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THERMOELASTIC EFFECT DURING TENSILE CYCLIC DEFORMATION

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Experimental results of the effects of thermomechanical coupling occurring in metal during a cyclic tension test are presented. In each cycle the thermoelastic effect, i.e. the decrease of temperature in the initial stage of deformation was observed. Afterwards the specimen was heated up due to initiation and evolution of the mechanisms of plastic deformation. The change of character of the temperature behaviour of the sample subjected to loading allowed us to determine the limit between the elastic and plastic regime. Moreover, it was noticed that the temperature characteristics vs. stress manifested the transition from the elastic to plastic deformation more distinctly than the stress-strain relations.

1. Introduction

When a stress applied to a sample of a metal is increased, it deforms elastically and then both elastically and plastically. Empirical identification of the boundary between the elastic and the plastic regimes of deformation is complex and ambiguous, since ambiguous is also the definition of the yield limit point as well the term used for elastic deformation. As a result, various criteria have been used in order to describe the initiation of yielding: the elastic limit, the proportional limit and the yield strength.

By applying a definition that yield point occurs in just that particular locus (in considered co-ordinates), where it is manifested by the first irreversible plastic deformations, this point can be macroscopically indicated on the basis of mechanical curves $\sigma(\varepsilon)$, acoustic emission, thermal emission etc. [1, 2].

The methods utilizing the thermal emission are based on a qualitative change of the temperature behaviour of the specimen under mechanical loading.

Change of temperature ΔT of a specimen, subjected to adiabatic uniaxial elastic deformation, called a thermoelastic effect, is related to a pure, volumetric deformation. Derived from the first law of thermodynamics it can be described as follows:

$$\Delta T_{el} = -\frac{\alpha T \Delta\sigma_s}{c_\sigma}, \tag{1}$$

where α – coefficient of linear thermal expansion, T – absolute initial temperature, $\Delta\sigma_s$ – isentropic change of stress, c_σ – heat capacity, $c_\sigma = c_p \cdot \varrho$, c_p – specific heat at constant pressure, ϱ – density of material.

Since usually $\alpha > 0$, the temperature decreases during the adiabatic elastic extension and increases during the compression test [2].

Assuming that coefficients of material used in Eq. (1) are constant, a linear dependence between the change of temperature and stress describes the elastic deformation [1, 2]:

$$\Delta T_{el} = -k\Delta\sigma_s \,. \tag{2}$$

The value of thermoelastic effect is rather small and for most of metals, it does not usually exceed the level of about 0.2 K. Therefore it is often neglected in theoretical approaches and design calculations. Nevertheless, repeatability and uniqueness of the thermoelastic effect allows some investigators to carry out the calibration of the measurement system [4], the selection of material [5], the evaluation of the residual stresses [6] and the determination of the beginning of plastic deformation [1, 2, 7].

Sometimes, after the special material treatment, the thermoelastic effect can be considerably higher and its value and influence can not be neglected.

The subject of this paper is the exploitation of the thermoelastic effect observed during cyclic tensile test. The onset of plastic deformation evaluated in subsequent cycles of loading was examined this way. The registered value of the thermoelastic effect are related to the extent of the strain hardening level.

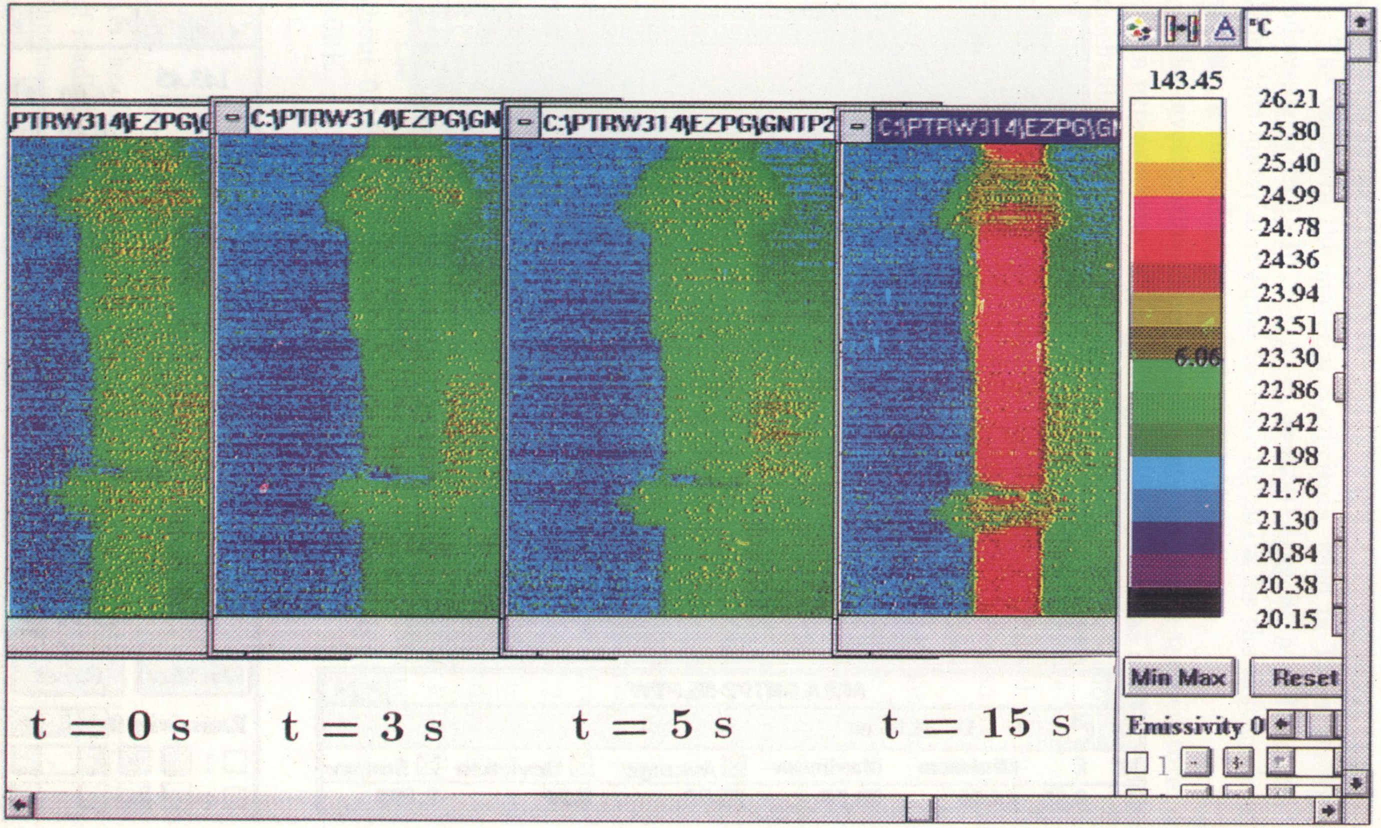
2. Experimental procedure

The investigations were performed on flat specimens of stainless steel 00H19N17Pr, subjected to subsequent uniaxial loading tests on an Instron testing machine. Mainly, the specimen was:

- strained to 1 mm (beyond the yield point),
- unloaded,
- cooled in ambient temperature,
- strained to 1 mm again.

In this way, five such cycles were performed. The chosen rate of deformation was constant during the loading and unloading and equal to $2 \cdot 10^{-3}\,\mathrm{s}^{-1}$.

The samples were prepared from the cold-rolled strips of steel with a cross-section 25 mm×4 mm, annealed at 1050° C for 40 min. The shape and dimensions of the specimen was shown in [2]. The chemical composition of the steel used is as follows; 0.05 wt% C, 1.35 wt% Mn, 1.0 wt% Si, 0.016 wt% P, 0.008 wt% S,



PTRW314\EZPG\G
C:\PTRW314\EZPG\GN
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°C
143.45
26.21
25.80
25.40
24.99
24.78
24.36
23.94
23.51
6.06
23.30
22.86
22.42
21.98
21.76
21.30
20.84
20.38
20.15
Min Max
Reset
Emissivity 0
t = 0 s
t = 3 s
t = 5 s
t = 15 s

[Fig. 1a]

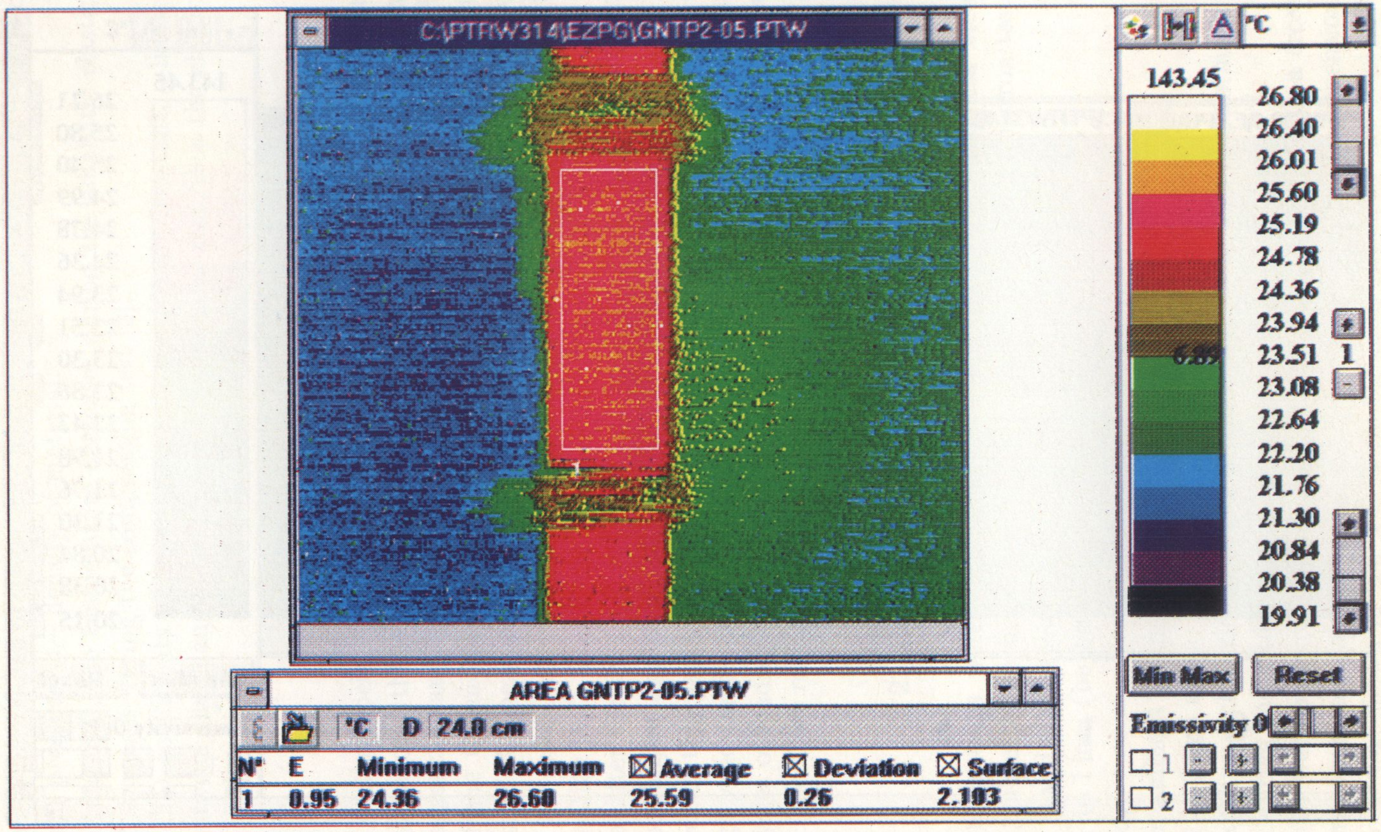

FIG. 1. a) example of thermograms obtained during elongation of the specimen of stainless steel, b) a thermogram showing chosen zone of specimen.

18.58 wt% Cr, 17.3 wt% Ni, 0.025 wt% W, 0.02 wt% Mo, 0.04 wt% Cu, 0.03 wt% V, 0.013 wt% Ti and the balance Fe. The grain size is about 50 μm.

The values of the material coefficients, used in Thomson formula (1) are as follows: $\alpha = 16.8 \cdot 10^{-6}$ 1/K, $c_p = 0.50$ kJ/kg K, $\varrho = 7.9$ g/cm^3. The value of E for this material is equal to $198 \cdot 10^3$ MPa for the first cycle and it decreases slightly in the subsequent cycles of deformation.

The investigations were carried out in ambient temperature, equal to 295 K.

An extensometer of gauge length 25 ± 5 mm was used in order to register the mechanical characteristics with sufficiently high precision.

During the experiment, the load vs. elongation, the load and elongation vs. time and the distribution of infrared radiation emitted by surface of the specimen were continuously registered. The infrared radiation was measured using the thermovision camera coupled with a computer system of data acquisition and conversion, what enabled us to store the obtained data on hard disk and to process it further by other software. The higher and more homogeneous emissivity of the samples was secured by blacking its surface by a carbon powder.

The measurement set used allowed us to obtain the thermovision pictures with various precision. During 0.06 s the camera created an image called a frame. A thermal picture of the frame contained few details but short time of its creation enabled us to register more accurately the beginning of temperature changes of a chosen area of the object. The analysis of these temperature changes was helpful for the exact determination of the beginning of the process of plastic deformation and monitoring of the thermoelastic effect. Four such frames superimposed over each other created a thermal picture, obtained during 0.24 s. This thermal picture was a basis for analysing temperature distributions of the examined surface. Such distributions can be presented in different units depending on the chosen curve of calibration. More details on that subject have been presented in [8].

The accuracy of temperature measurement obtained for the pictures was about 0.3 K; the sensitivity obtained for the analysis of the frames was about 0.02 K.

3. Experimental results

The distributions of intensity of infrared radiation, registered in each cycle of loading allow us to reconstruct the thermal pictures of specimens in form of thermograms. In Fig. 1 a the example of the thermograms of the surface of the specimen obtained before loading and after 3 s, 5 s and 15 s of deformation are given. The next, Fig. 1 b describes the chosen area of temperature measurement.

The investigations were performed in the homogeneous range of deformation. The homogeneity was verified by the uniform temperature distribution.

The mechanical characteristics, e.g. the stress-strain relations, obtained during the cyclic deformation, are shown in Fig. 2 (the given stress is true, i.e. the force is referred to the current cross-section of the sample). It is shown, that a clearly seen yield point appears in the course of the strain hardening of the material and it becomes more pronounced in the subsequent cycles of deformation.

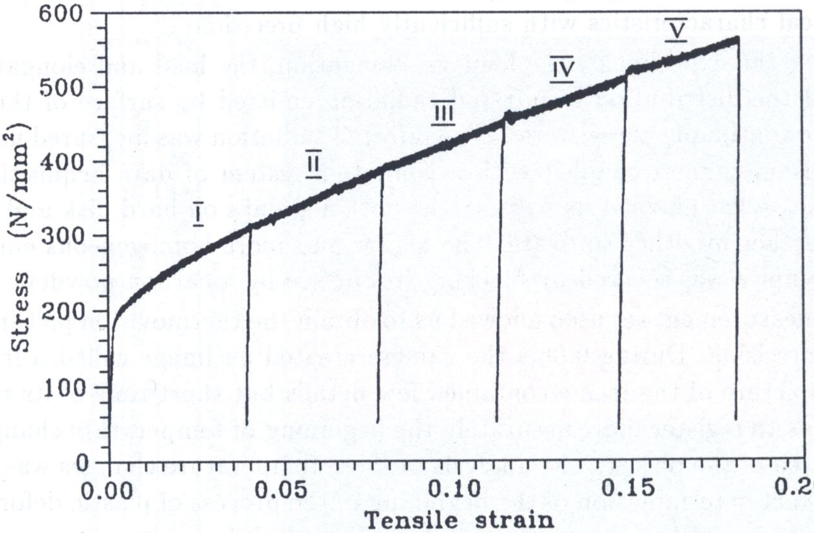

FIG. 2. Stress vs. strain during successive cycles of deformation.

The corresponding changes in temperature vs. time are given in Fig. 3. During the subsequent tensile tests (in the course of material hardening) the measured temperature decreases were each time higher, changing from the value of about −0.18 K for the first cycle to the value of about −0.60 K for the last, fifth cycle.

Change in temperature of the specimen subjected to the first cycle of deformation, plotted vs. stress, is shown in Fig. 4. In the initial stage of elongation, that change is linearly dependent on stress. After this smooth, quasi-reversible decrease in temperature, called thermoelastic effect, the sample heats up due do initiation and evolution of the mechanisms of plastic deformation (generation, motion and annihilation of the defects, mainly dislocations), involving energy dissipation (this characteristic was obtained during the experiment with the constant crosshead displacement and it can not be totally compared with the results obtained during the cyclic deformation).

The point of departure of the straight line $\Delta T = -k\sigma$, describing the elastic deformation, from the plot of measured temperature of the specimen indicates the beginning of the plastic deformation. Stress value corresponding to this point

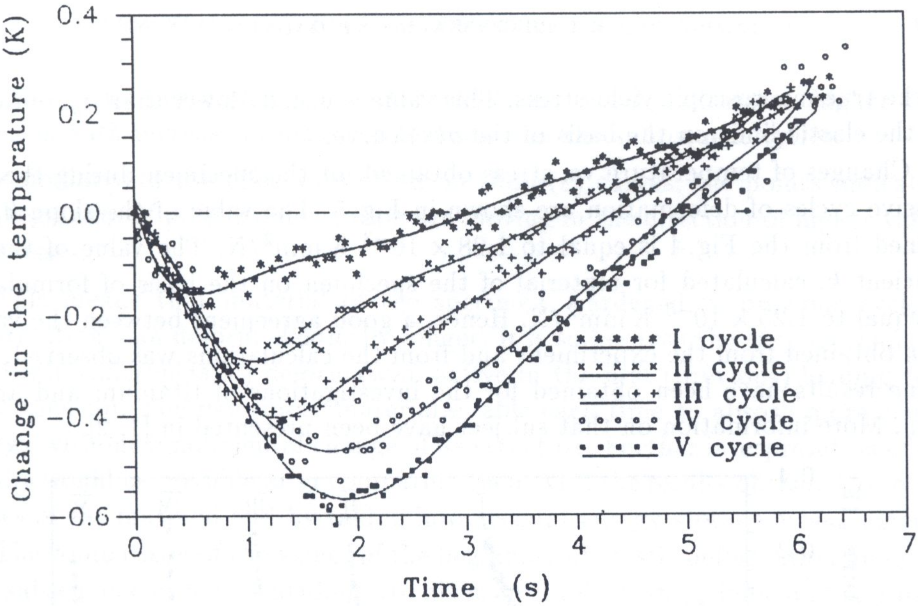

FIG. 3. Changes of the temperature of specimen of stainless steel during initial stage of successive cycles of deformation.

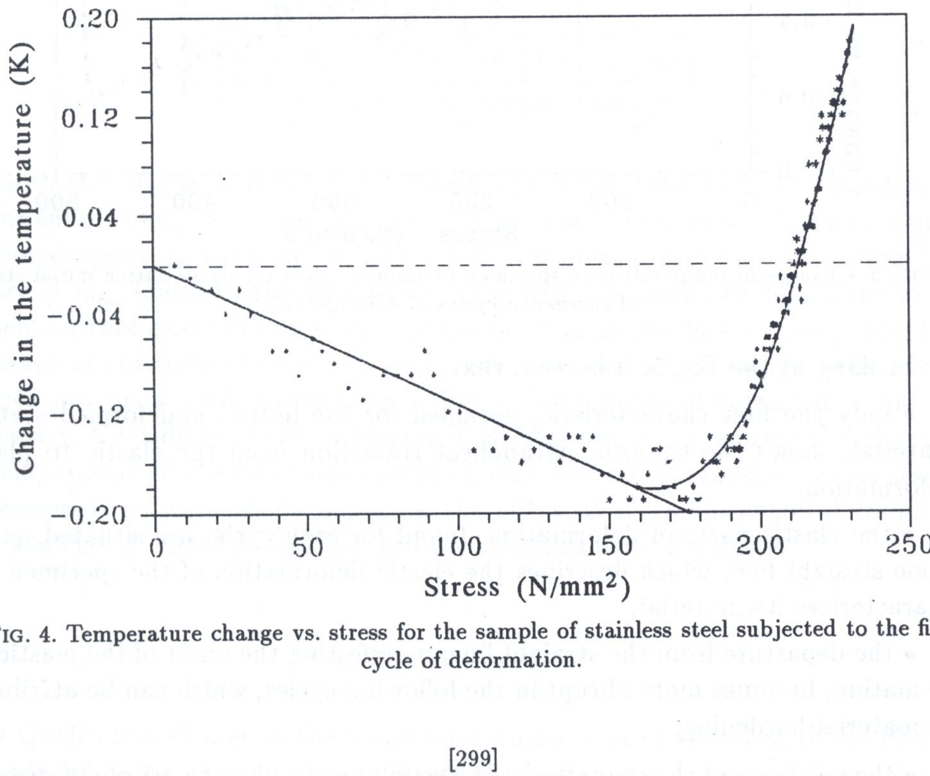

FIG. 4. Temperature change vs. stress for the sample of stainless steel subjected to the first cycle of deformation.

is the true macroscopic yield stress. This value is usually lower than σ_g, obtained as the elastic limit on the basis of the $\sigma(\varepsilon)$ curve.

Changes of temperature vs. stress obtained for the specimen during the successive cycles of deformation are shown in Fig. 5. The value of the slope k, obtained from the Fig. 4 is equal to 1.28×10^{-3} K mm^2/N. The value of the coefficient k, calculated for material of the specimen on the basis of formula (1) is equal to 1.25×10^{-3} K mm^2/N. Hence, a good agreement between the values of k obtained from the experiment and from the calculations was observed. The same results have been obtained for the investigations of titanium and armco iron. More information on that subject have been presented in [1, 2].

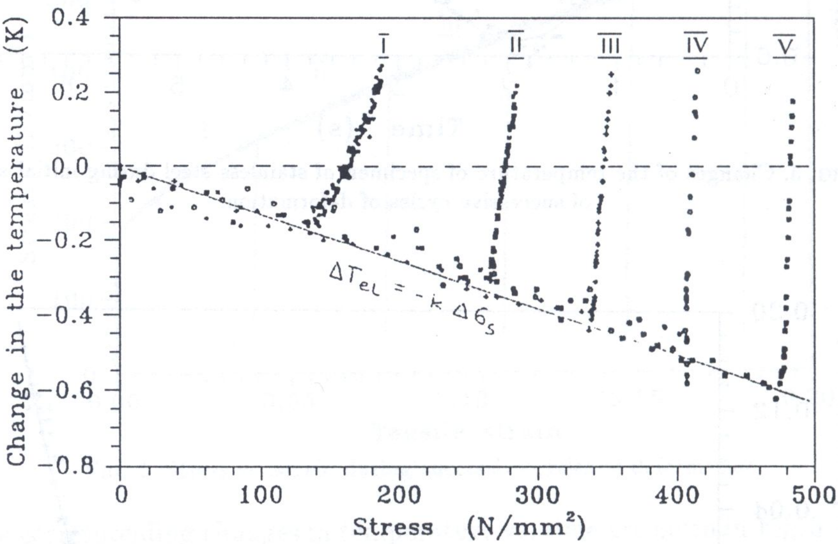

FIG. 5. Changes of temperature of specimen of stainless steel vs. stress during initial stage of successive cycles of deformation.

Looking at the Fig. 5, it is seen, that:

• only the first characteristic, obtained for the initial, undeformed state of material, shows the smooth, parabolical transition from the elastic to plastic deformation,

• the elastic parts of deformation, found for each cycle, are situated on the same straight line, which describes the elastic deformation of the specimen and characterizes its material,

• the departure from the straight line, manifesting the onset of the plastic deformation, becomes more abrupt in the following cycles, which can be attributed to material hardening,

• the segments of the characteristics describing the plastic part of deformation becomes more perpendicular to the stress axis, what indicates a higher heat emission with increase of plastic deformation in the subsequent cycles,

• similarly to the effects observed on the $\sigma(\varepsilon)$ curves, the points indicating the beginning of plastic deformation are moving in the direction of higher values of stresses.

This means that material of the specimen, hardened in previous cycle of deformation, can deform elastically longer. It is so because the easy mechanisms of plastic (microplastic) deformation, active in the first (previous) loading test, were used up. The deforming material is able each time to absorb more elastic energy without fundamental change of its structure. Further interpretation of the results would be possible after comparing them with the results obtained for other states of the material and by taking into account energy storage measurements.

The comparison of the values of the beginning of plastic deformation found for the subsequent cycles of loading are given in Table 1: $\sigma_{0.02}$ indicated the basis of $\sigma(\varepsilon)$ curves (Fig. 2) – in line 2, $\sigma_{pl.T}$ indicated the basis of $\Delta T(\sigma)$ relation (Fig. 5) – in line 3.

Table 1.

Cycle	1	2	3	4	5
$\sigma_{0.02}$ [N/mm^2]	195	313	390	454	516
$\sigma_{pl.T}$ [N/mm^2]	183	303	380	449	513

Both the $\sigma_{0.02}$ as well as $\sigma_{pl.T}$ are increasing in the course of strain hardening in the subsequent cycles of deformation. The values of the onset of plastic deformation detected on the basis of the temperature measurement are lower than the values of $\sigma_{0.02}$ found for the subsequent cycles of deformation. Besides, one should remember that exact determination of the onset of plastic flaw by measuring the mechanical characteristics $\sigma(\varepsilon)$ would require a specially designed experiment carried out on a small gauge length. Hence, an additional specimen would be necessary. Considering that nowadays it is often easier to register the changes in temperature of the examined specimen than to find its standard stress-strain characteristic, the methods based on the effect of thermomechanical coupling and associated with the temperature variations can be very useful.

4. Final remarks

• Qualitative change of the temperature behaviour of specimen in the elastic and plastic ranges enables us to indicate the beginning of plastic deformation.

• During the elongation, the macroscopic irreversible plastic deformation begins when the adiabatic dependence $\Delta T(\sigma)$ ceases to be a straight line.

• For materials without pronounced yield limit, the definition based upon the temperature measurement detects the onset of plastic strain earlier than the method based upon the conventional limit stress (0.02 offset yield stress) taken from the $\sigma(\varepsilon)$ curve.

• The temperature decrease (thermoelastic effect) observed in the initial stage of elongation becomes larger each time in the subsequent cycles of deformation which indicates the hardening of material in previous cycles.

• Similarly to the effects observed on the $\sigma(\varepsilon)$ curves, it is seen from $\Delta T(\sigma)$ relations that the departure from the straight line describing the elastic deformation becomes more abrupt in the following cycles. The points indicating the beginning of plastic deformation are moving in the direction of higher stresses.

• The initial parts of $\Delta T(\sigma)$ characteristics obtained for the subsequent cycles and describing the elastic deformation lie on the same straight line characterizing the material of the specimen. The value of the slope of this line remains in agreement with the value calculated for the material of specimen using Eq. (1).

• The further parts of $\Delta T(\sigma)$ relations which describe the initial plastic deformation become more perpendicular to the stress axis, which indicates more intensive heat emission in the subsequent cycles related to plastic strain.

• For the sample subjected to cyclic tensile deformation, a clearly seen yield point appears in the course of strain hardening and it becomes more pronounced in the subsequent cycles of deformation.

Material of the specimen hardened in the first (previous) cycle of deformation can deform elastically to larger extent. The easy mechanisms of plastic deformation were used up. Activation of the additional mechanisms requires supplying more energy.

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