SIMULATION MODEL FOR LASER HARDENING OF SMALL-DIAMETER HOLES

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DOI 10.3217/978-3-85125-968-1-32

ABSTRACT

The Gaussian laser beam can be transformed into a ring-shaped beam profile. The laser hardening can be performed by directing the obtained ring spot to the inner surface of the small-diameter holes. In this case, the laser irradiation falls inclined to the material surface. In this study, a simulation model was developed, which allows for the computation of temperature distribution during the laser hardening of the holes. The heat source model was developed to describe the intensity distribution on the inner surface of the holes as a function of the inclination, distance to the laser focal plane, and parameters of the laser beam. The intensity distribution changes during the hardening of complex holes (varied diameters along the hole). The developed simulation model accounts for the changes in the laser inclination, the distance to the focal plane, and the circumference of the irradiated area inside the hole during the processing. The simulations were performed using the open-source software FEniCSx. The developed model was validated by comparing the computed and experimentally measured temperature cycles.

Keywords: Heat source model, Laser hardening, Optimization

INTRODUCTION

Axicon lenses allow the transformation of the Gaussian laser beam into a ring-shaped beam. By directing the obtained ring spot to the inner surface of the holes the hardening can be performed. A significant advantage is that no optic elements must be inserted into the hole. It enables the hardening of small-diameter holes. However, this technique implies high incidence angles between the laser beam and the material surface. Fig. 1 schematically shows the process.

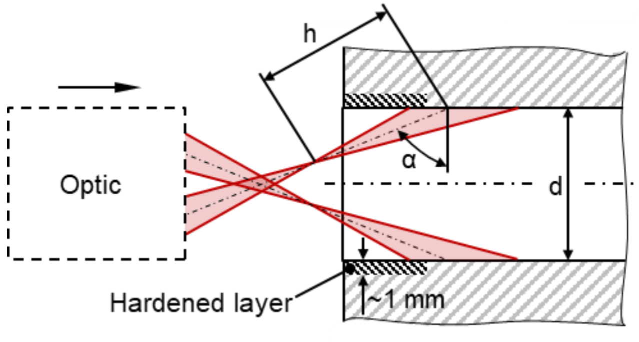

Fig. 1 Scheme of the hardening process

Such inclination leads to a crucial change in the size of the laser spot on the surface [1]. The higher the incidence angle (α), the larger the irradiated area and the lower the laser intensity. Moreover, processing outside of the beam focal plane ($h \neq 0$), besides further increase in the spot area, results in asymmetric intensity distribution [2,3]. Furthermore, the circumference of the irradiated area changes with the diameter of the hole, affecting the local intensity distribution. Geometric singularities such as sharp edges concentrate the heat flow, leading to local overheating and melting. To maintain the required temperature to achieve the uniform hardness distribution along the hole and to avoid melting, the laser power needs to be dynamically adapted during the processing. It can be normally handled by the control loops [4]. However, the integration of such loops is challenging due to the limited optical accessibility inside the hole. Alternatively, processing parameters can be optimized in advance using simulation techniques. The current study aims to develop a simulation model to enable prompt parameter optimization for the laser hardening of complex holes.

EXPERIMENTAL SETUP

Laser hardening of holes made of C45 steel was performed without shielding gas. The chemical composition of the alloy can be found in Table 1. First, the hardening of simple holes with constant diameter (d = 10 mm) was performed. The temperature cycles were measured using Ni/CrNi type K thermocouples. These trials served to validate the FE model. Subsequently, to demonstrate the applicability of the developed simulation model, the complex holes were hardened. The complex holes exhibit two diameters along the length (d_{max} = 13 mm and d_{min} = 7 mm).

Table 1: Chemical composition of C45 steel (wt. %) [5]

C	Si	Mn	Mo	Cr	Ni	P	S
0,42-0,5	<0,40	0,5-0,8	<0,1	<0,4	0,4	<0,045	<0,045

SIMULATION MODEL

Numerical simulation of the considered laser hardening technique primarily requires a heat source model, which properly defines the laser intensity distribution on the inner surface of the holes as a function of the processing parameters, hole geometry, and parameters of the applied laser beam. The influence of the beam inclination on the intensity distribution was extensively discussed in work [1]. In the current study, we adapted the suggested approach to the laser hardening of holes. Fig. 2 shows the irradiation area inside the hole. The laser energy is evenly absorbed along the entire circumference. As mentioned earlier the location of the highest intensity point does not match the geometrical center of the irradiated area if the material surface is outside the laser focal plane ($h \neq 0$ in Fig. 1).

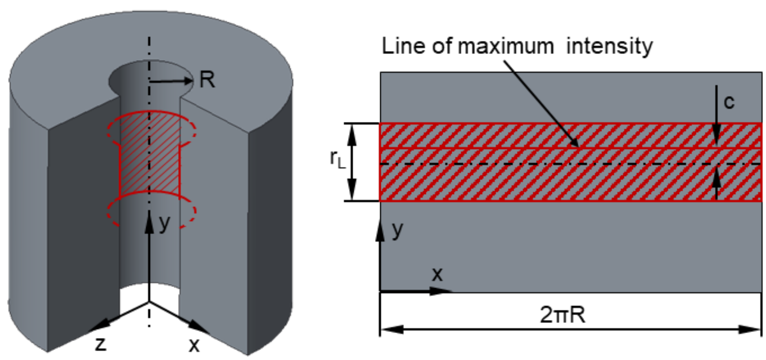

Fig. 2 Energy absorption inside holes

The geometrical parameters of the irradiated area can be calculated using the equations suggested in [1].

$$r_L = \sqrt{\frac{w_0{}^2+\theta^2 h^2}{\cos^2\alpha-\theta^2\sin^2\alpha} + \frac{(\theta^2 h\sin\alpha)^2}{(\cos^2\alpha-\theta^2\sin^2\alpha)^2}} \quad (1)$$

$$c = \frac{\theta^2 h\sin\alpha}{\cos^2\alpha-\theta^2\sin^2\alpha} \quad (2)$$

where α is the beam incidence angle, h is the distance to the focal plane, θ is the divergence half-angle of the beam and w_0 is the beam waist. The asymmetric intensity distribution was captured using the same principle as in the well-known double ellipsoidal model [6]. One half of the source is based on one ellipsoid and the other half on another ellipsoid. The surface heat source model for the two-dimensional axisymmetric FE model (Fig. 3) is then

$$q(x,y) = (2-f_2)\cdot\frac{\sqrt{2}\cdot P\cdot\eta}{\sqrt{\pi}\cdot r_{L1}\cdot 2\pi R}\cdot exp\left[-2\cdot\left(\frac{y^2}{r_{L1}{}^2}\right)\right] + f_2\cdot\frac{\sqrt{2}\cdot P\cdot\eta}{\sqrt{\pi}\cdot r_{L2}\cdot 2\pi R}\cdot exp\left[-2\cdot\left(\frac{y^2}{r_{L2}{}^2}\right)\right] \quad (3)$$

where the radius of the first r_{L1} and second r_{L2} ellipsoids are

$$r_{L1} = r_L - c \tag{4}$$

$$r_{L2} = r_L + c \tag{5}$$

and the coefficient f_2 is

$$f_2 = \frac{2}{1+\frac{r_{L1}}{r_{L2}}} \tag{6}$$

The heat efficiency coefficient depends on many parameters such as wavelength, polarization, surface roughness, surface contamination, formation of the oxide layer and therefore cannot be normally calculated precisely and should be determined experimentally. The heat efficiency coefficient was found to be 0.75 for the current research. The open-source software GMSH was used for meshing. The meshing strategy is shown in Fig. 3. All boundaries experience heat exchange with the ambient. The contact with the clamping device was neglected. Mesh convergence analysis was done to ensure mesh-independent computational results. The FE computations were performed using the open-source FEniCSx software. The FEniCSx implementation was successfully verified by comparing the results with the ones obtained using Ansys. Regarding the mathematical formulation required for FEniCSx please refer to work [1].

Additional subroutines have been added to calculate the hole radius, incidence angle, and distance to the focal point at any time step during simulations. The optimization algorithm to determine the required laser power is shown in Fig. 4. The peak temperature on the inner surface is assessed after each simulation step and compared to the target temperature, T_R. Based on this comparison the laser power is set for the next step.

The hardness model was established using physical simulations. The Gleeble-samples were heated up to various peak temperatures and cooled down at different rates. The hardness of the achieved microstructures was measured. In the simulation model, the hardness is calculated directly as a function of the temperature cycle. In detail, this approach is described in [7–9].

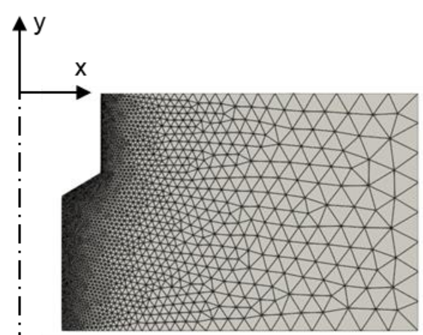

Fig. 3 Axisymmetric two-dimensional FE model (complex hole)

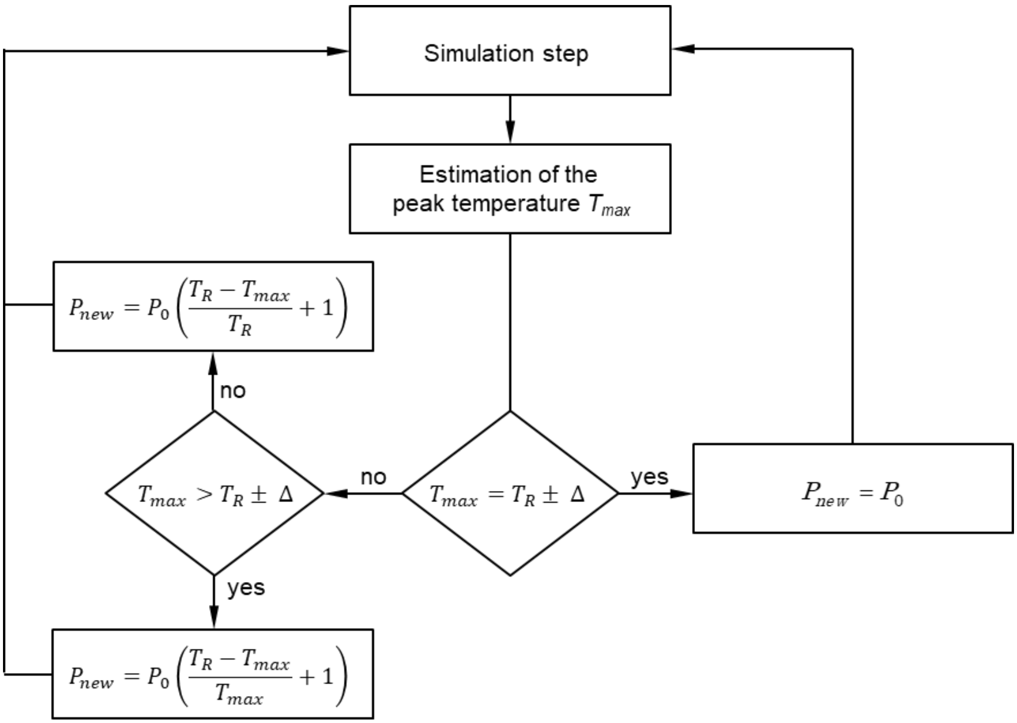

Fig. 4 Optimization algorithm

RESULTS AND DISCUSSION

The developed FE model allows computation of full temperature history during laser hardening of the holes. Fig. 5 shows computed temperature cycles (dashed lines) and hardness versus measured ones for the simple hole.

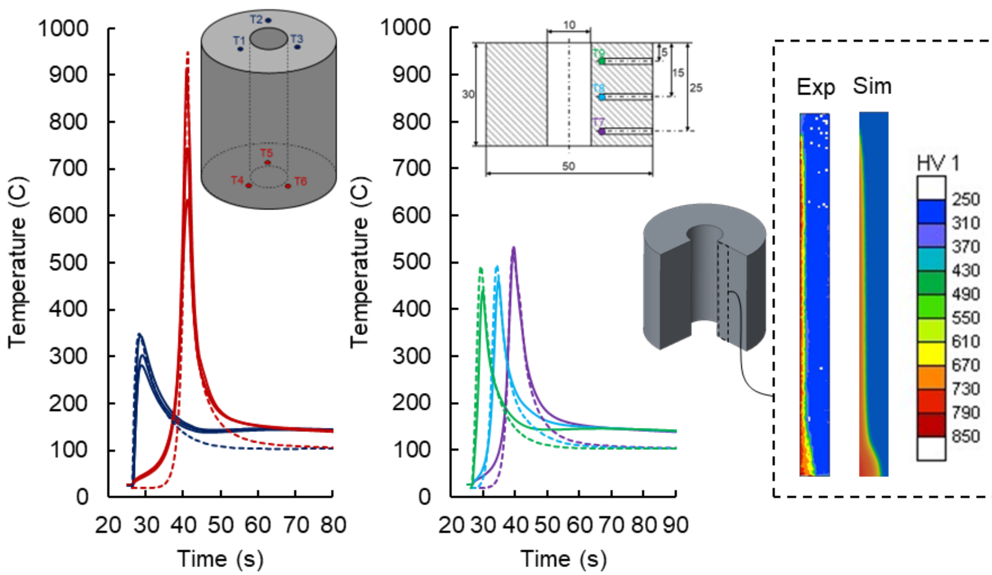

Fig. 5 Validation of the simulation model

As can be seen, the computed maximum temperatures, heating, and cooling rates as well as the hardness distribution are in good agreement with the measurements, thus validating the model. This validated model was used to compute the laser power for the hardening of the complex hole. The scanning speed was set to 2 mm/s. Fig. 6 shows the expected (computed) and real (measured) hardness profiles in the complex hole. The simulation showed that the hardening of the area next to the transition is challenging. The same area could not be hardened during the experimental trials in good agreement with the simulation. Since the irradiated area becomes large due to the beam inclination, melting of the sharp edges and hardening of the surfaces close to those edges cannot be controlled separately. The power is reduced to avoid the edge melting and at the same time, the temperature becomes insufficient to harden the material close to the edges. The developed simulation model makes it possible to identify the limits of the process and to show in advance whether the hole can be uniformly hardened. For the holes, which are is suitable for this hardening technique, the model can be used to determine the optimal processing parameters.

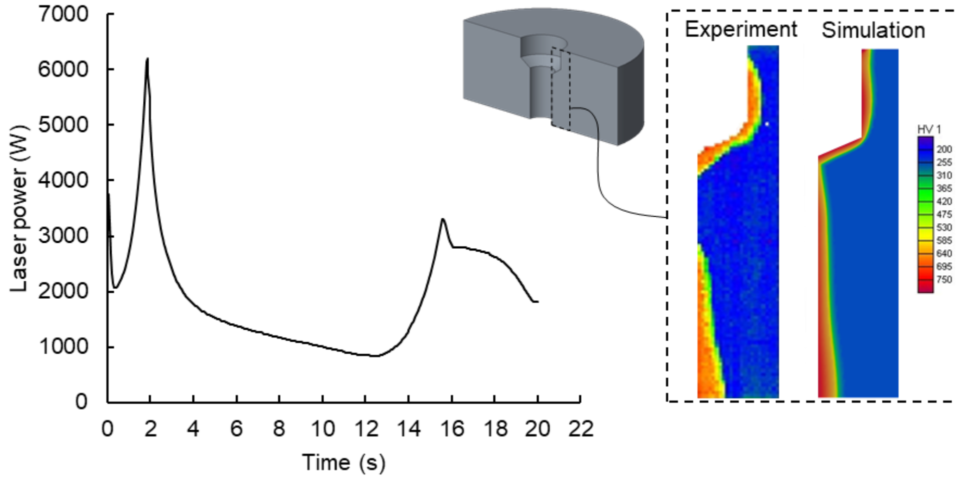

Fig. 6 Computed optimal laser power for hardening of the complex hole (left). The computed versus measured hardness profile (right)

CONCLUSIONS

The study presented a numerical model for laser hardening of holes. The heat source model calculates the intensity distribution on the inner surface as a function of beam parameters (beam waist, divergence half-angle), processing parameters (laser power, incidence angle, distance to the focal plane), and the circumference of the hole. The implementation was done using open-source FE code. The simulation allows optimization of the processing parameters, making the new hardening technique more attractive to the industry.

APPENDICES AND ACKNOWLEDGEMENTS

This work was supported by BTU Graduate Research School (Conference Travel Grant); German Federal Ministry for Economic Affairs and Climate Action [grant no. ZF4259517US9].

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