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Investigation of mechanical characteristics and low cycle fatigue of elements after electromechanical treatment

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1. Introduction

Engineering development increases the capacity of machinery, so velocities of moving parts and loads also increase. Therefore contacting surfaces rapidly wear out, lifetime of machinery gets shorter, and their reliability diminishes. One of the trends in scientific and technical progress is the creation of new materials for mechanical engineering also maintenance and quality improvement of existing materials. The aim is to provide higher reliability of machines and mechanisms, reducing their weight per unit of power, improving processability of new materials. Solution of the mentioned problems is concerned with the following surface layer characteristics of machine parts: roughness, hardness and hardening depth, wear and cyclic fatigue resistance. Operational reliability of machine parts highly depends on their surface. Material of the parts assures their strength and rigidity, while the surface secures necessary tribological, mechanical and cyclic characteristics. Therefore, wear resistance of friction units' increases, while their mass gets smaller. Lifetime and reliability increase of the machines provides savings of resources and energy, so various methods of surface treatment are very important for modern technologies. Besides conventional methods of parts' surface layer modification, such as: nitride hardening, carbonization, boronizing, various heat strengthening and etc., is being started for the implementation in new treatment methods, based on the application of concentrated energy flow [1, 2]. Methods of surface treatment by concentrated energy can be grouped into three types:

- as various coatings are sprayed onto the surface;
- as surface chemical composition change;
- as structure change of the surface layer.

In recent investigations great attention is devoted to formation of a "white layer", applying various methods for surface layer structure modification. One of the methods for functional layer treatment is electromechanical treatment (EMT) [3 - 8]. By such a method hard, with characteristic integrity and large amounts of austenite surface layer is formed, which is called a "white layer" or hardenite. Also, formed after EMT "white layer" assures optimal lubrication conditions, because, during its formation, roughness of the surface significantly diminishes, resulting its better quality. Nowadays in tribology in most cases a hard thin layer on a soft material substrate is used. Therefore, hard surface layer after EMT assures perfect wear protection of the parts, because characteristics of the surface layer provide reduction of friction.

2. Results of mechanical characteristics and low cycle fatigue investigation

Having objective to determine both mechanical and low cycle fatigue characteristics experiments were carried out using standard specimens of grade 45 steel, with effective diameter d=10 mm. Two EMT regimes were chosen, i.e. EMT1 and EMT2, those were selected according to regression models: 1) EMT1, as intensity of the current I=200 A; pressing force F=600 N; processing speed v=15.7 m/min; feed rate s=0.11 mm/rev; 2) EMA2: I=200 A; F=400 N; v=7.85 m/min; s=0.11 mm/rev. In both cases, hardening was performed twice (dual-pass). The character of microhardness variation at surface layer for both specimens is shown in Fig. 1.

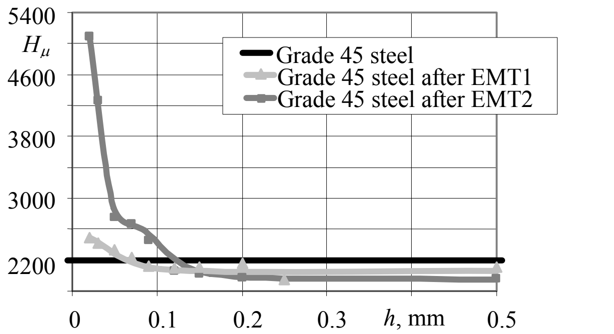

Fig. 1 Microhardness versus depth of hardened layers

Fig. 2 presents static tension curves. Tests were performed using 50 kN tension-compression testing machine, registering the curves of static and cyclic loading.

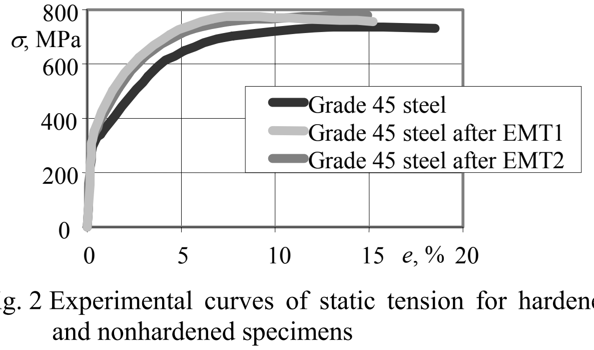

Fig. 2 Experimental curves of static tension for hardened and nonhardened specimens

The monotonic tension experiments showed the difference of mechanical characteristics for nonhardened and hardened specimens. Ultimate strength of hardened specimens is a bit higher, but strain at fracture is lower. The main difference is that hardened specimens loose yield plateau. The obtained mechanical characteristics for grade 45 steel and hardened specimens are presented in Table 1.

Table 1
Mechanical characteristics of the investigated materials

Materials / Characteristics	Grade 45 steel	Grade 45 steel after EMT1	Grade 45 steel after EMT2
σ_{pr}, MPa	271	285	291
σ_y, MPa	338	363	370
σ_u, MPa	735.4	777.0	780.4
S_k, MPa	1027	824	714
ψ, %	38	22.7	10.9
e_{pr}, %	0.212	0.191	0.188
e_u, %	47.8	25.8	11.5

Low cycle fatigue experiment was carried out under stress-limited symmetric (r=-1) loading. By means of the experiments fatigue curves were obtained. On EMT regimes depends both the depth and microhardness H_μ, of the hardened layer, also roughness and cyclic characteristics. During EMT2 by hardening tool grains of steel suffer higher plastic influence than during EMT1. The grains after EMT2 got elongated and due to rapid cooling got stratified, forming hard (up to H_μ=5088 MPa hardness) and having "white layer" of high dislocation density. As a result of EMT1 "white layer' was not formed, but very fine-grained structure of perlite-cementite was created [9]. The variation of hysteresis loop width is shown in Fig. 3.

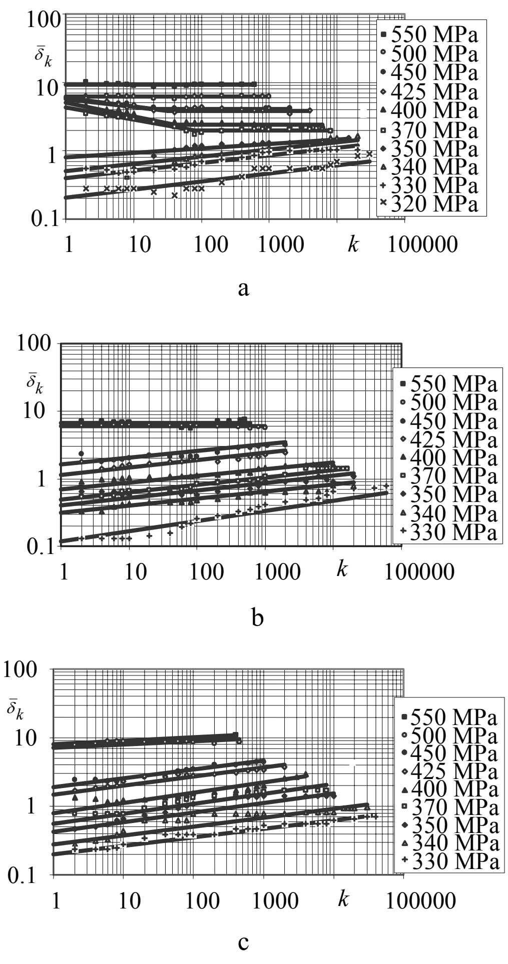

Fig. 3 Dependence of the width of hysteresis loop $\bar{\delta}_k$ on the number of loading semicycles k, under symmetric low cycle stress-limited loading (r=-1) for: a – grade 45 steel; b – grade 45 steel after EMT1; c – grade 45 steel after EMT2

The width of hysteresis loops of hardened specimens both after EMT1 and after EMT2 is smaller at low stress amplitudes, whereas durability of hardened specimens is higher, than that of nonhardened material specimens. Hardened layer due to its higher proportional limits prevents both transverse and longitudinal deformations under cyclic loading. Under low stress amplitude (fatigue fracture zone) hardened layer increased durability and prevented microcracks formation. Under high-to-moderate amplitude stresses (zones of intermediate and quasi-static damage) hardened layer after EMT1 and EMT2 regimes is not able for a long time to resist cycle plastic core deformations. Therefore, in more brittle hardened layer, microcracks appear more rapidly than in nonhardened specimens, they are of progressive type, accumulation of plastic deformation in tension direction $\bar{e}_{pk}$ increases and also increases the width of the hysteresis loop, so, damage of the specimen also increases.

In hardened specimens after EMT1 and EMT2 regimes the accumulated plastic strain in tension direction is always smaller than that of nonhardened steel. Under stress-limited cyclic loading the displacement of cyclic loading diagram in the direction of initial loading, i.e. tension direction was observed. "White layer" has less plasticity ψ and due to integrity of structural connection with nonhardened core prevents accumulation of transverse plastic strain [9].

Variation of accumulated strain for hardened steel is predetermined not only by accumulation intensities of the plastic strain of the core, but also by life time of hardened layer, under different amplitude stresses. The variation of residual plastic strain in tension direction is presented in Fig. 4.

As it is seen from Fig. 4, accumulated plastic strain depends on the amplitude of the stress. Under high amplitude stress within small number of semicycles till fracture the integrity of the hardened layer is destroyed and microcracks appear, but hardened layer still prevents transverse strain at the same time preventing unlimited accumulation of plastic strain. Due to the decrease of cross-section and because of appeared microconcentrators hardened specimens get damaged more quickly than nonhardened specimens of grade 45 steel. Under lower amplitude stress in specimens with hardened layer, due to the same reason, the accumulation of plastic strain is smaller than that of grade 45 steel.

By means of the experiments cyclic proportional limits s_T and also constants A_1 and A_2 for nonhardened and hardened specimens of grade 45 steel were determined. The dependence of hysteresis loop width could be expressed as follows

$$\bar{\delta}_k = A_{1,2}\left(\bar{e}_0 - \frac{\bar{s}_{T_1}}{2}\right)k^{\alpha} \quad (1)$$

Difference in constants A_1 and A_2 depends on the form of the first and second semicycle, which is evaluated by the changes of even and uneven semicycle. Coefficients of softening α, indicating the variation of hysteresis loop width from k and constants A_1, A_2 are given in Table 2.

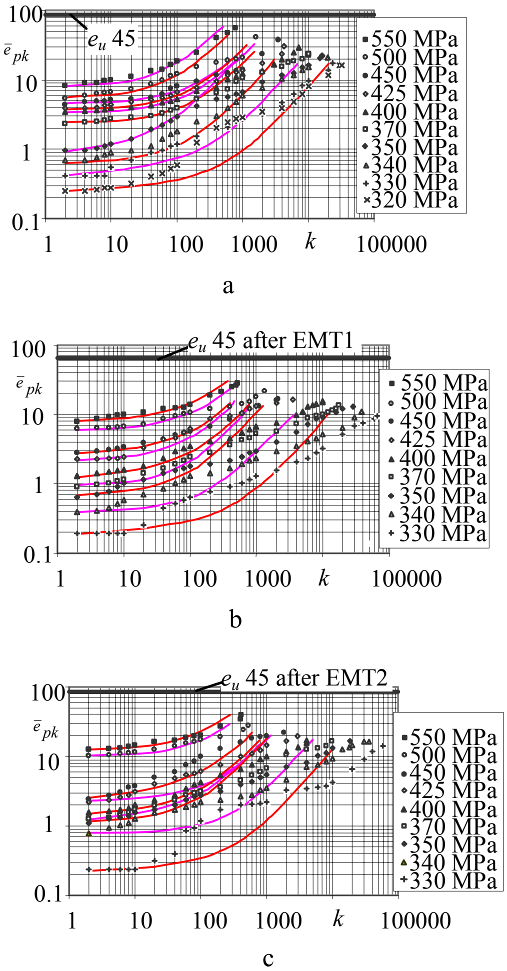

Fig. 4 Dependence of accumulated plastic strain $\bar{e}_{pk}$ in tension direction on the number of loading semicycles *k,* under symmetric low cycle stress-limited loading (r=-1) for: a – grade 45 steel; b – grade 45 steel after EMT1; c – grade 45 steel after EMT2

Table 2

Cyclic constants for symmetric (r=-1) loading

Grade 45 steel	A_1	A_2	ΔA
	1.023	1.079	0.056
	s_T = 1.658		
	α = -0.0446		
Grade 45 steel after EMT1	A_1	A_2	ΔA
	1.041	1.070	0.029
	s_T = 1.581		
	α = -0.1105		
Grade 45 steel after EMT2	A_1	A_2	ΔA
	0.809	0.901	0.002
	s_T = 1.333		
	α = -0.0876		

Under stress-limited symmetric low cycle loading positive effect on life time of the hardened by EMT2 regime specimens, if compared to nonhardened grade 45 steel, is noticeable only under stress amplitude regime specimens below 370/σ_{pr}=1.271 (Fig. 5), when “white layer” stays undamaged and prevents part damage and increases low cycle loading life of the part. However, as cyclic stresses are of high amplitude – close to ultimate limit, microcracks at “white layer” appear more rapidly (sources of local stress concentration arise). Because of high amplitude stress microcracks get localized faster, hardened layer gets fragmented and relevant conditions towards crack initiation are created, the effect of hardening no longer exist – the part experiences damage more quickly and fractures more rapidly.

Obtained by EMT1 regime hardened layer also prevents part damage, though is softer than “white layer”, however, microcracks emerge here not so rapidly. Therefore, the durability is higher than that of EMT2 regime. At comparison of the durability for the specimens after EMT1 regime and those of nonhardened grade 45 steel under symmetric stress-limited loading it is noticeable, that hardened by EMT1 regime specimens are more resistant to damage as stresses are lower than 425/σ_{pr}=1.568 amplitude.

Increase in durability at low levels under symmetric (r=-1) loading is influenced also by mechanical characteristics of the specimens after EMT1 and EMT2: i.e. by lower proportional strain, higher values of ultimate stress and etc. Damage curves for hardened and nonhardened specimens of grade 45 steel under stress-limited low cycle symmetric (r=-1) loading are presented in Fig. 5.

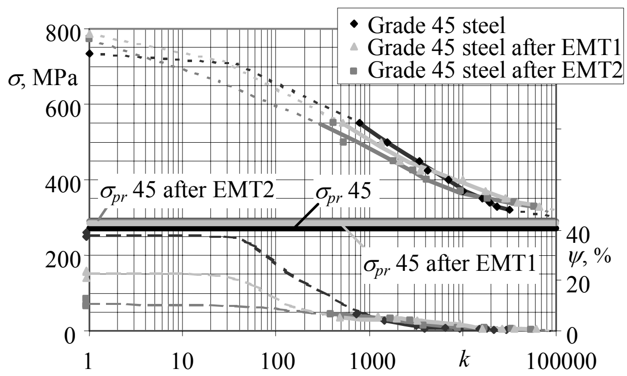

Fig. 5 Experimental curves of symmetric (r=-1) low cycle loading for nonhardened and hardened specimens

3. Investigation of strain-limited low cycle loading for grade 45 steel and grade 45 steel after EMT

Having objective to determine cyclic properties of nonhardened and hardened by regimes EMT1 and EMT2 specimens’ investigation of strain-limited low cycle fatigue was carried out. Under strain-limited low cycle loading strain is limited, so it is not accumulated in tension and quasi-static damage does not occur. In such a case specimen got damaged only because of cyclic plastic strain. According to the proposed by L. Coffin dependence

$$\bar{\delta} k_c^m = C \qquad (2)$$

where m and C are constants, $\bar{\delta}$ is a mean width of hysteresis loop, k_c is the number of semicyclestill crack. Total strain $\bar{\varepsilon}$ (Table 3) consists of plastic $\bar{\delta}$ and elastic $\bar{\varepsilon}_e$ components [10].

Durability of nonhardened and hardened by EMT1 and EMT2 specimens under low cycle strain-limited loading, is shown in Figs. 6 and 7.

Under conditions of strain-limited loading at high amplitude of strains, less plastic material, i.e. grade 45

Table 3
Constants of low cycle curve under strain-limited loading

Strain	Constant	Grade 45 steel	Grade 45 steel after EMT1	Grade 45 steel after EMT2
$\bar{\varepsilon}$	m	0.691	0.495	0.483
	C	986	215	190,2
$\bar{\delta}$	m_1	0.484	0.342	0.332
	C_1	315	109.4	120
$\bar{\varepsilon}_e$	m_e	0.207	0.153	0.151
	C_e	12.52	10.9	9.93

steel with hardened layer, damages more quickly because in the brittle and less plastic material microcracks increase faster. But at low loading amplitude of strain the hardened layer hinder microcracks appearance and propagation, that increases low cycle loading life of the part (Figs. 6 and 7).

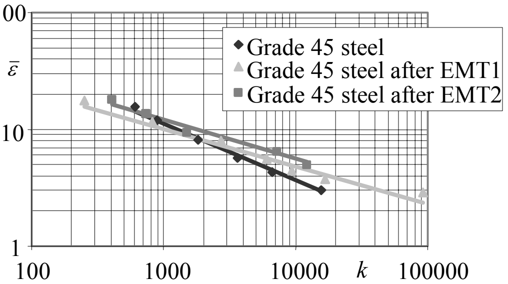

Fig. 6 Curves of strain $\bar{\varepsilon}$ for nonhardened and hardened specimens after EMT1 and EMT2 under strain-limited loading

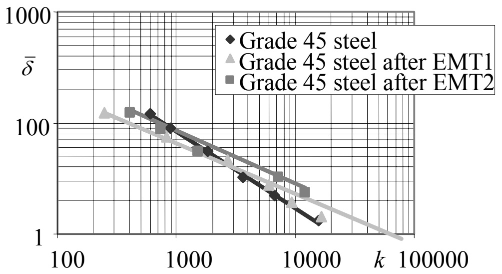

Fig. 7 Curves of plastic strain $\bar{\delta}$ for nonhardened and hardened specimens after EMT1 and EMT2 under strain-limited loading

4. Damage accumulation for grade 45 steel and for grade 45 steel after EMT

It is seen from the experiments, that the investigated specimens under stress-limited low cycle loading are accumulating plastic strain in tension direction. Therefore, at such material loading both the quasi-static and fatigue damage is accumulated.

So, it is possible to determine total damage of the material by the equation

$$d = d_N^q + d_K^l \tag{3}$$

where, d_N is fatigue damage, d_K is quasi-static damage [10].

In Fig. 8 the relation between quasi-static and fatigue damage is shown. In order to simplify the calculations commonly is used $q = l = 1$, but in our case indexes $q = l = 0.8$ were used and then the following can be written

$$d = d_N^{0.8} + d_K^{0.8} = 1 \tag{4}$$

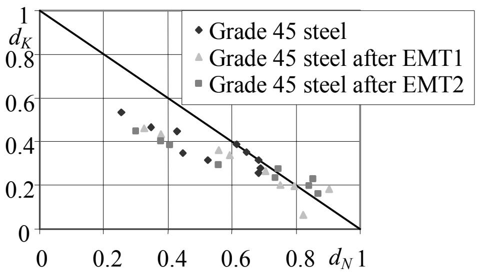

Fig. 8 Relation between quasi-static and fatigue damage under stress-limited loading

For estimation of the damage d_N under stress-limited loading it is necessary to have calculated low cycle fatigue curve with the number of semicycles k_c, which indicates only fatigue damage. To obtain the mentioned curve stress-limited loading is considered as nonstationary strain-limited loading, and total fatigue damage prior to crack initiation can be written by the equation

$$\sum_{1}^{k_c} \bar{\delta}_k \bar{\varepsilon}_k^{\alpha_3} = C_2 C_3^{\alpha_3} \tag{5}$$

where $C_2 = \dfrac{\bar{\delta}_{vid}}{k_c^{-\alpha_2}}$, $C_3 = 2^{\alpha_1} C_1$, $\alpha_3 = \dfrac{1-\alpha_2}{\alpha_1}$ [10].

Fig. 9 presents experimental curves of low cycle fatigue damage under stress-limited loading, representing total damage, i.e. quasi-static and fatigue damage, and theoretical curves, indicating only fatigue damage of investigated material.

Table 4 presents fatigue damage d_N, quasi static damage d_K and total damage d under symmetric loading that were calculated by Eq. 4. As it is seen, under higher amplitude stresses quasi-static damage dominates, while under smaller amplitude stresses predominant is fatigue damage.

Table 4
Damage accumulation under symmetric stress-limited loading

Material	Damage	550 MPa	450 MPa	400 MPa	370 MPa	340 MPa
Grade 45 steel	d_N	0.254	0.428	0.614	0.524	0.683
	d_K	0.533	0.446	0.390	0.314	0.313
	d	0.938	1.031	1.148	0.992	1.132
Grade 45 steel after EMT1	d_N	0.327	0.560	0.706	0.752	0.905
	d_K	0.460	0.363	0.263	0.203	0.180
	d	0.946	1.073	1.101	1.075	1.177
Grade 45 steel after EMT2	d_N	0.300	0.407	0.744	0.736	0.842
	d_K	0.447	0.385	0.274	0.234	0.197
	d	0.907	0.953	1.144	1.096	1.144

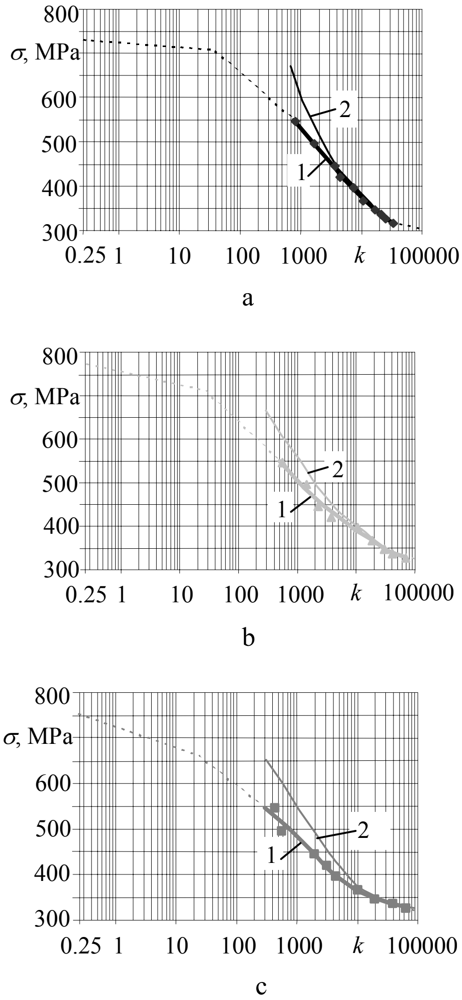

Fig. 9 Experimental curves of low cycle fatigue under symmetric stress-limited loading (1) in comparison with theoretical ones, representing only fatigue damage (2) for: a - grade 45 steel; b - grade 45 steel after EMT1; c - grade 45 steel after EMT2

5. Low cycle fatigue durability analysis for different diameter specimens of investigated materials

Though the process of electromechanical treatment is rather simple, but acting factors are complex. This is noticeable from the experiments on different diameter specimens of grade 45 steel. Specimens of 10, 15 and 22 mm diameter were hardened applying regime EMT2 (I=200 A; F=400 N; v=7.85 m/min; s=0.11 mm/rev) [11]. Then, low cycle fatigue experiments were accomplished on the specimens and both the parameters of cyclic loading and damage zones were determined. Also, polished sections of the specimens were prepared and microhardness of hardened specimens was measured. „White layer" was formed only when the specimen of 10 mm diameter was electromechanically treated. The layer obtained is significantly harder than that of hardened specimens having larger diameter. This is because of the influence of optimally chosen regimes that made possible the formation of quality "white layer" exactly in the specimens of that diameter.

In larger specimens of 15 and 22 mm diameter very fine-grained structure of perlite-cementite, similar to troostite structure, with characteristic of higher plasticity was formed. This structure has ferrite dissolved. "White layer" was not formed, as due to insufficient intensity of electrical current, small pressing force and because of small machining speed, the specimens of 15 and 22 mm diameter were not heated to a temperature high enough to form the "white layer" [12].

Low cycle fatigue investigation under tension-compression of the specimens showed the difference in durability between nonhardened and hardened specimens (Fig. 10). Hardened specimens of 22 mm diameter within investigated stress range got more fatigue resistant than other investigated specimens. Specimens of 15 mm diameter, with layer of perlite-cementite, have higher durability than both the hardened specimens of 10 mm diameter and nonhardened grade 45 steel as stress amplitudes are below $500/\sigma_{pr}$=1.845.

Hardened specimens of 10 mm diameter with present "white layer" show negative influence during low cycle fatigue experiment if compared with nonhardened grade 45 steel, except cases under stress amplitude below $370/\sigma_{pr}$=1.271.

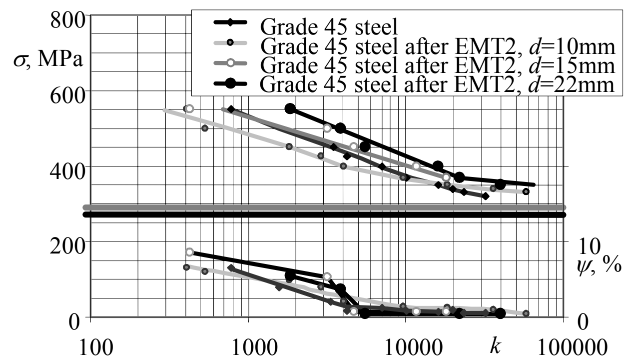

Fig. 10 Curves of low cycle fatigue and reduction of area ψ for nonhardened and hardened by EMT2 regime specimens of 10, 15 and 22 mm diameter under stress-limited symmetric (r=-1) loading

Table 5

Cyclic constants

Grade 45 steel	A_1	A_2	ΔA
	1.023	1.079	0.056
	s_T = 1.658		
	α = -0.0446		
Grade 45 steel after EMT2, d=10 mm	A_1	A_2	ΔA
	0.809	0.901	0.002
	s_T = 1.333		
	α = -0.0876		
Grade 45 steel after EMT2, d=15 mm	A_1	A_2	ΔA
	1.105	1.185	0.08
	s_T = 1.244		
	α = -0.0494		
Grade 45 steel after EMT2, d=22 mm	A_1	A_2	ΔA
	0.899	0.940	0.041
	s_T = 1.157		
	α = -0.0224		

Durability increase of larger diameter specimens depends on microhardness of hardened layer, hardening depth, structure of the hardened layer of perlite-cementite and portion of the hardened layer to nonhardened core, mechanical characteristics and etc. By electromechanical treatment of 15 and 22 mm diameter specimens' softer and less brittle hardened layer, than that of 10 mm diameter specimens was obtained, therefore, under high amplitude stress, the mentioned layer avoided microcracks for a longer time and so lifetime of the specimens was increased.

By experimental analysis cyclic proportional limits s_T and also constants A_1 and A_2 and α for different diameter specimens of nonhardened and hardened grade 45 steel (Table 5) were determined.

6. Conclusions

1. Electromechanical treatment of grade 45 steel results not only surface structure change of the part, but also changes both the mechanical and low cycle loading characteristics of low cycle. Grade 45 steel after EMT looses yield plateau and obtains increased proportionality and ultimate limits. Low cycle fatigue analysis showed that grade 45 steel is cyclically stable, whereas after EMT1 and EMT2 – is cyclically softening and accumulating plastic strains in tension direction. For the specimens hardened by EMT1 and EMT2 regimes this cyclically accumulated plastic strain is less than that of nonhardened steel.

2. Hardened by EMT1 regime specimens of grade 45 steel with formed layer of perlite-cementite under symmetric stress-limited low cycle loading have larger durability than specimens of nonhardened grade 45 steel, under stress amplitude below $425/\sigma_{pr}$=1.568, because hardened layer prevents the accumulation of plastic strain.

"White layer" formed by EMT2 regime under symmetric low cycle loading increases effect on durability only at stresses bellow the $370/\sigma_{pr}$=1.271 amplitude.

The layer of perlite-cementite is softer than "white layer", therefore, microcracks formation therein is not so rapid and effect on durability is increased up to $425/\sigma_{pr}$=1.568.

Besides the increase of durability under existing low amplitude stress is influenced by mechanical characteristics of specimens after EMT1 and EMT2, i.e. higher values of σ_{pr}.

3. Under strain-limited loading, when amplitude of strains is high, material of less plasticity, i.e. grade 45 steel with hardened layer, has lower durability than nonhardened grade 45 steel. Within the range of low stress amplitudes (> $400/\sigma_{pr}$=1.476) the specimens with hardened layer have higher durability, than the specimens from nonhardened grade 45 steel.

4. Before fracture in the investigated material at low cycle loading the fatigue and quasi-static damage accumulation takes place. The investigation of damage accumulation under low cycle loading showed that steel after EMT less accumulates quasi-static damage, than nonhardened steel.

5. By electromechanical hardening of different diameter specimens using the same EMT2 regime, different structure of hardened layer was obtained. Treatment of 10 mm diameter specimens results in formation of "white layer", whereas for larger specimens (15 and 22 mm diameter) very fine-grained structure of perlite-cementite is obtained.

"White layer" of hardened 22 mm diameter specimens after EMT2 regime was not formed, therefore it is more resistant to low cycle fatigue than specimens having diameter 10 mm and 15 mm respectively. Hardened specimens of 15 mm diameter with perlite-cementite layer have higher durability, than hardened specimens of 10 mm diameter and that of grade 45 steel, under amplitude stresses up to $500/\sigma_{pr}$=1.845. Hardening of 10 mm diameter specimens with "white layer" has negative influence on low cycle fatigue, if compared to specimens of nonhardened grade 45 steel, when the amplitude of stresses is lowered, down to $370/\sigma_{pr}$=1.271.

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ELEKTROMECHANISKAI APDIRBTŲ DETALIŲ MECHANINIŲ CHARAKTERISTIKŲ IR MAŽACIKLIO NUOVARGIO TYRIMAS

R e z i u m ė

Straipsnyje nagrinėjamos elektromechaniškai apdirbtų (EMA) ir neapdirbtų plieno 45 bandinių mechaninės charakteristikos ir mažaciklio nuovargio savybės esant minkštam ir standžiam apkrovimui. Pateiktos histerezės kilpos pločio ir vienpusės plastinės deformacijos priklausomybės nuo apkrovimo pusciklių skaičiaus. Nustatyta, kad plieną sukietinus padidėja bandinių ilgaamžiškumas dėl paviršinio sluoksnio sukietėjimo ir padidėjusių stiprumo mechaninių charakteristikų, kai amplitudiniai įtempiai mažesni už $370/\sigma_{pr}$=1.271. Straipsnyje palygintos sukietintų ir nesukietintų bandinių minkšto ir standaus mažaciklio apkrovimo eksperimentinės kreivės bei konstantos. Susumuoti nekietinto ir sukietinto plieno 45 pažeidimai. Išanalizuoti skirtingo skersmens sukietintų bandinių mažaciklio nuovargio ilgaamžiškumo tyrimų rezultatai.

M. Daunys, V. Staponkus

INVESTIGATION OF MECHANICAL CHARACTERISTICS AND LOW CYCLE FATIGUE OF ELEMENTS AFTER ELECTROMECHANICAL TREATMENT

S u m m a r y

Mechanical and low cycle fatigue characteristics after electromechanical treatment and nonhardened specimens of grade 45 steel are investigated under stress-limited and strain-limited loading in this paper. Dependences of the histeresis loop width and accumulated plastic strain on the number of loading semicycles are presented. Steel hardening increases durability of specimens because of hardened surface layer and increased strength mechanical characteristics under amplitude stresses below $370/\sigma_{pr}$=1.271. Experimental curves and constants of hardened and nonhardened specimens are compared under low cycle fatigue under stress-limited and stain-limited loading. Damage accumulation of hardened and nonhardened specimens of grade 45 steel is accomplished. Durability analysis for different diameter specimens after low cycle loading is made.

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ИССЛЕДОВАНИЕ МЕХАНИЧЕСКИХ СВОЙСТВ И МАЛОЦИКЛОВОЙ УСТАЛОСТИ ДЕТАЛЕЙ ПОСЛЕ ЭЛЕКТРОМЕХАНИЧЕСКОЙ ОБРАБОТКИ

Р е з ю м е

В статье рассматриваются механические характеристики и параметры малоцикловой усталости обработанных электромеханическим способом и необработанных образцов из стали 45 в условиях мягкого и жесткого нагружения. Приведены зависимости ширины петли упругопластического гистерезиса и односторонней накопленной пластической деформации от числа полуциклов нагружения. Установлено, что упрочнение стали увеличивает долговечность образцов из-за упрочнения их поверхностного слоя и повышения прочностных механических характеристик в условиях малоциклового нагружения при $<370/\sigma_{np}$=1.271. В статье приведено сопоставление экспериментальных кривых и констант малоцикловой усталости при мягком и жестком нагружениях для упрочненных и неупрочненных образцов. Выполнено суммирование повреждений упрочненной и неупрочненной стали 45. Приведен анализ исследований малоцикловой долговечности упрочненных образцов разного диаметра.

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