Influence of laser shock processing technology on a fatigue life of stainless steel specimen

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Abstract. The influence of laser shock processing technology on the fatigue life of 03Kh22N6M2 stainless steel has been investigated. The values of residual stresses in the test material were measured by using calculation methods and comparative curves of fatigue life were constructed. The high-efficiency of the examined technology’s application to increase the fatigue life of stainless steel was revealed.

1. Introduction

To improve the fatigue properties of materials used in aviation and aerospace engineering, one of the effective ways of influencing the functional surfaces of the products is a laser shock processing (LSP). Thus, both the mechanical and tribological properties of the metals are enhanced [1]. When using LSP, shock waves from the surface to be processed pass deep into the material, creating compressive residual stresses with a high dislocation density in the surface region.

The effectiveness of increasing fatigue properties using LSP significantly depends on the thickness of the product and the presence on the surface of stress concentrators such as holes and recesses. There are practically no works dedicated to taking heed of these circumstances.

The aim of this work is to assess the degree of increase in fatigue properties using LSP technology when processing stainless steel 03Kh22N6M2.

2. Research method

Fatigue properties were evaluated by the Finite Element Method in two stages. At the first stage, a finite element model of the specimen with a cutout (figure 1a) has been constructed in the ABAQUS/Explicit package and the residual stresses have been calculated. Using the data obtained at the first stage, the value of fatigue strength in the FE-SAFE finite element package was estimated at the second stage.

Specimens with three thicknesses of 2, 3, and 4 mm were used to assess the influence of the specimen thickness on the LSP efficiency, wherein the middle part of the specimen of 50×30 mm in size was processed according to the scheme shown in (figure 1b).

The load on the specimen was applied in the form of a pressure pulse with an amplitude of 5.2 HPa and a duration of 200 msec. At such time, the strain rate effects in the material are not less than...
10^6 s^{-1}, therefore, to estimate the stress-strain state in the specimen, the Johnson-Cook model has been used for plastic deformation of the material [2]:

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

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

\[
T^* = \frac{(T - T_0)}{(T_m - T_0)},
\]

where \(T_0\) – a room temperature; \(T_m\) – a melting point of a specimen material.

![Figure 1. Specimen drawing for the fatigue studies (a); scheme of exposure to the LSP sample surface (b).](image)

For 03Kh22N6M2 stainless steel, material constants of equation (1) are given in table 1.

| Table 1. Johnson-Cook equation constants for 03Kh22N6M2 steel. |
|---|---|---|
| Constant | Value | Dimension |
|  |  |  |
| \(A\) | 520 | MPa |
| \(B\) | 840.5 | MPa |
| \(C\) | 0.0124 | - |
| \(n\) | 0.1904 | - |
| \(m\) | 0.965 | - |

The assessment of the fatigue behavior of the material was evaluated using the deformation approach. The deformation fatigue curve was defined by the Coffin-Manson equation where fatigue failure is described by a change in strain in the loading cycle [3]. The Coffin-Manson equation constants are presented in table 2.

| Table 2. Coffin-Manson equation constants for 03Kh22N6M2 steel. |
|---|---|---|
| Parameter | Value | Dimension |
|  |  |  |
| \(\sigma'_f\) | 1443 | MPa |
| \(\varepsilon'_f\) | 0.549 | - |
| \(b\) | -0.125 | - |
| \(c\) | -0.551 | - |
For subsequent comparison of the numerical results obtained, a load was applied to the specimen material corresponding to the experimental data from work [4] after evaluating the distribution of residual stresses therein. Then, the data on the obtained stress-strain state were used in the FE-SAFE package to determine the value of fatigue life. Specimen behavior modeling during fatigue testing was carried out under soft loading with a cycle amplitude of 300 MPa and a cycle asymmetry coefficient of \( R = 0.1 \) and completely corresponded to the experiment described in work [4]. For comparative analysis, fatigue modeling was also performed without using the LSP specimen.

3. Results and discussion

The value of the maximum residual stresses before applying the LSP specimen of 4 mm thickness was 475 MPa at a depth of 0.25 mm from the surface, which acted parallel to the direction of processing. After applying the LSP, the maximum residual stresses were – 765 MPa at a depth of 0.18 mm, which acted perpendicular to the direction of processing.

The fatigue life of the specimen was increased when applying the LSP technology with a decrease in its thickness from 79% at 4 mm to 305% at 2 mm compared to a specimen without the LSP (figure 2).

![Figure 2](image-url)

Figure 2. Dependence of fatigue life on the thickness of stainless-steel specimens. 1 – before applying LSP, 2 – after applying LSP.

Fatigue curves for a 4 mm thick specimen constructed for soft loading with cycle amplitudes of 287.5 MPa and 275 MPa showed an increase in fatigue life by 297% and 402%, respectively (figure 3). This allows us to state that a decrease in the amplitude of loading leads to an increase in the efficiency of LSP. The experimental points shown in (figure 3) from the work [4] almost coincided with the calculated fatigue curves, which showed the adequacy of the developed models and approaches.

4. Conclusions

LSP leads to the creation of significant compressive residual stresses in the near-surface region to a considerable depth. The effectiveness of LSP for increasing fatigue life depends on the thickness of
the processed material and the magnitude of the amplitude of cyclic loading: the smaller they are, the higher the effect, which can reach about 402% compared with untreated material.

![Figure 3. Estimated fatigue curves. 1 – without treatment, 2 – after applying LSP, • - experimental data from [4].](image)

The increase in the fatigue characteristics of the material is associated with the rise in microhardness and the creation of high compressive stresses that prevent the generation and propagation of cracks in the surface layers of the material.

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