New data on the kinetics and governing factors of the spall fracture of metals

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Abstract. This paper presents two examples of significant departures from usual trends of varying the resistance to spall fracture (spall strength) with changing loading history, load duration and peak shock stress. In experiments with vanadium single crystals we observed an important decrease of spall strength when increasing the shock stress. This was interpreted in terms of disruption of the matter homogeneity as a result of its twinning at shock compression. In experiments with 12Kh18N10T austenitic stainless steel we observed a sharp increase of recorded spall strength value when short load pulses of a triangular profile were replaced by shock pulses of long duration having a trapezoidal shape. This anomaly is associated with formation of the deformation-induced martensitic phase.

The resistance of materials to high-rate fracture at load during a few microseconds or less is studied by analyzing the spall phenomena. Spalling is the process of inertial rupture of a body due to tensile stresses that are generated as a result of a compression pulse which is reflected from the free surface of a body. Determination of the resistance to spall fracture (spall strength) is based on results of measurements of the free surface velocity history at spalling and on analysis of the wave interactions following the reflection of a compressive pulse from the surface [1–3]. The analysis is based on the method of characteristics. The main trends of the spall fracture phenomena are illustrated in figure 1 which presents examples of measurements of the free surface velocity histories for the titanium alloy Ti-6Al [4].

The stress in the material at the lowest impact velocity in figure 1 is below the spall threshold. As a result, the free surface velocity history practically replicates the shape of the compression pulse in the sample. With increasing the impact velocity and, correspondingly, peak shock stress the magnitude of the tensile stress in the reflected rarefaction wave increases. When the peak tensile stress reaches the spall threshold, damage begins to accumulate. The tensile stress in the damage accumulation zone relaxes as the fracture develops. As a result, a compressive disturbance called a “spall pulse” or “spall signal” appears on the free surface velocity history. Thereafter, wave reverberation is observed within the scab between the free surface and the damage zone. The period of velocity oscillation is a measure of the thickness of the scab (or spall plate). The velocity pullback, $\Delta u_{fs}$, is proportional to the value of maximum tensile stress which was generated in the sample plate just before the beginning of spall fracture. Approximately constant average speed of the surface indicates the completing of the spall fracture during the
Figure 1. Free-surface velocity histories for the Ti-6Al alloy samples at various peak stresses and load durations [4] created by impact of flyer plates of different thickness with different velocities (waveforms 1 to 4) and by detonation of an explosive charge (waveform 5).

first half-period of the velocity oscillations. Increasing the shock amplitude does not significantly influence the magnitude of $\Delta u_{fs}$ for the Ti-6Al alloy. Increase of the total duration of triangular load pulse is accompanied by a decrease of recorded value of the velocity pullback $\Delta u_{fs}$ that is a manifestation of the rate dependence of the resistance to spall fracture. The velocity pullback in the shot with thick impactor plate is smallest, and even smaller than the $\Delta u_{fs}$ value, in the experiment with triangular loading pulse of long duration. This is a result of the wave distortion due to different propagation velocities of the spall pulse front and the part of the incident load pulse ahead of it in the elastic-plastic media [1–3]. In this paper, we briefly present two examples of significant departures from these trends. Details of these experiments will be discussed later elsewhere.

Figure 2 presents some results of our recent experiments with 12Kh18N10T austenitic stainless steel. The steel is analogous to stainless steel of the type 304 in AISI specification and contains 17–19 mass % Cr, 9–11% Ni, 0.6–0.8% Ti, $\leq 2.0\%$ Mn, $\leq 0.12\%$ C, $\leq 0.3\%$ Cu, $\leq 0.8\%$ Si, and the rest of the composition is comprised of iron. In the as-received state, the steel is usually in austenite $\gamma$-phase with face-centered cubic lattice; plastic flow at temperatures less than 100 $\degree$C induces transition of austenite into the $\alpha$-martensite with body-centered cubic lattice. The martensite obtained in this way is called “deformation induced martensite” [5]. The martensite phase has greater hardness, slightly smaller density and is ferromagnetic whereas the austenite phase is paramagnetic.

In the experiments shown in figures 2–5, the pulses of shock compression were generated in plane samples by impacts of copper flyer plates at impact velocities in the range of 300 m/s to 350 m/s. In the shots shown in figure 2 the flyer plate thickness was around 20% of the sample thickness. The main difference of the waveforms in figure 2 as compared to figure 1 is in protracted, slowly evolving spall fracture: the spall plate remains connected with the main sample plate and continues to decelerate for a long period of time after the initial appearance of the spall pulse. Due to incompleteness of the fracture, we may observe secondary re-reflection of the load pulse from the impact surface which causes a new rise of the free surface velocity. Similar behavior of the stainless steel was also recorded for longer load durations [6].
Figure 2. Free surface velocity histories of the stainless steel samples impacted by thin copper flyer plates. The number at waveforms shows the flyer plate and the sample thickness values.

Figure 3. Results of experiments with thick flyer plates. The free surface velocity history of a 4.2-mm-thick sample impacted by 0.8-mm-thick flyer plate is shown for comparison.

A more interesting and unexpected effect was observed when thin impactor plates were replaced by thick plates. The results of these experiments are shown in figure 3. In this case, the tensile stresses before the spalling rose slower and the spallation occurred at a larger distance from the free surface than in experiments with thin impactors. The larger value of the kinetic energy stored in the separating plate provides fast completion of the fracture process in this case. The most interesting and unexpected feature of these data is anomalous increase of the velocity pullback $\Delta u_{fs}$ with increasing duration of the load pulse. It is noteworthy that in experiments with titanium alloy shown in figure 1 the transition from triangular to rectangular shape of the incident load pulse was accompanied by a large decrease of the recorded $\Delta u_{fs}$ value.
Figure 4. Free surface velocity histories from figure 3 shifted to the same maximum velocity and the same temporal position of the unloading front. The numbers at waveforms indicate thickness of spall plate $\delta$. $D$ is the point of departure of the free surface velocity history from its extrapolation.

Figure 5. The spall strength of stainless steel 12Kh18N10T as a function of strain rate in the incident unloading wave; $\sigma^*$ is the spall strength value calculated for the point “$D$” of the free surface velocity history from the experiment with thick impactor. At smaller strain rate the spall strength is approaching the standard value of the true tensile strength $S_k$ which for this steel.
Figure 6. The free surface velocity histories of vanadium monocrystalline samples of around 3 mm in thickness impacted with different velocities. Numbers at the waveforms correspond to velocity pullback values.

In figure 4 the waveforms are shifted relative to each other in order to illustrate the anomaly more clearly. If, instead of minimums of the free surface velocity, we shall use the points “D” of departure from extrapolation for calculating the spall strength, then the anomaly that is related to the dependence of the spall strength on the strain rate disappears. Figure 5 presents the spall strength data from new and earlier [6] experiments with triangular load pulses (thin impactors). Over the strain rate range from $10^4$ s$^{-1}$ up to $10^6$ s$^{-1}$ the data are well approximated by the power function:

$$\sigma_{sp} = A(\dot{V}/V_0)^{0.155},$$

where $A = 3.83/10^{0.93}$. At smaller strain rate the spall strength is approaching the standard value of the true tensile strength $S_k$ which for this steel is around 1.6–1.8 GPa.

In order to interpret the observed anomaly, one has to keep in mind two processes which may occur in this steel under tension: the fracture itself and the martensitic transformation. Both these phenomena are accompanied by volume increase and should produce similar effects in the free surface velocity histories. However, whereas the fracture may cause complete relaxation of tensile stress, the stress relaxation at martensitic transformation is limited by a value that is certainly not very big. Note that all samples became magnetic after shock-wave treatment with spalling that means martensitic transformation occurred in all cases. The martensitic transformation of this steel occurs during plastic deformation and the obtained martensite phase is much harder than austenite. The spall fracture proceeds by means of nucleation, growth and coalescence of numerous voids. The plastic strains are largest near the growing voids and, correspondingly, the vicinities of voids are the sites where martensitic transformation occurs first of all and, due to the increase in yield stress, decelerates or even stops the void growth. Obviously, the final manner of the process is determined by the interplay between rates of nucleation and growth of the voids and the rate of martensitic transformation.

Concerning the peak stress in the preceding shock wave, there are reported cases in the body of literature concerning both independence of the spall strength of the peak stress [1–3] and growth of the spall strength with increasing the peak shock stress [7,8] or even non-monotonic varying
Figure 7. SEM micrograph of a cross-section of vanadium single crystals after shock-wave treatment.

of the spall strength with peak shock stress [9]. The growth is explained by the work hardening
effect which leads to increased resistance to void growth [8]. Figure 6 presents another example.
In the experiments with vanadium single crystals shown in this figure, we observed a decrease in
recorded spall strength value with increasing peak shock stress: from 5.9 GPa at 7.4 GPa of the
peak stress down to 4.7–4.9 GPa at 21.3 GPa. Figure 7 shows a micrograph of the vanadium
single crystal recovered after shock-wave compression which probably explains this effect. The
micrograph demonstrates intense twinning of the material which probably presents the main
contribution into the mechanism of plastic deformation in the shock wave. The intersection of
twins produces concentration stresses that may create the fracture nucleation sites.

The presented examples show that the spall fracture process may be more complicated than
it is usually believed to be. Polymorphic transformation in the negative pressure domain may
unexpectedly increase apparent value of the spall strength at relatively large load durations.
Violation of homogeneity of single crystal by its twinning during shock compression decreases
following resistance to spall fracture. Observed effects are essential, make contribution into
overall fracture process, and require their theoretical descriptions.

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