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SURFACE PROPERTIES OF SHOCKED LEAD

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Résumé - Les expériences hydrodynamiques nécessitent souvent des observations optiques des surfaces choquées. Cependant l'interprétation des résultats peut être rendue difficile par des phénomènes qui modifient l'apparence des surfaces. Nous avons élargi nos études sur l'éjection de matière à des structures de choc plus complexes. De plus nous avons utilisé des feuilles minces et une atmosphère contrôlée pour chercher à mettre en évidence un comportement hétérogène de la surface. Des mesures quantitatives de la masse éjectée ont été réalisées à l'aide de rayons X par transmission et la photographie ultra-rapide a fourni des données qualitatives. Nos résultats montrent que la quantité de matière éjectée dépend de la structure du choc. On a observé de nombreux effets singuliers que l'on suppose dus à la préparation de la surface, à une fusion partielle et à l'écaillage.

Abstract - Hydrodynamic experiments often require optical observation of shocked surfaces. However, phenomena that alter surface appearance can obscure the interpretation of data. We have extended our studies of material ejection to include more complicated shock structures. In addition, we have used both thin foils and an imposed atmosphere as ways of sampling the surface in search for nonhomogeneous behavior. Quantitative measures of mass ejection were obtained using x-ray transmission analysis, and high-speed photography provided qualitative data. Our results indicate that the amount of mass ejected is a function of shock structure. Many heterogeneous effects are observed that are presumed to be related to surface preparation, partial melting, and spall.

I - INTRODUCTION

The response of material surfaces to strong shock waves is not well understood, however, many hydrodynamic experiments are sensitive to the properties of a shocked surface. Where optical examination is required, such as in streak or framing camera records or in interferometric velocimetry, the data can be compromised or obscured by phenomena that alter surface appearance such as particle ejection and growth of surface perturbations.

Several studies have investigated prompt shock ejection from the surfaces of various materials. The work of Asay /1/ and Asay and Bertholf /2/ produced a consistent picture in which ejecta was directly related to surface defect volume, more or less independent of material. Of particular interest was a discontinuity of behavior observed when lead was shocked to pressures where melting was expected to occur. When the melt transition was crossed, a dramatic increase in ejecta occurred, and it became difficult to define a precise position for the free surface. The work of Andriot et al. elaborated on this work and indicated that melting, particularly as a microscopic phenomena, may play an even more important role in surface phenomena /3,4/.

Previous studies assumed homogeneity of the surface response on a macroscopic scale. The work of Perry indicates heterogeneous response of materials to low stress waves, where the wavelength of the observed perturbations was approximately the size of the material grains /5/. One objective of our effort was to look for the development of macroscopic perturbations while concurrently learning something of the state of the free surface masked by the ejecta. Our work is the first step in an extension of these studies, in which emphasis is placed on obtaining a correlation between observed surface effects and phenomena related to shock structure, melting, and metallurgical properties. We chose lead as an appropriate material for this study because of the ease with which it can be shocked into a molten state and because its inherent low strength should accentuate tendencies for surface perturbations to form.

II - EXPERIMENTAL METHODS AND RESULTS

Experiments were carried out on the 101-mm gun at Lawrence Livermore National Laboratory, and we achieved flyer velocities up to 2 mm/ μ s. Diagnostics consisted of multiple radiographic images and multiframe high-speed photography. Dual orthogonal, 200-keV x-ray transmission measurements provided a quantitative measure of ejecta mass and velocity. The optical images were obtained with an eight-frame, image converter (IC) camera system /6/. The configuration consisted of four independent, two-frame cameras, with four frames each dedicated to frontal and side views of the shocked surface as a function of time. Different shock structures were obtained by using composite flyers to subject the target to multiple shocks. For example, by placing a gap between the two components of the flyer, we could generate controlled spall scenarios in the target.

A schematic of a typical experimental setup is shown in Fig. 1. In all cases the targets were 3-mm-thick Pb (0.7% Ca) disks. The stainless-steel plate was required

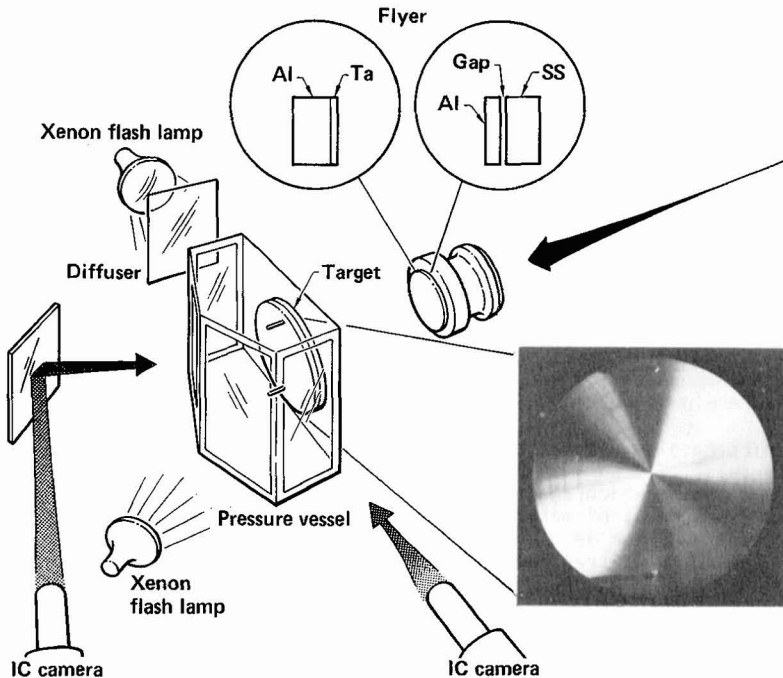


Fig. 1 - Schematic of experimental configuration.

to keep the lead target from bowing when an atmosphere was applied. When a gapless flyer was desired, we reduced the configuration to a simple sandwich of the required materials. The surface finish was in all cases produced by machining and was determined by a contact stylus device that produced a burnish mark as it moved across the surface. This mark appears in many of the photographs. Some targets were x-rayed and subjected to metallurgical analysis in search of macroscopic irregularities; we found nothing significant.

Table 1 contains a list of experiments designed to investigate the role that initial surface-defect volume plays in the case of multiple shocks. All data were taken in vacuum using the indicated flyers. The ejecta mass measurements are expected to have an absolute accuracy of only about a factor of two. The relative accuracy should be much better. The main difficulty arises from determining exactly where the ejecta ends and the free surface begins in the x-ray transmission data. The single shock data are in essential agreement with the predictions of Asay and Bertholf /2/. We have concluded that the shock structure does play a significant role in determining ejecta mass, and that as one goes further away from a pure single shock loading, the initial surface-defect volume becomes less important.

The degree of homogeneity of the ejecta was investigated by attempting to sweep up the fine particulates in hope of seeing larger structures, if they existed. This was done in two ways. The first involved placing an atmosphere over the shocked surface. The other employed a thin pickup foil in a vacuum environment. In both instances, photographic records were the diagnostic.

The atmospheric shots were performed with steel-backed lead targets. The targets were circularly machined to the fine and coarse finishes referred to in Table 1. A pressure of 1.5 atm was a convenient point at which to work; above this, target bowing became significant and the integrity of the gas housing became unreliable. Figures 2a-d show frontal views of the evolved lead surfaces several microseconds after impact for fine- and coarse-finished surfaces, both in vacuum and in an atmosphere. Figures 3a-d show the same data from a side view. In all cases the flyers were an Al/Ta combination at a velocity of 2 mm/ μ s.

The homogeneous spray emitted from both the fine and coarse surfaces in the vacuum shots obscured any microscopic structure that might be present. There is evidence

Table 1 - Summary of ejecta mass measurements.

Flyer	Pressure jump-off (kbar)	Calculated velocity of free surface (mm/ μ s)	Finish ^a	Ejecta (mg/cm ²)
Stainless Steel	480	2.2	Fine	1
Stainless Steel	480	2.2	Coarse	10
Stainless Steel/Ta	480	2.2/2.5	Fine	4
Stainless Steel/Ta	480	2.2/2.5	Coarse	12
Al/Ta	280	1.4/2.4	Fine	16
Al/Ta	280	1.4/2.4	Coarse	21

NOTE: Flyer velocity \sim 2 mm/ μ s.

^a Fine--AA \sim 0.15 μ . Coarse--AA \sim 0.75 μ .

of large wavelength residual perturbations, presumably arising from the initial machining process because of their circular symmetry.

The coarse-machined samples in the atmosphere shots did not interact with the gas in a simple way, and the ejecta was not uniformly swept up. The frontal view indicates a very mottled surface, while the side view shows prominent spikes of material due either to complicated flow in the interface region or to a distribution of relatively massive particulates. The fine-finish shot in atmosphere also clearly indicates features imposed by the machining process as well as random structures.

The features visible when an atmosphere was imposed on a fine-surface finish suggested that the technique could be used to look for more complicated interactions. Very little is known of spall in weak or molten materials. Presumably such materials, when driven into tension, will cavitate. We were

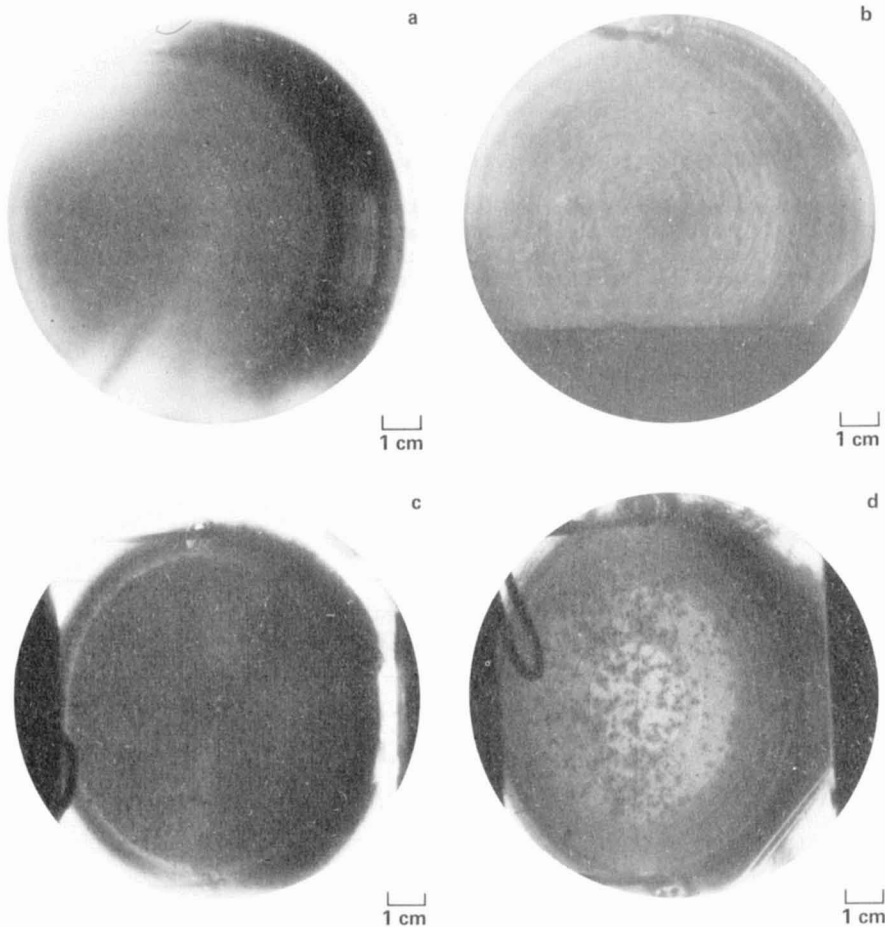


Fig. 2 - Frontal views of shocked lead surfaces (Al/Ta flyer at $2.0 \text{ mm}/\mu\text{s}$) with a 15-ns exposure: (a) coarse finish in vacuum at $7.8 \mu\text{s}$ after shock breakout, (b) fine finish in vacuum at $7.8 \mu\text{s}$, (c) coarse finish in atmosphere at $5.2 \mu\text{s}$, and (d) fine finish in atmosphere at $7.8 \mu\text{s}$.

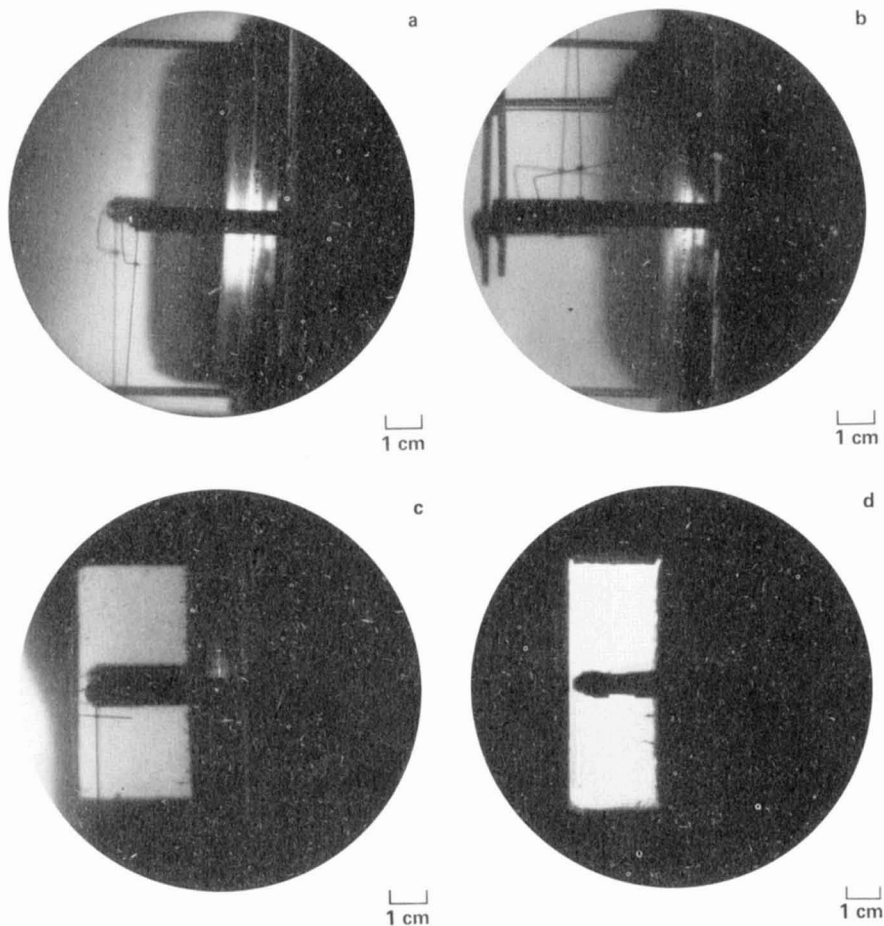


Fig. 3 - Side views of shocked lead surfaces (Al/Ta flyer at 2.0 mm/ μ s) with a 15-ns exposure: (a) coarse finish in vacuum at 7.8 μ s, (b) fine finish in vacuum at 7.8 μ s, (c) coarse finish in atmosphere at 5.2 μ s, and (d) fine finish in atmosphere at 7.8 μ s.

interested in determining if such an internal spall layer, when closed by a following stress wave, could generate surface perturbations. By using a sabot with a gap between the two flyers, we varied the position of the spall layer in the target.

Figures 4a-b show frontal and side views of an impact in atmosphere using a flyer consisting of 0.5-cm Al/0.07-cm void/0.5-cm steel. Figures 5a-b show data for a similar shot except the Al impactor was only 0.2-cm thick. Both shots used a fine-surface finish. The latter experiment would place the spall layer closer to the observation surface. In fact, very large perturbations to the surface were observed. The side view clearly indicates isolated plumes of material ejected. Presumably, this dramatic effect is because of the spall layer closing. Figure 4 reveals a number of interesting phenomena, but not the gross perturbations of Fig. 5. Either the effect was damped out by occurring deeper in the target, or

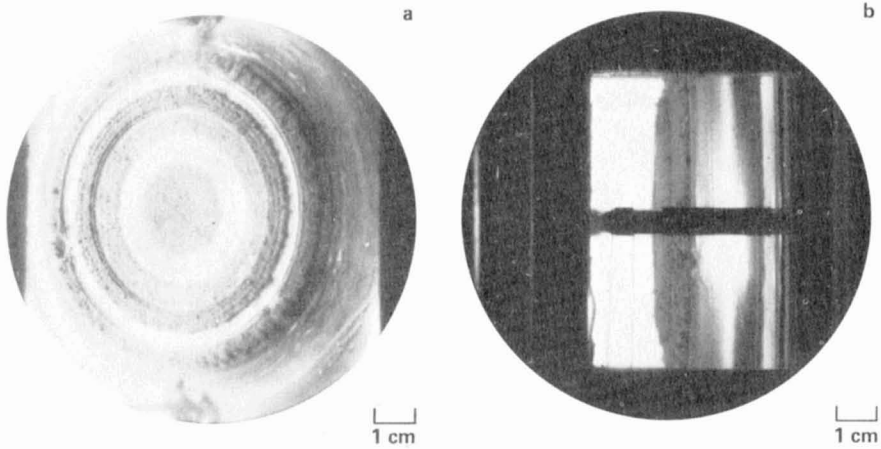


Fig. 4 - Views of shocked lead surfaces (flyer was 0.5-cm Al/0.07-cm void/0.5-cm stainless steel at $2.0 \text{ mm}/\mu\text{s}$) with a 15-ns exposure: (a) frontal view at $7.8 \mu\text{s}$ after jump-off and (b) side view at $10.3 \mu\text{s}$.

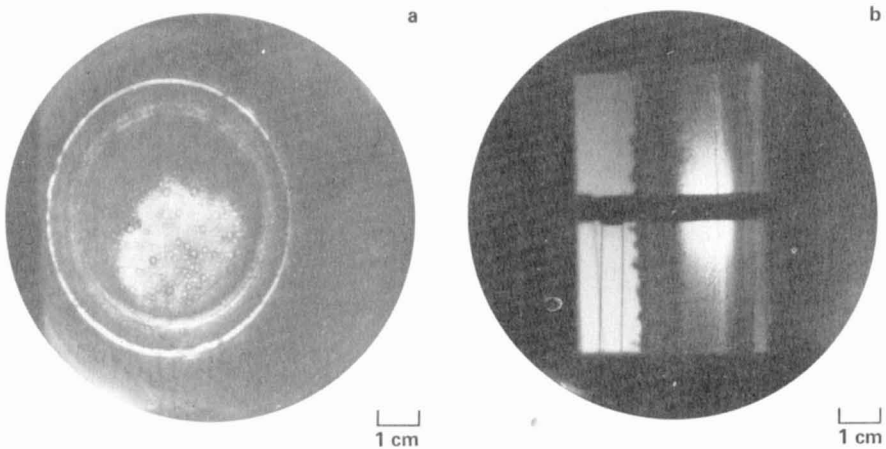


Fig. 5 - Views of shocked lead surfaces (flyer was 0.2-cm Al/0.07-cm void/0.5-cm stainless steel at $2.0 \text{ mm}/\mu\text{s}$) with a 15-ns exposure: (a) frontal view at $10.3 \mu\text{s}$ after jump-off and (b) side view at $10.3 \mu\text{s}$.

some significant feature of the shock and target interaction was different in the two experiments.

The shot that produced the large perturbations was redone in a vacuum using an aluminized mylar foil ($13\text{-}\mu\text{m}$ thick) as a momentum filter to see if these perturbations would be reproduced, and if so, obtain an estimate of the mass associated with them. Half the target was covered by the foil, which stood off 0.75 cm from the original free surface. Figures 6a-c show the results. In Fig. 6a, the foil is clearly being penetrated by isolated chunks of material before significant motion of the foil occurs. The side view (Fig. 6c) indicates that this

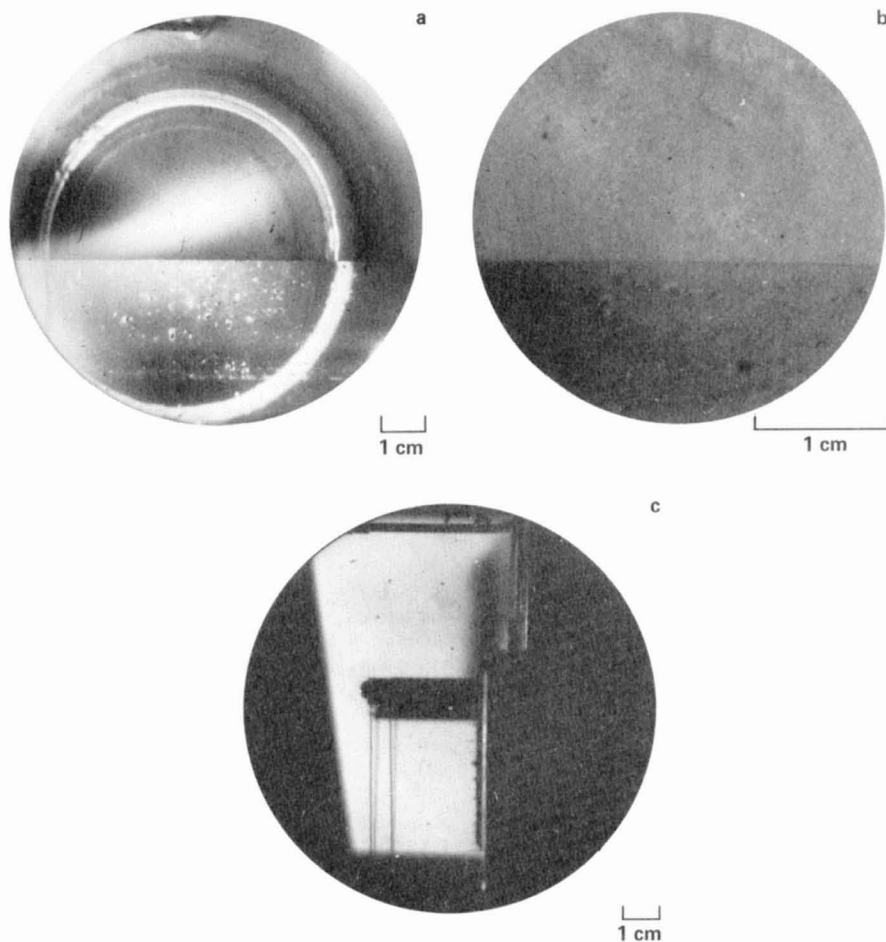


Fig. 6 - Interaction of ejecta with thin foil mounted 0.75 cm from original free surface (10-ns exposure): (a) frontal view at 3.9 μs after jump-off, (b) frontal view at 5.2 μs , and (c) side view at 5.2 μs .

material was not significantly slowed down by the foil. Figure 6b shows the foil at about the time the main body of the target impacts it. Imprints of circular grooves are evident on the foil. The target plus ejecta still retains information about its initial condition even after this complicated shock history.

Shock pressure was also found to have a dramatic effect on surface appearance. At 2 mm/ μs , the Al/Ta composite flyer brings the target to incipient melt on the first shock, and well beyond it on the second. In such a regime, the target lost nearly all its reflectivity, and photographic recording of surface features became extremely difficult.

At a flyer velocity of 1.5 mm/ μs , the lead is not expected to melt even on the second shock. Very fine points of high reflectivity develop, which in time grow and coalesce into ever larger structures (Fig. 7). This image should be compared

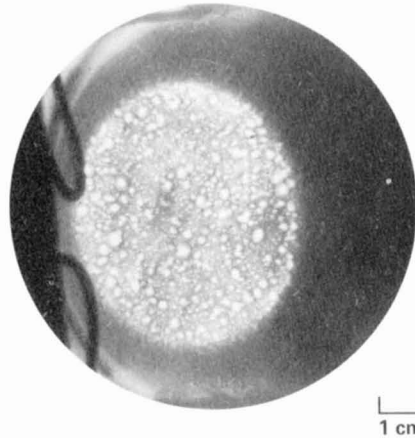


Fig. 7 - Lead shocked to near bulk-melt conditions (Al/Ta flyer at $1.5 \text{ mm}/\mu\text{s}$, $11.6 \mu\text{s}$ after jump-off). Exposure time was 15 ns.

with Fig. 2d, which is the same experiment at $2 \text{ mm}/\mu\text{s}$. The areas of high reflectivity are presumed to be molten regions which, under the influence of surface tension, form relatively smooth surfaces. A similar experiment was performed at a velocity of $0.9 \text{ mm}/\mu\text{s}$. In this case, the effect was even more pronounced, with the entire surface becoming highly reflective. Both shots were performed in an atmosphere.

III - CONCLUSIONS

- Throughout these experiments, the shocked surfaces often exhibited features associated with the initial machining process. It was not possible to consistently correlate these with variations in depth of the machine grooves. It is suspected that subtle changes in surface metallurgy that are induced by the interaction of the surface with the cutting tool are the cause of these perturbations.
- Shock structure played an important role in determining the character and amount of mass ejected. The ejecta is not necessarily homogeneous on a macroscopic scale.
- The role that melting plays in surface appearance is characterized by extremely heterogeneous behavior.

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