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The torsion-tensile testing method for the characterization of cold metal formability

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Abstract

In cold forming, the materials are subject to very large stresses, the cold formability is in that case an essential property. This can be characterized by the measure of the striction after a tensile test following a torsion test . A theoretical study of torsion-tensile testing, in large strain for elastoplastic behaviour with isotropic hardening is given. The problem is solved with the finite difference method, and a damage criterion is introduced for to expect the failure. A software has been made for to simulate the material behaviour in this test.

1. INTRODUCTION

Now, modern cold forming techniques play a more and more important role in the production of mechanical pieces, and the last possess excellent geometric characteristics as far as both dimensions and surface finish are concerned. This allows production time material losses and costs to be reduced.

The metal cold formability is so an essentiel quality, although, it's difficult to characterize because it depends in many factors. Different tests are usually used [1],[2]; among which torsion testing that can to obtain strains of the same order of size as thoses observed during cold forming processes [3]; the striction is generally the parameter used for characterizing the ductillity. Our aim is to study the formability test introduced in [4]; it consists in carrying out torsion testing followed by tensile testing . Our objective is to explain the striction curves obtained after torsion- tensile testing, and to elaborate a computer program that predicts these curves .

2. DESCRIPTION OF THE TEST

The principle is the following: different cylindrical test pieces of 50 mm length and 3 mm radius (R_0) are twisted off with strain rates growing up to the failure; then they are subject to tensile testing up to failure. The diameter of the broken section is mesured and enables striction calculation.

$$Z \% = (1 - \frac{S}{S_1}) \times 100$$

where S_1 is the section before tensile testing and S the broken section

Then we can draw a curve $Z=f(N)$ where N represents the number of prestrain rotation wich depends of the useful length and of the diameter of the specimen. These curves make up an finished surface that permits a classification of materials the greater surface area, the more easily will materials be deformed.

3. MODELINGS OF THE TEST

3.1. elastoplastic torsion testing

3.1.1. Kinematic aspects

During torsion testing in large strain, we can note a lead effect according to the axis of the test piece; this phenomena is calling “ Poynting effect” [5],[6]. Taking this observation into account, we choose a displacement field answering two hypothesis :

1. the strain is homogeneous according to the specimen axis
2. a straight section stays straight.

The field introduced by Murnagham [7] corresponds with these hypothesis:

$$\begin{aligned} \mathbf{r} &= \mathbf{r}_0 + \mathbf{u}(\mathbf{r}_0, \Phi(t)) & \text{where } \Phi(t) \text{ is the rotation by lenght unity} \\ \theta &= \theta_0 + \Phi(t). \quad z_0 & (\mathbf{r}_0, \theta_0, z_0) \text{ are the coordinates at the time } t_0 \\ z &= z_0 + w(\Phi(t))z_0 & (\mathbf{r}, \theta, z) \text{ are the coordinates at the time } t \end{aligned} \quad (1)$$

Then we can write the strain rate tensor expressed on the actual configuration:

$$\mathbf{D} = \begin{vmatrix} \frac{\mathbf{u}, \mathbf{r}_0, t}{1 + \mathbf{u}, \mathbf{r}_0} & 0 & 0 \\ 0 & \frac{\mathbf{u}, t}{\mathbf{r}_0 + \mathbf{u}} & \frac{1}{2} \frac{\mathbf{r}_0 + \mathbf{u}}{1 + \mathbf{w}} \Phi, t \\ 0 & \frac{1}{2} \frac{\mathbf{r}_0 + \mathbf{u}}{1 + \mathbf{w}} \Phi, t & \frac{\mathbf{w}, t}{1 + \mathbf{w}} \end{vmatrix} \quad (2)$$

and the spin tensor:

$$\mathbf{\Omega} = \begin{vmatrix} 0 & -z_0 \Phi, t & 0 \\ z_0 \Phi, t & 0 & \frac{1}{2} \frac{\mathbf{r}_0 + \mathbf{u}}{1 + \mathbf{w}} \Phi, t \\ 0 & \frac{1}{2} \frac{\mathbf{r}_0 + \mathbf{u}}{1 + \mathbf{w}} \Phi, t & 0 \end{vmatrix} \quad (3)$$

3.1.2. constitutive laws

We are introducing here an elastoplastic behaviour in making the hypothesis of the strain partition:

$$\mathbf{D} = \mathbf{D}_e + \mathbf{D}_p \quad (4)$$

We choose a *hypoeelastic* behaviour with the isotropic Hooke law:

$$\mathbf{D}_e = \frac{1+\nu}{E} \mathbf{D}_J \boldsymbol{\sigma} - \frac{\nu}{E} \text{tr}(\mathbf{D}_J \boldsymbol{\sigma}) \mathbf{1} \quad (5)$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor and $\mathbf{D}_J$ the Jaumann derivative operator

and an *incompressible plastic* behaviour with the Prandtl-Reuss equation and the Von Mises criterion:

$$\mathbf{D}_p = \lambda \mathbf{s} = \frac{3}{2} \cdot g'(\bar{\sigma}) \frac{d\bar{\sigma}}{d\bar{\sigma}} \mathbf{s} \quad \text{where } \mathbf{s} \text{ is the stress deviator} \quad (6)$$

$$\bar{\sigma} = \sqrt{\frac{3}{2} \mathbf{s}_{ij} \cdot \mathbf{s}_{ij}} \text{ is the Von Mises equivalent stress}$$

$$\text{we use a law of the type: } \bar{\epsilon}_p = g(\bar{\sigma}) = \frac{(\bar{\sigma} - \sigma_e)^{1/n}}{K^{1/n}}$$

where $\bar{\epsilon}_p = p = \int_{t_0}^t \sqrt{\frac{2}{3} \mathbf{D}_{p_{ij}} \cdot \mathbf{D}_{p_{ij}}} dt$ is the plastic cumulative strain.

σ_e , K and n are material constants

The calculations and the experiments are made for two different steels whose characteristics are summed up in the following table:

material	test	n	K	σ_e
18CD4	torsion testing	0.29	328	309
	tensile testing	0.49	530	
	torsion testing	0.43	344	
30CD4	tensile testing	0.416	560	361

and the incompressibility condition is :

$$\frac{u_{,r_0,t}}{1+u_{,r_0}} + \frac{u_{,t}}{r_0+u} + \frac{w_{,t}}{1+w} = \frac{3(1+2\nu)}{E} \sigma_H \quad (7)$$

where $\sigma_H = \frac{1}{3} \text{tr}(\boldsymbol{\sigma})$ represents the hydrostatic pression

3.1.3. equilibrium and boundary conditions

Taking into account the provement field choosen, the static equilibrium $\text{div } \boldsymbol{\sigma} = 0$ is reduced to only one equation:

$$\sigma_{rr,r} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} = 0 \quad \text{or after calculation} \quad \sigma_H = \int_r^R \frac{s_{rr} + s_{zz}}{r} dr \cdot s_{rr} \quad (8)$$

The boundary conditions are the following:

- on the cylindrical surface: $\sigma_{rr}|_{r=R} = 0$ (9)

- on the specimen extremities: $F_z = 2\pi \int_0^R \sigma_{zz} (r_0 + u)(1 + u_{,r_0}) dr_0 = 0$ (10)

$$C_z = 2\pi \int_0^R \sigma_{\theta z} (r_0 + u)^2 (1 + u_{,r_0}) dr_0 \quad (11)$$

3.1.4. résolution

The system of equations, (5 - 11) whose unknown are s_{rr} , s_{zz} , $s_{\theta z}$, σ_H , u , w and C_z , is solved by an incremental computation with the finite differences method.

Figure 1. identification of the hardening from the torque and the rotation by unit of length

The result of the calculation shows that the strains induced on the axis remain small ($\epsilon_{zz} < 0,5\%$) compared with the tangential strains ($\epsilon_{\theta z} = 150\%$) likewise the normal stresses do not exceed 7.5 MPa for tangential stresses of 450 MPa.

3.2 .tensile testing

The tensile testing is solved from the same basic equations (5-11), the boundary conditions changing ($C_z = 0$ and F_z unknown), as is the elastic boundary that depend on the radius. We can also remark the presence of residual stress after elastic slackness in torsion testing.

The following figures shows the evolution of the axial stress computed at the moment of the failure for different prestrain rates in torsion testing, the other stresses remain negligible.

Figures 2a and 2b. axial stresses in tensile testing at the failure after different rotations in torsion testing for the both metals.

On the next figure, we can note the good correspondance between the averaged axial stress measured and computed in tensile testing after torsion testing.

Figure 3. comparison between the averaged axial stress measured and computed in tensile testing after 3 rotations in torsion testing.

4. FAILURE CRITERION

We use three criterions that we are comparing:

* *isotropic plastic ductil damage* [9]

We introduce the isotropic plastic ductil damage variable D so as $D=0$ characterizes the blank material and $D=D_c$ gives the starting of a macro-crack:

$$D_{,t} = \frac{\sigma^{*,t}}{S} \cdot \left(\frac{\sigma^* - \sigma_D}{S(1-D)} \right)^s \quad \text{if } \sigma^{*,t} > 0 \text{ and } \sigma^* = \sup(\sigma_D, \sigma^*) \quad (12)$$

$$D_{,t} = 0 \quad \text{if } \sigma^{*,t} < 0 \text{ or if } \sigma^{*,t} > 0 \text{ and } \sigma^* < \sup(\sigma_D, \sigma^*)$$

where $\sigma^* = \sqrt{\frac{2}{3}(1+\nu)s_{II} + 3(1-2\nu)\sigma_H}$ is the equivalent stress.

σ_D , s and S are material constants given by the following table

material	test	D_c	σ_D	S	s
18CD4	traction	0.42	309	690	0.79
	torsion	0.402	348	363	1.55
30CD4	traction	0.39	361	701	1.04
	torsion	0.41	426	426	0.99

We make the hypothesis that the damage is cumulative ,

Fig 4. radial distribution of the computed damage for 18CD4

Fig 5. comparison between the averaged computed and measured damage

We can note on the figure 4. that , in torsion testing, the damage at the specimen periphery is greater than the failure damage D_c . The figure 5 shows the good agreement between the averaged calculated and measured damage for 18CD4.

On the figures 6a and 6b representing the radial repartition of the damage at the failure in tensile testing, we can observe for weak strains that the maximum damage is situated near the axis of the test piece, on the other hand, for large strains the maximum damage is situated on the periphery.

Figure 6 . radial repartition of damage at failure in tensile testing for different torsion prestrains

* *energetic criterion* [10]

introduced by Latham and Cokcroft :

$$C = \int_0^{\bar{\epsilon}_r} \frac{\sigma_1}{\bar{\sigma}} \bar{\sigma} d\bar{\epsilon} \quad (13)$$

where C material constant

$\bar{\epsilon}_r$ equivalent strain at failure

σ_1 the maximum tensile stress

* *plastic strain criterion*:

We calculate the plastic strain at the failure: $P_R = \frac{\bar{\epsilon}_r}{\left(\frac{2}{3}(1+\nu) + 3(1+2\nu)\right) \frac{\sigma_H}{\sigma}}$ (14)

P_R is averaged on the specimen section : $P_R = \frac{2}{R^2} \int_0^{R_1} P_R(r_1+u)(1+u_{,r1}) dr_1$

5. DETERMINATION OF THE CURVES $Z=f(N)$.

The next figures show that the curve obtained with the damage criterion corresponds well with the experimental curve, where we can observe a great decreasing of the residual striction from a certain torsion prestrain.

Fig 7 a-b-c-d comparison of residual striction for different failure criterions

6. COMPARISON TORSION+TENSILE TESTING AND EXTRUSION +TENSILE TESTING

We have realised extrusion experiments with the both materials, for different reduction rates about 20%, 40%, 60 %,and after we have made tensile testing on a specimen axially extracted of the extruded piece.

The next figure indicates the residual striction after torsion or extrusion.

Figure 8. comparison between the striction obtained after extrusion+tensile testing and torsion + tensile testing

We remark that both curves have the same configuration, in their first parts. We do not have points on the second part that corresponds to extrusion reduction rates above 65 %.

7. CONCLUSIONS

Our work shows that using a failure criterion based on the ductile damage, we can define the residual striction curves after torsion testing. The brutal fall of ductility from a certain strain in torsion testing can be explained by the fact that the material damage exceeds the critical averaged damage at the specimen periphery. The curve obtained for different torsion rates is comparable to the curve obtained for extrusion specimens. So the torsion-tensile testing is a good test for to determine the metal formability.

The numerical schema suggested permits restricting the experiment to one test in simple torsion testing and one other in simple tensile testing for to determine the material characteristics.

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