Symp. Trans. Jap. Inst. Metals 17
vol 17, p. 411 (1976)

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

J.R.C. Guimarães, J.C. Gomes e M.A. Meyers
Instituto Militar de Engenharia
Pça. Gen. Tibúrcio s/nº
Rio de Janeiro, ZC-82, RJ.

* Aceito para publicação nos anais do Simpósio Internacional sobre Reações Martensíticas promovido pelo "Japan Institute of Metals" JIMIS-I em Kobe, Japão (1976).

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J.R.C. Guimarães, J.C. Gomes and M.A. Meyers

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 uniformely 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 noteworth 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 precesses, while strengthtening 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 M_s and high stacking-fault energy (6-8), preventing ε martensite and fault formation and mininizing

Instituto Militar de Engenharia, Pça. Gen. Tibúrcio s/nº, Rio de Janeiro, ZC-82, RJ, Brasil.

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 $10^{-4}s^{-1}$ 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. M_s 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 M_s^{σ} by Bolling and Richman(9), above M_s (Fig.2). At the lowest test

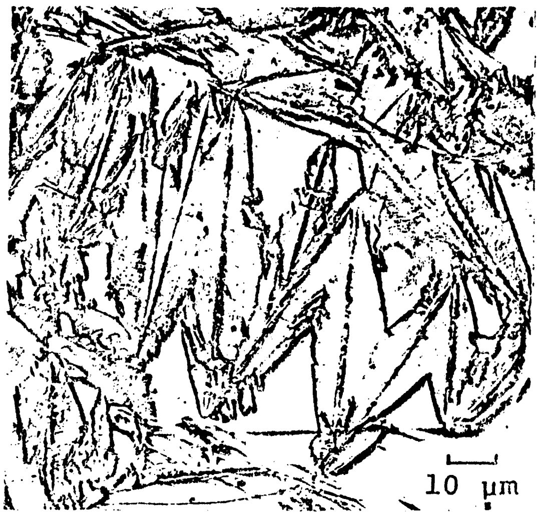

Fig.1 Optical Photomicrograph. Microstructure of a specimen deformed to fracture at 248 K.

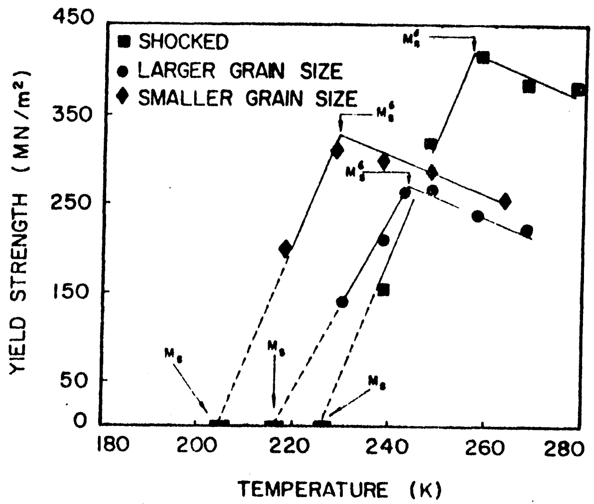

Fig.2 Temperature dependence of the material yield strength.

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^σ. These authors have also called the deformation-induced transformation modes of the austenite below and above M_s^σ "stress-assisted"(SA)and "strain-induced"(SI) respectively. However the above reported observation that no drastic morphology change was detected upon traversing M_s^σ 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^σ 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^σ is about 11×10^6 N/m^2 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_d (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 maximim 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^σ. 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.

Acknowledgements.

This work was supported by the Brazilian Army, FINEP and BNDE. A travel grant from CNPq is duly acknowledged. Thanks are due to J.F. Rocha for providing the explosives and to Professor J.C. Shyne (Stanford University) for kindly giving the alloy to us.

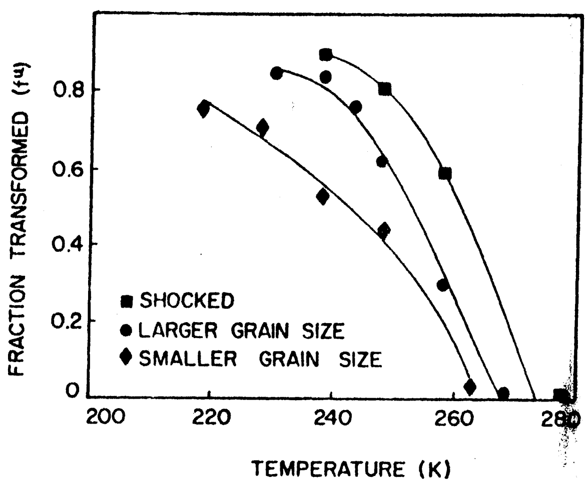

Fig.3 Temperature Dependence of the martensite content in specimens deformed to fracture at $\dot{e} \simeq 10^{-4}s^{-1}$.

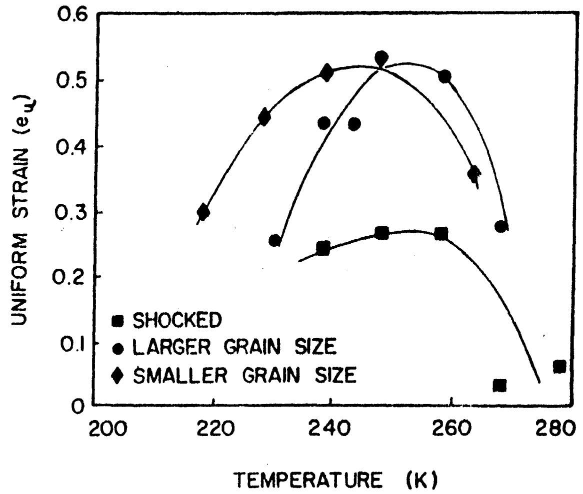

Fig.4 Temperature Dependence of the material neck strain. $\dot{e} \simeq 10^{-4}s^{-1}$.

References

(1) J.P. Bressanelly and A Moskowitz, ASM-Trans. Quart., 59 (1966) 223.
(2) V.F. Zackay, E.R. Parker, D. Fahr and R. Bush, ASM-Trans Quart., 60 (1967) 252.
(3) D. Fahr, Met. Trans., 2 (1971) 1883.
(4) A.R. Entwisle and J. Feeney, Institute of Metals Monograph No. 33 (1968) 156.
(5) M. Umemoto and W.S. Owen, Met. Trans., 5 (1974) 2041.
(6) S. Dash and N. Brown, Acta Met. 14 (1966) 595.
(7) M.A. Meyers, Ph.D. Thesis, University of Denver (1974).
(8) J.F. Breedis, Trans. TMS-AIME, 230 (1964) 1583.
(9) G.F. Bolling and R.H. Richman, Met. Trans., 2 (1971) 2451.
(10) G.B. Olson and M. Cohen, J. Less-Comm. Metals, 28 (1972) 107.
(11) S.R. Patel and M. Cohen, Acta Met., 1 (1953) 531.
(12) J.R.C. Guimarães and J.C. Shyne, Scrita Met., 4 (1970) 1019.
(13) P.C. Maxwell, A. Goldberg and J.C. Shyne, Met. Trans. 5 (1974) 1305.
(14) P.C. Maxwell, A. Goldberg and J.C. Shyne, ibid., 5 (1974) 1819.
(15) A. Rosen, R. Jago, T. Kjer, J. Mat Sci., 7 (1972) 870.