Thermal relaxation of residual stresses, arising in heat-resistant materials after application of laser shock processing technology

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Abstract. The study of thermal relaxation of residual stresses in heat-resistant steel 37Kh12N8G8MFB (GH2036) after the application of laser shock processing technology and subjected to annealing at temperatures up to 650°C. For estimating residual stresses and their relaxation from the action of high temperature a calculation model has been proposed. The high efficiency of the proposed technology for hardening the surface layers of thermally loaded material was shown.

1. Introduction
Parts of aircraft engines are subject to high temperatures and cyclic loads. The destruction of such products begins with the appearance of microcracks on the surface thereon. To increase the resistance of the surface of the material to the nucleation and development of cracks, various surface treatment methods are used, for example deep rolling or bead-blasting treatment, which create residual compressive stresses therein, preventing the occurrence of destructive processes on the surface of the product. The impact of high temperatures on the product leads to thermal relaxation of surface stresses. One of the modern effective ways to increase the fatigue characteristics of metals is the technology of laser shock processing (LSP).

There are a few works devoted to the study of the mechanical properties of highly-alloyed heat-resistant steels when exposed to high temperatures after applying LSP. In this regard, the aim of this work is to study the effect of high temperatures on residual stresses after applying LSP in highly-alloyed heat-resistant steel 37Kh12N8G8MFB.

2. Materials and research methods
For research, a sample in the form of a plate made from the highly-alloyed heat-resistant steel 37Kh12N8G8MFB (GH2036) with dimensions of 30x30x5 mm has been used, which, after applying LSP, has been annealed for 60 minutes at temperatures of 200, 300, 400, 500, 600, and 650°C. LSP technology consists of three stages. First, black ink with a low evaporation temperature is applied to the treatment space, then a transparent layer of water and thereafter the treatment surface is exposed to a laser beam with concentrated energy (figure 1). The laser pulse heats the paint, causing it to vaporize and form a plasma that is constrained between the transparent layer and the treatment surface. A pressure shock wave arises, deforming the material being processed from the surface to the depth of the body and with the creation of residual stresses therein [1].
Figure 1. LSP technology scheme: (a) – shock pressure wave occurrence; (b) – plastic deformation in surface layers; (c) – residual stresses. 1 – laser ray; 2 – water; 3 – black ink; 4 – shock wave; 5 – shock wave progress direction; 6 – plasma; 7 – laser pulse range; 8 and 9 – compressive and tensile plastic deformations; 10 – treated surface relaxation.

Modeling of the process of thermal relaxation of residual stresses after applying LSP was carried out by the finite element method in three stages. At the first stage, the task of dynamic analysis is solved in the LS-DYNA software package, where the strain values from the action of the applied technology are calculated. At the second stage, the obtained strains are used to determine the values of residual stresses, and at the third stage, using as the source data obtained in the previous step, an implicit thermomechanical problem is solved in the ANSYS software package with obtaining thermal relaxation values of residual stresses [2].

The strain rate in the material when applying LSP reaches at least $10^6$ s$^{-1}$, therefore, the Johnson-Cook model was used to calculate stresses [3]:

$$\sigma = \left( A + B\bar{\varepsilon}^n \right) \left( 1 + C\bar{\varepsilon}^* \right) \left[ 1 - \left( T^* \right)^m \right], \quad (1)$$

where $\sigma$ – a von Mises equivalent stress; $\varepsilon$ – an equivalent plastic deformation; $\bar{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$ – a dimensionless equivalent strain rate ($\dot{\varepsilon}_0 = 1.0$ s$^{-1}$); $T^*$ – a homological temperature, which relationship with the absolute temperature $T$ is determined as follows:

$$T^* = \frac{(T - T_0)}{(T_m - T_0)}, \quad (2)$$

where $T_0$ – a room temperature; $T_m$ – a melting point of a specimen material.

The constants of equation (1) for steel 37Kh12N8G8MFB are presented in the table 1.

| Table 1. Johnson-Cook equation constants for 37Kh12N8G8MFB steel. |
|-----------------|--------|--------|
| Constant | Value | Dimension |
| A | 900 | MPa |
| B | 1200 | MPa |
| C | 0.0092 | - |
| n | 0.6 | - |
| m | 1.27 | - |

Thermal relaxation of residual stresses is well described by the Zener-Wert-Avrami model [3]:

$$\frac{\sigma_{res}}{\sigma_{0res}} = \exp[-(At_{a})^m], \quad (3)$$
where $\sigma_{0}^{res}$ – residual stresses before annealing, $\sigma^{res}$ – residual stresses for a given annealing time $t_a$ and at a given annealing temperature $T_a$; $m$ – numerical parameter depending on the relaxation mechanism; $A$ – function dependent on material properties and temperature.

3. The results obtained and their discussion

According to the calculations, the maximum compressive residual stresses after applying LSP are concentrated under the treated surface of the sample at a depth of 0.62 mm and amount to 510 MPa, however, small tensile residual stresses also appear at a depth of 0.58 mm (figure 2).

Figure 2. Dependence of residual stresses on the distance from the treatment surface: (a) – perpendicular to the direction of processing; (b) – parallel to the processing direction. 1 – after applying LSP; 2 – 200°C; 3 – 300°C; 4 – 400°C; 5 – 500°C; 6 – 600°C; 7 – 650°C.

Thermal relaxation of residual stresses after applying LSP occurs under all heat treatment conditions, but compressive residual stresses are present in the surface layers at a temperature of 650°C. Moreover, in a depth of 0.5 mm from the processing surface, the residual stresses are practically zero at the highest annealing temperature. The influence of the heat treatment time comes down to the fact that intense thermal relaxation occurs in the first 30 minutes, then its change is insignificant.

A comparison of the experimental data from the work [4] and the calculations obtained using the proposed models showed a coincidence within a small scatter, which confirms the adequacy of the approaches used (figure 3).

Annealing temperature also affects the distribution of residual stresses. Thus, in zone 1 of (figure 3) residual stresses have a smaller increase in magnitude than in zone 2 which is explained by a sufficiently high temperature in zone 2 to reduce the material’s yield stress and therefore a thermal relaxation of residual stresses.

4. Conclusions

The technology of laser shock processing creates high compressive stresses in the surface layers that remain in the surface during heat treatment of the material with temperatures between 200°C and 650°C. Thermal relaxation of the material after applying LSP substantially depends on the time and temperature of annealing and the residual stresses on the surface of the sample relax faster than in its depth.

The research of one of several mechanisms of thermal relaxation has been conducted. To study other ones a more in-depth study of changes in the microstructure of the material with large residual stresses when exposed to high temperatures is required.
Figure 3. Dependence of residual stresses on annealing temperature: 1 – calculation results; 2 – work’s experimental results [4].

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