Calculation of stress-strain dependence from tensile tests at high temperatures using final shapes of specimen’s contours

Določitev odvisnosti napetost – deformacija z nateznimi preizkusi v vročem in na osnovi končnih oblik nateznih palic

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Abstract: The new mathematical model is proposed that enable calculation of true stress – true strain dependence from the results of tensile tests also after appearing of necking. Based on this model the computer program was developed which from the measured final shapes of the tensile specimens and from tensile testing data automatically determine the time evolution of the specimen’s contour, strain rate and stress-strain relation. In order to tests and validate the model tensile tests at different prescribed strain rates and temperatures on specimens made of nickel alloy Alloy201 were carried out on thermo-mechanical simulator Gleeble 1500D. It was found that after occurrence of neck the true strain rate is constantly increasing throughout the test. Further it was found that plastic part of the rod can be well approximated with constant and with catenary but Bridgman correction can be determined only if catenary is used. Comparison of predicted evolution of minimal radius at the neck with measured one showed excellent agreement.

Izvleček: V delu je opisan nov matematični model, s katerim je mogoče na podlagi rezultatov nateznih preizkusov tudi po pojavu skrčka določiti odvisnost prava napetost – prava deformacija. Na osnovi modela je bil narejen računalniški program, ki na podlagi izmerjenih končnih oblik

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nateznih palic in podatkov nateznih preizkusov avtomatično določi časovni razvoj kontur nateznih vzorcev in izračuna hitrost deformacije ter zvezo med napetostjo in deformacijo. Model je bil preizkušen in preverjen z nateznimi preizkusi, ki so bili za nikljevo zlitino Alloy201 pri različnih predpisanih konstantnih hitrostih deformacije in konstantnih temperaturah narejeni na simulatorju termomehanskih metalurških stanj Gleeble 1500D. Ugotovljeno je bilo, da prava hitrost deformacije po pojavu skračka začne naraščati in narašča vse do konca preizkusa. Nadalje je pokazano, da lahko del palice, ki je v plastičnem stanju, zelo dobro aproksimiramo tako s konstanto kot tudi z verižnico, vendar pa je Bridgmanov popravek mogoče določiti le pri aproksimaciji z verižnico. Rezultati razvoja minimalnega radija v skrčku, dobljeni s predlaganim modelom, se odlično ujemajo z meritvami.

Key words: tensile test, necking, hot deformation, strain-stress curves.
Ključne besede: natezni preizkus, skrček, deformacija v vročem, krivulje deformacija – napetost

INTRODUCTION

From the test for determination of hot workability of metallic materials it is required to enable measurement of force applied on sample as a function of its deformation at constant strain rate and constant temperature. There are three most important tests, i.e. compression test, torsion test and tensile test. Each of the tests has its own problems, i.e. weaknesses, which impeded gaining of reliable data about stress, strain, strain rate, deformability, etc. Compression test has seemingly the most advantages: geometry of cylindrical specimens is easy for machining and higher strains as well as strain rates can be achieved in comparison to tensile test, but due to the presence of friction between compression anvil and specimen buckling can occur especially at slightly higher strains. Thus uniaxial stress state in deformed specimen is present only up to the beginning of its buckling when also reliable value related to hot deformation can be obtained. In case of exceeding of mentioned compression strain additional software is needed for gaining of more reliable data. Hot torsion testing takes place without presence of friction; moreover this test is very appropriate for assessment of hot workability since higher strain can be achieved by this type of testing that increase the reliability. But its weakness is in control (maintenance) of constant temperature during test, inhomogeneity of deformation so along working length of specimen as well as in radial direction. Especially due to the latest weakness strain and strain rate can be expressed as equivalent strain and strain rate. At hot tensile testing also non-homogeneity of deformation occurs on specimen working length that is expressed by its necking. It is well known, that for tensile test homogenous deformation takes place only untilappearance of necking which occurs at strains of approximately between 0.2 and 0.3, depending on precision of manufacturing of the tensile samples, onmaterials inhomogeneity, on temperature gradient along the tensile axis, etc.

When the neck appears, the stress state change from uniaxial to multi-axialmust be taken into account. The correction due to multi-axiality is usuallydone by Bridgman correction, which presumes that portion of the contour inclose neighborhood of the minimal cross-section of the neck may be characterized by a single parameter, the radius of curvature of the circle osculating the profile at the neck.[1] But obtaining reliable data on stress – strain relation from tensile tests after appearance of necking is very difficult task especially if testing is conducted at elevated temperatures, which is exactly the case if one wants to study hot workability of metallic materials.

The aims of this study are therefore to evaluate the possibility of applicability of tensile test for determination of hot working properties of metallicmaterials also after the appearance of necking and to introduce appropriatemodel for calculation of stress-strain dependence from the final shapes ofcontours of tensile loaded specimens.

Experimental procedure

A commercially produced Ni alloy Alloy201 was supplied by Thyssen-Krupp Gmbh as hot drowned rods with chemical composition given in Table 1 and equiaxed grain structure with an average grain size of about 16 µm.

Cylindrical specimens with dimensions of 25 mm of effective length and of 8 mm in diameter where machined from supplied rods for hot tensile tests (see Figure 1 for specimen's geometry and dimensions).

Table 1. Chemical composition of the commercially pure Ni (Alloy201) tested in mass fractions *w*/%

Mo	**Cr**	**Si**	**S**	**Mg**	**Co**	**Cu**	**P**
0.001	0.004	0.05	0.001	0.03	0.07	0.006	0.006
Mn	**Ti**	**Fe**	**Sn**	**C**	**V**	**Al**	**Ni**
0.13	0.04	0.13	0.01	0.02	0.002	0.023	rest

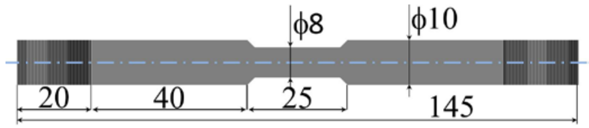
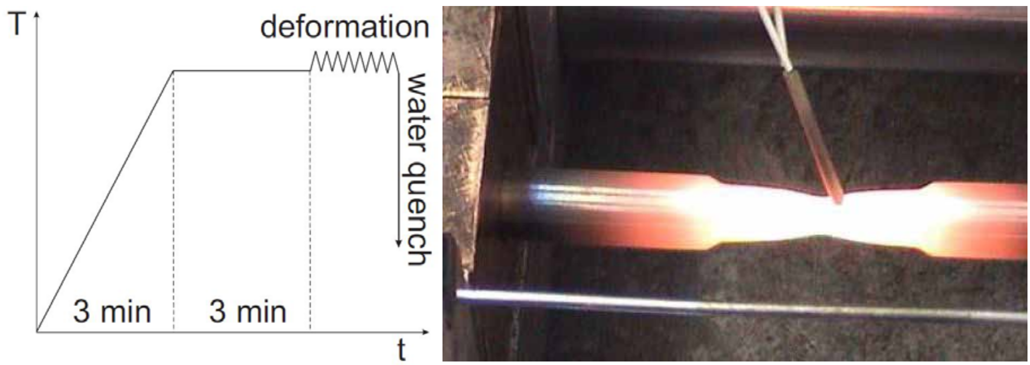


Figure1. Dimension of specimen's for tensile testing.



(a) (b)

Figure2. Schematic representation of temperature control (left), and shaping of contour (right) during hot tensile testing of Alloy201.

The hot tensile tests were carried out on Gleeble 1500D thermomechanical testing machine. The samples were deformed between 8 mm and 11 mm at temperatures from 800 °C to 1000 °C under prescribed constant strain rates between 10^{-3} s^{-1} and 10^{-1} s^{-1} assuming that deformation was homogeneous on entire working length. The temperature as a function of time during tensile tests is shown on Figure 2a, and specimen during testing is shown on Figure 2b.

DESCRIPTION OF THE MATHEMATICAL APPROACH

Model for description of contour of tensile specimen

Essentially the deformed shape-of-the-rod after tensile testing represents the history of traveling of the cross-section that separates the elastic and plastic state of material.[3, 4] The portion of material that in a given moment left the plastic state preserves its shape until the end of the experiment.Based on this fact, in what follows, the new model for description of evolution of specimen's contours during tensile testing will be introduced.

A cylindrical rod of radius, *r*, maintains its rotational symmetry around the longitudinal axis, *z*, during a tensile test, and thus its shape at given time, *t*, is determined by the rotational curve $r = r(z, t)$, which forms its surface after rotation around longitudinal axis, z, of the rod. Before the test this curve is a cylinder $r(z, 0) = r_0$, where r_0 is the initial radius of the rod. After the test is finished this curve must be carefully measured to obtain results in the form

$$r = r(z, t_k) \quad (1)$$

where t_k is the duration of the experiment. Initial volume of the rod of length, l_o, is $V_0 = \pi r_0^2 l_0$. The volume is conserved during plastic deformation, and thus volume for an arbitrary time can be expressed as

$$V(t) = V_0 = \pi \int_0^{l(t)} r^2(z,t)dz \quad (2)$$

where $l(t)$ is the length of the rod at time t. By comparison between final shape of the rod and its shape at arbitrary moment after occurrence of neck, but before the end of the test, we ascertain that both shapes differ only in the middle, but the end parts are the same. Namely, the rod at the intermediate time is shorter and it has a smaller neck. Thus, we can conclude that the parts of the rod, which have the same shape as it is at the end of the test, were at that moment in an elastic state and the part, which is different, was in plastic state. Consequently, on deformed rod there are always two points that at given moment separate the plastic and elastic parts of the rod. These two points were moving along the curve $r = r(z, t_k)$, during tensile test. Thus, the rod may be at any time divided into three parts

$$V_0 = \pi\Big(\int_0^{l_l(t)} r^2(z,t)dz + \int_{l_l(t)}^{l_d(t)} r^2(z,t)dz + \int_{l_d(t)}^{l(t)} r^2(z,t)dz\Big) \quad (3)$$

The first and last sections belong to the elastic part and the middle section to the plastic part of the rod. The final shape of the rod represents the line of movements of the points which separate plastic and elastic state of the material. The portion of the curve $r = r(z, t_k)$, that lies left of the minimal cross-section is a monotonically decreasing function and the portion on the right is a monotonically increasing function. Thus for the prescribed value of $l_l(t)$ the value of $l_d(t)$ can be calculated from the condition

$$r(l_l(t), t_k) = r(l_d(t), t_k) \quad (4)$$

From those two values the volume which is at given time in plastic state can be calculated

$$V_p = \pi \int_{l_l(t)}^{l_d(t)} r^2(z,t)dz \quad (5)$$

The idea for reconstruction of the intermediate shapes of the rod is now to find the approximate function $f(z,t) \approx r(z,t)$, for which

$$f(l_l(t),t) = f(l_c(t),t) = r(l_l(t),t_k) \quad (6)$$

where $l_c(t)$ is the length from the beginning of the rod to the end of the plastic part. Since the contour of deformed rod is smooth, it immediately follows for the left end side

$$\left.\frac{\partial f(z,t)}{\partial z}\right|_{z=l_l(t)} = \left.\frac{\partial r(z,t_k)}{\partial z}\right|_{z=l_l(t)} \quad (7)$$

and for the right end one

$$\left.\frac{\partial f(z,t)}{\partial z}\right|_{z=l_c(t)} = \left.\frac{\partial r(z,t_k)}{\partial z}\right|_{z=l_d(t)} \quad (8)$$

Due to the constancy of the volume during plastic deformation, it also follows

$$V_p(t) = \pi \int_{l_l(t)}^{l_c(t)} f^2(z,t)dz \quad (9)$$

The value of $l_c(t)$ which must be greater than the length of cylinder of the same volume and radius $r = r(l_l, t_k)$ on one hand and must be smaller than $l_d(t)$ on the other hand, is determined iteratively. For the function model that fulfils the conditions (6), (7), (8) and (9), the polynomial or any other suitable function could be used. In any case due to the mentioned conditions in every iteration step the system of linear or non-linear equations must be solved depending on selected function. The simplest choice for the selection of function is certainly the constant, which upon rotation around its axes forms cylinder. Unfortunately the conditions (7) and (8) cannot be fulfilled for approximation with cylinder. Besides that, the radius of curvature of the contour at the minimal cross-section is needed for calculation of the Bridgman stress correction,[1] but for the approximation by cylinder this radius is infinite. On the other hand, for an arbitrary function this radius, R,can be calculated from

$$R = \left| \left(\frac{\partial^2 f(z,t)}{\partial z^2}\right)^{-1} \left[1 + \left(\frac{\partial f(z,t)}{\partial z}\right)^2\right]^{3/2} \right|_{z=z(r_{min})} \quad (10)$$

where r_{min} is the minimal radius at time t.

Calculation of stress-strain dependence

After hot tensile testing the measurements of deformed rods were carried out by the measurement microscope, which automatically save the measured table of data $r_i = r_i(z_i)$. From measured data only those N points for which $r_i \leq r_o$, where r_o is radius of non-deformed rod, are taken into account. Additionally two points which are the nearest to the interval of N points are also considered. For reconstruction of contour the continuous function is needed and thus, cubic splines were applied for interpolation which yields continuous function $r = r(z)$. The next step is now the calculation of the volume of the rod which undergoes plastic deformation. Here the Simpson integration method[2] was employed for numerical integration of equation (2). In the present work two different functional models were chosen, namely catenary and constant. On deformed part of the rod K equidistant points separated for Δz, were selected and from that for the final length of deformed rod, $l(t_k)$, we find

$$l(t_k) = K\Delta z \quad (11)$$

After a number of trials we found that the value of $\Delta z = 0.5$ mm is most suitable. In order to meet the condition (4), we find for each value of $l_1 = i\Delta z$ corresponding value of l_d in every step $i \in [1, K]$ by bisection. For those two values which are at that particular moment in elastic state we calculated volume of the rod, V_e, as

$$V_e = \pi\left(\int_0^{l_l} r^2(z,t)dz + \int_{l_d}^{l} r^2(z,t)dz\right) \quad (12)$$

The above integrals (12) were also calculated by the Simpson's integration method. The volume of the part of the rod which is in plastic state the following is true $V_p = V_o - V_e$. For the part of the rod which is in the plastic state two additional conditions are valid, namely it cannot be longer than $s_1 V_p / \pi r^2(l_l)$ and cannot be shorter than $s_2 = l_d - l_1$, respectively.

Let construct the function

$$g(s) = V_p - \pi\int_0^{s} f^2(z,t)dz) \quad (13)$$

which on the interval $s_1 \leq s \leq s_2$ has the root, which is found by bisection. Further, the parameters of the functional model which fulfil the conditions (6)–(8) must be determined in every bisection step. We have the system of linear equations for the polynomial model (constant in the present work) and the system of non-liner equations for the catenary; where the last one is solved by the Newton method [2]. The iteration is interrupted when $g(s) < \varepsilon$, where $\boldsymbol{\varepsilon}$ is prescribed accuracy. First we determine r_{min} and then from (10) the radius of curvature of the contour at the minimal cross-section, R. Both of them are combined into the vector. Described procedure is iterated until $V_p > \varepsilon_1$ or $l_1 + l_d + s < l(t_k)$. At that point we only need two continuous functions for $r_{min}(l)$ and $R(l)$. Again interpolation by cubic splines is employed. By means of $r_{min}^{(i)}$ and $R^{(i)}$, which are written as vectors, the second derivatives are calculated. Thus, the values of in-

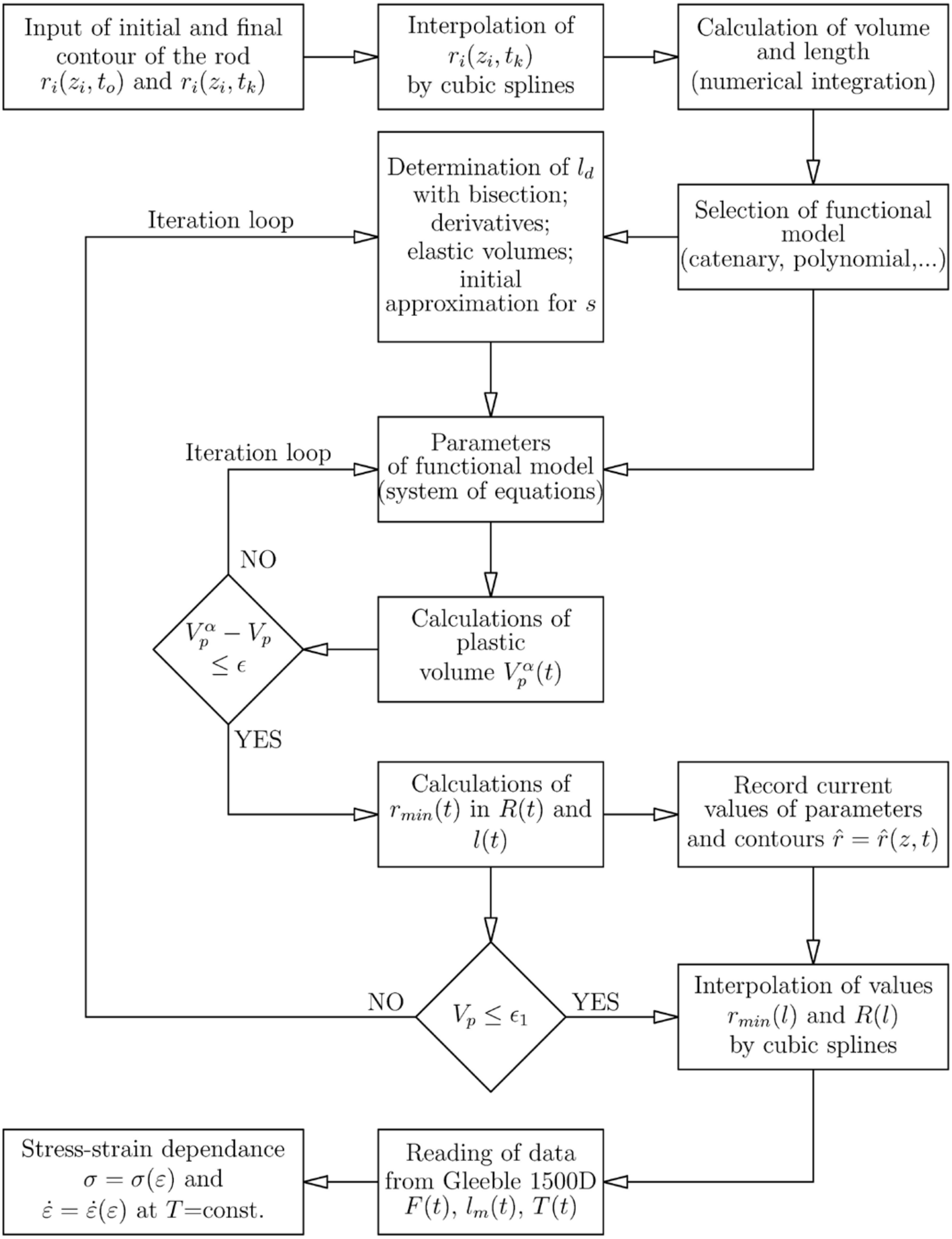


Figure 3. Schematic of the algorithm that from measured final contours of deformed rods and from force-displacement data enables calculations of stress-strain dependence, time evolution of contours and strain rates.

terpolation function for any l are calculated.Finally, from the experimental results of the tensile test, which was conducted at constant temperature, the true stress is determined, that is further corrected by Bridgman formula[1]. Thus, we have

$$\sigma_{Br}(t_i) = \frac{F(t_i)}{\pi r_{min}^2(l(t_i))[1 + 2R(l(t_i))/r_{min}(l(t_i))]\ln(1 + r_{min}(l(t_i))/2R(l(t_i)))} \qquad (14)$$

and for the corresponding strain

$$\varepsilon_i = \ln(r_0/r_{min}(l(t_i))) \qquad (15)$$

Since the dependence of strain on time is known, the dependence of strain rate on time during the test can be easily determined as

$$\dot{\varepsilon}_i = \frac{\varepsilon_{i+1} - \varepsilon_{i-1}}{t_{i+1} - t_{i-1}} \qquad (16)$$

The computer program which takes as an input the final shape of the contour of tensile rod and data from tensile test, i.e. force and length of the rod as a function of time and which executes all the above described steps and enable determination of true stress – true strain curves and time evolution of true strain rate was written in programming language C++. The schematic of this program and algorithm is given on Figure 3.

Results and Discussion

Technical curves and contour shapes of deformed rods

Tensile tests were carried out by uniaxial tension at prescribed displacements rates of anvils and at constant temperatures, where the tension force and displacement were continually recorded. After the test the contours for every deformed rod were carefully measured by microscope. The number of measured points on each section of the contour of deformed rod depended on its local curvature, but it always exceeded 100 points. Obtained technical curves for temperatures (800, 900, 1000) °C, and strain rates of (0.001, 0.01, and 0.1) s^{-1} with corresponding final shapes of rods are shown in Figure 4.

After the transition of the material from elastic to plastic state the stress remains uniaxial, but the strain is three-axial; namely the elongation is uniform at uniformly decreasing of diameter. Uni-axiality of the stress is preserved until the occurrence of the neck. During the test the measured force is initially increasing until it reaches the maximum, and afterwards decreasing up to the end of the test. The amount of strain where the force is at maximum depends on material and on constitutive relation $\sigma = \sigma(\varepsilon, \dot{\varepsilon}, T, ...)$ as well as on changing of cross-section of specimen. Technical curve reaches the maximum when $dF/dl = 0$, where F stands for force and l is elongation. From $F = \sigma S$, it follows that

$$\frac{dF}{dl} = \frac{dF}{d\varepsilon}\frac{d\varepsilon}{dl} = \frac{1}{l}\left(S\frac{d\sigma}{d\varepsilon} + \sigma\frac{dS}{d\varepsilon}\right) = \frac{S}{l}\left(\frac{d\sigma}{d\varepsilon} - \sigma\right) \quad (17)$$

where the constancy of the volume has been taken into account. Therefore the force is maximal when $d\sigma/d\varepsilon = \sigma$.

Formation of contours during straining

The key parameters that for the selected functional model determine how accurate the shape of contour can be determined are the volume V_o, which undergo plastic deformation, and the local slopes of the final contour. Of course, the last condition is not valid for the simplest i.e. cylindrical model, since the boundary conditions (7) and (8) cannot be fulfilled. Consequently, the shapes of contours calculated by cylindrical model are unrealistic (see Figures. 5a and c), but nevertheless, as it will be demonstrated later, this model gives surprisingly good prediction of the evolution of the minimal radius of the rod within the neck during entire tensile test.

As we mentioned earlier the volume, V_o, is obtained by integration of the final contour of the rod along the z-axis considering condition $r(z) \leq r_o$, where r_o is initial radius of the working area of the rod. Since some plastic deformation occurs always also outside of the working area, this contributes to error. Namely, the slope of the contour at boundary between outside and inside area is very high. Therefore the calculated lengths of rods at initial steps of deformation are too long, and cross-sections are even smaller than those obtained at the end of deformation. Moving along the deformed contour results in shortening of calculated length as well as in increasing the minimal cross-section. According to the present model the length of the rod initially increases with strain, which is nonsense. To avoid this inconsistency the contour was calculated with our model only after the calculated length begins to increase with strain, before that the contour was calculated assuming homogeneous deformation. The examples of calculation of the rod shapes evolution during deformation for cylinder and for catenary at temperatures 1000 °C and 900 °C, and prescribed strain rate of 0.1 s^{-1} are shown on Figure 5. If one wants to calculate the dependence of true stress on strain, the minimal cross-section, which is obtained from reconstruction of contour of the rod, must be given for every strain. The dependence of minimal radius on elongation for two temperatures calculated by catenary model is given on Figures 6a and 6b.

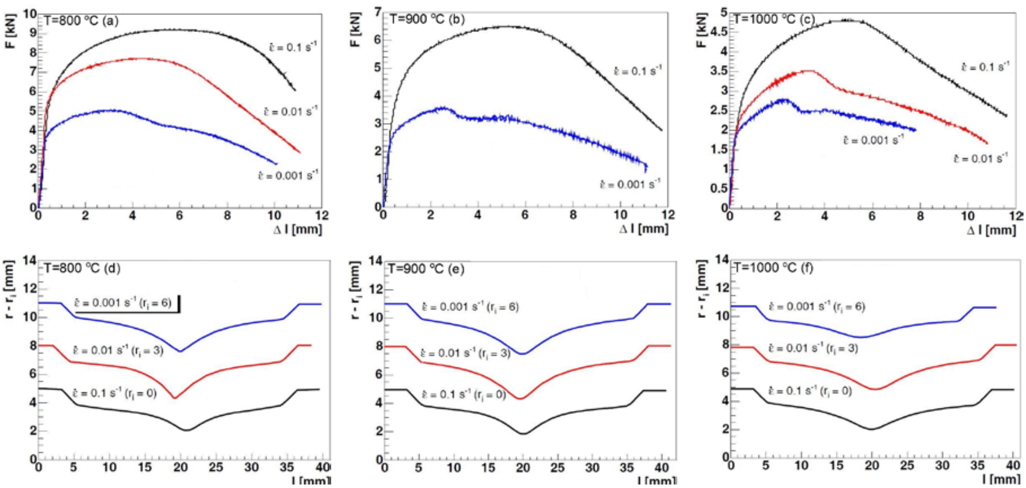


Figure 4. Technical curves force-elongation obtained wit tensile tests for strain rates of (0.001, 0.01 and 0.1) s^{-1} at temperatures of 800 °C (a), 900 °C (b), and 1000 °C (c) together with corresponding measured final shapes of deformed rods (d)–(f).

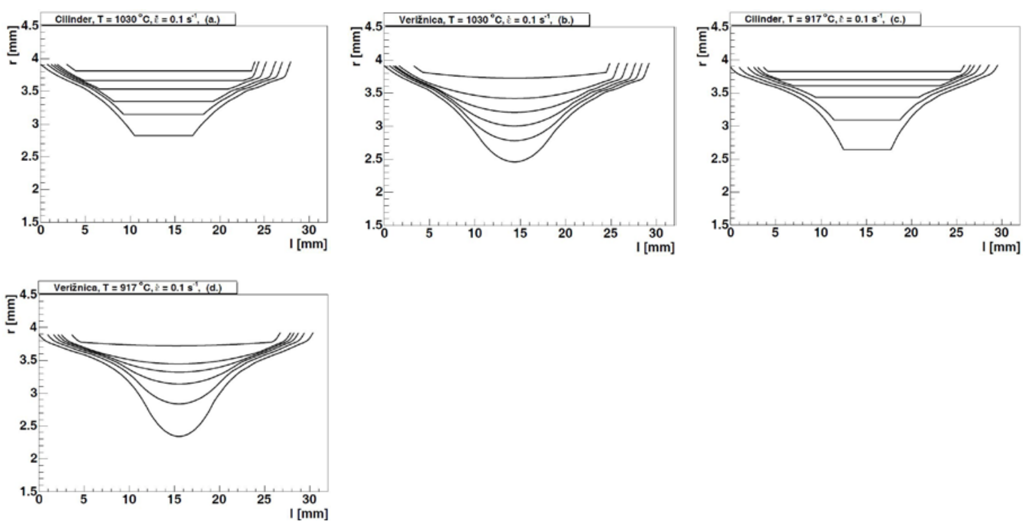


Figure 5. The calculated shapes of tensile rods for various stages of deformations at temperature of 1000 °C and strain rate of 0.1 s^{-1} for cylindrical (a) and for catenary model (b). Calculation for cylindrical (c) and catenary (d) models at T = 900 °C and strain rate of 0.1 s^{-1}.

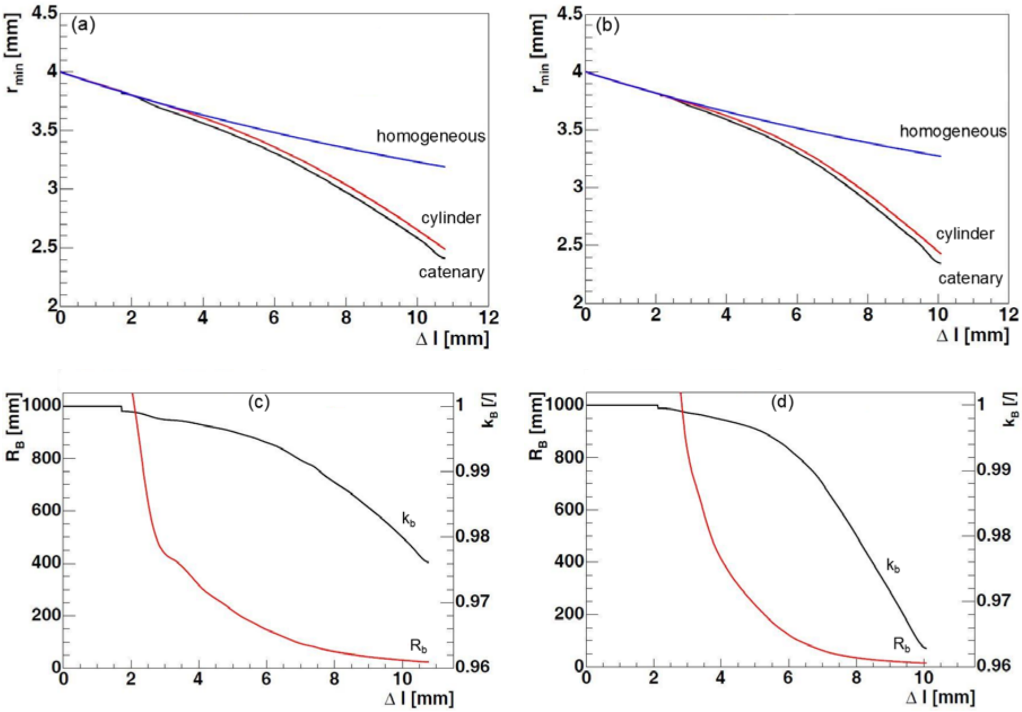


Figure 6. Comparison of dependence of minimal radius of deformed rod on elongation calculated by models for catenary, cylinder, and for assumption of homogeneous deformation for $\dot{\varepsilon}$ = 0.1 s^{-1}at T = 1000 °C (a), and T = 900 °C (b). Evolution of the radius of the circle osculating the profile at the neck, R_B, and corresponding dependence of Bridgman correction coefficient, k_B, on elongation calculated by catenary model at T = 1000 °C (c), and T = 900 °C (d).

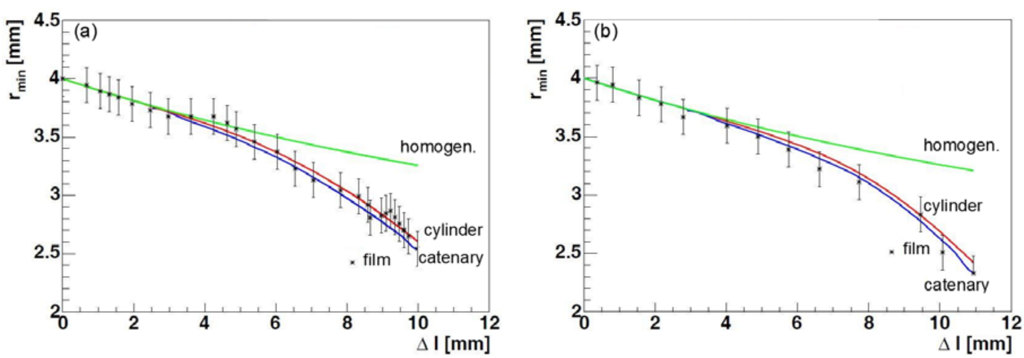


Figure 7. Comparison of dependence of minimal radiuses on elongation between measurements conducted by digital camera and calculated by studied models (catenary, cylinder, homogeneous deformation) for $\dot{\varepsilon}$ = 0.1 s^{-1}at T = 950 °C (a), and at T = 900 °C (b).

For comparison the minimal radiuses calculated by cylindrical model and by assumption of homogeneous deformation are also given. It can be seen that the radius obtained by cylindrical model is very close to one obtained by catenary, whereas as expected the radius according to homogenous deformation model after occurrence of necking start do deviate from values predicted by our models. Deformation is homogeneous approximately up to elongation of 2 mm that corresponds to strain ≈0.2. As it was already mentioned, the transition from homogeneous to nonhomogeneous deformation leads to transition of uniaxial to three-axial stress state. For calculation of Bridgman correction, k_B, the radius of the circle osculating the profile at the neck, R_B, is needed. The R_B is calculated by equation (10) from reconstructed contours. The evolution of R_B and k_B are given on Figure 6c, and 6d, respectively. When the contours are calculated by the homogeneous deformation model, we set $k_B \equiv 1$, consequently the dependence of $k_B(\Delta l)$ is discontinued at transition between both areas, with negligible error.

Calculated values of the time evolution of the minimal radius of the tensile specimens were compared with the values obtained from analysis of the pictures which were recorded by a digital camera, and we obtained reasonable agreement. These results are shown on Figure 7, were the maximal estimated errors for minimal radius measured with camera are denoted. Due to intensive radiation from hot samples, the sharp boundary between the rod and surrounding was indistinct, thus the determination of real minimal radius was hindered.

True stress–true strain curves

From technical force-elongation curves the true stress–true strain curves were determined by employing all the procedures explained in previous sections. They are shown on Figures 8a–c, whereas Figures 8d–e show the actual variation of strain rates during the tests.

For higher temperatures and/or lower strain rates the flow stress initially raises until a maximum is reached when hardening and softening are in balance. With increasing deformation, softening prevails over hardening and flow stress decreases. At strains $\varepsilon > 0.2$ flow stress starts to increase and increases until the end of the experiment. This kind of behaviour in the later stages of deformation is a consequence of the continuously increasing strain rate after the appearance of necking. For the same reason flow curves for low temperatures and/or higher strain rates do not reach a maximum. Thus, we can conclude that after necking, the stress-strain curves are not flow curves as by definition flow curves are stress-strain curves at constant temperature and strain rate.

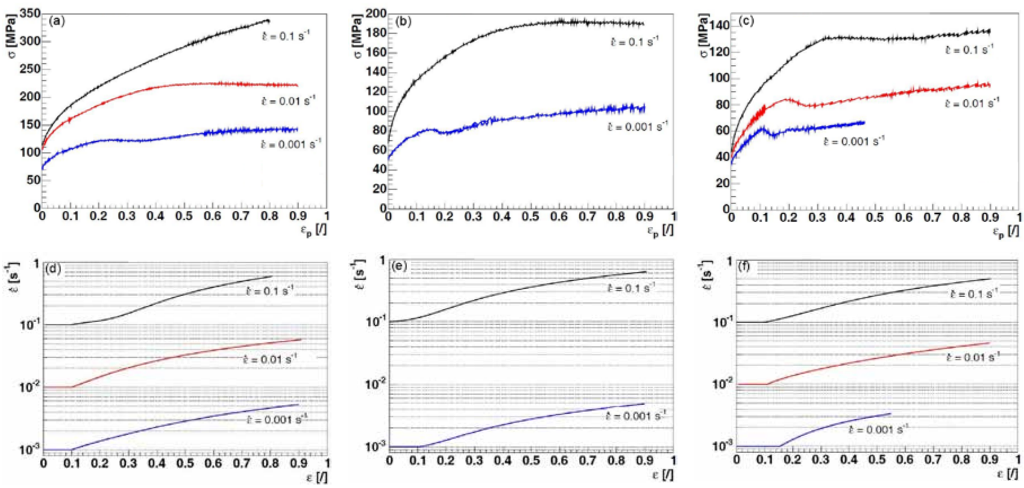


Figure 8. True stress-true strain curves, obtained by tensile tests for prescribed strain rates of (0.001, 0.01) s^{-1}, and 0.1 s^{-1} at temperatures of 800 °C (a), 900 °C (b), and 1000 °C (c) and corresponding variation of actual strain rate during the tests (d)–(f).

But in the future a series of carefully chosen testing conditions is planed with the aim to examine the possibility of finding the model that would the movements of jaws during the tests in such a way that constant true strain rate would be maintained during the entire test. Then it would be possible to determine flow curves with tensile testing to strains that are comparable with strains that can be obtained with compression testing.

CONCLUSIONS

In this work a new mathematical model for calculation of true stress – true strain dependence from the results of tensile tests, which can be used also after appearing of necking, was proposed. Furthermore the model was implemented into the computer program that enables determination of stress-strain curves from measurement of contours of deformed rods. The model and the computer program were validated by employing tensile tests for combinations of three different strain rates and temperatures on Gleeble 1500D testing machine for Ni alloy Alloy201. The main findings can be summarized as follows:

1. It was found that, if the jaws of testing device are controlled in such a way that constant strain rate is obtained if homogeneous deformation is assumed, after appearance of necking the true strain rate is no longer constant, but it is increasing. Thus, stress-strain curves obtained in this way are not true flow

curves, as by definition flow curves are stress-strain curves at a constant strain rate.

2. In the present work two functions for description of evolution of the part of the contour which is in given moment in the plastic state, were tested, i.e. constant (approximation with cylinder) and catenary. Based on the comparison of the predicted evolution of contour and contours obtained by measurements with film camera it was found that both functions are capable of description of evolution of minimal radius of the rod in the neck with accuracy within the measurement error.
3. The main problem of applying the simplest function, i.e. the constant, is that it is not possible to determine the evolution of radius of curvature of the couture at the minimal cross-section and consequently Bridgman stress correction due to three-axiality of the stress cannot be applied since for constant this curvature is infinite. On the other hand using catenary this problem is avoided and true stress – true strain curves including Bridgman correction can be determined.
4. It could be possible to predetermine the movements of jaws during the tests in such a way that constant true strain rate would be maintained during the entire test or at least up to the true strains up to the value of 1.0, but this will require many more tests for different materials and at different thermo-mechanical conditions.

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