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Short Communication

The effects of shock-loading temperature and pulse duration on the tensile response of AISI 304 stainless steel

MARC A. MEYERS

Department of Metallurgical and Materials Engineering, New Mexico Institute of Mining and Technology, Socorro, NM 87801 (U.S.A.)

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The residual substructure of shock-deformed AISI 304 stainless steel has been shown to consist of a mixture of planar arrays of dislocations, stacking faults, twins, α martensite and ϵ martensite (*e.g.* refs. 1 - 5). The relative amounts of these different defects have been shown to depend on peak pressure [4], pulse duration [4], position within specimen [6], grain size [3] and *pre explosionem* substructure [7]. In this communication we report an additional effect: shock-loading temperature.

AISI 304 stainless steel sheet (3.2 mm thick) was shock loaded at a peak pressure of 14.8 GPa and initial pulse durations of 1.2, 2.4 and 10.1 μs, after it had been annealed at 1073 K for 1 h to yield a grain size of 23 μm. Six separate explosive events were conducted: three at ambient temperature and three at 77 K. The stainless steel strips were included in the systems used to shock load nickel; the experimental details have been described previously [8].

Semiquantitative magnetic measurements were conducted on the samples of AISI 304 stainless steel after shock loading. The distance at which the attractive forces between the ferromagnetic sample and a magnet started to produce movement in the sample with specified dimensions was measured. The higher the ferromagnetism, the larger is the critical distance. Table 1 shows these distances. The force decreases with the square of the distance; hence an arbitrary scale is presented in Table 1 by squaring the critical distances. It should serve for comparison between the magnetization of the different specimens since α (b.c.c.) martensite is the only ferromagnetic phase; the magnetization is directly proportional to the amount of α martensite. The data of Table 1 show that (a) at both 77 and 300 K the amount of martensite increases with pulse duration and (b) the amount of martensite transformed at a fixed pulse duration is greater for the 77 K event. In order to ascertain that no α martensite was introduced exclusively by the low temperature, an AISI 304 stainless steel sample was dipped into liquid nitrogen; after removal, no attraction to a magnet was noticed. So it can be concluded that all martensite was introduced by the application of the shock pulse. The results of the room temperature shock events confirm the transmission electron microscopy observations of Murr and Staudhammer [4]. The same trend is observed for the 77 K events; however, for these conditions the volume fraction transformed is much higher. Since the residual deformation for AISI 304 stainless steel was much less than that of nickel, conditions can be taken as acceptable for shock wave propagation. The much greater amount of transformed α martensite at 77 K is also expected. The M_s temperature for this alloy should be close to 0 K; Manganon and Thomas [9, 10] found that $M_s < 4$ K and $M_d \approx 300$ K for AISI 304 stainless steel. It is well known (*e.g.* ref. 11) that for a certain

TABLE 1

Effect of shock-loading parameters and temperature on the amount of α (b.c.c.) martensite formed

Shock-loading system	*Distance for motion* (cm)	*Amount x of martensite*
1.2 μs; 300 K	1	1
2.4 μs; 300 K	1	1
10.1 μs; 300 K	2	4
1.2 μs; 77 K	4	16
2.4 μs; 77 K	4	16
10.1 μs; 77 K	6	36

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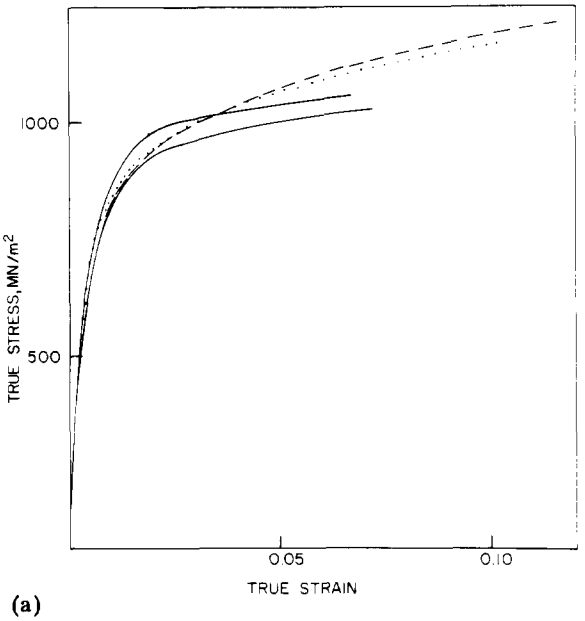
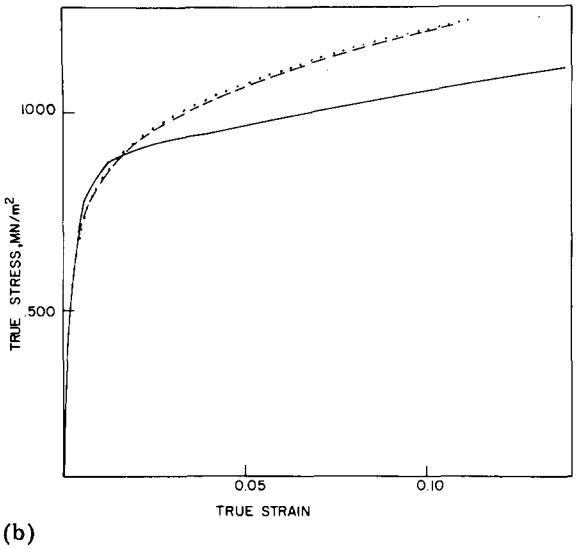
plastic strain the amount of martensite decreases with increasing temperature (above M_s).

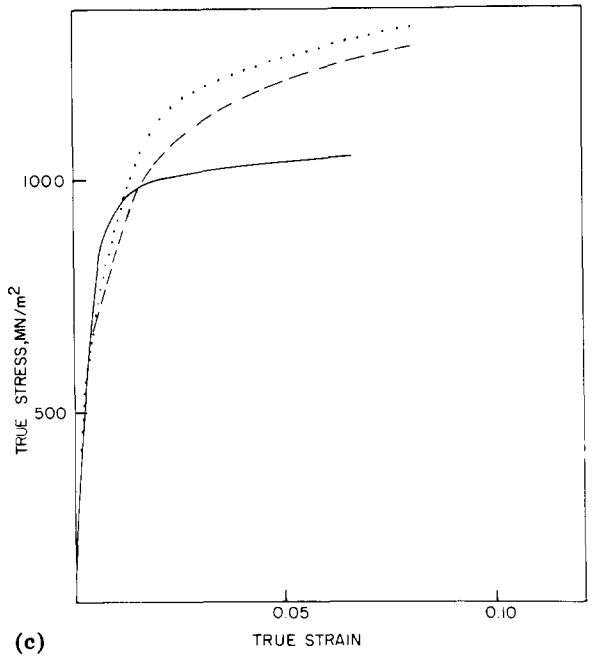
These differences in α martensite content did not result in any noticeable difference in the hardnesses of the various specimens. However, the tensile curves exhibit significant differences. Figure 1 shows the true stress–true strain curves for the six conditions. The curves were interrupted at the ultimate tensile strength. It is difficult to establish a yield stress for the different curves because of the gradual elastic-to-plastic transition and of the high initial work-hardening rates (especially for the low temperature explosive events). Therefore they are not given. The most striking difference between the low and high temperature events is the higher work-hardening rates for the low temperature events. These higher work-hardening rates are undoubtedly associated with the higher α martensite content of these conditions. Indeed, Ashby [12] investigated the effect of rigid particles on the stress–strain curves of metals in terms of statistically stored and geometrical-



(a)



(b)



(c)

Fig. 1. Effect of shock-loading parameters and temperature (– – –, · · · ·, 77 K; ——, 300 K) on the *post explosionem* tensile response in AISI 304 stainless steel for various pulse durations: (a) 1.23 μs; (b) 2.4 μs; (c) 10.1 μs.

ly necessary dislocations. He established that rigid particles generate large numbers of geometrically necessary dislocations which are responsible for the increased work-hardening rates. In the present case, we could apply this rationale to explain the differences. The α martensite is not rigid but presents a barrier to the motion of dislocations and would certainly be responsible for inhomogeneities in deformation during tensile testing. This, in turn, requires geometrically necessary dislocations which would be added to the already-existing statistically stored dislocations. Since the flow stress has been found to be proportional to the square root of the total (geometric and statistical) dislocation density, we would expect an increased work-hardening rate in the presence of α martensite.

We can only speculate as to which portion of the shock pulse is responsible for α martensite formation. It is doubtful that α martensite is formed at the front; if this were the case, there would be no effect of pulse length. The second possibility, α martensite formation during the duration part of the wave, is more realistic. Manganon and Thomas [9, 10] have established that, in AISI 304 stainless steel, deformation-induced martensite nucleates heterogeneously at the intersections of ϵ bands or where the ϵ bands abut twin or grain boundaries. It is well known that the formation of martensite is controlled by its nucleation; its growth can proceed at velocities of one-third of the velocity of sound [13]. We can perform a simple calculation for a hypothetical situation. It would take 0.017 μs for a plate with a length of 25 μm to grow. This is two orders of magnitude below the pulse duration; so it must be concluded that the growth of martensite is not hindered by the short duration. There seems to be a delay before nucleation takes place. However, it is the third possibility, α martensite formation at the rarefaction (release) portion of the wave, that is the most realistic, in our opinion. The rarefaction rates varied widely with pulse duration. As quoted in ref. 8, Table 1, the rarefaction rates (the slopes of the release portion of the wave) are -51 GPa μs^{-1}, -33 GPa μs^{-1} and -11 GPa μs^{-1} for the 1.2 μs, 2.4 μs and 10.1 μs events respectively. The formation of α martensite produces a lattice expansion. Hence it would be favored during the release portion of the wave, when the pressure is decreasing and local interactions might produce favorable conditions. If we look at the pressure–temperature diagram for iron, α formation (from γ (f.c.c.)) would only be favored during a pressure decrease cycle. It is also known that the amount of α martensite formed decreases with increasing strain rate [14]. The strain rates in the release portion of the shock pulse decrease with increasing pulse duration. Hence, a greater amount of α formation would be expected for the 10.1 μs pulse duration event; this is indeed observed for both the 77 K and the ambient temperature events.

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