

CRITICAL POINT OF THE ELASTOPLASTIC TRANSITION IN TERMS OF THERMOMECHANICAL COUPLING

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A review and justification of chosen papers related to the determination of the beginning of plastic deformation has been presented. A particular attention was paid to the criteria based on the temperature measurement. It was found, that the beginning of plastic deformation in metal subjected to elongation occurs when the dependence of temperature vs stress ceases to be the straight line. Finally, the results of initial own investigations were presented.

1. Introduction

With regard to load consequences, usually estimated by macroscopic means, the deformation is qualified as elastic, which is considered as almost completely recoverable, when the external loads are removed, and plastic, which is definitely irreversible.

Empirical identification of the limit between the elastic and plastic regimes of the deformation is complex and ambiguous. It is because that ambiguous is as well the definition of yield point as the used term of elastic deformation.

Let us accept a definition on this ground, that yield point occurs in just that particular place (in considered co-ordinates), where it is manifested by the presence of the first irreversible plastic deformations. It can be investigated with the aid of experimental techniques based on the acoustic emission, exoelectron emission, thermal emission phenomena (described more closely further), and by conventional methods.

In a conventional test procedure, a specimen from an investigated material is subjected to a continually increasing load in order to register a stress-strain curve. With most materials there is a gradual transition from the elastic deformation to the plastic one and the point, at which plastic deformation

begins is difficult to define. Then, in practice, one of the following three criteria has been used in order to describe the initiation of yielding: the elastic limit, the proportional limit, and the yield strength.

Elastic limit is the greatest stress, the material can withstand without any measurable permanent strain remaining after the complete release of load.

Proportional limit is the highest stress, at which stress is directly proportional to strain.

The conventional yield strength (offset yield stress), is the stress required to produce a small specified amount of measurable plastic deformation (0.2%, 0.1% or less).

The choice from the above-mentioned criteria is made according to the kind of material, type of deformation and, as may be required (cf Szczepiński et al. (1984)).

Other type of definition of the yield limit stress is given by Robinson (1985). He assumes that the beginning of plastic deformation occurs at the point, where a rate of plastic deformation ceases to be zero.

On the other hand, owing to the evolution of measurement techniques it is known, that crystalline and, in particular, metallic materials almost never behave exactly as an elastic continuum. Wack and Tourabi (1992) suppose, that only two extreme cases exist, in which metals may behave strictly as elastic materials. The first case is a state of crystalline structure without any defect, possible to obtain only in the form of whiskers. Another case, where the pure elastic deformation exists, is represented by the piano and other, highly hardened wires. The dislocation density is, on the contrary, so high there, and what is more, the dislocations are so entangled, that a very large stress is necessary to unpin them.

It means that in other materials, the mechanisms of initial irreversible plastic (microplastic) strain are developing from the beginning of deformation. This is related to the state of technological materials, usually far away from the ideal crystal, even after the proper preparation (full annealing in the case of metals).

Gradual transition from the elastic deformation to the plastic one in generally used materials allows us to determine their stress-strain curve, in the range of scattering, by a single constitute scheme (cf Wack and Tourabi (1992)). Similarly, in the case of recording and processing data by a computer, there is usually no need in practice for a precise determination of the yield point. A stress-strain curve, obtained during deformation test, is approximated by a single exponential curve, without specifying its linear (elastic) and nonlinear (plastic) range.

So, as a result of this short review we find that various definitions of the

yield limit stress are accepted and various procedures of its determination are used. Sometimes it is plainly no need to single out the elastic range of the stress-strain characteristic.

However, as well from the point of view of research work as practical applications it is often needed to specify the ranges of recoverable and irreversible deformation.

In order to suppress the above mentioned diversity of terms and to set up an unambiguous, more meaningful empirical macroscopic criterion for the described limit, various methods supported on the effect of thermomechanical coupling and associated with the temperature variations are proposed. This experimental approach is based on a qualitative change of the temperature behaviour of specimen under mechanical loading. During elastic deformation these changes are, in general, linearly dependent on stress, and are negative in the case of elongation test. Otherwise, during the plastic deformation they are nonlinear and always accompanied by the temperature increase. The yield point corresponds to this sudden inversion of the trend of the temperature vs the stress characteristic.

It was supposed, that this criterion, based on firmer physical grounds (dislocation processes, responsible for the plastic deformation involve a dissipation of energy), is a more sensible probe to detect the limit stress between microplasticity and macroscopic flow than the traditional one.

However, the last studies and investigations have shown, that using the measurement devices exact enough, the results obtained via conventional stress-strain characteristics should be convergent with the results obtained on the *base of change in temperature of the deformed specimens*. This follows from everexisting thermomechanical coupling between measured effects.

Considering, that nowadays it is often easier to register the changes in temperature of examined specimen than to find its standard stress-strain characteristic, a significant development of these experimental methods began in the last years.

The aim of this paper is to present a review and justification of chosen papers on this subject. In particular the papers, which revealed a quality correspondence between the macroscopic behaviour of crystalline materials and the microstructures phenomena controlling the deformation. Finally, the results of own investigations will be presented.

2. Thermomechanical couplings in solids – experimental and theoretical foundations

As we know from experiments, heating of a body produces in it changes in stress, strain and temperature, respectively. Conversely, the deformation of a body is associated with a change of heat contained in it. This mutual interaction between deformation and temperature fields is called thermomechanical coupling. A certain classification of these effects, occurring in metal subjected to deformation, was proposed by Klepaczko (1978). Depending upon the initial state of material, he specifies:

- I. Thermomechanical couplings in ideal crystals (without lattice defects)
- II. Thermomechanical couplings resulting in motion and mutual interaction of crystal defects.

In the first case one can observe:

- a) The effects of thermomechanical couplings, related to the change of the pressure and the volume of the examined body: $\pm \Delta p \rightarrow \Delta T$ or $\pm \Delta V \rightarrow \Delta T$, where p – pressure, V – volume of the body, T – absolute temperature of the body.
- b) The effects occurring in material via hysteresis loops. During cyclic tests, even in the elastic range of deformation, material shows certain dissipation of energy, caused by the existence of some defects, even in the initial state.

The second case concerns considerably higher external stresses, provoking transitions in the microstructure of material, related to its plastic deformation. These are generation, motion and annihilation of crystal lattice defects, mainly dislocations. Changes in the density and configurations of these defects always lead to the dissipation of energy, which involves the increase in temperature. These effects may be significant and quantitatively they are not comparable with the effects of thermomechanical coupling, classified as the first case.

The coupling between deformation and temperature fields was first postulated by Duhamel (1839), who originated the theory of thermal stresses. An attempt at justification of this theory was undertaken by Voight (1910) and Jeffrey (1930). Later Vakulenko (1961), Nowacki (1970) and others, worked on the foundation of thermomechanical theory.

A development of experimental investigations considering evaluation of heat exchange during plastic deformation of metals (case II) dates from 1920s

and was indicated by the contributions of Taylor and Quinney (1934). Later works concern the temperature measurements during the destructive investigations, as well in static as in dynamic testing and were done by Nadai and Manjoine (1941), Charles and Francis (1978), and others. Temperature of specimen was measured with the aid of thermocouple, thermistor, and other devices, that required direct connection with the surface of specimen. Considerable increase, both in the capabilities and in the accuracy of temperature measurements, occurred after the non-contact measurement systems, based on detection of infrared radiation and called thermovision, were introduced. Both inertialess methods of temperature measurements and the improvement of the construction of calorimeter influenced the development of the studies of energy storage during plastic deformation (cf Bever et al. (1973); Gadaj et al. (1982); Oliferuk et al. (1985), (1993), (1995)) simplified dynamic investigations (cf Klepaczko (1978); Kruszka et al. (1992)) and enabled monitoring of cyclic deformations (cf Blanc and Giacometti (1981); Schmidt (1988)).

Knowledge about the evolution of the material microstructure, related to the studies of the dissipated and the stored energy should help to explain the phenomena occurring in material during its deformation. Nevertheless, one ought to remember, that the change of temperature is an average effect of the changes resulting from deformation, modified by the thermal conductivity of the investigated material.

3. Identifying of the beginning of plastic deformation based on temperature measurements

As it was pointed out before, change in temperature of a body deformed during the initial, homogeneous stage of strain is caused by a pure volume deformation. In order to examine the beginning of plastic deformation on the base of temperature changes, it is necessary to determine the limit of pure volume, recoverable deformation. The relationships between the state of stress, strain and temperature changes can be derived on the base of thermodynamics.

A pioneer of such investigations was W.Thomson (Lord Kelvin), who gave evidence of the proportionality between the change in temperature of loading body and its stress. He proposed an equation (1851), allowing calculation of the change of temperature ΔT_s of a unit cross-section bar, subjected to adiabatic uniaxial elastic deformation

$$\Delta T_s = -\frac{\alpha T \Delta \sigma_s}{c_\sigma} \quad (3.1)$$

where

- α – coefficient of linear thermal expansion
- T – absolute initial temperature
- $\Delta\sigma_s$ – isentropic change in stress
- c_σ – heat capacity per unit volume at constant stress.

In the materials having a positive coefficient α , the temperature decreases during the adiabatic elastic extension ($\alpha > 0$, $\Delta\sigma_s > 0$; $\delta T_s < 0$) and increases during the adiabatic elastic compression test ($\alpha > 0$, $\Delta\sigma_s < 0$; $\delta T_s > 0$). These changes of temperature obtained for metals are usually smaller than 0.2°C (cf Bever et al. (1973)).

Assuming, that coefficients of material used in Eq (3.1) during the initial stage of deformation are constant, we obtain a linear dependence between the change of temperature and stress

$$\Delta T_s = -k\Delta\sigma_s \quad (3.2)$$

As follows from Eq (3.2), the pure elastic strain in material is described by the linear relationship between the change of temperature and the stress. On the other hand, the departure of the curve $\Delta T_s(\Delta\sigma_s)$ from the straight line indicates a change in the character of the process; it goes from the pure elastic to the elasto-plastic deformation.

4. A beginning of plastic deformation during the tensile tests – experimental results and used criteria

A specific objective of this section is to offer criteria and experimental evidence of the fact, that the temperature measurement of the specimen during deformation, correlated with the dynamic changes related to the elasto-plastic transition, detectable by different techniques, enable us to pinpoint the elasto-plastic limit stress.

A summary of typical experimental results obtained for a sample of austenitic steel subjected tension test is plotted in Fig.1. During an adiabatic test it initially undergoes thermoelastic cooling, hampered in the vicinity of the yield stress. Then, following this smooth, quasireversible decrease an increase in temperature is observed.

The thermoelastic cooling in the elastic range can be explained with the aid of model of crystalline material in the form of unidimensional oscillator, where particular atoms or molecules are considered as balls joined by springs.

thout special adaptation: gradual but fundamental, since irreversible change of its structure. Another words, the abilities of the initial state of material to maintain a purely elastic deformation are limited (cf Nowacki (1970)).

In order to describe the behaviour of material at this state of deformation in the microscopic scale, numerous attempts have been made since the pioneering work of Taylor (1934). Theoretical estimations, confirmed by further microscopic observations (cf Ashby (1969); Grabski and Kurzydłowski (1984)) showed, that in materials with regular structure, most likely is the generation of the linear defects, called dislocations, which systematically accommodate the microstructure of material to transferring the growing up loading. Dislocation mechanisms initially occur in proper (the weaker) points of favorably oriented grains.

Centers of microplasticity, developing independently, sometimes even from the beginning of deformation, act as an increasingly important source of thermal power promoting temperature increments in competition with the thermoelastic decrease in temperature. Temperature increments assist more and more efficiently the imposed deformation. Their action is like a positive feedback; step by step they drive the sample to a stage where finally coherent motion of dislocation trains along specific slip system sets in.

At that time a macroscopic plastic deformation – macroplasticity becomes the dominant state and the whole system self-organizes in an ordered spatio-temporal dissipative structure. This process is accompanied by the appearance of various macroscopically detectable phenomena, not occurring before or occurring slightly, like:

- Spontaneous increase of the temperature of the deformed specimen (thermal emission) (cf Gabryszewska (1964); Nowacki (1970); Bever et al. (1973); Gabryszewski and Śródka (1981); Gadałaj et al. (1982); Basz (1984); Chrysochoos et al. (1989); Oliferuk et al. (1993), (1995))
- Sudden and cardinal emission of acoustic phonons (acoustic emission) (cf Tandon and Tangri (1975); Jaffrey (1979); Bottani and Gaglioti (1982); Beghi et al. (1986); Pieczyńska et al. (1988); Szmidski (1988))
- Emission of electrons from the "new" surface of sample, revealed by a slip band (exoelectron emission) (cf Duś-Sitek et al. (1985))
- Partial relaxation of internal elastic stresses (cf Novozhilov (1965); Śródka (1979); Gabryszewski and Śródka (1981)).

Probably, these are not the only effects, appearing at this critical point of deformation. All of them, although so diverse in used techniques of detection

and measured values, base on firmer physical grounds. These are processes developing in material microstructure, like generation, motion and annihilation of dislocations, involved energy dissipation. They lead to a definitely irreversible macroscopic deformation. For that reason, all effects mentioned above, measurable by macroscopic means, can be used to study the initiation of plastic deformation (Fig.1).

Quantitatively, the emission of heat, followed by the change in temperature of deformed specimen, predominates here. This attribute as well as the relative simplicity of the temperature measurement, allow us to point out the limit between elastic and plastic deformation. The energetic contribution of other phenomena is rather small. (For example the estimated energy of the detectable signals of acoustic emission, related to the dislocation unpinning or breakaway is $\approx N \times 10^{-19}$ J.

Beghi et al. (1986) claim, that understanding of the mechanical behaviour of metals during tension can be improved by the methods of nonlinear thermodynamics of irreversible processes, where metal is treated as closed and non-isolated system subjected to an external flow of mechanical energy.

Elastic stage of deformation can be described by the second law of thermodynamics, written in local form as

$$\frac{\partial s}{\partial t} + \operatorname{div}\left(\frac{\mathbf{q}}{T}\right) = P(s) \quad (4.1)$$

where

- s – local entropy per unit volume
- \mathbf{q} – heat flux density vector
- T – absolute temperature of specimen.

In a metal subjected to deformation the entropy production has two components

$$P[s] = P_{th}[s] + P_{def}[s] \quad (4.2)$$

where

- $P_{th}[s]$ – is given by a product of the heat flux density vector and its conjugate force, $P_{th}[s] = \mathbf{q}\operatorname{grad}(1/T)$
- $P_{def}[s]$ – due to the transformation of the mechanical energy into the thermal energy involved in the creation, annihilation and motion of defects.

Since

$$\operatorname{div}\left(\frac{\mathbf{q}}{T}\right) = \mathbf{q}\operatorname{grad}\left(\frac{1}{T}\right) + \frac{1}{T}\operatorname{div}\mathbf{q}$$

Eq (4.1) takes the form

$$T\frac{\partial s}{\partial t} = -\operatorname{div}\mathbf{q} + TP_{def}[s] \quad (4.3)$$

In a general formulation, including plastic deformation

$$s = s[T, \xi_j] \quad (4.4)$$

where ξ_j represents both measurable quantities: e.g., the elastic strain tensor components and "hidden", e.g., dislocation densities.

Introducing the specific heat per unit volume, at constant configuration $\{\xi_j\}$

$$C_{\{\xi_j\}} = T \left(\frac{\partial s}{\partial T} \right)_{\{\xi_j\}} \quad (4.5)$$

into Eq (4.3) we obtain

$$C_{\{\xi_j\}} \frac{\partial T}{\partial t} + \operatorname{div} \mathbf{q} = TP_{def}[s] - T \sum_j \left(\frac{\partial s}{\partial \xi_j} \right)_T \frac{\partial \xi_j}{\partial t} \quad (4.6)$$

Using the Fourier law $\mathbf{q} = -k \operatorname{grad} T$, Eq (4.6) can be rewritten in the form of an effective Fourier equation for the temperature field

$$C_{\{\xi_j\}} \frac{\partial T}{\partial t} - k \nabla^2 T = Q_d + Q_c \quad (4.7)$$

where

- Q_d - power dissipated per unit volume related to crystal defects
- Q_c - "effective heat source", associated with configurational entropy changes

and

$$Q_d = TP_{def}[s] \quad Q_c = - \sum_j \left(\frac{\partial s}{\partial \xi_j} \right)_T \frac{\partial \xi_j}{\partial t}$$

Contribution of the components Q_d and Q_c undergoes evolution during deformation.

At the early stage of strain, during thermoelastic regime, Q_d is negligible and the only relevant ξ_j is the relative elastic volume variation, ε_{ii}^{el} (the trace of the elastic strain tensor). Then it is possible to consider entropy as the following function

$$s = s_0(T) + \frac{\alpha}{K_T} \varepsilon_{ii}^{el} \quad (4.8)$$

where

- $s_0(T)$ - thermal entropy of the undeformed material
- α - volume thermal expansion coefficient
- K_T - isothermal compressibility.

In the case of tensile test

$$\varepsilon_{ii}^{el} \approx \frac{1 - 2\nu}{E} \sigma$$

where

- E - Young modulus
- ν - Poisson ratio
- σ - applied stress.

Introducing a Grünesain parameter $\gamma = \alpha/(K_T C_V)$ and the thermal diffusivity $\chi = k/C_V$, Eq (4.7) can be rewritten as

$$\frac{\partial T}{\partial t} - \chi \nabla^2 T = -\gamma T_0 \frac{1 - 2\nu}{E} \frac{\partial \sigma}{\partial t} \quad (4.9)$$

This equation have been often developed in order to measure γ and χ , related to elastic deformation.

As the deformation grows, the thermodynamic component Q_d of Eq (4.7) becomes important. At one point of this upper limit of thermoelasticity, when a balance is reached between the applied external load and this limiting internal value of the stress itself, (characteristic of the material microstructure), the transient phase between the elastic and plastic deformation, called the Thermoelastic-Plastic Instability (TEPI) occurs.

The TEPI resembles such a process like an ordinary first-order phase transition, e.g. melting, controlled by an applied external parameter, or a non-equilibrium phase transformation, e.g. the convective Rayleigh-Benard instability. The difference between the transformations mentioned above and the TEPI consists in the fact, that in those transformations the simultaneously present phases (e.g. solid and liquid) are in equilibrium at the critical point, whereas during TEPI the "elastic" and "plastic" phases are not in equilibrium and the transition is intrinsically irreversible. As the system goes beyond the TEPI, it is impossible to get back to the initial state. It is caused by the irreversibility of dislocation processes. Once the dislocations have annihilated or reached the surface, they cannot be re-introduced by merely lowering the stress.

Finding a relation between the parameters of material microstructure and the macroscopic variables is still open problem, since it is really difficult to identify all of the thermodynamic forces and fluxes involved in TEPI. A certain proposal was presented by Beghi et al. (1986).

The production of entropy, as a measure of the irreversibility, can be written as

$$P_{def}[s] = f \frac{\sigma \dot{\varepsilon}^{pl}}{T} \quad (4.10)$$

where, during the tensile test σ is the applied tensile stress, $\dot{\varepsilon}^{pl}$ is the plastic strain rate and $\sigma\dot{\varepsilon}^{pl}$ is the applied mechanical plastic specific power. Dissipation coefficient f , providing the fraction of the plastic power converted into heat, turns out to be a function of the stress, the strain rate, the temperature and the previous history. High value of the quantity f indicates that a significant part of energy is converted into heat, small f shows that considerable part of energy is stored, mainly as a frozen potential internal energy caused by local stress intensification or by dislocations.

Our knowledge about the active mechanisms of dissipation is still limited. Beghi et al. (1986) quoted it after Nicholas as following:

- Kinetic energy of moving dislocations
- Damping of dislocation motion by radiation and scattering of acoustic waves
- Creation and annihilation of dislocations
- Creation and annihilation of point defects.

Determination of the amount of the energy dissipated during plastic flow is still rather complicated and, in generally, depends on the applied method of calculation or experimental evaluation.

Beghi et al. (1986) used the Eqs (4.7) and (4.10), written the following way

$$\frac{\partial T}{\partial t} - \chi \nabla^2 T = -\gamma T \frac{1-2\nu}{E} \frac{\partial \sigma}{\partial t} + f \frac{\sigma}{C_V} \frac{\partial \varepsilon^{pl}}{\partial t} \quad (4.11)$$

The values of required coefficients were obtained from experiment. The samples, made from austenitic steel, were deformed by tension inside a calorimeter with high temperature resolution (to 2×10^{-4} K). Experimental determination of the thermal and mechanical responses, $T(t)$ and $\varepsilon(t)$ (Fig.2) allows the authors to separate \dot{T}^{pl} related to the dissipation parameter f .

Taking advantage of the linearity of Eq (4.11) with respect to temperature we obtain

$$\dot{T} = \dot{T}^{el} + \dot{T}^{pl} \quad (4.12)$$

where

$$\dot{T}^{el} = -\gamma T \frac{1-2\nu}{E} \dot{\sigma} + \chi \nabla^2 T^{el} \quad (4.13)$$

is related to the pure thermoelastic cooling in the presence of heat diffusion, and

$$\dot{T}^{pl} = f \frac{\sigma \dot{\varepsilon}^{pl}}{C_V} + \chi \nabla^2 T^{pl} \quad (4.14)$$

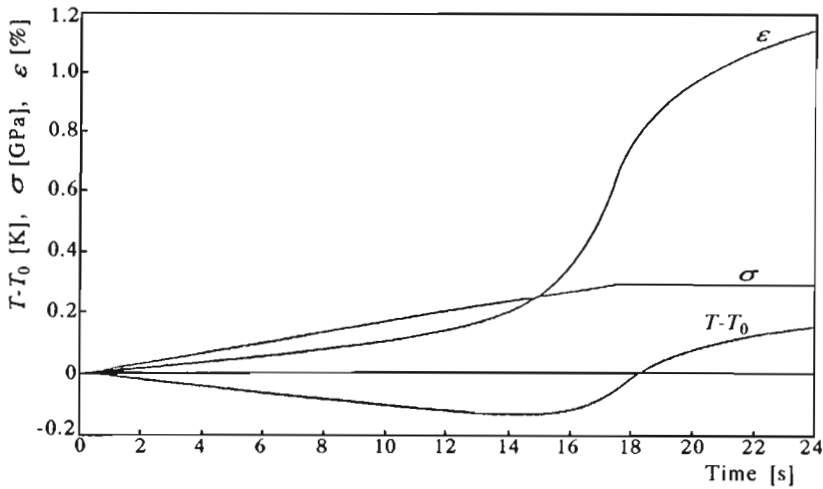


Fig. 2. Time dependence of temperature variation $T - T_0$ and deformation ε of an AISI 316 steel sample subjected to a tensile test at a constant stress rate $\dot{\sigma} = 9.6 \text{ MPas}^{-1}$ (cf Beghi et al. (1986))

is related to the pure plastic heating.

Describing the plastic strain rate as

$$\dot{\varepsilon}^{pl} = \dot{\varepsilon} - \frac{\dot{\sigma}}{E} \quad (4.15)$$

and the plastic specific power as

$$W_p = \sigma \dot{\varepsilon}^{pl} \quad (4.16)$$

the specific dissipated power accordingly means

$$W_d = f W_p = C_V (\dot{T} - \dot{T}^{el}) \quad (4.17)$$

Using Eqs (4.15) and (4.16) it is possible to evaluate W_p , W_d and f as a dissipation function of the applied stress (Fig.3).

The value of the dissipation parameter f , found by Beghi et al. (1986), (Fig.3) tends towards the average of the likely range of values for this kind of material, and decreases accordingly to the increase of strain. These data are in agreement with obtained results of the energy storage in metals subjected deformation (cf Bever et al. (1973); Oliferuk et al. (1993), (1995)).

One of the first experimental works, devoted to the problem of investigation of the beginning of plastic deformation are the doctor's thesis written by

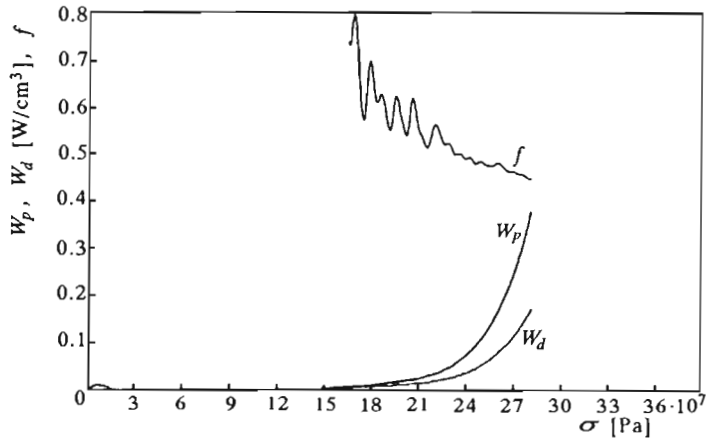


Fig. 3. Stress dependence of the specific plastic power W_p , the specific dissipated power W_d and the dissipation function $f(\sigma, \dot{\epsilon}/T)$ in austenitic steel (the oscillations in the f vs. stress curve are only due to numerical instabilities) (cf Beghi et al. (1986))

Gabryszewska (1964). On the base of theory given in the papers (cf Vakulenko (1961)), the effects of coupling between the fields of temperature and deformation were there discussed. It allowed the author to derive adequate relations, enabling finding the limit of reversible deformation by measuring temperature. Additionally, a contribution of the internal energy and the entropy in this relation was evaluated.

In order to verify the discussed relationships, different metals (Al, Cu, steel) and certain plastic materials (PVC, polystyrene, polyethylene) were subjected to uniaxial loading. The results obtained allowed the author to draw the following conclusions:

- in the elastic range of deformation, the temperature increments, both for a metals and plastic materials are negative, linear with respect to stresses, and their values depend on the kind of material,
- after crossing the proportional limit, in all of the materials being tested, a sudden inversion in the trend of the temperature vs stress is observed; moreover the temperature increments became non-linear,
- the values of proportionality limits, obtained from the $\sigma(\Delta T)$ relations, are slightly different from the results based on $\sigma(\epsilon)$ measurements.

The experimental as well as the theoretical part of Gabryszewska's work is very interesting. Unfortunately, significant anisotropy of the tested mate-

rials, in particularly plastic materials, and limited at that time possibilities of temperature measurements, prohibited the author to achieve a sufficient accuracy.

Basz (1984) presents the outline of the history of the investigations of metals, carried out mainly in the former Soviet Union. His own investigations were performed on the cylindrical specimens made of carbon steel, subjected to tension. The changes in temperature were measured with the aid of thermocouple and registered as a loading function.

It was found that the value of the thermoelastic effect and the character of $\Delta T(\sigma)$ curve depend on the rate of deformation and on the geometry of specimen. For longer specimens and the specimens of the smaller diameter the straight segment of $\Delta T(\sigma)$ was longer. Similar effect was caused by a higher rate of deformation. These effects were probably caused by the preservation or not of the adiabatic conditions of the experiment. However, this problem was not discussed. Besides the author did not compare his results with the mechanical characteristics and he did not relate the temperature behaviour to the yield stress of material.

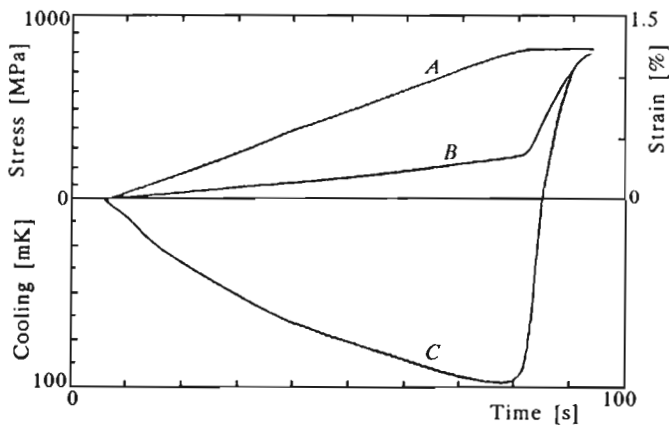


Fig. 4. A – stress, B – strain and C – temperature vs. time during a tensile test of 38NCD4 steel (cf Bottani and Caglioti (1982b))

In order to explain the behaviour of material, particularly in the beginning of deformation Bottani and Caglioti (1982a,b) present the empirical criteria, based on the temperature measurements and acoustic emission detection. The investigations were made on the specimens of austenitic steel (38NCD4), comes from an ingot. After annealing and quenching in proper terms the samples were subjected typical tensile test, performed by an Instron-TTM 111. The

applied strain rate was about 10^{-1} s^{-1} . During the deformation were registered: the stress σ , strain ε and temperature change ΔT (Fig.4).

A plot of the change of temperature of the specimen vs stress is present in Fig.5.

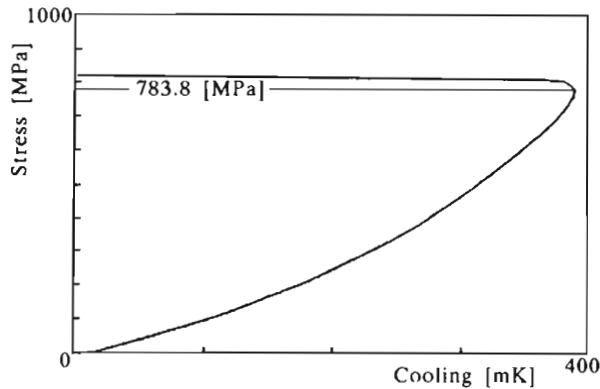


Fig. 5. Temperature vs stress for the sample of 38NCD4 steel of Fig.4 (cf Bottani and Caglioti (1982b))

As a yield stress, was defined a point, where the reciprocal of the temperature derivative of the stress vanishes (maximum of ΔT vs. σ occurs). This value was called by the authors as the thermoelastic limit stress σ_θ . The values of σ_θ , obtained for several samples, were compared with the conventional yield strength of this steel, obtained from the stress vs strain curves by the 0.2% offset method. For all the specimens, σ_θ values were lower than $\sigma_{0.2}$. Instead, the scatters of obtained valuables were comparable.

A method described above is simple and effective. The authors called it as a new one and regarded, that its sensibility could help to reduce the safety factors employed in structural design. It is rather difficult to agree with these conclusions, because the safety factors are applied with a big reserve. Besides, this method is not new; this kind of investigations were performed earlier (cf Gabryszewska (1964)).

Basing on the assumption, that yielding of material exhibits typical features of dynamic instability. Bottani and Caglioti (1982a) study this problem in terms of synergetic. They proposed a set of the non-linear balance equations for entropy and momentum governing the temperature and strain fields. The data for such equations were obtained from experiment. The following quantities were measured as a function of time during loading: imposed deformation $\varepsilon_a(t)$, stress $\sigma(t)$, temperature $\theta(t)$ of the sample surface (in the

median plane) and acoustic emission activity $AE(t)$ (Fig.6).

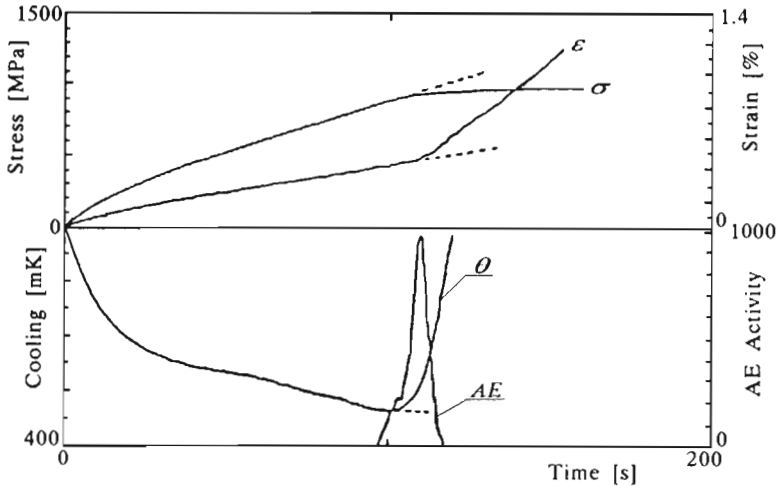


Fig. 6. Stress σ , strain ε , temperature θ and acoustic emission rate AE during deformation of 38NCD4 steel (cf Bottani and Caglioti (1982a))

In the authors opinion, at the level of deformation, corresponding to the abrupt change of the slope of $\sigma(\theta)$, a transition from the incoherent to the coherent motion of dislocations takes place. This point was called by them the true elastic limit of the material. Accordingly, in their theoretical approach, two regions were distinguished: thermoelastic region of the linear thermodynamic branch before and plastic region of the non-equilibrium dissipative structure, developed after this point.

Yielding in material consider the authors as a result of mutual interaction of phonons and dislocations. Besides, they confirmed experimentally, that signals of acoustic emission, that usually spontaneously occur in the vicinity of yield point, had, for a while, coherent character. Their amplitude was constant, what indicate that all the signals were caused by similar phenomena, responsible for the initiation of the plastic deformation.

The papers discussed in this section confirmed, that the qualitative differences in the adiabatic changes of temperature vs stress in the ranges of elastic and plastic deformation allow us to determine the beginning of plastic deformation during tensile test. This way of estimation is considered as simple in adaptation, and achieved accuracy as higher or similar to obtained via the stress-strain relations. In the last years, many successful attempts have been made in the direction of application of the effects of temperature field coupled with the strain field to the determination of the yield limit and

yield surface also in other kinds of loading as well as in not only elasto-plastic materials. Śródka (1979), Gabryszewski and Śródka (1981), carried out the investigations concerning temperature changes for tension, compression and torsion of plastic (steel) and semi-brittle bodies (grey cast iron). Gabryszewski and Pindur (1985) presented results of the yield surface investigation using the thermal-mechanical coupling method in anisotropic non-linear elastic material (zinc). Ochelski and Polański (1992) undertaken similar attempts in the case of plastic materials. Blanc and Giacometti (1981), used isentropic temperature variations in monitoring the behaviour of material during the fast and high frequency deformations. Examinations of materials on the base of coupled temperature – deformation fields have been evaluated in some theses (cf Gabryszewska (1964); Śródka (1979); Gadaj (1991); Schmidt (1988)). These examples show the broader interest in investigating the temperature – deformation relationships in stressed materials.

5. Influence of accuracy of determining the onset of plastic flow on the investigation of stored energy. Preliminary results

A metal subjected to stress deforms either elastically or plastically. Plastic deformation can be related to the hot and the cold work. The cold work, causing distortion and disarrangement of the lattice, is accompanied by work hardening, namely an increase in the resistance to farther deformation. The plastic deformation affects the internal energy of a body. This change, named the storage (latent) energy, remains in the structure of the metal until it is released during a restoring process.

According to the papers of Taylor and Quinney (1934), it was assumed for a long time, that the storage energy establishes a small part of the energy expended during the plastic deformation, while the remaining fraction of energy is dispersed in the form of heat.

At present, as a result of numerous investigations (cf Bever et al. (1973); Śródka (1979); Gadaj et al. (1982); Oliferuk et al. (1985), (1995); Chrysochoos and Martin (1989); Chrysochoos et al. (1989)) it can be stated, that the energy stored during the deformation depends on:

- the kind and the properties of the tested material,
- the range and the history of the deformation.

The amount of the energy found experimentally depends on the applied method.

The stored energy is not uniformly distributed throughout a sample of cold-worked metal. The effect of energy storage is explained both by the occurrence of the elastic forces between similarly oriented grains or blocks of grains (cf Novozhilov (1965); Śródka (1979)) and, mostly, by the generation, motion, blocking and annihilation of dislocations, leading to the changes in their density and arrangements (cf Bever et al. (1973); Gadaj et al. (1982), Oliferuk et al. (1985), (1993), (1995)). Generally, it is assumed, that both of the abovementioned phenomena operate simultaneously. However, there are reasons to believe, that initially (up to the deformation of about 2%), the kinematics type of hardening is significant, while during further deformation, the isotropic hardening, caused by the rebuilding of microstructure predominates (cf Śródka (1979)).

The applied methods of measuring the stored energy can be classified as:

I. Single-step methods, in which the energy expended in plastic deformation and the dispersed heat both are measured during the deformation in one experiment. These methods are based on a direct application of the First Law of Thermodynamics

$$E_s = \Delta E = Q + E_w \quad (5.1)$$

where

- ΔE - change in the internal energy of a body
- Q - heat, deformation heat; positive if absorbed and negative in the case of emission to the environment
- E_w - mechanical energy, expended during plastic deformation (cf Bever et al. (1973)).

II. Two-step methods, which determine the enthalpy difference between the cold-worked and the standard state. At constant pressure there holds

$$\Delta H = \Delta E + p\Delta V \quad (5.2)$$

where

- p - hydrostatic pressure
- ΔV - volume change, associated with the process.

Assuming $p\Delta V$ negligibly small (cf Bever et al. (1973))

$$\Delta E \approx \Delta H \quad (5.3)$$

A modification of the single-step method is the method elaborated in the IPPT PAN (cf Gadaj et al. (1982)). This method allows us to determine the energy storage during plastic deformation without interruption of the process.

Like in other single-step methods, the stored energy is obtained here as the difference between the plastic work done on the body and the evolved heat

$$E_s = E_w - Q \quad (5.4)$$

In the case of tensile test, the work done on the body is determined from the force vs. elongation plot. The evolved heat is determined by the so-called simulation of heating of the sample under loading on the basis of the Joule-Lenz effect. The idea is to deliver such an amount of the electrical energy to the unstrained sample, that the temperature increase during the simulation is the same as during the deformation. However, it would be difficult to model this way the temperature decrease, occurring during the thermoelastic effect. So, the heat evolved by the sample up to its recovery to the ambient temperature is calculated from the equation

$$Q = mc\Delta T \quad (5.5)$$

where

m – mass of the gauge part of sample

c – specific heat of the material

ΔT – change in the temperature, calculated from Eq (3.1) for the stress, at which the maximum of temperature occurred.

Such defined E_s is related to the initial temperature of specimen.

As follows from Sections 3 and 4, the point, where the maximum of the temperature decrease occurs, is not the beginning of plastic deformation, since the dislocation rearrangements begin earlier. This is confirmed by the departure of the curve $\Delta T(\sigma)$ from its initial linear form. Hence it is proposition to take just the same point – this point of departure of the curve $\Delta T(\sigma)$ from its initial straight dependence, as the beginning of plastic deformation as well in the energy storage investigations.

In order to verify the possibility of the practical usage of this criterion and generally, to make a thorough study of the temperature behaviour of the sample under tension, especially at the onset of the plastic deformation, initial experiments were performed. It was tensile test, carried out on the Instron 1251 testing machine. The investigations were performed on the samples, made of austenitic steel with composition 0.05 wt% C, 1.35 wt% Mn, 1.0 wt% Si, 0.016 wt% P, 0.008 wt% S, 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 samples (Fig.7) were prepared from the cold-rolled strips with a cross-section 25mm×4mm, annealed at 1050°C. In order to obtain the material with the homogeneous microstructure and suitable dimensions the specimens

were 50% cold-rolled, machined properly and, annealed in vacuum at 1100°C for 2.5 h.

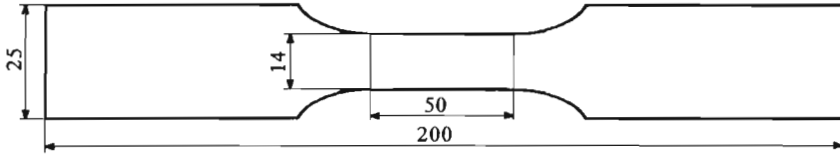


Fig. 7. The shape of the sample used in experiment

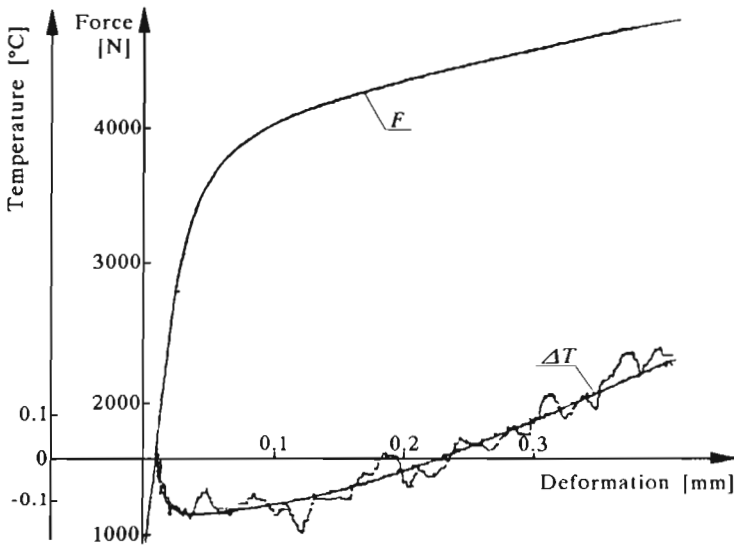


Fig. 8. Loading and temperature change vs deformation during the tensile test for the specimen of 00H19N17Pr austenitic steel (the fluctuations of temperature are caused by the measurement technique; there is a gap (≈ 2 mm) between the pens of X-Y plotter)

During the loading the time, force, deformation and the distribution of infrared radiation, emitted by the specimen surface, were registered. This distribution was evaluated with the aid of the thermovision system AGA-680, which measures the temperature in a non-contact way. The specially designed additional device, coupled with the camera, enables a continuous measuring and recording of the temperature at any chosen point. This device was used to register on the X-Y plotter the changes in temperature at the central point of the specimen. Simultaneously, by observing the temperature distribution on the monitor, the homogeneity of the deformation was controlled. Prior to the tensile tests the samples were blackened with carbon powder to ensure

a homogeneous emissivity of the surfaces. A typical experimental result is plotted in Fig.8.

The measurement of the temperature at the central point of the specimen surface, the stable circumstances and the properly chosen rate of deformation (the crosshead rate 10 mm/min) make this process partially isentropic and adiabatic. The accuracy of the measurements was estimated as being about 0.05°C , for the absolute value, and about 0.02°C , for the relative value of temperature changes.

In each case of tensile test a thermoelastic effect, i.e. the decrease of specimen temperature in the elastic range of deformation was observed. After this smooth, quasireversible decrease in temperature, the sample heats up due to the initiation and evolution of the plastic deformation.

The registered change in temperature can be plotted vs stress (Fig.9). In the initial stage of elongation these changes are linearly dependent on stress. The initiation of the mechanisms of plastic deformation causes the departure of the experimental result $\Delta T(\sigma_s)$ from the straight line typical to elastic deformation.

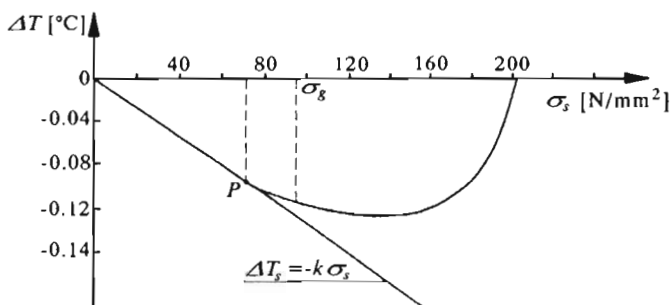


Fig. 9. Temperature change vs stress for the sample of austenitic steel

It means, that the stress value corresponding to a point P , where the departure of the straight line $\Delta T_s = -k\sigma_s$, describing the elastic deformation, from the plot of the measured temperature of the specimen under tension was observed, is the true macroscopic flow stress. This value is lower than σ_g (Fig.9), i.e. lower than the beginning of plastic deformation, indicated as the elastic limit on the base of $\sigma(\varepsilon)$ curve.

Exactly finding the onset of plastic flow by measuring mechanical characteristics $\sigma(\varepsilon)$ would require a specially designed experiment carried out on a small gauge length. Hence, an additional specimen would be necessary.

Measuring the change of temperature enables us to find the beginning of

plastic deformation directly on the specimen strained for the purpose of energy storage investigation. Besides, consistently taking the corresponding to P , point on the $\sigma(\varepsilon)$ curve helps to calculate the expended energy more precisely and it should enable more unique elaboration of the energy storage data.

It is necessary to remember that the mean square deviation of the energy storage measurements is particularly high at the initial stage of deformation. Sometimes it can even lead to incorrect results, for instance the negative values of stored energy, obtained by Śródka (1979).

Repeatability, uniqueness and simplicity in recording of the thermoelastic effect allowed Chrysochoos and Martin (1989), Chrysochoos et al. (1989) to apply this affect for the calibration of the system used for energy storage measurements. Notably a specially designed microcalorimeter was mounted on the specimen.

There are physical arguments to believe that taking the point where the $\Delta T(\sigma)$ curve departs from linearity as the onset of plastic deformation should increase the accuracy of measuring the stored energy, especially at the initial stage of plastic deformation.

6. Final remarks

- The physical phenomena occurring in material under loading decide whether material is reversibly (elastically) or irreversibly (plastically) deformed.
- Usually the onset of plastic deformation is determined as the end of the straight segment of the $\sigma(\varepsilon)$ diagram. However such a yield limit can be found more precisely by measuring the changes in temperature, the acoustic emission and the exoelectron emission.
- Monitoring of the changes in temperature of the specimen subjected tension in adiabatic condition allows us to determine the beginning of plastic deformation.
- During the tension test the irreversible plastic deformation begins when the adiabatic dependence $\Delta T(\sigma)$ ceases to be the straight line.
- It follows from the review of the literature that usually a point at which the temperature increment changes its sign is taken as the yield limit. This point corresponds to the minimum of temperature of the deforming

specimen. It is easier to find this point in experiment than to find the departure of $\Delta T(\sigma)$ curve from linearity.

- 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 (offset yield stress), taken from the $\sigma(\varepsilon)$ curve.
- It seems that taking the end of the linear part of the characteristic $\Delta T(\sigma)$ as the yield limit will increase the accuracy of measuring the stored energy, especially at the initial stage of plastic deformation.

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Przejście od odkształcenia sprężystego do plastycznego z punktu widzenia sprężen termomechanicznych – przegląd kryteriów

Streszczenie

W pracy oceniono kryteria i metody wyznaczania początku odkształcenia plastycznego metali. Główną uwagę zwrócono na kryterium termomechaniczne i związane z nim sposoby wyznaczania tego początku. Omówiono literaturowe wyniki badań przejścia materiału w stan plastyczny, zarówno przy jednoosiowym rozciąganiu jak i obciążeniach złożonych, oparte na pomiarach temperatury. Stwierdzono, że za początek trwałego makroskopowego odkształcenia plastycznego przyjmuje się zazwyczaj punkt, w którym temperatura próbki podczas rozciągania osiąga minimum. Na podstawie badań własnych, jak i danych literaturowych, uznano jednak, że początek makroskopowego odkształcenia plastycznego metali lepiej wyznacza punkt rozbieżności charakterystyki $\Delta T(\sigma)$ od początkowej zależności liniowej. To kryterium ma szczególnie znaczenie przy wyznaczaniu energii zmagazynowanej w metalu.