Strain Hardening Behaviour of PM Alloys with Heterogeneous Microstructure

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Abstract

Tensile stress-strain and dynamic acoustic resonance tests were performed on Fe-C-Ni-Cu-Mo high-strength steels, characterized by a heterogeneous matrix microstructure and the prevalence of open porosity. All materials display the first yielding phenomenon and, successively, a continuous yielding behavior. This flow behavior can be described by the Ludwigson equation and developes through three stages: the onset of localized plastic deformation at the pore edges; the evolution of plastic deformation at the pore necks (where the austenitic Ni-rich phase is predominant); the spreading of plastic deformation in the interior of the matrix. The analytical modeling of the strain hardening behavior made it possible to obtain the boundaries between the different deformation stages.

Keywords: PM Alloys, Strain Hardening, Continuous Yielding, Heterogeneous Microstructure

1. Introduction

In PM alloys the stress and strain concentration at the pores edges con lead to local plastic flow even for low values of the nominal stress [1]. This influences the tensile stress-strain behaviour and the initial elastic region is quite limited, because of a early deviation from linearity induced by microscopic yielding [2].

If the matrix microstructure is heterogeneous, as in the case of PM alloys produced using partially prealloyed powders, the shape of the stress-strain curve is also strongly influenced by the interaction between porosity and matrix microstructure. The presence of soft areas at the necks and hard areas far from the necks can induce a very early development of plasticity and a difficult spreading of plasticity into the matrix giving rise to a continuous yielding behaviour [2, 3]. In the present investigation, the continuous yielding of PM alloys with heterogeneous microstructure is analytically studied using the Ludwigson equation [4], with the aim of achieve further information on the plastic stress-strain behaviour of these materials and provide a useful approach for the mechanical designing with these materials.

2. Experimental and Results

For the present investigation, four high-strength Fe-C-Ni-Cu-Mo PM alloys were produced by compacting, at 400 and 700 MPa, partially prealloyed DistaloyAE powders (chemical composition: Fe-4%Ni-1.5%Cu-0.5% Mo, produced by Hoganaes AB, Sweden), admixed with 0.5 wt.-% graphite and 1 wt.-% of zinc stearate as a lubricant. Sintering was carried out in endogas at 1150 and 1250°C, for 20 minutes. In the adopted material codes, the notations "5" and "7" refer to the compacting pressure at 500 or 700 MPa, and the notations "LT" or "HT" refer to sintering at 1150 or 1250°C.

As well known, the microstructure of the materials under study is heterogeneous, and comprises Ni-rich austenite at the necks, and islands of martensite/upper bainite/pearlite/ ferrite in the interior of the matrix.

The tensile stress-strain tests were carried out using an Instron testing machine with a cross-head speed of 0.5 mm/min. and an extensimeter with a gauge length of 25 mm. Dynamic longitudinal elastic moduli were obtained by means of the acoustic resonance technique [2]. All tests were performed at room temperature.

During tensile testing, all the materials displayed a continuous yielding behaviour and the first yielding phenomenon, i.e. the early deviation from linearity because of microplasticity development at the pore edges. The values of the elastic modulus determined for stresses below such a deviation were found to be quite similar to the values obtained by the acoustic resonance method. This means that these values may be regarded as the "true" elastic moduli of the materials under study, as also illustrated in ref. [2].

In Fig.1, the true stress-true plastic strain curve of material E7LT is shown as an example (in a double logarithmic scale). It can be observed that the shape is not linear. Three regions can be recognized: region I for true plastic strains lower than ε_1, region II for true plastic strains between ε_1 and ε_2, and region III for true plastic strains larger than ε_2.

For strains lower than ε_2 (regions I and II), the flow curve can be described by the Ludwigson equation [4]:

$$\sigma = k_2 \cdot \varepsilon_p^{n_2} + \exp(k_1 + n_1 \cdot \varepsilon_p) \qquad (1)$$

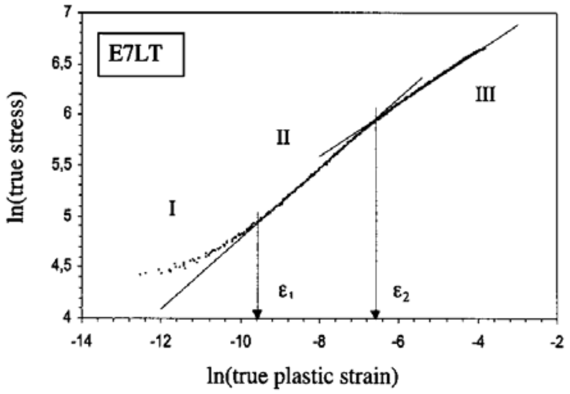

Fig. 1. Plot of the true stress against the true plastic strain for material E7LT (in a double logarithmic scale).

Where k_1, k_2, n_1 and n_2 are material constants. For strains larger than ε_2 the usual Ludwick-Hollomon equation can be used:

$$\sigma = k_3 \cdot \varepsilon_p^{n_3} \qquad (2)$$

Where, again, k_3 and n_3 are material constants. In Table 1, selected material constants of these two equations are shown. In the case of material E5LT, regions II and III almost overlap, and equation (3) is thus used to model the flow behaviour for strains larger than ε_1.

Table 1. Selected materials constants of equations (1) and (2).

Material	k_1	n_2	n_3	σ'_N,(MPa)
E5LT	3.035	-	0.262	20.8
E7LT	3.492	0.358	0.253	32.9
E5HT	3.16	0.343	0.265	23.6
E7HT	3.721	0.406	0.255	41.2

Setting ε_p=0 in equation (1), the following relation is obtained:

$$\sigma'_N = \exp(k_1) \qquad (3)$$

where σ'_N is an estimation of the true stress at which the stress-strain curve starts to deviate from linearity. The calculated values, included in Table 1, proved to be very close to the experimental values, obtained from the engineering stress-strain curves, and this confirms the validity of the approach.

In order to explain the existence of regions I and II in the materials under study, reference to the literature can be made. The occurrence of such regions, in fact, is typical of austenitic stainless steels, and is connected with the heterogenous plastic deformation of the alloys with a FCC structure [5]. Hence, this observation confirms that in regions I and II, plastic deformation is largely concentrated in the Ni-rich areas that are located at the necks, as is typical for this type of materials. This observation is consistent with the microstructural observations and is further supported by the fact that obtained n_2-values are closed to 0.35, which is a typical value for austenitic stainless steels.

For plastic strains larger than ε_2, plastic deformation involves the interior of the matrix. A bulk plastic deformation is thus achieved and it can be conveniently described by equation (2). The values of the strain hardening exponent (n_3) are lower the n_2-values (see Table 1), because plastic deformation involves the bainitic and martensitic areas that are characterized by a lower strain hardening behaviour.

3. References

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