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Reprinted from

Constitutive Relations and Their Physical Basis

Proceedings of the 8th Risø International Symposium on Metallurgy and Materials Science

7–11 September 1987

Editors

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MODELS OF TENSILE BEHAVIOUR OF META-STABLE Fe-Mn-Mo ALLOYS

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ABSTRACT

A semi-mechanistic model for predicting the flow behaviour of Fe-Mn-Mo steels displaying transformation-induced plasticity is developed in this paper. The model, based on the law of mixtures, takes into account the work-hardening of the individual principal phases (namely, lath-martensite and austenite/epsilon martensite). The composite strength of such a steel may be given by a modified law of mixtures which incorporates a dislocation density effect. To test the validity of the model, experiments have been performed using a magnetic reluctance technique to determine the extent of $\gamma + \varepsilon \rightarrow \alpha'$ transformation induced by tensile plastic deformation at room temperature. As the $\gamma + \varepsilon \rightarrow \alpha'$ transformation progressed the work-hardening of the steels was found to increase rapidly. It is concluded that the induced lath-martensite in a work-hardened austenite/epsilon matrix is most effective in enhancing strength and ductility.

1. INTRODUCTION

Some studies of deformation of equivolumic phase mixtures have been made (e.g. Shelton and Ralph, 1983; Durand and Coulomb, 1983, and Durand, 1987) although most of these investigations have involved deformation of non-ferrous alloys, and have used uniaxial tensile testing procedures. However, little seems to be known about the deformation of an equivolumic phase mixture of ferrous alloys at room temperature. The Fe-Mn-Mo steels display transformation-induced plasticity, a phenomenon similar to the one encountered in TRIP steels. This is expected to have a significant effect on the work-hardening behaviour of these steels. The aim of the present work is to develop a theoretical model for the composite flow behaviour of these steels containing initially approximately 50 volume % hard lath-martensite and 50 volume % soft austenite/epsilon martensite. The model will incorporate:-

(i) the effect of work-hardening of the individual microconstituents;

(ii) the effect of strain-induced transformation of austenite/epsilon phase to lath martensite;

(iii) the effect of lath-martensite-induced dislocation multiplication.

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2. THEORETICAL MODEL

ing tensile deformation of a two-phase alloy, many authors ıme a "law of mixtures". The law of mixtures is an ·ession that predicts a linear variation of stress or ain as a function of volume fraction of second phase and graphically represented in figure 1. Two simple models, ıl strain and equal stress, have often been employed to .mate the flow curve of a two-phase alloy from those of stituent phases, for example Dieter (1986).

The development of a theoretical model for plastic ·rmation of meta-stable Fe-Mn-Mo alloys. When meta-stable In-Mo is deformed at room temperature it transforms ensitically from austenite/epsilon to lath-martensite. dified form of the Ludwik-Holloman equation is assumed to ribe this behaviour:-

$$\sigma = k\,[\ln(1+\varepsilon)]^{n}\,[V_{\gamma+\varepsilon}] \qquad (1)$$

e σ is the contribution of strain-hardening of enite/epsilon, to the flow stress at any level of strain $V_{\gamma+\varepsilon}$ is the volume fraction of austenite/epsilon present the steel at this level of strain, k, the enite/epsilon strength factor, is a measure of the city of the austenite/epsilon to be strengthened by in and "n" in this case, will be the austenite/epsilon, in-hardening index or exponent.

The true-stress contribution of austenite/epsilon to in alone. To understand this, it is necessary to know relationship of the volume fraction of austenite/epsilon strain. The volume fraction of lath-martensite formed ıg deformation should be a continuous function of strain r than a function of stress (see e.g. Olson and Cohen, . 1982). However, the formation of the lath-martensite , in itself will produce dilational and uniform strains ıe surrounding structure. These strains will account for observed "automotive" nature of lath-martensite tion, that is, the ability of lath-martensite to erate the formation of additional lath-martensite (e.g. , 1954; Magee, 1970). To account for this "automotive" martensite, it seems reasonable to suggest a ionship

$$V_{\alpha'} = f(\varepsilon^{S})' \qquad (2)$$

$V_{\alpha'}$ is the volume fraction of lath-martensite, S is an ent to account for "automotive" lath-martensite. But as strain-induced transformation of austenite/epsilon to martensite proceeds, the volume fraction of nite/epsilon phase for further transformation is ally exhausted. This leads to modified equations of the wing form:-

$$V_{\gamma+\varepsilon} = 1 - \left(1 + \frac{\varepsilon^{-S}}{A}\right)^{-1} \qquad (3)$$

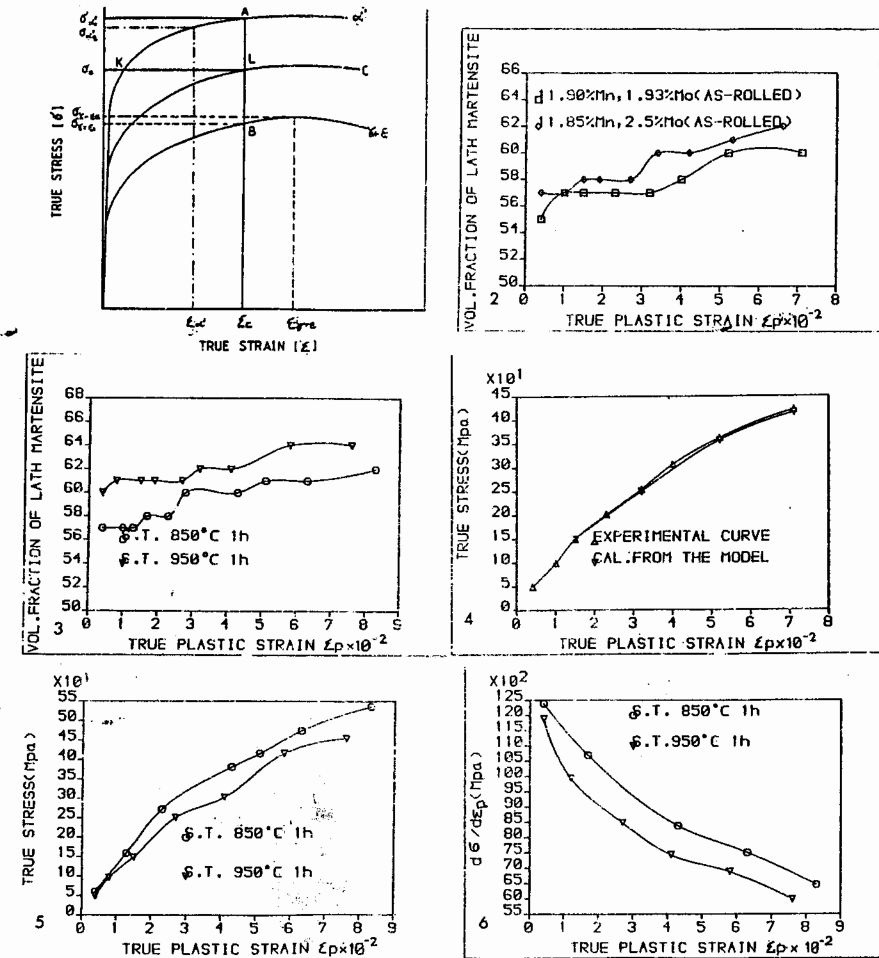

Figure 1. Schematic stress-strain curves of a soft phase matrix austenite/epsilon ($\gamma+\varepsilon$), hard phase lath martensite (α') and the composite (C). The lines KL and AB correspond to two different conditions (iso-stress and the iso-strain) of law of mixtures.
The iso-strain condition line AB means $\varepsilon_{\alpha'} = \varepsilon_{\gamma+\varepsilon} = \varepsilon_C$ and the iso-stress condition line KL will be $\sigma_{\alpha'} = \sigma_{\gamma+\varepsilon} = \sigma_C$

Figures 2-3. Volume fraction of lath martensite versus true plastic strain.

Figure 4. Curve fitting of the theoretical model for (11.90%Mn, 1.93%Mo), as-rolled.

Figures 5-6. Tensile true-stress and work-hardening rate versus true plastic strain for (11.85%Mn, 2.5%Mo) as solution treated.

$$\sigma_{\gamma+\varepsilon} = k\,[\ln(1+\varepsilon)]^n\,[1-(1+\frac{\varepsilon}{A}^{-S})^{-1}] \qquad (4)$$

In equation (4) $\sigma_{\gamma+\varepsilon}$ represents the ease with which an austenite/epsilon structure can undergo a strain-induced transformation to lath-martensite.

2.3. The effect of lath-martensite strengthening. The true-stress contribution of lath-martensite should be proportional to the volume fraction of lath-martensite $V_{\alpha'}$. Using the same procedure as above for lath martensite strengthening leads to the following equation:-

$$\sigma_{\alpha'} = T(1 + \frac{\varepsilon}{A}^{-S})^{-P} \qquad (5)$$

In this equation (5), the proportionality constant T represents the flow stress of the steel extrapolated to a fully lath-martensite structure, T is the lath-martensite strengthening factor. The exponent P is a measure of how effectively increasing amounts of lath-martensite in the structure are translated into an increased stress contribution from this lath-martensite.

2.4. The effect of the lath-martensite-induced dislocation density. Equation 4 shows the ease with which an austenite/epsilon structure can undergo a strain-induced transformation to lath-martensite. This must be followed up with extra dislocations generated continuously as a result of this strain-induced transformation which will contribute further to lath-martensite strengthening throughout the plastic deformation. If $\Delta\varepsilon$ is the microstrain or effective strain in austenite/epsilon due to lath-martensite transformation, formed over the strain interval ε to $\varepsilon + \Delta\varepsilon$, equation (4), can be re-written:-

$$\sigma_{\gamma+\varepsilon} = k[\ln(1 + (\varepsilon + \Delta\varepsilon)]^n\,[1 - (1 + \frac{\varepsilon}{A}^{-S})^{-1}]$$
$$\text{and} \quad \Delta\varepsilon = bLU \qquad (6)$$

where b is the Burgers vector, L is the length of free dislocations per unit volume which contribute to the strain, U is the mean distance crossed by each dislocation. As new nuclei may be formed by straining the material, the number of dislocations increases from about $10^8\ m^{-2}$ in a well-annealed structure to about $10^{12}\ m^{-2}$ in a heavily cold-worked material. If we assume that dislocations which are induced by the lath-martensite transformation are identical to this hypothetical heavily cold-worked dislocations, it then becomes possible to use the parabolic relationship to correlate mobile dislocation density with strain.

$$\rho = \rho_o + C\varepsilon_\rho^a \qquad \text{Hahn (1962)} \qquad (7)$$

where ρ = total dislocation density, $\rho_o(\text{at}\,\varepsilon_\rho = 0) \approx 10^{12}\ m^{-2}$; ε_ρ = plastic strain, and C and a are measured parameters.

Now, if the lath-martensite-induced dislocation density ρ_D is summed with the existing dislocation density ρ_o, then according to the assumption that the plastic strain ε_ρ in

(7) may be replaced by $\Delta\varepsilon$ leads to

$$(\rho_o + \rho_D) = \rho_o + C\Delta\varepsilon^a;\quad \rho_D = C\Delta\varepsilon^a;\quad \Delta\varepsilon = (\frac{\rho_D}{C})^{\frac{1}{a}} \qquad (8)$$

Equation (8) shows a physical explanation of $\Delta\varepsilon$ in terms of lath-martensite-induced dislocation density which can be measured. Substituting equation (8) into equation (7) gives

$$\sigma_{\gamma+\varepsilon} = k[\ln(1 + (\varepsilon + \frac{\rho_D}{C})^{\frac{1}{a}}]^n\,[1 - (1 + \frac{\varepsilon}{A}^{-S})^{-1}] \qquad (9)$$

2.5. The expression for the composite flow stress of meta-stable Fe-Mn-Mo alloys. If the expression for $\sigma_{\gamma+\varepsilon}$ and $\sigma_{\alpha'}$ in equations (9) and (5) respectively are taken into an additivity expression we arrive at:-

$$\sigma_C = k[\ln(1 + C\varepsilon + \frac{\rho_D}{C})^{\frac{1}{a}}]^n\,[1-(1 + \frac{\varepsilon}{A}^{-S})^{-1}] + T(1 + \frac{\varepsilon}{A}^{-S})^{-P} \qquad (10)$$

This is the flow-curve equation relating true-stress to strain of meta-stable Fe-Mn-Mo alloys.

3. EXPERIMENTAL METHOD AND TECHNIQUES

All tensile tests were carried out at a constant cross-head speed of (0.5mm/min.) corresponding to an initial strain rate of $8.33 \times 10^{-3}\ s^{-1}$. The phase content of the steels was determined using a commercial "Ferritescope" which quantifies ferromagnetic phase contents by monitoring magnetic reluctance.

4. RESULTS

The volume fraction of lath-martensite before deformation was approximately 50 volume percent. During deformation the amount of α' increased as shown in figures 2 and 3. The volume fraction of α' is a sigmoidal function of strain (c.f. Angel, 1954; Olson and Cohen, 1972, and Hecker et al., 1982). The values of the dislocation density were taken from Roberts (1970), and Vetter et al., (1977), who had worked on iron-manganese alloys. Tables 1 and 2 show the model and dislocation density values respectively. From the analysis of these data, the automotive lath-martensite index "S" values were closely grouped about "4.0". This finding suggested that the automotive aspect of the strain-induced transformation is insensitive to composition and conditions of treatment. It is also indicative that the equal strain law might be obeyed at these volume fractions (50%). Some of the experimental data set is given in table 3. Figure 4 shows the experimental curves and the curve calculated from the model. It may be seen from the curves that the experimental and model curves are very close, which suggests that the composite flow stress (σ_C) obeys the modified law of mixtures with equivolume phase proportions (see e.g. Durand, 1987).

4.1. Mechanical response. Examples of the true stress/true plastic strain curves and tensile work-hardening rate/true

TABLE I MODEL PARAMETERS

Alloys C%	Mn%	Mo%	K [MPa]	A [MPa]	T [MPa]	S	P	n
0.1	11.90	1.93*	2832	1244	1056	4	0.729	0.683
0.1	11.85	2.5 *	2829	1270	950	4	0.629	0.643
0.1	11.85	2.5 **	2673	1339	850	4	1.026	0.610
0.1	11.85	2.5 ***	2585	1485	895	4	1.058	0.580

* as rolled ** sol.treated 850 °C for 1 hour
*** sol.treated 950 °C for 1 hour

TABLE 2 DISLOCATION DENSITY PARAMETERS

		References
C	$2 \times 10^{9}\ m^{-2}$	Hahn (1962)
a	0.7	Hahn (1962)
ρ	$5 \times 10^{12} - 29 \times 10^{12}\ m^{-2}$	Roberts (1970) and Vetter et al., (1977)

TABLE 3 MECHANICAL PROPERTIES

Alloys C%	Mn%	Mo%	Elast Limit [MPa]	0.2% Proof Stress [MPa]	T.S. [MPa]	Elong. % [MPa]	Reduct. in area %
0.1	11.90	1.93*	422	1078	1480	24	50
0.1	11.85	2.5 *	414	837	1276	20	25
0.1	11.85	2.5**	424	788	1283	20	40
0.1	11.85	2.5***	441	882	1304	19	45
0.1	12.85	2.5**	245	784	1230	12	15
0.1	12.85	2.5***	245	833	1172	10	13

* as rolled ** sol. treated 850 °C for 1 hour
*** sol. treated 950 °C for 1 hour

plastic strain curves obtained from the tension tests are given in figures 5 and 6. The overall flow stress levels and trends of the curves show how as the $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ transformation progressed the work-hardening of the steels increased rapidly, The mechanical behaviour of a certain number of steels is drastically changed when these alloys can exhibit a martensitic transformation induced by plastic deformation (see Table 3).

5. DISCUSSION

The changing of phase content along the stress-strain curve may be linked to the model of Olson and Cohen (1975). This analysis provides a rationale for the formation of martensite with plastic strain and how this is affected by stacking fault energy and strain rate. During strain-induced transformation, plastic deformation of the parent phase creates the proper defect structures, which act as embryo for the transformation products. This will result in higher dislocation density in the end product. Therefore, this rapid work-hardening in this low strain region will reflect the continuous transition from a plastic deformation mechanism involving transformation induced lath-martensite, residual stresses and mobile dislocations to plastic deformation by a dislocation generation/dislocation glide mechanism. With these phenomena, this model based on the law of mixtures is more attractive; this has been quantified in figure 4 which gives the experimental curve and that calculated from the model of the composite (σ_C) and incorporates a dislocation density effect. If this mode of deformation of these alloys is compared with steels with only martensite as the second phase, which does not deform on plastic straining, it could be seen that the induced lath-martensite in a work-hardening matrix of austenite/epsilon is most effective in enhancing strength and ductility (Inegbenebor et al., 1987).

6. CONCLUSIONS

The model developed for predicting the flow behaviour of metastable Fe-Mn-Mo steels displaying transformation-induced plasticity is based on the law of mixtures of microstructures containing approximately 50 volume percent of soft phase (austenite/epsilon martensite) and hard phase (lath-martensite) as starting phases. It has been employed to calculate the composite flow stress of these alloys. The results of the calculations approach the actual behaviour of the alloys tested.

ACKNOWLEDGEMENTS

One of the authors, A.O. Inegbenebor, wishes to express his deep appreciation to the Federal Government of Nigeria for a scholarship to carry out this research. This research was supported in part by the Manganese Centre (France).

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