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SOFTENING OF MARTENSITIC CAST STEEL

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Abstract

In this paper there were presented test results of low cycle fatigue (LCF) behavior of martensitic cast steel under constant-amplitude loadings. Analysis of stabilization course was carried out by using two parameters of hysteresis loop. It was found that among physical quantities used in description of the fatigue process there was no one which would be insensitive to the changes of cyclic properties. Parameter, which was less sensitive to the changes of cyclic properties was plastic strain.

***Keywords**: cyclic properties, softening, fatigue life, martensitic cast steel*

1. Introduction

The range of low cycle fatigue (LCF) in metals in comparison to the range of high cycle fatigue (HCF) basically differs in value of observed plastic strains during cyclic loadings. Cyclic plastic strains generate complex series of phenomena in a material which depend on many factors [1,2,6, 7,9]. Generally they are called fatigue changes. Various physical quantities, which are calculated and measured during cyclic loading, can be accepted for their description. The most important ones include such hysteresis loop parameters as ε_{ac}, ε_{ap}, ε_{ae}, σ_a, (Fig. 1)[8].

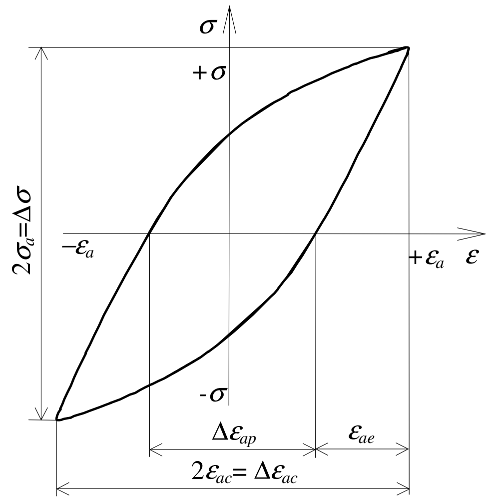


Fig. 1. Hysteresis loop with its basic parameters

Some of these parameters can be treated as criterial quantities which at present are employed in description of the fatigue process (strain, stress description) [3,4]. These descriptions are phenomenological and they are not directly connected with the real metal structure and physical character of occurring changes [5]. Observed relationships in various periods of fatigue life among hysteresis loop parameters and the number of loading cycles N are generally called cyclic properties and their values may change. When the cyclic properties changes, then this situation is called cyclic hardening or softening or when it is constant it is called cyclic stabilization. The research problem is both analytical description of the course of changes of cyclic properties during irregular or constant amplitude loadings and possibility to predict this course.

The main aim of this paper is the determination of the influence of strain level on the course of cyclic properties. The additional aim is an analytical description of changes of cyclic properties and also sensitivity of specific parameters of hysteresis loop to the changes of cyclic properties.

2. Description of tests

Specimens for the tests were made of GX12CrMoVNbN9-1 martensitic cast steel. The shape and dimensions of the specimens were in agreement with the standard [8] (Fig. 2.).

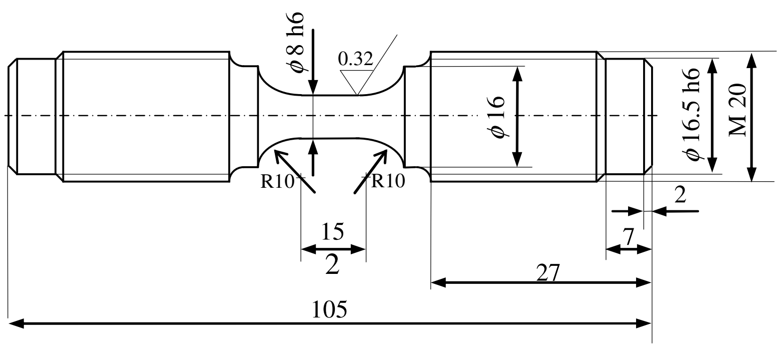
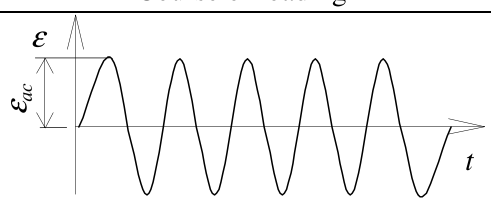


Fig. 2. Shape and dimensions of specimens used in tests

Fatigue tests were preceded by carrying out static tensile tests. The specimens used in the tests are shown in fig. 2. The specimens underwent increasing loading with the rate of machine piston displacement speed of 0.05 mm/s. Specimen's elongation was measured by a 12.5 mm gauge length axial extensometer with measuring range of 3.75 mm. The static tensile tests were carried out under temperature of 20°C. During these tests momentary loading forces and elongation of the specimen were recorded. After analyzing static tensile tests five levels of total strain ε_{ac} were accepted in low cycle tests according to table. 1.

Table 1. Parameters of loading programs

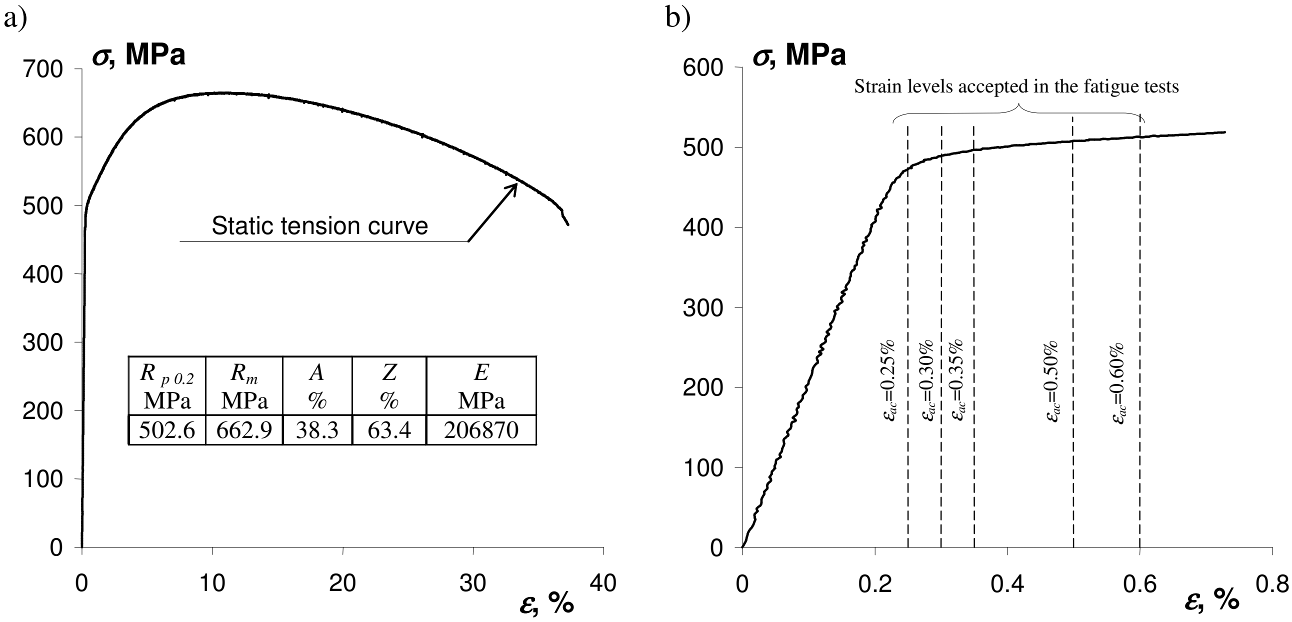
Course of loading	Parameters
	ε_{ac1}=0.25% ε_{ac2}=0.30% ε_{ac3}=0.35% ε_{ac4}=0.50% ε_{ac5}=0.60% f=0.2 Hz

LCF tests were conducted under controlled total strain ε_{ac}=const. The same procedure of measuring strain was employed for static tensile test. Test temperature of 20 °C and frequency of 0.2 Hz were employed. Accepted sampling frequency of force signal and strain signal allowed to describe loading cycles with set of 200 points. As the end criterion of the fatigue test, the deformation of hysteresis loop (during semi cycle of compression) is accepted. During the tests momentary values of loading force and strain for selected loading cycles were recorded.

3. Test results

3.1. Static tensile tests

Static tensile tests results are shown in Fig. 3a – in stress σ - strain ε coordinate system. Stresses in the specimen under tensile loading were calculated as the ratio of momentary value of loading force per cross-sectional area before the specimen loading.



$R_{p\,0.2}$ MPa	R_m MPa	A %	Z %	E MPa
502.6	662.9	38.3	63.4	206870

Fig. 3. Stress-strain curve: a) full plots, b) levels of total strain employed in LCF

Stress-strain curve was minutely investigated to determine basic strength parameters. The most important results are collected in table in Fig. 3a. Figure 3b illustrates a part of stress-strain curve which is bonded only to strain of 0.8%. Strain levels accepted in the fatigue tests were placed on this graph.

3.2. Fatigue tests

Analysis of cyclic properties of cast steel specimens was carried out with the use of hysteresis loop parameters (ε_{ap} and σ_a) which influence directly the test results (according to [8]). Momentary stress values σ in the specimen were calculated by dividing momentary value of loading force by cross-sectional area before the specimen was loaded.

During LCF changes of the basic hysteresis loop parameters were observed in the function of the number of cycles. The above is the proof of the changes of cyclic properties of tested material. In the result of the changes, the shape of hysteresis loop registered during various periods of fatigue life also changes. In order to illustrate this problem in Fig. 4 there were presented exemplary hysteresis loops which were obtained only for two levels of strain - the lowest

ε_{ac}=0.25% and the highest ε_{ac}=0.60% in various periods of the fatigue life. The numbers of cycles corresponding to the presented loops are placed on the diagram.

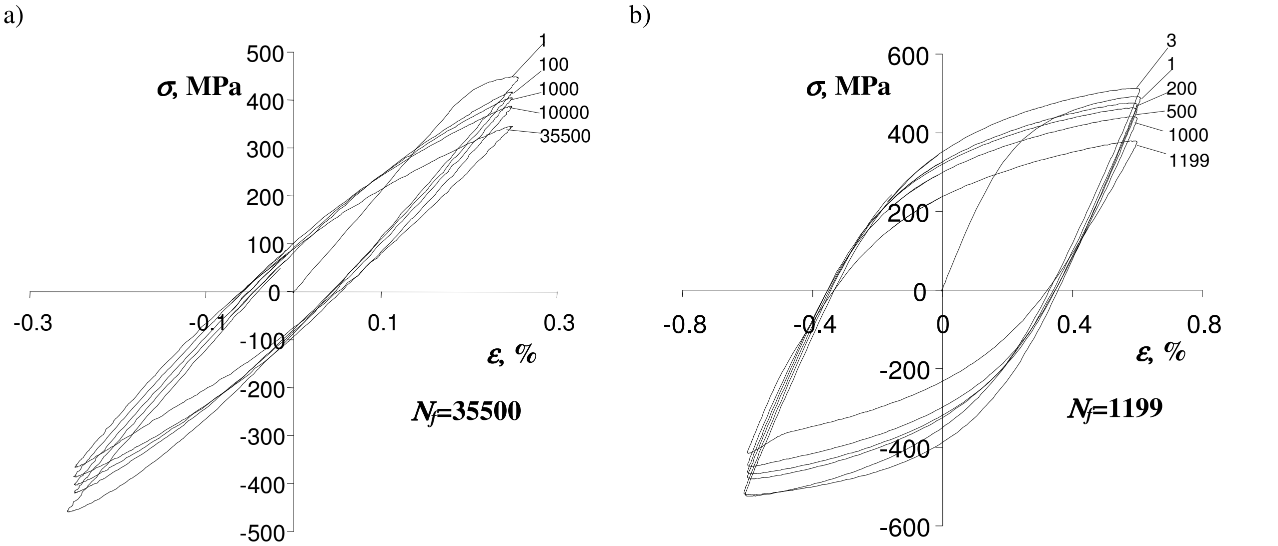


Fig. 4. Hysteresis loops obtained for two levels of total strain and during various periods of fatigue life: a) ε_{ac}=0.25%, b) ε_{ac}=0.60%

Basing on the presented hysteresis loops it can be stated that on both levels of strain changes of the loops are noticeable with increasing of the number of cycles. Stress amplitude decreases and plastic strain amplitude increases with increasing of the number of cycles. In Fig. 5. there are presented the courses of stress amplitude σ_a and plastic strain amplitude ε_{ap} in the function of the number of loading cycles obtained for all implemented levels of total strain ε_{ac}.

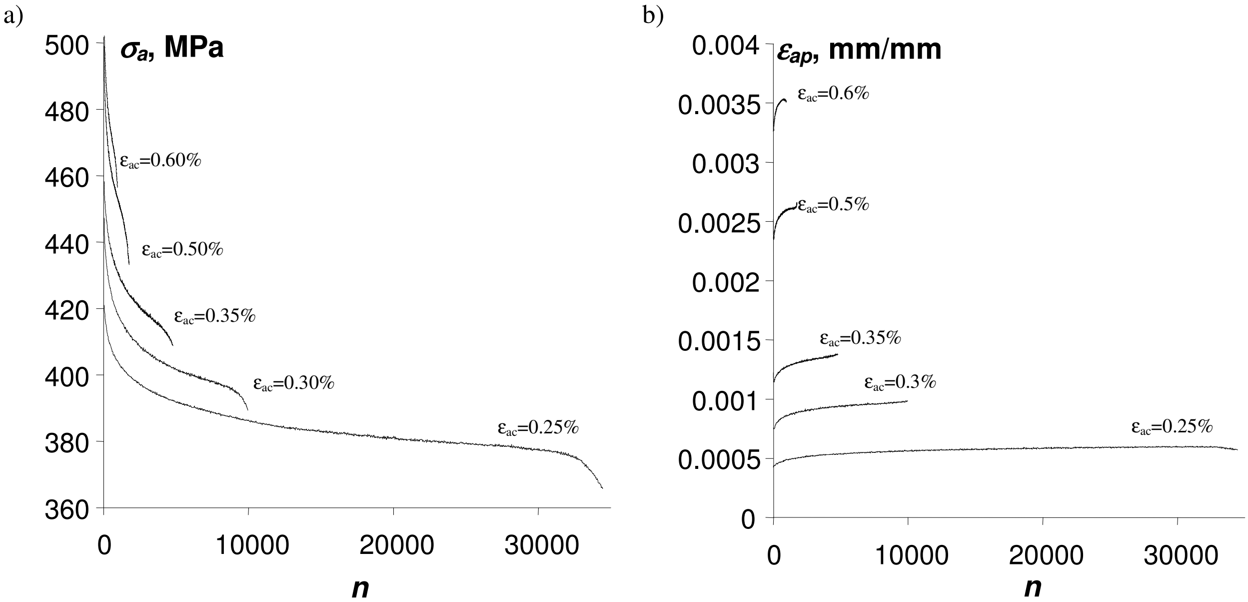


Fig. 5. Changes of hysteresis loop parameters for five levels of strain: a) $\sigma_a=f(n)$, b) $\varepsilon_{ap}=f(n)$

Basing on the obtained results it can be stated that momentary values of the loop parameters (σ_a and ε_{ap}) depend on fatigue damage degree (the number of cycles) and total strain level ε_{ac}. In order to illustrate course of changes of cyclic properties and to discuss characteristic stages accompanying the fatigue process in Fig. 6 there were shown example diagrams of changes of loop parameters (σ_a and ε_{ap}) for the highest level of total strain (ε_{ac}=0.60%).

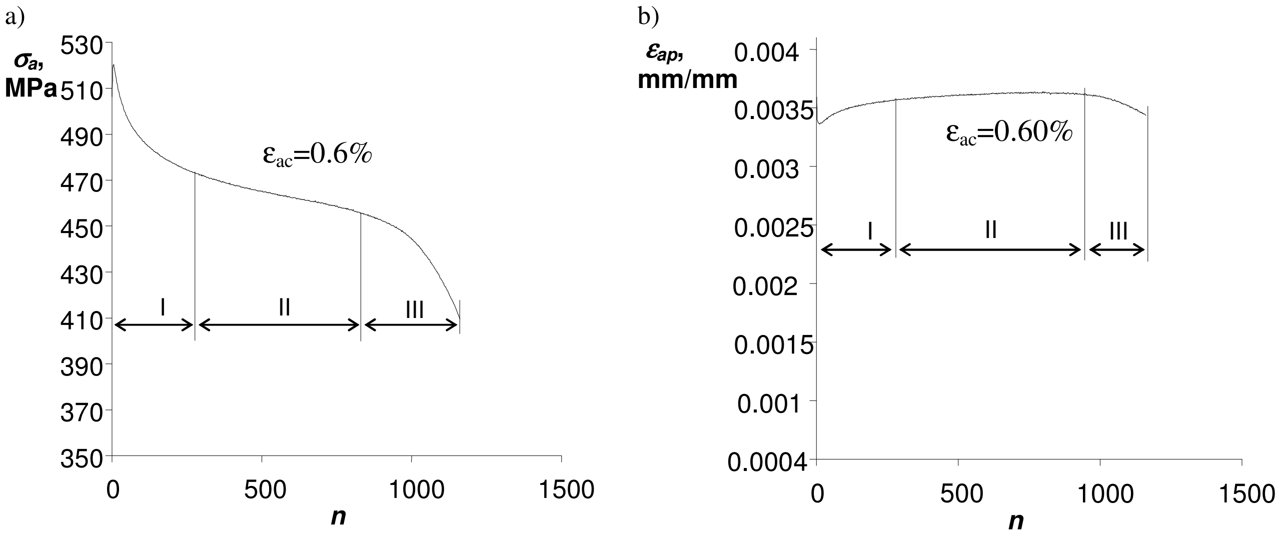


Fig. 6. Changes of hysteresis loop parameters for total strain level of ε_{ac}=0,6 %: a) $\sigma_a=f(n)$, b) $\varepsilon_{ap}=f(n)$

Basing on the analysis of diagrams (Fig. 5-6) it can be stated that independently on the level of total strain in the course of changes of the hysteresis loop parameters, three distinctive stages can be drawn:

Stage I – cast steel clearly softens. Characteristic feature of this stage is high speed of softening which decreases with increase of the number of cycles. Length of this stage depends on the level of strain and equals from 5 % of all cycles N_f until failure on the level of $\varepsilon_{ac}=0.25\%$ to about 25% of all cycles on the level of $\varepsilon_{ac}=0.60\%$.

Stage II – hysteresis loop parameters change insignificantly. Softening speed is constant. Length of this stage covers about 50% of all cycles until failure on the level of $\varepsilon_{ac}=0.60$ % and about 90% of all cycles on the level of $\varepsilon_{ac}=0.25$ %

Stage III – cast steel undergoes further significant softening, the speed of which increases. Crack initiation takes place here and eventually leads to fatigue failure. The length of this stage depends also on total strain level with the range from a few percent (for $\varepsilon_{ac}=0.60\%$) to 15% (for $\varepsilon_{ac}=0.25\%$) of all cycles until failure.

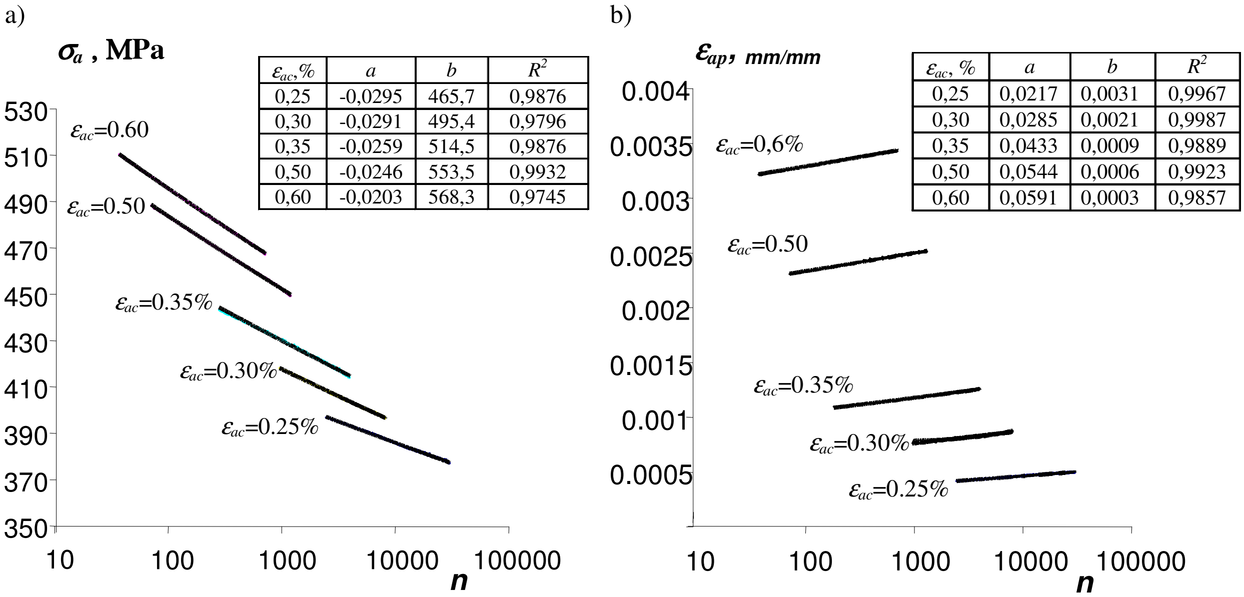
The characteristic stages of changes of cyclic properties of the martensitic cast steel can be observed both on the diagrams which depict changes of stress amplitude $\sigma_a=f(n)$ and diagrams of plastic strain changes $\varepsilon_{ap}=f(n)$. Independently on the total strain level, the stage II is always the longest stage.

An attempt was made of analytical description of changes of the hysteresis loop parameters for the stage II in the function of the number of loading cycles. Description was made in semi logarithmic coordinate system with the use of the following equations:

$$\sigma_a = a \cdot \log N + b \quad \text{- for stress } \sigma_a \qquad (1)$$

$$\varepsilon_{ap} = a \cdot \log N + b \quad \text{- for strain } \varepsilon_{ap} \qquad (2)$$

In Fig. 7 there are shown diagrams of the stress and the strain in the semilogarithmic coordinate system (semi-log plots log$N$-σ_a in Fig. 7a and log$N$-ε_{ap} in Fig. 7b) in the function of the number of cycles. The tables of slope values are also presented here.



a)

ε_{ac},%	a	b	R^2
0,25	-0,0295	465,7	0,9876
0,30	-0,0291	495,4	0,9796
0,35	-0,0259	514,5	0,9876
0,50	-0,0246	553,5	0,9932
0,60	-0,0203	568,3	0,9745

b)

ε_{ac}, %	a	b	R^2
0,25	0,0217	0,0031	0,9967
0,30	0,0285	0,0021	0,9987
0,35	0,0433	0,0009	0,9889
0,50	0,0544	0,0006	0,9923
0,60	0,0591	0,0003	0,9857

Fig. 7. Changes of hysteresis loop parameters during II stage of fatigue life: a) $\sigma_a=f(n)$, b) $\varepsilon_{ap}=f(n)$

Basing on the presented diagrams it can be stated that during stage II of fatigue process, changes of cyclic parameters can be approximated by power function. Confirmation of this fact are high values of coefficient of determination R^2. Moreover it can be stated that both parameters (ε_{ap} and σ_a) were constantly changing without visible stabilization period. Magnitude of changes of the hysteresis loop parameters depends on the total strain level. For the σ_a stress the most significant changes take place for the lowest total strain levels whereas for the plastic strain ε_{ap} the most significant changes are visible for the highest total strain levels. Changes of slope values in the function of total strain level ε_{ac} are shown in Fig. 8.

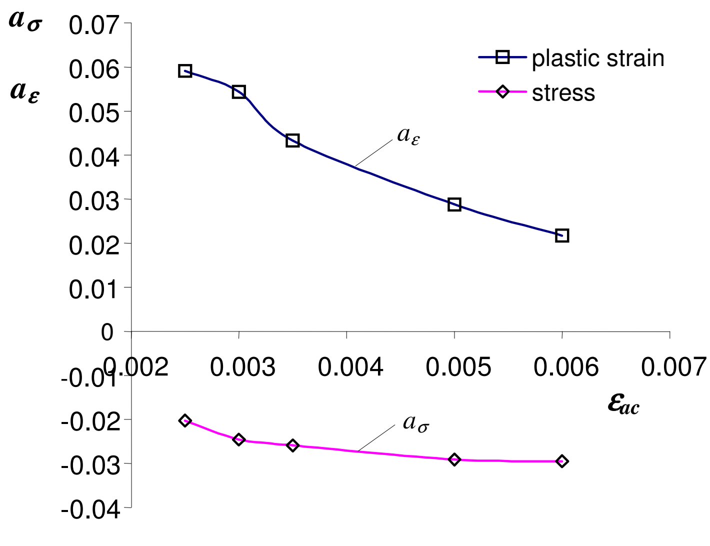


Fig. 8. Slopes of the regression line describing hysteresis loop parameters according to the level of total strain

The comparative analysis of the slopes values allows for a statement that among assumed hysteresis loop parameters changes in the function of the number of loading cycles are lower in the case of the stress amplitude σ_a for all accepted strain levels. Obtained results have very essential practical meaning. This is so because they confirm validity of conducting LCF tests under both controlled total strain (ε_{ac}=const) and stress (σ_a=const).

4. Conclusions

1. Martensitic cast steel is a material, which significantly softens during LCF tests. Process of softening is visible on all strain levels.
2. Course of the softening process can be divided into three characteristic stages with different speed of softening. Independently on the total strain level there always occurs the stage where the softening speed is constant. In this stage changes of the hysteresis loop parameters(σ_a and ε_{ap}) can be described by a power function.
3. Among hysteresis loop parameters, the one which is less sensitive to changes of cyclic properties of cast steel is the stress amplitude.
4. Lack of cyclic stabilization of the cast steel in the strain and stress approach demonstrates the need to search for other hysteresis loop parameters which would be insensitive to the changes of the cyclic properties. For example such a parameter is plastic strain energy described by the area of hysteresis loop. This parameter takes into account mutual interactions between stress and strain, therefore energy description is being accepted as more relevant than stress and strain description.
5. Conducted tests of the cast steel softening included only constant-amplitude loadings. In order to generalize formulated conclusions it is necessary to verify observations under irregular loadings.

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