

Peculiarities of evolutions of elastic-plastic shock compression waves in different materials

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Abstract. In the paper, we discuss such unexpected features in the wave evolution in solids as strongly nonlinear uniaxial elastic compression in a picosecond time range, a departure from self-similar development of the wave process which is accompanied with apparent sub-sonic wave propagation, changes of shape of elastic precursor wave as a result of variations in the material structure and the temperature, unexpected peculiarities of reflection of elastic-plastic waves from free surface.

1. Introduction

Measurements of decay of the elastic precursor wave are used to determine the initial plastic strain rate as a function of stress [1, 2]. In the last years we performed multiple series of experiments of such kind with metals and alloys, ceramics, and glasses [3–11]. In the course of these measurements we have observed several unexpected effects which have not got exhaustive explanations yet. The time range available for measurements has been expanded down to picoseconds, which allows approaching ultimate shear and tensile strengths and observations of general trends. One needs to analyze the material states very far from equilibrium that requires new models and approaches. In this paper we summarize these observations with the goal to stimulate deeper analysis of the wave dynamics in relaxing media.

2. Approaching the ideal strength

Figure 1 presents examples of determining the free surface velocity histories of iron films 250 nm and 540 nm in thickness irradiated by a femtosecond laser pulses [3]. They exhibit strong decay of both the compression pulse as a whole and the first shock wave of the two-wave configuration. The velocity of the first wave front is around 6.45 km/s, which means that the first wave is the elastic precursor wave. The compression stresses behind the elastic precursor front is 27.5 ± 2.5 GPa at 250 nm of the propagation distance and 11.0 ± 1 GPa at the distances of 250 nm.



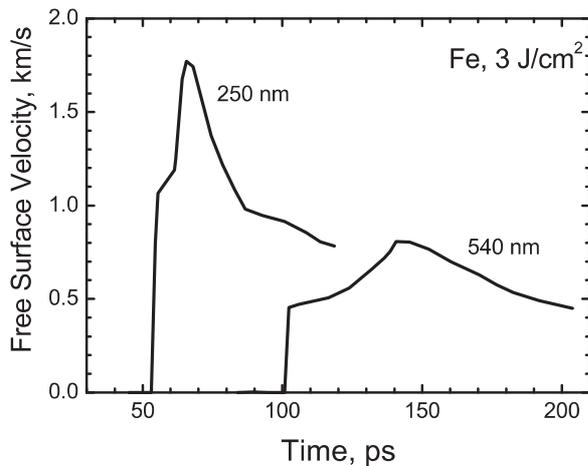


Figure 1. Evolution of compression pulses propagating in nanometer iron films [3].

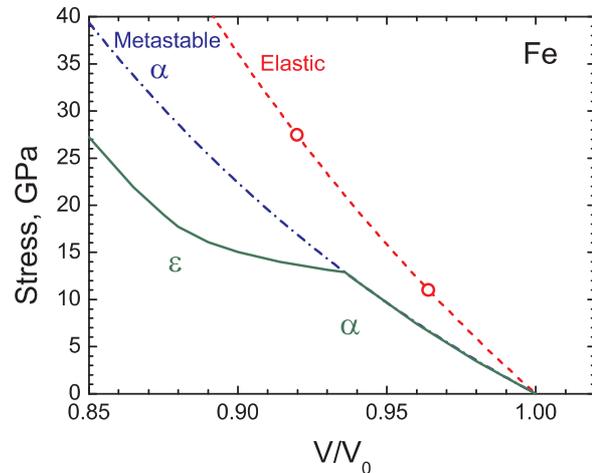


Figure 2. The phase diagram of iron with parameters of the state behind the elastic precursor front at distances of 250 and 540 nm.

Figure 2 presents corresponding diagram of states of the iron where the estimated metastable elastic Hugoniot, the equilibrium adiabat $p(V)$ of the low-pressure α -phase, and the Hugoniot with the transition to the high-pressure ε -phase are plotted. Besides of all, the diagram demonstrates essential non-linearity of the metastable elastic compression Hugoniot. For further analysis and simulations it would be useful to find simple universal approach for such metastable Hugoniots.

It has been shown earlier [12] a natural approach for estimations of longitudinal sound speed assuming constant Poisson's ratio is in reasonable agreement with known experimental data for metals. It would be interesting to check out whether or not this approach is applicable for metastable elastic Hugoniot. In this case the ratio of longitudinal and bulk sound speeds c_l/c_b is constant. Using the quasi-acoustic approach [12] for the bulk sound speed c_b it can be shown the ratio $c_l(V)/c_b(V)$ is the same at equilibrium and metastable Hugoniots only if the coefficient b in the linear relationship between the shock velocity U_S and the particle velocity u_p , $U_S = c_0 + bu_p$, is the same for both Hugoniots. Figure 3 illustrates applicability of this approach for existing experimental data.

3. Annealing effects

It is known that the annealing of work-hardened metals decreases their hardness and, correspondingly, their yield stress. It is, however, not necessarily true for sub-microsecond shock loading conditions. Figure 4 demonstrates difference of annealing effect on shock response of pure copper [6] and tantalum [7]. Whereas the Hugoniot elastic limit (HEL) of copper has been decreased significantly by annealing the HEL of tantalum (as well as some other *bcc* metals) has been increased. In the case of vanadium titanium whose response is shown in figure 5 the annealing resulted not only in the increase of HEL value but also in the change of the precursor shape. Appearance of a spike at the front part of the elastic precursor wave is an evidence of intense multiplication of dislocations immediately behind elastic shock discontinuity [13]. In principle, these observations do not contradict to existing data on strength properties of crystalline solids. In the crystals without dislocations, such as whiskers, the yield stress approaches its ultimate value. It, however, decreases rapidly with appearance of a small amount of dislocations and grows as soon as the dislocation density exceeds some certain "critical" value.

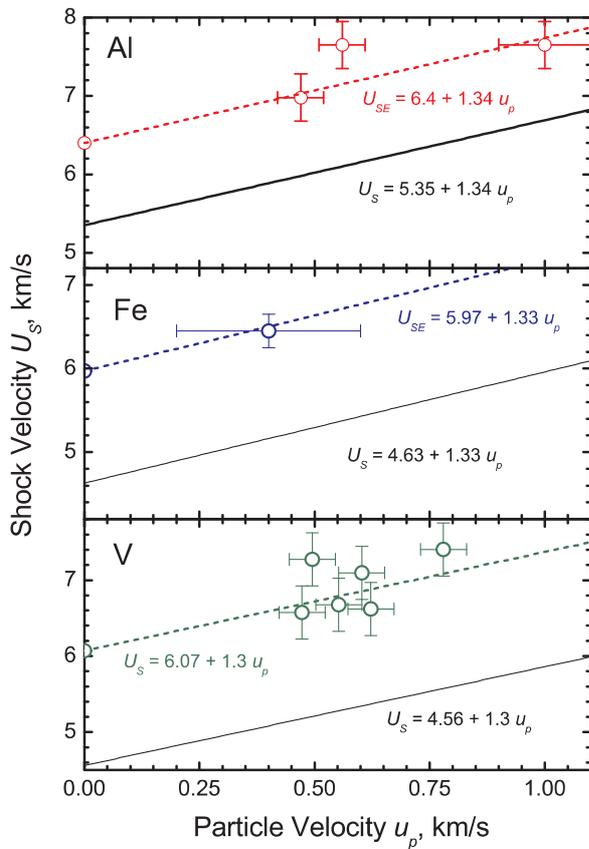


Figure 3. Experimental data on shock and particle velocities of the elastic precursor waves in thin films of aluminum [4], iron [3] and vanadium [5] in comparison with prediction based on the approach of constant Poisson’s ratio.

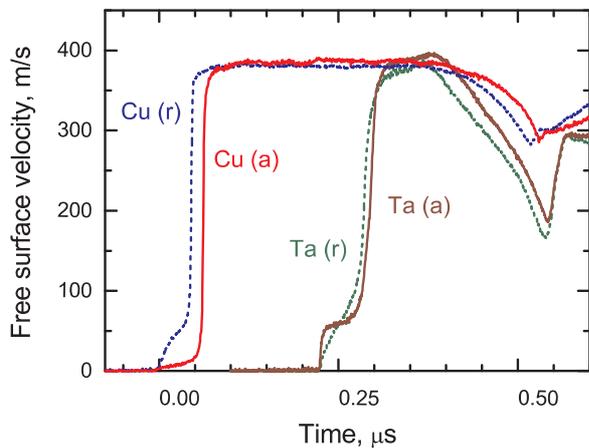


Figure 4. The free surface velocity histories of “as rolled” (dashed lines indexed as “r”) and annealed (solid lines indexed as “a”) copper [6] and tantalum [7] samples 2 mm in thickness.

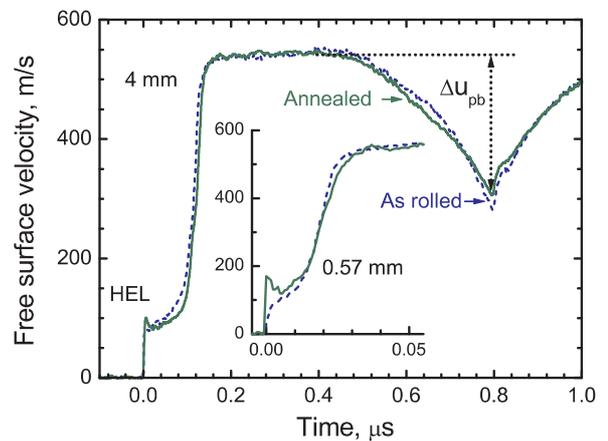


Figure 5. The free surface velocity histories of “as rolled” and annealed titanium samples of two different thicknesses.

Since the dynamic yield stress may grow with annealing while the static hardness may decrease at the same time, we may conclude that this “critical” dislocation density is different for different strain rates.

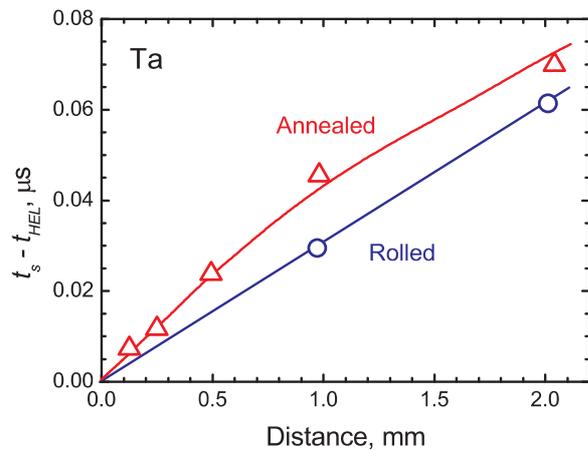


Figure 6. Time interval between middle points of the elastic precursor front and those of the plastic shock wave as a function of the propagation distance in experiments with as rolled and annealed tantalum samples.

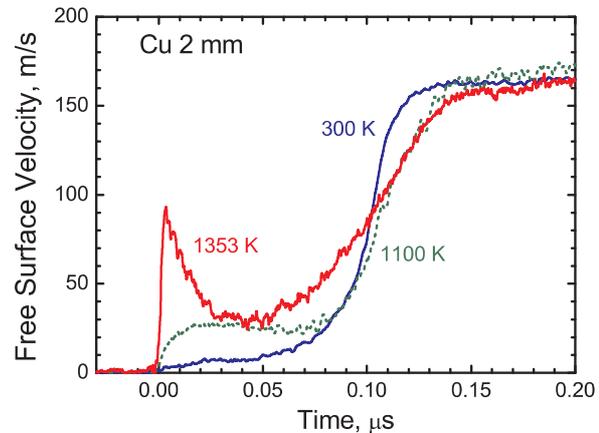


Figure 7. Front parts of the free surface velocity histories of 2-mm copper samples impacted at different temperatures [3].

It is apparent from figure 4 that annealing changes the time interval between elastic and plastic waves. Figure 6 presents results of measurements of these time intervals for as rolled and annealed tantalum as a function of the sample thickness. Apparent velocity of plastic shock wave at distances $h < 1$ mm is equal to the bulk sound speed c_b in tantalum; in some other cases it can be even less [8]. Subsonic velocity of plastic shock wave is often associated with loss of shear strength during shock compression [14], [15]. Actually, the later may be true only for steady waves while in the discussed examples we deal with the processes of establishing of the steady wave. Unsteady processes in relaxing media obviously require more sophisticated analysis which has not been done yet.

4. Multiplication effects

From strong non-linear dependences of the initial plastic strain rate just behind the precursor front upon its amplitude and from unexpectedly large values of the initial strain rate it follows that the process is controlled by the rate of nucleation or generation of dislocations rather than by their speeds [9]. It looks like a significant nucleation may occur already during compression in the elastic precursor front or just immediately after that. Figure 7 shows the front parts of the free surface velocity histories of 2-mm copper samples shocked at different temperatures [16]. The HEL grows with increasing temperature as a result of increasing phonon drag [16]. The dispersion of the elastic precursor front decreases with the temperature that is evidently associates with increasing stress at HEL. The sharp decrease of the rise time of the elastic shock front is accompanied by the change of the shape of the elastic precursor wave. The extended elastic shock compression wave is the place where the processes of dislocation nucleation may start. When the rise time of the elastic wave becomes too small the dislocation nucleation process and, respectively, the stress relaxation are shifted from the compression wave to the time and space immediately behind the elastic discontinuity. Multiplication of dislocations provides acceleration of the stress relaxation that forms the spike-like shape of the elastic precursor wave.

Figure 8 illustrates an important feature of the evolution of the spike-like elastic precursor wave. The value of the free surface velocity at the post-spike minimum increases with the impact velocity whereas the recorded HEL value is virtually independent of the peak shock

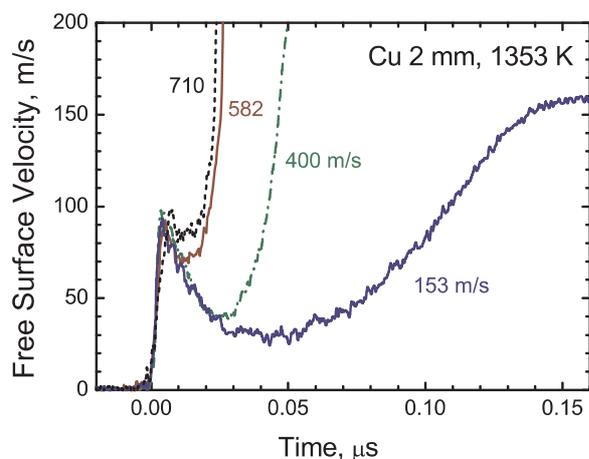


Figure 8. Free surface velocity histories of 2-mm copper samples impacted at various velocities at 1353 K [6].

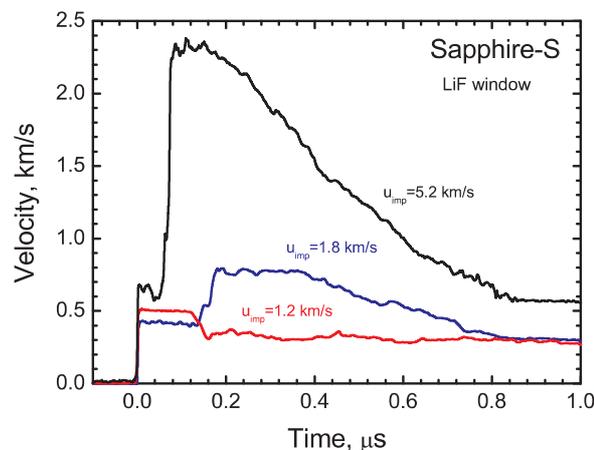


Figure 9. Results of experiments [10] with *s*-cut sapphire samples 5 mm in thickness at three different peak stresses.

stress. The part of the elastic precursor wave between the spike and the minimum is reproduced well for various impact velocities. This means that mechanical perturbation from plastic wave does not pass through the minimum and can not affect the evolution of the front part of the precursor wave. Estimations [6] show that in this case the density of mobile dislocations increases almost by order of magnitude during first 13–15 ns and after that stays virtually unchanged as the stress approaches the post-spike minimum. Cancellation of the dislocation multiplication accompanying the reduction of stress obviously means that the dislocation multiplication is governed not only by strain but also by the stress. Further material compression by plastic shock wave is accompanied by the increase of the shear stress and, thus, by significant dislocation multiplication.

Generally speaking, it would be natural to expect the larger HEL value at the larger peak stress since the precursor starts to decay from different values of initial stress. Such behavior was reported in literature not infrequently. On the other hand, figure 9 presents another example of varying of HEL value in shock tests. Inelastic deformation of sapphire occurs, to a large measure, by twinning. The unexpected and unusual decrease of sapphire HEL [10] with the increase of the impact velocity from 1.2 km/s to 1.8 km/s may be probably explained by the fact that the stress required for the nucleation of twins is much higher than that needed for their growth.

5. The rise time effects

Since intense nucleation of dislocations is supposed to take place during elastic compression, it is natural to analyze the effects of the rise time of the elastic precursor wave on the transient HEL values and on further evolution of the wave. Figures 10 and 11 show an example of such study performed with annealed samples of pure vanadium [11]. In the figure 10, the free surface velocity histories obtained at shock, ramp-shock and ramp compression are compared. The increase of the rise time in the upper part of the elastic compression wave indeed lowers the transient HEL value. From our point of view the stress values at the points of velocity minima between elastic and plastic waves shown in figure 11 as a function of the propagation distance are more interesting. These data although obtained after either shock, or ramp-shock, or ramp loading differ insignificantly and can be approximated by a single dependence.

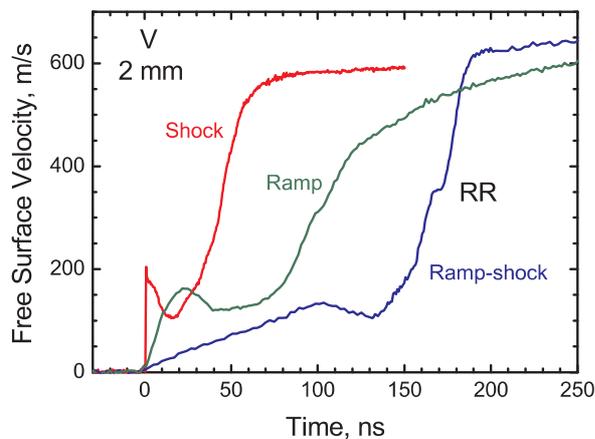


Figure 10. Results of experiments [11] with vanadium samples 2 mm in thickness at shock, ramp-shock and ramp loading.

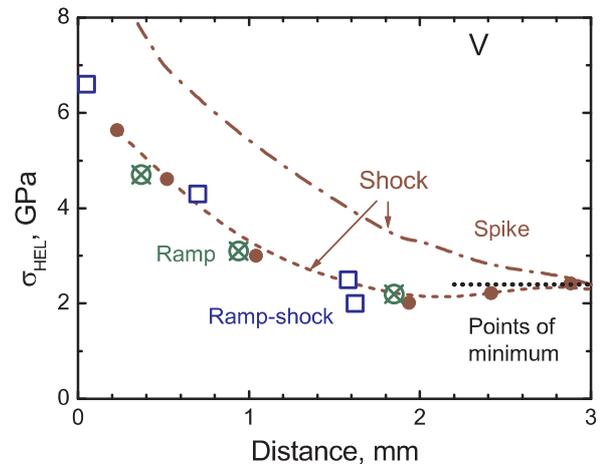


Figure 11. Decay of elastic precursor wave at shock, ramp-shock and ramp loading. The plot presents the data for the point of minimum between elastic and plastic waves; dotted horizontal line at the right side shows estimated final HEL value after decay.

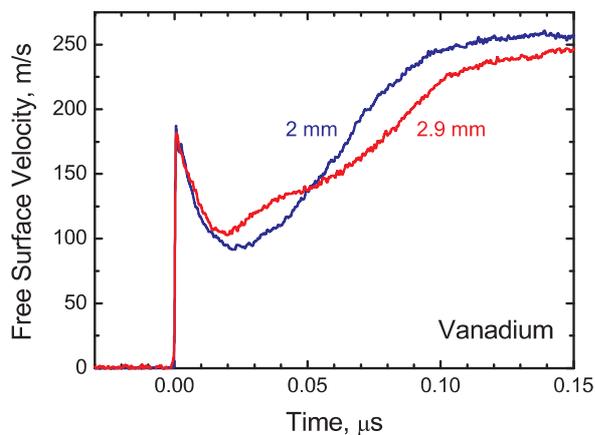


Figure 12. The free surface velocity histories of annealed vanadium samples of two different thicknesses impacted in the anomalous evolution region. The thickness values are mentioned at corresponding waveforms.

In the experiments with shock compression the multiplication of dislocations does not occur in the elastic compression wave or does occur in the smallest degree. At the ramp-shock compression the multiplication of dislocation in elastic wave becomes noticeable, and it reveals itself in the largest degree at the shockless compression. The coincidence of the decay curves corresponding to the wave parameters at the points of minima apparent from figure 11 means that in spite of the difference of the loading paths the material arrives at these points with the same density of mobile dislocations. The free surface velocity history of the ramp-shock loaded sample in figure 10 contains an additional step RR at the plastic shock wave. Usually, this feature is associated with subsequent reflections of the elastic wave from the free sample surface and then from the plastic shock wave. However, it is not quite clear how the amplitude of re-reflected elastic wave may substantially exceed the HEL.

Figure 11 illustrates also intriguing observation [7] of non-monotonic evolution of elastic-plastic wave in annealed vanadium. The decay of elastic precursor wave is caused by the stress

relaxation. The relaxation cannot, however, cause any growth of the stress while the wave propagates through the sample. The observed growth of the point of minimum between 2 mm and 3 mm of the propagation distance may be explained only by interaction of elastic and plastic waves. Indeed, the juxtaposition of the waveforms in figure 12 clearly indicates an emission of a new elastic precursor from the plastic shock wave at the wave propagation distances greater than 2 mm. This means that the stress state ahead of the plastic shock wave has fallen below the material's elastic limit. After that, newly emitted elastic precursor wave increases the stress ahead of the plastic shock wave and brings it closer to the transient value of the elastic limit. It seems that we observe a result of interplay between the multiplication of dislocations and the relaxation of stress and their influence on the wave dynamics. Probably a similar HEL overshooting is also responsible for occasionally observed its non-monotonic variation after shock-loading to different peak stress.

6. Conclusion

In this paper we discussed a departure from self-similar scenario of the wave process which is accompanied by an apparent sub-sonic wave propagation, by the changes of shape of the elastic precursor wave as a result of variations in the material structure and temperature, by unexpected peculiarities of reflection of elastic-plastic waves from free surface, by effects of internal friction at shock compression of glasses, and by some other effects which are not described by existing theories. It seems the experimental data contain more information about kinetics of the time-dependent phenomena than we are able to get from their analysis at present.

Acknowledgments

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