MODELLING OF STRAIN HARDENING OF DUAL PHASE STEELS

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الملخص

تم دراسة سلوكيات الإصلاد الانفعالى للصلب ذى الطورين لعينات ذات النسب الحجمية المختلفة من طور المارتنسيت باستخدام معادلات تجريبيه. تم التحقق من قابلية تطبيق "التعبير اللوغاريتمى" (Log-method) لوصف منحنى العلاقة بين الاجهاد والانفعال الحقيقين أثناء التشكيل اللدن للصلب ذو الطورين. وقد تم تحليل بيانات اختبار الشد بواسطة معادلة "هولومون" (Hollomon) وأظهرت النتائج عدم فعالية هذه المعادلة لمرحلة التشوه اللدن للصلب ذو الطورين.

أُستخدم "جذر متوسط التربيع للنسبة المتبقية" (RMSRP) كمؤشر أداء للمنحنيات التي تم الحصول عليها بواسطة صيغ الانحدار. توافقت قيم معاملات التعبير اللوغاريتمى التي تم الحصول عليها بواسطة صيغ الانحدار بشكل جيد مع االنتائج المعملية.

عند تطبيق معادلة "التعبير اللوغاريتمى" وٌجد أن هناك زيادة ملحوظة على قيم الانفعال الحقيقي في بداية نقطة التعنّق (n_{u_L}) عند زيادة النسب الحجمية لطور المارتنسيت. في حين استخدام معادلة "هولومون"، وجد أن قيم الإنفعال الحقيقي عند بداية نقطة التعنّق (n_{u_H}) تزداد بنسبة بسيطة مع زيادة النسب الحجمية لطور المارتينسيت.

ABSTRACT

The strain hardening behaviors of dual phase steel with different volume fraction were studied using empirical models. The applicability of Log-method in describing the true stress-true plastic strain of dual phase steels was investigated. The tensile test data were analyzed by Hollomon equation and the results showed that the equation was not applicable for total plastic deformation stage.

The root-mean-square of residual percentage (RMSRP) was calculated for the curves obtained by regression formulae. The values of the Log-method parameters obtained by regression formulae were in good agreement with the experimental data.

It was found that increasing the volume fraction of martensite has a noticeable effect on the value of true strain at necking instability (n_{u_L}), when Log-method model is used. On the other hand, by using Hollomon model, the value of true strain at necking instability (n_{u_H}) was moderately increased by increasing the volume fraction of martensite.

KEYWORDS: Constitutive Equations; Tensile Strength; Strain-Hardening; Dual Phase Steels; Plastic Deformation; Necking Instability.

INTRODUCTION

The engineering tension test is excessively used to extend basic design information on the strength of materials and as an acceptable test to specify ~~of~~ materials. In order to make the required design and safety analysis of the structure, the exact mechanical properties of metals are required. To apply these mechanical properties data to the analysis, designers need accurate analytical expressions to represent their data for the test conditions of interest.

The increasing interest in mathematical modelling of mechanical and metallurgical deformation processes requires that an accurate representative expression for the stress-strain behavior of materials to be available.

Dual-phase (DP) steels are often composed of a high-strength phase, such as martensite or bainite, enclosed within a softer matrix, ferrite. Analytical equations based on various constitutive equations are routinely used to investigate the strain hardening behavior of dual phase steel. The Hollomon analysis [1], the Ludiwik equation [2], and the Swift equation [3] are the most prevalent analyses. The true stress-true plastic strain curves of dual phase steels typically cannot be characterized by a simple parabolic function across a homogeneous strain range, according to analyses employing various analytical methods, and dual phase steels deform principally in two or three independent stages [4-10].

There is a simple relationship between the maximum uniform strain and the strain hardening exponent for plastic materials that display a single stage of strain hardening, which may be easily, determined using the Considère instability criterion [11] and the Hollomon equation. However, these correlations are fallacious for polymeric materials that display multiple stages of strain hardening, such as dual phase steels. Several attempts have been made to link the strength and ductility of dual phase steels to their strain hardening behavior [4, 11-14].

The strain hardening which takes place during uniform plastic deformation can be expressed by power law relationships, often referred to as Hollomon's equation [1]:

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

Where σ is the true stress, K is the strength coefficient, ε_p is the true plastic strain and n is the work hardening exponent.

The work-hardening exponent and the work-hardening coefficient are both determined from the logarithm of the true stress versus the logarithm of the true plastic strain in the region of uniform elongation. If the Hollomon equation is satisfied by the experimental data, a linear regression line can be determined and the parameters $K\ and$ n are easily estimated. The work hardening exponent measures the ability of a metal to work hardens. Larger magnitudes indicate larger degrees of work hardening. The magnitudes of K and n depend on material type and material condition. The strain-hardening exponent value is less than unity. For metals it ~~is~~ usually varies between 0.1 and 0.5, however, perfectly elastic plastic-solids have a strain-hardening exponent of zero [15-16].

The work hardening exponent (n) is a good measure of the material's work hardenability. The pace at which the material work hardens is proportional to the value of the work hardening exponent. For procedures involving plastic deformation, a material with a high strain-hardening exponent is preferred. The materials' high strain hardening value allows them to be deformed before becoming unstable, and they may be stretched further before necking occurs, allowing a component to be created with less localized thinning [16].

In ductile material, the stable plastic flow will continue until the true stress (σ) exceeds the rate at which the material is able to work harden. The necking onset takes place when the internal force reaches a maximum value. The Considère Criterion asserts that the work-hardening coefficient $\left(\frac{d\sigma}{d\varepsilon}\right)$ drops below the flow stress (σ) value at a certain plastic strain rate ($\dot{\varepsilon}$) at the commencement of necking [11-14]. Instability strain, also known as necking strain, is defined as the intersection of the curve of work hardening rate versus the curve of true strain and the curve of true stress versus true strain. The work-hardening at strain rate $(\dot{\varepsilon})$ can be expressed as:

$$\left.\frac{d\sigma}{d\varepsilon}\right|_{\dot{\varepsilon}} = \sigma \tag{2}$$

By differentiating equation (1) and substituting in equation (2), the following relation is obtained:

$$n = \varepsilon_{u_H} \tag{3}$$

Where ε_{u_H} is the true uniform strain at necking instability (the limit of uniform strain). The physical meaning of hardening exponent is the true strain at the onset of necking.

For procedures involving plastic deformation, a material with a high work-hardening exponent value is desired. Its significance is that it is a measure of a material's stretch formability. The higher the n value, the more the material can deform before becoming unstable, and the longer it can be stretched until necking occurs [17].

The Log-method model can be considered as modified Hollomon model. This kind of modification was done in order to obtain a better description for the stress-strain curve at high as well as at low strains. The Log-method has been offered as a refinement of Hollomon's equation to express the genuine stress-true strain relationship [18]. This type of adjustment was made in order to provide a more accurate depiction of the stress-strain curve at both high and low strain. The modification leads to the formula:

$$\sigma = A\varepsilon^{(B+C\ln(\varepsilon/\varepsilon_o))} \tag{4}$$

Where σ, ε and ε_o are true stress, true plastic strain and yield strain respectively. The characteristics of this model is that the parameters A, C, $(B - C\ln(\varepsilon_o))$ are not a function of yield strain (ε_o) [18]. The right hand side term is identical to Hollomon's model where the constant $(B - C\ln(\varepsilon_o))$ is equivalent to the n values on Hollomon. The next term, $\varepsilon^{(C\ln(\varepsilon))}$, was employed to correct the deviation of Hollomon's equation from real behavior at low strain.

The parameters A, B and C are material constants; the parameter A is similar to parameter K of Hollomon's equation and has the meaning strength factor (numerically, equal to the stress extrapolated to unit strain), parameter B is the mean differential work hardening exponent from yield to unit strain (Equation 4):

$$\left.\overline{\frac{d\ln\sigma}{d\ln\varepsilon}}\right|_{\varepsilon=\varepsilon_o}^{\varepsilon=1} = \frac{(B+C\ln\varepsilon_o)+(B-C\ln\varepsilon_o)}{2} = B \tag{5}$$

It is numerically equal to the differential work-hardening exponent at $\varepsilon = \varepsilon_o^{0.5}$. Parameter C expresses the deviation from Hollomon's model

$$\lim_{C\to 0}\sigma = A\,\lim_{C\to 0}\varepsilon^{(B+C\ln(\varepsilon/\varepsilon_o))} = A\varepsilon^B \tag{6}$$

In the logarithmic form, this model is a second order polynomial while Hollomon's model is a first order polynomial. Differentiating equation (4) yields:

$$\ln\sigma = \ln A + (B + C\ln(\varepsilon/\varepsilon_o))\ln\varepsilon$$

$$\frac{d\ln\sigma}{d\ln\varepsilon} = B + C\ln(\varepsilon^2/\varepsilon_o)$$

$$\left(\frac{d\sigma}{d\varepsilon}\right) = \frac{\sigma}{\varepsilon}\left[B + C\ln(\varepsilon^2/\varepsilon_o)\right] \tag{7}$$

Equation (5) and equation (2) can be combined and the final equation takes the form:

$$\sigma = \frac{\sigma}{\varepsilon_{u_L}}\left[B + C\ln\left(\varepsilon_{u_L}^2/\varepsilon_o\right)\right]$$

$$\varepsilon_{u_L} = \left(\frac{\varepsilon_o}{2C}\right) \pm \frac{1}{2}\sqrt{\left(\frac{\varepsilon_o}{C}\right)^2 - 4\varepsilon_o\left(\frac{B}{C} - 1\right)} = n_u \tag{8}$$

Where ε_{u_L} is the true strain at necking instability (the limit of uniform strain). The result of equation (8) has two opposite values. The negative value is discarded because the value of true strain is always positive.

In this study, the experimental data for flow behavior of Dual phase (DP) steels will be fitted into two empirical equations (Hollomon and Log-method) and the effect of martensite volume fraction (V_m) on these models parameters, will be investigated. Also the true strain at necking instability is investigated and the ε_{u_H} values from Hollomon's equation will be compared with the ε_{u_L} values calculated from Log-method Equation.

EXPERIMENTAL TECHNIQUE

Sample preparation and heat treatment

In this study, carbon-manganese steel was used for all investigations. Table (1) lists the chemical composition of the steel used. The material was supplied in the form of hot rolled 24 mm round bar. The samples for tensile testing were cut from the as-received hot rolled rods. The dimensions of the test pieces were produced according to ASTM E8 specifications [19], as shown in Figure (1).

Table 1: Chemical composition of the investigated steel (wt. %)

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Fe
0.11	1.2	0.12	0.04	0.02	0.06	0.08	0.01	0.12	Balance

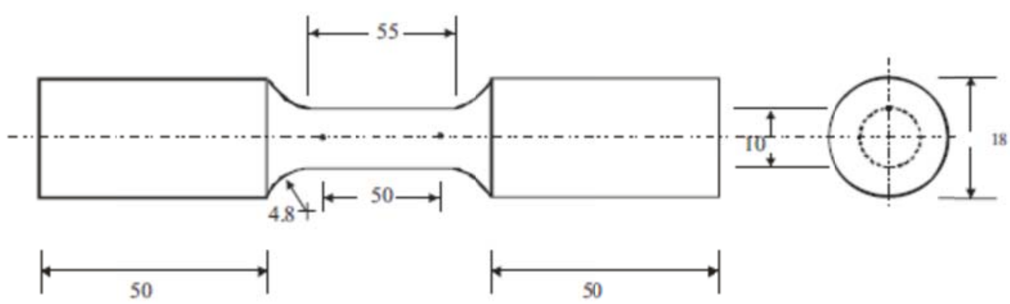

Figure 1: Dimensions of the tensile test specimens (in mm)

Using Andrews' formulae [20], the lower and higher critical temperatures (AC_1 and AC_3) were determined to be 720^oC and 840^oC, respectively, for the current study. Intermediate quench (IQ) was used on tensile specimens, which was a two-step process. To obtain martensitic structure, the specimens were initially immersed at 900^oC for 30 minutes before being quenched in a mixture of ice and brine (10 percent table salt solution in water). After that, the specimens were kept for 20 minutes at intercritical temperatures of 730, 750, 775, and 800^oC before being quenched in the same cooling liquid. The heat treatment procedure which is used in this study is shown in Figure (2).

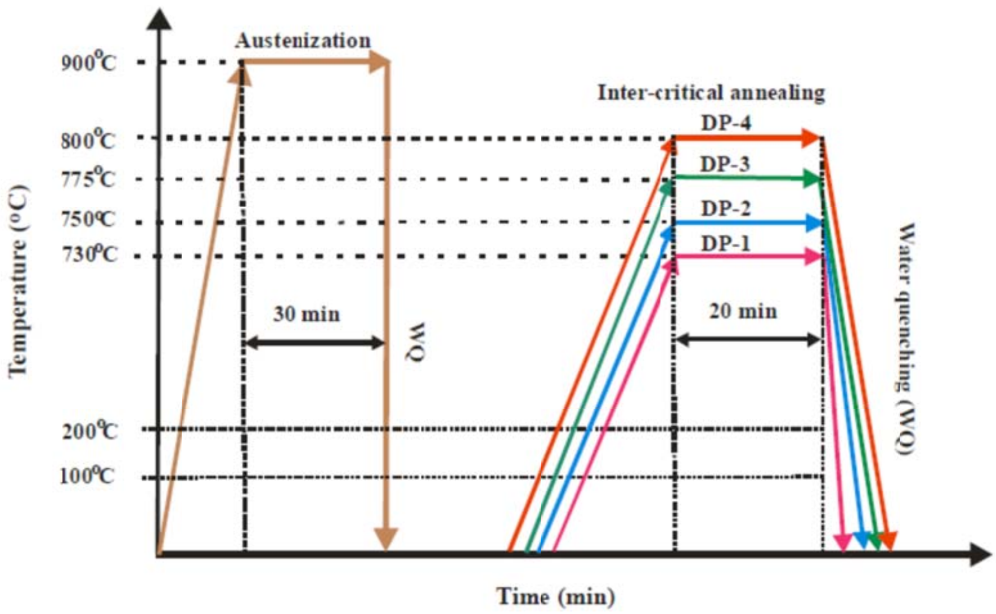

Figure 2: Schematic drawing of heat treatment cycle used in this investigation

The tensile test specimens DP_1, DP_2, DP_3 and DP_4 were heated to an intercritical temperature range (between AC_1 and AC_3) and held for 20 minutes before being quenched in water to produce ferrite-matrix with distributed hard martensite islands with volume fractions (V_m) of 0.22, 0.29, 0.39, and 0.47, respectively. The microstructures of dual phase steel with different volume fraction are detailed elsewhere [21].

After the intercritical annealing treatment, tensile tests were conducted at room temperature with a constant strain rate $(\dot{\varepsilon}) = 8.3x10^{-4}\, s^{-1}$, using a tensile tester (810 Material Test System, 100 kN load capacity). An extensometer of 50 mm gauge length was used for strain measurements. The loads versus elongation data were recorded to determine the standard tensile properties of the specimens. At least three specimens representing each intercritical annealing treatment were tested. The experimental true stress-true strain data, obtained for each case, were limited to the uniform plastic strain region. The yield strength was characterized as the 0.2% offset value for materials with continuous deformation.

The experimental data were checked for curve fitting to equation (1) and equation (4) by regression techniques [22]. The equation parameters were determined and a theoretical stress-strain curve was calculated for each case. The experimental true stress-true strain data for each specimen were used as a scatter diagram. At least 1500 pairs of values were used for each case. For each of the model equation functional values of stress were determined for the given experimental values of strain in terms of the equation parameters. The differences between the experimental stress values and the functional values of stress as determined for each model for each strain values is then established as function of the model equation parameters.

The root-mean-square of residual percentage (RMSRP) was chosen as a performance index which obtained by regression formulas [23]. The RMSRP was calculated using the following equation:

$$RMSRP = \frac{\sqrt{\sum_{\sigma_{ex}}\left(\frac{\sigma_{regr}-\sigma_{ex}}{\sigma_{ex}}x100\right)^{2}}}{N} \quad (9)$$

Where σ_{ex} is the experimentally measured true stress; σ_{regr} is the true stress calculated by regression formula; and N is the number of experimental points of each true stress-true plastic strain curve.

RESULTS AND DISCUSSION

The Hollomon expression, which describes the work hardening behavior of martensite, was compared with Log-method expression for different volume fraction of martensite phase on dual phase steel. The predicted true stress-true plastic strain values for each model were compared with experimental data.

Figure (3) shows the experimental true stress-true strain curves for dual phase steel with various martensite percentages (broken line). Theoretical curves (solid lines) derived using Hollomon's equation are placed on the same illustration. The experimental and theoretical curves representing each volume fraction of martensite intersect at two points dividing the curves to three portions. The predicted curves pass much above the observed values at relatively modest stresses. The experimental points significantly exceed the values anticipated by Hollomon's model at intermediate strain settings. Theoretical curves once again exceed experimental curves in the high-strain zone. The enormous number of movable dislocations formed in ferrite (the continuous phase) next to the martensite grains by the austenite-martensite transformation stresses during quenching result in extremely low experimental true stress values at very low strains. These stresses are compressive in the radial direction and tensile in the circumferential direction. They exceed the yield stress in the ferrite layer adjacent to the martensite particles. During tensile loading, ferrite yields first in the ferrite layer adjacent to the equator of the martensite grains, as assessed with / respect to the tensile axis, at very low stress levels. This makes the experimental curves pass much lower than the theoretical ones at the onset of plastic deformation and low strain values. Because martensite is still elastically deforming at this stage, the work-hardening rate is high, increasing as the volume fraction of martensite increases. As a result, the experimental curves intersect and surpass the best-fitting Hollomon's lines. After a certain amount of strain has been accumulated, martensite begins to give. This amount of strain diminishes when the carbon content of the martensite (hardness of the martensite) drops and the volume fraction of the martensite increases [24-26]. Both factors rise as the temperature of the intercritical treatment rises. When martensite yields, the entire composite deforms together, and the work hardening features of the experimental curves change. The work hardening rate is abruptly reduced, resulting in a jump-wise fall in Hollomon's work-hardening exponent [27]. Because Hollomon's model only has one constant exponent, it averages the high value experienced when martensite deformed elastically early in its deformation and the low value representing both ferrite and martensite plastic flow. As a result, the two curves will cross again, with the experimental curves passing beneath the calculated one. The difference between the experimental and theoretically derived curves will grow as the strain increases. This will also be the result of raising the martensite volume fraction.

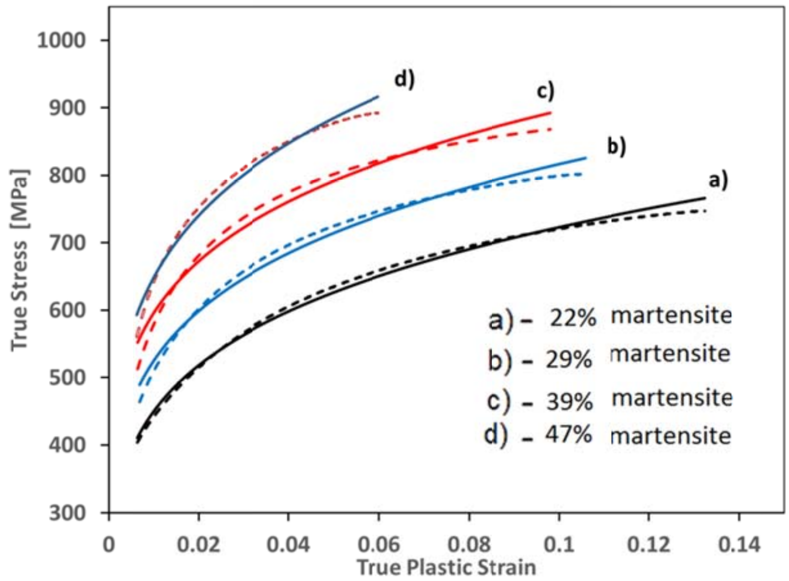

Figure 3: Correlation between the experimental true stress-true plastic strain curves for dual phase steel with different volume fraction of martensite (broken lines) and the corresponding theoretical ones calculated according to the Hollomon's model (solid lines)

Since Hollomon's model includes only one constant exponent, hence it averages the high value experienced when martensite deformed elastically in the early stage of deformation and the low value representing the plastic flow of both ferrite and martensite. Therefore, the two curves will intersect again and the experimental curves will pass below the calculated one. With increasing strain, the discrepancy between the experimental and theoretically calculated curves will increase. This is also the effect of increasing the volume fraction of martensite.

The parameter values found for volume fraction of martensite analyzed in Hollomon's model was reported in Figure (4). As expected, it is evident that Work hardening coefficient (K) increases with ~~an in~~ martensite volume fraction while the work hardening exponent (n) vary with the martensite volume fraction.

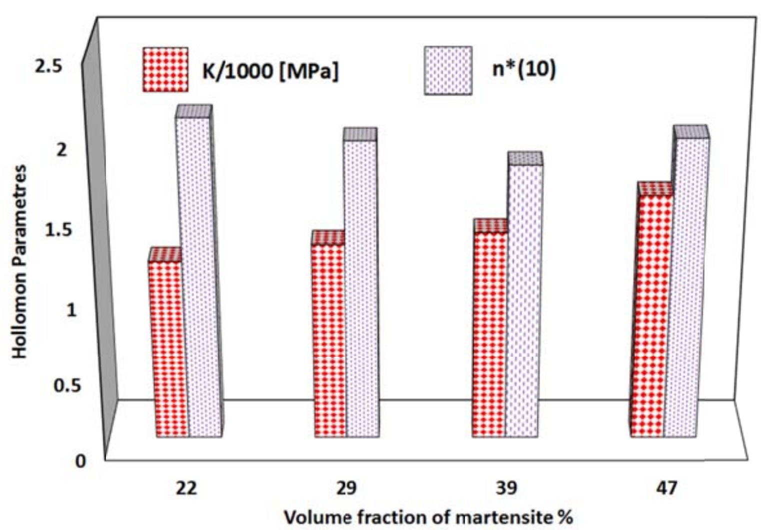

Figure 4: Effect of volume fraction of martensite on Hollomon parameters

When the stress-strain data for dual phase steel are super imposed (values) on those calculated according to the Log-method, the matching is almost perfect (Figure 5). This model was basically proposed to fit the experimental data for dual-phase steel via the introduction of the coefficient C which counts for the deviation from linearity of the $\ln \sigma \, versus \, \ln \varepsilon$ plot (Equation 1). It is assumed that derivative of this relationship $(i.e. \; d \ln \sigma / d \ln \varepsilon)$ is a linear function of $\ln \varepsilon$ with C characterizing the slope of the linear relationship. In such a way the change from the high work-hardening, characteristic for low strain levels in dual phase steel, to the low work-hardening observed at higher strains is replaced by a gradual change with C as the controlling quantity. The double intersection in the correlation between the experimental curves and Hollomon's curves, (Figure 3) is thus counted by the modified Log-method and the experimental and calculated curves almost coincide.

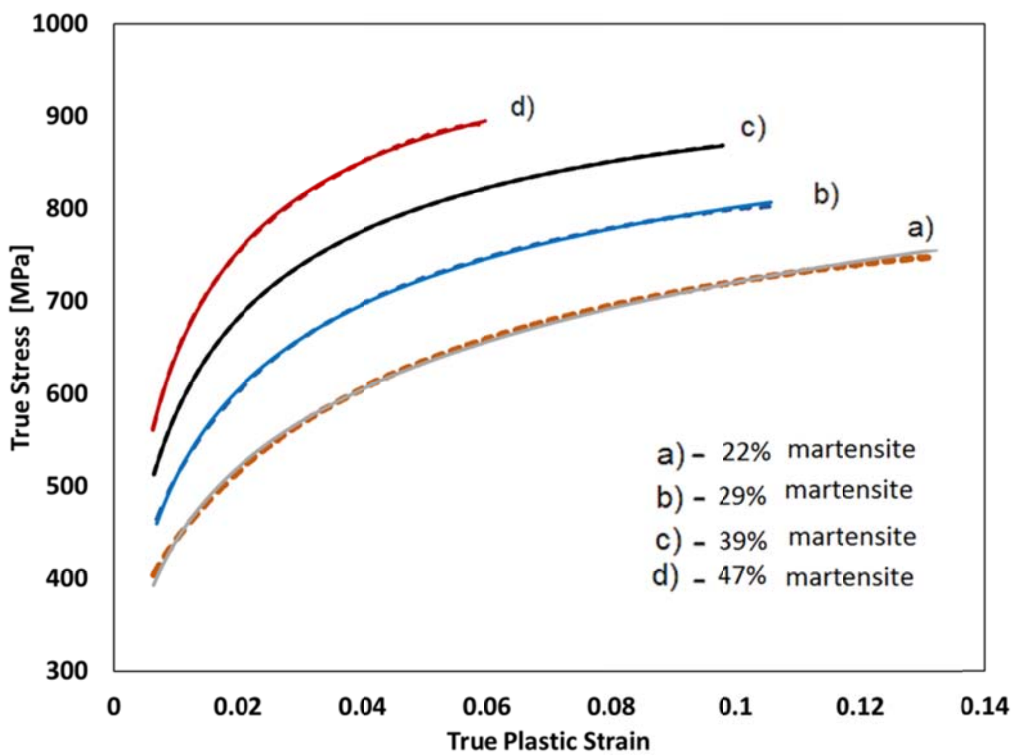

Figure 5: Correlation between the experimental true stress-true plastic strain curves for dual phase steel with different volume fraction of martensite (broken lines) and the corresponding theoretical ones calculated according to the Log-Method's model (solid lines)

Figure (6) shows the variation of the fitting parameters of the experimental data to the Log-method with increasing the volume fraction of martensite (V_m). The parameter A decreases almost linearly with increasing the martensite volume fraction. This decrease may be understood in the light of the changes in the work-hardening characteristics of dual phase steels with increasing (V_m).

As seen in Figure (6) the fitting parameter C is negative and decreases with increasing Vm. This effect may be looked for in the residual stress pattern formed in dual phase steel as a result of the intercritical treatment. Due to martensitic transformation, residual stresses are created in the ferrite thin layers surrounding the martensite particles. These stresses exceed the yield strength of ferrite and a microscopic plastic zone is formed around each martensite particle.

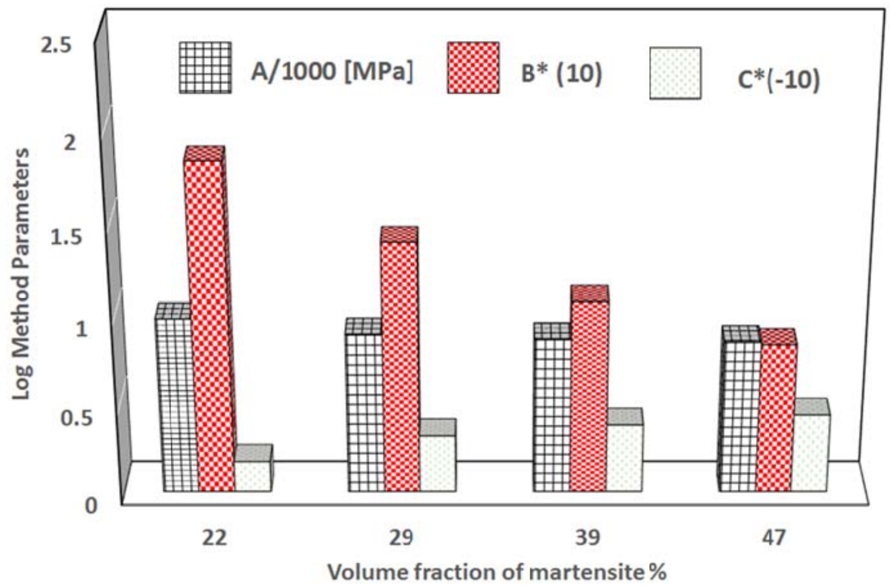

Figure 6: Effect of volume fraction of martensite on ~~v~~ parameters

The root-mean-square of residual percentage (RMSRP) was calculated for the curves obtained by regression formulas. Figure (7) shows the RMSRP for all of the tested DP steels. The values of the Log-method parameters obtained by regression formulas are in good agreement with the experimental data, RMSRP always being less than 0.15 pct. on other hand, the Hollomon parameters obtained by regression formulas are in disagreement with the experimental data, RMSRP always being less than 0.35 pct. Figure (7) shows that the Log-method model is the best at reproducing the experimental tensile curves for DP steels based on an examination of the average RMSRP produced for each model.

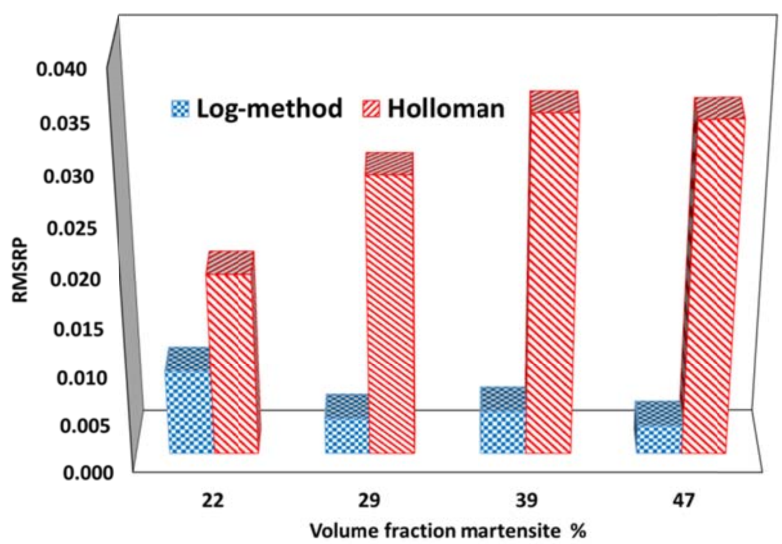

Figure 7: Fitting and predictive ability of all the tested models for dual phase steel

Figure (8) shows the variation of true uniform strain at necking instability of dual phase steels with different volume fraction of martensite. It can be seen that the value of true strain at necking instability (n_{u_L}), for Log-method model decreased with the increase of martensite quantity while it can be observed that the value of true strain at necking instability (n_{u_H}) for Hollomon model slightly decreases with increasing the volume fraction of martensite when ferrite is the continuous phase.

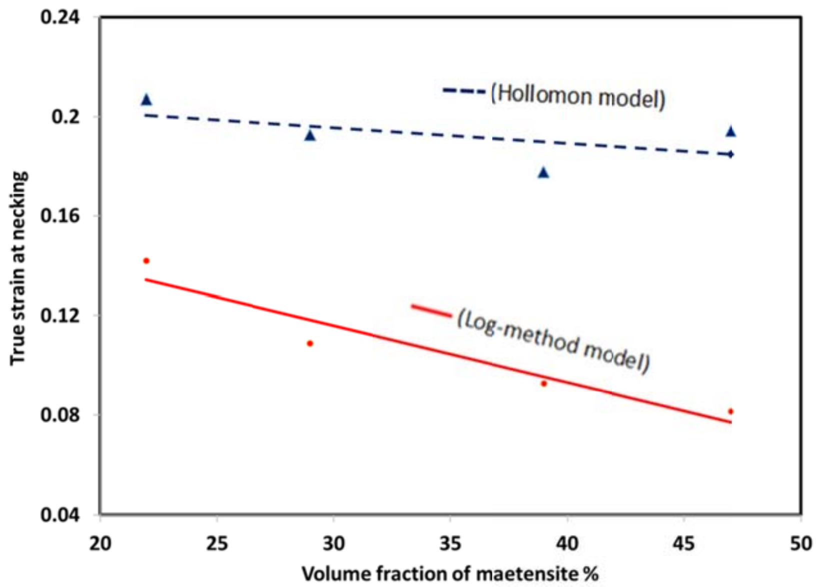

Figure 8: True strain at necking instability as a function of the volume fraction martensite.

CONCLUSIONS

On the basis of the analysis of the true stress–true strain curves using the main strain hardening models (Log-method and Hollomon) that was carried out and presented in this article, the following conclusions can be drawn.

- The Log-method shows a good correlation between experimental and theoretical results.
- The fitting curves well reproduce the experimental ones for all the analyzed models. Among them, the Log-method model shows the best fitting ability, while the Hollomon model shows the worst fitting ability.
- For Hollomon model, no evident of transition between the strain hardening behavior at low strains due to the plastic ferrite deformation and that at high strains due to plastic martensite deformation was revealed.
- A clear transition between the strain hardening behavior at low strains due to plastic ferrite deformation and that at high strains due to plastic martensite deformation was discovered using the Log-method model.
- The strain hardening exponent can be used as an important parameter to evaluate the ductility properties of dual phase steels. Decrease of both the n_{u_L} and n_{u_H} increase the ductility with a decrease in volume fraction of martensite; the n_{u_L} value has greater influence than n_{u_H} values (in case of ductility)

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