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Experimental determination of Tensile Strain-Hardening Exponent and Strength Coefficient of the S355J2+N steel grade

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Abstract

The purpose of this paper is to determine tensile strain-hardening exponent and strength coefficient of the S355J2+N steel grade utilizes stress-strain data obtained in a uniaxial tension test. Tensile data were obtained in continuous and rate-controlled manner via displacement control. Ramberg-Osgood relationship was used to describe the uniaxial tension behaviour of the S355J2+N steel grade. The tensile strain-hardening exponent and strength coefficient are determined from an empirical representation over the relation between the true-stress versus true-strain.

Keywords: strain-hardening exponent, strength coefficient, yield stress-strain

1. INTRODUCTION

It is well known that both the strain-hardening exponent and the strength coefficient are basic mechanical behaviour performance parameters of metallic materials. When the tensile properties of metallic materials are being evaluated, these two parameters must be known. The value of strain-hardening exponent gives measure of the material's work hardening behaviour and is usually between 0 and 0.5. Values of strength coefficient and strain-hardening exponent for some engineering alloys are given in [1].

There are many methods for determination strength coefficient and strain-hardening exponent. Theoretical calculation of the strain-hardening exponent and the strength coefficient of metallic materials were presented in [2]. Authors were obtained some theoretical results from the deduced expressions and compared with test data. Some authors investigated strain-hardening exponent with a new method named "Double Compression Test". The test was performed experimentally and the results were compared with those obtained by the conventional method [3]. Predicting work hardening exponent of engineering metals using residual indentation profiles of nano-indentation were presented in [4].

Today steels represent the most used group of mechanical materials. Steels are used in various branches of industry for constructing bridges, buildings, ships, cars, rail vehicles, railways. There are several thousand types of steel obtained by an appropriate combination of carbon and alloying elements of different characteristics.

Because of good mechanical properties, good cutting, forming (forging, rolling, extrusion, pressing), good weldability and low prices, structural steels are widely used in industry. The most commonly used steel for producing carrying parts of structures, exposed to dynamic loads and low temperatures is medium-strength S355J2+N steel grade.

This paper presents determination of tensile strain-hardening exponent and strength coefficient of the S355J2+N steel grade utilizes stress-strain data obtained in a uniaxial tension test according to ASTM E646-00 [5].

2. THEORETICAL BASES

The uniaxial tension test is the most common method for determining the mechanical properties of materials, such as strength, ductility, toughness, elastic modulus, stress-strain behaviour and strain hardening capability. Uniaxial tension stress-strain properties are usually reported in handbooks and are used in many specifications. Stress-strain behaviour is obtained from uniaxial tension test where specimen with circular or rectangular cross section with the uniform gage length is subjected to increasing tensile force until it fractures.

When the load (force) is applied, the specimen elongates in proportion to the load, called linear elastic behaviour. If the load is removed, the specimen returns to its original length and shape.

As the load is increased, the specimen begins to undergo nonlinear elastic deformation at a stress called the proportional limit. At that point, the stress and strain are no longer proportional, as they were in the linear elastic region, but when unloaded, the specimen still returns to its original shape. Permanent (plastic) deformation occurs when the yield stress, of the material is reached.

Property of material that the increase of plastic deformation leads to an increase of yield strength is called work hardening. Knowledge of these property is very important to describe the behaviour of metals in the region of plasticity. In the plastic region, a commonly used relation to define the relation between stress and strain is given by equation:

$$\sigma = K\left(\varepsilon_p\right)^n, \tag{1}$$

where K is strength coefficient and n strain hardening coefficient.

According to equation (1) and relation that the total strain equals the sum of the elastic and plastic strain and in the region of elasticity Hooke's law is valid, equation for total strain can be derived. Equation (2) represents analytical true stress – true strain relationship, often referred to as the "Ramberg-Osgood relationship" [1], [6], [7], [8]:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n}}. \tag{2}$$

In equations (1) and (2) σ and ε represent true stress and true strain. True strain is the natural logarithm of the ratio of instantaneous length, l, to the original gage length l_0 that is:

$$\varepsilon = ln\left(\frac{l}{l_0}\right) = \ln\left(1+e\right). \tag{3}$$

True stress is the instantaneous normal stress, calculated on the basis of the instantaneous cross-section area, A, that is:

$$\sigma = \frac{F}{A} = S\left(1+e\right). \tag{4}$$

In equation (3) e represent engineering strain – dimensionless value that is the change in length Δl per unit length of original linear dimension l_0 along the loading axis of specimen:

$$e = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0}. \tag{5}$$

In equation (4) S represent engineering stress – the normal stress, expressed in units of applied force, F, per unit of original cross-section area, A_0:

$$S = \frac{F}{A_0}. \tag{6}$$

3. EXPERIMENTAL PROCEDURE

Experimental determination of tensile strain-hardening exponent and strength coefficient of the S355J2+N steel grade, was done on SHIMADZU Servopulser EV101K3-070-0A [9] (Figure 1.).

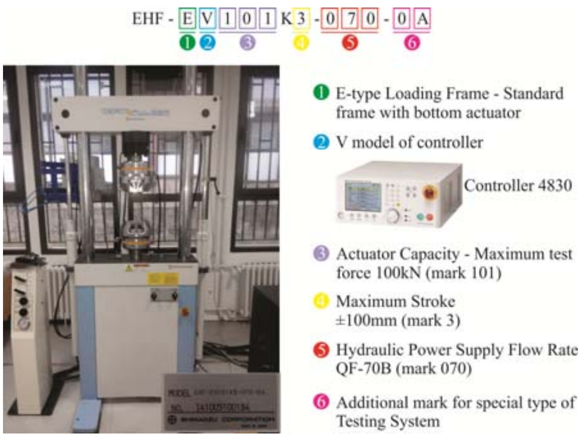

Fig. 1. SHIMADZU Srevopulser EHF-EV101K3-070-0A

Experimental determination of tensile strain-hardening exponent and strength coefficient of the S355J2+N steel grade was done at room temperature ambient (23±5ºC) under static loading conditions.

The shape and dimensions one of tested specimens are shown on Figure 2., in accordance with standard ASTM E646-00 [5].

In preparing the specimens, it is necessary to make a representative specimen, which is flat and the same thickness in all cross sections. Especially attention should be paid to prevent of appearance any possible residual stresses.

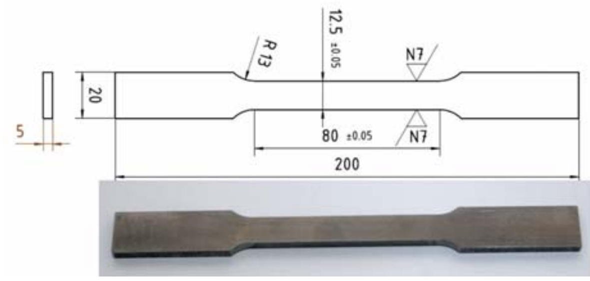

Fig. 2. Specimen for determining Tensile Strain-Hardening Exponent and Strength Coefficient

Testing of specimens for determining tensile strain-hardening exponent and strength coefficient were done at room temperature ambient in stroke control, without change speed of testing, during the strain interval over which n was determined (region of plasticity). Rate of speed load is 4mm/min.

For the purpose of measurement of elongation, on gage length (50mm), extensometer Mess & Feinwerktechnic GmbH MFA25 was used (Figure 3.).

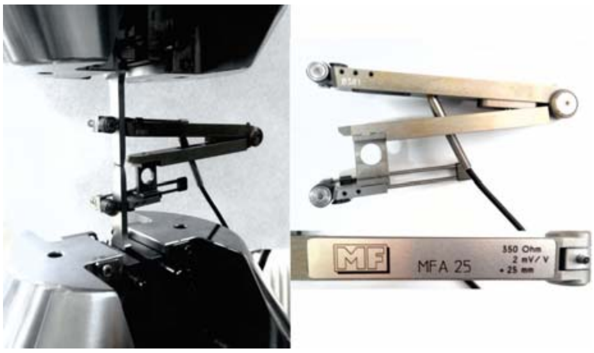

Fig. 3. Extensometer MFA25

4. RESULTS AND DISCUSSION

Load-engineering strain diagram, with data-pairs, for determination of tensile strain-hardening exponent and strength coefficient of the S355J2+N steel grade is shown on Figure 4. Measured values of force and corresponding values of engineering strain into nine equal intervals in the plastic region, obtained during the tests procedure are shown in Table 1.

All other parameters necessary for the further determination of tensile strain-hardening exponent and strength coefficient could be obtained based on the values of force and elongation. Values of engineering and true stress and engineering and true strain can be determined from the equations (6), (4), (5) and (3), respectively.

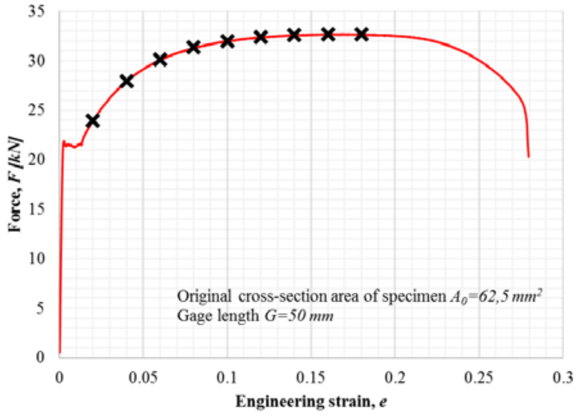

Fig. 4. Load-engineering strain diagram with data-pairs (S355J2+N)

For determination of tensile strain-hardening exponent n and strength coefficient K it necessary logarithmic form of the equation (1). Logarithmic form of the power curve representation of the true-stress versus true-strain curve within region of plasticity is given by:

$$\log\sigma = \log K + n\log\varepsilon \,. \tag{7}$$

According to selected data-pairs and calculated logarithm values of true-stress (logσ) and true strain (logε), via linear regression analysis, tensile strain-hardening exponent n can be determined by

$$n = \frac{N\sum_{i=1}^{N}\left(\log\varepsilon_i \log\sigma_i\right) - \left(\sum_{i=1}^{N}\log\varepsilon_i \sum_{i=1}^{N}\log\sigma_i\right)}{N\left(\log\varepsilon_i\right)^2 - \left(\sum_{i=1}^{N}\log\varepsilon_i\right)^2}, \tag{8}$$

where N represents number of data-pairs.

Equation (8) are made convenient by symbolic representation for: Y=logσ, X=logε and b=log$K$, as follows:

$$n = \frac{N\Sigma XY - \Sigma X \Sigma Y}{N\Sigma X^2 - \left(\Sigma X\right)^2} \,. \tag{9}$$

Strength coefficient K can be determined by:

$$K = 10^b \,, \tag{10}$$

where

$$b = \frac{\Sigma Y}{N} - n\frac{\Sigma X}{N} \,. \tag{11}$$

All test results for experimental determination of tensile strain-hardening exponent and strength coefficient of the S355J2+N steel grade are shown in Table 1. According to previously derived equations, experimentally obtained results of test and via linear regression analysis tensile strain-hardening exponent and strength coefficient were determined. Procedure of their determination were summarized in algorithm and given in Table 2.

Table 1 Determination of *the Strain Hardening Exponent and Strength Coefficient – Testing Results*

Data pair	Load [kN]	S [MPa]	σ [MPa]	Y $\log_{10}\sigma$	Y^2	Δl [mm]	e	ε	X $\log_{10}\varepsilon$	X^2	XY
1	23.972	383.52	391.22	2.592	6.721	1	0.02	0.012	-1.703	2.901	-4.416
2	27.965	447.44	465.34	2.668	7.117	2	0.04	0.039	-1.407	1.978	-3.752
3	30.121	481.94	510.85	2.708	7.335	3	0.06	0.058	-1.235	1.524	-3.344
4	31.355	501.68	541.81	2.734	7.474	4	0.08	0.077	-1.113	1.240	-3.045
5	31.995	511.92	563.11	2.751	7.566	5	0.10	0.095	-1.021	1.042	-2.808
6	32.434	518.94	581.22	2.764	7.642	6	0.12	0.113	-0.946	0.894	-2.614
7	32.628	522.05	595.13	2.775	7.699	7	0.14	0.131	-0.883	0.779	-2.449
8	32.671	522.74	606.37	2.782	7.744	8	0.16	0.148	-0.829	0.686	-2.306
9	32.694	523.10	617.26	2.791	7.787	9	0.18	0.166	-0.781	0.610	-2.180

Table 2 Algorithm and Worksheet for Calculating the Strain Hardening Exponent and Strength Coefficient of steel S355J2+N grade

Marks:

X=log ε

Y=log σ

n – strain hardening coefficient

b – log of the strength coefficient

All data were taken from Fig. 4 and evaluated in Table 1. The number of data pairs is N=9. All logarithms are base10.

A. Ordering data from Table 1.

$$\Sigma X = \Sigma(\log \varepsilon_i) = -9.9169$$

$$\overline{X} = \frac{\Sigma X}{N} = \frac{-9.9169}{9} = -1.1019$$

$$\Sigma X^2 = \Sigma(\log \varepsilon_i)^2 = 11.6560$$

$$\Sigma Y = \Sigma(\log \sigma_i) = 24.5651$$

$$\overline{Y} = \frac{\Sigma Y}{N} = \frac{18.0788}{9} = 2.7295$$

$$\Sigma Y^2 = \Sigma(\log \sigma_i)^2 = 67.0826$$

$$\Sigma(X \cdot Y) = \Sigma((\log \varepsilon_i) \cdot (\log \sigma_i)) = -26.9125$$

B. Determination of strain hardening exponent n

Step 1 $\quad \frac{\Sigma X \cdot \Sigma Y}{N} = \frac{-9.9169 \cdot 24.5651}{9} = -27.0677$

Step 2 $\quad S_{XY} = \Sigma(X \cdot Y) - \text{Step 1} = -26.9125 - (-27.0677) = 0.1552$

Step 3 $\quad \frac{(\Sigma X)^2}{N} = \frac{(-9.9168)^2}{9} = 10.9272$

Step 4 $\quad S_{XX} = \Sigma X^2 - \text{Step 3} = 11.6560 - 10.9272 = 0.7288$

Step 5 $\quad n = \frac{S_{XY}}{S_{XX}} = \frac{\text{Step 2}}{\text{Step 4}} = \frac{0.1552}{0.7288} = 0.2129$

C. Determination of strength coefficient K

Step 6 $\quad n\overline{X} = 0.2129 \cdot (-1.1019) = -0.2346$

Step 7 $\quad b = \overline{Y} - n\overline{X} = \overline{Y} - \text{Step 6} = 2.7295 - (-0.2346) = 2.9640$

Step 8 $\quad K = 10^b = 10^{2.9640} = 920.4955\,\text{MPa}$

The red line of stress-strain diagram on Figure 5 shows that the power function with determined tensile strain-hardening exponent and strength coefficient is a good approximation of the plastic portion of the curve true-stress versus true-strain obtained by experiment.

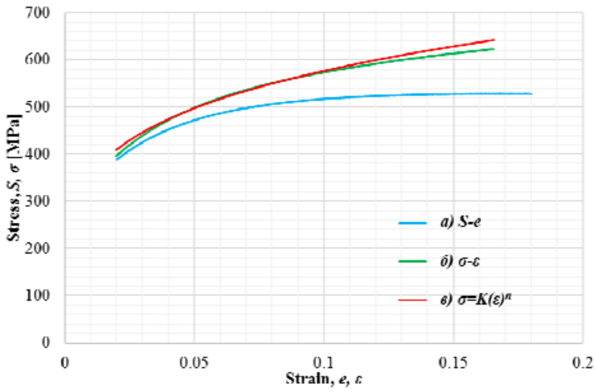

Fig. 5. Stress-strain diagram

5. CONCLUSIONS

This paper describes the determination of the tensile strain-hardening exponent and strength coefficient of the S355J2+N steel grade exhibiting a continuous stress-strain curve in the plastic region. The stress-strain data was obtained in a uniaxial tension test. The displacement was applied in a continuous and rate-controlled manner while the normal tensile load and strain are monitored. Based on obtained data and test results, true-stress and true-strain were calculated. According to ASTM E646-00 and calculated logarithm values of true-stress and true strain, via linear regression analysis, tensile strain-hardening exponent and strength coefficient were determined.

Results obtained by power function with determined tensile strain-hardening exponent and strength coefficient show good approximation of the plastic portion of the curve true-stress versus true-strain obtained by experiment. This results and their good matching give a good basis for further research and analysis.

6. ACKNOWLEDGEMENTS

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