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Inhomogeneities of shock-wave deformation in Fe-32 wt. % Ni-0.035 wt. % C alloy

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Low-pressure plane impact experiments performed on Fe-32 wt. % Ni-0.035 wt. % C alloy revealed, after recovery, markings which are attributed to shock-induced inhomogeneities. Shear of the material does not occur homogeneously, but in preferential planar regions. These regions are made visible by a martensitic transformation [fcc (austenite)→bcc (martensite)] produced by the tensile pulses generated by the reflection of the compressive shock wave at a free surface. The bands with higher plastic deformation served as preferential nucleation sites for martensitic transformation. The formation of these bands is attributed to inhomogeneous yielding due to work softening of the material during tensile loading.

A high-purity inclusion free Fe-Ni-C alloy produced by vacuum induction melting was used in this investigation. Its composition was found by chemical analysis to be Fe-32 wt. % Ni-0.035 wt. % C. The alloy, received in the form of a 15.5-mm-thick plate, was rolled down to a thickness of 10 mm and heat treated in vacuum at 1100 °C for two hours. The M_S (temperature at which martensitic transformation starts by cooling) was estimated, by resistivity measurements, to be − 60 °C for the Fe-Ni-C alloy.

The SRI-International 63.5-mm (2.5-in)-diam gas gun was used for the shock events. The purpose of the shock 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 waves on reflection generate a tensile pulse. AISI 304 stainless steel and 6061-T6 aluminum were used for the projectiles. The projectile always had a thickness equal to half the target thickness, which ensured that the maximum tensile pulse occurred close to the center of the target. In order to avoid lateral tensile pulses in the target, a "puck" with a diameter of 30 mm was inserted in a larger 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 so chosen that a uniaxial strain configuration was assumed in the central puck, throughout the duration of shock wave propagation. The detailed experimental setup is described elsewhere.[1]

The recovered target disks were sectioned along the vertical axis and mechanically ground and polished using conventional techniques. After the final mechanical polishing step (0.05-μm alumina suspension), the surface was chemically polished in a solution of 80% H_2O_2, 5% HF, and 15% H_2O. The chemical activity of the martensite (transformed phase) is greater than that of the austenite (retained parent phase), so that the martensite etches preferentially. In a similar way, regions with higher plastic strain show a greater activity.

Martensitic transformation[2] is known to be affected by the applied stresses and comprises a dilatational strain of 0.04 and a shear strain of 0.18. Patel and Cohen[3] established that martensite formation is favored by uniaxial tension and compression stresses, and is opposed by hydrostatic compression stresses. Based on this rationalization it was inferred that since hydrostatic compressive stresses oppose the transformation, hydrostatic tensile pulses should raise the M_S temperature and favor the transformation.

Impact experiments were performed as a function of pressure, temperature, and duration of the tensile pulse. The threshold pressure for the transformation to occur, without subsequent spalling, was estimated to be 1.4 GPa for temperatures less than − 10 °C. This dynamic failure would be undesirable because of the relief waves generated by the new surfaces produced by the spall. Figure 1 shows the micrographs of the cross sections of recovered target specimens impacted at a constant stress level (1.4 GPa) and temperature (− 40 °C), and tensile pulse duration ranging between 0.22 to 1.76 μs. The transformation product (martensite) can be perfectly distinguished from the parent phase because it appears darker and is localized in the center of the targets where the tensile pulse is of maximum amplitude and duration. It can also be seen that the transformed phase appears in the form of linear stringers, with thicknesses between 0.1 and 0.5 mm, running in different directions. The amount of transformation is also observed to increase with increasing pulse duration.

In order to perceive a variation in the duration of tensile pulse in a single event, an experiment with a slanting flyer plate[4] was performed. A flyer plate with varying thickness, such that the two flat faces are not parallel (tapered at 8°), was used. This ensured a variation in pulse duration ranging from 0.25 to 0.80 μs across the diameter of the target specimen.

Figure 2 shows the micrograph of the cross section of a specimen impacted with a slanted flyer plate projectile at a velocity of 95.7 m/s. This micrograph was taken with the Nomarski prism technique; it distinctly shows the marten-

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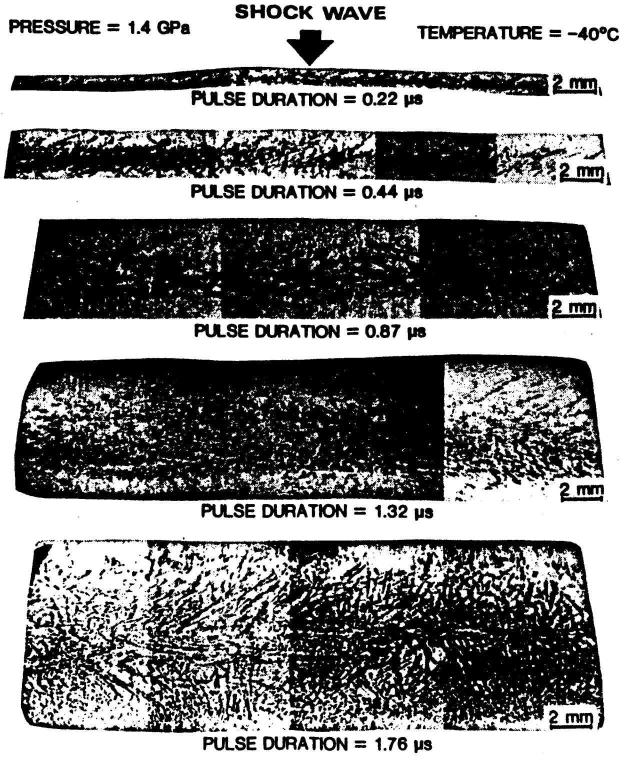

FIG. 1. Micrographs of cross sections of recovered targets impacted at varying tensile durations and constant temperature (− 40 °C) and impact pressure (1.4 GPa).

site phase running as stringers. The regions near the impact and free surface show the presence of linear features or bands and the martensite stringers appear to have preferentially nucleated along these bands. The enlarged view of the insert in Fig. 2 illustrates this effect very clearly. Thus, it can be concluded that the martensite stringers form on bands of highly strained material. These bands are only observed in impacted specimens (specimens that were not impacted were prepared by the same technique and did not exhibit bands), and are more pronounced in specimens subjected to lower pressures. In specimens impacted at higher temperatures (> − 10 °C) and containing no martensite, the bands ran undisturbed along the complete width of the impacted tar-

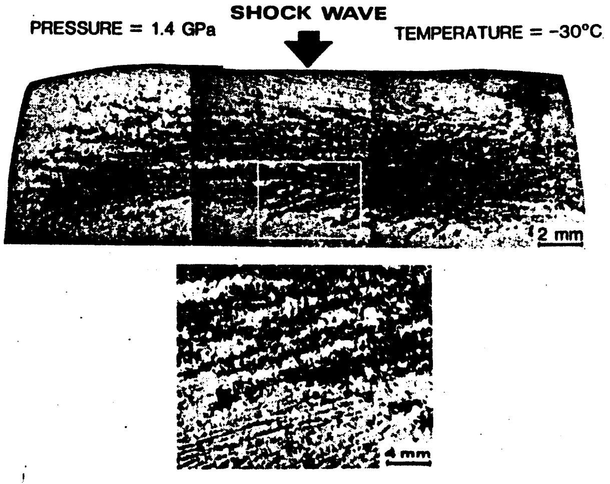

FIG. 2. (a) Micrograph of cross section of recovered target impacted with a slanted flyer plate at − 30 °C. (b) Magnified view of the insert in (a).

Figure 3 is a micrograph of a part of the width of the cross section of a specimen showing this feature. The bands (marked by arrows A and B) near the impact and free surface run from edge-to-edge, forming a bow in the middle. At the center of the cross section, the bands (marked by arrows C and D) run parallel to the surfaces.

In specimens which had undergone the transformation, the pattern of bands is more irregular. They seem to follow a pattern which is consistent with the distribution of tensile pulses in the target specimen. This is clearly evident in Fig. 4, where the bands appear more intense at the position of maximum tensile pulse duration. As the impact and back free surfaces are approached the spacing between the bands increases and their intensity decreases. It is worth mentioning that these bands do not follow the crystallography of slip within the grains; nor are they aligned along planes of maximum shear.

The formation of these bands and the preferential nucleation of martensite stringers along them could be a manifestation of chemical inhomogeneities in the alloy. It was therefore essential to determine any significant variations in the contents of nickel or any other elements (e.g., Ti, Al, Si, S) in the alloy. An electron microprobe analysis was performed on the unshocked (as-annealed) and shocked specimens. Compositional variations were determined by scanning along two positions across both the width and thickness of the specimens. Figure 5 shows the variation of nickel across the thickness and width of the unshocked and shocked specimens. Although there is some scatter in the nickel content of the alloy (due to insufficient homogenizing time during heat treatment), there does not appear to be any directional pat-

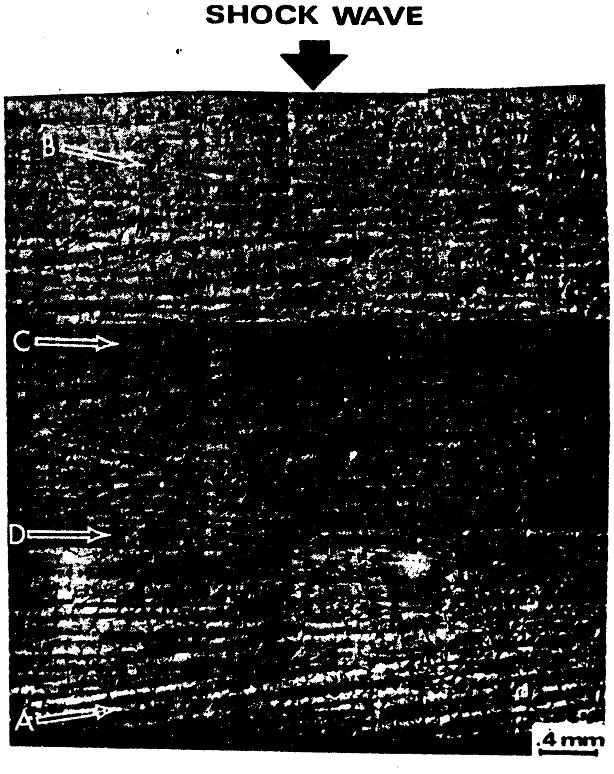

FIG. 3. Micrograph of the specimen impacted at − 10 °C amd 1.4 GPa showing shock-induced bands running undisturbed across the complete cross section of the target.

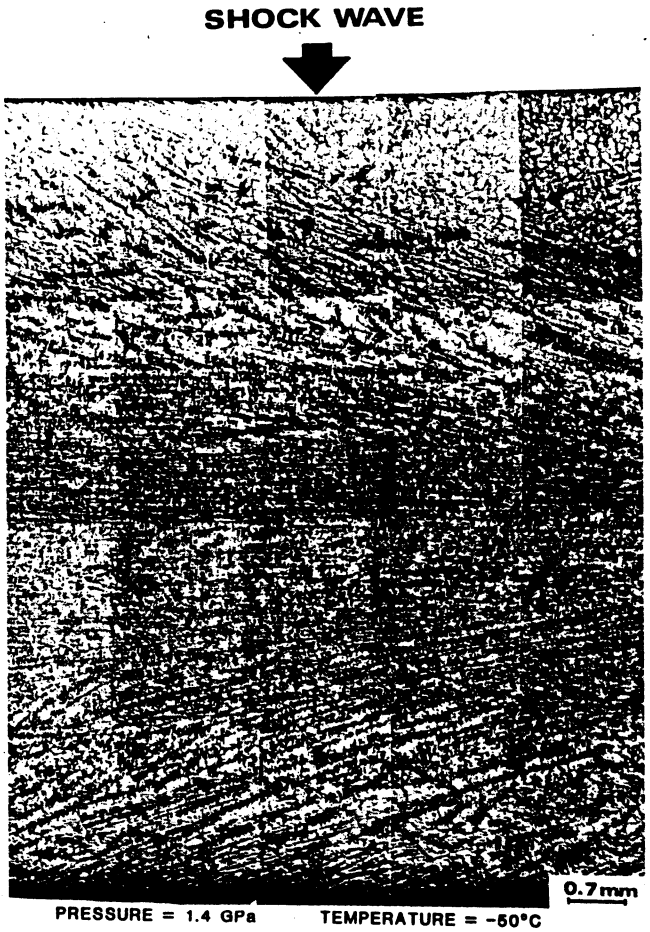

FIG. 4. Micrograph of cross section of specimen impacted at − 50 °C and 1.4 GPa, showing martensite stringers along bands in a pattern of the distribution of tensile waves.

tern in the variation of nickel, which could be considered to account for the formation of the bands. Hence these bands are an effect of shock deformation.

One can associate the formation of these bands to an heterogeneous yielding phenomenon[5] similar to "Luder's bands." Heterogeneous yielding is thought to be the result of a localized shear process like adiabatic shear banding. This is generally observed in metals deformed under very rapid loading conditions. These bands are highly stressed and strained regions as compared to the adjacent matrix.

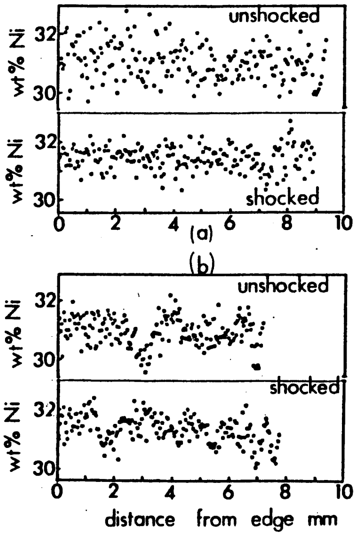

FIG. 5. Variation of nickel in unshocked and shocked specimens across (a) thickness, and (b) width.

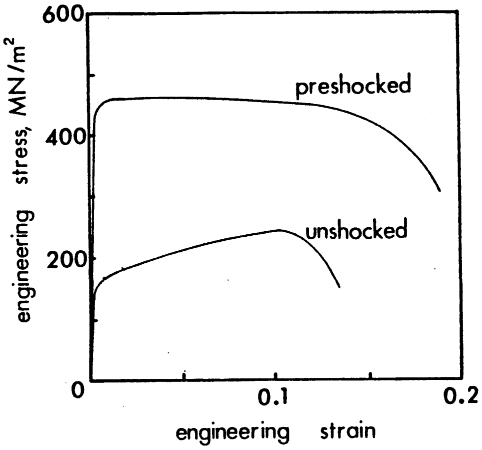

FIG. 6. Engineering stress vs engineering strain tests for unshocked and shocked target specimens.

The observed instabilities in plastic flow could be due to either mechanical or thermal softening. It is not felt that thermal softening alone can account for these bands, since the impact pressure is fairly low and the temperature rise is not significant. Mechanical softening on the other hand, could be playing an important role. Meyers[6] observed that the substructure introduced by shock loading nickel at 20 GPa was unstable upon postshock tensile deformation; shock loaded nickel work softened beyond the yield stress. In order to investigate this hypothesis, quasi-static tension tests were performed on Fe-32 wt. % Ni-0.035 wt. % C alloy specimens of a substandard size (10-mm gage length and 2.3 mm^2 in cross-sectional area) in the unshocked (as-annealed) and preshocked conditions. Figure 6 shows the engineering stress versus engineering strain curves for the unshocked and preshocked specimens. The curve for the preshocked specimen has a flat plateau following the yield point, whereas the unshocked (as-annealed) specimen shows conventional work hardening. It is presumed that since the preshocked specimen did not show any work hardening in the quasi-static tension test, it would in fact undergo work softening under dynamic loading conditions.

Work softening is a manifestation of dynamic recovery, once the yield stress of the material is reached. Hence, what is happening is that the material is first shock hardened by the passage of the compressive shock wave. It then appears that the tensile stress pulse following the compressive shock wave forces the material to undergo inhomogeneous yielding because of work softening, preferentially along bands. The onset of plastic flow in these regions would result in a decrease of the dynamic flow stress with a subsequent concentration of deformation. Hence, this inhomogeneous plastic flow could produce regions of high dislocation density or favorable residual stresses, thereby favoring preferential martensite nucleation. In this sense the martensite stringers act as markers, making these shock-induced inhomogeneous regions more visible.

Hence the following conclusions can be drawn: (a) Shock-induced inhomogeneities manifesting themselves as planar regions with random crystallographic orientation are observed in a Fe-32 wt. % Ni-0.035 wt. % C alloy impacted at 1.4 GPa pressure. Adjacent planar regions are parallel, but no systematic orientation relationship with the shock propagation direction is observed; (b) These bands are made more evident by the preferential nucleation of martensite stringers along them; (c) The bands are not formed because of chemical inhomogeneities and are observed only in shock-loaded specimens; (d) The formation of these bands is the result of inhomogeneous yielding because of work softening undergone by the material during the tensile phase of dynamic loading.

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