THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI.
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N^0. 2 – 2009, ISSN 1453 – 083X

ESTABLISHING THE CONSTITUTIVE LAW OF A CrMo ALLOYED STEEL

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The paper shows the results of the researches for establishing the equation of the deformation behavior of alloyed steel with chromium and molybdenum. The behavior law is established in the experimental way, using the results of a set of torsion tests. The composed constitutive law had very good experimental verification.

KEYWORDS: constitutive equation, torsion test, stress, strain, temperature.

1. Introduction

The establishing of the equation of plastic deformation behavior is a process of transformation of the torsion moment function in the stress intensity function, respectively, the equation between the stress intensity, strain, strain rate and temperature [1]:

$$\sigma = \sigma(\varepsilon, \dot{\varepsilon}, T) \qquad (1)$$

In this equation, σ is the stress intensity, in the real deformation conditions, ε - strain intensity, $\dot{\varepsilon}$ - strain rate intensity, T – temperature.

This equation is used in the modelling and simulation process of the plastic deformation to apply the three-dimensional constitutive law according to the mono-dimensional constitutive law (1).

With this aim, the paper presents the results of researches carried out for the transformation of the torsion moment diagrams [1], in the equation of plastic deformation behavior for chromium, molybdenum alloyed steel.

The start point is the experimental data concerning the variation of the torsion moment with the strain, strain rate and temperature.

2. Establishing the viscoplastic law

Generally, we can define the function of the torsion moment under the form:

$$M = M(\varepsilon, \dot{\varepsilon}, T) \qquad (2)$$

In the differential form, the relation (2) becomes:

$$dM = \frac{\partial M}{\partial \varepsilon} d\varepsilon + \frac{\partial M}{\partial \dot{\varepsilon}} d\dot{\varepsilon} + \frac{\partial M}{\partial T} dT \qquad (3)$$

For the maximum values of the torsion moment the equation (2) may be written:

$$dM_{\max} = \frac{\partial M_{\max}}{\partial \dot{\varepsilon}} d\dot{\varepsilon} + \frac{\partial M_{\max}}{\partial T} dT$$

Thus, we can establish the function:

$$M_{\max} = M_{\max}(\dot{\varepsilon}, T) \qquad (4)$$

which describes the functional influence of the strain rate and temperature on the deformation strength.

Using the experimental results obtained for the sixteen combinations between the strain rate and temperature, [1] we have the data written in the table 1.

Table 1. *Values of the maximum torque*

Strain rate, s^{-1}	Temperature, ^{0}C			
	850	900	950	1000
0.0964	3.9642	3.2257	2.6622	2.2347
0.2849	5.1439	4.2807	3.4807	2.0342
0.8949	5.9657	5.0637	4.2325	3.6532
3.0217	6.5681	5.7102	5.0102	4.1836

In the graphical form, the data from the table 1 are rendered in figure 1.

The maximum torsion moment increases when the strain rate increases and decreases when the temperature increases.

The variation of the maximum torsion moment depends on the strain rate by a power function and on the temperature by an exponential function.

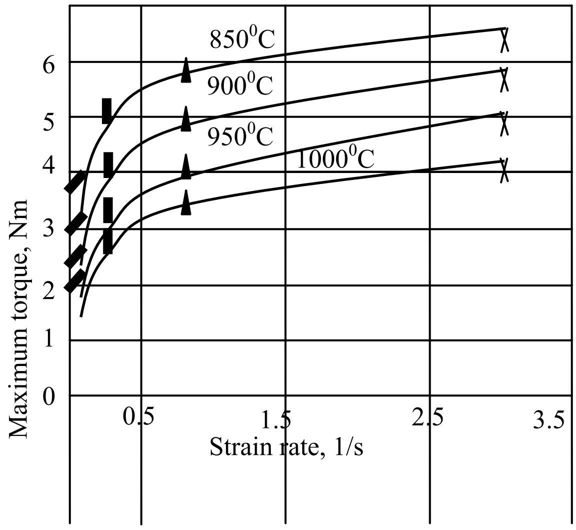

Fig. 1. *Variation of the maximum torque with strain rate and temperature*

Thus, the mathematical expressions of the dependence of the maximum torsion moment, frequently used for the characterization of the plastic deformation behavior, are the following:

$$M_{\max} = A_1 \cdot \dot{\varepsilon}^m \cdot \exp(-\alpha \cdot t) \quad (5)$$

$$M_{\max} = A_2 \cdot \dot{\varepsilon}^m \cdot \exp\left(\frac{m \cdot Q}{RT}\right) \quad (6)$$

$$M_{\max} = A_3 \cdot \ln\left(\frac{Z}{B}\right) \quad (7)$$

In these expressions, m is the sensibility of the stress at the strain rate, α – the temperature coefficient, t, T – temperature, in ^{0}C and K, respectively, Q – activation energy, R – constant of the perfect gas, A_1, A_2, A_3, B – experimental constants, Z – Zener-Hollomon parameter.

We used DATAFIT software for statistical calculus for the evaluation of the mathematical models of the plastic deformation behavior showed above.

We obtained the following results:

- For equation (5): A_1=0.06949; m=0.168387; Q=247294 J/(kmol·K) and the Coefficient of Multiple Determination (R^2) = 0.9739782376
- For equation (7): A_2=117.06; m=0.168387; α=-0.00351 and the Coefficient of Multiple Determination (R^2) = 0.9743690499
- For equation (8): A3=0.682538; B=131757975; Q=254727 J/(kmol·K). Coefficient of Multiple Determination (R^2) = 0.9842024264.

$$M_{\max} = 0{,}694 \cdot \dot{\varepsilon}^{0{,}1683} \cdot \exp\left(\frac{5005{,}6792}{T}\right) \quad (8)$$

$$M_{\max} = 117{,}06 \cdot \dot{\varepsilon}^{0.1683} \cdot \exp(-0{,}00351 \cdot t) \quad (9)$$

$$M_{\max} = 0.682538 \cdot \ln\left(\frac{\dot{\varepsilon} \cdot \exp\left(\frac{254727}{8314 \cdot T}\right)}{131757975}\right) \quad (11)$$

The three equations (5), (6) and (7) have a very good verification on the basis of the experimental results.

The tension is defined by the relation:

$$\sigma = \frac{\sqrt{3}}{2\pi r^3} \cdot \left(3M + \varepsilon \frac{\partial M}{\partial \varepsilon} + \dot{\varepsilon} \frac{\partial M}{\partial \dot{\varepsilon}} + T \frac{\partial M}{\partial T}\right) \quad (12)$$

The tension that corresponds to the maximum torque, for the constant temperature, if we use the expression (8), is defined by the relation:

$$\sigma_m = \frac{\sqrt{3} \cdot (3+m)}{2\pi r^3} \cdot M_{\max} \quad (13)$$

In this relation, r is the radius of the sample used at the torsion tests.

Considering the equation (8) for the value of the radius of 3mm, we obtain:

$$\sigma_m = 22.434 \cdot \dot{\varepsilon}^{0{,}1683} \cdot \exp\left(\frac{5005{,}6792}{T}\right) \quad (14)$$

The variation of the maximum torsion moment with the strain must be described by a compose function. The first part must be a hardening factor described by a power or, recommended, by an exponential expression.

The second part will be defined by an exponential function that must consider the caloric effect of the plastic deformation.

In these conditions, the general expression of the plastic deformation stress may be written as below:

$$\sigma(\varepsilon, \dot{\varepsilon}, T) = \begin{cases} A_1 \cdot (1 - \exp(-n\varepsilon) \cdot (\bar{\dot{\varepsilon}})^m \cdot \exp\left(\frac{mQ}{RT}\right) & for\ \varepsilon \le \varepsilon_0 \\ A_2 \cdot \exp(-p(\varepsilon - \varepsilon_0))(\bar{\dot{\varepsilon}})^m \cdot \exp\left(\frac{mQ}{RT}\right) & for\ \varepsilon > \varepsilon_0 \end{cases} \quad (15)$$

Table 2. *Values of the strain to maximum torque*

Strain rate, s^{-1}	Temperature, ^0C			
	850	900	950	1000
0.0964	0.4240	0.4337	0.4144	0.3754
0.2849	0.4558	0.5983	0.5128	0.3954
0.8949	0.2564	0.2849	0.2294	0.2279
3.0217	0.5858	0.7856	0.6268	0.2369

In this expression ε_0 is the strain according to the maximum of the torsion moment.

The values of the ε_0 are rendered in table 2 and are shown in the graphic form in figures 2 and 3.

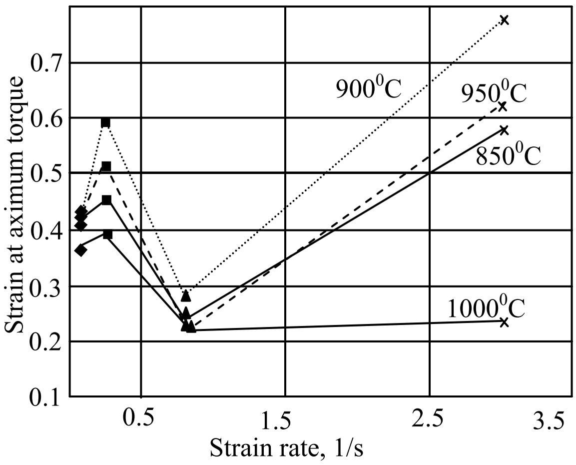

Fig. 2. *Variation of the strain at maximum torque with strain rate and temperature*

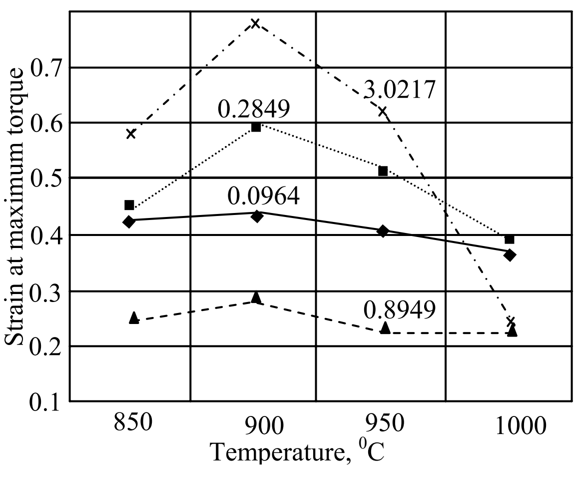

Fig. 3. *Variation of the strain at maximum torque with strain rate and temperature*

The influence of the temperature and strain rate on the strain at the maximum torque has a complex character because, in the domain of the testing temperature, the deformation process is simultaneous with the structural transformations. Thus at 850^{0}C, the transformation perlite-austenite is finished, but the process of the carbides solving is at the beginning. At 1000^{0}C, the process of increasing the austenite grains is very strongly activated and, consequently, the intensity of the deformation hardening is greater.

Very complex is the influence of the strain rate explained through the interaction of the plastic deformation hardening and the opposite process as the caloric effect of the plastic deformation. For a very small value of the strain rate, the ε_0 factor has a smaller dispersion rate. Also, for a mean value of the strain rate, the value of the ε_0 factor decreases and the dispersion is small, but at the great value of the strain rate, relatively, the dispersion of the values of the ε_0 factor is great.

This is the reason why it is necessary to extend researches for establishing the complete data for the ε_0 factor.

The constants form of the equation (15): A_1, A_2 n, p may be established on the basis of experimental researches [2].

4. Conclusions

The knowledge of the constitutive equation of the material is necessary for the modelling, simulation and optimization of the plastic deformation process. The best method for establishing the constitutive equation is the torsion testing. Applying a research program aton, the torsion testing machine in the Plastic deformation laboratory at the Faculty of Metallurgy and Materials Science from *Dunarea de Jos* University of Galati established the constitutive equation of steel for wires with a view to reinforcing concrete.

The constitutive equation shows that the influence of the strain rate is described by the power mathematical function, while the influence of the temperature is described by an exponential function.

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