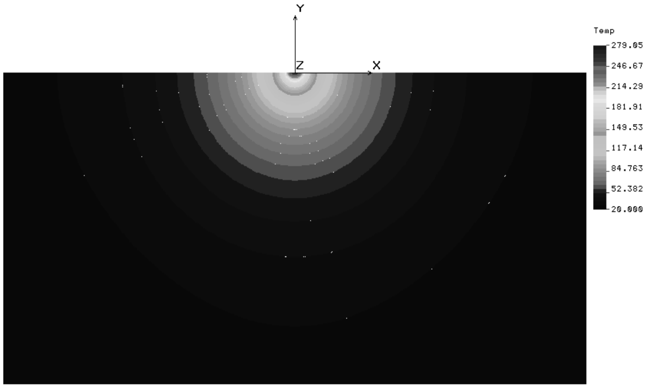

Fig. 11 A temperature field of ABS

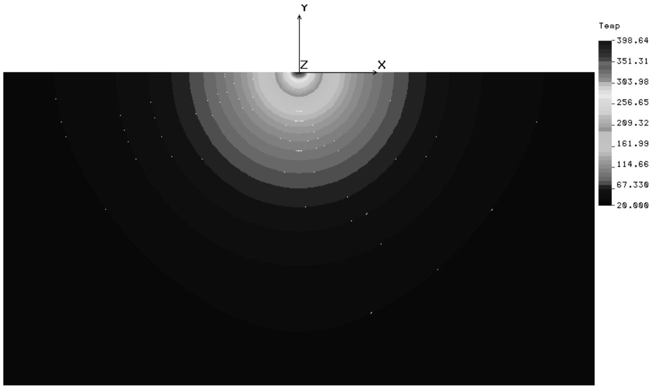

Fig. 12 A temperature field of PTFE

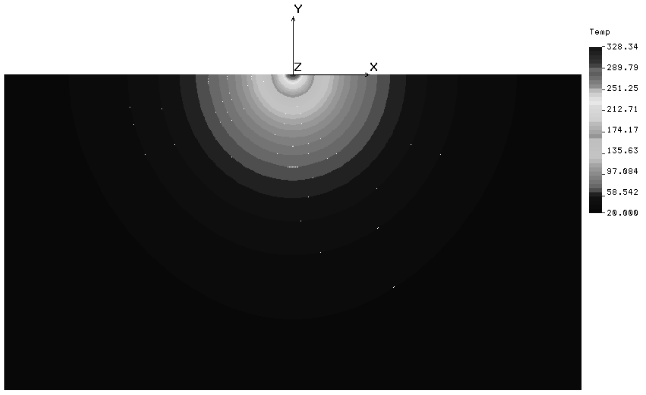

Fig. 13 A temperature field of PP

B. The methodology FEM of modeling of transient temperature field after beam passed through

The PMMA was evaluated as ideal material for laser machining was due to its properties and transparency. For this reason more simulations and their evaluation was performed just for this material.

The PMMA side wall gradually cools after the laser light passed through in the specific cut. At the same time the thermal flow is distributed from the cut plane to the internal dimension of the wall. The thermal process is described by Fourier-Kirchhoff differential equation (2).

The thermal conductivity of thermoplastic materials is (100-1000) times less then metals. That fact cause that plastics keep high differences of temperatures between external and internal layers. The parametric analysis of the thermal field was realized by the finite element method. The analysis was run by software COSMOS/M developed by Company SRAC, USA in actual version 2.5.

The thermal modulus HSTAR makes possible to realize cases of the thermal dependent material properties. Material data can be entered as a function of the temperature. In this case changes of the temperature at intervals 20-370°C are concerned. The physical characteristics of the thermoplastic materials are changed very expressively in this temperature interval. Values λ, ρ, c were entered as the function of the temperature through medium of the thermal curves.

The time variable heat flow was entered into the particular flat elements (constituent the model half of cut) by time curves i=1,2,3 (fig. 13). The heat flow values were entered as the variable parameters. Progressive ignition and extinction of the heat flow simulates the ray laser movement. The maximal temperature was regulated on the already alluded cracking temperature by the repeated change of the heat field value and following thermal field calculation.

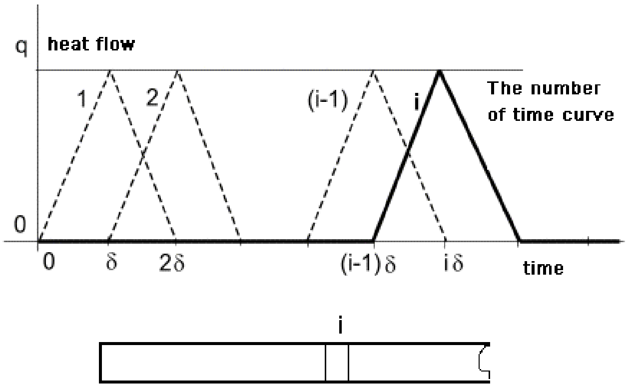

Fig. 14 Schema of boundary conditions of the movement ray laser

The dimension of the select specimen is showed in the figure 15.

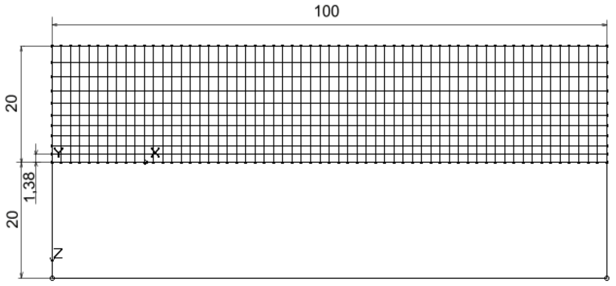

Fig. 15 The dimension of the specimen (mm) and finite element mesh

The thermal field was taken for two values of the cutting speed, namely 5 mm/s and 20 mm/s.
Made results are presented in the following figures.

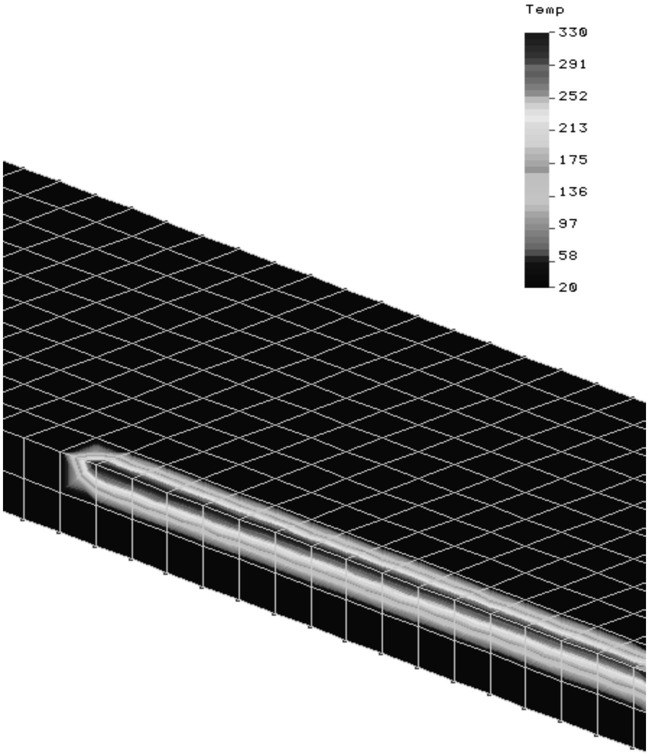

Fig. 16 3D model of the thermal field for cutting speed 5 mm/s in time t=30 second

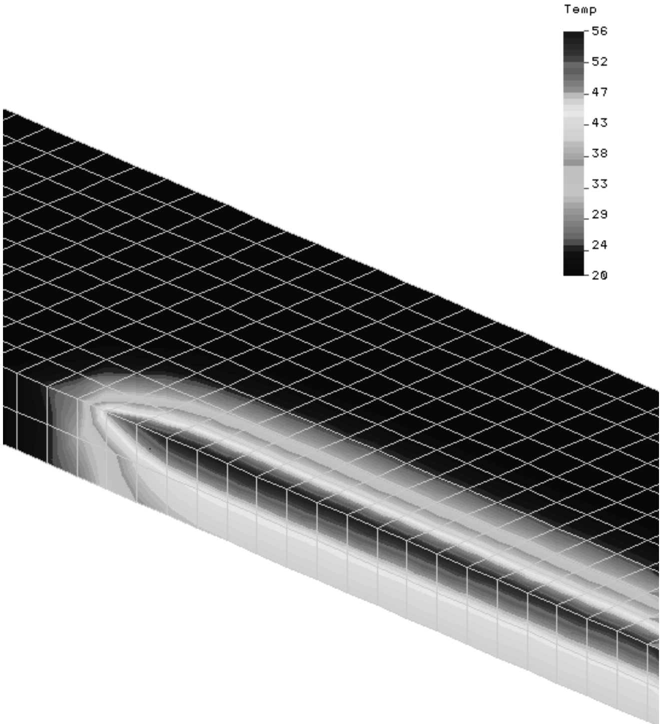

Fig. 17 3D simulation of the heat distribution in vicinity surrounds after 3 min. (speed 5 mm/s)

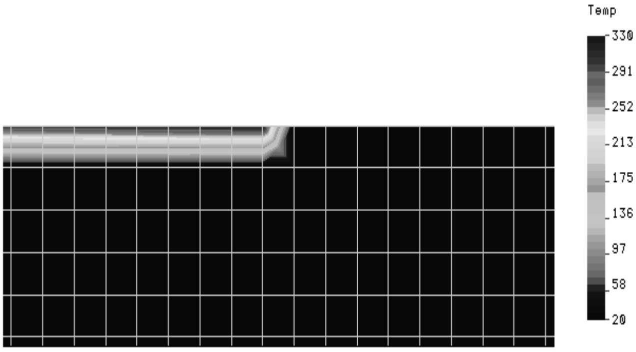

Fig. 18 2D model of the thermal field for cutting speed 5 mm/s in time t=30 second

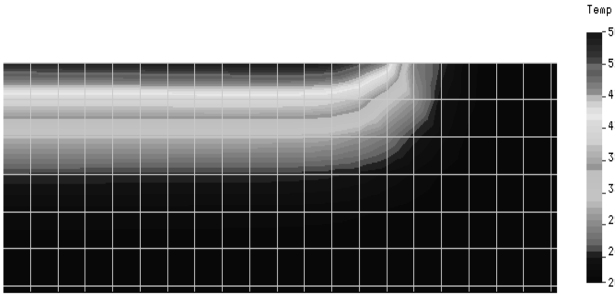

Fig. 19 2D simulation of the heat distribution in vicinity surrounds after 3 min. (speed mm/s)

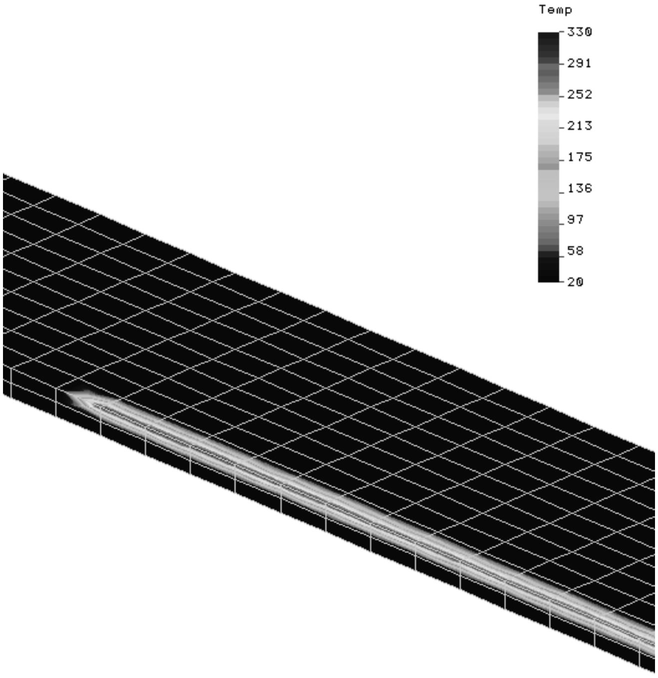

Fig. 20 3D model of the thermal field for cutting speed 20 mm/s in time t = 30 second

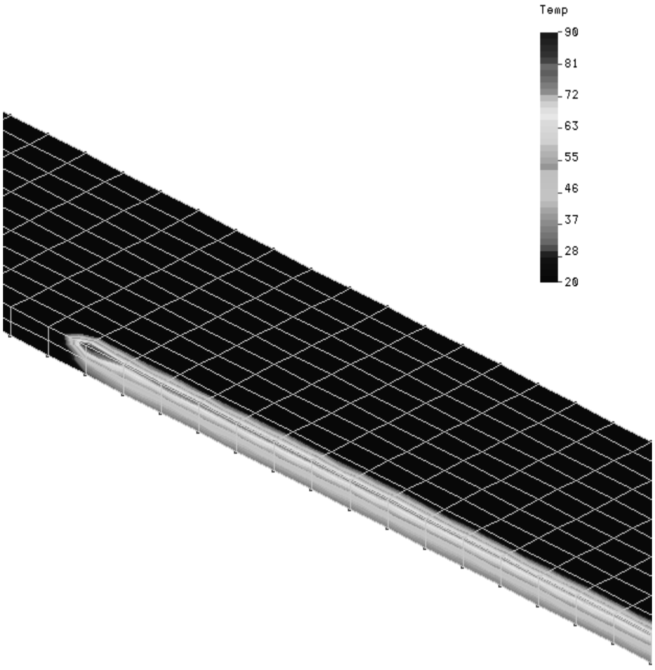

Fig. 21 3D simulation of the heat distribution in vicinity surrounds after 300 s. (speed 20 mm/s)

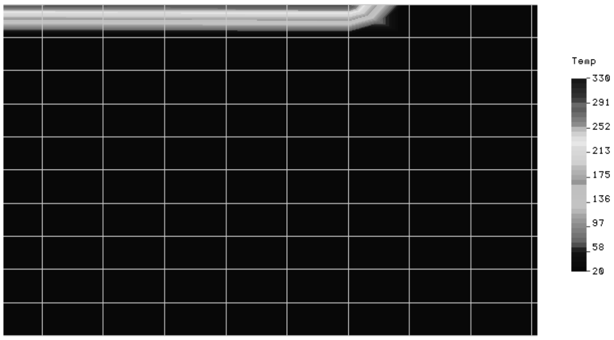

Fig. 22 2D model of the thermal field for cutting speed 20 mm/s in time t = 30 second

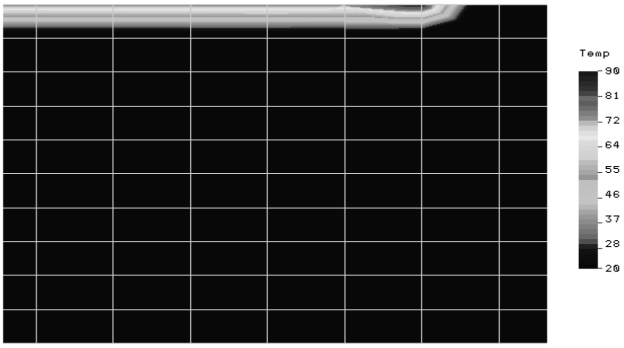

Fig. 23 2D simulation of the heat distribution in vicinity surrounds after 300 s. (speed 20 mm/s)

V. 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).

Glass transition temperatures Tg, creep temperature Tf of amorphous polymers and the melting temperature Tm of crystalline polymers are for convenience and their importance since they form the interface between the phase states of polymers listed in the following table.

Table I. Glass transition temperatures Tg, creep temperature Tf and melting temperature Tm of the types of polymers

Type of polymer	Phase transformation	T_g [°C]	T_f [°C]	T_m [°C]
PVC	amorphous	80	180	
PMMA	amorphous	100	170	
ABS	amorphous	105	195	
PS	amorphous	100	180	
PC	amorphous	145	220	
PA 66	crystalline			265
POM	crystalline			160
PTFE	crystalline			290
PP	crystalline			165
PA 6	crystalline			215

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].

The laser beam is a tool of the future. It can cut without affecting the surrounding material. Its energy is clean, reliable and it is ready to be tamed and handled to give an unequalled quality to the process. Quality of cut depends on the working parameters of laser cutting process (laser power, feed rate, material thickness.)

Resulting structures can be very exact. High quality of surface in dependence on laser parameters and on type of machining materials is reached. The biggest problem is the transformation of unremoved material again into the solid state. This phenomenon causes deterioration of both accuracy of dimension and quality of surface.

If technological conditions (moving speed of the laser head, the beam output, mode parameters of the optics) are optimized, a good quality of the cut can be reached for wide spectrum of materials.

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