Johnson-Cook Constitutive Model for OL 37 Steel

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Abstract: - Experimental studies proved that the strain rate has a high influence on the mechanical characteristics of materials and consequently on their response to different stresses. The exact determination of materials response to dynamic loadings permits the economic and adequate use of the material, through a corect design of structures, systems and equipments, which implies a technical-economical progress step. In the present work we present some aspects regarding the determination of Johnson-Cook coefficients for OL 37 steel, by using a gasodynamic single-stage equipment and the finite element method.

Key-Words: - OL 37, Johnson-Cook coefficients, strain rate, flow stress, gasodynamic equipment, equation of state.

1. Introduction

The first theoretical and experimental researches regarding the properties of materials in static and quasistatic regime were first made in the Middle Age (Leonardo da Vinci); the determination of the properties of materials in dynamic regime (excluding the case of shock waves) represents a more recent target.

Regarding the particular case of the Taylor test, the start of theoretical and experimental researches is represented by the year 1948, when G. Taylor published a theory which permitted the determination of an average value of the flow stress limit in dynamic regime, σ_c, for a material submitted to high strain rates.

The experiment consisted in the collision between a cylinder made of the tested material and a rigid plate. Suite of the tests, Taylor obtained a relation among the dynamic flow stress of the material and the report between the initial and final length of the cylinder (L_0/L_f). By renewing the experiment for several different materials (different steels, copper, lead) and dimensions, he demonstrated that σ_c exclusively depends of the impact speed and sample's geometry.

For his model, Taylor considered that the cylinder's material develops an ideal plastic behaviour, and in this case the elastic limit, σ_e, of the material coincides with the dynamic flow stress σ_c. Moreover, there were added the following hypotheses [6]:

- The speed of the elastic wave should be much greater than the impact speed and than the elasto-plastic wave speed;

- Radial forces of inertia should have low values, because, in this theory, they are neglected;
- There are considered only plastic deformations of the missile, the elastic ones being neglected.

Further, the growing necessities of data concerning the behaviour of material solicited in the field of high speeds, leaded to a large scale utilisation of the Taylor experiment [1]:

- in 1953, Lee and Tupper re-staged the experiment, using an elasto-plastic theory for analysis;
- in 1968, Hawkyard, Eaton and Johnson actualised the Taylor test for high temperatures with different one-dimension analysis, but the results obtained were not conclusive;
- in 1972, Wilkins and Guinan performed a bi-dimensional elasto-plastic analysis in order to study the cylinder wave propagation and to design the material behaviour using an elasto-plastic law. With this type of analysis, they confirmed the results obtained by Taylor;
- in 1984, C. Erlich brings two important modifications to the classic Taylor method:
  - Using an ultra speed TV camera (10^6 images/s), he measured the sample strain during the impact. Next, he compared the results obtained experimentally with those obtained with numerical simulation;
  - He replaced the rigid plate with another cylinder, identical with the missile as geometry and material. After the impact he observed that both specimens deform identically.

  The test was performed both at room temperature and at high temperatures.
- in 1985, Bois and Grave experiences, using the Taylor test, two types of steel and a titanium alloy and compares the results with those obtained using J. Cook's method;
- in 1988, G. Paulus establishes Taylor-type formulas, which he applies for several studies, including the no-strained part of the cylinder;
- in 1992, Holt, Moch, Zerlli and Clark study the influence of microstructures charges modifications and also the thermal effect of the shock in the material;
- in 1994, Woodmark, Burman and Baxter perform the Taylor test on Hopkinson bars, taking also into consideration the elastic strain of the rigid surface.

2. Theoretical aspects

The determination of the dependence $\sigma = \sigma(\varepsilon, \dot{\varepsilon}, T)$ represents the determination of the constitutive model of a material.

In the literature there are two types of constitutive models:

- Semi-physical models based on the combination of experimental determinations and analytical approach;
- Models totally based on experimental determinations, case justified by the phenomena complexity.

The most well-known and used constitutive model for metallic materials is the Johnson-Cook model [3]. It evidences the influence of plastic strain and temperature on flow stress. In its original form, this law is expressed with the relation

$$\sigma = \left[A + B\left(\varepsilon^p\right)^n\right]\left[1 + C\ln\dot{\varepsilon}^*\right]\left[1 - T^{*m}\right] \qquad (1)$$

where: σ - equivalent stress (von Mises);

ε^p - equivalent plastic strain;

$\dot{\varepsilon}^* = \dfrac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}$ - equivalent plastic strain rate (non-dimensional);

$\dot{\varepsilon}^p$ - plastic strain rate;

$\dot{\varepsilon}_0$ - quasistatic strain rate;

T^* - function of temperature;

A, B, n, C, m – material characteristics.

The elaboration of an algorithm for the material coefficients extraction is based, as evidenced by House in his paperwork [4], on the relationship between the differential equations that describe the one-dimension behaviour of a material submitted to the Taylor test.

In the view of considering with equal importance the three base parameters of a Taylor test (mushroom diameter, final length and undeformed length) we consider an objective function *f*, function of minimum, expressed by the relation [5]

$$f = \frac{\sum_{i=1}^{N}\sqrt{\left(\dfrac{L_{F,i}^C - L_{F,i}^M}{L_{F,med}}\right)^2 + \left(\dfrac{L_{FU,i}^C - L_{FU,i}^M}{L_{FU,med}}\right)^2 + \left(\dfrac{D_i^C - D_i^M}{D_{med}}\right)^2}}{N} \qquad (2)$$

where: N – number of tests;

L_F – final length of the cylinder;

L_{FU} – final length of the undeformed part of the cylinder;

D – final diameter of the mushroom;

C and M – indicate the calculated and measured value, respectively;

med – average value.

In the process of determination/validation of the Johnson-Cook coefficients of the material by using the finite element method, it is necessary to use also an equation of state of the material that only represents the relationship between the hydrostatic pressure, local density (or the specific volume) and the specific local energy (or the temperature). It finds use especially in the case of processes that have as a result the induction of a compression status in the materials.

The importance of the equation of state during impact processes and/or perforation is given by the fact that, in the case of such a process, a material presents important modifications of its' thermo-dynamic status. Therefore, the material might present solid, liquid, gaseous or even mixed phases. In the present work, we have used the Mie-Gruinesen equation of state, whose form is given by the expression [2]

$$p - p_0 = \frac{\gamma}{V}\left(\varepsilon - \varepsilon_0\right) \tag{3}$$

where: p – pressure;

p_0 – pressure at 0 Kelvin;

V – specific volume;

ε - internal energy;

ε_0 - internal energy at 0 Kelvin;

γ - Gruneisen parameter.

It is a characteristic of the Gruneisen equation that while p and ε depend both of volume and temperature, p_0 and ε_0 depend only of volume.

Another characteristic of the above-mentioned equation (3) is that the γ parameter is determined by measuring shock waves induced in the analysed material.

3. Apparatus and Experimental equipment

In the view of the determination of Johnson-Cook coefficients it was used a gasodynamic single-stage device.

The OL 37 steel, under the form of cylindrical samples of 7.9 mm diameter and three different lengths: 25, 32 and 37.9 mm, has been submitted to tests by using this device (Fig.1).

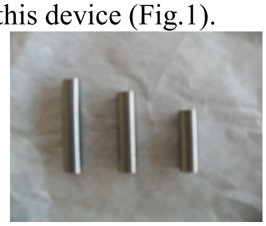

Fig.1 Cylindrical samples

The main parts of the experimental device are:

- Installation composed by compressor, holder, tank, electrovent, pipe, protection box, target, device for the measure of the speed and manometers (Fig.2);
- Sabot-cylinder assembly (Fig.3).

Fig.2 *Gasodynamic device*

Fig.3 Sabot-cylinder assembly

4. Experimental data and discussions

On the basis of theoretical aspects presented above, we submitted to analysis an OL 37 steel with the following characteristics: density - 7830 kg/m^3; Young modulus – 2.10x10^5 N/mm^2; transverse elastic modulus – 0.880x10^5 N/mm^2; Poisson coefficient – 0.26; static flow stress – 220 N/mm^2 and melting temperature - 1793 K.

In order to determine Johnson-Cook coefficients of material, we considered the minimisation of f function, the determination of calculated dimensions using numerical simulations in the program LsDyna. The numerical simulations started with the unitary value for the material coefficients.

Considering a simple gradient algorithm, we pursued the minimisation of the objective function that leaded to a good agreement of the form obtained numerically with the one determined experimentally.

After the rolling of several steps, we obtained for the OL 37 steel the following values of Johnson-Cook coefficients (Table 1).

Table 1

A (MPa)	B (MPa)	n	C	m
220	620	0.12	0.010	1.00

The experimental determinations and numerical simulations leaded to the obtaining of the results presented in Table 2, Table 3 and Table 4. The results as graphics are given in Fig.4.

Table 2

No.	*D_i (mm)*	*L_i (mm)*	*V_i (m/s)*	*D_F (mm)*	
				measured	*calculated*
1	7.9	25	87	8.90	8.71
2	7.9	25	98	9.02	8.91
3	7.9	25	125	9.71	9.55
4	7.9	32	156	10.71	10.55
5	7.9	32	174	10.93	11.18
6	7.9	37.9	100	9.12	9.02
7	7.9	37.9	134	9.71	9.90
8	7.9	37.9	182	11.34	11.55
9	7.9	37.9	209	12.41	12.66

Table 3

No.	*D_i (mm)*	*L_i (mm)*	*V_i (m/s)*	*L_F (mm)*	
				measured	*calculated*
1	7.9	25	87	23.71	24.08
2	7.9	25	98	23.12	23.85
3	7.9	25	125	22.87	23.22
4	7.9	32	156	28.37	28.67
5	7.9	32	174	28.12	27.88
6	7.9	37.9	100	36.30	36.09
7	7.9	37.9	134	34.99	34.82
8	7.9	37.9	182	32.91	32.75
9	7.9	37.9	209	31.71	31.45

Table 4

No.	*D_i (mm)*	*L_i (mm)*	*V_i (m/s)*	*L_{FU} (mm)*	
				measured	*calculated*
1	7.9	25	87	15.05	15.44
2	7.9	25	98	14.73	15.17
3	7.9	25	125	14.09	14.64
4	7.9	32	156	17.49	17.83
5	7.9	32	174	17.95	17.51
6	7.9	37.9	100	23.80	23.61
7	7.9	37.9	134	22.87	22.27
8	7.9	37.9	182	20.85	20.18
9	7.9	37.9	209	19.60	19.35

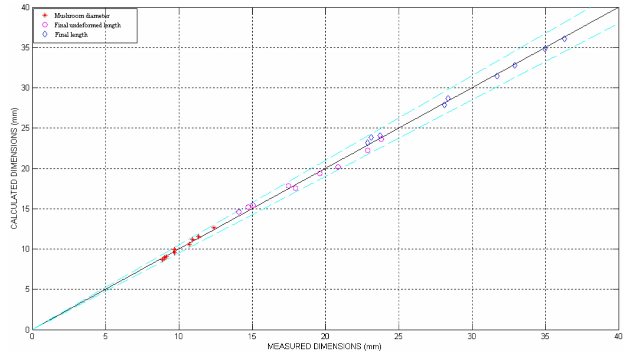

Fig.4 Measured vs. calculated values

The determination of the expression of Johnson-Cook model allowed a room temperature evaluation of flow stress in function of strain and three different strain rates (Fig.5).

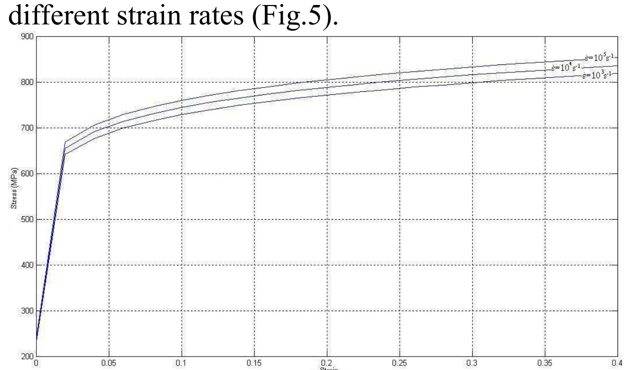

Fig.5 Variation of flow stress

We obtained a similar shape, as the one given in Fig. 5, in the case of numerical simulation in LsDyna (Fig.6):

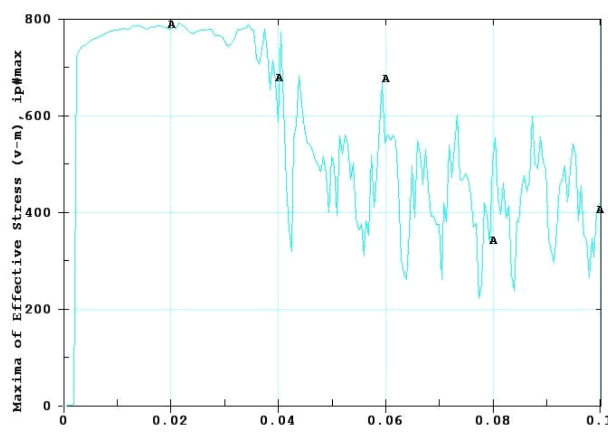

Fig.6 Variation of flow stress for OL 37 at a 100 m/s speed impact

After the impact between the cylindrical sample and the rigid target we were able to observe a radial increase of the sample and a decrease of its' length; the profile of the cylindrical sample after such an impact is given in Fig. 7 and Fig.8:

Fig.7 Sample profile after a 100 m/s speed impact

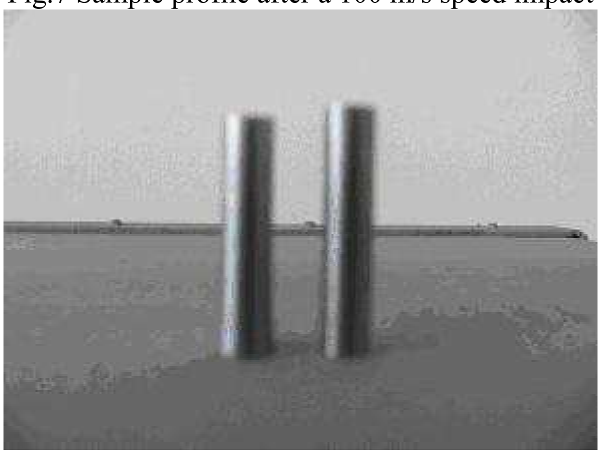

Fig.8 Sample profile before and after the impact

5. Conclusions

The present paperwork frames the experimental works that study the response of dynamically solicited materials.

The analysis of numerical data from the tables above evidenced the fact that the difference among the values calculated and those measured regarding all the three analysed dimensions, is in a ±5% range.

The results obtained evidenced the fact that the OL 37 steel, as the vast majority of steels, presents a rather high sensitivity to the variation of the strain rate.

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