



Determination of the maximum strain–hardening exponent

Tianhan Xu^{a,b,*}, Yaorong Feng^c, Zhihao Jin^b, Shengyin Song^c, Danghui Wang^a

^a School of Materials Science and Engineering, Xi'an Shiyou University, Xi'an 710065, PR China

^b School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

^c Tubular Goods Research Centre of CNPC, Xi'an 710065, PR China

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ABSTRACT

The method for the rapid and accurate determination of the maximum strain–hardening exponent was developed by investigating the change trend of the strain–hardening exponent of the steels with different microstructures. The quantitative relationship between the maximum strain–hardening exponent and the yield strength ratio was also determined by using the available yield and tensile strengths of the materials. The three methods of determining the maximum strain–hardening exponent were evaluated.

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1. Introduction

strain–hardening is an important strengthening process for steel, particularly in obtaining high-strength rods and wires. The strain–hardening exponent (SHE) is one of the most important indicators of the strain–hardening properties of metallic materials [1]. The strength, ductility, toughness, and deformability of materials are intimately related to their strain–hardening characteristics. For this reason, numerous investigations on strain–hardening behaviour and mechanism have been conducted [2–4]. SHE as a parameter can be used to measure the strain–hardening capacity in the uniform plastic deformation stage during the tensile process, as it not only dominates the punch-forming properties of materials but is also indicative of the ability of the material to retard the localisation of deformation. Although SHE is usually taken as a constant independent of the strain, experimental results indicate that SHE changes with increasing strain and possesses a maximum strain–hardening exponent (MSHE) during the strain–hardening process. MSHE is indicative of the highest rate of strength increase with the increase in strain during the strain–hardening process.

At present, several methods for determining the SHE of a material are available [5,6]; however, they are mainly used to determine the uniform SHE and not the MSHE of materials. Hence, developing a method for MSHE determination is necessary. The

current research aims to explore a method for MSHE determination based on the Hollomon relation under different conditions [7]. The change trends of the MSHEs of steels with different microstructures are investigated based on this relation, and the quantitative relationship between MSHE and the yield strength ratio of a material is also determined.

2. Experimental procedures

The materials used in this study were three steels with different microstructures commonly used in casing–drilling technology, namely, pearlite–ferrite (PF) steel, ferrite–bainite–martensite (FBM) steel, and tempered martensite (TM) steel. The chemical compositions of the materials (wt%) (Table 1) conform to the API Specification 5CT (8th Edition). No significant differences in the C, Mn, S, and P contents of the three types of steel are observed.

The specimens for optical microscopy (OM, MeF3A) were etched with a solution of 4% HNO₃ + ethanol. The phase microstructures were analysed using a transmission electron microscope (TEM, JEM-2000CX).

For each type of steel, the room-temperature tensile properties were ascertained from five tensile specimens with polished surfaces, a gauge length of 35 mm, and a diameter of 8.9 mm. The specimens were tested on a CMT5105 machine at an initial strain rate of $1 \times 10^{-3} \text{ s}^{-1}$. The microstructures of the tensile specimens were analysed using a TESCAN VEGAII XMH scanning electron microscope (SEM).

* Corresponding author at: School of Materials Science and Engineering, Xi'an Shiyou University, Xi'an, Shannxi 710065, PR China. Tel.: +86 29 88382539; fax: +86 29 88382598.

E-mail address: xutianhan@xsyu.edu.cn (T. Xu).

Table 1
Chemical composition of the steels with different microstructures (wt%).

Materials	Elements (wt%)											
	C	Si	Mn	P	S	Cr	Mo	Ni	V	Ti	Cu	Fe
PF steel	0.36	0.32	1.51	0.025	0.0085	0.028	0.025	0.004	0.006	0.004	0.007	Balance
FBM steel	0.38	0.23	1.38	0.015	0.0076	0.023	0.021	0.003	0.006	0.003	0.007	Balance
TM steel	0.32	0.23	1.47	0.013	0.0058	0.036	0.027	0.010	0.089	0.003	0.045	Balance

3. Methods for MSHE determination

3.1. Method of determining the start and end points of the strain-hardening process

If a notable yield point in the stress-strain curve is observed, the point corresponding to the start of a monotonic increase in the stress is defined as the start point of the strain-hardening process. However, if no visible yield point exists, the point corresponding to an elongation of 0.2% is defined as the start point, and the point corresponding to the highest stress point is designated as the end point. The strains corresponding to the start and end points are represented by ε_y and ε_{br} , respectively.

3.2. Method of determining the average SHE within the adjacent region of the research point

If a point in the true stress-strain curve can be determined, the average SHE of the adjacent region of the point can be determined using the Hollomon relation, as follows [7]:

$$S = Ke^n \quad (1)$$

where S is the true stress (MPa), K is the strength coefficient (MPa), e is the true strain, and n is the SHE.

The geometric meaning of the n value is the slope of the straight line of the true stress-strain hardening curve fitted by the least-squares method on a double logarithmic plot.

$$n = \frac{d \lg S}{d \lg e} \quad (2)$$

By assuming that the sampling frequency is high enough, and the adjacent sampling node is close enough, Eq. (3) is obtained by substituting the difference in the numerical value into Eq. (2), as follows:

$$n \approx \frac{\Delta \lg S}{\Delta \lg e} = \frac{\lg S_2 - \lg S_1}{\lg e_2 - \lg e_1} \quad (3)$$

Given the considerable uniform deformation, the engineering stress and strain can be converted to the true stress and true strain, respectively, using Eqs. (4) and (5) by assuming a uniform cross-sectional area along the gauge length.

$$S = (1 + \varepsilon)\sigma \quad (4)$$

$$e = \ln(1 + \varepsilon). \quad (5)$$

Substituting Eqs. (4) and (5) into Eq. (3) yields Eq. (6), which is expressed as

$$n = \frac{\lg((1 + \varepsilon_2)\sigma_2) - \lg((1 + \varepsilon_1)\sigma_1)}{\lg \ln(1 + \varepsilon_2) - \lg \ln(1 + \varepsilon_1)} \quad (6)$$

$$n = \frac{\lg(\sigma_2(1 + \varepsilon_2)/(\sigma_1(1 + \varepsilon_1)))}{\lg(\lg(1 + \varepsilon_2)/\lg(1 + \varepsilon_1))}, \quad (7)$$

where ε_1 and ε_2 are the strains corresponding to the first and secondary key points, respectively, and σ_1 and σ_2 are the stress corresponding to ε_1 and ε_2 , respectively (MPa).

The SHE corresponding to the regime between the two key points can be determined using Eq. (7).

3.3. Method for MSHE determination

(1) Determination of the two key points in the tensile curve

The “start point” and “end point” in the strain-hardening curve can be used to determine the two key points, namely, $(\varepsilon_1, \sigma_1)$ and $(\varepsilon_2, \sigma_2)$, as follows:

$$\varepsilon_1 = 0.33\varepsilon_{br} + 0.67\varepsilon_y \quad (8)$$

$$\varepsilon_2 = 0.67\varepsilon_{br} + 0.33\varepsilon_y, \quad (9)$$

where ε_y and ε_{br} are the strains corresponding to the start and end points in the strain-hardening curve, respectively.

(2) Dividing the entire strain-hardening curve into three sections based on the two key points $(\varepsilon_1, \sigma_1)$ and $(\varepsilon_2, \sigma_2)$

The SHEs of the three sections can be calculated using Eqs. (10)–(12), as follows:

$$n_1 = \frac{\lg(\sigma_1(100 + 33\varepsilon_{br} + 67\varepsilon_y)/(100\sigma_y(1 + \varepsilon_y)))}{\lg((\lg(100 + 33\varepsilon_{br} + 67\varepsilon_y) - 2)/\lg(1 + \varepsilon_y))} \quad (10)$$

$$n_2 = \frac{\lg(\sigma_2(100 + 67\varepsilon_{br} + 33\varepsilon_y)/(\sigma_1(100 + 33\varepsilon_{br} + 67\varepsilon_y)))}{\lg((\lg(100 + 67\varepsilon_{br} + 37\varepsilon_y) - 2)/(\lg(100 + 37\varepsilon_{br} + 67\varepsilon_y) - 2))} \quad (11)$$

$$n_3 = \frac{\lg(100\sigma_{br}(1 + \varepsilon_{br})/(\sigma_1(100 + 67\varepsilon_{br} + 37\varepsilon_y)))}{\lg((\lg(1 + \varepsilon_y))/(\lg(100 + 33\varepsilon_{br} + 67\varepsilon_y) - 2))} \quad (12)$$

where σ_y and σ_{br} are the stresses corresponding to the start and end points in the strain-hardening curve, respectively (MPa).

(3) A higher SHE is determined by comparing n_1 , n_2 , and n_3 .

(4) The higher SHE is assigned to variable N .

(5) The left and right end points of the section corresponding to the higher SHE are represented by $(\varepsilon_y, \sigma_y)$ and $(\varepsilon_{br}, \sigma_{br})$, respectively. Procedures (1)–(3) are then repeated, and the newly obtained higher SHE is compared with the N value. If the new SHE is higher than the N value and the deviation is higher than that of the reference value, procedures (4) and (5) are repeated. However, if the newly obtained SHE is higher than the N value but the deviation is lower than that of the reference value, the new SHE can be considered the MSHE; if the new SHE is lower than the N value, the N value is considered the MSHE.

3.4. Relationship between MSHE and the yield strength ratio

Based on Eq. (6), if any two points at the plastic deformation stage in the tensile curve are determined, the MSHE within the area between the two points can be obtained using the abovementioned method. However, if the two points correspond to the yield and tensile strength points, the MSHE of the material can be estimated using Eq. (13), as follows:

$$n_{\max} \approx \frac{\lg((1 + \varepsilon_b)\sigma_b) - \lg((1 + \varepsilon_s)\sigma_s)}{\lg \ln(1 + \varepsilon_b) - \lg \ln(1 + \varepsilon_s)}, \quad (13)$$

where $n_{\max}$ is the MSHE; σ_s and σ_b are the yield and tensile strengths, respectively (MPa); and ε_s and ε_b are the strains corresponding to the yield and tensile strengths, respectively.

However, the MSHE obtained using the yield and tensile strength points is notably low. This low value is attributed to the non-linearity of the strain-hardening curve of the material on the double logarithmic plot. Based on the experimental data of

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