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MARTENSITIC TRANSFORMATION INDUCED BY TENSILE STRESS WAVES

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It is shown that tensile pulses generated by the reflection of compressive shock waves at a free surface can produce ($\gamma \rightarrow \alpha'$) martensitic transformation in an Fe-32.3 wt pct Ni-.035 wt pct C alloy. The tensile hydrostatic component of the stress interacts with the dilatational strains (0.04) produced by the martensitic transformation resulting in an increase of M_s, the martensitic start temperature. The shock waves were produced by normal impact of a target by a projectile accelerated in a one-stage gas gun. Experiments were conducted at temperatures between -10° and -50°C (M_s = -61°C) at a constant pressure of 1.5 GPa and pulse duration of 0.75 μs; and at variable pulse durations (0.19 - 1.5 μs) at a constant pressure of 1.5 GPa and a temperature of -30°C. Shock-induced inhomogeneities were observed in the recovered specimens. They manifested themselves as long bands with no crystallographic relationship to the structure and provided preferential nucleation regions for martensite. The observed inhomogeneous "stringers" serve as markers for the shock-induced inhomogeneities.

1. INTRODUCTION

The formation of martensite — the product of a diffusionless, displacive transformation, with kinetics and morphology determined principally by strain energy (1) — is known to be affected by externally applied stresses. Patel and Cohen (2), expanding and systematically investigating this effect, first studied by Scheil (3), found that tensile and compressive uniaxial stresses raised M_s (the temperature at which martensitic transformation starts) while hydrostatic compressive stresses lowered the M_s. They proposed a rationale based on the interaction of externally applied forces and the stresses generated by the martensitic transformation; the latter can be considered as a dilatational strain of 0.04 and a shear strain Of 0.20. Meyers and Guimaraes (4) in 1976 found that tensile pulses produced by the reflection of shock waves at a free surface generated martensite in a Fe-Ni-C alloy, while compressive pulses only generated dislocations. Later, Meyers (5) observed the same phenomenon in a paper published by Snell et alii (6) and used this interpretation in the estimation of a nucleation time for martensite.

Martensitic transformation has been classified, according to its kinetic behavior, into athermal and isothermal (7). While the fraction of the transformed phase increases with time, at a specific temperature, for the isothermal case, it is considered constant for the athermal martensite. There have been proposals (e.g., (8)) that athermal martensite is an ultra-fast isothermal transformation. This investigative program used shock waves with the objective of generating conditions for martensite formation in the microsecond range. Shock waves were used as a metallurgical tool in order to gain an improved understanding of martensitic transformations.

2. EXPERIMENTAL TECHNIQUES

A well characterized alloy used in a previous investigation (9) and known to exhibit athermal burst behavior, was used in this study; its composition was found by chemical analysis to be Fe-32.3 wt pct Ni-.035 wt pct C. The alloy, received in the form of a 15.5 mm thick plate, was rolled down to 10 mm and heat treated in vacuum for 24 hours at 1200°C. The function of this heat treatment was to homogenize the composition throughout the alloy. The resulting grain size, as determined by the linear intercept method, was 0.06 mm. The M_s temperature was determined by slowly cooling the alloy and measuring the change in resistance. It was found to be -61°C.

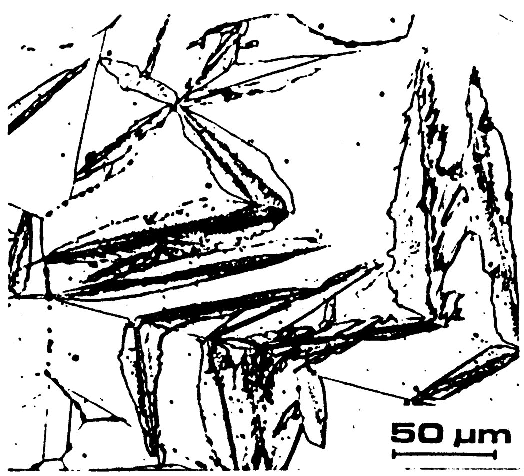

Figure 1. Optical micrograph of thermally induced martensite.

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Figure 1 shows the micrograph of the thermally-produced martensite. It is clearly of the "lenticular" type with a mid-rib and central twinned region. Precipitation at the grain boundaries is also noticeable.

The SRI 2.5 inch (6.35 mm) gas gun was used for the shock experiments. The purpose of the impact experiments was to generate tensile pulses and not only compressive waves. Hence, the targets were not protected by spall plates so that the shock wave, on reflection from the back surface, would generate a tensile pulse. AISI 304 stainless steel (which has a shock impedance very close to that of the alloy investigated) was used for the projectile. The projectile always had a thickness equal to half the target thickness; this ensured that the maximum tensile pulse occurred in the center of the target. In order to avoid lateral tensile pulses in the target, a "puck" with a diameter of 25 mm was inserted in a large disk; upon impact the central "puck" was ejected and the tensile lateral relief waves were interrupted at the interface. The diameter of the projectile was chosen so that a uniaxial strain configuration was assumed in the central "puck". Cooling of the target was accomplished by copper coils attached to the back of the external portion of the target. The temperature was continuously monitored by means of an iron-constantan thermocouple welded to the target.

Quantitative metallography to determine the fraction transformed was conducted by the point counting technique. In this technique a transparent grid is placed on a micrograph and the fraction of points falling on the martensite is computed. In general, ten photomicrographs were taken across the central cross-section of each specimen at a magnification of 100X and a total of 1027 points was counted on each micrograph.

3. RESULTS AND DISCUSSION

The main objective of the investigation was to systematically investigate the effect previously detected by Meyers and Guimaraes (4) and discussed by Meyers (5): tensile pulses generate martensite at temperatures above M_S (at ambient pressure). According to Patel and Cohen's rationalization, a hydrostatic compressive pressure decreases M_S; hence a hydrostatic tensile pressure would increase M_S. In order to verify the correctness of this hypothesis and to systematically study the effect, a number of impact experiments were conducted above -61°C (M_S at ambient pressure). It was first established what the maximum impact velocity could be without producing spalling. Spalling would be an undesirable feature because of the relief waves produced by the generation of new surfaces. The maximum compressive wave amplitude was found to be 1.5 GPa. At higher pressures the tensile pulse produced intergranular spalling. This weakening of grain boundaries was produced by the precipitates evident in Figure 1. The two major findings of this investigation are presented and discussed in the next two sub-sections.

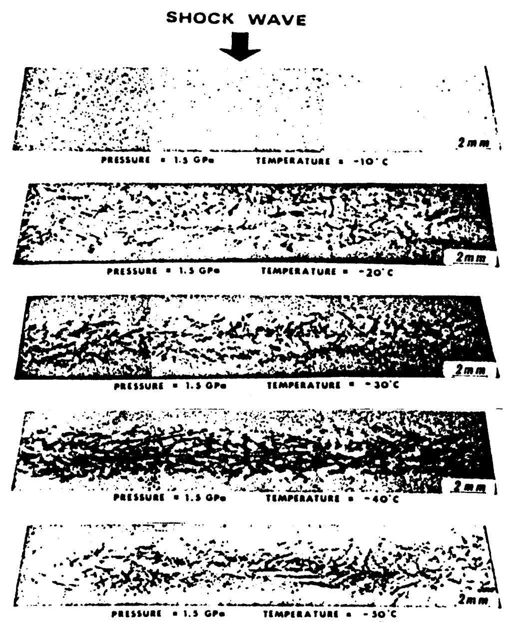

Figure 2. Cross-sections of targets impacted at a constant velocity providing pressure of 1.5 GPa and pulse duration of 0.75 μs, and varying temperatures.

3.1 Transformation Kinetics

In the first series of experiments the pressure (1.5 GPa) and pulse duration (0.75 μs) were kept constant and the temperature was varied between -10°C and -50°C. Figure 2 shows the cross-sections (after polishing and etching) of the five targets. The martensite regions can be perfectly distinguished from the parent phase, because they become dark after etching. Two observations can readily be made. i) The transformation is induced by the tensile pulse and not by the compressive wave; were it produced by the shock wave the region adjoining the target-projectile interface would exhibit the greatest amount of martensite. ii) The fraction transformed increases with decreasing temperature. The fraction transformed at the center of the specimens was computed and is shown in Figure 3. One can clearly see that the fraction increases from 0.07 to 0.5, as the temperature is decreased from -10°C to 50°C. By extrapolating the curve one can say that the M_S at the applied tensile stress level and for the tensile pulse duration is -5°C. The prediction from Patel and Cohen's (2) rationalization is quite different: i) One cannot extrapolate linearly from Patel and Cohen's (2) experiments, ii) Patel and

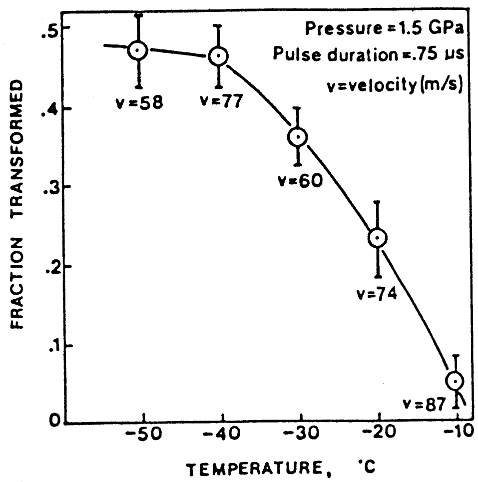

Figure 3. Variation of fraction transformed as a function of temperature, at a constant pressure and pulse duration.

Cohen's results apply to a quasi-static stress situation, while the present results apply to stress pulses of the order of one microsecond.

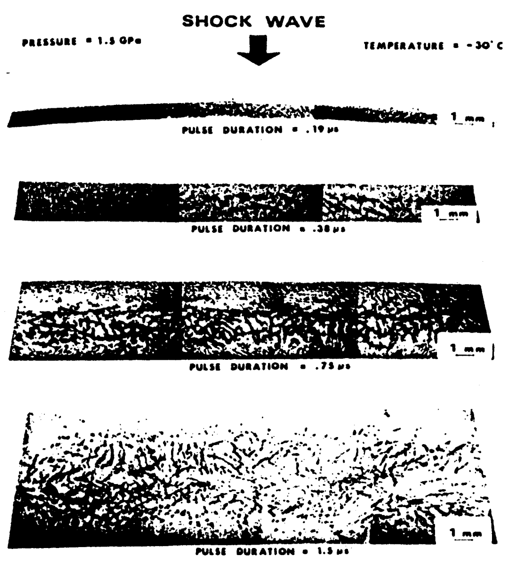

Figure 4. Cross-sections of targets impacted at a constant temperature (-30°C) and pressure (1.5 GPa) and varying pulse duration.

In the second series of experiments the temperature (-30°C) and pressure (1.5 GPa) were kept constant, while the pulse duration was varied between 0.19 μs and 1.5 μs. The cross-sections of the four targets are shown in Figure 4. The projectile thickness/target thickness ratio was kept constant at 1/2, and this is evident from the martensite distribution. The corresponding transformed fractions at the center of the specimens are shown in Figure 5. If one accounts for the difference in impact velocity between the various experiments (due to uncontrollable factors) one can say that the fraction transformed increases with the duration of the tensile pulse; the 0.19 μs specimen was impacted at a velocity higher than the desired one, while the 1.5 μs target was impacted at a lower velocity (73 m/s). The respective velocities are shown below the data points in Figure 5. These results lend strong support to the hypothesis of the isothermal nature of the "athermal" transformation suggested by Entwisle (8). However more accurate experiments are needed to quantify this effect.

3.2 Shock-Wave Induced Inhomogeneities

The martensitic transformation observed in Figures 2 and 4 is not homogeneously distributed, but tends to occur, in the plane of the section, in "stringers". These "stringers" seem to be associated with regions of strain inhomogeneities, as evidenced by Figure 6, which shows the section of the specimen subjected to a pressure pulse of 1.5 GPa, and duration of 0.75 μs at the temperature of -30°C (shown in Figure 4). The inclined illumination (produced by Nomarski prism) accentuated the irregularities of surface relief produced by etching. It can be seen that the "stringers" tend to align themselves with

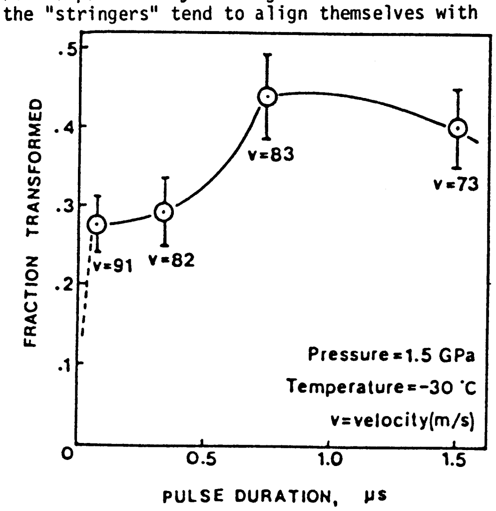

Figure 5. Variation of fraction transformed as a function of pulse duration, at a constant nominal velocity and temperature.

Figure 6. Cross-section of specimen impacted at $-30^{\circ}C$, 1.5 GPa, and 0.75 μs, showing martensite stringers and linear features on parent phase.

the surface irregularities. This is especially evident by the region indicated by an arrow in Figure 6. No clear directional pattern could be found in the various specimens. These streaks were absent prior to impact and are a result of impact. They do not follow the crystallography of slip within the grains. Inhomogeneous plastic flow produced by the low amplitude shock wave seems to be the cause of the streaks; Davison and Graham (10) describe heterogeneous yielding and indicate that it is an important feature of low-amplitude shock loading. It is well known that martensitic transformation is affected by both elastic and plastic stresses. Hence, this inhomogeneous plastic flow could produce regions of higher dislocation density or residual stresses where martensite nucleation could be favored. In this sense, the martensitic "stringers" act as markers, making these regions more visible.

4. CONCLUSIONS

a) It is shown that tensile pulses produced by the reflection of shock waves at a free surface can induce martensitic transformation above the ambient pressure M_s in an Fe-32.3 wt pct Ni-.035 wt pct C alloy.
b) The martensitic transformation, considered to be athermal for this alloy system, seems to exhibit an isothermal behavior in the microsecond regime.
c) The martensitic transformation occurred in "stringers", which seem to be associated with inhomogeneities of plastic flow induced by the shock wave.

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