The influence of laser hardening on the performance of steel 30KHGSA by the finite elements method

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Abstract. The article presents the results of the computer simulation in the Solid Works using the method of finite elements. In the research described a computer model that was tested on experimental sample that was made of steel 30KHGSA. Data of thermal processes and residual stresses in a sample after laser processing were received during the research. Calculations of the depth of the hardened zones and the strength of the prototype were obtained during the simulation. The process of laser hardening a "Water jet engine sleeve" was simulated in the research. The results and conclusions obtained during this work are given in the conclusion.

1. Introduction
Requirements to the quality of manufactured machine parts are continuously increasing. They stipulate using highly effective methods of processing and improvement of technological processes. Applying of laser hardening is one of the most promising and productive methods. The main advantages are: reducing the duration of the thermal cycle of hardening, locality impact, no deformation and high processing speed and efficiency [1,2].

Modeling processes of heat treatment will allow to solve the problem of structurization and modernization surfaces in real products [4]. Modeling of laser hardening will allow considering a large number of factors with different nature (thermal, physic-chemical, etc.). The analysis of these factors will ensure adequate forecasting of the processes of hardening the structure and improving the qualities of the surface.

The computer model of a laser hardening process was developed for steel 30KHGSA [5]. The steel is pre-tempering and annealing which increases its abrasion resistance, strength, plasticity. The advantages of steel are the possibility to temper and anneal further. This steel is cheap enough, as it doesn’t have expensive additives. The steel is highly weldable, resistant to corrosion and impact, it also has a moderate toughness. The steel is mostly applied in aviation industry, but due to high consumer properties it is widespread in other branches of engineering [5].

This paper discusses examples of the application of the computer simulation for the selection of conditions and modes of laser thermal hardening and study of its influence on performance characteristics of parts, enable optimizing the technological process of laser hardening.
Computer simulation will allow to reduce the cost of research, to get the automatic calculation module of processing modes in the production, and to reduce the time to design and field research on selection of modes.

The aim of this work is to obtain a computer model of laser thermal strengthening of steel 30KHGSA which is able automatically to select the processing modes for different parts, as well as identifying improvements to operational characteristics from the use of this method of processing.

2. Model description

Computer modeling of laser hardening was worked out on a plate with a thickness of 5 mm made of steel 30KHGSA.

This research was conducted to check the truthfulness computer model and assessment of its performance. Computer simulation was carried out by the finite element method in Solid Works to solve three tasks:

- Calculation of the temperature fields in the material of steel 30KHGSA, taking into account the spatial and temporal characteristics of laser radiation.
- Determination of the effect of laser hardening on the performance of the material and the influence of residual stresses in the sample.
- Determination of the optimal conditions of processing for a specific technological process.

Temperature field’s formation research with the continuous laser radiation in three dimensional statements was carried out in the program Solid Works Simulation. The type of analysis was thermal, with the selection of the transition process. Formulas of the temperature fields were used for the process of propagation of heat instantly a localized source emitted at the surface of a semi-infinite body (1).

\[
T(R,t) = \frac{2Q}{c\gamma(4\pi at)^{3/2}} e^{-\frac{R^2}{4at}} + T_0
\]

and the basic amount of heat distributed in the body in a certain period of time (2) [1].

\[
dT(R,t-t') = \frac{2dQ}{c\gamma[4\pi a(t-t')]^{3/2}} e^{-\frac{R^2}{4a(t-t')}}
\]

Where in formulas (1) and (2),
- \(T\) – the temperature in a considered point;
- \(t\) – time counted from the moment of introduction of heat;
- \(R\) – the distance from the heat source \(Q\) to the points of the body;
- \(a\) – thermal diffusivity;
- \(T_0\) – the ambient temperature;
- \(c\gamma\) – heat capacity material;
- \(Q\) – quantity of heat;
- \(t-t'\) – a period of time [1].

The material properties of the sample corresponded to the steel 30KHGSA. Plastic properties of steel 30HGSA such as modulus of elasticity \(E\), Poisson's ratio \(\nu\), tensile strength \(\sigma\) and yield strength \(\sigma_y\) were used for the prototype (plate). The prototype is divided into 10 zones 1 mm. For each zone in a certain time used laser radiation acting on the surface. Simulation of heating continuous laser radiation applied on the plate with a total duration of 0.5 s with a time increment of 0.05 seconds. The cooling time of the workpiece was – 1 s. The total spot size of the laser radiation was 1×1 mm. On each plot the distribution of the laser energy density was taken evenly. The convection coefficient was used in simulation with room temperature of 300 K. Laser radiation power need to be programmed in Solid Works during the simulation. The optimum power range of laser hardening is 800 to 2500 Wt for the
required structure of the material [3]. For the model was created standard high density grid which is allowed to simulate the fast process of laser hardening with sufficient accuracy.

3. The results of the experiment
According to the results of modeling were obtained the plot figure 1, which shows the movement of the laser beam, heat distribution in the underlying layers of material, the depth of thermal influence and the heating temperature of a material by laser radiation. It should be noted that in the simulation of thermal processes were carried out iteration for selecting the optimal heat range. It is necessary to pay more attention on the iterations in Solid Works environment because of model does not reflect the true result without it.

![Figure 1. Heat plot, with visible movement of the laser beam and the heat distribution around the prototype.](image1)

Then, the residual stress of a test sample determined after exposure to laser radiation. For this, in simulations, the thermal effect of laser radiation programmed on each heat affected zone at a particular time and incorporated the type of fastening. The fixation was carried out on the sides of the plate as seen as in figure 2. In the simulation on the prototype can be seen compressive and tensile stresses, which can show the strength of the material in zone of laser irradiation. Similarly, it is necessary to pay more attention the iteration of the selection of an optimum range of residual stresses with the aim of obtaining accurate results.

![Figure 2. Plot of residual stresses after laser irradiation on the prototype.](image2)
According to the results of computer modeling in Solid Works environment was measured the depth of the hardened zones and calculated the strength of the prototype under different conditions of laser treatment (table 1).

Table 1. Characteristics of heat-affected zones (depth, strength).

| Cipher zone | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-------------|------|------|------|------|------|------|------|------|------|------|
| Laser radiation power $P$, W | 2500 | 2000 | 1500 | 1200 | 1100 | 1050 | 1000 | 900  | 850  | 800  |
| Depth heat affected zone, mm | 3.56 | 3.22 | 3.170| 2.766| 2.554| 2.243| 1.994| 1.98 | 1.87 | 1.83 |
| Strength N/mm² | 2125 | 1922 | 2228 | 2318 | 2234 | 2155 | 2147 | 2098 | 1970 | 1889 |

Data obtained by computer simulation, used as a base for conducting practical confirmation of the truthfulness of the model. Practical confirmation consists of 3 stages:
- Testing technological modes of laser thermal strengthening on a plate made of steel 30KHGSA.
- Measure the depth of the hardened layer and the hardness of zones with different modes of processed.
- Study the microstructure on the different modes of processed.

To confirm the truthfulness of the model and to estimate the selection of the modes of laser treatment, the results obtained during the practical part of the experiment were compared with the simulation results.

4. Verification

The experimental research was carried out on laser robotized complex of the Russian development which includes:
- Ytterbium fiber laser power 3 kW production of company IRE Polus (Fryazino Moscow region);
- FLW D50 laser head with lens Ø 50 mm production of company IRE Polus (Fryazino Moscow region);
- Interface, the cockpit door, automatic disabling the laser radiation production of Engineering center (Vladimir);
- A six-axis robot and two-axis positioner, production of company Fanuc.

For the identification deviation between theoretical and experimental data, and identification of the error model were compared the results of computer simulation and experiment. Table 2 shows the comparison of the depths of heat-affected zones and the strength of the surface depending on the modes of laser hardening.

The experimental results practically coincide with results of computer simulation as you see from table 2. The average deviation in depth of heat-affected zones is 3.9% and the average deviation for strength is 4.6%. It should be noted that the results of verification while using laser radiation power 2600 and 2000 W their average deviation higher than the others. The reason for this was overheating of the part and on the surface appeared melt. Also it can be concluded that the temperature plots and plots of residual stresses of the prototype show the correct values consistent with the values obtained as a result of laser hardening. This proves the adequacy of the model and makes it workable, what enables to use this model in the calculation of the modes of laser hardening of the real details.

For example, was selected the "Water jet engine sleeve" detail made of steel 30KHGSA. New modes and conditions of processing were used to simulate the process of laser hardening on Sleeve. Plots of distribution of temperature fields and residual stresses of a 3D computer model of the part the Sleeve was obtained in Solid Works environment (figure 3).
Table 2. Comparing computer models and experimental data.

| Cipher zone                      | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|----------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Laser radiation power $P$, W     | 2600| 2000| 1500| 1200| 1100| 1050| 1000| 900 | 850 | 800 |
| Depth heat affected zone in      |     |     |     |     |     |     |     |     |     |     |
| modeling, mm                    |     |     |     |     |     |     |     |     |     |     |
| Depth heat affected zone in      |     |     |     |     |     |     |     |     |     |     |
| experiment, mm                  |     |     |     |     |     |     |     |     |     |     |
| Deviation, %                    |     |     |     |     |     |     |     |     |     |     |
| Strength in modeling, N/mm$^2$   | 2125| 1922| 2228| 2318| 2234| 2155| 2147| 2098| 1970| 1889|
| Strength in experiment N/mm$^2$  | 1920| 1775| 2145| 2345| 2310| 2310| 2225| 2200| 2100| 1920|
| Deviation, %                    | 9.0 | 7.0 | 3.4 | 1.2 | 3.3 | 6.8 | 3.6 | 4.7 | 6.2 | 1.7 |
5. Conclusion
In the conducted research were obtained:

1. Models of thermal plots, which shows: the depth of thermal influence and heat temperature of a material by laser radiation.

2. Model plots of residual stress that can determine the strength characteristics of material in zone of laser irradiation.

3. The good tests results of computer models were obtained by the verification in experiment.

4. The computer model of laser thermal hardening of steel 30HGSA which can obtain optimal processing modes and strength characteristics of the part by 3D simulation.

5. Results that can help to develop a module for selection of technological modes of laser handling in the laser robotic complex.

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