MECHANIKA TEORETYCZNA
I STOSOWANA
Journal of Theoretical
and Applied Mechanics
4, 31, 1993

AN ANALYSIS OF THE INFLUENCE OF OVERLOADS ON THE FATIGUE LIFE OF 45-STEEL WITHIN THE RANGE OF LOW-CYCLE FATIGUE

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The results of our investigations into the influence of overloads on a fatigue life and the course of some phenomena concomitant with a fatigue process within the range of low-cycle fatigue are presented in this paper. Overloads were realized as a block of cycles or single cycles with amplitudes significantly greater than the base strain amplitude. Investigations were performed for the base total strain $\varepsilon_{ac} = 0.008$, whereas overloads were realized at levels: $\varepsilon_{ac_p} = 2.0\varepsilon_{ac}$; $2.5\varepsilon_{ac}$; $3.0\varepsilon_{ac}$, respectively. An analysis of the test results showed that in all cases of overloads the fatigue lives of specimens were less than the one obtained under the base strain conditions. The value of fatigue life depended on the load program. In all cases general hardening followed, as a result of overload, while an analysis of stress courses against the total strain in phase with overload amplitude changes, showed the existance of typical ranges of hardening, stabilization (relaxation, saturation) and softening. What can be treated as an evidence of a change in the fatigue properties of 45-steel as a consequence of overload.

Notations

ε_{ac}	–	amplitude of total strain in the case of constant amplitude loading
ε_{ac_p}	–	amplitude of total strain in the case of overloads
$k = \varepsilon_{ac_p}/\varepsilon_{ac}$	–	overload coefficient
ε_{ap}	–	amplitude of plastic strain
ε_{ae}	–	amplitude of elastic strain
σ_a	–	stress amplitude of the base loading MPa
σ_{ac_p}	–	stress amplitude of overload cycles MPa
σ_{as}	–	stress amplitude of stabilization state of material MPa

N_f – number of cycles until fatigue failure
N_1 – number of cycles from the begining until occurance of a single overload or a block of overloads
N_p – number of single overloads in a block of overloads
ΔN – number of cycles between single overloads or between overloads blocks
N_2 – number of cycles between the last overload and the number of cycles until fatigue failure N_f
N_{pc} – total number of overloads during fatigue tests.

1. Introduction

From an analysis of reference data, it follows that the present methods of calculation of construction parts fatigue lives are based on the results of fatigue investigations in the range of low-cycle fatigue and that the results of these investigations are presented as a function of cycle number against a total strain (cf Kocańda, 1985; Kocańda and Kocańda, 1989) or of a cycle number against a dissipation energy (cf Kujawski, 1984; Ellyin and Fakinlede, 1985; Gołoś and Ellyin, 1988; Kaleta et al., 1991). The methods mentioned above can be divided into several following catagories: methods in which the period until the initiation of fatigue crack is taken into account (so-called: initiative methods), methods in which only the range of crack propagation is taken into account (so-called: propagative methods) and more detailed methods in which both periods (ie. time until initiation and range propagation) are considered (so-called: initiative-propagative methods), Majumdar and Morrow (1974), Glinka (1981), Skorupa and Skorupa (1986).

Using methods in which the range until crack initiation is considered (initiative and initiative-propagative ones alike), data determined upon the hysteresis loop of saturation range are used in the calculations of fatigue parameters (stress and strain) in notch (cf Neuber, 1961; Seeger and Heuler, 1980; Dowling, 1982). In the case of the fatigue lives for construction parts calculations, with complex geometrical forms (in the case of random loading), there exists an anxiety (among manufactures) concerning the lack of a range of stabilization of fatigue parameters in the meaning of the stabilization of these parameters (that is, in the case of sinusoidal loading with constant amplitude of total strain). The analysis of these phenomena can be partly performed basing on the results of fatigue investigations in the range of low-cycle fatigue using load programs which contain, however, different-shaped overloadings.

Reference data showed that the effects of overloads depend on loading conditions. Results of fatigue investigations within the range of low-cycle fatigue of notched specimens made of 45-steel after normalization were presented by Szala (1978). These investigations showed that the influence of the loading program form (i.e. sequence and levels of stress cycles) is insignificant in the range of stress amplitudes close to the fatigue limit. However this influence increases with an increase in stress amplitudes and in the range close to the low-cycle fatigue reaches the highest level (in extreme cases more than 100%). Aurzednik (1981) describes investigations into high-cycle range, in which overloads in a form of overload blocks with strain cycle amplitudes lying within the range of low-cycle fatigue ($\varepsilon_{ac_p} = 0.008$), have been enclosed. The significant influence of existence of overload blocks on a fatigue life has been already apparent.

In the aforementioned works, an influence of overloads on a stabilization of stress-strain hysteresis loop was not considered. The lack of this data makes it impossible to make proper assumptions for counting methods of a fatigue life of notched specimens under conditions of a variable amplitude loading. But first of all, it makes it impossible to prove the influence of the assumption concerning a hysteresis loop stabilization on the results of a fatigue life calculations.

The aim of investigations presented in this paper is, therefore, an evaluation of the influence of different forms of overload programs on a fatigue life and on the course of phenomena – hardening, stabilization and softening of normalized 45-steel in the range of low-cycle fatigue for both overload cycles and cycles of base loading.

In this paper, an overload is called a cycle or a block of cycles in which a total strain amplitude or a plastic strain amplitude increases significantly under conditions of controlled strain. Overloads can be described by the overload coefficient $k = \varepsilon_{ac_p}/\varepsilon_{ac}$.

2. Description of investigations

Normalized, 45-steel was applied to the investigations. Strength parameters and chemical constitution is presented in Tables 1 and 2, respectively. The specimen, used in the investigations, is presented in Fig.1.

Table 1. Chemical constitution of normalized 45-steel

C [%]	Mn [%]	P [%]	S [%]	Si [%]	Mo [%]	Cr [%]	Ni [%]	Fe %
0.476	0.593	0.015	0.027	0.201	0.047	0.160	0.116	98.1

Table 2. Mechanical parameters of normalized 45-steel

Rm [MPa]	Re [MPa]	A_5 [%]	Z [%]	HB
730	435	25	44	190

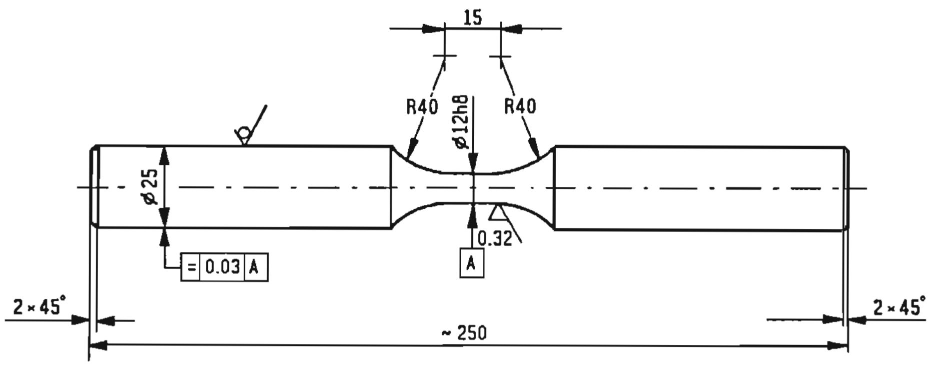


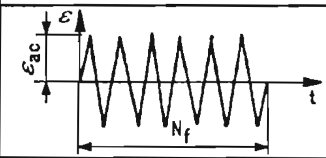
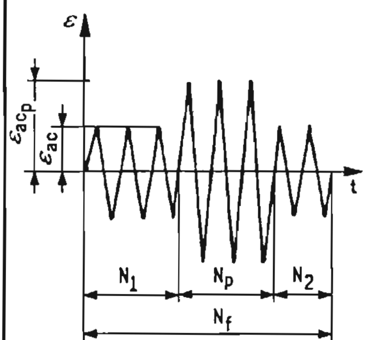
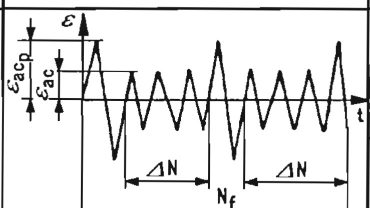
Fig. 1. The test specimen

During the investigations, the following three types of loading programs were used: constant amplitude tests, tests applying an overload block and with an application of the single overload, respectively. Constant amplitude histories and histories with overloads consisted only of oscillatory cycles. The schemes of loading programs and variants of their realization are presented in Table 3.

Fatigue investigations were performed using an MTS-SYSTEM strength-testing machine. A hydraulic cylinder (servo) which makes it possible to reach forces of $P_{\max} = 25 \cdot 10^3$ daN at frequencies up to $f_{\max} = 70$ Hz is a part of the machine. The computer PDP m-11/01, which allows us to control a fatigue test upon an assumed load program and to record test results, is an integral part of the test machine.

Constant amplitude tests (program 1) were carried out for five different values of a total strain in accordance with the polish standard PN-84/H-04334. The following values of total strain ε_{ac} were assumed: 0.02, 0.01, 0.008, 0.005, 0.0035. Three fatigue tests were performed for every value of a total strain. Changes in specimen strains were measured using the MTS strain gange with the measurement base equal 10 mm. Tests were performed using frequency $f = 0.2$ Hz. The first three hysteresis loops were recorded and then these which revealed a process of cyclic softening, hardening or initiation of a fatigue crack. The time of sampling was 0.025 s. A 2% decrease of the peak stress after a range of stabilization of fatigue properties was assumed as the criterion of the failure. Values of changes of strain and force were recorded on a computer hard disc.

Table 3. The loading programs used during tests

No.	Scheme of the loading program	Values of parameters: variable	Values of parameters: constant
1		ε_{ac} = 0.0035 ε_{ac} = 0.005 ε_{ac} = 0.008 ε_{ac} = 0.01 ε_{ac} = 0.02	f = 0.2 Hz R = -1
2		ε_{ac_p} = 2.0 ε_{ac} ε_{ac_p} = 2.5 ε_{ac} ε_{ac_p} = 3.0 ε_{ac}	ε_{ac} = 0.008 N_1 = 650 N_p = 10 f = 0.2 Hz
		N_p = 10 N_p = 20 N_p = 30	ε_{ac} = 0.008 ε_{ac_p} = 2.5 ε_{ac} N_1 = 650 f = 0.2 Hz
		N_1 = 0 N_1 = 300 N_1 = 600 N_1 = 900	ε_{ac} = 0.008 ε_{ac_p} = 2.5 ε_{ac} N_p = 20 f = 0.2 Hz
3		—	ε_{ac} = 0.008 ε_{ac_p} = 2.5 ε_{ac} N = 50 f = 0.2 Hz

Investigations of the influence of overloads on stabilization, hardening and softening were carried out at one level of base strain $\varepsilon_{ac} = 0.008$. This strain level was assumed taking into consideration an analysis of charts of static and cyclic tension (Fig.4) as included in the range of cyclic stabilization of 45-steel. Values N_1 in programs 2a and 2b were set at $N_1 = 0.5 \cdot N_f$ i.e. on the level of the base strain without overloads.

Values of all parametres for realized programs are shown up Table 3.

3. Analysis of the results

3.1. Results of constant amplitude tests

Numbers of cycles until fatigue failure for different levels of total strains are shown in Table 4.

Table 4. N_f number of cycles until fatigue failure occurs

ε_{ac}	0.0035	0.005	0.008	0.01	0.02
Test No.	Fatigue lives N_f obtained during the tests				
1	12000	4200	1300	650	85
2	11750	4150	1350	620	80
3	12050	3825	1300	615	86

Changes in total strain amplitude were described, in accordance with the polish standard PN-84/H-04334, using the following formula

$$\frac{\Delta\varepsilon_{ac}}{2} = \frac{\Delta\varepsilon_{ap}}{2} + \frac{\Delta\varepsilon_{ae}}{2} = \varepsilon'_f(2N_f)^c + \frac{\sigma'_f}{E}(2N_f)^b \tag{3.1}$$

where

- $\Delta\varepsilon_{ac}$ – range of total strains
- $\Delta\varepsilon_{ap}$ – range of plastic strains
- $\Delta\varepsilon_{ae}$ – range of elastic strains
- ε'_f – cyclic plastic strain coefficient
- σ'_f – fatigue strength coefficient
- c – index of a cyclic plastic strain
- b – index of a fatigue strength
- $2N_f$ – number of loading reverses.

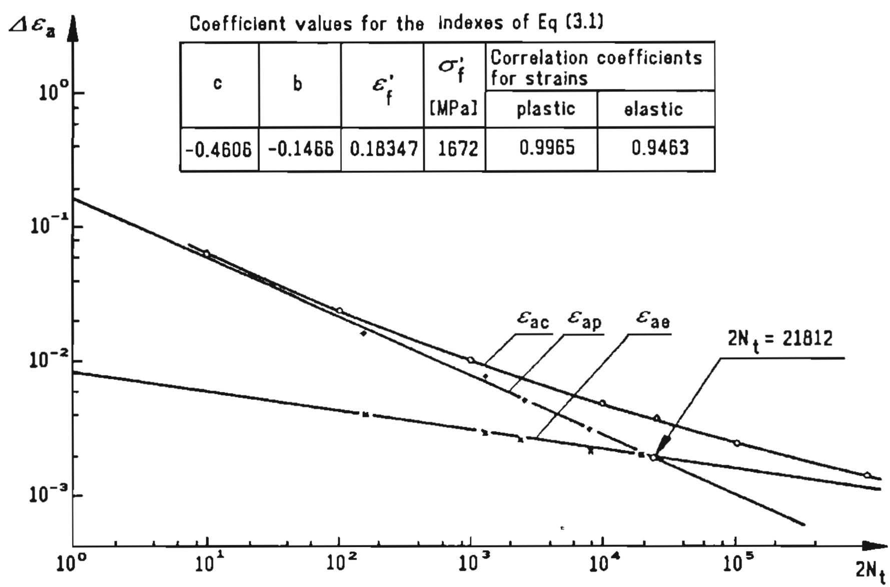


Fig. 2. Changes of strains ε_{ac}, ε_{ae}, ε_{ap} as a function of number of loading reverses $2N_f$

Amplitude changes of plastic strains ε_{ap} and elastic strains ε_{ae} were approximated using straight lines. An amplitude of total strain ε_{ac} was calculated in terms of these two components. The courses of the changes in strains ε_{ac}, ε_{ap}, ε_{ae} described by the formula (3.1) as well as the values of coefficients and indexes are presented in Fig.2. An analysis of hereto shown results allows us to notice a high correlation coefficient for approximated (using straight lines) plastic and elastic strains. Obtained values of indexes (b and c) were included in intervals expected for this grade of steel.

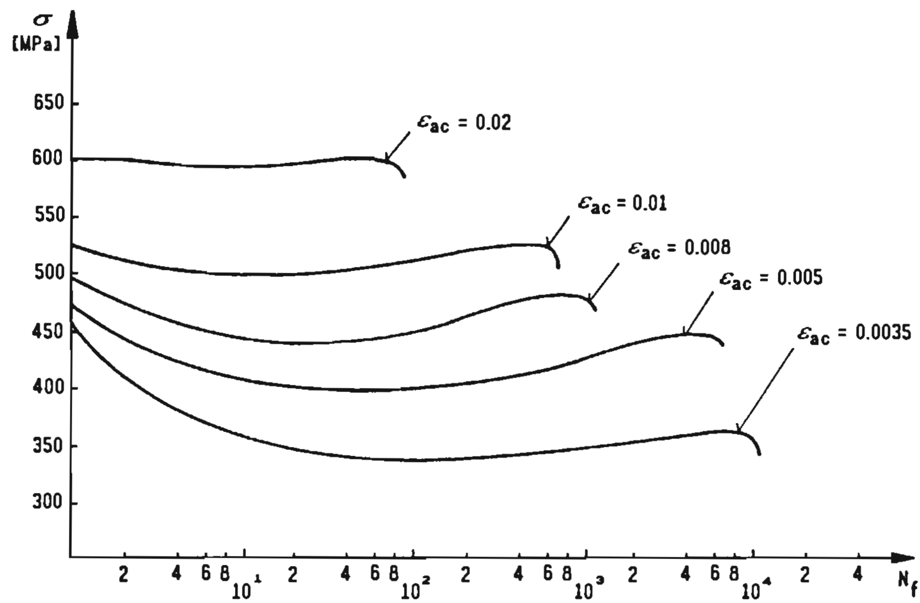


Fig. 3. Changes of stress amplitude as a function of number of cycles, for different values of total strain ε_{ac}

An interesting course is seen in the changes of stress amplitude considered as a function of cycles number for particular loading levels (Fig.3). This material, up to $0.20N_f$ shows a cyclic softening. Next, after a range of stabilization, hardening occurs (up to approximately $0.9N_f$), next phases are: stabilization, rapid softening and the failure of specimen. For significant total strains $\varepsilon_{ac} = 0.02$ and $\varepsilon_{ac} = 0.01$, the decrease in stress amplitude within the softening period is equal to the increase of the amplitude within the hardening range. Whereas, for strains from $\varepsilon_{ac} = 0.0035$ to $\varepsilon_{ac} = 0.008$ considerably greater amplitude differences are characteristic for the range of softening. This tendency is distinct and becomes more distinct as ε_{ac} diminishes.

Such changes were confirmed by the mutual position of curves of cyclic strain and static tension (Fig.4). An evaluation of the stress of saturation σ_{as} (necessary

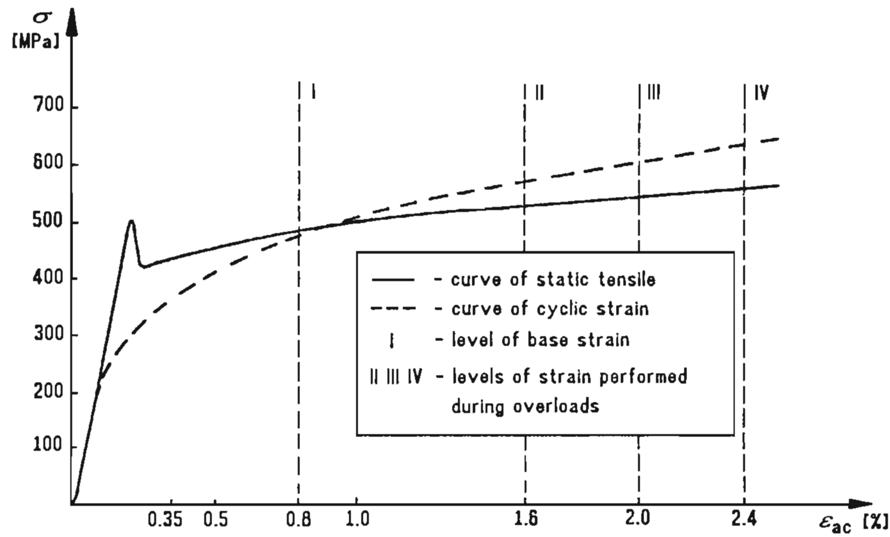


Fig. 4. Charts of cyclic strain and static tensile

for drawing a cyclic strain chart) is generally accepted upon the first range of stabilization. Looking at the chart, it can be stated that strains with amplitudes $\varepsilon_{ac} = 0.0035$ and $\varepsilon_{ac} = 0.005$ cause the softening of material. For strains $\varepsilon_{ac} = 0.008$ and $\varepsilon_{ac} = 0.01$, stabilization is characteristic for this steel. However, for strains ε_{ac} greater than 0.01 the steel displays a slight hardening.

3.2. Results of tests with overloads

3.2.1. Influence of the overload ε_{ac_p} amplitude

Results of investigations performed for different values of overload amplitudes are set in Table 5. Changes of maximum stress in half-cycle of tension for constant amplitude loading and loading with the overload block (program 1a), respectively, are shown in Fig.5. A course of stress changes for a loading with an overload block can be divided into three stages: up to the occurance of the overload block, the overload block and the stage after the occurance of the overload block. In the first stage, the course of phenomena is analog to constant amplitude tests i.e. softening, stabilization and gradual hardening. The block of overloads occurs during the hardening process. It is characterized by the slight increase of stress amplitude within the first four cycles of overload, and the further stabilization. After the block of overloads, material shows the ranges of softening and stabilization ($\varepsilon_{ac_p} = 0.024$), softening, stabilization and slight hardening until reaching the renewed stabilization ($\varepsilon_{ap} = 0.02$ and $\varepsilon_{acp} = 0.016$), respectively. After these ranges, a very quick softening occurs and then the failure of specimen takes place. The course of these phenomena is similar for all overload levels. Differences concern only the time of particular ranges (number of cycles) and the value of stabilizatin stress σ_{as} after overload. The greater the value of strain amplitude during overload is, the greater is the stress level σ_{as}.

Table 5. Fatigue lives for different values of amplitude ε_{acp}

No.	Amplitude of the base cycle ε_{ac}	Amplitude of the overload cycle ε_{acp}	Number of cycles in the block N_p	Position of the block N_1	N_f
1	2	3	4	5	6
1					875
2		0.016			1200
3					1250
4					1000
5	0.008	0.02	10	650	1100
6					1025
7					775
8		0.024			1040
9					950

Comparing the courses of the stress-amplitude chart after overload with the base chart (constant amplitude loading), we can state that such phenomena like: softening, stabilization or hardening at the stage after occurance of overload block take place under higher stresses than in the case of the base history for the same numbers of loading cycles.

Based on the results being obtained, it can be found that the value of overload influences on the fatigue life and on the courses of such phenomena like hardening, softening and stabilization which occure during a fatigue test. Changes of stress amplitude in the overload block for the tensile half-cycle have the same form at different values of amplitude ε_{ap}.

3.2.2. Influence of a number of overloads

The results of investigations into the influence of the number of overloads on fatigue life are drawn up in Table 6. Changes of maximum stress in tensile half-cycle in the case of constant amplitude loading and loading with an overload block (program 2b), respectively are shown in Fig.6. Similarly, as in the case of testing the influece of overload amplitude value on stabilization, hardening and softening, also in this case only the stage of overload block and the stage after the occurance of overload can be analyzed. During the realization of the overload block, there

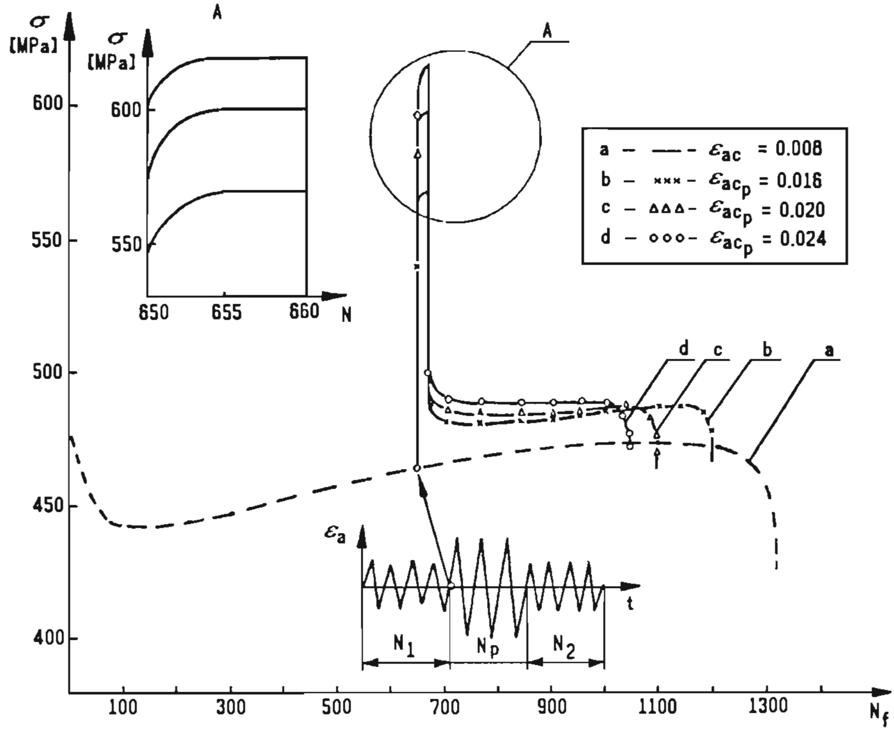


Fig. 5. Changes of stress amplitude after occurance of the overload block consisting of $N_p = 10$ cycles, for different values of the overload amplitude ε_{ac_p}

can be observed the occurence of: a hardening range for 10 overloads, ranges of hardening and stabilization for 20 overloads and ranges of hardening, stabilization and slight softening for blocks consisting of 30 overloads.

At the stage after overload, the following phenomena are characteristic: occurence ranges of softening, stabilization, short-duration stabilization and hard softening under the overload block consisting of 10 cycles; the occurence only of ranges of stabilization and softening under the overload block consisting of 20 cycles and the occurence only of ranges of hardening under the overload block consisting of 30 cycles. The decrease in the fatigue life is (obviously) a result of the shortening of the stabilization and hardening ranges (soccesing after the overload), under the overload block consisting of 20 and 30 cycles.

Comparing three courses of stress amplitude presented above, it can be stated that they differ, similarly as in program 2a, in values of the stabilization stress amplitudes σ_{as} after occuring of the overload. Higher values of σ_{as} are obtained for higher number of cycles in the overload block.

Table 6. Fatigue lives for different numbers of overload cycles N_p

No.	Amplitude of the base cycle ε_{ac}	Amplitude of the overload cycle ε_{ac_p}	Number of cycles in the block N_p	Position of the block N_1	N_f
1	2	3	4	5	6
1					1000
2			10		1100
3					1025
4					825
5	0.008	0.02	20	650	800
6					1000
7					800
8			30		750
9					750

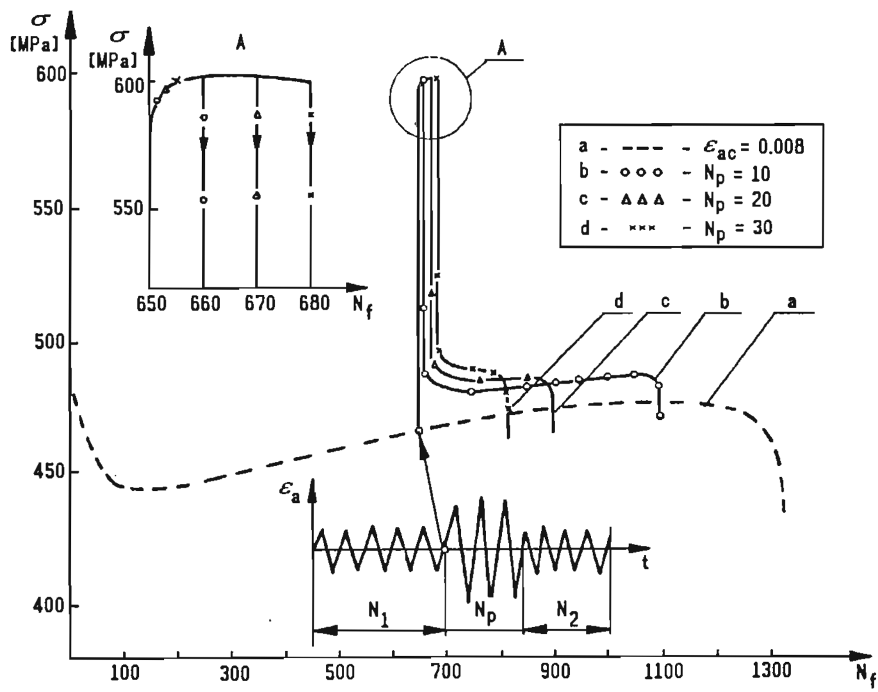


Fig. 6. Changes of stress amplitude after occurance of the overload block with the amplitude $\varepsilon_{ac_p} = 2.5\varepsilon_{ac}$, for different number of cycles in the overload block

3.2.3. Influence of position of overload occurence

Results of fatigue life investigations for different positions of the overload block are presented in Table 7.

Table 7. Fatigue lives for different positions of overload block

No.	Amplitude of the base cycle ε_{ac}	Amplitude of the overload cycle ε_{ac_p}	Number of cycles in the block N_p	Position of the block N_1	N_f
1	2	3	4	5	6
1	0.008	0.02	20	0	665
2					950
3					925
4				300	700
5					950
6					825
7				600	825
8					800
9					950
10				900	904
11					990
12					950

Changes in amplitude of nominal a stress in tensile half-cycle for the base loading and for different variants of position of the overload block (program 2c) are shown in Fig.7. An analysis of a changes of nominal stress amplitude for four histories displays significant differences among them. These differences concern the overload block and the stage after overload. Whereas, in the case of the overload block, the differences concern the values of maximum stress in tensile half-cycle for different positions of the overload block. An increase in this stress for higher N_1 values can be observed. A form of changes in the mentioned stress is the same for particular tests i.e. an increase in the stress during the first four cycles and then stabilization. An analysis of stress changes (after overload block) also displays signifficant differences. In the case of an overload block which occured at the beginning ($N_1 = 0$), after overload, the material shows softening, stabilization, hardening and then softening until fatigue failure. The hardening stage disappears when N_1 increases and for $N_1 = 900$ only softening occurs.

The position of a block influences the stress level on which the phenomena take place. The greater N_1 is the greater is the stabilization stress after the overload.

Based upon comparison between the analysis of histories with overload and the base history, we can state that the overload block realized at different stages of specimen: the history "e" at the beginning of the test, the history "d" at

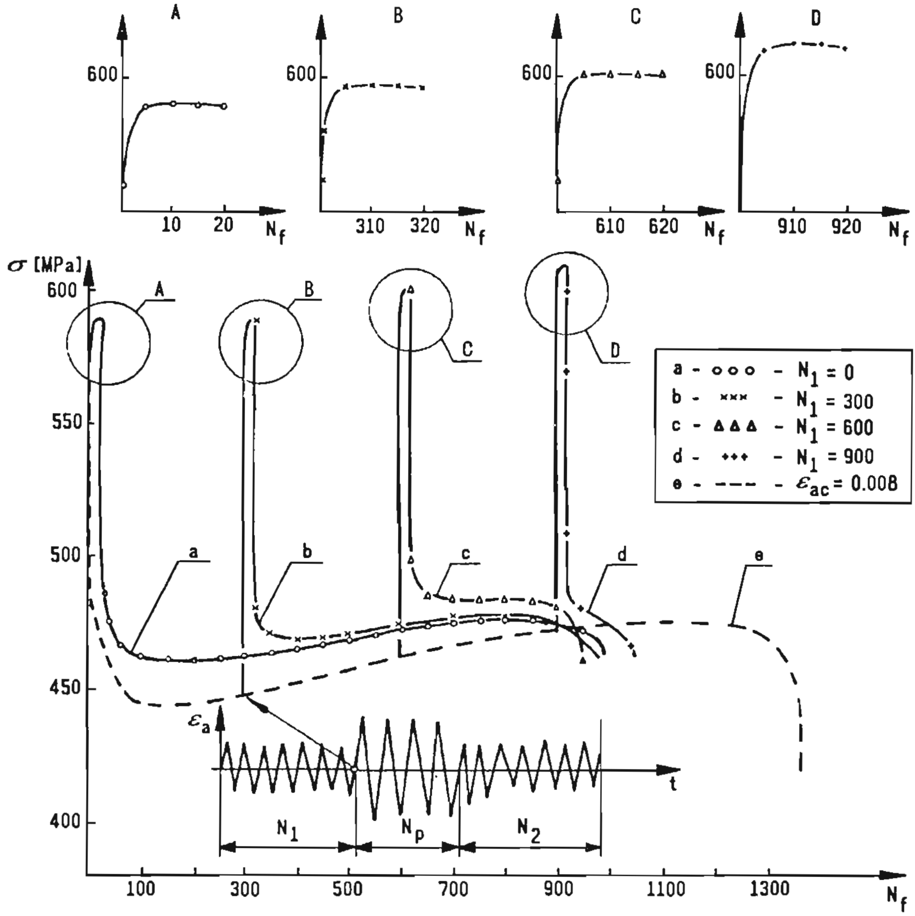


Fig. 7. Influence of position of the overload block, consisting of $N_p = 20$ cycles, on changes of a nominal stress amplitude after the overload

the stabilization stage, the history "c" at the hardening stage, the history "b" at the stabilization stage. Results obtained upon these tests and the previous results allow us to state that the position of the overload block influences, in a slight degree, the behaviour of the material after the overload. The graphical presentation of influence of the overload block position on the low-cycle fatigue life is shown in Fig.8. An analysis of the chart allows us to state that the overload blocks (with parameters shown in Table 3) cause near 35 % decrease in the fatigue life. We can additionaly notice that this decrease is equal for different positions of a block.

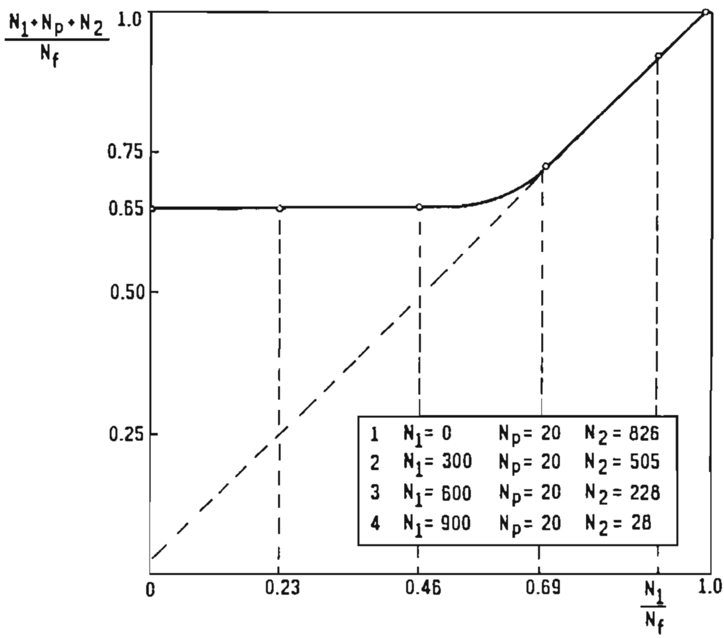


Fig. 8. Influence of the overload block position on a fatigue life

3.2.4. Influence of single overloads

Results of investigations into the influence of single overloads on a fatigue life are shown in Table 8.

Table 8 Fatigue lives in the case of single overloads

No.	Amplitude of the base cycle ε_{ac}	Amplitude of the overload cycle ε_{ac_p}	Interval ΔN	Number of overloads N_{pc}	N_f
1	2	3	4	5	6
hline 1				17	832
2	0.008	0.02	50	18	850
3				15	720

A comparison of above set results with the results contained in Table 7 shows that the same number of overloads N_p given as single cycles and in the block form causes obtaining different values of fatigue lives. Single given overloads cause a greater decrease in a fatigue life.

An analysis of the chart (Fig.9) allows us to state that the uniform overloads during fatigue tests cause a significant disturbance of changes taking place inside

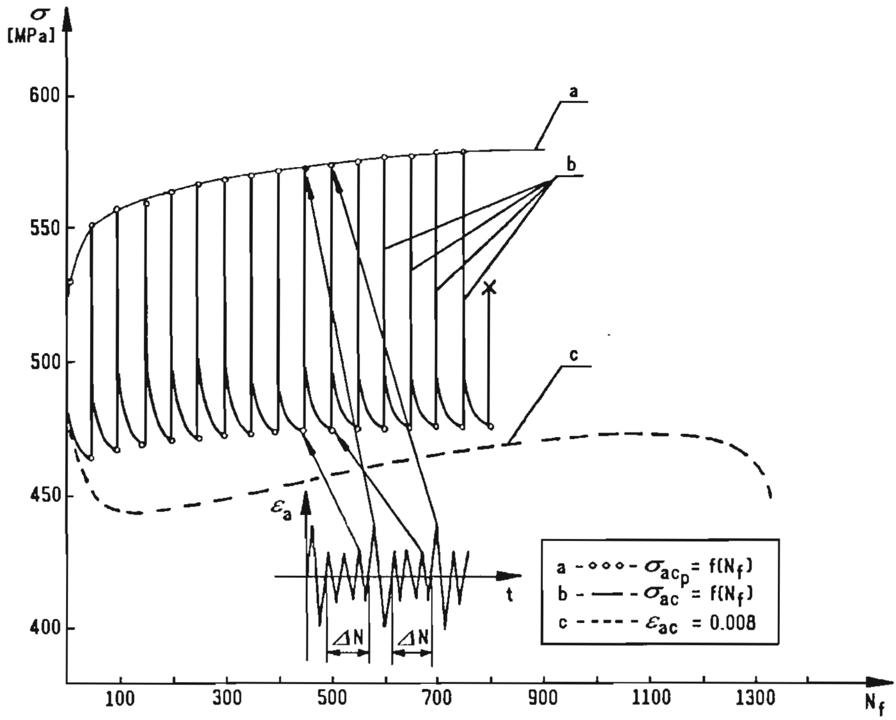


Fig. 9. Influence of single overloads on a fatigue life and on the changes of stress amplitude after overload

the material in the case of a constant amplitude loading. Test results, under conditions of single overloads, can be analysed basing upon: stress σ_{ac_p} changes in tensile half-cycle for overload cycle (chart "a"), stress σ_{ac} changes for the cycle preceeding the overload cycle (chart "b"), stress σ_{ac} changes for cycles given among single overloads (histories "d"). The types of changes in chart "a" shows that, during the test, a constant increase in the overload cycle stress (in the case of constant overload strain) can be observed. It can be expected mutual influence of single overloads. A similar type of changes can be seen in chart "b". Between particular overloads, the material shows clear softening with a tendency to stabilization, which is not reached. It makes impossible the successive overload cycle.

4. Conclusions

The following conclusions can be drawn from the analysis of the test results presented in the paper.

1. Overloads realized during the investigations have a significant influence on the decrease in the fatigue life of the specimens made of normalized 45-steel. The degree of the shortage in a fatigue life depends first of all on the value of total strain amplitude at the overload stage and on the number of overload cycles. This influence, in the tests considered in this paper, was from 10 to 30 %. A significant influence of the overload position (on the axis of cycle number) on the fatigue life is not apparent.

2. The comparison between the courses of stress changes in tensile half-cycle after overload and the base history (Fig.5 ÷ 7) shows that overloads cause the significant increase in stress. The neglection of this fact in fatigue calculations can cause significant differences between fatigue life results for machine elements as related to calculations and tests.

3. The lack of a distinct stabilization stage follows from the analysis of stress courses in tensile half-cycles as a function of the number of loading cycles in the case of assumed levels of total strain (Fig.3).

4. Comparing fatigue lives determined under conditions of the same levels of total strain amplitude and number of overload cycles, respectively, the significant differences were observed between: the fatigue life in the case of program in block form and the fatigue life in the case of program with a single cycle overload. In the second case, a fatigue life is shorter which can be explained by the fact that relative stabilization of the material properties does not exist during overloding of the specimen by means of single cycles.

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Analiza wpływu przeciążeń na trwałość zmęczeniową stali 45 w zakresie niskocyklowego zmęczenia

Streszczenie

W pracy przedstawiono wyniki badań wpływu przeciążeń na trwałość zmęczeniową oraz przebieg niektórych zjawisk towarzyszących procesowi zmęczenia w zakresie niskocyklowego zmęczenia. Przeciążenia realizowano w postaci bloku cykli lub pojedynczych cykli o amplitudzie istotnie większej od amplitudy odkształcenia bazowego. Badania zrealizowano na poziomie bazowego odkształcenia całkowitego $\varepsilon_{ac} = 0.008$ natomiast przeciążenia odpowiednio na poziomach $\varepsilon_{ac_p} = 2.0\varepsilon_{ac}$; $2.5\varepsilon_{ac}$; $3.0\varepsilon_{ac}$. Analiza wyników badań wykazała, że we wszystkich przypadkach przeciążenia trwałość zmęczeniowa próbek była mniejsza od trwałości wyznaczonej w warunkach odkształcenia bazowego. Wartość trwałości zależna była od programu obciążeń. W wyniku przeciążeń we wszystkich przypadkach następowało ogólne umocnienie, natomiast analiza przebiegu wykresów zmian naprężenia od amplitudy odkształcenia całkowitego w fazie przeciążenia, wykazała istnienie charakterystycznych okresów umocnienia, nasycenia (stabilizacji) i osłabienia. Powyższe świadczy o zmianie własności zmęczeniowych stali 45 na skutek przeciążenia.

Manuscript received March 18, 1993; accepted for print April 14, 1993