THE EFFECTS OF SHOCK LOADING AND GRAIN REFINING ON THE TENSILE RESPONSE OF A META-STABLE Fe-31%Ni-0.1%C ALLOY

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Abstract

The tensile behavior of Fe-31%-Ni-0.1%C pre-shocked at
80 Kbar (8GPa) and pulse duration of 2 μs was comparatively
studied to those of the annealed condition and annealed but
grain refined. The variation of the yield stress with
temperature was found to follow the description of the
"temperature-transformation-deformation" interactions
provided by Olson and Cohen. Depending upon the test
temperature the load-elongation curves exhibited serrations
which were attributed to martensite bursts. It was found
that, independently of its initial condition, the material
exhibited a maximum in neck strain at some intermediate
temperature. Shock loading was found to stimulate the
transformation while grain refining had the opposite effect.

Introduction

An impressive combination of strength and ductility can
be obtained with austenitic steels which are metastable
toward martensite transformation at the deformation
temperature (1-3). The martensite reaction is generally
accepted as a critical factor for the overall mechanical
response of these materials. Therefore the interactions
"temperature-deformation-transformation" should be well
understood in order to fully assess the applicability of
this type of alloy. This study was aimed at that goal; the
method chosen was that of perturbing the aforementioned
interactions and observe the material response, particularly
its yielding and ability to deform uniformly during tensile
tests at different temperatures. "Perturbation" was
accomplished either by grain refining or subjecting the
material to a plastic shock wave. Among the several reasons
for the choice of these processes the noteworthy are: a) the
austenite stability has been observed to be linked to its
grain size (4,5); b) the effect of this parameter upon the
deformation induced martensite reaction has not been well
clarified; c) shock loading may provide the material with
a high dislocation density without affecting the grain
shape (7) and d) both processes, while strengthening the
austenite, may have opposite effects on its stability(5,6).
The alloy chosen to be studied was Fe-31%Ni-0.1%C for its
convenient sub-zero Mₐ and high stacking-fault energy (6-8),
preventing ε martensite and fault formation and minimizing

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twinning during shock loading.

Experimental Procedures

The alloy, received in the form of round bars (6.2 mm diameter), was subjected to a sequence of deformation and heating treatments to be transformed into flat, 1 mm thick, strips which were separated into three lots. Two of these were machined to make flat tensile specimens (27 x 4 x 1 mm useful gage dimensions) and given annealing treatments in vacuum to yield larger (1373 K) and smaller (1223 K) grain size "annealed" specimens. The third lot was also annealed to obtain a large grain size, shock loaded (8GPa and 2 μs pulse duration) and machined into tensile specimens. The details of the experimental set-up for shock loading the material can be found elsewhere(7). Tensile tests were conducted with an Instron TT-DM machine at a nominal rate of 10⁻²s⁻¹ at temperatures ranging from 208 up to 278 K. Mechanical properties were determined from the Instron chart. The martensite content in the specimens was obtained by point counting in the screen of a Leitz MM5 microscope. Substructure observations were made with a JEOLCO 100B electron microscope, operated at 100kV. Mₕ temperatures were determined by observing, after cooling to fixed temperatures, the development of "tilts" on a pre-polished surface of the sample.

Experimental Results and Discussion

a) Microstructure characterization.

Fairly equiaxed but twinned grains were typical of the annealed alloy. The total surface area per unit volume was determined to be 14.2 ± 0.5 and 29.6 ± 0.9 mm⁻¹ in the larger and finer grained material, respectively. In the as-shocked state, evidence of mechanical twinning could be found. T.E.M. showed a dense dislocation density wherein incipient cell formation was clearly visible. The martensite found in all types of specimens after tensile deformation to rupture (but away from fracture) is well distributed throughout the gage length and exhibited a "mid-rib". "Zig-zag" formations, typical of autocatalytic activity were very frequently detected, Fig.1, but no drastic change in the martensite morphology could be observed to result from shock loading, grain refining or deformation at different temperatures. However plate fragmentation and a few formations of what could be called "butterfly martensite" were observed at the highest deformation temperatures.

b) Characterization of the yielding process.

The yield strength was always found to reach a maximum at some intermediate temperature, called Mₕ by Bolling and Richman(9), above Mₕ (Fig.2). At the lowest test
temperatures, load drops accompanied by loud "clicks" could be detected in the "elastic" regime. In these cases the first drop was taken as determining the macroscopic yield point of the alloy. It is worth mentioning that data extrapolation to zero stress determined temperatures in the range bracketed for the material $M_S$ by the alternative method. This pattern of behavior is clearly consistent with the rationale of the "temperature-transformation-deformation" interactions recently offered by Olson and Cohen(10). They considered martensite transformation and slip as competitive processes for the macroscopic yielding of metastable austenites, the latter being predominant above $M_S$. These authors have also called the deformation-induced transformation modes of the austenite below and above $M_S$ "stress-assisted"(SA) and "strain-induced"(SI) respectively. However the above reported observation that no drastic morphology change was detected upon traversing $M_S$ suggests that at least in this particular alloy there is no basic difference between the mechanisms of either reaction mode. That is, classification of a deformation induced reaction as "SA" or "SI" based upon the temperature $M_S$ would be primarily operational. These facts can be considered as supporting an hypothesis that deformation-induced martensite would be an extreme case of "austenite mechanical sensitization"(12) as well as the findings of Maxwell et al. (13). It is also considered worth mentioning that the average value (among the three sets of data) of the slope of the "Yield Strength" vs. "Temperature" line between $M_S$ and $M_S$ is about $11 \times 10^6$ N/m² K⁻¹, which is in the range of the data reported by Patel and Cohen(11).
c) The stress-strain curves and the reaction kinetics.

The overall behavior of the material agreed with that reported for similar alloys by other workers, e.g., Maxwell et al (15). At high temperatures the material failed before any obvious transformation could occur; smooth load-elongation curves are typical of this behavior. However, deformation at lower temperatures can induce transformation. First it is restricted to the fracture zone surroundings, but as $M_s$ is approached it occurs throughout the useful gage length. In the course of this regime of "deformation-induced transformation" the load-elongation curves become rough. Serrated flow accompanied by loud sonic emission occurs and develops sooner in the deformation process as the deformation temperature is lowered. Nearer $M_s$ they occur while the material is still within its "elastic" regime, as mentioned before.

The effects of refining the austenite grain on these phenomena were (i) to reduce the size of the load drops and (ii) to decrease the temperature wherein they could be first noticed. The opposite trend was observed with the pre-shocked material. Then it is appropriate to recall that for alloys of the Fe-Ni-C system, Umemoto and Owen (5) reported both $M_s$ depression and reduction in the corresponding burst as a result of austenite grain refinement while Dash and Brown (6) were able to sensitize a similar austenite toward subsequent martensite transformation by shock-loading it. These reported results indicate that "normal" martensite reaction in Fe-Ni-C alloys is affected by shock-loading and grain refinement in a way very similar to the phenomena developed during the tensile deformation of our Fe-31Ni-0.1C alloy under conditions of deformation-induced transformation. Thus it is suggested that the observed serrated flow and its associated sonic emission were caused by the autocatalytic formation of martensite, an hypothesis which is supported by optical metallography, Fig.1, as well.

Consequently it is expected that pre-shocking should enhance the deformation-induced reaction while grain refining would produce the opposite effect. These effects find experimental support in the plots of Fig.3, which depict the temperature dependence of the fraction transformed, $f_u$, at plastic engineering neck strain, $e_u$. The plots indicate that all types of material behave similarly but the finer grained austenite transformed less and the pre-shocked one transformed more than the larger grained, annealed only alloy. This observation is also considered important because it supports the earlier contention that, at least in this alloy, both the deformation-induced and the "normal" reaction would have common roots, the former being a limiting case of "mechanical sensitization".

d) The onset of necking.

Probably the most typical characteristic of mechanical
behavior of metastable austenites is the possibility of reaching a maximum in uniform elongation at some intermediate temperature between $M_s$ and $M_f$ (temperature above which deformation would not induce martensite transformation). This was always observed with the alloy studied in the different initial conditions. Fig. 4. Reducing the grain size did not affect the maximum amount of $e_u$ but decreased the corresponding critical temperature. This behavior is different from the low stacking-fault energy Fe-Ni-Cr steels studied by Rosen et al. (15), who found grain refining always detrimental to large extents of uniform elongation. It is clear that in the present case, reducing grain size would help in achieving larger neck strains at the lower temperatures, while the opposite trend is observed at the higher temperatures. The pre-shocked material exhibited 50% less uniform strain and its strain "hump" was much less pronounced than in the other two cases but the temperature of maximum $e_u$ practically did not vary relatively to the annealed material (although it was more difficult to determine). Work is in progress to attempt to correlate both mechanical and kinetic data in order to model the overall behavior of this type of material.

Final Remarks and Conclusions.

The following conclusions can be drawn about the deformation-transformation behavior of the alloy studied:

1) It displayed a yielding dependence on temperature compatible with Olson and Cohen's rationale.
2) At the onset of necking the finer grain material exhibited less martensite than the larger grained one at all temperatures investigated; the opposite was true for the pre-shocked condition.
3) No specific morphology change was observed in the martensite upon traversing $M_s$. The typical martensite features observed had a mid-rib.
4) Serrated flow developed along deformation path at the lower temperatures. It is proposed to be a result of autocatalytic formation of martensite (bursts).
5) Grain refinement did not reduce the amount of uniform elongation but depressed the temperature where it may be achieved. Consequently it improved the material ductility at lower temperatures.
6) Pre-shocking caused a reduction in the attainable neck strain, but did not change markedly its critical temperature.

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Fig. 3 Temperature Dependence of the martensite content in specimens deformed to fracture at $\dot{\varepsilon} \approx 10^{-4} \text{s}^{-1}$.

Fig. 4 Temperature Dependence of the material neck strain. $\dot{\varepsilon} \approx 10^{-4} \text{s}^{-1}$.

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