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INFLUENCE OF HARDENED SURFACE ON LOW CYCLE FATIGUE CHARACTERISTICS AT TENSION-COMPRESSION AND BENDING

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Abstract

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This paper analyses electromechanical hardening of the steel parts surface, when in the contact area so called “white layer” is formed. The experiments were performed to show the influence of “white layer” on strength of the steel C45 specimens under low cycle loading. This paper analyses monotonic and low cycle tension compression and pure bending characteristics of specimens with electromechanically hardened surface. The Performed experiments showed that under monotonic tension strength characteristics (σ_{pr}, σ_{02}, σ_u) are increasing and strain characteristics (e_u, ψ) are decreasing. During cyclic stress limited tension compression at low loading levels both the width of plastic strain hysteresis loop and accumulated plastic strain are decreasing, therefore the lifetime is increasing. Under pure bending this tendencies persist, but in this case the lifetime at all loading levels is larger than the lifetime at tension compression.

Keywords: low cycle fatigue, pure bending, electromechanical treatment

INTRODUCTION

The most common loading mode of operating structures, mechanisms and machinery is cyclic loading, which initiates fatigue damage. The increasing loading velocities of this equipment and the reduction of their dimension made such extreme working conditions. At the same time, it is necessary to effect high strength and durability of these equipment. All these purposes cannot be achieved without knowledge of materials low cycle strength and durability characteristics at different loading type. Very often the durability of the element depends not on the properties of the whole element but only on the properties of its surface. One of effective methods, increasing durability of elements, is surface hardening, as in most cases the fracture starts on surface due to overloads, decreased resistance to plastic strains or due to influence of operating medium. One of the methods for surface hardening is electromechanical treatment (Barry *et al.*, 2002). Therefore research object of this work is to examine low cycle fatigue characteristics of the hardened by EMT steel C45 under tension-compression, pure bending and stress concentration by defining following problems:

1. to determine and compare the influence of electromechanically hardened surface on strength and durability of the parts under low cycle tension-compression and pure bending;
2. to evaluate analytically strength and durability of the surface-hardened parts.

Methodology of Electromechanical Treatment

Electromechanical treatment (EMT) is the metal element surface treatment method based on local impact of force and heat in contact zone. In the contact zone of tool and treated surface electric current of high intensity and low voltage flows. As the high intensity current flows on the small contact area then due to electric resistance in contact zone high heat energy is emitted and contact zone is heated to the high temperature. The amount of temperature is sufficient for austenitic transformation. The volume of heated surface layer is quite small, so the heat is quickly directed to the depth towards element core. Thus the heated element layer quickly cools down and due to internal structural changes it hardens. In this way the "white layer" is composed (Bagmutov *et al.*, 2005).

For the hardening surface in KTU EMT equipment applied to work on turning lathe was used (Daunys *et al.*, 2004). Treatment tool – hard-fusion T15K6 plate was inserted into pressing device. Tool press force *F* is controlled using device indicator. Using EMT, simultaneously two processes occur: smoothing of surface roughness and surface layer hardening. During electromechanical hardening the following processing parameters were used:

1. hard-fusion T15K6 plate pressing force $F = 400$ N;
2. frequency of specimen rotation $n = 250$ revs/min;
3. processing speed $v = 7.85$ m/min;
4. feed of instrument $s = 0.11$ mm/revs;
5. electric current intensity $I = 220$ A;
6. passing number $i = 2$ (Daunys and Sabaliauska, 2005).

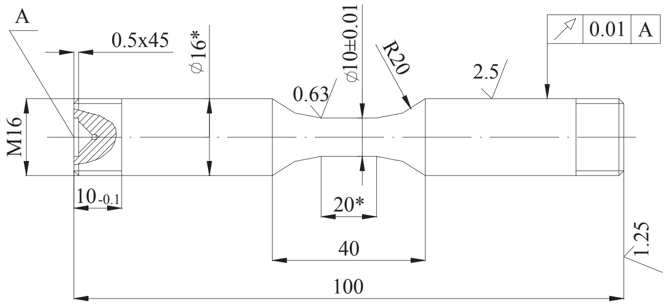
Methodology of Static and Low Cycle Tension-compression

Low frequency mechanical loading device with electronic-mechanic stress strain curves recording device was used for investigation of the monotonic and low cycle loading. 50 kN and 100 kN testing machines were used for monotonic and low cycle tension-compression experiments (Daunys, 2005).

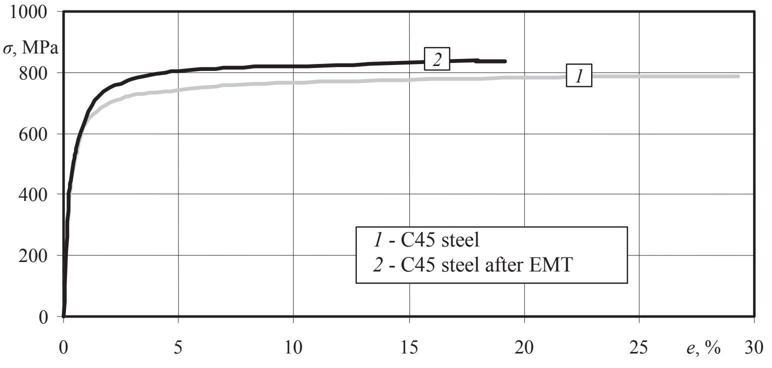
Circular cross-section specimens were used for monotonic tension and low cycle tension-compression experiments were applied. These specimens were machined from bars of rolled C45 steel to the form and dimension shown in Fig. 1.

The monotonic tension curves are presented in Fig. 2. The determined mechanical characteristics of C45 steel and C45 steel after EMT are presented in Tab. I.

As it can be seen in Fig. 2 and Tab. I, after electromechanic processing differences in metal mechanical characteristics occur. The proportional limit σ_{pr} and ultimate strength σ_u for electromechanically hardened specimen are larger but the ultimate strain e_u is smaller.



1: *Specimen for monotonic and low cycle tension-compression loading*



2: *Monotonic tension stress-strain curves*

I: *Mechanical characteristics of steel C45 and steel C45 after EMT*

σ_{pr}, MPa	$\sigma_{0.2}$, MPa	σ_u, MPa	σ_f, MPa	e_{pr}, %	$e_{0.2}$, %	e_u, %	Z, %
			Steel C45				
375	544	786	882	0.22	0.42	29	65
			Steel 45 after EMA				
424	580	842	769	0.24	0.24	25	19

During low cycle tension-compression stress limited loading was applied. Because under low cycle loading stress strain curves are changed depending on load level and number of semicycle, so it is important to have precisely recorded these curves.

It is known, that the hysteresis loop width for anisotropic material is wider in even semicycle, than in uneven, i.e. $\bar{\delta}_2 > \bar{\delta}_1$. Therefore the expression of width of hysteresis loop in semicycle *k* is written (Daunys, 2005):

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

here
A_1, A_2 and α ...cyclic characteristics of material,
$\bar{e}_0$......................strain of initial semicycle,
$\bar{s}_T$......................cyclic proportional limit,
k.......................number of semicycle.

For determination of constants A_1 and A_2 according to experimental low cycle stress limited tension-compression data we compose graphical dependence $\bar{\delta}_{1,2} = f(\bar{e}_0)$ according to which:

$$A_{1,2} = \frac{\delta_{1,2}}{\left(\bar{e}_0 - \frac{\bar{s}_T}{2}\right)}. \tag{2}$$

The width of hysteresis loop and accumulation of plastic strain depend on the number of semicycles. After *k* semicycle accumulated plastic strain may be written as (Daunys and Rimovskis, 2002):

$$\bar{e}_{pk} = \bar{e}_0 - \bar{\sigma}_0 + \sum_{1}^{k}(-1)^k \bar{\delta}_k, \tag{3}$$

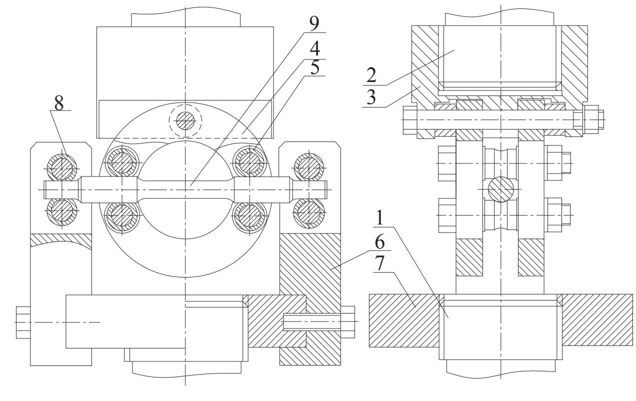
here
$\bar{\sigma}_0$......................stress of initial semicycle.

Methodology for Low Cycle Pure Bending

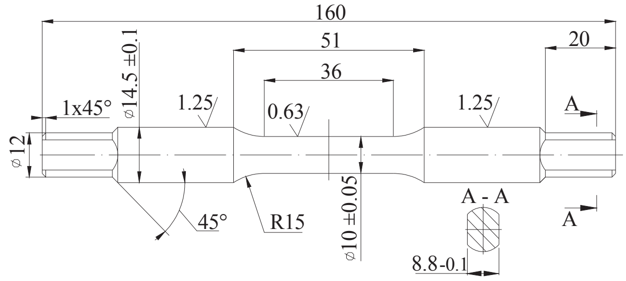
The experimental investigations of low cycle pure bending were performed using the above described equipment. Special set-up for specimen fixing was used for low cycle pure bending fatigue test. Using this set-up in specimen operational area permanent bending moment M_b was created (Daunys and Rimovskis, 2002). Fig. 3 shows a sketch of specimen fixing set-up. It consists of two sections: one (the nut 3 with the pair of ring 4 and supporting rollers 5) is fixed on machine's stationary grip 2; the other (the plate 7 with the supports 6 and supporting rollers 8) is screwed on machine's shifting grip 1.

At pure bending the requirements for the specimen are the same as for the tension compression specimen (Daunys and Rimovskis, 2006). The scheme of used hardened and non-hardened specimen for pure bending is showed in Fig. 4.

During low cycle pure bending loading with limited stress was also performed, i.e. fixed load was applied. After the experiments the changes of hysteresis loops, constants, which evaluate anisotropy, periodically accumulated plastic strains of different load stages were also calculated.



3: *Cyclic pure bending tests set – up*



4: *Specimen for pure bending*

II: *Values of constants A_1 and A_2*

Non-hardened			Hardened		
A_1	A_2	ΔA	A_1	A_2	ΔA
Low cycle tension-compression					
1.86	2.0	0.14	0.91	1.15	0.24
Low cycle pure bending					
1.26	1.3	0.04	1.07	1.18	0.11

RESULTS

In accordance to Eq. (2) the constant A_1 and A_2 for non-hardened and hardened grade 45 steel are presented in Tab. II.

The obtained results show that after electro-mechanical treatment, the constants A_1 and A_2 decrease. This is due to decreasing widths of the hysteresis loops. For experimental low cycle stress limited symmetric loading elastic-plastic strain hysteresis loops variation dependence on semicycle number is presented in Figs. 5 and 6. This data were obtained by performing experiments from $\bar{\sigma}_0 = 1.01$ to $\bar{\sigma}_0 = 1.95$ in case of tension compression and from $\bar{\sigma}_0 = 1.04$ to $\bar{\sigma}_0 = 1.8$ in case of pure tension. Where:

$$\bar{\sigma}_0 = \frac{\sigma_0}{\sigma_{pr}}, \tag{4}$$

here

σ_0......................stress of initial semicycle for non-hardened steel,

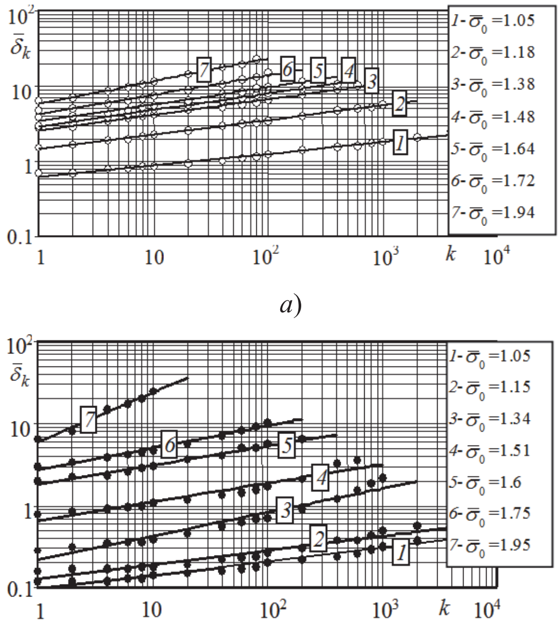
σ_{pr}.....................proportional limit for non-hardened steel.

As it was mentioned above, the width of hysteresis loop for anisotropic materials is larger in even semicycles than in uneven semicycles; therefore during the load of low cycle loading the material receives the increase of plastic strain in the direction of tension. The experimental tension-compression and pure bending curves of accumulated plastic strain $\bar{e}_{pk}$ are presented in Figs. 7 and 8.

The diagrams show that during tension-compression the accumulation plastic strain in the direction of tension in hardened material is slower. And only in a very large stress range ($\bar{\sigma}_0 = 1.95$), $\bar{e}_{pk}$ it may reach the value of relative fracture strain $\bar{e}_u$.

In case of pure bending the plastic strain is accumulated more slowly and for hardened steel, when the loading amplitude is close to proportional limit, this accumulation is very small.

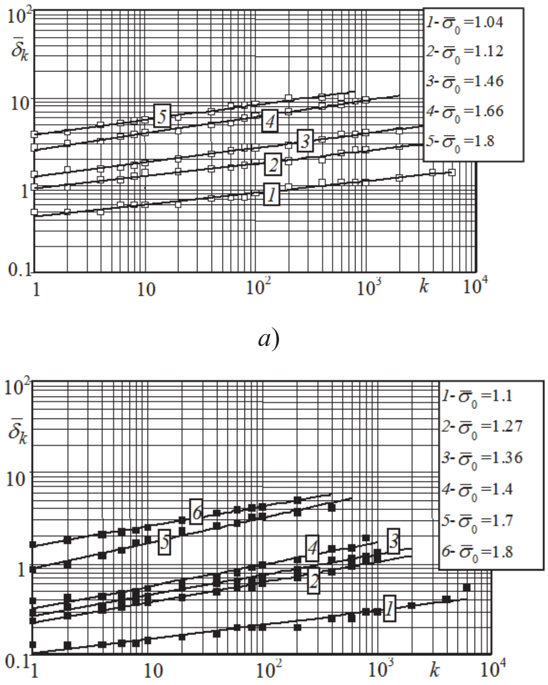
The layer, hardened by EMT, prevents influence of the plastics strains. This is extremely obvious when middle and high amplitude tensions are given. As the e_u of hardened steel is smaller, so with high amplitude cyclic loading it is reached rather quickly.



a)

b)

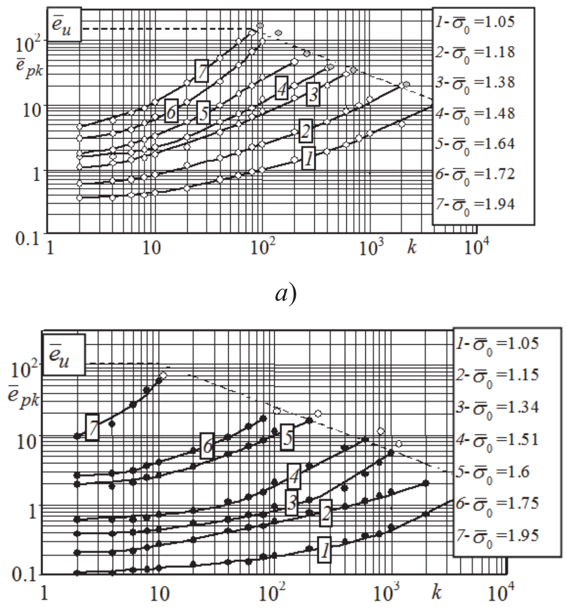
5: *Dependence of the width of hysteresis loops on semicycle number k and load level σ_0, at low cycle tension-compression: a) steel C45; b) steel C45 after EMT*



a)

b)

6: *Dependence of the width of hysteresis loops on semicycle number k and load level σ_0, at low cycle pure bending: a) steel C45; b) steel C45 after EMT*



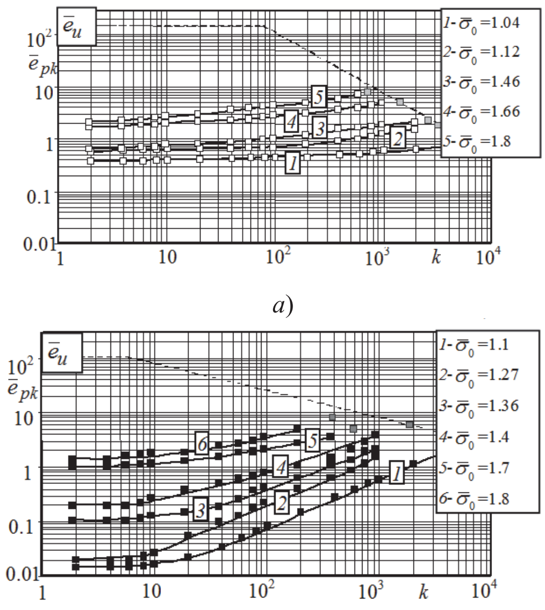
a)

b)

7: *Dependence of accumulated plastic strain e_{pk} at tension-compression on semicycle number k and load level σ_0: a) steel C45; b) steel C45 after EMT*

Therefore the durability of hardened specimen decreases. Having small amplitude loading, the "white layer" blocks accumulates of plastic strain, so the durability of specimen is increasing. This can be seen in Fig. 9 both in case of tension-compression (curves *3*, *4*) and in case of pure bending (curves *1*, *2*).

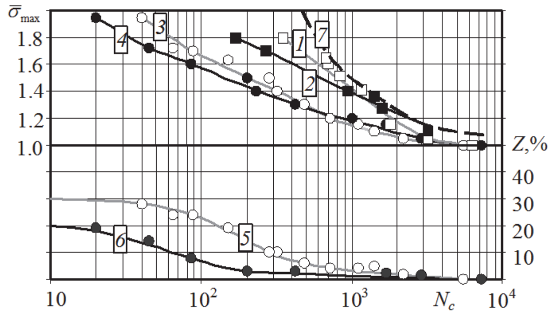
On Fig. 9 curve (*7*) represents only fatigue damage of stress limited loading only.



a)

b)

8: *Dependence of accumulated plastic strain e_{pk} at pure bending on semicycle number and load level σ_0: a) steel C45; b) steel C45 after EMT*



9: *Low cycle fatigue curves for non-hardened (curves 1, 3, 5) and hardened (curves 2, 4, 6) specimen; analytic fatigue curve of grade 45 steel (curve 7)*

CONCLUSION

1. The investigation of low cycle fatigue showed that non-hardened and hardened specimens of steel C45 using EMT are cyclically weakening and accumulating plastic strains. Therefore fatigue and quasi-static damage accumulation occurs.
2. During pure bending the width of histeresis loop of elastic plastic strain and the accumulation of plastic strain in the direction of tension is smaller than these parameters at tension-compression. This decrement is originated from the resistance of elastically strained inner layers of specimen to plastic strain of outer layers during the pure bending.
3. In both tension-compression and pure bending cases the hardened surface layer decreases the width of plastic strain histeresis loop and the accumulation of strain in the direction of tension.
4. Under high loading level electromechanical hardening reduced the ultimate strain e_u therefore has negative influence on element lifetime. But at middle and low loading level lifetime due to reduced e_u is increasing.

The paper analyses electromechanical treatment method for element surface hardening. During this treatment high intensity electric current flow and the treatment tool contacts with the element. On the contact area hardened "white" layer is composed. During the experiments the influence of this layer was investigated. The specimens of steel C45 were applied by low cycle tension-compression. After processing experiment results the dependencies of how hardened surface influences the change of the width of hysteresis loop, accumulation of plastic strain, and durability of specimens were obtained.

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