

# Numerical modeling of cutting process of steel sheets using a laser beam

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**Abstract.** Laser beam cutting technology is becoming increasingly popular in various industries. Advantages of this method is a very high cutting speed and a precision of edges of cut elements. Good quality depends on many technological parameters. Numerical prediction of the effect of cutting process parameters on the quality of the surface can be useful for technologists. The work concerns the numerical analysis of the laser cutting process of sheet made of steel. The influence of selected parameters on the energy efficiency of the heat source and the cutting speed are analyzed. Numerical calculations are performed in Abaqus software. Three-dimensional discrete model of the analyzed system is developed. The standard material parameters of austenitic steel changing with the temperature are taken into account. Gauss model describing the distribution of movable heat source of a laser beam power are assumed in the solution algorithms. The influence of various parameters of the laser beam on obtained temperature field and shape of cut zone is estimated on the basis of numerical calculations. The results are compared with the results of the experiment.

**Keywords:** Laser cutting, numerical modelling, Abaqus software, temperature field,

## 1 Introduction

Large and medium manufacturing facilities use cutting processes in the production. Currently, one of the most popular methods for cutting of various types of materials is laser beam cutting. Presently, rapid technological advances in the design and construction of laser equipment and control system has made the laser cutting process the basic method of materials processing [1, 2]. This method is characterized by high cutting precision, high speeds of the laser source, a narrow cutting zone and heat affected zone resulting in a very good edge quality of the cut [2, 3].

During the cutting process, the energy of the laser beam directly affects the cutting area in which the material is melted. The molten material is partially evaporating and the

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remaining part is blown out of the gap by the flow of associated gas [2-4]. In the cutting process, it is important to choose the right process parameters. Proper selection of these parameters has a significant impact on the obtained cut quality. Technologists have to determine the optimum technological parameters of cutting [2, 3]. In some cases, the choice of these parameters is time-consuming and experiment is quite expensive [5-9]. Therefore, the numerical research is increasingly being conducted. In the numerical analysis, it is necessary to adopt appropriate mathematical models and develop an appropriate numerical model [7-9].

The paper presents a numerical analysis of thermal phenomena in the cutting process of sheets using a laser beam. Experimental research of the cutting process of sheets with four different thicknesses is performed. For all cases, the same laser beam power is used in the cutting process. The other parameters are chosen to obtain a good quality of cut [3, 9]. On the basis of the dimensions and technological parameters of experience, a three-dimensional discrete model is developed in the Abaqus program and simulation tests are carried out. It is possible to model of movement of the laser beam using implemented additional subroutine to the numerical calculation program. Thermophysical parameters of S235Jr steel found in the literature are adapted in calculations [10]. Gaussian cylindrical models of heat sources are assumed in numerical calculations due to small differences in the gap width on the upper and lower flat surfaces. This model assumes the form of the source, an equivalent volume of a cylinder of radius  $r_o$  and a height  $h$  of the assumption of a constant value of beam power through the entire depth ( $h$ ) of penetration of the beam in the material [11].

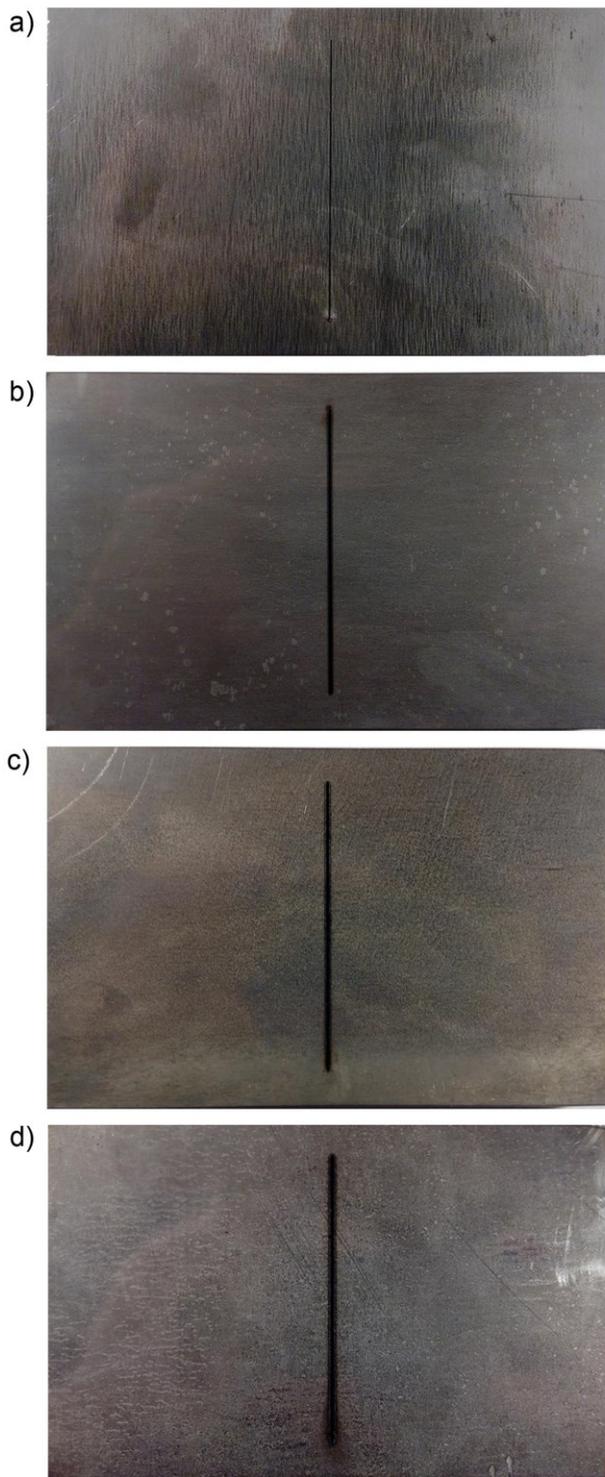
On the basis of the numerical simulation, the temperature field is determined and the shape of the cutting zones is estimated. The obtained results are compared with the experiment, where the comparative criterion is the width of the cut.

## 2 Experiment

Laser cutting of specimen made of S235Jr steel is carried out on a fiber laser. Experimental studies are performed for sheets with dimensions 100×160 mm, and four different thicknesses of 5 mm, 8 mm, 10 mm and 15 mm. The cut is made along the short side at a length of 80 mm. Figure 1 shows laser cut sheets.

Technological parameters used in the experiment are presented in Tables 1. For all cases, the same laser beam power of 4000 W is used. Due to the different thicknesses of the cut elements, different beam speeds were used. In the case of a 5mm thick sheets, nitrogen as shielding gas is used. However, in other cases, due to the thickness of the sheets oxygen is used. As you can see from the pictures of sheets, the gap width grows with increasing thickness of the element. It is connected with the need to obtain a deeper penetration of the heat source.

Table 2 shows the measured widths of the resulting gaps. The measurement is made using the workshop method - a feeler gauge.



**Fig. 1.** Laser cut sheets, a) 5 mm, b) 8 mm, c) 10 mm, d) 15 mm

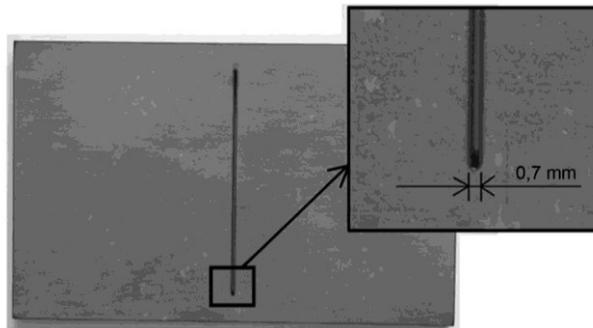
**Table 1.** Process parameters of laser cutting

Parameters of laser cutting	Steel thickness [mm]			
	5	8	10	15
Cutting speed [mm/s]	70,0	35,0	25,0	13,0
Gas pressure [bar]	18,0	0,70	0,75	0,75
Power [W]	4000	4000	4000	4000
The height of the nozzle above the material	0,5	1,0	1,0	1,2
Focus [mm]	-3,0	+2,0	+2,5	+3,5
Nozzle diameter [mm]	3,0	1,5	1,5	2,0
Protective gas	nitrogen	oxygen	oxygen	oxygen

**Table 2.** Measurement of the cutting gap

Steel thickness [mm]	Width of the gap [mm]	
	Top surface	Lower surface
5	0,2	0,2
8	0,6	0,7
10	0,7	0,8
15	0,9	1,2

The experimental tests are used to verify the adopted mathematical and numerical models. In the presented work, the numerical analysis is made for the sheet with a thickness of 8 mm. It was assumed for analysis that the gap on the upper and lower surface is identical and amounts to 0.7 mm (Figure 2).



**Fig. 2.** Assumed gap width for a sheet with a thickness of 8mm

### 3 Analysis of thermal phenomena

Numerical calculations of thermal phenomena occurring in the cutting process are carried out in the Abaqus/Standard solver. Numerical analysis of temperature field in laser cutting is determined on the basis of the solution of energy conservation equation with Fourier law [12]:

$$\int_V \rho \frac{\partial U}{\partial t} \delta T dV + \int_V \frac{\partial \delta T}{\partial x_\alpha} \cdot \left( \lambda \frac{\partial T}{\partial x_\alpha} \right) dV = \int_V \delta T q_v dV + \int_S \delta T q_s dS, \quad (1)$$

where  $\lambda$  is a thermal conductivity [W/m °C],  $U = U(T)$  is a internal energy [J/kg],  $q_v$  is a laser beam heat source [W/m<sup>3</sup>],  $T = T(x_\alpha, t)$  is a temperature [°C],  $q_s$  is a boundary heat flux [W/m<sup>2</sup>],  $\delta T$  is a variational function,  $\rho$  is a density [kg/m<sup>3</sup>],  $T = T(x_\alpha, t)$  is temperature [°C].

Equation in thermal analysis (1) is completed by initial condition  $t = 0 : T = T_o$  and boundary conditions of Dirichlet, Neumann and Newton type with heat loss due to convection, radiation and evaporation taken into considerations [11]:

$$T|_\Gamma = \tilde{T} \quad q_{sym} = -\lambda \frac{\partial T}{\partial n} = 0 \quad q_s = -\lambda \frac{\partial T}{\partial n} = \alpha_k (T|_\Gamma - T_o) + \varepsilon \sigma (T|_\Gamma^4 - T_o^4), \quad (2)$$

where  $\alpha_k$  is convective coefficient (assumed as  $\alpha_k = 50$  W/m<sup>2</sup>°C,  $\varepsilon$  is radiation ( $\varepsilon = 0.5$ ),  $\sigma$  is Stefan-Boltzmann constant and  $q(r, 0)$  is the heat flux towards the top surface of welded workpiece ( $z = 0$ ) in the source activity zone of radius  $r$ ,  $T_o = 20^\circ\text{C}$  is an ambient temperature.

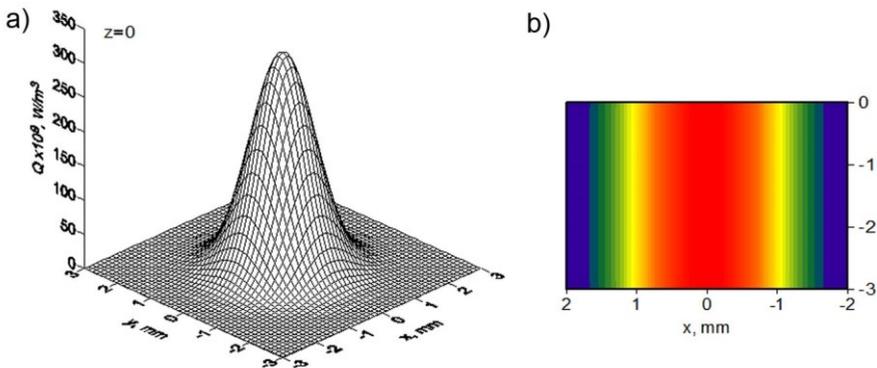
### 4 Heat source model

In order to model the movement of the laser beam additional subroutine to the calculation solver is implemented. The distribution of power intensity and the trajectory of the heat source movement are modeled. Due to small differences in the width of the cutting gap on the upper and lower surface (Fig. 2), the Gaussian model is assumed in calculations, with the cylindrical shape of the heat source [11] :

$$Q_v(r, z) = \frac{Q_L}{\pi r_0^2 h} \exp\left(-\frac{r^2}{r_0^2}\right), \quad (3)$$

where:  $Q_L$  is a laser beam power [W],  $r_0$  is a beam radius [m],  $r = \sqrt{x^2 + y^2}$  is actual radius [m],  $h$  is penetration depth [m],  $z$  is actual penetration [m].

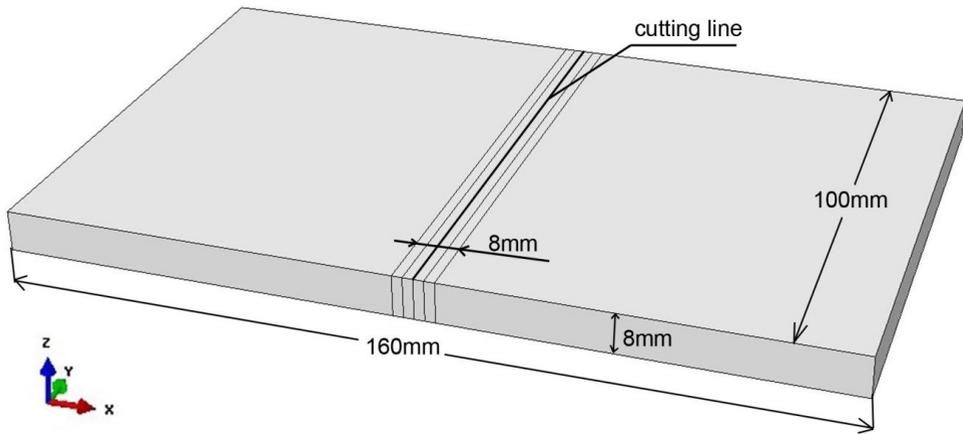
Figure 3 shows an example of the distribution of laser beam power with a distribution described by equation (3)



**Fig. 3.** Power distribution of the laser beam source a) on the upper surface, b) in the axis of the heat source

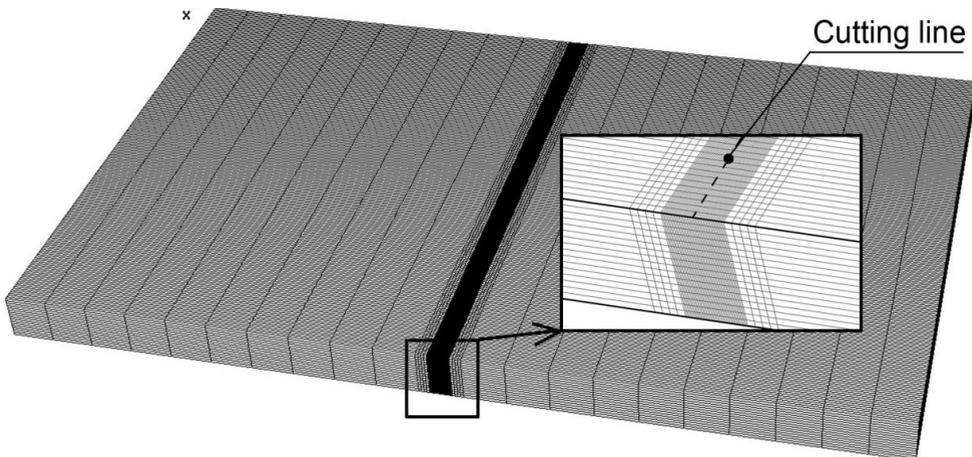
## 5 Numerical model

The three-dimensional model of the analyzed sheets is developed in Abaqus program. The geometrical dimensions of the model are identical to those in the experiment. Figure 4 shows the scheme of the system with dimensions. For numerical calculation used experiment technological parameters of the cutting process are adopted as follows: the power of the laser source  $Q_L = 4000$  W and the speed of the source of  $v = 35$  mm/s. On the other hand, on the basis of numerical verification, the beam radius  $r = 0.16$  mm and the penetration depth, which is equal to the thickness of the cut sheet  $h = 8$  mm.



**Fig. 4.** Scheme of considered system

Developed discrete model of laser-cutting of steel sheets is presented in Figure 5. Rectangular finite elements are adapted in the developed model. Due to the high temperature gradient in the cutting zone, the very high speed of the source and the small radius of the laser beam, it is necessary to adopt a significant compaction of the grid at the place of operation of the cutting source [7, 13].



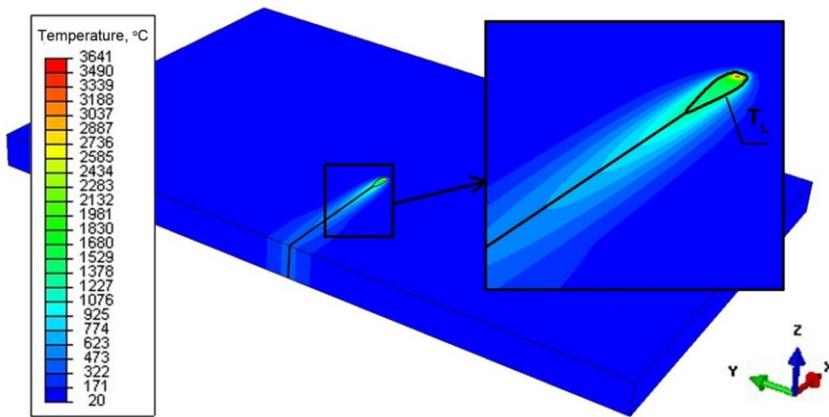
**Fig. 5.** Discretization of analyzed domain

In the developed model, the dimension of the mesh element is  $0.05 \times 0.05 \times 0.05$  mm. Such density has a significant impact on the stability of the algorithm solution but at the same time extends the duration of the numerical simulation. In order to minimize the calculation time further away from the cutting line, the size of the element is much larger.

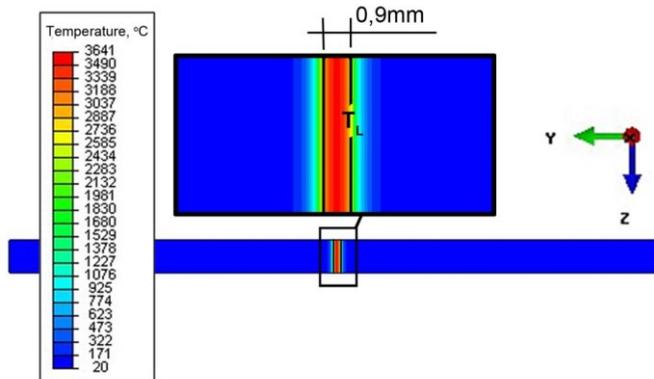
In the calculations for the Abaqus program, thermophysical properties of S235JR steel were adopted, which was taken from the literature [13].

## 6 Results and discussion

The temperature field in the sheet is numerically determined on the basis of the adopted mathematical and numerical model developed in the Abaqus program. The width of the cutting zone is numerically estimated. Fig. 6 shows the temperature distribution in the overview. Figure 8 shows the distribution in the transverse direction to the cutting line. In the drawings, the boundaries of molten metal zones are marked with a solid line (isoline  $T_L \approx 1460^\circ\text{C}$ ). The obtained temperature distribution significantly exceed the melting temperature of steel. It can be assumed that part of the material consumed on the cutting line has been evaporated and the remaining part will be blown through the shielding gas.

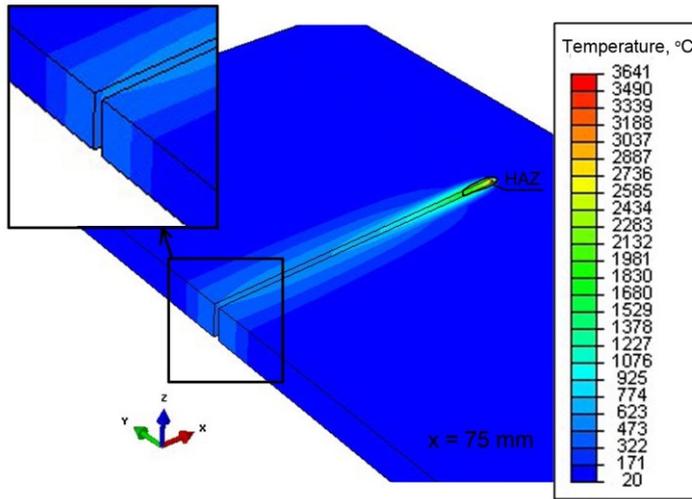


**Fig. 6.** Temperature distribution of the welded T-joint, a) comparing the numerically predicted shape of melted zone with the experiment b)



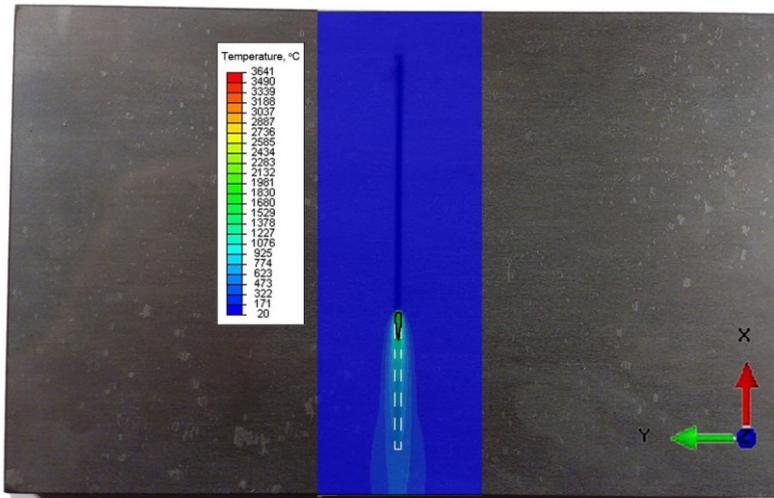
**Fig. 7.** Temperature distribution in the cross section of cutting element

To show the cutting width in the Abaqus program, all elements in which the temperature exceeded the liquidus temperature value are deactivated by the program (Figure 8). Additionally, in Figure 7 the HAZ Boundary is marked.



**Fig. 8.** Temperature distribution in the cross section of cutting element

Figure 9 shows a comparison of the cutting area with image estimated by a numerically analysis. When comparing both images, it can be concluded that numerically a similar gap was obtained, which indicates the correctness of the adopted numerical models.



**Fig. 9.** Comparison numerical modeling with experimental research

The small differences between the experiment and the numerical tests obtained may result from the adoption of the cylindrical shape of the beam power distribution. The second factor that can be influenced is the numerical verification of the beam radius. This radius should be determined automatically by the program on the basis of information such as: the distance of the nozzle from the upper surface of sheet and the place of focus of the laser beam.

## 7 Conclusions

Numerical analysis of thermal phenomena occurring during laser beam cutting process requires reliable process conditions. Conducting analyzes in commercial engineering programs requires the implementation of additional modules.

The paper compares the results of numerical simulation with experience, where the gap, resulting from the laser beam cutting, is taken as a comparison criterion. On the basis of the process parameters accepted for the calculation, the numerically estimated gap width is 0.9 mm. Small differences in the gap width are present in the comparison with the experiment, which may result from the heat source Gaussian model and from the simplifications in determining the diameter of the laser beam. The developed numerical model can be an effective tool for technologists to determine the optimal process parameters of the cutting process.

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