HIGH TEMPERATURE DEFORMATION RESISTANCE OF BCT STEEL

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Abstract:

The knowledge of deformation resistance is needed for simulation of forming processes at higher and high temperatures. A static tensile test does not give an answer how deformation resistance depends on deformation rate. Deformation resistance was measured using dilatometer DIL805A/D equipped with hydraulic unit. This setting allows compression tests during high-temperature material forming. Material forming can be carried out under controlled conditions. Such conditions are deformation level, deformation temperature and deformation rate. Deformation rate can be set between 0.001 and 20 s^{-1}. Temperature can be kept from ambient temperature up to 1500 °C. BCT steel was used for experiments. Deformation resistance was measured for experimental matrix of 5 deformation temperatures by 5 deformation rates. The experimental results were described by a proposed mathematical model where deformation curve is a function of deformation. In addition, an equation is proposed for calculation of deformation resistance as a function of two variables: degree of deformation and temperature of deformation. Prediction of deformation curves was done using above equation for the temperatures of (850, 950, 1050, 1150) °C. A visualization of curves for various temperatures is shown in a paper.

1 Introduction

A dilatometer DIL805A/D [1] is designed mainly for measurement of phase transformations [2] and CCT diagrams [3, 4] (CCT – Continuous Cooling Transformation). It is equipped with hydraulic unit that allows compression deformation. A deformation mode allows forming of material under controlled conditions such as degree of deformation, deformation temperature and rate of deformation. A true compression stress is calculated from true deformation force and true sample cross-section. This relationship allows to construct true strain-true stress curves that are known as deformation curves [5, 6]. A curve deformation stress as a function of deformation is shown in Fig. 1. The Garofalo empirical equation [7, 8] is used to describe a high temperature deformation, which describes a strain rate in relation to a flow stress and an absolute temperature

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$$\acute{\varphi} = A \cdot [sinh(\alpha \cdot \sigma_p)]^n \cdot exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where

$\acute{\varphi}$[s^{-1}] – strain rate
T [K] – absolute temperature
σ_p [MPa] – flow stress (peak stress)
Q [J.mol^{-1}] – activation energy of deformation
R [J.K^{-1}.mol^{-1}] – universal gas constant
n [–] – material constant
A [s^{-1}] – material constant
α [MPa^{-1}] – material constant

Calculation of constants Q, n, C and α in equation (1) using experimental data is described in details in [9]. Experimental data used are as follows: peak stress, peak deformation, deformation rate and temperature of deformation. However, equation (1) does not contain deformation variable φ. Therefore constants Q, n, C and α in equation (1) are expressed as polynomials containing variable φ.

$$Q = B_0 + B_1\varphi + B_2\varphi^2 + B_3\varphi^3 + \cdots + B_m\varphi^m \quad (2)$$

$$n = C_0 + C_1\varphi + C_2\varphi^2 + C_3\varphi^3 + \cdots + C_m\varphi^m \quad (3)$$

$$Ln\ A = D_0 + D_1\varphi + D_2\varphi^2 + D_3\varphi^3 + \cdots + D_m\varphi^m \quad (4)$$

$$\alpha = E_0 + E_1\varphi + E_2\varphi^2 + E_3\varphi^3 + \cdots + E_m\varphi^m \quad (5)$$

Degree of polynomial m in equations (2-5) takes values from 5 to 9. Value m=5 was chosen in [10]. In order to increase precision of approximation even higher degree of polynomial is often used, e.g. m=6 was used [11,12]. Even more, degree m=9 was used in [13] and 40 regression coefficients were calculated. Non-linear regression was needed to do so. Simpler empirical equation was used in this work that allows describe deformation curves while calculation of regression coefficients is easier.

2 Description of experiment

The measurements of deformation resistance were carried out using dilatometer DIL805A/D. The samples were in a form of cylinder with diameter of 5 mm and height of 10 mm. The temperatures of (800, 900, 1000, 1100, 1200) °C were used in the experiments. A deformation can be set in interval 0.05 up to 1.2. Deformation rate from 0.001 up to 20 s^{-1} can be used. The following values were chosen in experiments (0.001, 0.01, 0.1, 1, 10) s^{-1}. Steel with addition of boron knows as BCT steel was used for measurement of deformation resistance. This kind of steel is not standardized and belongs to group of special steels. Its chemical composition is shown in Table 1.

Table 1 Chemical composition of BCT steel (wt.%)

Element	Content
C	0.12
Mn	1.60
Si	0.45
P	0.013
Cr	0.04
V	0.002
Mo	0.02
Ni	0.07
Nb	0.04
Al	0.03
S	0.005
W	0.01
B	0.002
Fe	balance

A computer controlled equipment records deformation resistance of each test into individual file. Data are then exported for subsequent graphical and numerical treatment. An example of measured curves for deformation rate of 0.1 s^{-1} is shown in Fig. 1.

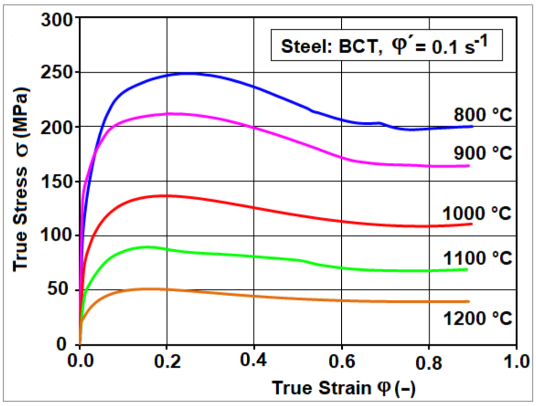

Fig. 1 Deformation resistance curves

3 Mathematical model of deformation curve

Mathematical model – equation describing deformation curve as function of deformation at constant deformation rate and deformation temperature should fulfill the following requirements:

- passing through origin of coordinates, i.e. [0,0] point
- it has an extreme (maximum) at peak stress
- it has an inflexion point and continues to steady state without oscillations
- easy evaluation of regression coefficients that does not require use of non-linear regression

Deformation curve shown in Fig. 2 passes through origin of coordinate system following linear trend. Curve is subsequently growing to maximum at stress peak. It is lowering in third part due to a softening [14, 15] followed by steady state [16, 17].

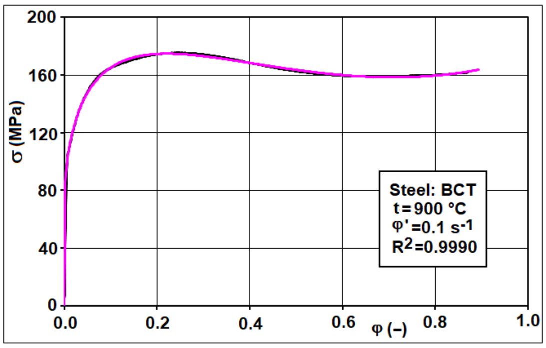

Fig. 2 Deformation curve

Deformation resistance as a function of deformation is recorded during hot compression test under controlled conditions, i.e. sample geometry, temperature and deformation rate [18, 19]. Based on an observed deformation curve the following equation is proposed

$$\sigma = \sigma_0 \varphi^{a_0} e^{F(\varphi)} \qquad (6)$$

where

σ [MPa] – deformation resistance
σ_0 [MPa] – material constant
φ [–] – logarithmic deformation
a_0 [–] –constant
F(φ) –appropriately selected function

The following polynomial equation is suitable as an *F*–function, i.e. function describing logarithmic deformation [20]

$$F(\varphi) = a_1\varphi^{-3} + a_2\varphi^{-2} + a_3\varphi^{-1} + a_4\varphi + \\ + a_5\varphi^2 + a_6\varphi^3 \qquad (7)$$

Comparison of measured (black) and calculated (violet) curves is shown in Fig. 2. Regression coefficients were calculated using generalized linear regression. They are listed in Table 2. It should be noted that material constant σ_0 does not represent peak stress. Correlation coefficient R^2 has a value of 0.999.

Table 2 Regression coefficients for equation (6), unit σ_0 is (MPa)

Coefficient	Value
σ_0	3.526 257 E+02
a_0	2.741 264 E–01
a_1	-2.614 953 E–10
a_2	-8.274 522 E–07
a_3	1.027 312 E–03
a_4	-1.409 801 E+00
a_5	3.020 686 E–01
a_6	3.936 252 E–01

4 Mathematical model of deformation resistance for two variables

Equation (6) extended on variable of deformation temperature is used to describe deformation resistance depending on deformation and temperature [21]. Constant a_0 is replaced by an appropriate function of temperature *E(t)* and *F*–function is also extended to reflect temperature dependence. Thus equation (6) can be written as

$$\sigma = \sigma_0 \varphi^{E(t)} e^{F(\varphi,t)} \qquad (8)$$

where

σ [MPa] – deformation resistance
σ_0 [MPa] – material constant
φ [–] – logarithmic deformation
t [°C] – deformation temperature
E(t) – appropriately selected temperature function
F(φ,t) – appropriately selected deformation and temperature function

As *E*–function an equation (9) is suitable

$$E(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \qquad (9)$$

Dimensions of constants a_0, a_1, a_2 and a_3 are such as to keep function $E(t)$ dimensionless. Next, F– function is extended to reflect new variable – deformation temperature, as shown in equation (10) constants $ln\sigma_0$, a_1-a_3, b_1-b_{15} are shown in Table 3 in semi-logarithmic form. Resulting graph is shown in

$$F(\varphi, t) = b_1\varphi^{-3} + b_2\varphi^{-2} + b_3\varphi^{-1} + b_4\varphi + b_5\varphi^2 + b_6\varphi^3 + b_7 t + b_8 t^2 + b_9 t^3 + \\ +(b_{10}\varphi^{-3} + b_{11}\varphi^{-2} + b_{12}\varphi^{-1} + b_{13}\varphi + +b_{14}\varphi^2 + b_{15}\varphi^3)t^{-1} \qquad (10)$$

Table 3 Regression coefficients for equation (8)

Coefficient	Value
$ln\ \sigma_0$	-3.753 950 E+02
a_0	3.275 665 E+03
a_1	-1.429 949 E+03
a_2	2.078 764 E+02
a_3	-1.006 274 E+01
b_1	6.009 430 E–10
b_2	-1.817 740 E–05
b_3	8.812 151 E–02
b_4	-9.254 156 E+01
b_5	1.264 784 E+02
b_6	-6.274 135 E+01
b_7	1.134 173 E+02
b_8	-8.792 280 E+00
b_9	5.240 818 E–02
b_{10}	-4.147 687 E–09
b_{11}	1.251 116 E–04
b_{12}	-6.124 560 E–01
b_{13}	6.267 982 E+02
b_{14}	-8.728 506 E+02
b_{15}	4.379 170 E+02

Dimensions of constants b_1 – b_{15} are such as to keep equation (10) dimensionless. Equations (8), (9) and (10) are used to visualize agreement between measured and calculated values of BCT steel for

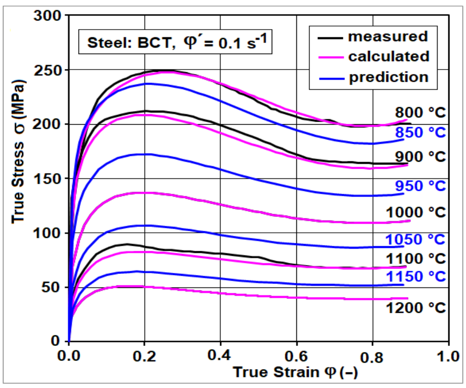

Fig. 3 Deformation resistance curves and their prediction

temperatures of (800, 900, 1000, 1100, 1200) °C at constant deformation rate of φ'=0.1 s^{-1}. Regression Fig. 3. Black curves are measured values of deformation resistance, the violet ones are calculated from equation (8). Prediction of deformation curves (blue in Fig. 3), i.e. their calculation from equation (10) was made for temperatures of (850, 950, 1050, 1150) °C. It was recognized during calculations that use of logarithmic temperature instead of direct temperature is more suitable leading to better agreement between observed and calculated values with increase of correlation coefficient.

5 Discussion of results

Garofalo semi-empirical equation [7] was used long time to describe high-temperature deformation resistance. Its disadvantage is that it describes peak stress as a function of temperature and deformation rate [22, 23]. Various empirical equations were suggested in order to overcome this problem [24]. The constants in Garofalo equation were replaced by polynomial functions where variable is deformation. Number of regression constants in such case is from 24 up to 40 [10–13]. Mathematical model for calculation of deformation resistance for one variable deformation, equation (6) as well as for two variables – deformation, deformation temperature, equation (8) – is proposed. Using this model it is possible to calculated deformation curves for the temperatures that were not measured – see Fig. 3, blue curves.

6 Conclusion

A new mathematical model describing deformation curves allow calculate deformation resistance for two independent variables that are deformation and deformation temperature. Increase of precision of simulation of forming processes such as FEM (finite elements method) is possible by using this model. All proposed equations for calculation of deformation resistance are possible to be transformed into linear relationship via their logarithmic form. It allows use of linear regression operations instead of complicated non-linear regression. Such approach makes it easier to treat experimental data. No specific software is needed – common software like Excel can be used to perform all calculation and graph drawing. Multi-linear regression, that is included in Excel, can be used or it can be programmed using Visual Basic that is part of MSO package.

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