T H E   A R C H I V E   O F   M E C H A N I C A L   E N G I N E E R I N G

Vol. L   2003   Number 4

Key words: *low – cycle properties, fatigue life, programmed loading*

STANISŁAW MROZIŃSKI)*

INFLUENCE OF LOADING PROGRAM SEQUENCE ON THE COURSE OF THE 45 STEEL STABILIZATION PROCESS

Results and low-cycle fatigue tests analysis of 45 steel in conditions of block programmed loading with a different sequence of levels were presented in the paper. During tests four types of programs were applied: gradually increasing, gradually decreasing, gradually increasing and decreasing, and irregular. The sequence of levels in the block loading program was the parameter, which diversified the applied programs. The results of tests were analysed in the aspect of influence of loading program character on the course of the stabilization process. The analysis of the stabilization process was performed by comparing the stress loading amplitude for the chosen levels of the program in the following blocks. The hardening index was proposed as a description of the stabilization process. The comparative analysis showed similarity of the stabilization processes both under the programmed and the constant – amplitude loading.

NOMENCLATURE

i – number of levels in the program,
k – current number of strain program repetition,
K' – coefficient of cyclic strain curve,
n – current number of cycles,
n_i – number of cycles for the ith strain level,
n_o – total number of cycles in the strain program (block contents),
n' – exponent of cyclic strain curve,
N – number of cycles to failure fatigue life under constant amplitude loading or programmed loading,

*) *University of Technology and Agriculture in Bydgoszcz, Faculty of Mechanical Engineering, Al. Prof. S. Kaliskiego 7, 85-763 Bydgoszcz, Poland; E-mail: stmpkm@atr.bydgoszcz.pl*

ε_{ac} – amplitude of the total strain,
ε_{ap} – plastic strain amplitude,
λ – number of the strain program repetitions to failure,
σ_a – stress amplitude [MPa],
σ_{as} – stress amplitude of stabilization state of material [MPa],
ζ – coefficient of spectrum density.

1. Introduction

One of the basic assumptions of the fatigue life calculation method based on local strain and stress analysis is stability of hysteresis loop parameters during cyclic loading. First works by prof. Kocańda team [2], [3], [4] based on fatigue tests of metal materials, pointed at changes of hysteresis loop parameters during constant-amplitude loading and connected with them, difficulties associated with defining the stabilization period of cyclic properties.

In the works carried out by prof. Szala and his co-workers [5], [6], [7], [11], [12] based on 45 steel tests in overloading conditions, the authors showed that after every change of the loading level there was a phenomenon of material hardening. The comparison of hysteresis loop before and after a change of the loading level revealed changes of cyclic properties of the material, and most of all, the loss of the stabilization state obtained at the previous level of loading. The changes of material properties were evaluated during axial loading and bending.

Loading courses applied in the tests, discussed before, considered simple two-level loading programs. In the case of an operating loading realization, we deal more often with a random sequence of amplitude values of loading cycles, average values and frequency. The research work performed in 1996–1998 by prof. J. Szala team [9], [10], [13] was concerned with the process of fatigue failure accumulation. Diversified loading programs and materials were applied during the tests. The work proved lack of stabilization of cyclic properties and imperfection of calculation methods based on the assumption of existence of stabilization period.

In the paper [7] by Mroziński (2003), based on constant- amplitude test results of aluminium alloy PA7, the author performed an analysis of stabilization process in energetic aspect. In this paper, the possibility of description of stabilization process with the use of n' and K' parameters defined in various life periods was observed.

The research problem is both a description of the course of cyclic properties changes during irregular loading and the possibility of anticipation of the course i.e. basing on the data obtained during constant-amplitude loading. Solving of the problems calls for a comparative analysis of the stabilization process course during irregular and constant-amplitude loading.

The basic aim of the paper is evaluation of the influence of different sequence levels of irregular loading on the course of the 45 steel stabilization process. The additional aim is the comparative analysis of the stabilization process during irregular and constant-amplitude loading.

2. Description of tests

Specimens for fatigue tests were made of standard 45 steel in accordance with ASTM standard [1]. Block programmed loading with a different sequence of levels in a block was applied during tests (Fig. 1):
Lo-Hi – increasing loading (Low-High),
Hi-Lo – decreasing loading (High-Low),
Lo-Hi-Lo – gradually increasing next decreasing (Low-High-Low),
I – irregular graduation (Irregular).

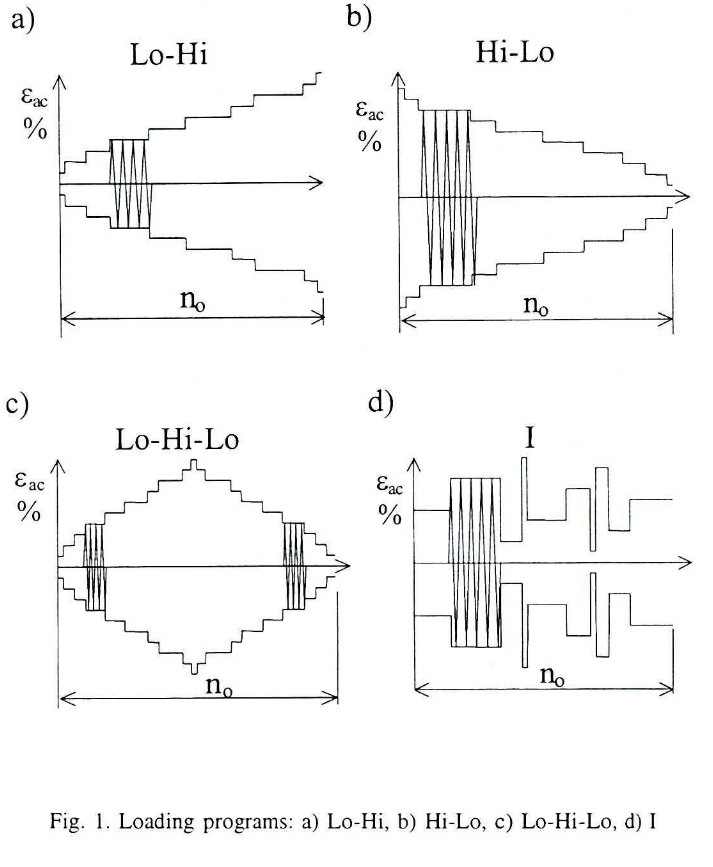


Fig. 1. Loading programs: a) Lo-Hi, b) Hi-Lo, c) Lo-Hi-Lo, d) I

The course of irregular random cycle sequence was the basis for elaboration of the block loading program. The distribution of amplitudes in the random course was achieved by using the beta distribution function

$$f(\varepsilon_{ac}) = \frac{1}{B(\alpha,\beta)}\varepsilon_{ac}{}^{\alpha-1}(1-\varepsilon_{ac})^{\beta-1} \tag{1}$$

where: B – beta function stated by the gamma function $B(\alpha,\beta) = \Gamma(\alpha)\Gamma(\beta)/\Gamma(\alpha+\beta)$,

α, β – parameters of the beta distribution.

Through the proper selection of α and β parameters, one could obtain an irregular course of loading, characterised by maximum amplitude value of the total strain ε_{acmax} in one block of loading program and the coefficient of spectrum density ζ:

$$\zeta = \sum_{i=1}^{i=10}\frac{\varepsilon_{aci}}{\varepsilon_{ac\max}}\frac{n_i}{n_o} \tag{2}$$

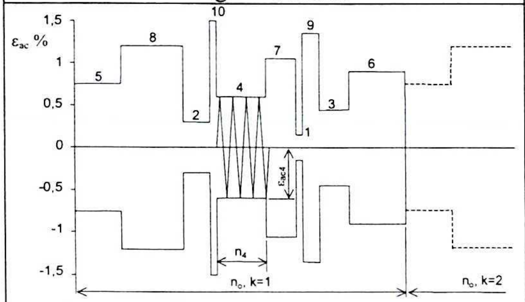
For distribution parameters $\alpha = 3$ and $\beta = 3$ we obtained $\zeta = 0.56$. The irregular course of strain was subjected to the cycle counting process by the peak counting method. The obtained block spectrum was used to elaborate loading programms with a different level sequence. Constant parameters for the used loading programs are shown and described in the table, based on the example irregular program "I".

Table 1

Parameters of loading programs

Table 1. Parameters of loading programs

Program scheme



Parameters

Level	$\varepsilon_{ac(i)}$ %	n_i	Rest
1	0,15	2	n_o=100 ζ =0,56
2	0,3	8	
3	0,45	9	
4	0,6	15	
5	0,75	14	
6	0,9	17	
7	1,05	9	
8	1,2	19	
9	1,35	5	
10	1,5	2	

Fatigue tests were performed on the servo hydraulic fatigue machine INSTRON 8501. The constant value of total strain increase of the measured part, equal to 1 %/s, was taken during the tests. The total strain of the specimen gauge part, measured with an extensometer, installed in the fatigue machine, was an operating parameter during the tests. The complete blocks, chosen for the tests were recorded during loading (100 cycles).

3. Test results

3.1. Fatigue life

Numbers of program blocks obtained for individual program types are presented in Table 2. The complete number of cycles, applied as the fatigue life, was that consisting of the cycles up to the moment at which there appeared 5% decrease of loading on the *ith* level" in relation to maximum loading at this level. The table also contains calculation results of fatigue life average values obtained for individual loading programs.

Table 2

Test results

Specimen number	Fatigue life							
	Lo-Hi		Hi-Lo		Lo-Hi-Lo		I	
	λ	N	λ	N	λ	N	λ	N
1	17.25	3450	17.84	3568	18.77	3754	14.15	2830
2	15.75	3150	14.5	2900	17.7	3540	15.1	3020
3	15.3	3060	15.33	3067	15.5	3100	15.8	3160
Average value	16.1	3220	15.89	3178	17.32	3465	15.02	3003

3.2. Cyclic properties in a block

Basic parameters values of the hysteresis loop, which are stress amplitude σ_a, plastic strain amplitude ε_{ap} and plastic strain energy ΔW_{pl}, were specified for the following recorded blocks of loading. In this work, in order to simplify the analysis, we limited it to stress σ_a. The courses of stress σ_a changes, in individual loading blocks, are shown as charts in Fig. 2.

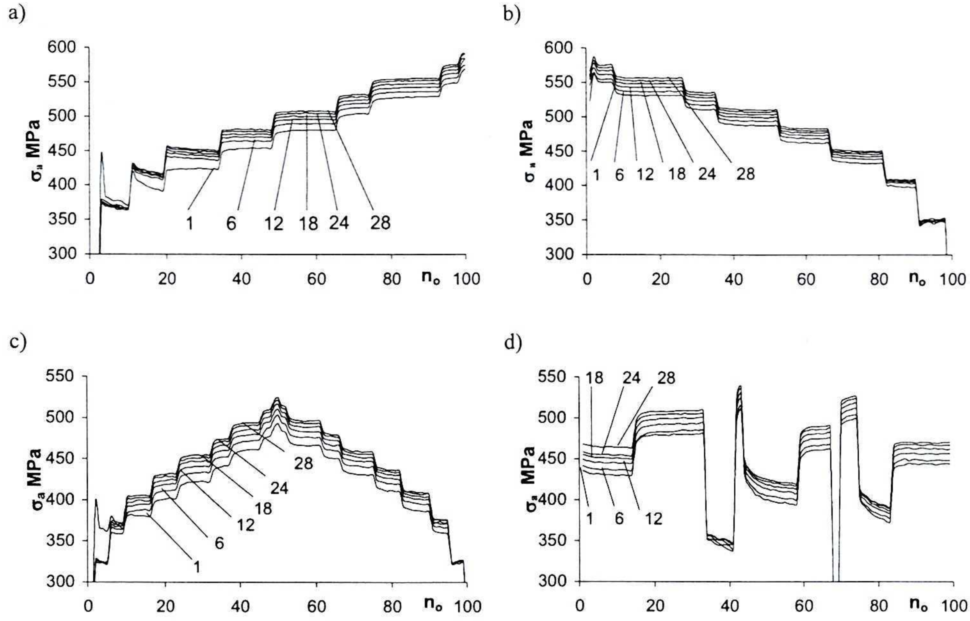


Fig. 2. Changes of σ_a in a block for a loading program: a) Lo-Hi, b) Hi-Lo, c) Lo-Hi-Lo. d) I

4. Analysis of test results

4.1. Fatigue life

As it was expected, the number of loading blocks λ, realised to the moment of crack, is similar for each type of loading. The variancy analysis was carried out for four average values of life obtained for individual types of loading programs. The analysis, performed at the a = 0.05 level of significance, proved that there were no grounds for rejecting the zero hypothesis about equilibrium of fatigue life average values obtained for individual loading programs. Basing on the obtained results we could state that the sequence of loading program levels did not influence the fatigue life. The fact that similar lives were obtained for diversified loading programs provided confirmation that only the sequence of levels in a program block decided about the stabilization process.

4.2. Cyclic properties

Basing on the analysis of σ_a courses in following blocks of loading we can state that, irrespectively of the loading program, the material exhibits cyclic hardening. The increase of the stress σ_a at the same levels of subsequent blocks of loading programs provides an evidence about it. The courses of the stress σ_a changes at individual levels of the realised programs were analysed in the work in detail. In Fig. 3–6 courses of σ_a were shown for two representative levels of programs with amplitudes ε_{ac} = 0.6% and 1.2%.

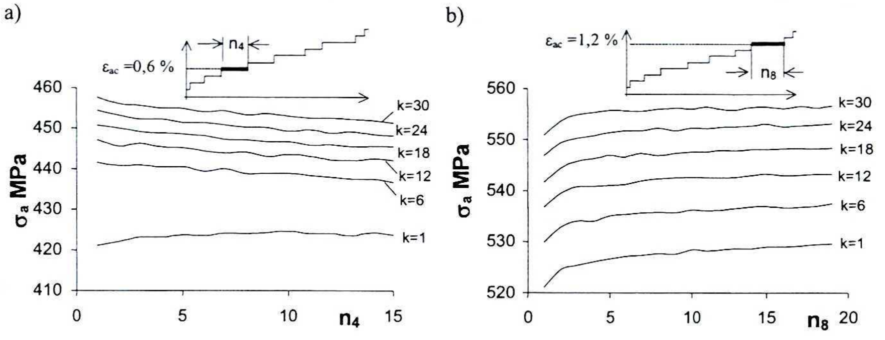


Fig. 3. Changes of σ_a, on two levels of the loading program Lo-Hi: a) ε_{ac} = 0.6%, b) ε_{ac} = 1.2%

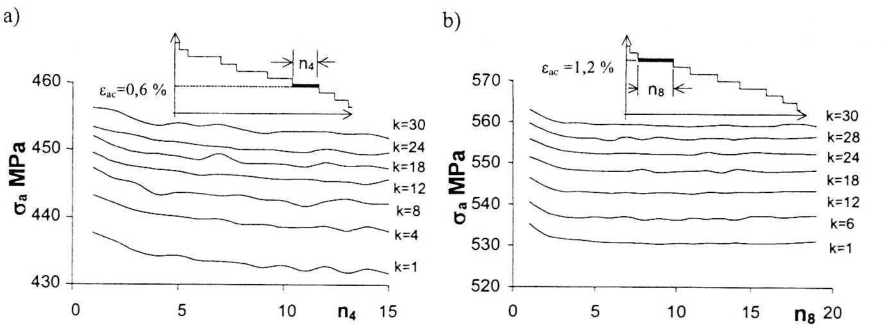


Fig. 4. Changes of σ_a, on two levels of the loading program Hi-Lo: a) ε_{ac} = 0.6%, b) ε_{ac} = 1.2%

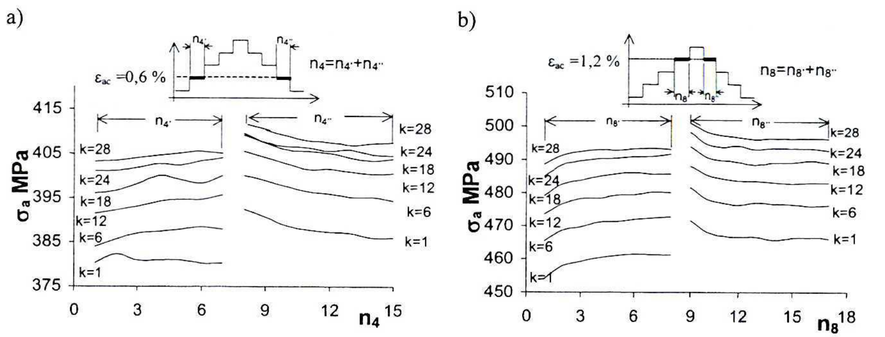


Fig. 5. Changes of σ_a, on two levels of the loading program Lo-Hi-Lo: a) ε_{ac} = 0.6%, b) ε_{ac} = 1.2%

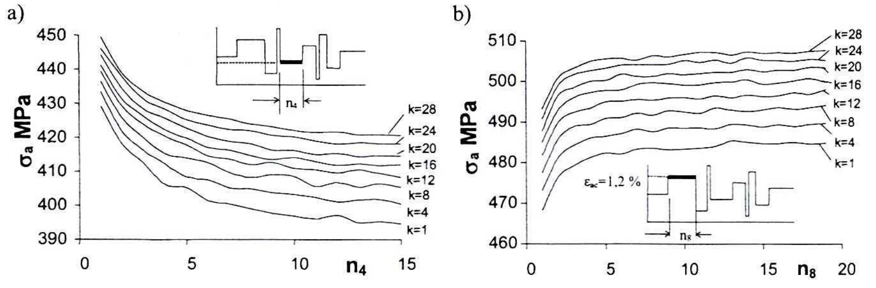


Fig. 6. Changes of σ_a, on two levels of the loading program I : a) ε_{ac} = 0.6%, b) ε_{ac} = 1.2%

The analysis of charts shown in Fig. 3–6 proves that the courses of σ_a changes depend on the loading program. The change of strain amplitude from the highest in the lowest one leads most frequently to a temporary softening of the material at the following level and obtaining a new level of stabilisation stress σ_{as} at that level. This stress is higher than the stabilisation stress obtained at the same level in the previous block. Moreover, the transition to the higher level of strain leads most frequently to the process of the material hardening, which gives a new stabilization stress σ_a. The stress is also higher than stabilisation stress for the same loading level in the previous block. Various courses are observed for strain changes in Lo-Hi and Lo-Hi-Lo programs at strain levels $\varepsilon_{ac} < 0.6\%$.

In spite of transition from the lower to the upper amplitude level, the material does not exhibit large softening at these levels. In order to illustrate this property, Fig. 7 shows the course of σ_a changes at the level $\varepsilon_{ac} = 0.45\%$ for the Lo-Hi program.

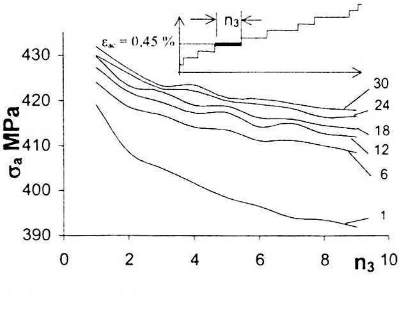


Fig. 7. Changes of σ_a, on the strain level ε_{ac} = 0.45% for the program Lo-Hi

Higher stabilisation stress σ_{as} at the level with ε_{ac} = 0.45 amplitude in following blocks shows that despite the temporary softening at this level, the material is under cyclic hardening.

The description of σ_a changes during Lo-Hi-Lo loading (Fig.6) needs a special attention. The courses of σ_a changes in this loading program have a different character than those observed during gradually increasing and then decreasing loading. The levels of stabilization stress σ_{as} at the same levels during increasing and then decreasing loading are not equal. Lower values of σ_a stress can be noticed during increasing loading while the higher ones appear during decreasing loading. The difference among stresses σ_a at the same level during decreasing and increasing loading decreases with the number of repetitions k of loading of program blocks. In Fig. 8 the above feature was illustrated for of 45 steel. The figure shows the course of σ_a changes in the last cycle of levels with the amplitude ε_{ac} = 0.6%, ε_{ac} = 1.2% during increasing and decreasing loading. It results from the position of the charts that the difference among stresses σ_a disappears in a final period of life.

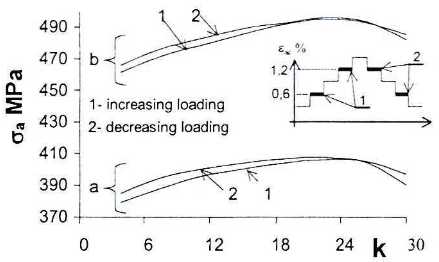


Fig. 8. Stress σ_a for Lo-Hi-Lo program on the end of levels ε_{ac} = 0.6% (a) and 1.2% (b)

Basing on the analysis of σ_a stress changes on individual levels of the program, we can notice that the parameter depends on a life period. The comparative analysis of the stress change value for individual levels of the block and constant-amplitude loading was done in the work.
The index of material hardening W_σ, expressed in percentages, was accepted to evaluate σ_a changes:
for block loading:

$$W_\sigma = \frac{\Delta\sigma_{a(i,k)}}{\sigma_{a(i,k=1)}} = \left(\frac{\sigma_{a(i,k)} - \sigma_{a(i,k=1)}}{\sigma_{a(i,k=1)}}\right)100\% \tag{3}$$

and for constant amplitude loading :

$$W_\sigma = \frac{\Delta\sigma_{a(n,i)}}{\sigma_{a(n=1)}} = \left(\frac{\sigma_{a(n,i)} - \sigma_{a(n=1,i)}}{\sigma_{a(n=1)}}\right)100\% \tag{4}$$

where:

$\sigma_{a(i,k)}$ – stress amplitude for the *ith* level and the *kth* block repetition of loading program,

$\sigma_{a(i,k=1)}$ – stress amplitude for the ith level and the first block repetition of loading program,

$\Delta\sigma_{a(i,k)}$ – the increase of stress amplitude σ_a for the *ith* level between the first and the *kth* block repetition of loading program,

$\sigma_{aa(n,i)}$ – stress amplitude for the *nth* cycle of constant amplitude loading with $\varepsilon_{ac(i)}$ amplitude,

$\sigma_{a(n=1,i)}$ – stress amplitude for the first cycle of constant amplitude loading with $\varepsilon_{ac(i)}$ amplitude,

$\Delta\sigma_{a(n,i)}$ – the increase of the stress amplitude σ_a between the first (n = 1) and the *nth* cycle of constant amplitude with $\varepsilon_{ac(i)}$ amplitude.

The graphic interpretation in Fig. 9 shows that the $\Delta\sigma_{a(i,k)}$ increases for block loading and the $\Delta\sigma_{a(n,i)}$ increases for constant amplitude loading.

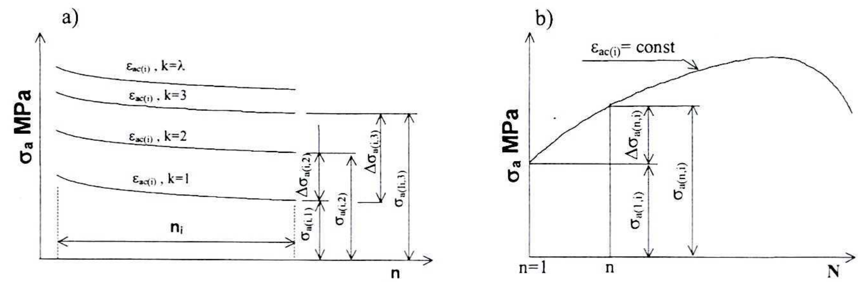


Fig. 9. $\Delta\sigma_{a(i,k)}$ for block program (a) and $\Delta\sigma_{a(n,i)}$ for constant-amplitude loading (b)

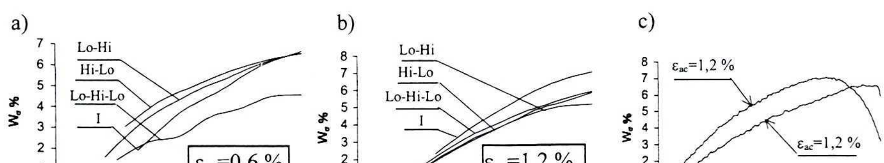


Fig. 10. Dependence of the index W_σ on life for loading: programmed (a), (b) and constant-amplitude (c)

The Fig. 10 shows the courses of the hardening index W_σ changes for two levels (ε_{ac} = 0.6% and ε_{ac} = 1.2%) of programmed and constant-amplitude loading in the function of relative live n/N, where: n – current number of the programmed or constant amplitude loading cycle; N – the number of cycles to the fatigue crack during programmed or constant-amplitude loading. The results of 45 steel tests in the conditions of constant-amplitude loading were taken from the paper [5].

The comparative analysis of the index W_σ for different programs and block levels (Fig. 10a and 10b) shows that its value does not depend significantly on the loading program, neither on the value of strain at the level. Small differences of the W_σ index for different loading programs in the same periods of life confirm this conclusion. For each of the realized programs, the W_σ index increases with the number of loading cycles. The increments of the W_σ index are smaller and smaller in the final stage of life. The comparative analysis of the hardening index value during programmed and constant-amplitude loading emphasizes the similarity in the range of the index course and its values in the same periods of life.

To compare directly the course of the hardening process taking place during constant-amplitude and block programmed loading we present the courses of σ_a in the function of relative live n/N in Fig. 11–14.

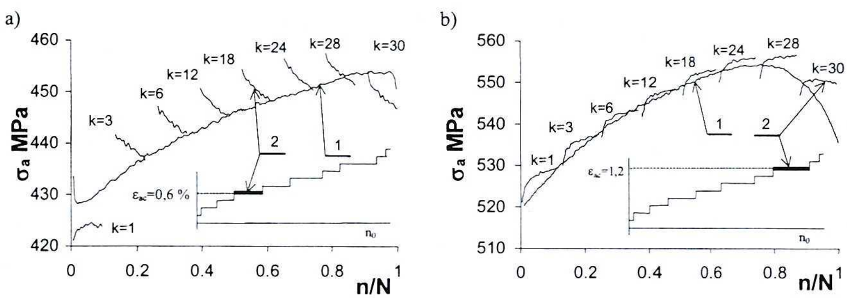


Fig. 11. Changes of σ_a on two levels of strain: ε_{ac} = 0.6% (a) and 1.2% (b), 1 – constant-amplitude loading, 2 – Lo-Hi loading

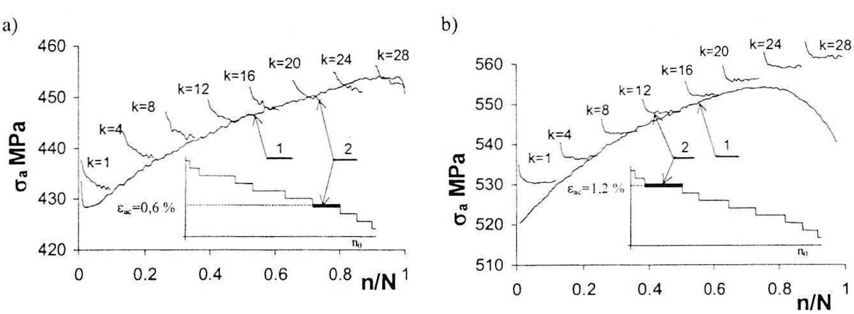


Fig. 12. Changes of σ_a on two levels of strain: ε_{ac} = 0.6% (a) and 1.2% (b), 1 – constant-amplitude loading, 2 – Hi-Lo loading

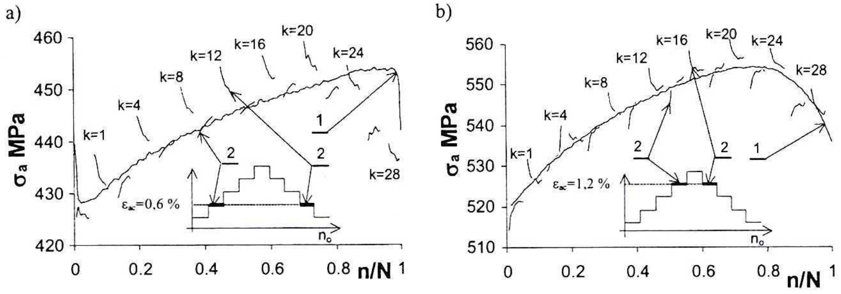


Fig. 13. Changes of σ_a on two levels of strain: ε_{ac} = 0.6% (a) and 1.2% (b), 1 – constant-amplitude loading, 2 – Lo-Hi-Lo loading

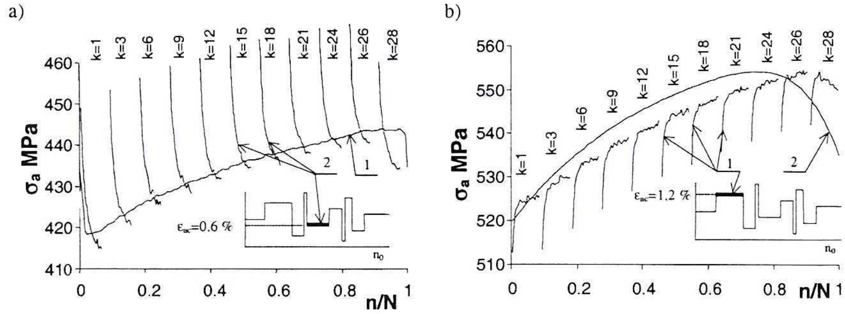


Fig. 14. Changes of σ_a on two levels of strain: ε_{ac} = 0.6% (a) and 1.2% (b), 1 – constant-amplitude loading, 2 – irregular loading I

Basing on the analysis of charts shown in Fig. 11–14, one can easily notice the quality and quantity similarity in the course of the stabilisation process during constant-amplitude and programmed loading. Stresses σ_a, which specify temporary properties during constant-amplitude and programmed loading, have similar values in the same life periods. The charts show that the material, despite disturbance of the stabilisation process by the change of strain amplitude, seems to "remember" the course of the stabilisation process recorded in the material structure. In σ_a change charts drawn for programmed loading, one can see very clearly that there is a trend of changes of cycle properties. The trend of changes is very similar to the course of the process of cyclic properties changes, which appears during constant-amplitude loading. It is visible for each loading program realised during tests. Stresses a obtained in the final cycles of level loading with the amplitude ε_{ac} = 0.6% and ε_{ac} = 1.2% approache the stress level corresponding to σ_a stress for constant-amplitude loading.

The above observation may have serious practical consequences, because it reveals the possibility of predicting the course of stabilization process of the material under usage loading on the basis of a similar process for constant amplitude loading. The knowledge of the course of stabilization process of the material under usage loading may allow for performing fatigue life calculations taking into consideration the processes of hardening, softening or stabilization occuring in the material. Such an approach to the problem of fatigue life calculations may be of special importance in the case of fatigue life calculations of construction elements made of materials which are characterised by the lack of stabilization period (aluminium and copper alloys). The only difficulty of such an approach lies in the necessity to define the low-cycle data according to ASTM [1], for example n' and K', not for one period (stabilization period) but for various life periods. The proposal of the method defining material data in various life periods was presented in the paper [8].

5. Conclusions

The analysis of test results let us formulate the following conclusions:

1. The sequence of levels of the block loading program does not influence fatigue life.
2. During programmed loading likewise during constant-amplitude loading of 45 steel, there is no stabilisation period of cyclic properties. That is why there are doubts about the fatigue life calculation method basing on the assumption of existence of cyclic properties stabilisation period.
3. The level sequence of the loading program influences the course of the cyclic properties stabilisation process of 45 steel at levels of the block loading program. The changes of cyclic properties that appear in the material, consisting in temporary hardening or softening, depend on the strain amplitude of levels.
4. The course of the cyclic hardening process which appears during constant-amplitude and programmed loading, analysed by means of the σ_a stress amplitude, shows the quality similarity that applies to temporary values of the parameter in the same periods of life.
5. The material (45 steel), which was used during tests was characterized by cyclic hardening in various loading cycles. The evaluation of stabilization process was performed with the use of only one parameter, the stress σ_a. In order to formulate general conclusions, it would be necessary to perform verification tests using materials of variable cyclic properties and formulate other descriptions of fatigue processes like strain description or energetic description.
6. Similarity of the course of the stabilization process during programmed and constant-amplitude loading let us formulate the thesis on possibilities

of anticipation of temporary cyclic properties of the material during service loading on the basis of the data obtained from the standarized tests (constant-amplitude loading in accordance with, for example, ASTM and PN standards).

Manuscript received by Editorial Board, June 24, 2003;
final version, January 20, 2003.

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Wpływ sekwencji programu obciążenia na przebieg procesu stabilizacji stali 45

Streszczenie

W pracy zamieszczono wyniki oraz analizę niskocyklowych badań zmęczeniowych stali 45 w warunkach obciążeń programowanych blokowych o różnej sekwencji stopni. Podczas badań stosowano cztery typy programów: stopniowo narastające, stopniowo malejące, stopniowo rosnące a następnie malejące oraz obciążenia o nieregularnej kolejności stopni. Wyniki badań analizowano w aspekcie wpływu postaci programu obciążenia na przebieg procesu stabilizacji. Analizę procesu stabilizacji prowadzono porównując amplitudę naprężenia dla wybranych stopni programu w kolejnych blokach. Do opisu procesu stabilizacji zaproponowano w pracy wskaźnik umocnienia. Analiza porównawcza wskaźnika uwidoczniła podobieństwo przebiegu procesu stabilizacji podczas obciążeń programowanych oraz stałoamplitudowych.