Determination of Plastic Fracture Deformation of Steel

Bueno, R.
Department of Mechanic and Structures. University of Seville, Spain
Avenida Reina Mercedes, 2. 41012 Seville, Spain
(email: rbueno@us.es)

Abstract

This study develops a new method for determining the plastic fracture deformation of steel, 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 an optical profile projector. This procedure eliminates the disadvantages of the current method employed to determine elongation at fracture (A5d or A10d) , steel mechanical property required in the structural concrete codes of many countries (Germany , France , Spain ,etc) and presents immediate applications in the field of Science and Engineering of Materials and Quality Control of Metals.

Keywords: true strain, 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 (Fig1).

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.

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.

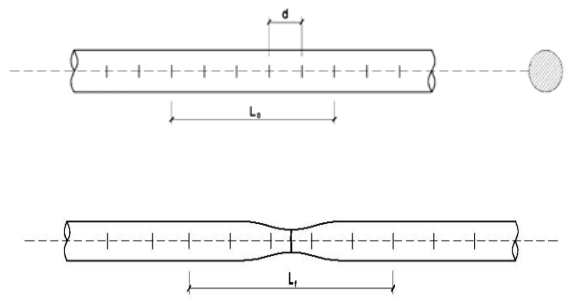

Fig 1: A5d measuring procedure

The present parameters will weigh the overall longitudinal deformations in this range, but do 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 (Morrison, 1968), to date no conclusive result has been reached. 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 (true strain) of round section bars.

2. Description

The main innovative aspect of the new procedure 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):

$$\dot{\varepsilon}_{ij} = \begin{pmatrix} \dot{\varepsilon}_r & 0 & 0 \\ 0 & \dot{\varepsilon}_\theta & 0 \\ 0 & 0 & \dot{\varepsilon}_z \end{pmatrix} \quad \text{where} \quad \begin{aligned} \dot{\varepsilon}_r &= \frac{\partial \dot{u}}{\partial r} \\ \dot{\varepsilon}_\theta &= \frac{\partial \dot{v}}{\partial \theta} \\ \dot{\varepsilon}_z &= \frac{\partial \dot{w}}{\partial z} \end{aligned} \quad (1)$$

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

$$\begin{aligned} \dot{\varepsilon}_r &= \frac{\dot{r}}{r} = \frac{\dot{D}}{D} \Rightarrow \varepsilon_r = \int \frac{\dot{D}}{D} dt = Ln \frac{D}{D_0} \\ \dot{\varepsilon}_\theta &= \dot{\varepsilon}_r \end{aligned} \quad (2)$$

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:

$$lD^2 = l_o D_o^2 \quad \Rightarrow (l_o + u_z) D^2 = l_o D_o^2 \quad \Rightarrow \quad (3)$$

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

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

$$\varepsilon^p = \int d\varepsilon^p = \int_o^t \sqrt{\left(\frac{2}{3} \varepsilon^p \cdot \varepsilon^p\right)} dt = 2 \int_o^t \frac{\dot{D}}{D} dt = -2Ln \frac{D}{D_o} \quad (4)$$

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

$$\varepsilon_f^p = 2 \cdot Ln \frac{D_o}{D_f} \quad (5)$$

where D_0 is the initial diameter of the test specimen and D_f is the necking diameter at the time of fracture.

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 procedure that may be used for measuring the plastic deformation at fracture. 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 rib 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).

To determine the final diameter (D_f) once uniaxial tension test is finished, we will proceed with the following steps:

- Placing the specimen on the profile projector, reassemble the two pieces of the sample. These pieces are placed over two accessories in a “ V ” form (Fig. 2) , so that their axes are located on a straight line. To prevent the sample from moving during the measurementes, provide clamping screws on the ends it fix the two pieces of the specimen.

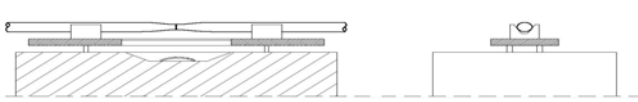

Fig.2: Arrangement of the sample on the profile projector

- Once the longitudinal axis of the sample is aligned with the X-axis of the profile projector, and after placing the absolute reference to zero, measure on the projector screen profiles (Fig. 3, 4) in the fracture zone the value of minimum diameter at the necking (y2-y1)

Fig.3: 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. Test performed in the laboratory of GP Manufacturas del Acero S.A (Seville / Spain)

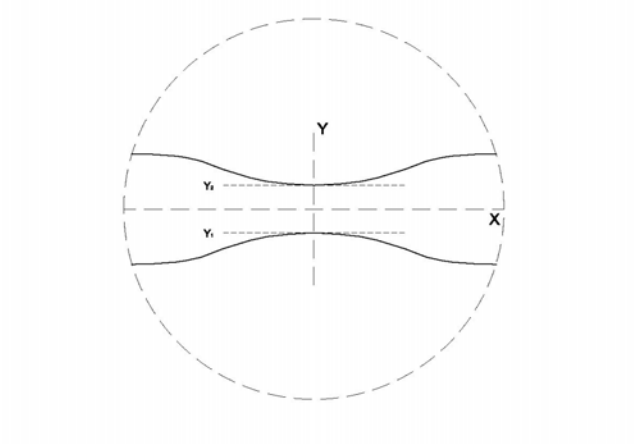

Fig.4: Determining Df as y2-y1 on the projector screen

The boundary conditions of the test (clamps) generate uncertainty about the determination of stresses and strains in the area immediately adjacent to loads (Saint-Venant). Also, the effect of compression of the clamps on the bar, in order to prevent slipping, produces significant geometric alterations during the process of tensile test (Fig. 5)

Fig.5: Altered geometry in the area of the clamps

The tests carried out shows that the uniformity on deformation is recovered at a maximun distance of 50 mm (about 2.5 times the nominal diameter) from the end of the clamps.

We establish , therefore , as a minimun distance to validate te test that the fracture should take place at a distance gretaer than 70 mm and three times the initial diameter of the sample , measured from the zone of actions of the clamps (Fig.6).

Fig 6.-Validity interval of the test

Furthermore, considering the experimental evidence that the initial samples are not perfectly cylindrical and that due to anisotropy of material, circular cross sections do not remain circular during tensile test, instead of measuring only one diameter we propose considering the arithmetic mean of two measurements, taken in perpendicular directions.

4. Example of quantification in steels

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.

All the tests were performed using Arcelor-Mittal steel in the laboratory of the industry G.P Manufacturas del Acero S.A in Seville (Spain).The figure below shows the conventional $\sigma - \varepsilon$ diagrams for each type of steel considered.

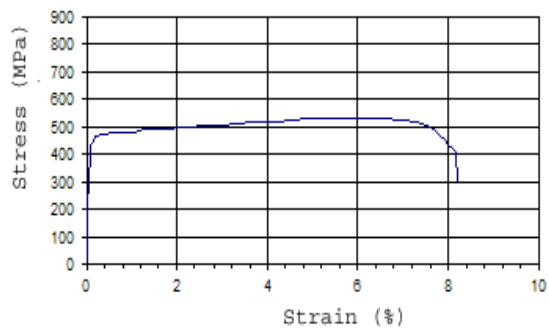

Fig.7: Test 1. SAE 1015 steel. Conventional $\sigma - \varepsilon$ diagram

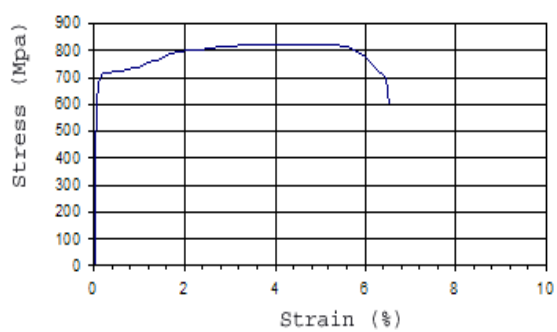

Fig.8: Test 4. SAE 1045 steel. Conventional $\sigma - \varepsilon$ diagram

The average of the mechanical characteristics () and the standard deviation (s) obtained experimentally after the tensile test for each type of steel are summarized in the table below:

Table 1.- Mechanical characteristics of the SAE 1015 and SAE 1045 tested

Tests	$\bar{f}_y (MPa)$	$\bar{f}_s (MPa)$	$\bar{f}_s / \bar{f}_y$	$\bar{A}_{gt} (\%)$	$\bar{A}_{5d} (\%)$
$\bar{x}$ 1,2,3	482,9	532,6	1,103	5,28	16,38
s	13,,00	11,66	0,06	0,34	1,63
$\bar{x}$ 4,5,6	728,8	823,9	1,130	3,38	11,36
s	14,63	12,01	0.07	0,25	1,34

In the table of mechanical values (Table 1) 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. 9) 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.

Fig. 9: 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 10 and 11) show the projection of both geometries on this equipment. With these measurements we can quantify the plastic deformation at fracture (true strain) for each type of steel.

Fig. 10: Sample 1.-Necking.

Initial diameter (D_0) =16.02 mm

Final diameter (D_f) = 8.87 mm.--- $\varepsilon_f^p = 1.18$

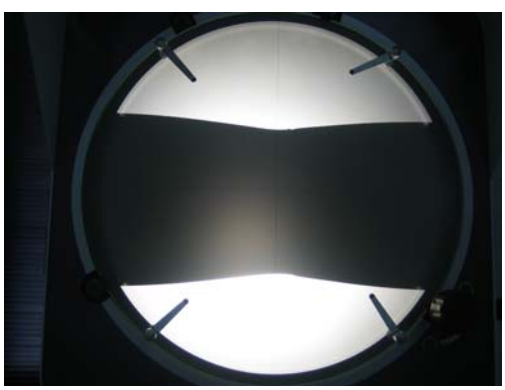

Fig. 11: Sample 2.- Necking.
D_0 =15.97 mm
D_f = 12.79 mm --- $\varepsilon_f^p = 0.44$

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 true strain 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. (this value is about 75% higher than the obtained with A_{5d} and A_{10d})

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 propose a new procedure for determining plastic deformation at fracture (true strain) .

The method consists in the evaluation of the sectional deformation in the necking after the uniaxial tensile test by means of an optical profile projector. This provides a clear understanding of the minimum diameter with an accuracy of ± 0.005 mm .(ten times greater than the currently used).

It is noteworthy an important difference (about 75%) with the results of current parameters , A_{5d} and A_{10d} , which may involve better use of steel in volumetric deformation processes, both in industry and in its applications.

References

ASTM E8 / E8M-08 American Standard “Methods for tension testing of metallic materials”.2009

BARBA , M.J . Mem. Soc. Ing. Civils France , pp 682-684. 1880

BRIDGMAN , P.W., 1944. The stress distrbution at the neck of a tensile specimen.Trans. Amer. Soc. Metals , Vol 32 , pp 553-574

BRIDGMAN , P.W., 1952. Studies in Large Plastic and Fracture, McGraw-Hill , New York.

CABEZAS E., CELENTANO D.,2004. Experimental and numerical análisis of the tensile test using sheet specimen. Finite Elements un Analysis and Design. 555-575

DAVIDENKOV y SPIRIDINOVA., 1946. Análisis of the state of stress in the neck of a tensión specimen” , Proc.Amer. Soc.for testing Mater.,Vol 46 , pp 1147-1158

EISENBERG , M y YEN , C., 1983. An isotropic generalization of the Bridgman analysis of tensile necking. Eng.Mater.Technology,Vol 105

EN-10002-1 Euronorm : “Metallic materials. Tensile tests”.2002

GOICOLEA , J., 1985. Numerical modelling in large strain plasticity with application to tube collapse analysis . Tesis Doctoral. University of London.

ISO 2566-1 International Standard “Steel. Conversion of elongation values”.2000

JONES , GILLIS., 1983. Analysis of a plane strain neck in a flat sheet. Mechanics o Materials 3. 35-40

JP 144588 Patent 2004. Tensile test Method and Device

JP 325403 Patent.2004 . Material Testing Machine

KAPLAN, M.A.,1973. The stress and deformation in mild steel during axisymmetric necking ., J. Appl.Mech.,Vol 40 , pp 271-276.

MANSOO , J., GUN , E ., CHEOL , L., 2008. A new meted for acquiring true stress-strain curves over a large range of strains using a tensile test and finite element method. Mechanics of Materials.586-893

MORRISON , W.B , 1968 . The elongation of Superplastic Alloys. Transactions of the Matalluegical Society of AIME..Vol.242 , pp 2221-2227.