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# INVESTIGATION OF MATERIALS BEHAVIOR UNDER COMBINED LOADING CONDITIONS

BY

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**Abstract.** The paper presents an experimental investigation on material behavior subjected to combined loading conditions. The methodology consists in two steps loading of solid cylindrical specimens by initial twisting at different degrees of plastic deformations and sequentially by tensile loads, until break. Has been assessed the influence of plastic deformation obtained by twisting on different characteristics of metallic materials. Experimental results show that hardness, tensile yield and tensile stress increase with energy associated to plastic deformation, due to the changes of mechanisms that occur at the material microstructure.

**Key words:** combined loading; material testing; hardness measurements.

## 1. Introduction

Experimental investigations in different combined loadings conditions are necessary to describe accurate material behavior. To apply axial load (tensile or compression) and torque to solid circular or tubular specimens, can be used two different experimental testing setups: with independent machines with active control systems (servo hydraulic, servo mechanical, electrical) or

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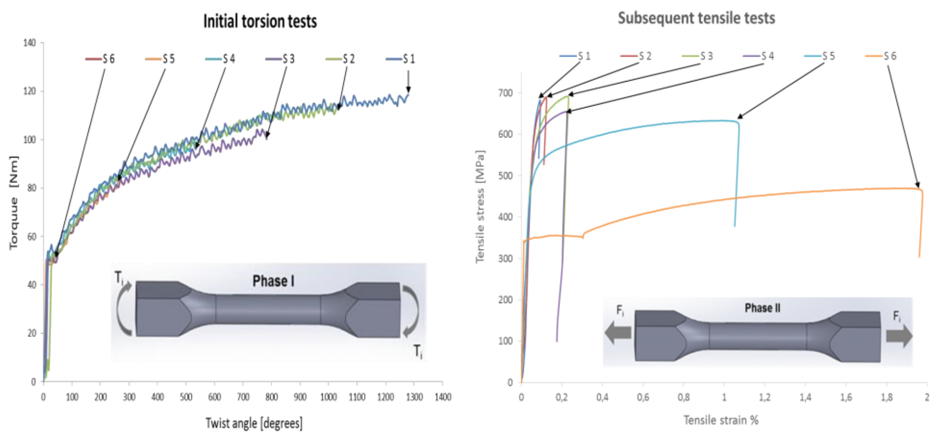
specific devices attachable to universal testing machine. With torsion tests can be obtained large strains of ductile materials and can produce severe plastic deformation (Wang *et al.*, 2013), thereby achieving a higher plasticity strain compared with axial tests (Wang *et al.*, 2014). Torsion testing of solid circular specimens can be done in two ways, with respect to end conditions: with fixed-end and with free-end, which allows axial displacement. During free-end torsion of different materials was experimentally observed a second order effect, called Swift effect (Swift, 1947) caused by crystallographic texture development. The phenomenon consists in elongation/contraction of solid circular specimens, from polycrystalline materials, during large plastic deformations in torsion. A review of experimental and numerical simulated Swift effect from literature can be finding in Duchene *et al*. (2007). Revil-Baudard *et al*. (2014) demonstrated the existence of a connection between Swift effect in free end torsion and tensile/compression asymmetry. Classical von Misses yield criterion expressed in terms of equivalent stresses and strains, is incompletely because it disregards pressure dependence and nonlinearity of elastic strains. A new failure theory postulated by Christensen states that failure represents the end of elastic behavior and not plastic behavior, and divides the stress tensor in two: dilatation part and distortion part (Christensen, 2014). Deformations in the case of materials with predominantly ductile behavior can be divided in several domains: linear elastic, nonlinear elastic, hardening and plastic.

## 2. Material and Methods

To analyze material behavior, two different loading tests were performed (Fig. 1):




*a* *b*

Fig. 1 – Type of loading *a*) torsion and *b*) tensile tests.

In phase I, specimens are initially subjected to different levels of plastic deformation by the application of various rotation angles (twist angles) through free end torsion (Fig. 1*a*). In phase II, specimens initially loaded by torsion are subjected subsequently to uniaxial tensile test (Fig. 1*b*). Torsion of a solid circular specimen assume deformation and stress gradients along radial direction, while stretching of a pre-twisted sample with its inhomogeneous deformation history and internal stresses also induces radial stress gradients (Giessen & Neale, 1993), but this multiaxiality is lower and better detected than the tree-dimensional state inside necks from uniaxial tensile tests (Wu & Giessen, 1991). Material used in experiments was 1.0037 structural steel.

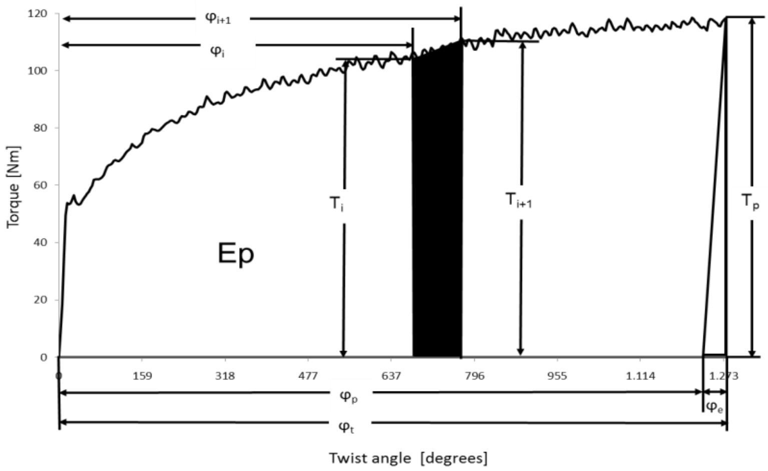



Fig. 2 – Determination of energy corresponding to plastic deformations.

Elastic deformation energy and plastic deformation energy are determined from torque-twist angle curve like in Fig. 2, using eq. (1) in the case of torsion test and for tensile test from force-extension curve. The elastic part of energy is represented by the area to the right of the unloading line. The plastic energy is area under the curve, and can be expressed as:

$$Ep = \sum_i \left[ \left( \frac{(T_{i+1} + T_i) \cdot (\varphi_{i+1} - \varphi_i)}{2} \right) \right] - \left( \frac{T_P \cdot \varphi_E}{2} \right) \qquad (1)$$

where $\varphi_i$, $\varphi_{i+1}$ are the rotation angles values given by testing machine in positions $i$ and $i$+1; $T_i$, $T_{i+1}$ represents torque values in positions $i$ and $i$+1; $T_i$ is ultimate value of torque corresponding with curve end point and $\varphi_i$ − represents values of twist angle corresponding to elastic unloading area. After the specimens were subjected to different degrees of plastic deformation, hardness was measured and then tensile loads were applied, until break.

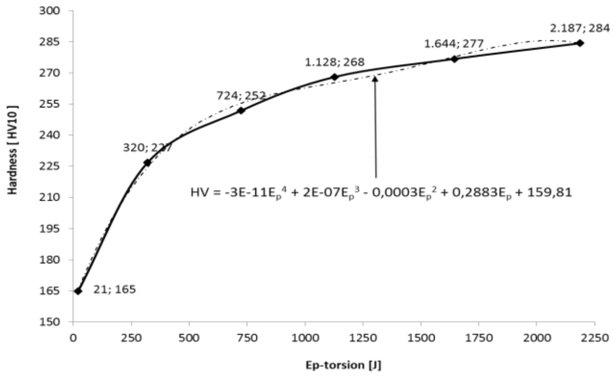



Fig. 3 – Variation of hardness with energy associated with plastic deformation obtained by gradual torsion.

Vickers hardness measurements are made on 13 points indentation, along longitudinal direction on the surface of specimen gauge section. To describe variation of hardness as a function of plastic deformation degree, it is used the medium value of hardness from each specimen, as illustrated in Fig. 3. Hardness values increased with energy associated with plastic deformation obtained during initial torsional loading.

## 3. Results and Discussions

In this analysis, six different levels of plastic deformations are considered in order to examine the effects of combined loadings on material behavior.

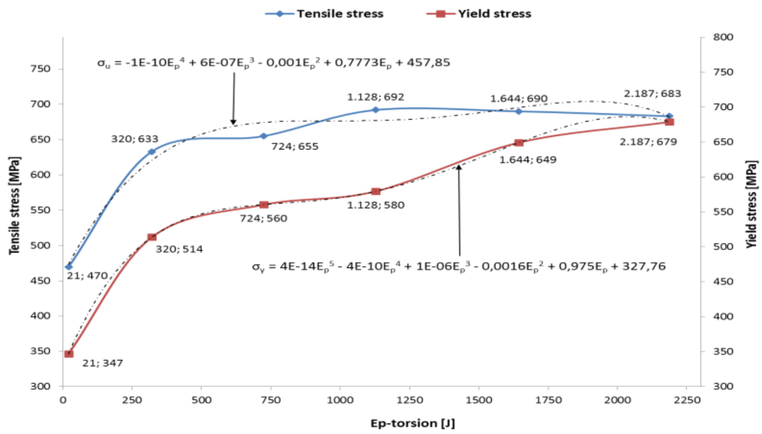



Fig. 4 – Evolution of tensile stress and yield stress with energy associated with plastic deformation obtained by gradual torsion.

Both tensile and yield stress increase with energy associated with plastic deformation for all specimens, and for highest deformed specimen values of stresses are approximately the same. Another observation is that the same samples have higher values of yield stress and tensile stress. To illustrate these remarks were plotted curves from Fig. 4, which shows the variation of yield stress and ultimate tensile strength (obtained by subsequent tensile test) with respect to corresponding energy of plastic deformation produced by different rotation angles.

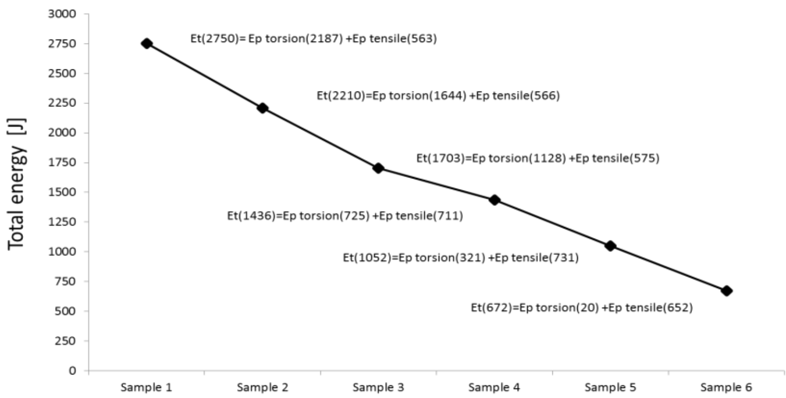



Fig. 5 – Variation of total deformation energy until break.

Can be observed that total deformation energy decreases with the degree of plastic deformation applied to samples, and that maximum energy in torsion (2750 J) is about three times higher that maximum energy in traction (731 J), as illustrated in Fig. 5. In the case of sample no. 3, the energy from torsion is almost equal with energy from tensile test, which means that the influence of the two types of tests on the material plastic deformation is almost the same. This phenomenon's are related to material strengthening that take place during torsion deformation, and is assigned to changes in material microstructure.

## 4. Conclusions

This study investigates the influence on material mechanical characteristics of complex loading conditions. Specimens with large plastic deformations caused by twisting presents small specific deformations in traction and the same samples have higher values of yield stress and tensile stress. Increasing of tensile stress, yield stress and hardness is related to material hardening that occurs during torsion deformation, and is associated with changes in material microstructure. There are significant differences in terms of characteristic curves obtained by tensile tests to failure on samples previously subjected to large plastic deformations through torsion test. Torsion testing, by producing large plastic deformations, acts on predominantly ductile material behavior as a mechanical strengthening treatment.

## REFERENCES

Christensen R.M., *Failure Mechanics - Part I: The Coordination Between Elasticity Theory and Failure Theory for all Isotropic Materials.* Journal of Applied Mechanics, **81**, 8, 1–7 (2014).

Duchene L. *et al.*, *Length Changes and Texture Prediction During Free-end Torsion Test of Copper Bars with FEM and Remeshing Techniques.* Int. J. Plast., **19**, 1417–1438 (2007).

Giessen E., Neale K.W., *Analysis of Inverse Swift Effect Using a Rate-Sensitive Polycrystal Model.* Computer Methods in Applied Mechanics and Engineering, **103**, 291−313 (1993).

Revil-Baudard B. *et al.*, *Correlation Between Swift Effects and Tension-Compression Asymmetry in Various Polycrystalyne Materials.* Journal of the Mechanics and Physics of Solids, **70**, 104–115 (2014).

Swift H., *Length Changes in Metals Under Torsional Overstrain*. Engineering, **163**, 253−257 (1947).

Wang C. *et al.*, *Experimental Microindentation of Pure Copper Subjected to Severe Plastic Deformation by Combined Tension-Torsion.* Materials Science & Engineering A, **571**, 95–102 (2013).

Wang C. *et al.*, *Microstructure Evolution, Hardening and Thermal Behavior of Commercially Pure Copper Subjected to Torsion Deformation.* Materials Science & Engineering A, **598**, 7−14 (2014).

Wu P.D., Giessen E., *Analysis of Elastic-Plastic Torsion of Circular Bars at Large Strains.* Applied Mechanics, **61**, 89−103 (1991).

## INVESTIGAREA COMPORTAMENTULUI MATERIALELOR ÎN CONDIȚII DE SOLICITĂRI COMBINATE

(Rezumat)

În această lucrare se analizează comportamentul materialelor supuse la încercări combinate de torsiune şi tracţiune, cu solicitarea epruvetelor din oţel, în regim de încărcare static. Testele s-au realizat după cum urmează: iniţial, epruvetele circulare solide au fost răsucite cu anumite grade de deformare, prin intermediul unui dispozitiv ataşabil la maşina de încercat universală. Apoi, s-au efectuat măsurători ale durităţii materialului pe cele şase epruvete. Ultima etapă a constat din încercarea epruvetelor cu deformaţii plastice introduse prin torsiune la tracţiune uniaxială, până la rupere. S-a constatat că limita de curgere, rezistenţa la rupere şi duritatea materialului studiat au crescut odată cu energia asociată deformaţiei plastice obţinută prin diferite rotaţii aplicate epruvetelor, şi că această creştere s-a datorat întăririi materialului, prin modificarea acestuia la nivel de microstructură.