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STATISTICAL EVALUATION OF FLOW CURVE MEASURMENT RESULTS

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Abstract: Flow curves of metals to be formed must be known if we want to calculate the forces for metal-forming processes. If we can not find flow curve for the material to be formed, we have to carry out an experiment to get flow curve for this material. Instead of expensive and long-time experimental work, flow curve can be determined by using statistical methods. This paper presents determination of flow curves by using multi- regression analysis based on few experimental points of torsion test.

Keywords: flow curve, torsion test, statistical analysis;

1 INTRODUCTION

To calculate the forces required for metal forming processes, it is necessary to know the flow curves of the metals to be formed. If the flow curve is known, the ideal work required for metal forming can be calculated. In general, flow curves are determined by experiments such as tensile test, the upsetting test, bending test and torsion test. There is no “best” experiment since each has a special focus of application. The proper choice of testing method depends on the metal-forming process to be simulated.

This article shows statistical evaluation of experimental data of torsion test for steel W. Ni. 1. 4057 (X22CrNi17). Experimental data can be processed by determination of statistical characteristic of experimental results.

2 DETERMINATION OF FLOW STRESS BY TORQUE AND TORSION TEST

The relation between torsion torque and shear stress is given by

$$M = 2\pi\int_0^R \tau(r) r^2 \, dr \qquad (2.\ 1)$$

By using Tresca yield criterion and limit value for radius of a cilindrical specimen r=R (Fig. 1), equation (2. 1) can be written as

$$M = \frac{2\pi R^3}{\gamma^3{}_R}\int \tau(\gamma)\gamma^2 \, d\gamma \qquad (2.\ 2)$$

The shear strain at distance r from the axis along test piece at a twisting angle α is given by $\gamma = \frac{r}{l}\cdot\alpha$. Torque M depends on shear strain γ and after differentiation of equation (2. 2), the equation for shear stress is

$$\tau = \tau(\gamma) = \frac{1}{2\pi R^3}\left(3M + \gamma\frac{dM}{d\gamma}\right) \qquad (2.\ 3)$$

When we add shear strain rate $\dot{\gamma}$ in equation (2. 3), then this equation can be written as

$$t = t\left(g, \dot{g}\right) = \frac{1}{2pR^3}\left(3M + g\frac{dM}{dg} + \dot{g}\frac{dM}{d\dot{g}}\right) \qquad (2.\ 4)$$

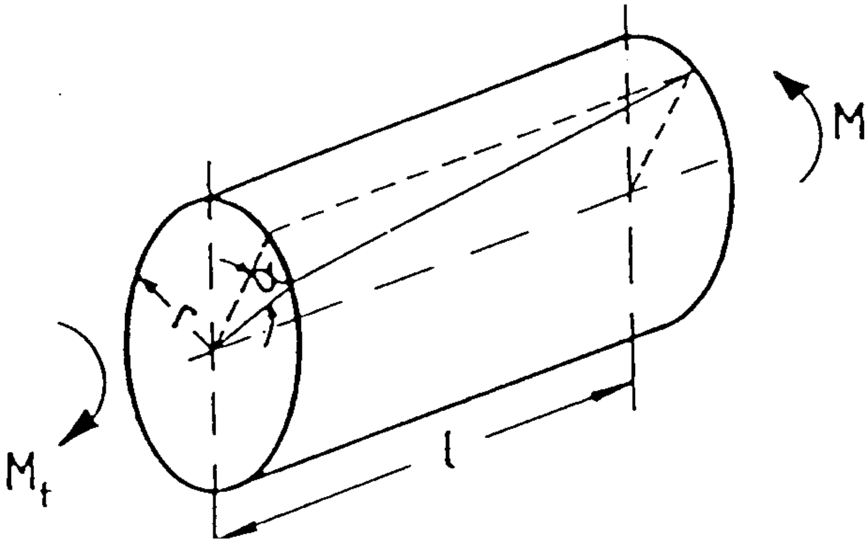

Figure 1: torsion test (cylindrical specimen)

Relation between torque and shear strain rate is given by

$$M = M_0 \cdot \dot{g}^{m} \tag{2. 5}$$

and relation between torque and shear stain is given by

$$M = 10^{\left\langle\left(a_0 + 2 a_2 \log^2 \gamma \right)\right|} \cdot \gamma^{a_1} \tag{2. 6}$$

m, log γ, a_1, a_2 are empirical coefficients which take into account strain rate and strain φ.

When we insert equations (2. 5) and (2. 6) in the equation (2. 4), we get equation for shear stress

$$\tau\left(\gamma, \dot{\gamma}\right) = \frac{M}{2\pi R^3}\left(3 + m + p\right) \tag{2. 7}$$

$p = \left(a_1 + 2 a_2\right)$ ....empirical coefficient

Because of low influence of deformation to torque by high temperature and low strain rate, equation (2. 7) can be written as

$$\tau = \frac{M}{2\pi R^3}\left(3 + m\right) \tag{2. 8}$$

According to Tresca yield criterion $k_f = 2\tau_{max}$ and equation (2. 8), the relation between k_f and M is given by equation

$$k_f = 2\tau_{max} = \frac{M}{\pi R^3}\left(3 + m\right) \tag{2. 9}$$

3 DETERMINATION OF CONDITIONS OF TESTING

Among many possible tests for determination of the flow stress, we decided to use torsion test. In this test a cylindrical specimen is twisted by a torque acting around its axis (Fig. 1). Stress k_f has to be calculated from the measured torque M, and strain from the twisting angle α.

With our testing device it is possible to change the temperature of the test piece with electric-inductive heater between 700°C and 1300°C. We can also change number of rounds per minute between 2 and 1500 min^{-1}.

During experiment we measure torque, temperature and number of twists of test piece until it breaks. Test pieces had dimension $\Phi 6 \times 60 mm$.

They have been annealed for 60 minutes at temperature 800°C before experiment.

We decided to change three parameters:

- temperature (T) between 900°C and 1300°C
- strain φ between 0,1 and 1
- strain rate $\dot{\varphi}$ between 0,2 and 4 s^{-1}

For evaluation of experimental results we used statistical multi-parameters method, which allows with small number of experimental points the greatest information about influence to mathematical model of the process.

Distribution of experimental points have been done according to central composition plan in 3D space. Total number of experiments (N) with repeating in central point was N=20.[2]

We choose mathematical model for statistical method [2]

$$k_f = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i\langle j}^{k} b_{ij} x_{ij} + \sum_{i=1}^{k} b_{ii} x_i^2 \qquad (3.1)$$

For our case:

$$k_f = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{12} x_{12} + b_{13} x_{13} + b_{23} x_{23} + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 \qquad (3.2)$$

Coefficients $b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{11}, b_{22}, b_{33}$ can be determined by using regression analysis in program SPSS for Windows.

The code form of three parameters (temperature, strain and strain rate) is given by :

$$x_1 = \frac{T - 1100}{200} \;;\quad x_2 = \frac{\varphi - 0{,}55}{0{,}45} \;;\quad x_3 = \frac{\dot{j} - 2{,}1}{1{,}9} \qquad (3.3)$$

When we insert the values of coefficients calculated by regression analysis into equation (3.2), we get:

$$kf = 11{,}218 - 4{,}469\, x_1 - 0{,}166\, x_2 + 1{,}042\, x_3 - 0{,}575\, x_1 x_3 + 0{,}10\, x_2 x_3 + 0{,}645\, x_1^2 -$$
$$- 0{,}24\, x_2 - 0{,}221\, x_3^2 \qquad (3.4)$$

Equation (3.4) represents flow curve for chosen material in testing area. Results, which we got by using equation (3.4) are shown in table 1 under model results.

If we compare model results with experimental results (equation 2.2) we can see, that the difference is less than 3 %.

Table 1. Experimental results and model results

Experiment(N)	1	2	3	4	5	6	7	8	9	10
Model results [10N/mm^2]	14,5	6,8	14	6,2	17,6	7,4	17,4	7,3	20,5	5,5
Experimental results [10N/mm^2]	14,9	7,0	14,2	6,1	18,0	7,6	17,5	7,2	20,0	5,6

Experiment(N)	11	12	13	14	15	16	17	18	19	20
Model results [$10N/mm^2$]	10,4	10,3	8,7	12,3	11,2	11,2	11,2	11,2	11,2	11,2
Experimental results [$10N/mm^2$]	10,2	10,4	8,5	12,2	11,0	11,0	11,3	11,2	11,4	11,3

4 CONCLUSION

By using regression analysis for mathematical processing of experiment data, it is possible to get a complete picture of the influence of strain, strain rate and temperature to flow curve. It is necessary to do only a few experiments in some points of intervals for each parameter.

With the help of equation, which we get by using regression analysis, we can determine flow stress for every value of three parameters inside the interval.

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