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To cite this version:
M. Haque, M. Hashmi. CONSTITUTIVE EQUATIONS FOR STRUCTURAL STEEL (En-8) AT STRAIN RATES OF 10³ TO 10⁵ PER SECOND AND TEMPERATURES OF -30°C TO 235°C. Journal de Physique Colloques, 1985, 46 (C5), pp.C5-41-C5-47. <10.1051/jphyscol:1985506>. <jpa-00224736>

HAL Id: jpa-00224736
https://hal.archives-ouvertes.fr/jpa-00224736
Submitted on 1 Jan 1985

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CONSTITUTIVE EQUATIONS FOR STRUCTURAL STEEL (En-8) AT STRAIN RATES OF 10^3 TO 10^5 PER SECOND AND TEMPERATURES OF -30°C TO 235°C

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Résumé - Les caractéristiques contrainte-déformation d'un acier En-8 aux vitesses de déformation allant de 10^3 à 10^5 par seconde environ et aux températures allant de -30°C à 235°C ont été déterminées. La technique expérimentale utilise des enregistrements photographiques pour dériver les données de contrainte-déformation. Une équation constitutive a été proposée en se basant sur les résultats de contrainte-déformation. Cette équation tient compte de l'influence de la déformation et de la vitesse de déformation sur la contrainte.

Abstract - Stress-strain characteristics of En-8 steel at strain rates ranging from about 10^3 to about 10^5 per second and at temperatures ranging from -30°C to 235°C have been determined. The experimental technique uses high speed photographic records to derive the stress-strain data. Based on the stress-strain results a constitutive equation has been suggested which accounts for the effect of strain and strain-rate on the stress.

I - INTRODUCTION

It has long been realised that strain rate as well as temperature affect many material properties. The strain rate has greater effect on flow stress in the hot working range and relatively smaller effect in the cold working range, this applies especially when large strains are imposed. The stress-strain characteristics of metals under dynamic loading, machining and high rate forming conditions are of great importance in design calculations. Attempts to analyse these forming and cutting processes and to predict structural collapse and catastrophic failure require reliable data and better understanding of material behaviour at high strain rates.

A critical review of some relevant works by a number of researchers has recently been published in reference/1/ in which details of a new experimental technique for determining dynamic stress-strain characteristics of metals have also been described. In this technique a ballistic test equipment was used to affect deformation and a high speed IMACON camera was used to record the deformation-time history of the specimen in a continuous mode. Such photographic records enabled derivation of strain, force, stress and strain rate histories during the entire deformation process. From these results the stress-strain characteristics of the test material could be determined.

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In this paper, the stress-strain characteristics and the corresponding constitutive equation for En-8 steel (0.41%C, 0.78%Mn, 0.26% Si and 0.13%Ni) at strain rates between $10^3$ and $10^5$ per second and temperatures between -30°C to 235°C over a strain of about 50% are presented.

In evaluating the results, proper account has been taken of the strain-rate variation and total strain during a test. The effect of strain rate history of the specimen has also been investigated. The effects of friction, material inertia and temperature rise have been assessed in presenting the results.

II - EXPERIMENTAL EQUIPMENT AND PROCEDURE

A detailed description of the procedure and equipment used in this technique has been given in reference /1/ and hence only a short description is included in this paper. The ballistic test equipment is shown schematically in Fig.1 which permits firing of a cylindrical tool steel projectile on to a small cylindrical test specimen placed on a rigid anvil. The compressed air driven projectile cuts a laser beam, thereby switching on the flashes and after a pre-set delay time triggers the IMACON high speed camera immediately before the projectile makes contact with the specimen. An oscilloscope records the time during which the laser beam remains obstructed by the projectile and provides data for calculating impact speed.

![Fig.1 Schematic diagram of the experimental set-up](image-url)
The camera records continuously and accurately the position of the projectile during deformation process which lasts for about 15 micro seconds. A typical photographic record and a line diagram illustration are shown in Fig.2. Displacement of the projectile, measured from such photographic record, using a travelling microscope, together with the dimensions of the specimen and known mass of the projectile are then used to obtain stress, strain and strain rate-time histories and hence the stress-strain characteristics of the material. From a single test only limited stress-strain results corresponding to within 10 per cent of the initial strain rate are possible to be deduced. Beyond this small strain the strain rate diminishes rapidly and hence the rest of the data cannot be used. It is therefore, necessary to conduct dynamic compression tests on specimens machined from statically pre-deformed cylindrical pieces. Such static deformation is carried out under minimum friction conditions and to various levels ranging from 10% to 40% natural strain. Dynamic stress-strain results obtained from tests carried out on statically undeformed and pre-deformed specimens are then used to construct the stress-strain curve over large strain values corresponding to a given initial strain rate.

It should be noted that the total strain imposed on a specimen from a single test should not exceed about 25%. This is essential so that useful stress-strain results (within 10 per cent of the initial strain rate) can be obtained over strains of about 3 to 5 per cent.
Fig. 3(a) shows typical stress-time and strain-time histories corresponding to a single test in which the acceptable part of the curve is clearly indicated. Fig. 3(b) illustrates the procedure for obtaining a complete stress-strain curve from the results of tests carried out on a number of specimens pre-strained to different levels. The stress-strain curve for each specimen is plotted by shifting it along the strain axis by an amount equal to the pre-straining. The maximum acceptable stress-strain points on these curves are then joined to obtain the complete curve.

Results from an elaborate test programme suggests /2/ that variable strain-rate history has negligible effect on the stress-strain characteristics of En-8 steel.

For tests at sub-zero temperatures, the anvil of the test rig was kept at -30°C using CARDICE and an aerosol freezer (type B.S.3914). The specimen was cooled down to -70°C using a liquid nitrogen filled container and the temperature drop vs transportation time was carefully calibrated. Test was carried out when the temperature of the specimen had reached -30°C (± 5°C).

For warm temperature range, the anvil and specimen temperatures were again calibrated for temperature loss in transportation and testing time and tests were conducted at 235°C (± 5°C). Full details of these calibration techniques are given in reference /2/.

III - STRESS-STRAIN PROPERTIES OF En-8 STEEL

Following the experimental technique described above the stress-strain properties of En-8 were determined at strain rate ranging from $7.32 \times 10^3$ to $8.74 \times 10^4$ per second and at temperatures ranging from -30°C to 235°C. These results are shown in Fig. 4 (a), (b) and (c) for test temperatures of -30°C, 22°C and 235°C respectively. Since all the dynamic tests at 22°C and 235°C were carried out under dry
friction condition to obtain clear photographic record, it was necessary to adjust the experimental results for frictional contributions /3/. No such adjustments were done to the test results at -30°C, since it was found that the very thin layer of ice formed on the specimen surface virtually eliminated any frictional constraint. The results presented in Fig. 4(a), (b) and (c) therefore, correspond to zero friction condition. Full details of this adjustment procedure is given in reference /1/and /2/.

Also, since from each test only limited data during the initial stages of deformation were used, the effect of material inertia and temperature rise was considered to be negligible /4/.

IV - CONSTITUTIVE EQUATION

In reference /5/ a constitutive equation was used to describe the dynamic flow stress of 0.2%C steel. This equation assumes that the effect of strain-rate is independent of strain. The results for En-8 steel shows that the strain hardening effect decreases with strain hence an equation of the following form was proposed.

$$\sigma = A\varepsilon^m (1 + B\dot{\varepsilon}^3)$$

where, $A$ = material constant, $\varepsilon$ = natural strain, $m$ = strain hardening index, $B$ = constant, $\alpha = e^{3.25\varepsilon}$, $f = \ln(\dot{\varepsilon}/\dot{\varepsilon}_0)$, $\dot{\varepsilon}$ = prevailing strain rate, $\dot{\varepsilon}_0$ = constant at 1 per second, $\sigma$ = dynamic flow stress.

Fig. 4 Stress-strain curves of En-8 steel at various strain rates and at (a) -30°C, (b) room temperature (22°C), and (c) 235°C.
The value of 'A' was derived from the quasi stress-strain curve for En-8 steel tested at different temperatures at natural strain = 1. The constant 'n' was determined by trial and error until a close fit of the quasi-static curve was obtained. The value of the constant 'B' was determined again by trial and error using the experimental stress values at strain rates ranging from $10^3$ to $10^5$ per second. All these values for different test temperatures are listed in Table 1.

### TABLE - 1

<table>
<thead>
<tr>
<th>Test Temperature (°C)</th>
<th>Constants</th>
<th>A (kN/mm²)</th>
<th>n</th>
<th>B (x 10⁻⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>1.10</td>
<td>0.17</td>
<td>7.20</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1.00</td>
<td>0.18</td>
<td>5.85</td>
<td></td>
</tr>
<tr>
<td>235</td>
<td>0.88</td>
<td>0.30</td>
<td>7.3</td>
<td></td>
</tr>
</tbody>
</table>

Applying the values of the constants to the proposed equation, the stress values for En-8 steel at temperatures between -30°C and 235°C were calculated for different strains and strain rates. These are graphically presented in Figs. 5(a), (b) and (c) by broken curves, where the solid curves represent actual results determined experimentally.

Fig. 5 Stress-strain curves obtained by using proposed equation and those obtained experimentally at (a) -30°C, (b) room temperature (22°C) and (c) 235°C.
V - CONCLUSIONS

The following conclusions have been drawn from the experiments carried out at strain rates between about \(10^3\) to \(10^5\) per second and at temperatures between \(-30^\circ C\) to \(235^\circ C\).

(a) The En-8 steel showed a strong strain rate sensitivity despite its higher carbon content.

(b) A flow rule has been proposed incorporating the effects of work-hardening and strain rate sensitivity of the material.

ACKNOWLEDGEMENTS

Dr M M Haque is grateful to the authorities of Bangladesh University of Engineering and Technology for allowing him leave of absence to study for PhD at Sheffield City Polytechnic, UK.

REFERENCES


