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Short Communication

Shock-induced martensite formation in a Fe–31% Ni–0.1% C alloy

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The Fe–31% Ni–0.1% C alloy belongs to a class of steels which can easily be kept metastable in the austenite (f.c.c.) structure at ambient temperature. The martensite transformation in this alloy occurs by bursting at about 223 K but plastic deformation may sensitize the alloy, *e.g.* 50% rolling at ambient temperature raises M_s by about 18 K [1]. In a similar alloy of the same system, with M_s = 245 K, no martensite was observed when shock loaded to a pressure of 27 GPa (270 kbar) [2]; the residual structure was characterized by dislocations and deformation twins. The same observations were made by Dash and Brown [3] for another alloy of the same class with M_s = 240 K. It is the objective of this note to report the occurrence of martensite in certain specific positions of a shock-loaded specimen of Fe–31% Ni–0.1% C. An explanation is provided in terms of special wave configurations in certain regions of the sample.

The alloy, received in the form of a round bar (16 mm diameter), was forged into 10 mm thick strips, vacuum annealed in sealed quartz capsules (1373 K, 5×10^{-5} mm Hg) during 18 hours and subsequently rolled down to 1 mm. This material was reannealed in vacuum for 2 hours, yielding an average grain diameter of about 213 μm. The strip was shock loaded at a pressure of 8 GPa (80 kbar) and pulse duration of 2 μsec; the dimensions of the explosive system were calculated according to Orava and Wittman [4]. The assembly containing the sample strip is shown in Fig. 1. The sample is sandwiched between a stainless steel cover plate and a steel anvil. Further experimental details are provided elsewhere [5]. Both sides of the sample strip were free of contact with metal, so that the lateral components of the wave reflected into the sample. However, in the left side (indicated by A) a very small gap was allowed between the sample and the support, while the right side (indicated by

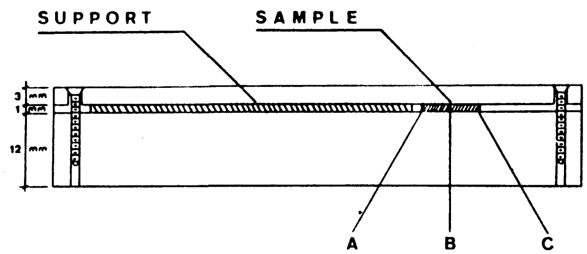


Fig. 1. Assembly showing position A where reflection but no deformation can occur, position C where both reflection and deformation can take place and position B, traversed by the compressive wave.

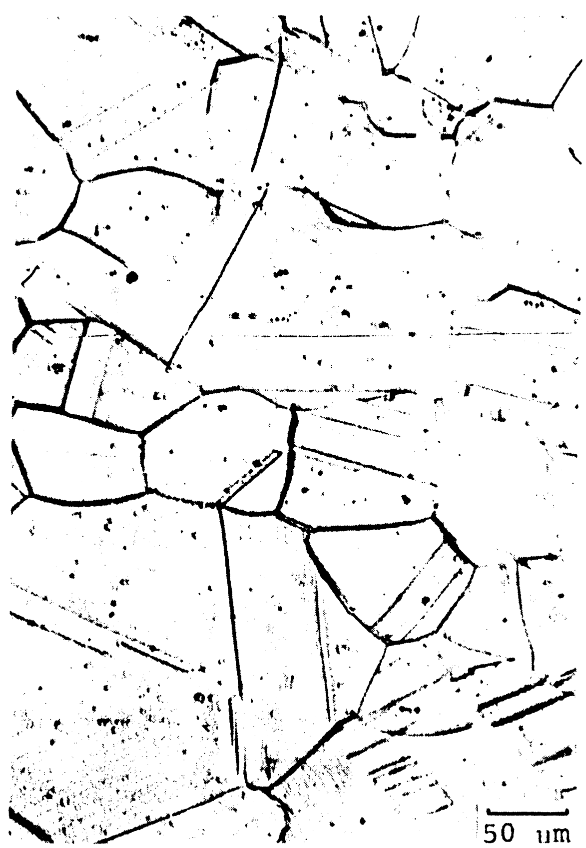
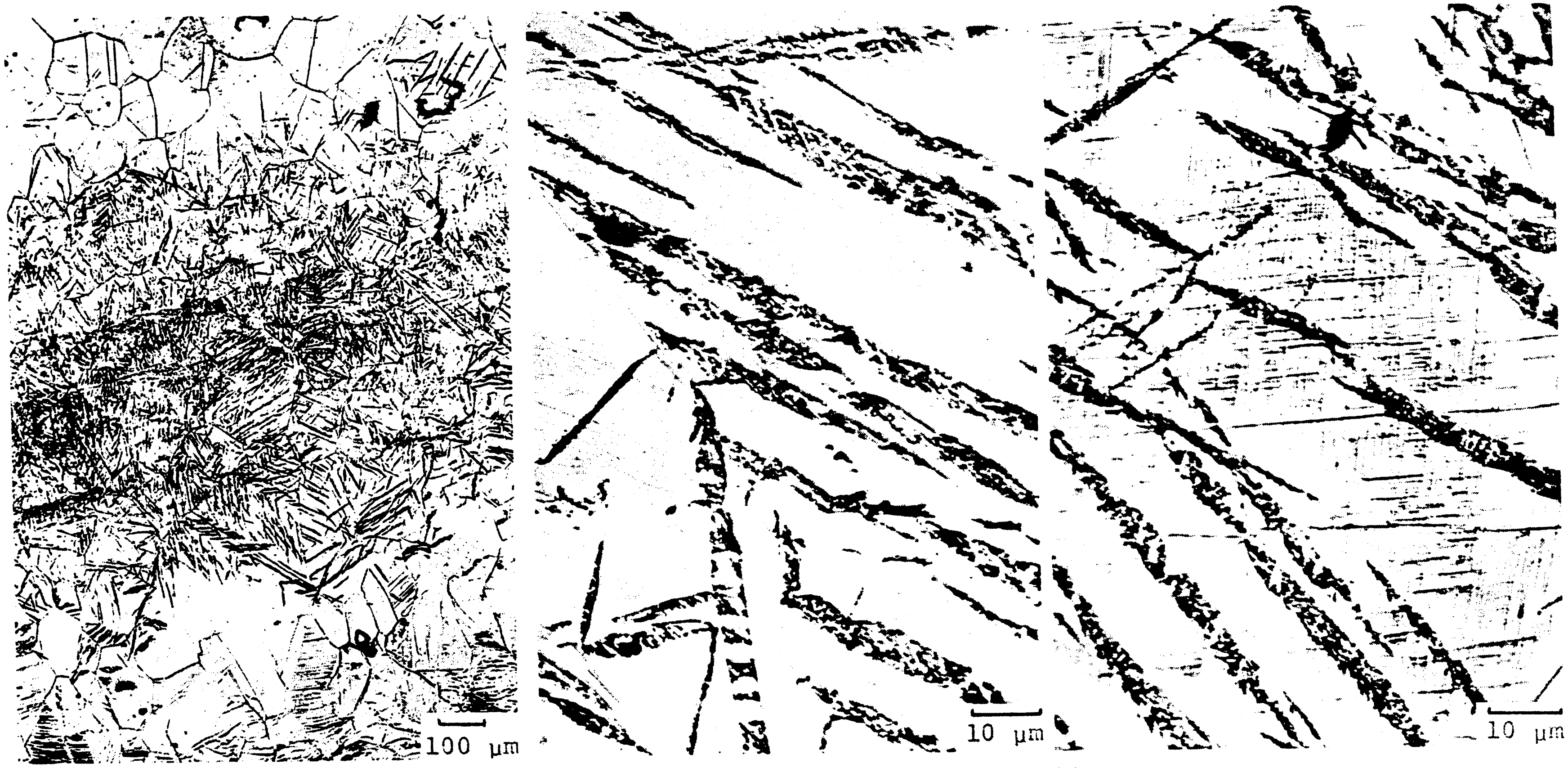
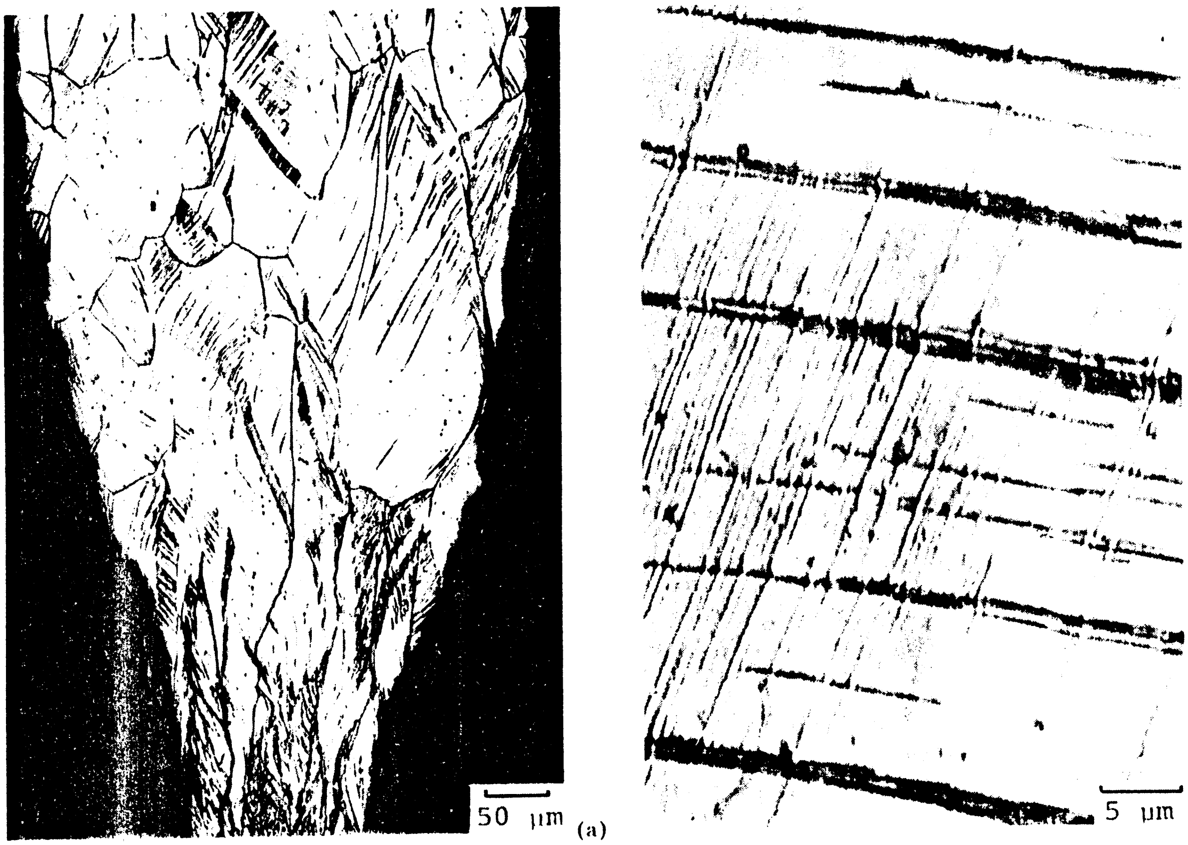


Fig. 2. Optical micrograph of position B.



(a) (b) (c)

Fig. 3. Optical micrographs of position A; (a) general view of the martensite "tube"; (b) fragmented plates; (c) details of "martensite features" superimposed on twin-like striations.



(a) (b)

Fig. 4. Optical micrographs of position C; (a) general view of deformed strip; (b) "hairy-wave" features superimposed on twin-like striations.

C) remained entirely free, owing to the absence of support. This resulted in negligible residual deformation on side A. The microstructures typical of positions B, A and C are shown in Figs. 2, 3 and 4, respectively.

Figure 2 represents the bulk of the material. It was solely traversed by a compressive wave with an amplitude of 8 GPa (80 kbar). The isotropy of grains was maintained and residual deformation was minimum. Mechanical twins were observed but transmission electron microscopy showed that the substructure consisted mostly of a high density of dislocations wherein incipient cell formation was clear [6].

Figure 3(a) shows the portion where the compressive and tensile reflected wave would have interacted; it shows a dense array of plate-like features similar to the martensite which is observed in the alloy after cooling below M_s. A "tube" of these features was formed parallel to the left lateral face of the strip. The existence of b.c.c. lines in the corresponding X-ray diffractogram supports the identification of the features as martensite. In addition to the matrix lines, the characteristic {100} and {200} martensite peaks were obvious in the diffractogram. Also smaller peaks were observed at 2θ angles of about 38.8° and 45°. Since a "scan" of the bakelite mount did not show any characteristic "peak-spectrum" one may think of those peaks as due to some complex Fe–Ni carbide resulting from tempering. It is noteworthy that both the transient temperature at the shock wave and the residual temperature are well above the initial temperature of the experiment (approximately 300 K); plate martensite has not been reported in this alloy after deformation of 75% by rolling [7] or by tensile deformation at room temperature [6]. The authors are aware of the fact that the tensile reflected wave might produce an adiabatic cooling. The analysis of this complex problem is beyond the scope of this note.

A detailed observation of the "martensite plates" indicated that they are fairly fragmented, Fig. 3(b), resembling the microstructure of plates heated to temperatures where reversion into austenite could occur [8]. This possibility is consistent with the conditions available in the experimental set-up. However, since the diffractogram indicated b.c.c. lines it is clear that the reversion, if it occurred, was only partial. Another reasonable possibility and also consistent with the diffraction data would be the occurrence of martensite decomposition by tempering.

Other relevant information is provided by the photograph of Fig. 3(c). It is obvious in the picture that the martensite-like features are superimposed on the finer striations. These are likely to be either deformation twins or bands which are known to form in shock-loaded austenites. Therefore the phase transformation of our concern *followed* the formation of striations in region A; this supports the hypothesis that martensite resulted from "secondary" wave interactions.

The microstructure revealed by Fig. 4 (representative of position C in Fig. 1) is entirely different. The grains are heavily elongated and the thickness of the sample is substantially reduced in this area. This is due to the fact that the cover plate was free to come down upon impact by the flyer plate. Consequently, high-velocity forming was superimposed on shock loading. The "hairy-wave" marks seen within the grains do not resemble at all the features of Fig. 3(a); they may be attributed simply to deformation bands or to "strain-induced martensite" as identified by Maxwell *et al.* [9]. This transformation has been reported by them to occur at temperatures very much above M_s (perhaps above M_d)* and to have a unique morphology characterized by long, parallel bands or laths. Figure 4(b) shows very obviously that the "hairy features", which are part of band such as the ones in Fig. 4(a), caused a shearing of the other striations more straightforwardly associated with mechanical twinning. The continuity of the striations throughout the "laths" and the systematic tilts are both consistent with a shear mechanism of formation, *i.e.*, they could very well be what Maxwell *et al.* [9] called "strain-induced martensite".

*M_d = highest temperature at which austenite may be transformed into martensite as a result of deformation.

As a summary, it can be said that a "tube" of plate-like features was observed parallel to the free lateral surface of the sample (position A in Fig. 1). It is suggested that this tube resulted from a martensite transformation induced by the tensile and almost hydrostatic state of stress created by the reflected lateral wave. This "negative pressure" thermodynamically favors the martensite transformation by affecting the austenite–martensite equilibrium and thus raising the transformation temperature. The position C of the sample, in Fig. 1, was characterized by heavy residual deformation. It was subjected to both reflected waves and high-velocity deformation, resulting in a microstructure substantially different from the one in position A or B.

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