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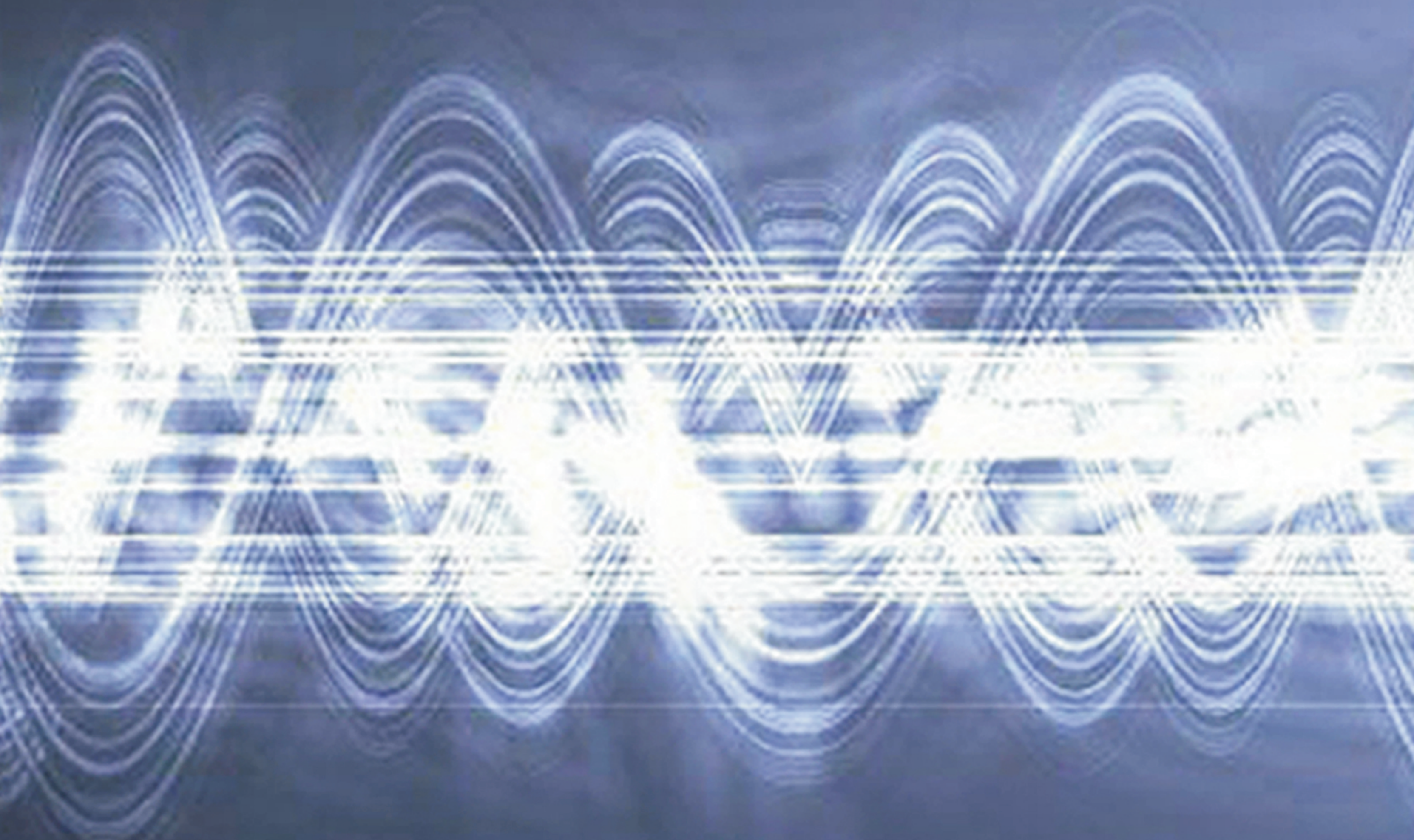

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Effects of Cumulative Fatigue Damage under Tensional Cyclic Loading on the Constitutive Relation of AISI 1045 Steel

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Abstract
The paper presents results of the influence of initial fatigue loadings on the tensile stress-strain curves of AISI 1045 steel. Tensile characteristics were determined using servo-hydraulic testing machine at wide range of strain rates. It was found that the cumulative fatigue damage introduced into material may significantly affect the mechanical behavior of AISI 1045 steel. Lower CFD values, i.e. 25% and 50% induce the increase in the flow stress value, whereas further increase of CFD to 75% results the softening in the material due to fatigue damage. Higher pre-strain stress amplitude enhances influence of fatigue on the stress-strain curves. Strain rate sensitivity may be also modified by pre-fatigue loadings.

Keywords
Fatigue, constitutive equation, AISI 1045 steel

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Introduction

Development of the reliable method of the cumulative fatigue damage (CFD) assessment is major engineering challenge. Many structural effects related to the fatigue loadings still requires further research despite the fact that first works of Palmgren [1] and Miner [2] concerning the linear rule of fatigue damage growth were presented almost one hundred years ago. The investigations which have been carried out until nowadays were focused mainly on prediction of the structure lifetime on the basis of stress or strain magnitude and number of cycles [3-5]. Very comprehensive review of various methods of CFD estimation may be found in another paper [6].

On the contrary, instead of lifetime prediction, in this work attention has been focused on analysis of the effect of fatigue damage growth on the constitutive relation describing mechanical properties of AISI 1045 steel. The presented approach may be very important for the purposes of numerical simulation of structures behavior under extreme loading conditions i.e. energy absorbing structures [7]. Currently, FEM analysis are usually carried out applying viscoplastic material properties determined for the as-received material state [8]. Therefore, the influence of operational loads applied to the structure in normal use are not taken into account. This kind of simplification may lead to discrepancy between the simulation results and real behavior of the structure. Incorporating into calculation of the cyclic loadings influence on the evolution of elastoplastic material behavior may lead to increase accuracy of FEM modeling.

The number of papers concerning influence of the fatigue loadings on the visco-plastic material properties is very narrow despite practical importance of this phenomenon. According to the researches that have been carried out [9] the influence of fatigue loadings on the evolution of stress-strain characteristics may be different depending on the material microstructure. For the 6061-T6 aluminium alloy the influence of cyclic loadings on the characteristics determined at quasi-static and dynamic loading conditions may be neglected whereas the test carried out under the same loading conditions for AISI 4140T steel shows clearly visible effects of flow stress lowering.

Similar analysis has been done for 2017A-T3 and 5454-O aluminium alloys [10]. The specimens pre-strained under the high cycle fatigue loading conditions were subsequently subjected to tensile loadings at high strain rate equal to $300s^{-1}$. For the 2XXX series alloy a very significant drop of tensile force has been found, whereas the second alloy was insensitive to initial fatigue. The authors conclude that tensile curve is determined by microstructure of a given material since the pre-strain loading parameters has no results on the tensile curve.

In order to estimate the influence of the localization of Ti-6Al-4V alloy micro damages on the tensile characteristic the research composed of two stages has been carried out [11]. At the first phase the pre-fatigued specimens were subjected to tensile test. Subsequently, in the phase two, material after the same initial loadings like for the phase one was machined in order to remove surface layer. Afterwards the machined specimens were tested at tensile conditions. On the basis of comparison between tensile test carried out in the phases one and two, the authors conclude that the surface layer has a crucial importance in the phenomenon of mechanical properties degradation.

This work presents the results of analysis of the influence of initial tensile cyclic loadings on the constitutive relation estimated on the basis of stress-strain curves obtained at strain rates within the range from $10^{-4}s^{-1}$ to $10^{0}s^{-1}$. Proposed methodology of hybrid loadings was applied on the example of AISI 1045 steel. The chemical composition of the tested material is presented in Table 1. The specimens were fabricated by machining from a drawn rod of 1045 AISI steel. The shape of specimens was cylindrical with tangentially blending fillets between the test section and the ends. The gauge length and diameter were equal to 12 mm and 4 mm respectively. The surface was polished after machining.

Table 1. Chemical composition of AISI 1045 steel

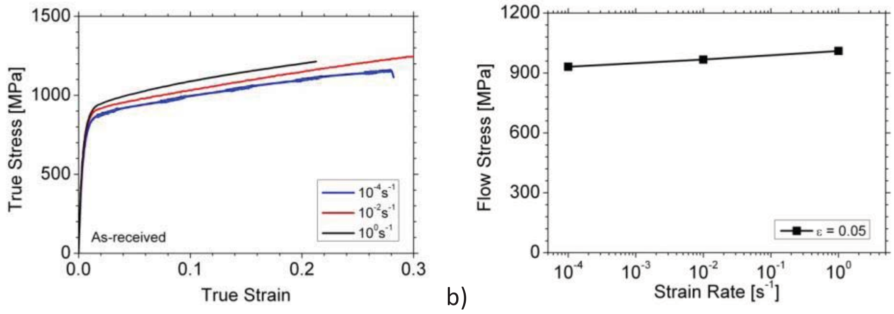
C	Mn	Si	P	S	Cr	Ni	Cu	Mo
0.43	0.71	0.25	0.015	0.017	0.07	0.08	0.22	0.018

The research procedure consists of the following stages:

- determining of the stress-strain curves of AISI 1045 steel in the as-received state at wide range of strain rates;
- estimation of Wöhler chart of steel under cyclic tensile loading conditions;
- introducing initial fatigue damage into specimens;
- determining the stress-strain curves of pre-fatigued material;
- calibration of coefficients of the Johnson-Cook's constitutive equation on the basis of stress-strain curves [12].

1. Tensile test of AISI 1045 steel at wide range of strain rates

The tensile stress-strain curves of AISI 1045 steel in the as-received state were determined using the Instron servohydraulic testing machine. The strain of specimen was measured using electro-mechanical extensometer with a length of 10 mm. In order to obtain the true stress and strain values the axial strain was recalculated using the final diameter of the neck near the fragmentation zone. The characteristics obtained at three various strain rates equal to $10^{-4}s^{-1}$, $10^{-2}s^{-1}$ and $10^{0}s^{-1}$ are presented in Fig.1a. The strain rate sensitivity chart of AISI 1045 steel is shown in Fig. 1b. The tested material shows clearly visible effects of work hardening and strain rate hardening as well.



a) b)

Figure 1. Mechanical properties of 1045 steel in the as-received state a) stress-strain curves; b) strain rate sensitivity chart

2. Fatigue tests

The next stage of analysis has been made in order to determine the S-N curve of AISI 1045 steel. The fatigue tests were carried out under the tensile loading conditions (R=0) at various stress amplitudes σ_a within the range from 550MPa to 750MPa. Obtained characteristic is presented in Fig. 2. Subsequently, initial fatigue loadings of two selected amplitudes i.e. 550MPa and 750 MPa have been introduced into specimens. Using the following formula:

$$CFD = \sum_{i=1}^{k} \frac{n_i}{N_i} \quad (1)$$

the number of cycles was selected in order to obtain CFD value, estimated using Miner's linear rule equal to 25%, 50% and 75%. The number of cycles was equal to 98 000, 196 000 and 294 000 for fatigue stress amplitude equal to 550MPa and 10 750, 21 500 and 32 250 for fatigue stress amplitude equal to 750 MPa.

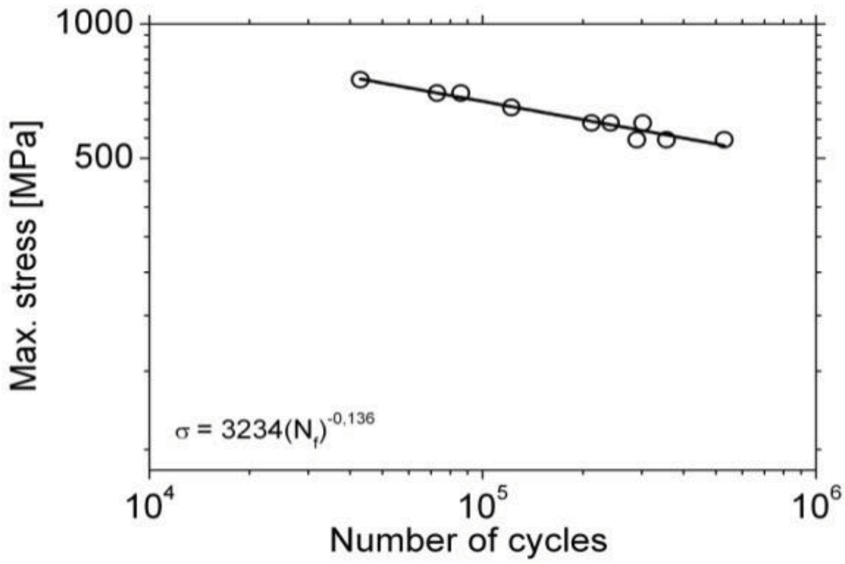


Figure 2. S-N curve of the 1045 steel

3. Tensile tests of pre-fatigued specimens

The tensile stress-strain curves recalculated to true values are presented in Fig. 3 and Fig. 4 for pre-fatigue amplitude equal to 550MPa and 750 MPa, respectively.

The tests were carried out at various strain rates. The limited material softening effect may be observed at CFD equal to 75% for specimens pre-strained at amplitude equal to 550MPa. The effect of material softening at the same CFD value is stronger at pre-strain amplitude equal to 750MPa. Moreover, after the initial hardening at CFD equal to 25% and 50% the clearly visible lowering of the flow stress due to fatigue damage growth may be observed.

The increase in work hardening modulus at strain rate equal to $10^0 s^{-1}$ may be found for both pre-fatigue stress amplitudes. The effect is clearly visible at CFD=25% and 50%. The further increase of initial fatigue cycles to CFD=75% reduces the effect, however it still may be observed.

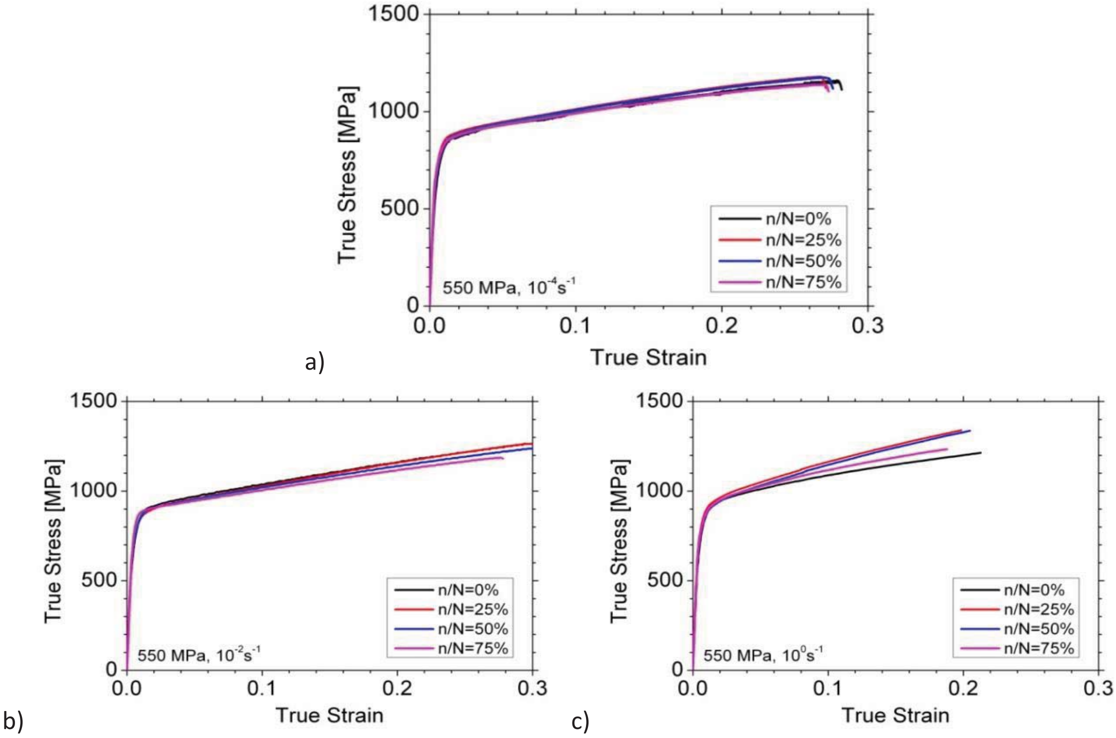


Figure 3. Stress strain curves of 1045 steel, after given number of pre-fatigue loadings cycles of magnitude equal to 550 MPa; a) $\dot{\varepsilon} = 10^{-4} s^{-1}$; b) $\dot{\varepsilon} = 10^{-2} s^{-1}$; c) $\dot{\varepsilon} = 10^{0} s^{-1}$.

The strain rate sensitivity chart is presented in Fig. 5. For the pre-fatigue stress amplitude equal to 550 MPa the effect of flow stress lowering may be found at strain rate equal $10^{-2}s^{-1}$ whereas at strain rate equal to $10^{0}s^{-1}$ flow stress has higher value in comparison to as received material. The phenomenon influence of CFD on the strain rate sensitivity disappears for pre-strain amplitude equal to 750 MPa.

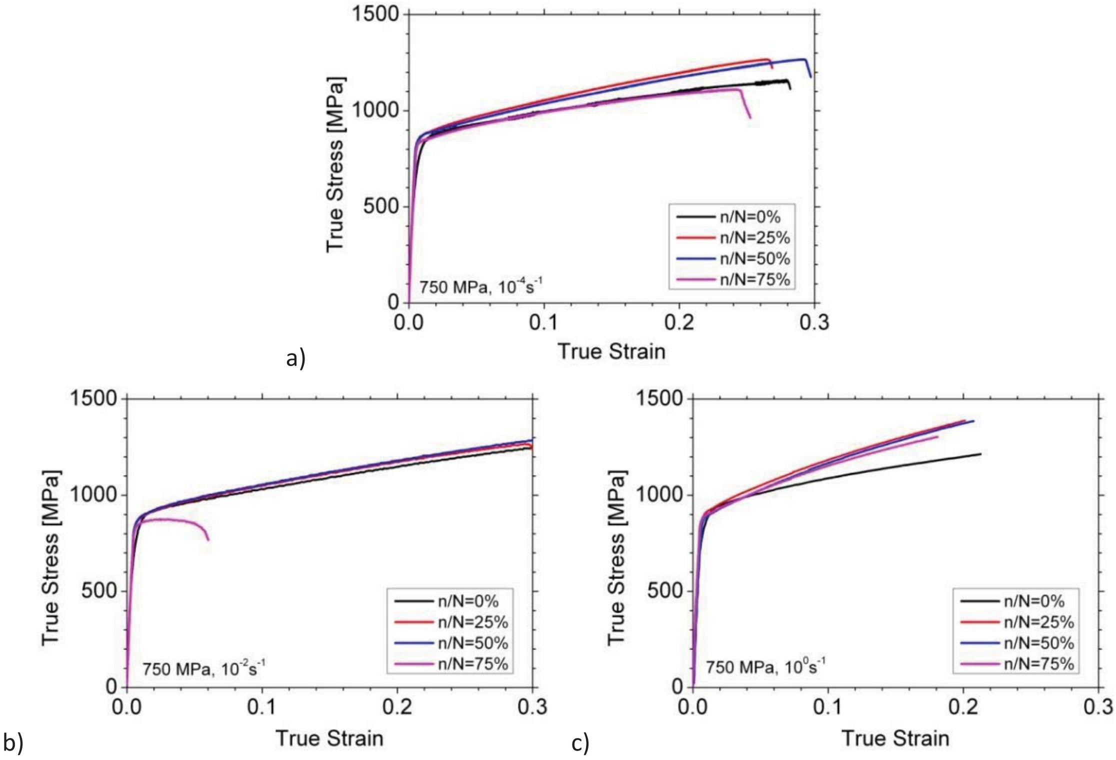


Figure 4. Stress strain curves of 1045 steel, after given number of pre-fatigue loadings cycles of magnitude equal to 750 MPa; a) $\dot{\varepsilon} = 10^{-4} s^{-1}$; b) $\dot{\varepsilon} = 10^{-2} s^{-1}$; c) $\dot{\varepsilon} = 10^{0} s^{-1}$.

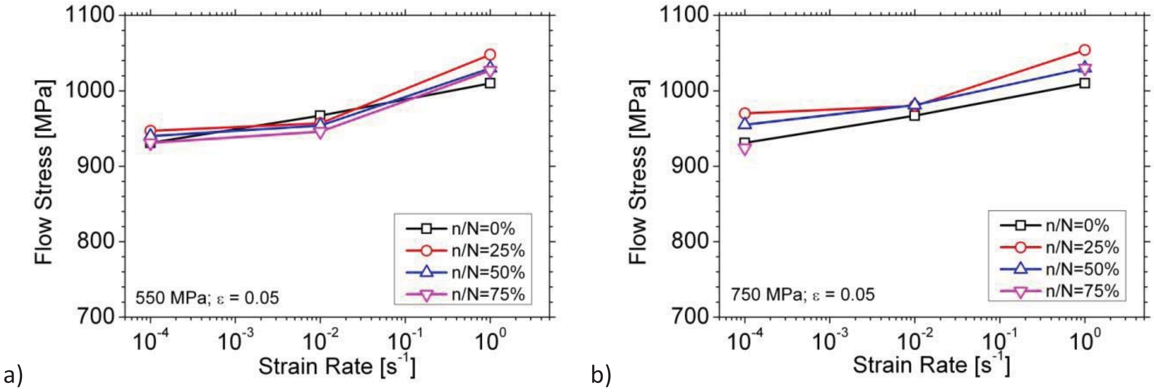


Figure 5. Strain rate sensitivity of 1045 steel after given number of pre-fatigue loadings cycles of magnitude equal to a) 550 MPa; b) 750 MPa

4. Constitutive modeling using Johnson-Cook's equation

Coefficient A, B and n of the Johnson-Cook's constitutive model of ASISI 1045 steel were calibrated on the basis of tensile curves determined at quasi-static loading conditions i.e. strain rate equal to $10^{-4}s^{-1}$. The analyses were carried out for as-received and pre-strained material. The comparison between measured and calculated stress-strain characteristics presented in shown in Fig. 6. A good agreement between experimental and model based curves has been achieved. The influence of strain rate on the flow stress is presented in Fig. 6. It may be stated that pre-fatigue introduces a large discrepancy between experimental and numerical predictions, especially for the case of pre-fatigue stress amplitude equal to 550 MPa.

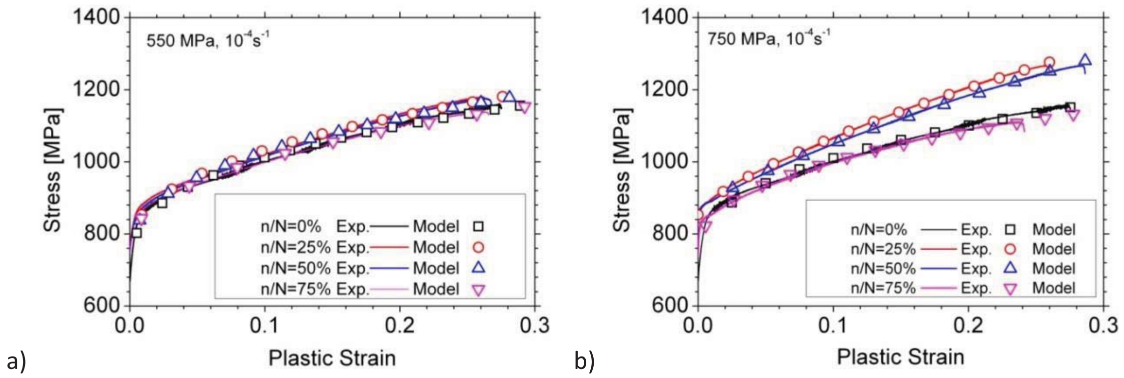


Figure 6. Quasi static stress-strain curves of 1045 steel calculated using JC model after given number of pre-fatigue loadings cycles of magnitude equal to a) 550 MPa; b) 750 MPa

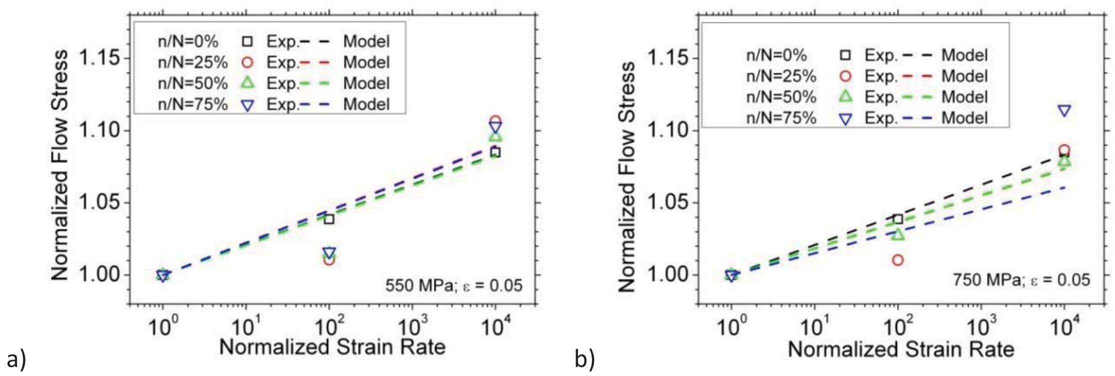


Figure 7. JC model of 1045 steel after given number of pre-fatigue loadings cycles of magnitude equal to a) 550 MPa; b) 750 MPa

Table 2. JC Coefficients

Max. Stress [MPa]	CFD [%]	JC coefficients			
		A	B	n	C
As-received material	0	679	723	0.33	0.009
550	25	750	734	0.41	0.010
	50	735	736	0.40	0.009
	75	750	673	0.41	0.009
750	25	852	1102	0.70	0.008
	50	860	1085	0.43	0.007
	75	738	652	0.39	0.006

Conclusions

The tensile fatigue loadings influence on the stress strain characteristics of AISI 1045 steel. Therefore the coefficients of constitutive equation describing mechanical properties of the material are also affected.

For both pre-fatigue stress amplitudes for CFD equal to 25% and 50% the increase of flow stress in comparison to as-received material may be found. The further increase in the number of cycles up to CFD=75% induces opposite effect i.e. material softening due to fatigue damage growth. Comparable effect may be found in both pre-fatigue cases, however for the initial stress amplitude equal to 750 MPa the phenomenon is much more intensive.

Some changes in the strain rate hardening curves may be also found for the material pre-fatigued by stress amplitude equal to 550 MPa. In comparison to as-received material, the initial loadings results in lowering of flow stress at a strain rate equal to $10^{-2}s^{-1}$, and increase of the flow stress a strain rate equals to $10^{0}s^{-1}$. The comparable phenomenon, however diminished, may be observed for the specimens, which are initially loaded at amplitude is equal to 750 MPa.

References

[1] Palmgren A. Die Lebensdauer von Kugellagern *Verfahrenstechnik,* Vol. 68, pp. 339–41, 1924.
[2] Miner M. A. Cumulative damage in fatigue *J. Appl. Mech.,* Vol. 67A, pp. 159–164, 1945.
[3] Socha G. Experimental investigations of fatigue cracks nucleation, growth and coalescence in structural steel *International Journal of Fatigue,* Vol. 25, pp. 139–147, 2003.
[4] Socha G. Prediction of the fatigue life on the basis of damage progress rate curves *International Journal of Fatigue,* Vol. 26, pp. 339–347, 2004.
[5] Dietrich L. and Radziejewska J. The fatigue damage development in a cast Al–Si–Cu alloy *Materials and Design,* Vol. 32, pp. 322-329, 2011.
[6] Fatemi A. and Yang L. Cumulative fatigue damage and life prediction theories: a survey of the state of art for homogeneous materials *Int J Fatigue,* Vol. 20, pp. 9-34, 1998.
[7] Moćko W. Application of Austenitic Steels in Energy Absorbing Structures *Journal of Kones,* Vol. 19: 3, pp. 305-310, 2012.
[8] Moćko W. and Kowalewski Z. L. Application of selected constitutive equations to mechanical behaviour description of VP159 high-nitrogen steel *Modelowanie inżynierskie,* Vol. 42, pp. 203-210, 2012.
[9] Sánchez-Santana U., Rubio-González C., Mesmacque G., Amrouche A. and Decoopman X. Effect of fatigue damage induced by cyclic plasticity on the dynamic tensile behavior of materials *International Journal of Fatigue,* Vol. 30, pp. 1708–1719, 2008.
[10] Froustey C. and Lataillade J. L. Influence of the microstructure of aluminium alloys on their residual impact properties after a fatigue loading program *Materials Science and Engineering A,* Vol. A500, pp. 155–163, 2009.

[11] Galán López J., Verleysen P., De Baere I. and Degrieck J. Tensile properties of thin-sheet metals after cyclic damage *Procedia Engineering,* Vol. 10, pp. 1961–1966, 2011.
[12] Johnson G. R. and Cook W. H. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures *Proceedings of Seventh International Symposium on Ballistics, The Hague, The Netherlands* ,pp. 541–547, 1983.
[13] Moćko W. and Kowalewski Z. L. Dynamic Compression Tests – Current Achievements and Future Development *Engineering Transactions,* Vol. 59, pp. 235-248, 2011.
[14] Moćko W., Rodriguez-Martinez J. A., Kowalewski Z. L. and Rusinek A. Compressive Viscoplastic Response of 6082-T6 and 7075-T6 Aluminium Alloys Under Wide Range of Strain Rate at Room Temperature *Experiments and Modelling Strain,* Vol. 48, pp.498-509, 2012.