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Complex-shaped hardened parts fatigue limit prediction according to the witness sample study results

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Abstract. The aim of this study is to investigate the possibility of assessment of the effect of preparatory surface plastic deformation by hydraulic shot blasting on the fatigue strength of cylindrical parts of different diameters (10-40 mm) of D16T alloy with circular notches of semicircular section, based on measurements of residual stress (initial deformations) of a witness sample. The residual stresses of smooth parts were used to calculate the residual stresses of parts with stress raisers. These were used to predict the increment of these parts fatigue limit caused by hardening hydraulic shot blasting. It was found that the highest compressive residual stresses in the smooth parts obtained through calculations differ from the observed values not more than by 7%, and in notched parts by 8%. Using the criterion of mean integral residual stresses, we calculate the increments of the fatigue limit of parts due to superficial hardening. The discrepancy between the experimental and calculated increment values of the fatigue limit of hardened parts with raisers does not exceed 17%.

Key words: Residual stresses, criterion of mean integral residual stresses, fatigue limit, surface hardening.

1. Introduction

Improvement of reliability and durability of machine parts is one of the most important problems, a full and comprehensive solution of which accompanies the production and operation of all products of modern technology. It is known that the main type of destruction of machine parts is fatigue failure that leads to severe consequences, as this type of failure develops suddenly.

One of the most important characteristics of machine parts by their fatigue strength is their fatigue limit, the predicted value of which largely depends on the reliability of the calculations performed on the stages of design and development of design documentation. This is why the selection of design, materials, geometric parameters of parts with stress concentrations, and their production techniques pose very sophisticated challenges.

Witness samples are commonly used to monitor the processing procedure of part hardening by various methods of superficial plastic deformation (SPD). These samples of a certain shape and size undergo the whole technological cycle of processing together with a standard part. Generally, processed parts are costly and labor-intensive products, so this non-destructive method of quality control hardening has an undeniable advantage over other methods, primarily in terms of cost efficiency and especially in mass production.


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The use of witness samples is based on the assumption that the part and the witness sample, after having been processed together, receive the same initial strain at SPD. We studied the results of fatigue tests and the results of experimental determination of residual stresses of cylindrical samples of D16T aluminum alloy, given in [1]. Figure 1 shows a sample with the external diameter D, the hole diameter *d*, and the diameter of the weakest section of the D_1 sample.

Before notching, smooth specimens were subjected hydraulic shot blasting (HSB) for 8 minutes with 2 mm shots in oil at a pressure of 0.19 MPa (D16T alloy). As witness specimens in a study of the above-described batches of specimens, we used cylindrical sleeves with the dimensions of 51.5x45 mm/mm, which are commonly used for determination of residual stresses through the depth of the hardened superficial layer by the method of rings and strips [2].

2. Residual stresses' calculating

The computational part of the study was carried out by the method of finite element modeling, using PATRAN/NASTRAN software package. Finite-element models in an axially symmetric form represented a quarter section of the sample, with imposition of appropriate boundary conditions. In the simulation, a flat triangular 2D-Solid element with six nodes was used.

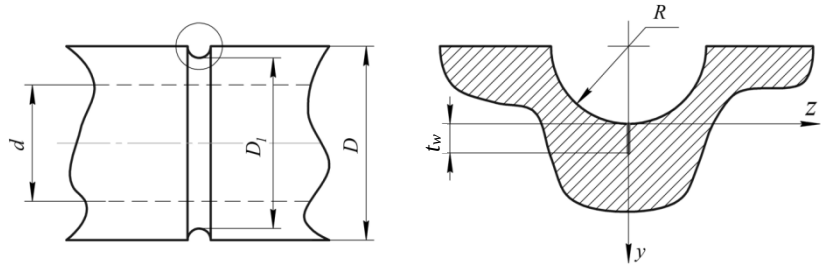


Figure 1. Cylindrical specimen with a non-propagating fatigue crack

When determining the initial strain, we used the observed distribution of the axial σ_z residual stresses in thickness *a* of the hardened superficial layer of a witness sample (sleeve) as the source data. It was established that, under the assumptions made, three iterations are sufficient to achieve agreement of the distribution of the values of the axial residual stress, calculated on the basis of the initial strain and the experimental values in the witness specimen.

The next stage of the calculations was performed using finite-element models of the smooth test specimens, on the basis of the initial deformation of the witness specimen. It is known [1, 4] that axial residual stresses are principal in assessment of the incremental fatigue limit. For that very reason the comparison of calculated and experimental distributions of residual stresses through the depth of the hardened superficial layer for the test specimens was performed for the axial component. The experimental results [1] and the calculation of distribution of residual stresses σ_z through the depth of the superficial layer for the smooth test specimens of D16T alloy are shown in Figure 2.

The maximum difference between the calculated and experimental values of the largest axial compressive residual stress was 10% at *D/d* = 10/0 mm/mm, in other cases, the difference did not exceed 2%.

Prior to fatigue tests, circular notches of semicircular section with the radius *R* = 0.3 mm were made on both non-hardened and hardened smooth samples. Axial σ_z residual stresses in thickness *a* of the thinnest (weakest) section of the notched samples, were determined by analytical and numerical methods, using calculated distributions of residual stresses of smooth specimens.

It should be noted that the residual stresses calculated with the two methods were in good agreement.

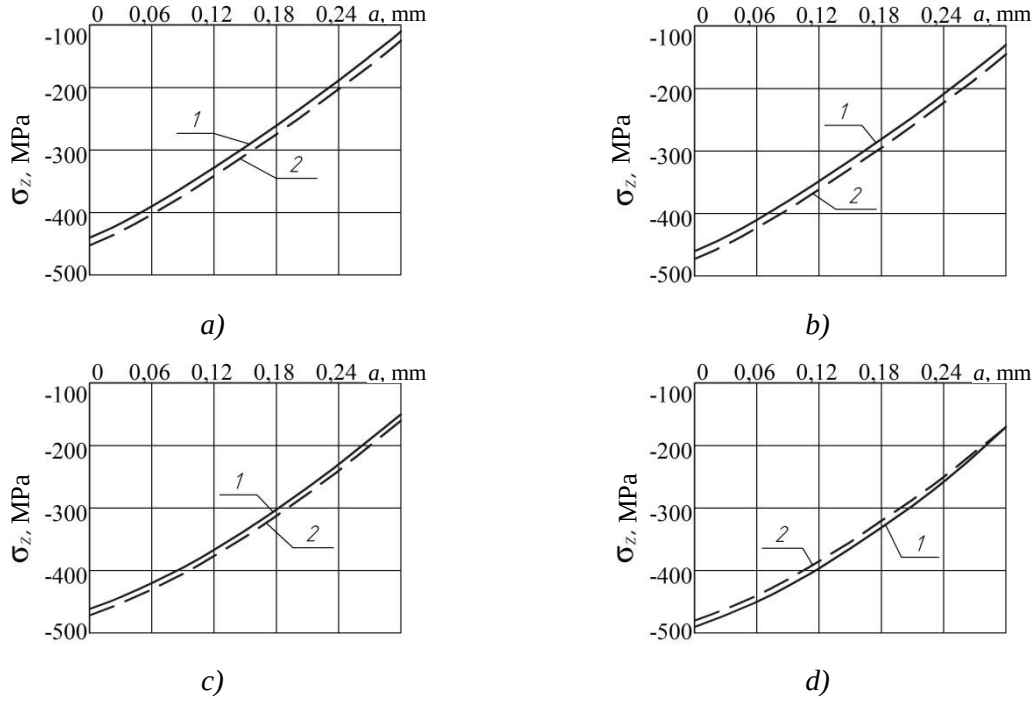


Figure 2. The distribution of axial σ_z residual stresses after HSB determined by experimental (1) and calculation (2) methods in smooth samples of D16T alloy with the following diameters: *a* – *D* = 10 mm, *b* – *D* = 15 mm, *c* – *D* = 25 mm, *e* – *D* = 40 mm

3. Residual stresses' rating

Prediction on the effect of superficial hardening on the increment of the fatigue limit of notched parts at bending in the case of a symmetric processing cycle $(\Delta\sigma_{-1})_{calc}$ was made based on the criterion of mean integral residual stresses $\overline{\sigma}_{\text{res}}$ [12]

$$(\Delta\sigma_{-1})_{calc} = \overline{\psi}_{\sigma}\left|\overline{\sigma}_{res}\right|, \tag{1}$$

where $\overline{\psi}_{\sigma}$ is the factor of effect of surface hardening on the fatigue limit at bending according to the criterion $\overline{\sigma}_{\text{res}}$;

$$\overline{\sigma}_{res} = \frac{2}{\pi}\int_0^1 \frac{\sigma_z(\xi)}{\sqrt{1-\xi^2}}\,d\xi; \tag{2}$$

$\sigma_z(\xi)$ are axial residual stresses in the weakest section of the sample (part) with a stress raiser through the thickness of the superficial layer a; $\xi = a/t_w$ is the distance from the surface of the weakest section of the sample (part) to the layer in question, expressed as a fraction of t_w; t_w is the critical depth of a non-propagating fatigue crack occurring in a hardened sample (part) with a stress raiser at operation at the fatigue limit (Figure 1).

The critical depth t_w of a non-propagating fatigue crack was determined from the dependence, established on the basis of numerous experiments described in [1-5]

$$t_w = 0.0216D_1\left[1 - 0.04\left(\frac{d}{D_1}\right)^2 - 0.54\left(\frac{d}{D_1}\right)^3\right], \tag{3}$$

where D_1 is the diameter of a dangerous section of the sample (part) with a stress raiser.

The values of the criterion of mean integral residual stresses $\overline{\sigma}_{\text{res}}$ were calculated using the formula (2), and the thickness of the superficial layer of the weakest section of notched samples t_w using the

calculated residual stress distribution. The factor $\overline{\psi}_\sigma$ of the effect of superficial hardening on the fatigue limit of the criterion $\overline{\sigma}_{\text{res}}$ was calculated using the dependence established in [19]

$$\overline{\psi}_\sigma = 0.612 - 0.081\alpha_\sigma , \quad (4)$$

where α_σ is the theoretical stress concentration factor, which was determined using diagrams from the reference book [4].

Further, according to the formula (1), the values of the increment of the fatigue limit $(\Delta\sigma_{-1})_{calc}$ at HSB hardened notched samples were calculated and compared with the experimental values $(\Delta\sigma_{-1})_{\text{exp}}$ given in [5].

4. Conclusions

The difference between the calculated and experimental values of the increment of the fatigue limit does not exceed 17%. Therefore, using the results of the determination of residual stresses in witness samples, it is possible to predict the fatigue strength of superficially hardened parts in conditions of stress concentration with a precision acceptable for high-cycle fatigue.

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