YIELD POINT DETERMINATION BASED ON THERMOMECHANICAL BEHAVIOUR OF POLYCRYSTALLINE MATERIAL UNDER UNIAXIAL LOADING

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Abstract: The paper is devoted to yield point determination based on the thermomechanical coupling that takes place in the material during its uniaxial tension. Experiments were performed on aluminum alloy and on austenitic steels. The stress value corresponding to the temperature minimum is treated as the critical resolved stress at which plastic deformation on the macroscopic scale begins. The obtained results are compared with values of stress which produces the irreversible strain equal to 0.2%. Such value of the stress is usually regarded as the yield point determined from the stress-strain curve. It is found that the values of yield point determined on the ground of the thermomechanical coupling are lower than these obtained from stress-strain curve.

1. INTRODUCTION

Some polycrystalline materials such as austenitic steels under uniaxial tension are characterized by the smooth stress-strain curve. Determination of the yield point for such materials is more difficult than for materials where the Lüders bands appear. The majority of methods applied for determining the onset of plastic deformation are based on the stress-strain curve. In tests of materials under uniaxial loading, three criteria of the initiation of yielding are used. They are: elasticity limit, proportionality limit and yield point. The elasticity limit is the greatest value of applied stress that the material can withstand without any measurable irreversible deformation. With an increase in sensitivity of strain measurement, a decrease in value of elasticity limit is obtained. Determination of the elasticity limit requires a continuous incremental loading-unloading procedure. For this reason the elasticity limit is often replaced by the proportionality one. The proportionality limit is the highest value of stress at which the applied stress is directly proportional to strain. Yield point is the stress necessary to obtain an assumed value of irreversible (plastic) strain. The assumed value is equal 0.2% (Beluch, 2002). The aim of this paper is to present the method of yield point determination that doesn't need the assumed value of irreversible strain that correspond to the yield point and to compare obtained results with the values of stress corresponding to 0.2% plastic strain. This method is based on thermomechanical coupling that takes place during unixial tension.

2. YIELD POINT DETERMINATION BASED ON THERMOMECHANICAL COUPLING

Deformation process always modifies the temperature field of a material. Under loading at adiabatic conditions temperature of sample changes. During elastic deformation of the material with positive coefficient of thermal expansion, its temperature decreases whereas during plastic deformation the temperature of tested material rises. These phenomena can be used for the determination of the yield point. Change in a material temperature during deformation is an example of a mutual conversion of the potential and kinetic energy of lattice atoms. That phenomenon of temperature variation accompanying the elastic deformation is named thermoelastic effect. This variation can be expressed by the Kelvin formula (Oliferuk, 1997):

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

where: α – coefficient of linear thermal expansion, T – initial absolute temperature, c_σ – heat capacity per unit volume at constant stress, $\Delta\sigma_S$ – change of stress (change in the uniaxial Kirchoff stress tensor).

3. CONTACTLESS METHOD OF TEMPERATURE MEASUREMENT

Each body with an absolute temperature greater than 0^0K emits electromagnetic radiation in the infrared range. This radiation, named thermal one, was discovered in 1800 by Federic Herschel. Josef Stefan formulated a relation between temperature T of the black body and total radiation power of its surface as:

$$g(T) = \sigma T^4, \tag{2}$$

where σ=5.6703·10^{-8}W/m^{2}K is Stefan*'s* constant and T is the absolute temperature of the black body (Jaworski and Piński, 1976). This result was also derived by Ludwig Boltzmann and now it is called Stefan-Boltzmann law. Note that the radiation power per unit area of the black body surface depends only on the its temperature and not on any other parameters of the object. It is a single-valued function of the temperature. Thus, the Stefan-Boltzmann

law constitutes foundation of contactless methods of temperature measurement (Rudowski, 1978).

The radiation emitted by a surface of real object is dependent not only on its temperature but also on the feature of its surface. This feature is described by the quantity κ that called emissivity. Emissivity κ is the ratio of the radiation power of the real surface to the radiation power of the black body surface at the same temperature. Emissivity of the tested surface shows how much energy is emitted by the unit of the real surface during unit time period in comparison with the energy emitted by the unit of the black body surface during the same period and at the same temperature. Values of the emissivity are included in range from 0 to 1.

Thus Stefan-Boltzmann law for real surface has a form as follows (Jaworski and Piński,1976):

$$E = \kappa g\left(T\right) = \kappa\sigma T^4, \tag{3}$$

where E is radiation power emitted by unit surface of the κ emissivity at T temperature.

Infrared radiation is measured by an IR detector that is a main part of IR Thermographic System. The signal S on the IR Thermographic System out-put includes two parts: one is generated by IR radiation emitted by the tested object and another one caused by the surroundings IR radiation (Oliferuk, 2008):

$$S = \kappa f(T_0) + (1-\kappa) f(T_a), \tag{4}$$

where: T_a is the absolute ambient temperature, T_0 is the absolute object temperature, $(1\text{-}\kappa)f(T_a)$ is a signal as a function of an ambient temperature, $\kappa f(T_0)$ is a signal as a function of the object temperature.

The temperature of the tested surface can be measured when the value its emissivity, ambient temperature and calibration curve of IR Thermographic Systems are known. Usually the tested surface is covered with soot, because the emissivity of the soot is known and equals to 0.95.

Let us note that method of temperature measurement based on detection of IR radiation is non-destructive. Up-to-date IR Thermographic Systems enable to determine surface temperature distribution. A such kind of System was used in the presented work.

4. EXPERIMENT PROCEDURE AND RESULTS

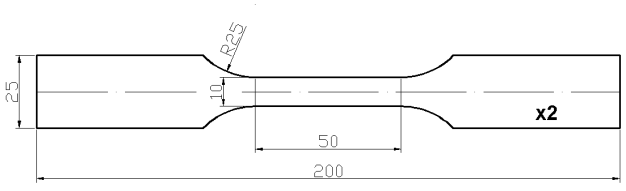

Fig. 1. Shape and dimensions of specimens

The experiments were performed on specimens made from austenitic steels and aluminum alloy (Tab. 1). The shape and dimensions of the specimens are shown in Fig. 1.

Tab. 1. Specimens used in experiments

Specimen	Material	Symbol	Chemical composition
1	austenitic steel	00H19N17 (304)	Cr19%Ni17%
2	austenitic steel	00H17N14M2 (316 L)	Cr17%Ni14%Mo2%
3	aluminium alloy		Si8%Cu3%

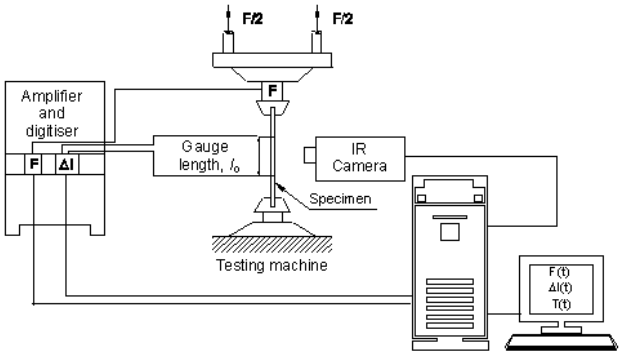

Fig. 2. Experimental set-up used for determination of yield point

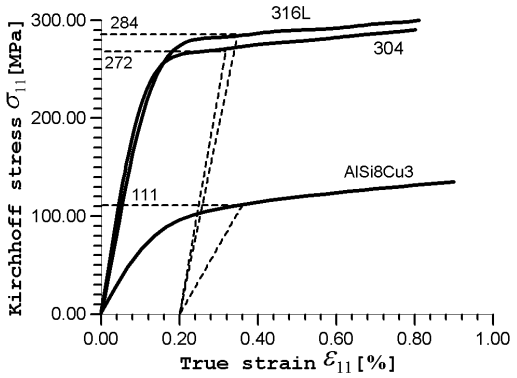

Fig. 3. Stress-strain curve for tested materials and procedure of the yield point determination

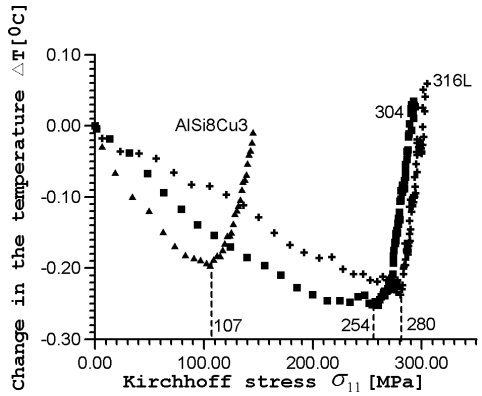

Fig. 4. The dependencies of the change in the specimen temperature versus stress in early stage of tension

All specimens were strained using the MTS testing machine with constant strain rate equal $5\cdot10^{-3}$ s^{-1}. During the tensile test the temperature distribution on the surface of the specimen was measured by IR camera. Simultaneously, the stress and strain were determined as a function of the deformation time.

In order to obtain an uniform emissivity of the tested specimen surface and to enhance method sensitivity the specimen surfaces were covered by the sooth.

Schematic diagram of the experimental set-up designed for determination of yield point is shown in Fig. 2.

The frequency of thermal image, stress and strain recording was equal 50 Hz.

Fig. 3 shows the typical stress-strain curves for the tested materials. From these stress-strain curves, the yield point as the stress corresponding to plastic strain ε_p=0.2% was determined for each material (Fig. 3).

On the basis of the stress and the temperature experimental data, the dependence of the change in the specimen temperature vs. stress was determined (Fig. 4).

It is seen that, with growing stress, the specimen temperature decreases, reaches minimum and then starts to rise rapidly. It can be assumed that the specimen heating due to micro-plastic deformation before the temperature minimum is negligible small. Consequently, the stress value corresponding to the temperature minimum can be treated as the critical resolved stress at which plastic deformation on the macroscopic scale begins (Fig. 4) (Kuo et al., 2005; Lee and Shaue, 1999).

5. CONCLUSIONS

The values of yield point determined by two different methods are shown in Tab. 2. It is seen that the values of yield point determined on the ground of the thermomechanical coupling are lower than these obtained from stress strain-curve (Tab. 2, Fig. 5, Fig. 6, Fig. 7). Method based on thermomechanical coupling is more precise.

Tab. 2. Yield point values obtained from thermomechanical coupling and from stress-strain curve.

Material	Yield points obtained from thermomechanical coupling analysis [MPa]	Yield points obtained from tress-strain curve [MPa]
304	254	272
316L	280	284
Al	107	111

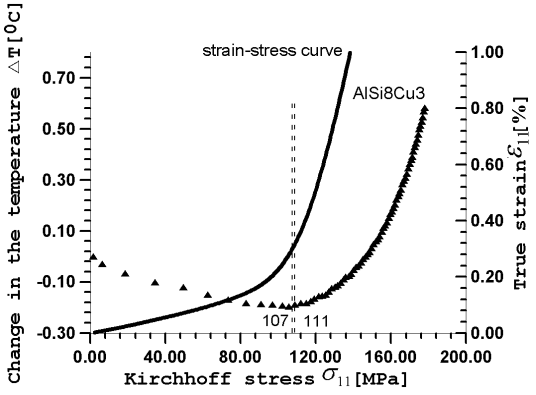

Fig. 5. Strain-stress curve and change in the temperature-stress for aluminum in early tension stage.

The method based on thermomechanical effect is especially useful for materials in which Lüders bands don't appear and for materials with non-linear elasticity. It should been emphasized that the instant at which the temperature reaches the minimum can be found more precisely than the point when the stress-strain curve ceases to be the straight-line. We can see it clearly in Fig. 5.

It should be noted that the presented method is based on physical phenomena connected with energy conversion in the deformed material. The method doesn't need the assumed value of plastic strain.

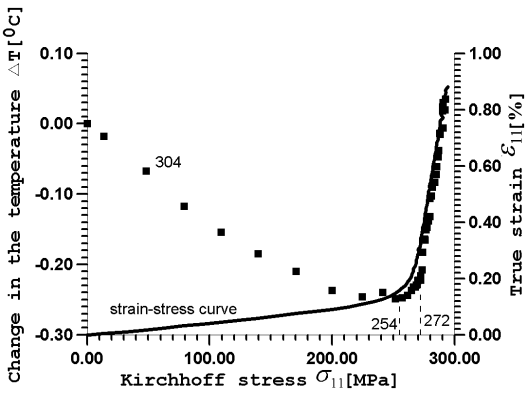

Fig. 6. Strain-stress curve and change in the temperature-stress for 304 steel in early tension stage

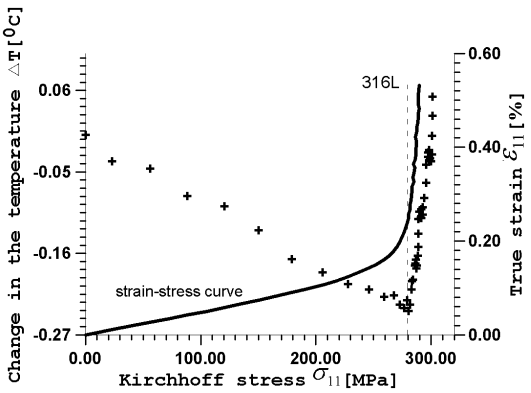

Fig. 7. Strain-stress curve and change in the temperature-stress for 316L steel in early tension stage

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