NEW PARAMETER FOR DETERMINING PLASTIC FRACTURE DEFORMATION OF METALLIC MATERIALS

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ABSTRACT

This study develops a new parameter for determining the plastic fracture deformation of metallic materials, using for this purpose the simple standardized tensile test on a cylindrical test specimen and evaluating the sectional deformation in the necking after rupture by means of the analytical expression proposed, as developed from the Theory of Plasticity.

The procedure for measuring this parameter by means of an optical profile projector is also explained, as are the practical applications of this parameter.

This formulation will eliminate the disadvantages of presents parameters (like A5d and A10d) and will enable a definite value which permit comparison with other values obtained by means of geometrically different samples, opening up the path to immediate applications in the field of Science and Engineering of Materials, Quality Control of Metals and Numerical Method.

KEY WORDS : Elongation , Ductility , Necking , Uniaxial Tension Test

1.- INTRODUCTION

The maximum fracture deformation that a metal is capable of withstanding appears amongst the basic mechanical characteristics when it comes to defining the technical properties of this material.

Nowadays a procedure is employed to determine fracture deformations in metallic materials. This procedure is accepted worldwide and standardized in the same way by the two main international standards:

- Euronorm EN-10002-1 *"Metallic materials. Tensile tests"*
- American standard ASTM E8 / E8M-08 *"Methods for tension testing of metallic materials"*

This method, referred to in Article 11 of Euronorm EN-10002-1 as *"Determination of percentage elongation after fracture (A)"* consists, in the case of round section metallic test specimens, of joining together the two broken pieces of the sample, after the simple tensile test, so that their axes are situated in a straight line and checking the longitudinal elongation that has taken place. It is necessary to establish calibration marks on the test specimen beforehand for subsequent calculation of its percentage elongation (Fig 1).

The main drawback of this procedure lies in that the phenomenon of necking or localized deformation predetermines the measurement tremendously and arouses considerable doubts as to the result. Considering, furthermore, that local necking elongation (α) depends in turn on the diameter of the bar, we reach the conclusion, validated experimentally, that total plastic deformation at fracture (ε_f) for round-section test specimens is a function of the geometry of the sample.

Numerous attempts have been made to rationalize the distribution of tensile test deformations. Perhaps the most generally acceptable conclusion that may be drawn is that geometrically similar test specimens develop geometrically similar neckings. In accordance with Barba (1880), local elongation at the necking may be expressed as $\alpha = \beta\sqrt{A_0}$, where β is a coefficient of proportionality and A_0 the initial area.)

The above equation shows that, in order to compare deformations at fracture of different-sized test specimens, these have to be geometrically proportional, the geometric factor being the one that has to be maintained.

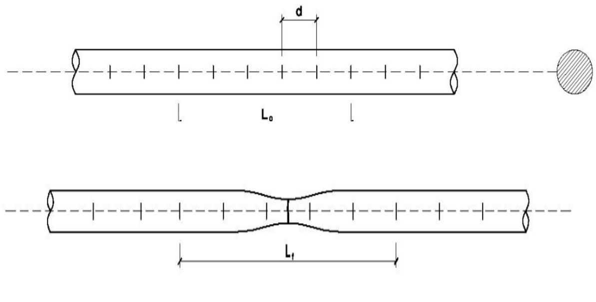


Fig 1.- A5d measuring procedure

Thus, as for the same steel the elongation of a centimetre of bar at the neck depends on the actual diameter of the bar, we are forced to define the necking elongation by taking as the measurement base not a centimetre, but a multiple of the bar diameter. The fact that a multiple is set in some standards but not in others underscores the conventionalism surrounding the procedure used at the present time. By way of example, in countries such as Spain or Germany five diameters (A_{5d}) was adopted as the measuring standard, while other countries, like Italy or Austria adopted ten diameters (A_{10d}) as the base.

The main disadvantages of the present parameter are, on the one hand, the lack of physical sense of A5d or A10d, as this parameter will weigh the overall longitudinal deformations in this range, but it does not indicate the maximum plastic deformations which are generated at fracture. Furthermore, depending on the diameter of the sample, different necking deformation values are obtained, so no comparison may be made between one another.

Despite research to try and establish a correlation between plastic deformations at fracture for samples of different geometry, to date no conclusive result has been reached. In fact, International Standard ISO 2566-1 *"Steel. Conversion of elongation values"* sets out to allay this disadvantage by means of the use of proportional samples as well as tabulating with tables and graphs the correspondences between values obtained with samples of different lengths. In practice, the infinite number of cases makes this unfeasible.

The aim of this article is the development of a new procedure that will eliminate the disadvantages described above and which will enable a definite value to be obtained for the plastic tensile deformation of round section bars.

2.- DESCRIPTION.

The main innovative aspect of the new parameter lies in the quantification not of the longitudinal plastic deformations, as at the present time, but of the sectional necking deformations. We will go on to give a brief description of the fundamentals of this proposal, as this is essential in the method proposed.

Study of the distribution of stresses and deformations in the necking of a bar subjected to traction was first undertaken by Bridgman in 1944. His work opened up a path to various contributions on this subject. Davidenkov and Spiridinova (1946) put forward expressions on the basis of experimental evidence. Kaplan (1973) extends the work of Bridgman beyond the minimum section and predicts the shape of the neck of the test specimen with its same parameters. Eisenberg/Yen (1983) generalize their expressions for orthotropic bars, while Cabezas/Celentano (2004) and Jones/ Gillis (1983) extend it to flat sheets.

The result obtained from using cylindrical coordinates is that, in the central section of the test specimen, where the necking takes place, the state of deformation is defined by the following tensor (Bridgman):

$$\dot{\varepsilon}_{ij} = \begin{pmatrix} \dot{\varepsilon}_r & 0 & 0 \\ 0 & \dot{\varepsilon}_\theta & 0 \\ 0 & 0 & \dot{\varepsilon}_z \end{pmatrix} \quad \text{where} \quad \dot{\varepsilon}_r = \frac{\partial \dot{u}}{\partial r} \quad \dot{\varepsilon}_\theta = \frac{\partial \dot{v}}{\partial \theta} \quad \dot{\varepsilon}_z = \frac{\partial \dot{w}}{\partial z} \qquad (4)$$

Considering the hypothesis that radial deformations are uniform (Davidenkov/Spiridinova (1946) and Goicolea (1985)), we get:

$$\dot{\varepsilon}_r = \frac{\dot{r}}{r} = \frac{\dot{D}}{D} \Rightarrow \varepsilon_r = \int \frac{\dot{D}}{D} dt = Ln \frac{D}{D_0} \qquad (5)$$

$$\dot{\varepsilon}_\theta = \dot{\varepsilon}_r$$

where r and D are the radius and the diameter at the necking at any time of the test and D_0 at the initial time

Similarly, in order to obtain the distribution of axial deformations, elastic deformations are disregarded and the condition of incompressibility is imposed:

$$lD^2 = l_o D_o^2 \quad \Rightarrow (l_o + u_z) D^2 = l_o D_o^2 \quad \Rightarrow$$

$$\dot{u}_z = -2l \frac{\dot{D}}{D} \Rightarrow \dot{\varepsilon}_z = \frac{\partial \dot{u}_z}{\partial z} \Rightarrow \varepsilon_z = -2 \cdot Ln \frac{D}{D_0} \qquad (6)$$

Effective or equivalent plastic deformations at the neck are obtained by again disregarding elastic deformations and considering that tangential deformations are nil, whereby:

$$\varepsilon^p = \int d\varepsilon^p = \int_o^t \sqrt{\left(\frac{2}{3} \varepsilon^p \cdot \varepsilon^p\right)} dt = 2 \int_o^t \frac{\dot{D}}{D} dt = -2 Ln \frac{D}{D_O} \qquad (7)$$

On the basis of the state of deformations deduced above, it is necessary to make an immediate check that the stress tensor at the neck section is:

$$\sigma = \begin{pmatrix} \sigma_r & 0 & 0 \\ 0 & \sigma_r & 0 \\ 0 & 0 & \sigma_z \end{pmatrix} \qquad (8)$$

Bridgman resolves the plastic problem by introducing the following hypotheses:

-The neck contour is approached by means of an arc of circumference
-The cross section in the necking area remains round during the test
-The deformations are constant at the neck cross-section points.

Obtaining the expression:

$$\frac{\sigma_{eq}}{\overline{\sigma}_z} = \frac{1}{\left[1+\frac{2}{\sqrt{\varepsilon_z - 0{,}1}}\right]\cdot\left[Ln\left(1+\frac{\sqrt{\varepsilon_z - 0{,}1}}{2}\right)\right]} \qquad (9)$$

On the basis of these studies and on the confirmation of their hypotheses by means of numerical simulation, we reach the following conclusions regarding the state of the necking stresses and deformations:

1.- The components of the tensor deformation and the equivalent plastic deformation are equivalent at the neck section and may be expressed as:

$$\varepsilon_r = \varepsilon_\theta = -Ln\frac{D_0}{D} \text{ (radial and circumf. deformation)}$$

$$\varepsilon_z = 2Ln\frac{D_0}{D} \qquad \text{(axial deformation)}$$

$$\varepsilon_{eq}^p = 2Ln\frac{D_0}{D} \qquad \text{(equivalent plastic deformation)}$$

where D_0 is the initial diameter of the test specimen and D the necking diameter, for a given moment, during the progress of the tensile test.

2.- From the previous point we observe how parameter $\varepsilon_{eq}^p = \varepsilon_z = 2Ln\, D_0/D$ defines the state of neck section deformation and determines the triaxial stress state that arises at the necking.

3.- At the time of fracture, the maximum deformation reached, which is the parameter we want to measure, may be therefore be found by means of the expression $\varepsilon_f^p = 2\cdot Ln\dfrac{D_0}{D_f}$, where D_0 is the initial diameter of the test specimen and D_f is the necking diameter at the time of fracture.

We will refer to this new parameter as DUCT, in reference to ductility. This expression, which we will use to quantify plastic deformation at fracture and which, as may be appreciated, does not evaluate longitudinal, but sectional deformations. In this way, we successfully eliminate the present drawbacks described in the previous point.

3.- MEASURING PROCEDURE

We describe below the simple procedure that may be used for measuring the new parameter proposed. Owing to its actual formulation we only have to measure the diameter of the test specimen before and after the test.

Although D_0 may also be determined with a gauge or a Vernier calliper, for measuring the smallest necking diameter and determining D_f the profile projector provides an accuracy and promptness that has not been proposed in other methods (e.g. JP 2004325403 and JP 144588). Besides the afore-mentioned advantages, a further benefit of the use of this equipment is that it is standard in materials testing laboratories.

This equipment, used by materials testing laboratories for measuring the corrugation geometry of reinforcements, is an optical instrument that allows us to measure distances directly on a screen where the enlarged profile of the sample is shown. The precision of this equipment is 0.005 mm , ten times greater therefore than that of the gauge (0.05 mm).

In the photographs we show the following images of this equipment during measuring. Figure 3 shows the placement of the test specimen and the optical measuring equipment. Figure 4 shows the screen of the projector on which the measuring is carried out.

Fig.3.- Arrangement of the sample on the profile projector.

Fig.4.- Profile projector screen where the formation of necking in the sample may be observed after the tensile test. The neck diameter is measured on this screen.

4.- APPLICATION OF THE NEW PARAMETER.

4.1.- Range of validity in the creep curve.

We can express the creep curve using σ_{eq} and ε_{eq}^{p} by means of Hollomon's potential function (1945) $\sigma_{eq} = K\left(\varepsilon_{eq}^{p}\right)^{n}$, which may be used to predict tensile plastic deformation performance in metallic materials, in modes of loading other than those of tensile testing.

In relation to the necking study, this equation is used recurrently in the finite element models in elastoplastic regime with considerable metal deformations: García-Garino (2006), Mansoo (2008) and Valiente (2001).

Parameters K and n have a clear physical interpretation: K is equal to the stress corresponding to a unitary deformation and it is easily shown that n corresponds to the actual deformation at maximum load $\varepsilon_{s} = Ln\left(1 + A_{gt}\right)$. Parameter n is referred to as the cold deformation embrittlement or hardening coefficient, and we may observe its significance graphically by representing the pencil of curves, fixing $K = 662$ and varying n between 0.15 and 0.25.

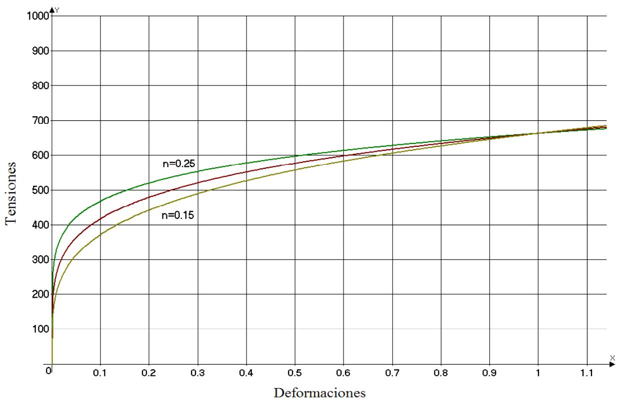


Fig. 6.-Representation of $\sigma_{eq} = 662\left(\varepsilon_{eq}^{p}\right)^{n}$, for values of n of 0.15, 0.20 and 0.25

For manufacturing processes, said factor n has an immediate application. Thus, for instance, materials with a high n are of interest for cold forming purposes. In this way, when the load applied eventually brings about localized necking at a given point, the material in that area will undergo considerable consolidation and it will be the less resistant adjoining areas that will advance the deformation.

More uniform deformation of the material will therefore be achieved, instead of there being a progression in the localized necking at the early stages of the forming process, which would give rise to the fracture of the material.

The above-stated curve coefficients may be found easily after the tensile test, since, by forcing this curve to pass through the point ($\sigma_{s}, \varepsilon_{s}$), at that moment, prior to the start of necking, we have:

$K = \dfrac{\sigma_{s}}{\varepsilon_{s}^{n}}$ where σ_{s} is the real stress at maximum load: $\sigma_{s} = f_{s}\left(1 + A_{gt}\right)$

ε_{s} the real deformation at maximum load: $\varepsilon_{s} = Ln\left(1 + A_{gt}\right)$

n the exponent of hardening: $n = \varepsilon_{s}$

And therefore the expression of the creep curve may be formulated as:

$$\sigma_{eq} = K \cdot \left(\varepsilon_{eq}^{p}\right)^{n} = \frac{\sigma_{s}}{\varepsilon_{s}^{\varepsilon_{s}}} \cdot \left(\varepsilon_{eq}^{p}\right)^{\varepsilon_{s}} \qquad (10)$$

an equation valid in the range $0 \leq \varepsilon_{eq}^{p} \leq DUCT$ and dependent only on f_{s} and A_{gt}. In this range our ductility parameter specifies and defines the maximum plastic deformation possible.

4.2.- Ductility quantification in steels.

At the start of this study characterisation of the maximum plastic deformation at fracture of a metal by means of a single parameter was set as the main aim. Obviously, this purpose is the prime and immediate application of the parameter $DUCT$ proposed.

To show this experimentally, we tested bars 16 mm in diameter and 500 mm long, belonging to two different types of steel, SAE 1015 and SAE 1045. Three specimens of each type of steel were tested and similar results were obtained for each group. The figure below shows the conventional $\sigma - \varepsilon$ diagrams for each type of steel considered.

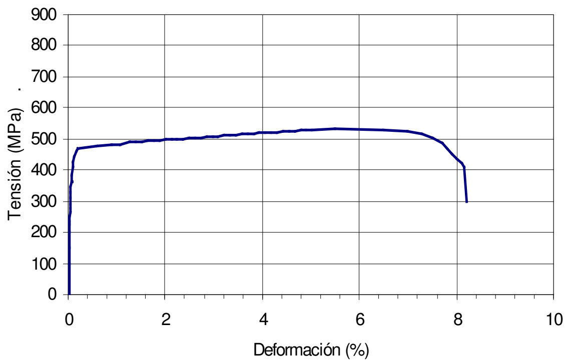


Table 2.- Sample 1. SAE 1015 steel.
Conventional $\sigma - \varepsilon$ diagram

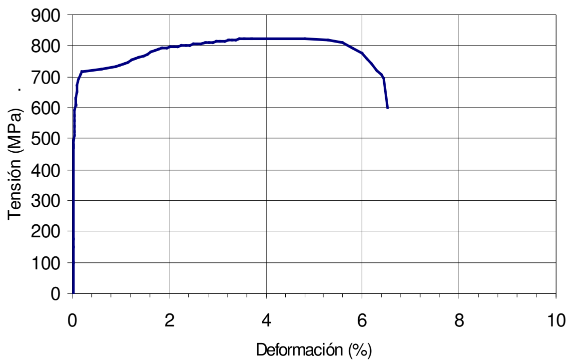


Table 3.- Sample 2. SAE 1045 steel.
Conventional $\sigma - \varepsilon$ diagram

The mechanical characteristics obtained experimentally after the tensile test for each type of steel are summarized in the table below:

Test	$f_y(MPa)$	$f_s(MPa)$	f_s/f_y	$A_{gt}(\%)$	$A_{5d}(\%)$
1	482,9	532,6	1,103	5,28	16,38
2	728,8	823,9	1,130	3,38	11,36

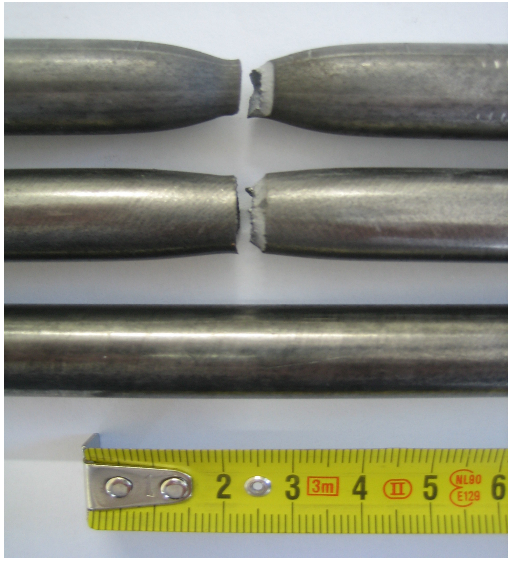
Table 4.- Mechanical characteristics of the SAE 1015 and SAE 1045 tested.

In the table of mechanical values (Table 4) we see that Sample 1 presents lower values for yield strength and maximum loading stress. Following metallurgical logic, we observe that the greater the resistance is the lower the deformation, and vice versa.

For this reason, the maximum load deformation and elongation at fracture values, on the basis of five diameters, are greater in Sample 1 than in Sample 2 . The hardening factor (f_s/f_y), however, is greater for the second sample, than for the first one.

Analysis of the geometry at fracture, using the method proposed in this article, enables us to obtain information supplementary to that set out above.

The image below (Fig. 7) shows a photograph with the original geometry of the bar and the two types steel subjected to tensile testing. We may observe at first glance that the degree of deformation in the neck achieved by Sample 1 is greater in comparison to Sample 2, which breaks without hardly any necking.



S. 1

S. 2

Orig.

Fig. 7.- Comparative image of the fracture in the two types of steels tested and the initial geometry. We may observe the greater deformation in the neck of Sample 1.

If we examine the geometry of the fracture using the profile projector method suggested, we may quantify the shortening of the bar diameter occurring in the necking area, with a precision of ± 0.005 mm .

The following images (Figures 8 and 9) show the projection of both geometries on this equipment. With these measurements and the application of the proposed parameter ($DUCT$) we can quantify the plastic deformation at fracture capacity for each type of steel.

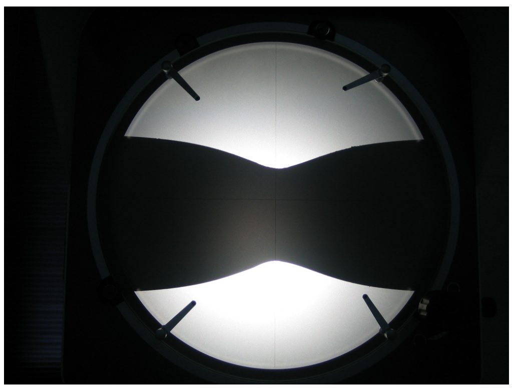


Fig. 8.- Sample 1.-Necking.
Initial diameter (D_0) =16.02 mm
Final diameter (D_f) = 8.87 mm.--- $DUCT = 1.18$

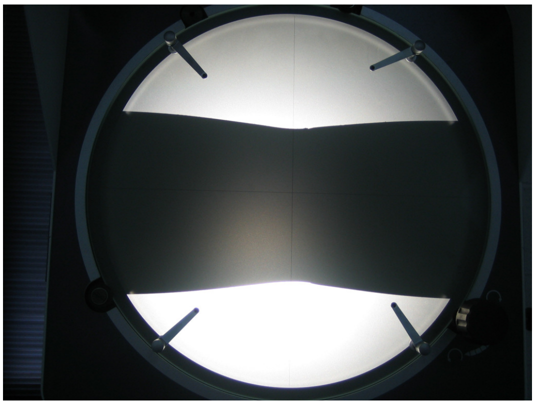


Fig. 9.- Sample 2.- Necking.

D_0 =15.97 mm

D_f = 12.79 mm --- $DUCT = 0.44$

Once the initial ad final (diameters are known, the expression $\mathrm{DUCT} = 2 \cdot \mathrm{LnD}_0 / \mathrm{D}_\mathrm{f}$ enables us to ascertain the ductility of each type of steel. In the images we may observe that Sample 1 presents what we could call "ductile fracture" as compared with the "brittle fracture" presented by the second Sample, which breaks without hardly any deformation.

In fact, for Sample 1 we obtain a ductility factor of 1,18 , while for Sample 2 we obtein the value of 0,44. Sample 1 is, therefore, 2.7 times more deformable than Sample 2.

We observe, therefore, that the factor proposed allows us to quantify the ductility of metals by means of a single parameter, which is the main aim of this research.

5.- CONCLUSIONS

This article has carried out an in-depth examination of the current procedure for measuring deformations at fracture of metallic materials. Starting from Bridgman's studies and analysing the necking stress-deformation state of a round test specimen subjected to tensile testing, we have reached the following conclusions:

1.- We set out to quantify the maximum plastic deformation at fracture of a metal by means of the factor $DUCT = 2 \cdot Ln\left(D_0 / D_f\right)$, where D_0 is the initial diameter of a round test specimen and D_f is the necking diameter after fracture.

2.- The main advantage compared with other parameters proposed, including that currently used for measuring deformations at fracture (A_{5d}), is its physical sense. This parameter represents the equivalent plastic deformation (ε_{eq}^{p}) in the neck section at the time of fracture, which, defined for consistency and parallelism with Von Mises stress, is a measure of overall plastic deformation.

3.- The parameter proposed may be obtained simply by means of the tensile test, the internationally accepted procedure for characterizing a steel mechanically. A Vernier type gauge may be used for measuring the diameters, although use of the profile projector, standard equipment in laboratory mechanical testing, is recommended on account of its greater precision ($\pm$0.005 mm) = (0.005·E-3 m.).

4.- The creep curve may be adjusted by means of a potential expression of the type $\sigma_{eq} = K \cdot \left(\varepsilon_{eq}^{p}\right)^n$, an expression valid in the range $0 \leq \varepsilon_{eq}^{p} \leq DUCT$, the range of validity of the equation being defined therefore by the new parameter. This curve may be used in numeric models with plasticity and large deformations.

5. The new parameter allows a definite value of maximum plastic deformation to be obtained and its comparison with geometrically different test specimens.

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