EXPRESSING THE FLOW CURVES OF DUAL PHASE HSLA AND NORMALIZED CARBON STEELS VIA THE LOG METHOD EQUATION

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الملخص

تم اختبار إمكانية استخدام معادلة التعبير اللوغارتيمي $\sigma = A\varepsilon^{(B + C\ell n(\varepsilon/\varepsilon_o))}$ المقترحة حديثاً للتعبير عن سلوك الإجهاد والانفعال لبعض المعادن والسبائك وذلك لتوصيف هذا السلوك في الصلب المرتفع المقاومة – المنخفض السبيكية المعالج إلى طوارئ (الفيريت + المارتنزيت) [الصلب ذو الطورين] وكذلك الصلب الكربوني المعالج حرارياً بالمعادلة ولتحقيق هذا الهدف عولجت عينات من الصلب المرتفع المقاومة – المنخفض السبيكة (HSLA) بثلاثة أنظمة مختلفة للمعالجة الحرارية للحصول على بنى ذات طورين تتزواح نسبة المارتنزيت بها بين 33% و 63% كذلك عولجت عينات مماثلة من الصلب الكربوني من الأنواع AISI – 1008 و 1018 و 1045 حرارياً بالمعادلة إلى بنية (الفيريت + البيرليت) .

تم اختبار هذه العينات بالشد عند درجة حرارة الغرفة بمعدل انفعال 0.05 في الدقيقة. جرى التحقق من إمكانية التعبير عن نتائج الاختبار بواسطة معادلة التعبير اللوغارتمي وذلك باستخدام طرق التحليل الانحداري اللاخطي. وأظهرت النتائج تطابقاً متميزاً للمنحيات المختبرية مع المعادلة. كما أتضح أن قيم المعاملات الثابتة (a,b,c) تتبع توجهات محددة كشفت عن معانيها الفيزيائية وأوضحت المناقشة أن مرونة هذه المعادلة وقدرتها على التعبير عن نتائج الاختبار لمواد ذات بنى ابتدائية متباينة تعود إلى قدرة المضروب الانحرافي $\varepsilon^{C\ \ell n(\varepsilon)}$ على استيعاب كافة الانحرافات في النتائج المعملية عن معادلة هولومون الشائعة الاستخدام.

ABSTRACT

The "log method" equation $\sigma = A\varepsilon^{(B + C\ell n(\varepsilon/\varepsilon_o))}$ proposed lately to express the stress-strain behavior of certain metals and alloys, was checked for applicability to dual phase high strength low alloy (HSLA) and normalized carbon steels. Specimens of a HSLA steel were subjected to different heat treatment regimes to obtain structures with different volume fractions of martensite ranging between 0.33 and 0.63. Similar specimens of AISI 1008, 1018 and 1045 were normalized to ferritic-pearlitic structures. The specimens were subjected to tensile testing at room temperature and strain rate of 0.05 $min.^{-1}$. The obtained data were checked for best fitting to the "log method" equation using non-linear fitting techniques. The fitting was perfect and the fitting parameters were observed to follow certain patterns revealing their physical

significance. The flexibility of the equation to fit data for various initial structures was analyzed on the basis of the deviator term $\varepsilon^{C\ \ell n(\varepsilon)}$, which relates the "log method" equation to the widely used Hollomon equation.

KEYWORDS: Materials, Dual phase steel, Heat treatment, Structural parameters, Log-method.

INTRODUCTION

The shape of the stress-strain curves in metals and alloys is a function of: a) their phase structure; b) the initial dislocation structure in each phase; c) the evolution of the dislocation structure due to its interaction with various structural elements and d) the possibility of stress-assisted phase transformations [1-3].

In FCC alloys with low stacking fault energy (SFE), the restrictions on cross-slip of dissociated dislocations raise the alloy yielding point, while the ease of subsequent planar glide decreases the initial work hardening rate [4,5]. On the other hand, in mixed equi-axed multiple phase structures the formation of a harder phase may induce plastic deformation in the adjacent portions of the softer phase (e. g. dual phase steel). As a consequence, a high density of dislocations is created giving rise to yielding at lower stresses and to a high initial work hardening rate with extended uniform deformation region [6-8]. Furthermore, if one of the micro-constituents is composed of two intervening phases (e. g. ferritic-pearlitic steel), the deformation mode will depend on the yielding point ratio of the phases [9]. These effects are reflected in the wide variety of behavior in the low strain portion of tensile stress-strain curves.

From the practical point of view, the analysis and modeling of metal forming operations emphasize the need for mathematical expressions that match the deformation behavior most precisely. Several empirical expressions have been proposed to describe the stress-strain curves for different metals and alloys [10-14]. Of these model Hollomon's equation [10] has attained the widest utilization. It simulates the stress-strain relation via a simple parabola of the differential form $\frac{\partial \ell n(\sigma)}{\partial \ell n(\varepsilon)} = n$, where n is a constant. However, there is a great amount of deviations from any of these equations.

One of the latest empirical expressions called the "log method" [15] replaces the constant n of the above equation by a first order binomial of the form $(B - C\ \ell n(\varepsilon_o)) + 2C\ \ell n(\varepsilon))$ to account both for the yield strain (ε_o) and for the variations in the low strain portion of the curves (B and C are empirical constants and ε_o is experimentally determinable). After integration and reorganization the solution a quires the form:

$$\sigma = A\varepsilon^{(B + C\ \ell n(\varepsilon / \varepsilon_o))} \qquad (1)$$

where A – integration constant, termed "the strength factor", numerically equals the flow stress, extrapolated to unit strain.

B – constant, numerically equals the mean differential work hardening exponent from yielding to unit strain.

C – constant, termed "the structural factor", which depends upon the mobility of dislocations and the ease of formation of cell structure.

It has been shown that Equation (1) fairly well describes the deformation behavior of pure aluminum, austenitic stainless steel and single and double phase aluminum bronze [15,16].

The aim of this paper is to introduce additional data supporting the applicability of the log method to represent the stress-strain data for dual phase steels as well as ferritic-pearlitic steels. The general applicability of that equation to account for different behaviors at the earlier stages of deformation will be justified.

MATERIALS AND PROCEDURES

The materials cited in this investigation were:

A) HSLA pipeline steel of the following composition (in wt %). 0.057 C; 1.72 Mn; 0.25 Si; 0.323 Mo; 0.013 V; 0.036 Cr; 0.014 Ni; 0.013 Cu; 0.052 Cb; 0.022 As; 0.018 P and 0.002 S. The material was intercritically heat treated to soft ferrite matrix with evenly distributed islands of martensite amounting for volume fractions of 0.33; 0.41, 0.48 and 0.63.

B) Commercial hot rolled plain carbon steel rods of AISI 1008, 1018 and 1045, normalized to ferritic-pearlitic structure with pearlite volume fraction of 0.21, 0.35 and 0.61; respectively.

Tensile tests were carried out on round specimens prepared according to ASTM E8-82 at room temperature and at strain rate of 0.05 $min.^{-1}$. (For more details see [17]). The experimental data were checked for curve fitting to the log method equation by regression analysis using the least squares method [18]. The equation parameters were determined for each case and the corresponding stress-strain curves were calculated.

RESULTS AND DISCUSSION

Figures 1 and 2 introduce superposition of the experimental tensile data and the stress-strain curves calculated according to the log method equation for both the dual phase HSLA steel and normalized carbon steel respectively. High degree of coincidence between the experimental and calculated data is evident, particularly in the low strain range, where theoretical models frequently fail to match the experimental data. This is particularly true for dual phase steel, where the formation of martensite during quenching from the intercritical temperature sets a complicated residual stress pattern. This is further complicated during the various stages of plastic deformation, giving rise to the characteristic tensile deformation behavior.

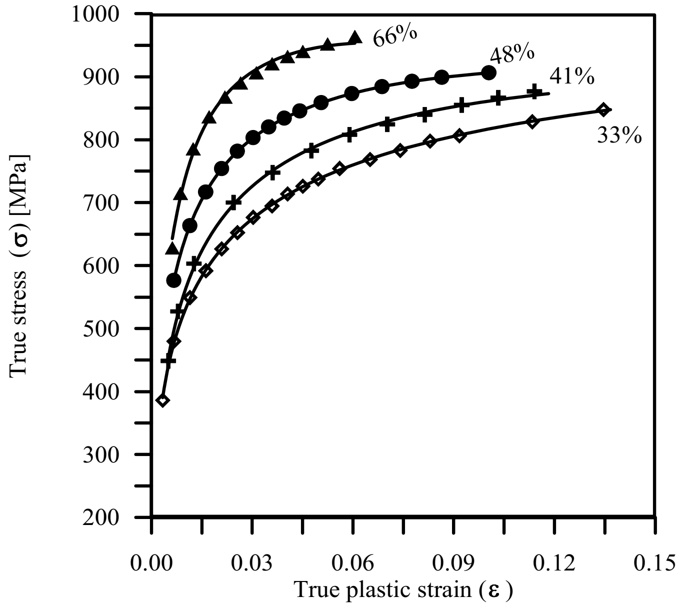

Figure 1: Superimposed experimental data (points) and stress-strain curves calculated according to log method (solid lines) for dual phase HSLA steel with different martensite volume percent.

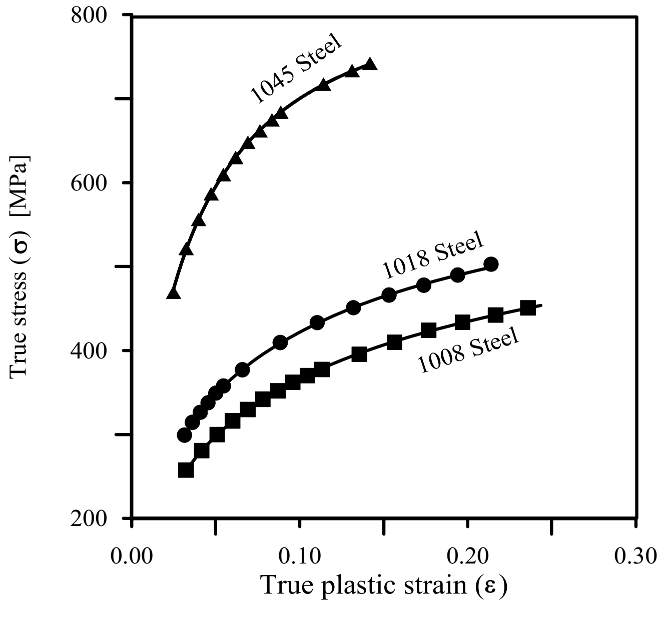

Figure 2: Superimposed experimental data (points) and stress-strain curves calculated according to the log method (solid lines) for normalized carbon steel of various grades.

As with other alloys reported previously [16,17], the fitting parameters of the log method equation for both normalized and dual phase steels were found to follow a certain pattern. Figure 3 indicates that the parameter (A) increases with the increase in volume fraction of pearlite (V_p) in normalized steel. On the contrary in dual phase steel parameter (A) is shown to decrease with increasing the volume fraction of martensite (V_m). These different patterns are probably due to the different behavior of pearlite and martensite and their effect on flow stress. For the ferritic-pearlitic normalized steels, where the ratio of the yield stresses of pearlite σ_Y^P to that of ferrite σ_Y^f (i.e. σ_Y^p / σ_Y^f) is about 1.5, the law of mixture is valid both for the yield and the flow stresses [8]. Under such conditions a monotonous increase in the flow stress at any given value of strain is expected to grow with increasing V_p. Since the parameter A expresses the extrapolated flow stress at $\varepsilon = 1$, the increase of A with V_p is justified.

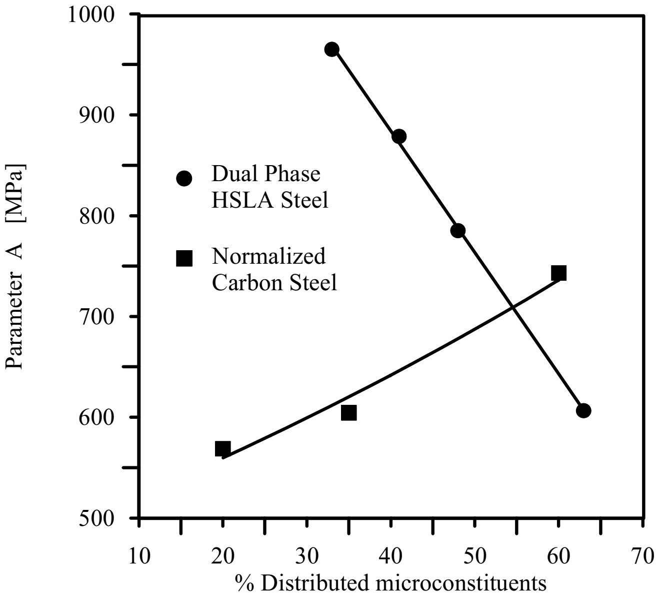

Figure 3: Variations of the fitting parameter A with the volume percent of the distributed microconstituents (i.e. martensite in dual phase steel and pearlite in carbon steel).

On the other hand, the decrease in A with increasing V_m in dual phase steel may be attributed to the change in the work hardening characteristics. At low strain, where only ferrite is plastically deforming, the work hardening rates are high and increase with increasing V_m. This effect lasts for very short strain range, which decreases with both increasing V_m and decreasing the hardness of martensite [8]. As a consequence the larger the volume fraction of martensite V_m, the higher the initial portion of the stress-strain curve is situated and the earlier it ends. When the martensite starts to deform plastically while ferrite is highly work hardened, the curves abruptly change their work hardening characteristics towards lower rates. The higher the volume fraction of martensite the stronger is that effect [8]. The extrapolated curves are likely to intersect at strain values well below $\varepsilon = 1$ and those with higher V_m approach $\varepsilon = 1$ at lower flow stress values and the parameter A decreases with increasing V_m.

Figure 4 introduces the change in the values of the fitting parameter C with increasing the volume fraction of the distributed micro-constituents in both normalized carbon steel and dual phase HSLA steel. In all cases the values of C are negative and decrease with increasing both V_p and V_m. However, for dual phase steel the rate of decrease is higher. The negative values of C are probably due to the increased mobility of dislocation in ferrite as a result of the transformation of adjacent austenite regions into either martensite (during the intercritical treatment of HSLA steel) or pearlite (during normalizing). Even the small stresses created by normalizing are sufficient to activate mobile dislocations in such a high SFE phase as ferrite. However, the rate of stress build-up in dual phase steel is higher due to the larger specific volume of martensite as compared with pearlite.

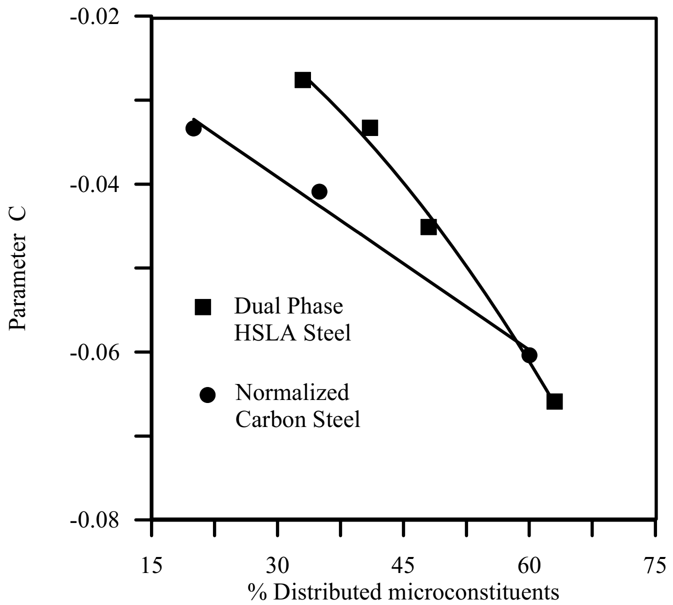

Figure 4: Variations of parameter C as a function of the volume percent of the distributed microconstituents.

The complexity of the tensile behavior of dual phase steel in the initial plastic strain range cannot be accounted for by simple parabolic or exponential relationships, which are commonly used in empirical models. The log method formula modifies the simple power law by multiplying it by a deviator term, which takes a minimum (or maximum) value just on yielding and rapidly increases (or decreases) approaching unity at intermediate strain, where the simple parabola fairly well expresses the steady state deformation of grains with well developed cell structure [16]. This can be better seen when the modified equation is rewritten in the form:

$$\sigma = A\varepsilon^{(B - C\ \ell n(\varepsilon_o))}\varepsilon^{C\ \ell n(\varepsilon)} \qquad (2)$$

The term $A\varepsilon^{(B - C\ell n\varepsilon_o)}$ is a simple parabola while the deviator term $\varepsilon^{C\ell n\varepsilon}$ accounts for the negative deviations from the simple parabola at low strains, caused by the increased mobility of dislocations through the negative values of the parameter C.

If on the contrary the structure contains features, which retard the dislocation movement (e.g. age hardening alloys as duralumin; highly concentrated solid solutions of low SFE as austenitic stainless steels; etc..), positive deviations from the simple parabolic law are expected. Such deviations are accounted for by positive values of the parameter C. The values of the deviator fall rapidly approaching 1 at intermediate strains. Figure 5 shows how the deviator term changes with strain for two hypothetical values of the parameter C with both positive and negative signs.

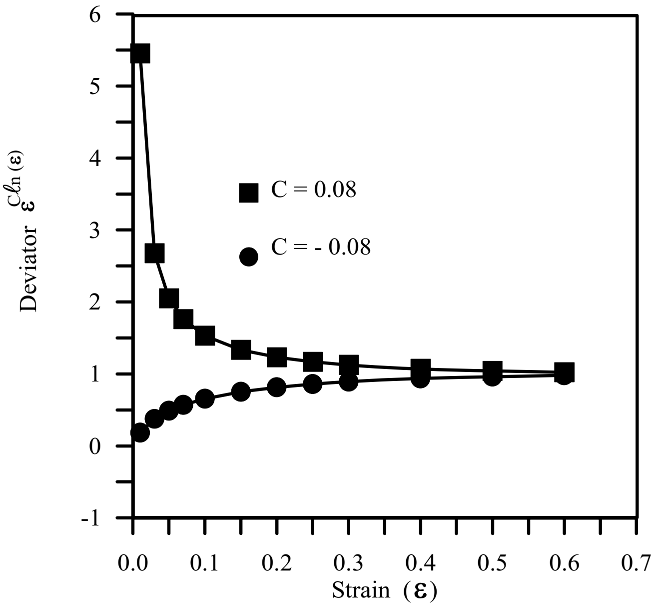

Figure 5: Changes in the value of the deviator term $\varepsilon^{C\ \ell n(\varepsilon)}$ as a function of strain for two hypothetical values of the parameter C (-0.08 and 0.08).

Moreover, in cases where contradicting factor affect the dislocation structure and mobility in the initial low strain deformation range, the net effect of these inhomogeneities is accounted for by the value and sign of the parameter C. This is the case for example with dual phase Al-bronze, where martensite transformation results in compressive stresses in the adjacent Cu-base solid solution phase. These stresses add to Poisson's compression and accelerate cross slip of dislocations inherent in this low SFE phase [15]. The log-method parameter C for these alloys was found positive but decreasing with increasing the volume fraction of martensite (Figure 6). Furthermore, in annealed double phase Al-bronze the parameter C changed its sign from positive to negative with increasing the eutectoid volume fraction. This effect was attributed to stress concentration in the plastic zones surrounding the crack tips created in the extremely brittle (phase lamellae of the eutectoid) [15]. The constraints imposed by these stresses on the dissociation of dislocations enable them to contract and cross slip easily. As a result, dislocations acquire high mobility and the C parameter changes its sign from positive to negative.

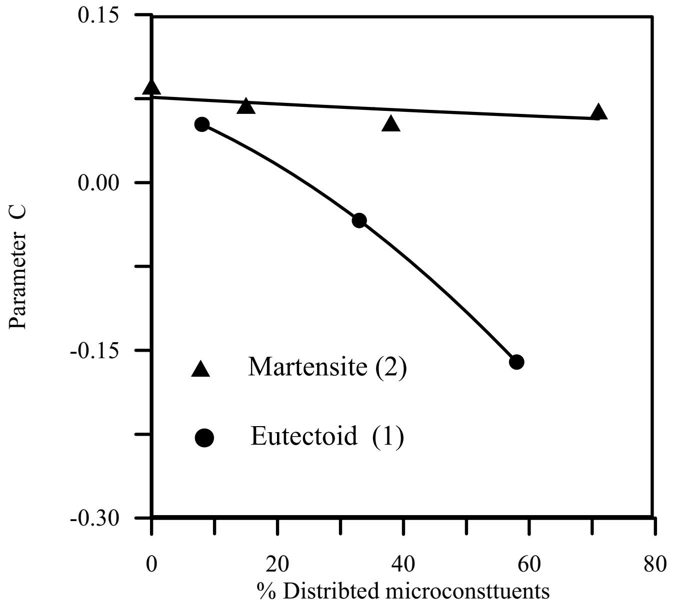

Figure 6: The effect of the volume percent of the distributed microconstituents on the value of the C parameter for Al-bronze treated to:- (1) α+eutectoid; (2) α+martensite [15].

CONCLUDING REMARKS

It is evident that the power logarithmic form of the deviator term and the variation in the sign and value of the structure-sensitive parameter (C) in Equation (1) allow to accommodate any significant variation in the yield stress and the initial work hardening rate. The deviator approaches unity at intermediate strains giving rise to a simple parabolic law. Such results allow the log-method equation to be used in the case of smooth change from conditions of structural inhomogeinity at the early stage of deformation to the well developed cell structure without the need to use different parameters for different stages.

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