DAMAGE ACCUMULATION IN STRESS CONCENTRATION ZONES OF PARTS WITH HARDENED SURFACE UNDER LOW CYCLE TENSION-COMPRESSION AND BENDING

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Abstract: This paper provides experimental and analytical evaluation of durability of nonhardened and hardened by EMT specimens of grade 45 steel with stress concentrators, under low cycle tension-compression and pure bending. For both type of loading modes was carried out durability analysis, taking into account fatigue and quasi-static damage depending on loading level and number of s. Stress and strain concentration coefficients were calculated by analytical and finite element methods (FEM) under elastic plastic cyclic loading. Performed analytical investigation showed, that suggested method for quasi-static and fatigue damage summation, when accumulated plastic strain and the width of the hysteresis loop are taken into account, provides a very good agreement with the experimental results at stress concentration zones of surface-hardened parts under tension-compression and bending.

1. INTRODUCTION

Despite the long-term investigation history of metal fatigue these problems and nowadays still are of great importance. In exploitation conditions some parts of modern machines and machinery are working under elastic-plastic cyclic loads.

Exploitation durability of the parts in most cases depends not on entire part, but only on the surface layer properties. One of the efficient methods to increase durability of the parts, is hardening of the surface layer, because, in most cases, crack initiates exactly at the surface due to insufficient quality of the surface, exploitation damage, or of working environment influence. One of the methods for surface strengthening is electromechanical treatment (EMT). Electromechanical treatment was used by Bagmutov et al (2005), Daunys et al (2004) and Barry and Byrne (2002). Electromechanically strengthened surface is influenced by concentrated thermal flow and gets deformed plastically. Such complex influence on surface is the main point of electromechanical treatment technology. A flow of concentrated heat is obtained when electrical current passes tool-part contact. Due to high amperage current (100 - 1200 A) surface may be heated above the 900°C temperature. Surface heating and deformation produces more fine-grained microstructure of the steel. Because the process is rapid and recrystallization is not still occurring, specific fine-grained hardened surface layer, i.e. "white" layer, is obtained. "White" layer consists of significantly deformed blocks, with existing structureless martensite. Electromechanically hardened layer is highly resistant to abrasive wear. Hardening by alternating current produces hardened layer of segmented macrostructure, i.e. with alternate areas of hardened and tempered steel. Such surface is characterized by good tribological properties. Surface of the hardened by EMT parts is significantly more hard, more wear and fatigue resistant than surface hardened by common thermal treatment. EMT is widely applied for surface strengthening of new and renewable machine parts.

In machine parts and structural elements often stress and strain areas are distributed nonuniformly, i.e. stress strain concentration zones appear. An attempt completely to avoid stress concentration is impossible. Especially, as concentration zones appear because of shape and geometry peculiarities of structural parts. Low cycle loading investigations in stress strain concentration zones, taking into account cyclic characteristics of the material, the shape of concentrators, character of nominal loads and asymmetry of loading cycles, have been analyzed by Macutov (1981) and Daunys and Narvydas (1999) and discussed in other publications.

Three main modes of parts' loading are known: tension-compression, bending and torsion. During tension-compression normal stresses are uniformly distributed across the entire cross-section of loaded element. Experimental technique applied for this loading mode is well analyzed and most commonly used.

Real exploitation conditions are those causing some parts of the mechanisms to experience cyclic bending. Under particular working regimes, machinery can experience momentary overloads. Because of such load, the proportional limit is exceeded, the durability of these parts may decrease, i.e. low cycle fatigue may occur.

In papers by Daunys and Rimovskis (2006) and Stowell (1968) works analyzed low cycle tension-compression and pure bending by means of results experimental and analytical investigation. This investigation, showed that low cycle strength and durability of the parts depends not only on cyclic properties of the chosen material, but also on loading mode. Because the damage, under tension-compression is accumulated in entire cross-section of the element, while under pure bending in most deformed outer surfaces.

2. INVESTIGATION OF LOW CYCLE STRENGTH AND DURABILITY IN STRESS CONCENTRATION ZONES

2.1. Coefficients of stress concentration

Local stress is predetermined by the shape of the part and usually is defined by the methods of elasticity theory. Main factor of the local stress is the theoretical stress concentration coefficient:

$$\alpha_\sigma = \frac{\sigma_{\max}}{\sigma_{\text{nom}}} . \tag{1}$$

To determine stress strain state in concentration zones under elastic-plastic loading it is necessary to use these three parameters: stress concentration coefficient α_σ of elastic zone and both stress concentration coefficient K_σ, and strain concentration coefficient K_e for elastic-plastic zone. Machutov (1981) proposed an expression for evaluation of stress concentration by theoretical stress concentration coefficient α_σ, level of nominal stress $\bar{\sigma}_{in}$, and material deformation curve $f(\sigma, e)$,

$$\frac{K_\sigma \cdot K_e}{\alpha_\sigma} = F\left[\alpha_\sigma, \bar{\sigma}_{in}, f(\sigma, e)\right], \tag{2}$$

Applying Machutov Eq.°(2), the following is obtained

$$K_\sigma = \frac{\alpha_\sigma^{\frac{2m_0}{1+m_0}} \bar{\sigma}_{in}^{\frac{m_0-1}{m_0+1}}}{\left(\alpha_\sigma \bar{\sigma}_{in}\right)^{n\frac{1-m_0}{1+m_0}\left[1-\left(\bar{\sigma}_{in}-1/\alpha_\sigma\right)m_0\right]}}, \tag{3}$$

and $$K_e = \frac{\alpha_\sigma^{\frac{2}{1+m_0}} \bar{\sigma}_{in}^{\frac{1-m_0}{1+m_0}}}{\left(\alpha_\sigma \bar{\sigma}_{in}\right)^{n\frac{1-m_0}{1+m_0}\left[1-\left(\bar{\sigma}_{in}-1/\alpha_\sigma\right)\right]}}, \text{ when } \bar{\sigma}_{in} \le 1, \tag{4}$$

and $$K_\sigma = \frac{\alpha_\sigma^{\frac{2m_0}{1+m_0}}}{\left(\alpha_\sigma \bar{\sigma}_{in}\right)^{n\frac{1-m_0}{1+m_0}\left[1-\left(\bar{\sigma}_{in}-1/\alpha_\sigma\right)\right]m_0}} \tag{5}$$

$$K_e = \frac{\alpha_\sigma^{\frac{2}{1+m_0}}}{\left(\alpha_\sigma \bar{\sigma}_{in}\right)^{n\frac{1-m_0}{1+m_0}\left[1-\left(\bar{\sigma}_{in}-1/\alpha_\sigma\right)\right]}}, \text{ when } \bar{\sigma}_{in} > 1. \tag{6}$$

Equations of Machutov have modified by Stowell (1968) and Glinka and Newport (1987), however subsequent works has showed, that theirs dependences are less precise. Therefore in subsequent our calculation Eqs. (3)–(6) were used.

Theoretical stress concentration coefficients for specimens with throat radius R = 3 mm are α_σ =1.46 for tension- compression and α_σ =1.32 for pure bending. Values of these coefficients 1.48 and 1.34 by FEM were obtained. Coefficients K_e and K_σ where calculated by analytical (Eqs. (3)–(6)) and FE methods (Daunys and Sabaliauskas, 2007).

2.2. Stresses and strains in stress concentration zones

Under low cycle loading for the zone of concentration the following would be written (Daunys, 2005):

$$\bar{S}_{ik} = \bar{S}_{ink} K_{Sk} , \tag{7}$$

$$\bar{\varepsilon}_{ik} = \bar{\varepsilon}_{ink} K_{\varepsilon k} . \tag{8}$$

By calculating K_{Sk} and $K_{\varepsilon k}$, mentioned above dependencies were used, but static stress $\bar{\sigma}$ replaced with the cyclic $\bar{S}$, static strain $\bar{e}$ -with $\bar{\varepsilon}$ and strengthening coefficient of static tension curve m_0 - with strengthening coefficient of cyclic loading curve m_k. For cyclically nonstable materials low cycle loading curves of every loading semicycle would be different, therefore K_{Sk}, $K_{\varepsilon k}$, and m_k would also be different.

The strengthening coefficient m_k of low cycle loading curves exponential approximation is defined by the dependence (Daunys, 2005):

$$\bar{S}_{ik} = \bar{\varepsilon}_{ik}^{\,m_k} , \tag{9}$$

then $$m_k = \frac{\lg \bar{S}_{ik}}{\lg \bar{\varepsilon}_{ik}} , \tag{10}$$

or $$m_k = \frac{\lg \bar{S}_{ik}}{\lg\left[\frac{A_{1,2}}{\bar{s}_T}\left(\bar{e}_0 - \frac{\bar{s}_T}{2}\right)F(k) + \bar{S}_{ik}\right]} \tag{11}$$

Cyclic parameters and coefficients depend both on loading level and number of semi-cycles. Cyclic plastic strain intensity (width of the hysteresis loop) in the concentration zones was defined by the dependence (Daunys, 2005):

$$\bar{\delta}_{ik} = \left(\bar{\varepsilon}_{ik} - \bar{S}_{ik}\right)\bar{s}_T . \tag{12}$$

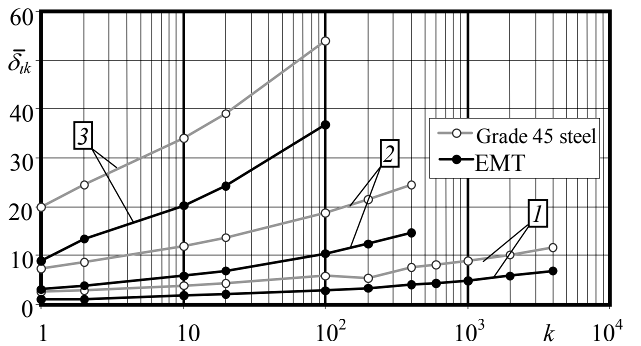

Fig. 1. Cyclic plastic strain intensity in the concentration zones at k loading under tension: 1 – $\bar{\sigma}_{in} = 1.1$; 2 – $\bar{\sigma}_{in} = 1.4$; 3 – $\bar{\sigma}_{in} = 1.8$

Calculation results of plastic strain intensity in the zones of stress concentration under stress-limited loading are given in Figs. 1 and 2.

After calculation by the Eq. (12) $\bar{\delta}_{ik}$ and known stress and strain intensities for initial loading $\bar{\sigma}_i$ and $\bar{e}_i$, it is possible to determine the intensity $\bar{e}_{ipk}$ (Daunys, 2005) of accumulated strain in tension direction at the zone of stress concentration depending on $\overline{\sigma}_{in}, \alpha_{\sigma}$ and k, under stationary nominal stress-limited loading.

$$\overline{e}_{ipk} = \overline{e}_0 - \overline{\sigma}_0 + \sum_1^k (-1)^k \overline{\delta}_{ik} \ . \tag{13}$$

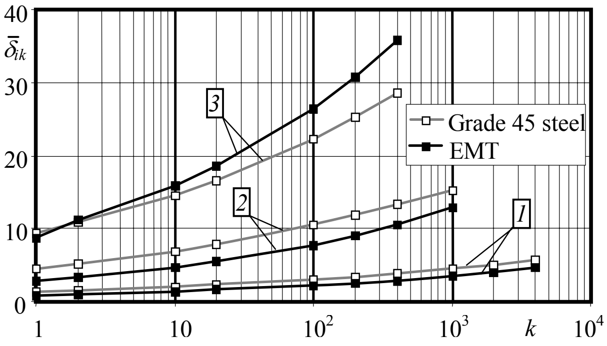

Fig. 2. Cyclic plastic strain intensity in the concentration zones at k loading under pure bending: 1 – $\overline{\sigma}_{in} = 1.1$; 2 – $\overline{\sigma}_{in} = 1.4$; 3 – $\overline{\sigma}_{in} = 1.7$

Calculated intensity of $\overline{e}_{ipk}$ in the zone of stress concentration is presented in Figs. 3 and 4.

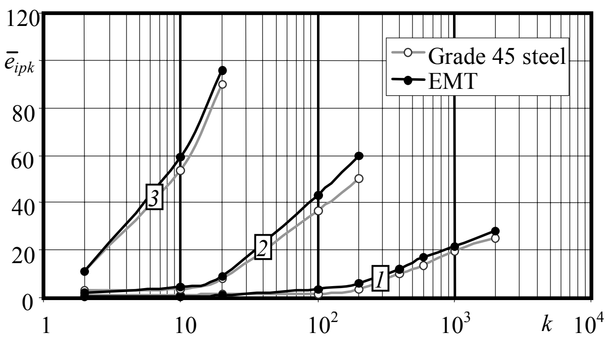

Fig. 3. Intensity of accumulated plastic strain in tension direction, in the zone of concentration under the tension: 1 – $\overline{\sigma}_{in} = 1.1$; 2 – $\overline{\sigma}_{in} = 1.4$; 3 – $\overline{\sigma}_{in} = 1.8$

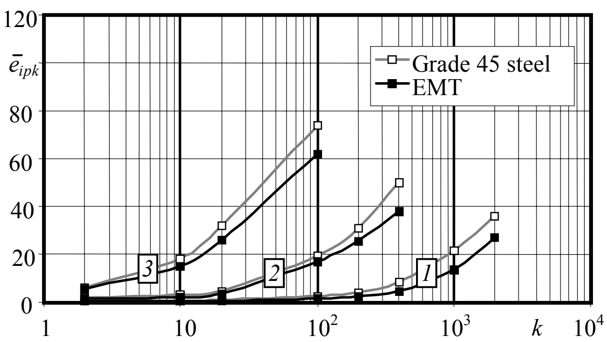

Fig. 4. Intensity of accumulated plastic strain in tension direction, in the zone of concentration under pure bending: 1 – $\overline{\sigma}_{in} = 1.1$; 2 – $\overline{\sigma}_{in} = 1.4$; 3 – $\overline{\sigma}_{in} = 1.7$

As it is evident from Figs. 3 and 4, that plastic strain in tension direction is also accumulated at the zones of concentration. And in this case, under pure bending $\overline{e}_{ipk}$ accumulation is slower than under tension.

2.3. Durability in stress concentration zones

By experimental results fatigue curves, presented in Fig. 5 have been formed. The *1* and *2* are experimental fatigue curves under the tension-compression of grade 45 steel and grade 45 steel after EMT. Due to reduce accumulated plastic strain in tension direction at low levels of stress resistance to damage of hardened steel is higher than that of nonhardened steel. Therefore, under low loading level electromechanically treated grade 45 steel has higher durability. This fatigue durability transformation occurs under the stress $\overline{\sigma}_{\max} \leq 1.3$.

The curves *3* and *4* from Fig. 5 are presenting the data of low cycle pure bending experiments. It is evident, that under low cycle pure bending, specimens after electromechanical hardening get damaged more rapidly. And, only under loading level, which is close to proportionality limit of grade 45 steel, fatigue life of the specimens made of grade 45 steel and grade 45 steel after EMT becomes equal.

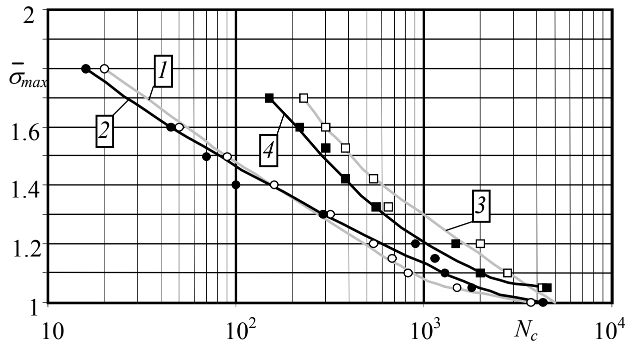

Fig. 5. Experimental curves of low cycle fatigue for nonhardened (curves *1,3*) and hardened (curves *2,4*) specimens with concentrators (*1,2* – under tension–compression *3,4* – under bending)

Performed stress-strain state analysis in the zones of stress concentration makes it possible to conclude, that, under stationary nominal loading, stress and strain at the zones of concentration changes nonstationary. Furthermore, at the zones of stress concentration under elastic plastic loading high plastic strains are obtained.

Stress-strain state analysis showed, that in zones of concentration, depending on $\alpha_{\sigma}, \overline{\sigma}_{in}, \overline{e}_{in}$, mechanical and cyclic properties of the materials, accumulation not only of fatigue damage d_N, but also quasi-static damage d_K is possible.

In this case (Daunys, 2005)

$$d_N = \frac{\sum_1^{k_c} \frac{\overline{\delta}_{ik}}{D_e} \left(\frac{\overline{\delta}_{ik}}{D_e} + \overline{S}_{ik} s_T \right)^{m_3}}{C_2 C_3^{m_3}}, \tag{14}$$

and $$d_K = \frac{\overline{e}_i - \overline{\sigma}_i + \sum_1^{k_c} (-1)^k \overline{\delta}_k}{\overline{e}_{u_2} D_e} \tag{15}$$

Analytical curves of low cycle durability under symmetric loading, calculated by the Eqs. (14) and (15), for grade 45 steel and grade 45 steel after EMT at the zones of concentration under stress-limited loading, as $q = l = 0.8$, are presented in Figs. 6 and 7.

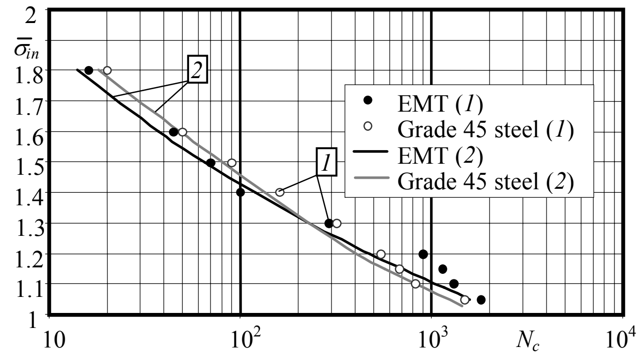

Fig. 6. Experimental results (*1*) and analytical fatigue curves (*2*) of nonhardened and hardened specimens with stress concentrators under tension-compression

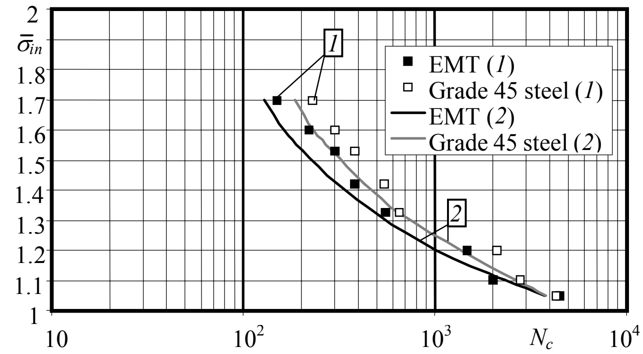

Fig. 7. Experimental results (*1*) and analytical fatigue curves (*2*) of the nonhardened and hardened specimens with stress concentrators under pure bending

From Figs. 6 and 7 is seen that calculated durability using summation of quasi-static and fatigue damages (Eqs. (14), (15) for tension compression and pure bending loading are close to experimental results.

3. CONCLUSIONS

1. Under medium and low loading levels, the durability of the hardened specimens increases, whereas under high loading levels EMT have negative influence on durability. Under high stress level "white" layer cracks more rapidly and the grade steel 45 after EMT has lower durability. Because of reduced quasi-static damage at middle loading levels durability for hardened specimens under low cycle pure bending is higher than under tension-compression.
2. It was determined, that in specimens with the stress concentration under low cycle pure bending, hardened surface has less influence on durability, when under tension-compression, while under low cycle tension-compression the positive influence starts when stress amplitude $\overline{\sigma}_{\max} \le 1.3$ value. Under pure bending accumulated plastic strain is lower when under tension-compression and therefore in stress concentration zones have nonsignificant effect on durability.
3. Performed analytical investigation showed, that suggested method for quasi-static and fatigue damage accumulation, when accumulated plastic strain and the width of the hysteresis loop are taken into account, provides a good agreement with the experimental results in stress concentration zones of surface-hardened parts under tension-compression and bending.

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ВЛИЯНИЕ УПРОЧЁННОЙ ПОВЕРХНОСТИ НА ДОЛГОВЕЧНОСТЬ ПРИ МАЛОЦИКЛОВОМ РАСТЯЖЕНИИ СЖАТИИ И ИЗГИБЕ В ЗОНАХ КОНЦЕНТРАЦИЙ НАПРЯЖЕНИЙ

Резюме: В настоящей работе при статическом и мало-цикловом растяжений сжатий и изгибе исследовано прочность и долговечность образцов из стали 45 с уп-рочненной поверхностью. Проведен анализ долговечности при обоих типах нагружения в зависимости от уровня и числа циклов нагружения. Расчет коэффициентов концентрации напряжений и доформации при упруго-пластическом нагружении проведен аналитическим и числовым методами. Проведенное аналитическое исследование показало, что предложен метод суммирования усталостных и квазистатических повреждении, хорошо соответствует результатам эксперимента в зонах концентрации напряжении как при растяжений-сжатий, так и при изгибе.