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THE INFULUENCE OF SHOCK PRE-STRAIN AND PEAK PRESSURE ON SPALL BEHAVIOR OF 4340 STEEL

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A fundamental study of the influence of peak stress amplitude and pre-strain on the spall fracture of pearlitic 4340 steel is presented. Spall tests were performed at projectile velocities to achieve approximately 5, 10 and 15 GPa peak stress amplitudes. Some spall tests were preceded by a pre-shock and recovery test at 10 and 15 GPa. Spall strength measurements suggest that there is a decrease in the spall strength of 4340 with an increase in the shock wave amplitude as the transition pressure of 13.1 GPa is approached. At this transition pressure, a substantial increase in the spall strength, as well as a change in a mode of fracture from brittle to ductile are observed, both attributed to the allotropic phase transformation at this amplitude.

I. INTRODUCTION

The majority of shock-spall studies have concentrated on investigating the dynamic fracture and strengthening of annealed or stress-relieved metals and alloys [1,2]. Few studies have explored the shock response of materials possessing a pre-existing dislocation substructure formed via heat treatment, quasi-static deformation or prior shock loading [3-6].

An additional complication in the dynamic response of iron and steels is the reversible, allotropic phase transformation which occurs at approximately 13 Gpa. Above this pressure the spall morphology [7-13] and the measured spall strength of iron and alloyed steel (this study) changes drastically. The phase transformation, α to ϵ and back to α, has been linked to the change in the mode of fracture from brittle to ductile and to the formation of the smooth fracture topography at spall pressures above 13 GPa [7-13].

The purpose of this study is to correlate the measured changes in the spall strength and the observed changes in fracture morphology with the peak stress amplitude and the changes in deformation substructure caused by the shock preceding the spall test.

II. EXPERIMENTAL PROCEDURE

The material used in this investigation was pearlitic 4340 steel. Shock recovery experiments, preceding spall, were performed using an 80-mm single-stage-gas gun as described elsewhere [6,14]. The flyer plates and all assembly components were fabricated from 4340 steel.

The spall assembly consisted of a 7-mm-thick, 19-mm-dia sample, surrounded by two concentric rings with outside diameters of 25.4 and 57 mm. The sample and the surrounding rings were placed on a plexiglass backing plate (1.37-mm-thick) and then on a plexiglass holder 5.7-mm-thick and 76-mm-dia. A manganin gauge measuring the resistance vs. time response during the spall test, was placed immediately behind the center of the sample and sandwiched between the plexiglass backing plate and plexiglass holder.

Spall tests with and without a shock pre-stresses were performed at 5, 10 and 15 GPa peak stress amplitudes for a 1-μs pulse duration. Some spall samples were pre-shocked in a shock recovery test at 10 and 15 GPa peak stress amplitude for 1-μs. The residual plastic strain in the pre-shocked samples (defined as the change in sample thickness divided by the starting sample thickness) was $\leq 2\%$. All samples were soft-recovered in a water catch chamber positioned behind the impact area. The fracture topography of all the spalled samples was analyzed using scanning electron microscopy (SEM). In addition, samples for optical and transmission electron microscopy (TEM) were cut from selected shock recovered and spalled samples.

III. RESULTS AND DISCUSSION

In order to present the results it is of value to examine the effects of shock pre-stress on the microstructure and stress-strain curves obtained by subsequent reloading. The microstructures of samples subjected to peak stress amplitudes below the level needed for the phase transformation consisted of a lower density of deformation twins and dislocations than observed in samples which were spalled at 15 GPa or pre-shocked at 15 GPa and subsequently spalled at either 10 or 15 GPa. Fig. 1 shows the high density of dislocations and deformation twins observed in 4340 pre-shocked at 15 GPa. This high density of dislocations combined with the high density of twins is reflected in the increase in the reload yield stress from 350 MPa for the annealed pearlitic 4340 steel to 500 and 620 MPa for 4340 samples which were pre-shocked at 592 m/s (10 GPa pressure) and 871 m/s (15 GPa pressure), respectively (Fig. 2). The reload stress-strain curves of the shock-recovered 4340 further show that, the rate of strain hardening is higher initially and then quickly saturates. Due to the shock hardening introduced during the pre-shock the sample appears to be saturated by a high density dislocation networks and numerous deformation twins, prior to the spall event. This microstructure may provide the nucleation sites for either brittle or ductile fracture.

Spall experiments were conducted on both as heat treated and shock pre-stressed samples. The spall strength are summarized in Table 1. The numbers reflect an average of two or more tests.

The spall strength measurements suggest that there is a decrease in the spall strength of 4340 associated with an increase in the spall pressure up to the α - ϵ transformation pressure. Samples spalled above this pressure show a significant increase in the spall strength combined with a change in the mode of fracture, from cleavage below, to ductile fracture above the phase transition pressure. Shock pre-stressing prior to the spall is observed to substantially change the spall strength of the sample, decreasing the gap between the spall strength of the sample tested in a simple spall test, (below and above the phase transformation pressure), but no significant change with respect to the fracture mode is observed. Samples spalled below the phase transformation pressure either directly or preceded by a pre-shock regardless of pressure, exhibit a cleavage fracture mode, shown in Fig. 3. Fig. 4 shows the ductile mode of fracture obtained in a spall test performed at a pressure above 13 GPa. This fracture appearance is representative of the fracture obtained in a simple spall test or a spall test preceded by a pre-shock at an amplitude of 10 or 15 GPa.

TABLE 1

	SPALL STRENGTH (GPa)		
Pressure Amplitude (GPa)	Spall Test	Pre-shock at 10 GPa and Spall	Pre-shock at 15 GPa and Spall
5	- 3.1(B)	NA	NA
10	- 2.6(B)	- 2.3(B)	- 2.8(B)
15	- 4.8(D)	- 2.9(D)	- 3.9(D)

(B) corresponds to brittle mode of fracture
(D) corresponds to ductile mode of fracture

In discussing the results it is of value to consider three important features: i) the decrease in spall strength with increase shock pressure up to the 13 GPa, ii) the observation that in the brittle spall regime (i.e. below 13 GPa) the spall strength is independent of shock pre-stress, iii) the decrease in spall strength in the ductile regime (i.e. greater than 13 GPa) for shock pre-stress of 10 or 15 GPa.

In spall fracture it is difficult to consider the separation of nucleation and propagation events in the fracture process. However, in the brittle process at lower pressures, cleavage is influenced by the local hydrostatic pressure [15]. Thus in the spall process the fracture occurs under triaxial tension. As the superimposed hydrostatic tensile pressure increases with shock pre-stress, the spall strength decreases. It is important to note, that the spall strength is independent of shock pre-stress in the brittle regime. This suggests that the brittle fracture process is dynamic and therefore independent of work hardening and damage induced by pre-shock. If we now consider the change in fracture mode with pressure, the question arises as to why there is such a pronounced change in the mode of fracture in this material associated with the allotropic phase transition, as shown in Figs. 3 and 4. In addition, the fracture surface morphology of the 4340 steel spalled at 15 GPa is very smooth in comparison to the rough surface of the sample spalled at 10 GPa. Several studies have previously investigated this problem [7-13]. Erkman [7], Banks [8] and Barber and Hollenbach [9] have all proposed that formation of a smooth spall is related to the existence of a rarefaction shock wave fan, created during the phase transformation at a high pressure. The phase transformation provides a sudden pressure drop in the wave resulting in a sudden rise in the tensile stress pulse occurring in a very narrow region. Therefore, the fracture region is very localized, as we have also observed by metallographic examination, and consequently the spall is much smoother in appearance. In the case of a spall below the phase transformation pressure, the tensile stress pulse increases slowly and monotonically, allowing for the deformation to occur in a wider region, and initiation of a large number of fracture sites. Consequently, we observe a very irregular deformation zone extending deep into the material. Our metallographic observations of the cross sections of spalled samples are consistent with this hypothesis.

An additional reason for the ductile mode of fracture at a higher stress amplitude, may be a sudden local increase in temperature, prompted by the thermodynamics of the phase transformation and a high deformation strain rate localized in a very narrow region. Recently, Zehnder and Rosakis [16], used an infrared method to measure the local temperature increase at the vicinity of dynamically propagating cracks in 4340 steel. Their experimental data show that a temperature increase of up to 465°C may occur at the tip of the dynamically propagating cracks in 4340 steel, and that the region of intense heating (> 100°C) may extend to as much as a third of the active plastic zone size. Others have shown that such a temperature increase in Armco iron [17] or in low carbon steel [18], deformed at a strain rate of approximately 10^4 s^{-1}, is sufficient to promote ductile fracture even when the spall pressure is far below that necessary for the α - ϵ phase transformation. This temperature is above the dynamic fracture toughness corresponding to the ductile-to-brittle transformation temperature DTBT, promoting void growth and coalescence. Thus at pressures above 13 GPa we propose that either the substructure modifications due to the α - ϵ and ϵ - α transformations or the local temperature increase may raise the stress for brittle fracture above the peak stress level. Hence, ductile rather than brittle fracture is observed. The observation that the spall strength in the ductile regime is decreased by shock pre-stress is consistent with this model because both local deformation events occurring during pre-stress and the decrease in hardening capacity due to shock pre-stress would aid the ductile fracture process and thus lower the observed spall strength. Further experiments are in progress to examine the link between the deformation structure evolution and fracture behavior of 4340 steel.

IV. SUMMARY

In this study we measured the spall strength of 4340 pearlitic steel as a function of peak stress amplitude and pre-stress and correlated it with the mode of fracture and substructure evolution. It is evident from this study that the phase transformation has a major influence on the change in the mode of fracture from brittle (below), to ductile (above the 13 GPa pressure) and the spall morphology from rough (below) to smooth (above 13 GPa) and consequently on a spall strength. Spall strength of this material increases due to the phase transformation. Pre-stress decreases the spall strength of 4340 spalled at above the 13 GPa transition pressure, but does not change the mode of fracture. In addition, we have qualitatively rationalized the reason for the change in the mode of fracture from cleavage to ductile at 13 GPa. Although, we do not yet have conclusive evidence, the possibility exists that the excessive heating due to the localized deformation initiated by the phase transformation, combined with high dislocation and twin density may by itself be sufficient to initiate ductile mode of fracture in this material.

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Fig. 1

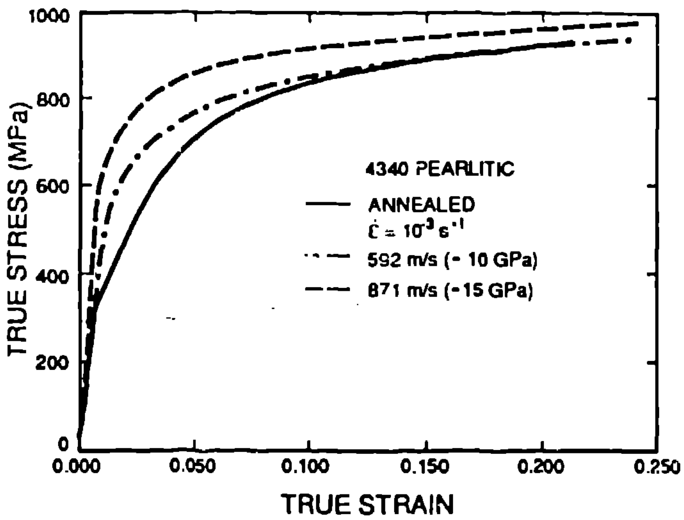

Fig. 2

Fig. 3

Fig. 4

FIG. 1. *Transmission electron micrograph of 4340 steel shock pre-stressed at 15 GPa showing high dislocation and twin substructure.*

FIG. 2. *The reload true stress - true strain curves of 4340 steel, as annealed, and pre-shocked at 10 and 15 GPa.*

FIG. 3. *Scanning electron micrograph of 4340 steel spalled at 10 GPa showing brittle mode of fracture.*

FIG. 4. *Scanning electron micrograph of 4340 steel spalled at 15 GPa showing ductile mode of fracture.*