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A THEORETICAL MODEL FOR THE FLOW BEHAVIOUR OF AN ALLOY UNDERGOING A DEFORMATION- INDUCED PHASE TRANSFORMATION

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ABSTRACT

Models for predicting the flow behaviour of some new wear resistant iron - manganese- molybdenum steels displayin transformation-induced plasticity are developed in this paper. The models, based on the law of mixtures, take int account the strength of the individual principal phases (namely, lath-martensite, and austenite). The composite streng of such a steel may be given by a modified law of mixtures combined with the ideas of other workers. The expression derived for the models show good agreement with experimental data.

INTRODUCTION

During tensile deformation of a two-phase alloy, many authors assume a "law of mixtures". The law of mixtures is an expression that predicts a linear variation of stress or strain as a function of volume fraction of second phase. It holds under the assumption that the strain in the harder phase must be the same as in the softer phase during deformation[1]. From this, quantitative models of the deformation of duplex structures have been constructed (e.g. Mileiko[2]; Tomota et al [3], and developed further by other workers [4-10]). Yegneswaran and Tangri[8,9] investigating the early stages of deformation of two-phase copper-aluminum alloys, noted that the work-hardening rate of the alloys was controlled mainly by the work-hardening rate of the softer phase.

However, the models developed so far presume a knowledge of the strength of each phase. In the treatment developed here this presumption is not required and further, the case of a system where the relative volume fraction of the phases changes during deformation is a central feature of the modelling, the aim being to consider those cases where transformation-induced phas transformation occur.

1.0 THEORETICAL MODEL

Tamura and Tomota [10] proposed tha the average stress or composite stress an average strain or composite strain in an (γ.α' alloy could be represented by: -

$$\sigma_c = V^{o}_{\alpha'} \sigma_{\alpha'} + V^{o}_{\gamma} \sigma_{\gamma} \quad ....(1)$$

$$\varepsilon_c = V^{o}_{\alpha'} \varepsilon_{\alpha'} + V^{o}_{\gamma} \varepsilon_{\gamma} \quad ....(2)$$

where $V^{o}_{\alpha'}$ and V^{o}_{γ} are volume fractions c lath martensite and austenite respectively, $\sigma_{\alpha'}$, ε and σ_{γ}, ε_{γ} are the corresponding true stress an strains of austenite, martensite and lat martensite respectively, and σ_c and ε_c are th composite flow stress and strains. This law c mixtures is graphically represented in figure These two simple models, that is equal strai and equal stress, have often been employed t estimate the flow curve of two-phase alloy fror those of the constituent phases [11].

In order to use the law of mixtures a the basis for models of the type of steel whic is reported here, it is necessary to look at it micro structural characterization The ne section will deal in brief with thes microstructural features and the operative mechanisms.

1.1 Microstructure

The micro structure of metastable Fe-Mn-Mo steel comprises primarily of austenite, epsilon martensite and lath martensite. As such, this complex microstructure makes quantitative characterization difficult, and this problem is compounded by the many simultaneously operating strengthening mechanisms in the structure. The major difficulties in detecting the randomly distributed lath martensite phase in austenite/epsilon matrixes are the lack of contrast between lath martensite and the austenite/epsilon martensite phase mixture. 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 the material. In strain-induced transformations plastic deformation of the parent phase creates the proper defect structure to act as an embryo for the transformation product. For example, in austenitic stainless steels, embryos are formed at the intersections of microscopic shear bands, e.g. stacking faults, twins and hcp epsilon martensite[12] The morphology of the transformation product is described as lath-like[13-15] Typically, transformation of the parent phase occurs before plastic deformation and takes place by dislocation multiplication or twining.

When metastable Fe-Mn-Mo steel is deformed at room temperature it transforms martensitically from austenite/epsilon to lath martensite[16-17]. The same effect has been noted in type 304 stainless steel. This transformation in type 304 stainless steel has been studied extensively in uniaxial tension at low strain rates by many workers[12,15,18] The Fe-Mn-Mo steel and type 304 stainless steel, are similar in that both have hcp epsilon martensite as an intermediate phase. Moreover, manganese can replace nickel since both elements are austenite stabilizers and they can perform the same function in the respective steels. The epsilon martensite (hcp) coexists with austenite (fcc). Olsen and Cohen[19] have shown that intersections of shear bands in metastable austenite are effective sites for strain-induced martensitic nucleation. The shear bands may be in the form of epsilon martensite, mechanical twins, or dense bundles of stacking faults all being promoted by low austenite stacking-fault energy. The intersection of shear bands generates lath martensite embryos at low strains. This is a plausible suggestion because it is known that martensite in these steels does not deform until high strains [20,21] The respective initial volume fractions of phase in these alloys are such that:-

$$V^o_{\alpha'} + V^o_\gamma = 1 \text{..............(3)}$$

In a multi phase alloy like the Fe-Mn-Mo steels considered here, each phase makes certain contributions to the overall properties of the aggregate. Therefore, the model will need to incorporate:

i) the effect of the strength of the individual microconstituents;
ii) The effect of the strain-induced transformation of austenite./epsilon phase to lath martensite

Expressions will be developed for the composite flow stress of such a steel undergoing a deformation induced phase transformation.

2.0 THE DEVELOPMENT OF A THEORETICAL MODEL FOR THE FLOW BEHAVIOR OF ALLOYS UNDERGOING A DEFORMATION INDUCED PHASE TRANSFORMATION.

2.1 Strain-induced transformation of austenite/epsilon and strain-hardening.

Ludwick- Hollman equations, had been derived for metal which do not undergo strain-induced transformation of phase. In order to take care of metastable alloys, which transform during strain-induced processes, this equation needs to be modified to accommodate such alloys.

A modified form of the Ludwik-Hollmann equation is assumed to describe this behaviour:

$$\sigma = K\,[\ln(1+\varepsilon)]^n\,[V_\gamma] \text{............(4)}$$

where, σ is the contribution of strain-hardening of austenite/epsilon, to the flow stress at any level of strain ε, and V_γ is the volume fraction of austenite/epsilon present in the steel at this level of strain. 'K' is the austenite/epsilon strength factor, that is a measure of the capacity of the austenite/epsilon to be strengthened by strain. And 'n' in this case, will be the austenite/epsilon, strain-hardening index or exponent.

2.2 The true-stress contribution of austenite/epsilon to strain alone.

To understand this, it is necessary to know the relationship of the volume fraction of austenite/epsilon to the strain. The volume fraction of lath martensite formed during deformation should be a continuous function of strain, rather than a function of stress[22,23].

A successful kinetic model accounting for the dependence of volume fraction of martensite ($V_{\alpha'}$) on plastic strain (ε) over a range of strain states has been made[15,19]

The principal feature of the transformation-deformation function is given by the following relationship:

$$V_{\alpha'} = f(e) \text{.....................(5)}$$

where $V_{\alpha'}$ = volume fraction of lath martensite. However, the formation of a lath martensite plate in itself will produce dilational and uniform strains in the surrounding structure. These strains will account for the observed "automotive" nature of lath martensite formation, that is, the ability of lath martensite to accelerate the formation of additional lath martensite. This automotive nature of lath martensite formation has been noted previously by Angel[18] and Magee[24] in deformed 304 stainless steel. To account for this "automotive" lath martensite, it seems reasonable to modify relationship (5), to:

$$V'_\alpha = f(\varepsilon^s) \text{..................(6)}$$

where 's' is an exponent to account for the growth in volume fraction of the "automotive" lath martensite. As the strain-induced transformation of austenite/epsilon to lath martensite proceeds, the volume fraction of the austenite/epsilon phase remaining for further transformation is gradually exhausted. To account for this exhaustion, equation (6) is further modified to:

$$V_{\alpha'} = f[(\varepsilon^s)(V_\gamma)] \text{............(7)}$$

If the rate of change of a function is always directly proportional to the function, the function can be transformed into an equation as follows:

$$V_{\alpha'} = A\dot{\varepsilon}^s(V_\gamma) \text{............(8)}$$

where A is the proportionality constant

Suppose the initial volume fraction of these phases is such that (equation 3):

$$V^o_{\alpha'} + V^c_\gamma = 1,$$

From equation (8):

$$V_{\alpha'} = A\varepsilon^{s}(V_\gamma)$$

Equation (8) can be interpreted in such a way that $V_{\alpha'}$ and V_γ are instantaneous volume fractions of lath martensite (by the process of strain-induced transformation) and V_γ the remaining austensite/epsilon.

Equation (8) can be rewritten in an alternative form:

$$V_{\alpha'} = A\varepsilon^{s}(V^{o}_{\gamma} - V_{\alpha'}) \quad \text{............ (9)}$$

Modification of this equation leads to the following form:

$$V_{\alpha'} = V^{o}_{\gamma}(1+\varepsilon^{-s}/A)^{-1} \quad \text{...........(10)}$$

$$V_\gamma = V^{o}_{\gamma} - V_{\alpha'} \quad \text{.......... (11)}$$

where V_γ is the austenite remaining in the system in equation(8)

Equation (11) may the be rewritten as

$$V_\gamma = V^{o}_{\gamma}[1-(1+\varepsilon^{-s}/A)^{-1}] \quad \text{............ (12)}$$

By substituting (12) in (4) and with some further manipulation the following equation arises:

$$\sigma_\gamma = k[\ln(1+\varepsilon)]^{n} V^{o}_{\gamma}[1-(1+\varepsilon^{-s}/A)^{-1}] \quad \text{..... (13)}$$

In this equation, σ_γ represents the stress with which an austenite/epsilon structure can undergo a strain-induced transformation to lath martensite. This is the flow stress of austenite/epsilon at any level of strain and volume fraction.

2.3 The effect of lath martensite strengthening

The true-stress contribution of lath martensite $\sigma_{\alpha'}$ should be proportional to the volume fraction of lath martensite.

$$\sigma_{\alpha'} \propto V_{\alpha'} \quad \text{............... (14)}$$

This proportionality may be transformed into an equation as follows:

$$\sigma_{\alpha'} = T\, V^{p}_{\alpha'} \quad \text{............... (15)}$$

Substituting (10) in (15) gives the following equation:

$$\sigma_{\alpha'} = T\, V^{o}_{\gamma}(1+\varepsilon^{-s}/A)^{-p} \quad \text{......... (16)}$$

Assuming that the total content of lath martensite in the system increases from the initial lath martensite content by the strain-induced transformation then the strengthening effect of lath martensite will be:

$$\sigma_{\alpha'} = T[V^{o}_{\alpha'} + V^{o}_{\gamma}(1+\varepsilon^{-s}/A)^{-p}] \quad \text{........(17)}$$

In equation (17), the proportionality constant T represents the flow stress of the steel extrapolated to a fully lath martensite structure (i.e. 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. "P" is termed the martensite strengthening index.

2.4 Composite flow stress of an alloy undergoing a deformation induced phase transformation.

From equation (1):

$$\sigma_c = V^{o}_{\alpha'}\sigma_{\alpha'} + V^{o}_{\gamma}\sigma_\gamma$$

a constitutive flow relation for metastable austenitic steel during strain-induced martensitic transformation has been derived by Narutani and co-workers[25] The composite flow stress has been expressed in the following form:

$$\sigma_c = \sigma_s - \Delta\sigma_d \quad \text{.................. (18)}$$

where σ_s is the static-hardening effect of the two-phase mixture and is the dynamic-softening effect of the transformation as a deformation mechanism:

$$\sigma_s = [1-f]\cdot\sigma_\gamma(\varepsilon-\alpha f) + f\sigma_{\alpha'}(\varepsilon-\alpha f) \quad \text{.... (19)}$$

$$\Delta\sigma_d = \beta\, df/d\varepsilon \cdot \sigma_s \quad \text{.................... (20)}$$

[Here, $\alpha = 0.12$, $\beta = 5.3 \times 10^{-2}$.

f is the volume fraction of lath martensite. ε is the plastic strain [25]].

By combining equations (19) and (20) together Narutani and coworkers derived constitutive relation for the plastic flow of a metastable austenitic steel in form of equation (21).

$$\sigma_c = \{[1-f]\cdot\sigma_\gamma(\varepsilon-\alpha f) - f\sigma_{\alpha'}(\varepsilon-\alpha f)\}[1-\beta\, df/d\varepsilon] \quad \text{............... (21)}$$

Substituting equations (13) and (17) in equation (21) leads to the following equation:

$$\sigma = \{[1-f]\cdot K[\ln(1+\varepsilon)]^{n} V^{o}_{\gamma}[1-(1+\varepsilon^{-s}/A)^{-1}][\varepsilon-\alpha f] + T[V^{o}_{\alpha'} + V^{o}_{\gamma}(1+\varepsilon^{-s}/A)^{-p}][\varepsilon-\alpha f]\}\cdot[1-\beta\, df/d\varepsilon] \quad \text{.................. (22)}$$

3.0 COMPARISON OF THEORETICAL MODEL WITH EXPERIMENT

The composite flow stress equation (22) was tested against a new wear resistant/high strength iron-manganese-molybdenum steel. A series of low carbon steels with compositions in the range 11 to 14% Mn and 2 to 4% Mo were produced. All the tensile tests were carried out at a constant cross-head speed (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 quantified ferromagnetic phase contents by monitoring magnetic reluctance in-situ and dynamically during the mechanical tests. Full details of the experimental methods have been described elsewhere.[26]

3.1 Results and Discussion

The volume fraction of the lath-martensite which transformed during the tensile deformation was found to increase as the plastic strain increased (fig 2), a result which can be compared with the results of other workers [14,15] which had similar curves of such transformation. In order to obtain the value of the exponent, "S" which accounts for the growth in volume fraction of the automotive lath martensite, equation (6) was rearranged and plotted on a log/log scale; a series of virtually parallel straight lines was obtained. The slope, "S", was approximately equal to 2 and was independent of steel composition and metallurgical condition. The constant "A" however, varied with both these factors. The values of constant K and n were obtained by a least square method from equation (13). An iterative computation was used to evaluate the other parameters T and P. The experimental values of materials parameters used to calculate the composite flow curves can be seen in Table 1.

Figures 3 shows the experimental results and data calculated from the theoretical model. It can be seen that good agreement was found. The reasons of the difference in the theoretical values which are less than the experimental values, have not been looked into in this study. However, it might be suggested that the differences in the values, would be as a result of the increased volume fraction of the lath martensite during the deformation processes.

4.0 CONCLUSIONS

(a) A model has been developed to describe the flow behaviour of some new wear resistant iron-manganese-molybdenum steels displaying transformation-induced plasticity.

(b) Expressions for the composite flow stress have been derived incorporating various contributions to the flow stress due to:

(i) the strength of the matrix austenite/epsilon martensite; and

(ii) the strength of lath-martensite.

(c) The model is very simple and can be easily extended to other commercial steels such as dual phase, stainless and TRIP and its variants.

(d) Steels with coexisting epsilon martensite and austenite phase can be grouped together as one parent phase and easily incorporated into the model in the place of austenite phase, e.g. metastable Fe-Mn-Mo steel.

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TABLE I: Experimental Values of Material Parameters

Parameter	Value
	0.05% C, 11.30% Mn, 3.61% Mo (S.T. at 850°C for 1 hr and air-cooled)
K	2534 (MPa)
n	0.536
T	350 (MPa)
S	2
P	0.217
A	0.1348

where:
K = the value of stress in a fully γ/c Structure at unit true strain
n = austenite strain-hardening exponent
T = flow stress of a fully lath martensitic structure
S = automotive lath martensite index
P = lath martensite strengthening index
A = strain-induced transformation constant

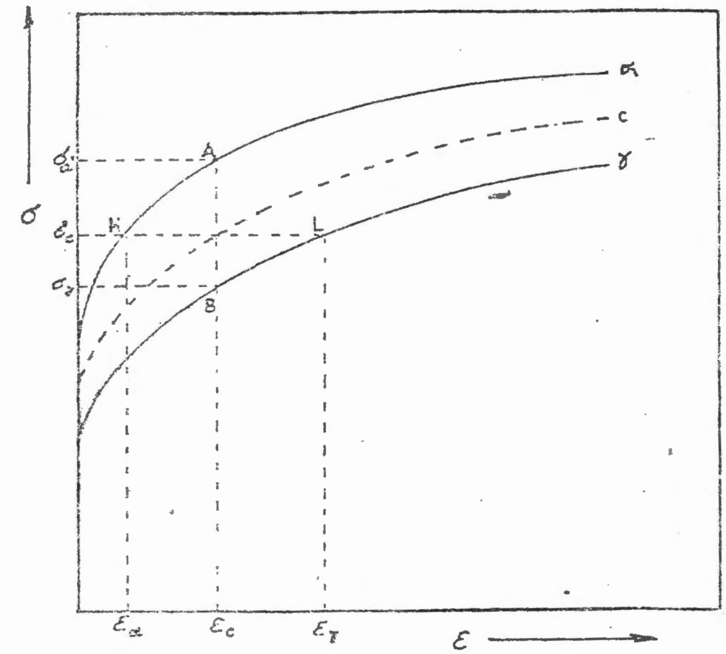

Fig 1. Schematic stress-strain curves of a soft phase matrix austenite (γ), hard phase lath martensite (α') and the composite (C). The lines KL and AB correspond to the two limiting conditions of the law of mixtures. For an isostrain condition (AB), $\varepsilon_\gamma = \varepsilon_\alpha = \varepsilon_c$ while for an isostress condition (KL).

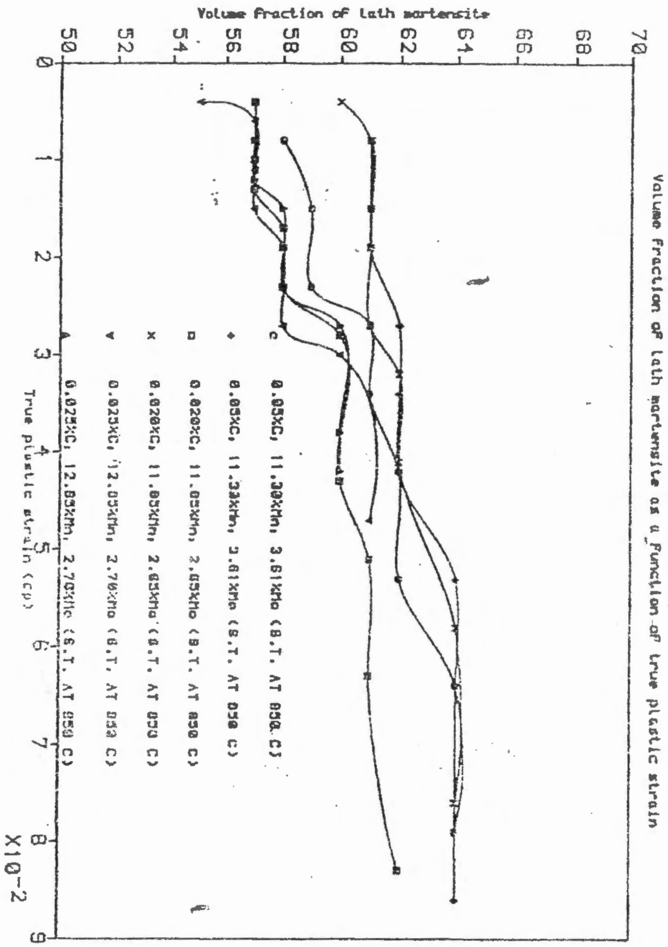

Fig 2 Relationship between the volume fraction of lath martensite and true plastic strain for a number of the steels studied

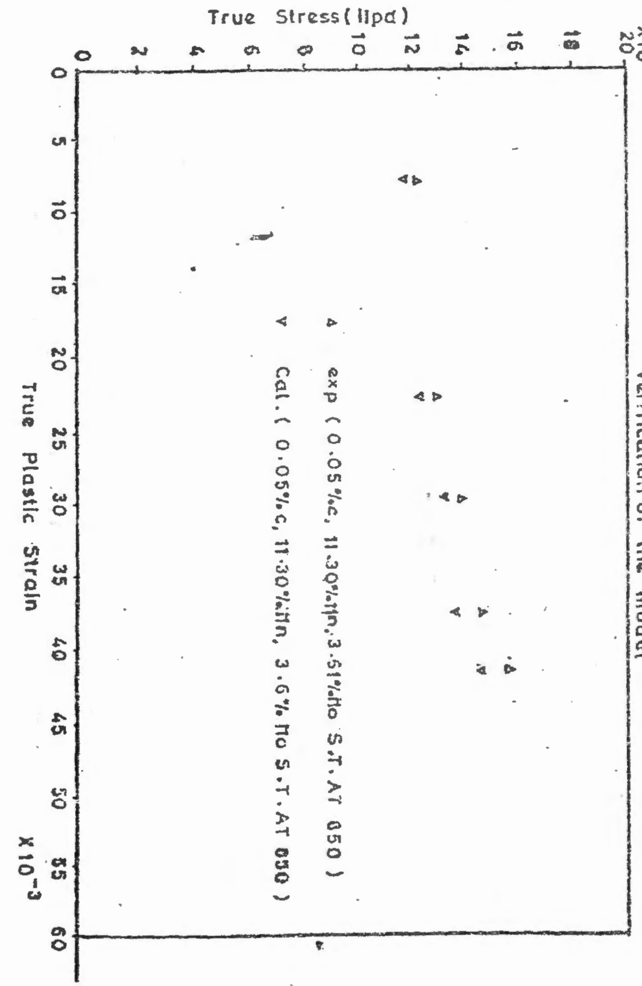

Fig 3: A Comparison between theoretical Model and Experimental data.

bones were exported in 1994 alone to various countries which incidentally are the countries of origin of gelatine importation. (Tables 3 and 4).

Survey of other raw materials (e.g. Hydrochloric acid, hydrogen Peroxide, Phosphoric acid and glacial acetic acid) required for medium and large scale production of industrial grade gelatine was carried out in Lagos. The result indicated that these materials are readily available through local chemical vendors. Raw materials requirement for a 2-tonne gelatine production per day is shown on Table 5.

Equipment Availability Survey

Table 6 summaries the sources of various machine and equipment which can be used to produce industrial grade gelatine.

FINANCIAL AND PROFITABILITY ANALYSIS

Financial and profitability analysis were based on the following assumptions:

(i) Production Volume/Day - 2 Tonnes
(ii) Production Days/Annum -250 Tonnes
(iii) Production Volume/Annum- 500 Tonnes

The profitability ratios and financial indices based on the total investment of about ₦417m (including fixed capital investment working capital and pre-production expenses) for the first year of production are summarised below:

(i) Return on Equity - 151.6%
(ii) Return on Investment - 60.6%
(iii) Internal Rate of Return (IRR) - Above 60%
(iv) Net Profit: Gross Sales - 32.05%
(v) Pay-back period - About 2 years
(vi) Break-Even Volume - About 27%

Commercial production of industrial grade gelatine is of immense economic benefits. These include:

- provision of employment opportunities.
- growth of downstream industries in the areas of raw materials processing or sourcing.
- generation of foreign exchange through export serves as a drift from oil-dependent mono-economy thus generating income through non-oil sources: and so on.

CONCLUSION AND RECOMMENDATION

The study shows that it is technically possible to produce industrial grade gelatine from bones on commercial basis in Nigeria. The production is also economically rewarding. The bones we export today could be used for gelatine production thus saving the country some foreign exchange used in yearly importation of gelatine. There is probably no known company in Black Africa producing gelatine on commercial basis. It is recommended that both private and public enterprises (Local, State and Federal Government in particular) should invest in gelatine production. It is also recommended that a full techno-economic feasibility study on the production be carried out before such investment is embarked upon. FIIRO offers technical Assistance Services (TAS) to would-be investor in gelatine production.

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