Shock waves—Phenomenology, experimental, and numerical simulation

Klaus THOMA, Ulrich HORNEMANN, Martin SAUER, and Eberhard SCHNEIDER*

Fraunhofer-Institut für Kurzzeitdynamik, Ernst-Mach-Institut, Eckerstrasse 4, D-79104 Freiburg, Germany
*Corresponding author. E-mail: schneider@emi.fraunhofer.de

(Received 30 September 2004; revision accepted 02 May 2005)

Abstract—The purpose of this paper is to review the results of long-term cooperation between Dieter Stößler and the authors in the field of shock wave deformation of minerals and rocks. First, the principal phenomena of shock wave generation and propagation, predominantly in solid media, are presented, and then analytical and numerical mathematical treatment of shock wave processes on the basis of mass, momentum, and energy conservation laws will be described and discussed. Experimental methods of shock wave investigations by means of impact and explosive techniques are summarized, including hypervelocity acceleration facilities and high-pressure explosive devices. Shock pressure barometry by means of mineralogical evidence of distinct material phase transitions and characteristic shock structures is also discussed.

INTRODUCTION

Shock waves are of fundamental importance in nearly all dynamic material systems, from cosmological aspects, such as interstellar dust cloud transport processes, star and galaxy formation, the evolution of planets and other celestial bodies as well as their individual surface morphologies, to everyday life experiences. Whenever material transport velocities exceed respective acoustic wave propagation velocities, shock waves are dominant processes to dissipate energy.

In this paper, some shock wave phenomena as well as their experimental and numerical simulation will be outlined. Thus, it should not be considered a review paper covering all geological and mineralogical evidence of shock processes. The authors essentially present examples of their cooperation with Dieter Stößler in the field of shock wave experiments and point out some shock wave phenomena on the basis of their own experience.

PHENOMENOLOGY

In this section, some prominent shock phenomena are listed and illustrated. Well-known examples are shock waves in air, which were first visualized by the famous Ernst Mach. Figure 1 shows one of Mach’s very first schlieren photos of a bullet travelling in air. Detonation events, supersonic airplanes, and rather simple processes like the crack of a whip are sources of such shock waves in air. Another source for shock wave formation in condensed matter is fast material collision processes, predominantly hypervelocity impact. Large meteorites, asteroids, and comets, but also micrometeorites (so-called space debris) generate impact craters on the surfaces they collide with. Depending on the impacting mass, crater diameters range from micrometers to hundreds of kilometers. Well-known examples of large terrestrial impact structures are the Nördlinger Ries Crater, with a diameter of 24 km, and the “Steinheimer Becken,” Germany, with a diameter of 3.8 km, which resulted from the Ries/Steinheim twin event about 15 Myr ago (Engelhardt et al. 1967; Engelhardt and Stößler 1968). Another prominent, rather recent terrestrial impact site is Barringer Crater near Flagstaff, Arizona, (Fig. 2), which is 1.18 km in diameter and about 50,000 yr old. Hydrocode simulations of terrestrial impact structures have been performed, among others, by Stößler et al. (2002). Figure 3, the simulation of an early stage of a 45° impact event, is an example taken from that reference (see also the “Mathematical Description and Numerical Solution Methods for Shock Waves” section).

Impact craters created by micrometeoroids have been detected on many lunar surface samples. A nice example is given in the scanning electron micrograph (SEM) image in Fig. 4. It shows an Fe-Ni particle found in a lunar regolith sample from the Apollo 16 mission, which was exposed to the interplanetary meteoroid flux on the Moon. A very similar experimental impact crater in a ductile metal target is shown in Fig. 5. It is a cross-section of an Al target that was impacted by an Al sphere with a 10 mm diameter at an impact velocity of 7 km/sec. The spallation at the rear of the target is due to shock wave reflection at the free surface. A tiny crater in a brittle material is shown in Fig. 6. It is a small, broken glass sphere, also discovered in a lunar soil sample. Figures 7 and 8 show laboratory craters of different sizes in glass targets. The
Fig. 1. A schlieren photo of a Mach wave taken by Ernst Mach (Mach Archives, Deutsches Museum, Munich).

Fig. 2. Barringer Crater near Flagstaff, Arizona (diameter 1.18 km). (http://www.solarviews.com/cap/earth/meteor.htm).

Fig. 3. A hydrocode simulation of the formation of a terrestrial impact structure (Stöffler et al. 2002).

Fig. 4. A lunar Fe-Ni particle with small micrometeoroid impact craters (image width about 500 μm; from Schneider et al. 1973).

Fig. 5. A cross-section of a laboratory-produced crater in a metal target (Ernst-Mach-Institut, Freiburg).

Fig. 6. A lunar glass sphere with a typical micrometeoroid crater (image width 500 μm; Max-Planck-Institut für Kernphysik, Heidelberg).
spallation zones around the central pits are caused by shock waves that propagated radially from the impact site. In the
case of a thin glass pane (Fig. 8), the shock wave produces a
nearly regularly shaped radial and concentric crack system
over the entire target. Figure 9 shows a μm-size laboratory-
produced crater in glass, which was cut open by a tangential

crack to nicely display a central pit lined by impact molten
target and projectile material surrounded by a narrow zone of

shock-crushed material. The shock-crushed material lines the
lower edge of the crater as revealed along the fracture surface.

Other impact-related macroscopic shock structures are
the so-called “shatter cones,” which are found predominantly
in impact-loaded sedimentary rocks like limestone and
sandstone targets (Fig. 10). These are conical structures with
striated surfaces physically detached from the surrounding

material. Such cones have also been produced in laboratory
impacts. A fragment of a laboratory-produced shatter cone is
shown in Fig. 11 (from Schneider and Wagner 1976). Other
indicators for shock loading occur in geological samples in
the form of phase transitions, for example, to stishovite or
coesite, which are high-pressure modifications of quartz (see
the Phase Transformations section), and other shock
metamorphic phenomena.

Shock Metamorphism

In the past decades, many shock-induced deformation
and transformation phenomena in rocks and minerals have
been found in terrestrial crater structures, lunar rocks,
meteorites, and experimental analogues. They were

Fig. 7. Laboratory-produced impact craters in glass, typical of brittle
targets (image width 3.5 mm; from Schäfer et al. 1998).

Fig. 8. A laboratory crater produced in a glass pane with a 1.5 mm Al-
sphere at an impact velocity of 9 km/sec (a sphere of equal size was
placed into the central pit for demonstration) (Schneider et al. 1990).

Fig. 9. An SEM photo of a laboratory-produced μm-size crater in a
glass target that was randomly cut by a tangential crack (Max-
Planck-Institut für Kernphysik, Heidelberg, and Physikalisches
Laboratorium, Mosbach).

Fig. 10. A shatter cone from the Steinheimer Becken with positive
and negative structures (Ernstson and Claudin http://www.impact-
structures.com).
generated by shock wave processes induced for a short time under high pressure and temperature. In comparison to other geological deformation processes, the deformations by shock waves imply exceptionally high strain rates. Therefore, the term “shock metamorphism” is used for all irreversible shock features in rocks and minerals. These characteristic features are now an important diagnostic tool in recognizing impact processes in both terrestrial and extraterrestrial materials.

During the formation of a meteorite crater, the shock wave energy attenuates rapidly with distance from the impact center and pressure and temperature decrease in quasi-hemispherical fashion. Accordingly, the degree of shock metamorphism has a strong radial and vertical gradient. With increasing shock pressure, the following irreversible phenomena can be classified:

- Fracturing
- Plastic deformation
- Solid-state phase transformation
- Decomposition, melting, and vaporization

Figure 12 shows six stages of progressive shock metamorphism related to a generalized Hugoniot curve of framework silicates (Stöfler 1971).

Several laboratory test facilities were developed at the Ernst-Mach Institut to simulate shock wave phenomena in rocks from meteorite impacts. Shock pressures up to 100 GPa can be generated by plate impacts using light gas guns or high explosive devices. These methods offer the possibility of determining thermodynamic equation of state (EOS) data from minerals at high pressures and temperatures. In addition, experiments can be carried out to study the formation...
conditions of irreversible shock effects after recovery of the shocked samples. The main parameters of interest are the mineral type, the angle between shock wave direction and crystallographic orientation of a mineral, peak pressure, and sample temperature.

Experimentally calibrated shock effects in minerals and rocks give evidence that many terrestrial and lunar craters have been generated by high-velocity meteorite impacts. In Germany, the Nördlinger Ries and the Steinheimer Becken are two well-known large craters with diameters of 24 and 3.8 km, respectively. The shock metamorphism of the rocks in these craters has been investigated extensively (e.g., Shoemaker and Chao 1961; Stöffler 1971, 1972, 1974; Stöffler and Langenhorst 1994). Zones with characteristic shock effects in the minerals could be established that indicate distinct levels of shock wave energy. A comparison with results of experimentally shock loaded minerals has led to many shock wave barometers.

**Shock Effects in the Low-Pressure Range**

At shock pressures below the Hugoniot elastic limit (HEL), irregular fractures in rocks are usually generated due to tension waves following the compression. Generally, the intensity of fracturing is proportional to the peak pressure. Plastic deformation is caused by shock pressures exceeding the HEL. Typical shock effects in minerals are planar fractures, planar elements, mechanical twins, and mosaicism. The main process is crystal gliding under extremely high strain rates and shear forces during shock transition. They have also been observed in many minerals from laboratory shock-recovery experiments.

In single-crystal quartz, planar elements parallel to \{10\bar{1}3\} were found at pressures above 12 GPa and parallel to \{10\bar{1}2\} in the 16–20 GPa range (Müller and Defourneaux 1968; Hörz 1968). They occur as multiple sets of parallel optical discontinuities with a spacing of about 2–10 μm. Between 27 and 30 GPa, a strong decrease in refractive index and density of shocked quartz has been observed, which was caused by the formation of submicroscopic lamellae in quartz and amorphous SiO$_2$ (Fig. 13) (Arndt et al. 1971; Grothues et al. 1989; Müller 1969; Stöffler 1974). Shock-induced twin lamellae were produced in clinopyroxene with widths of as little as 0.2 μm (Hornemann and Müller 1971). In olivine, characteristic deformation structures were observed as planar, fractured, and lamellar discontinuities parallel to \{130\} (Fig. 14). They are not formed under static loads. With increasing pressure, the number of deformation structures increases, yet without the formation of new orientations (Müller 1970; Müller and Hornemann 1969).

**Phase Transformations**

At shock pressures above the HEL, solids may undergo transient and/or permanent phase changes. In the two-phase region of the Hugoniot curve, a mineral is partially transformed. Often the high-pressure phase can be preserved during pressure release. At higher pressures, some minerals crystallize completely to a new phase. The final state after pressure release will, however, be strongly influenced by the post-shock temperature. The minerals melt, decompose, and finally, at very high pressures, a vapor phase is produced. All types of permanent shock effects occurring in natural impact rocks can be duplicated by laboratory shock experiments, except the vaporization phenomenon.

Quartz, the mineral most intensively investigated for permanent shock effects (Langenhorst and Stöffler 1994; Grieve et al. 1996), transforms to the high-pressure phase stishovite at shock pressures of 15–45 GPa. Above 50 GPa, a
liquid-state melt will be produced. The synthesis of coesite, a second high-pressure phase of quartz, was never observed in our shock-recovery experiments (Schneider and Hornemann 1976). The durations of pressure pulses have probably been too short. Coesite was found in suevite of the Ries crater embedded in diaplectic quartz glass (Stöffler 1971b; Shoemaker and Chao 1961). Shock melting of orthoclase, oligoclase, and labradorite was produced in shock-recovery experiments at pressures between 47.5–57.5 GPa, when the post-shock temperature was high enough (Stöffler and Hornemann 1972). Andalusite samples that are shocked up to 57.5 GPa completely decompose to Al₂O₃ and SiO₂ (Schneider and Hornemann 1977).

Recently, many planar and concentric shock tests up to peak pressures of 85 GPa were carried out with calcite to determine the decomposition and vaporization limits. CaO was not detected. But the recovered specimens consisted of finely grained, foamy aggregates containing many vesicles, bubbles, and other structures, all of which indicate gas release (Fig. 15). It can be assumed that, in the decompression phase, the sample was hot enough to partially decompose. However, a rapid recombination of the CO₂ gas with the solid CaO took place (Ivanov et al. 2002).

**Influence of Temperature on Shock Metamorphism**

Observations made at large impact structures indicate that deep-seated crustal rocks are affected by high shock stresses at elevated temperatures. Therefore, it was of great interest to carry out shock experiments with preheated samples. Indeed, high-temperature shock metamorphism is different from that at room temperature. For example, at 25 GPa, experimentally shocked quartz heated up to 630 °C shows a sudden decrease of the refractive indices (Fig. 16). It is completely transformed to amorphous diaplectic glass (Langenhorst et al. 1992). Quartz shocked at room temperature changes into the isentropic state at pressures between 25–35 GPa. Further, the orientations and the frequency distributions of planar deformation features (PDFs) and the X-ray diffraction patterns are quite different for unheated and heated shocked quartz. These results are of great importance because quartz is the most intensively studied mineral for shock wave barometry. The dependence of shock effects on the pre-shock temperature of quartz indicates that experimentally determined shock barometers as a function of temperature should be generated for many additional minerals.

**MATHEMATICAL DESCRIPTION AND NUMERICAL SOLUTION METHODS FOR SHOCK WAVES**

In principle, shock waves are waves with very high pressure and density gradients. They can be produced in solids, fluids, and gases. Typically, the thickness of a shock wave is in a range from 0.1–1 μm for mono-atomic gases and 10–100 μm in solids. It propagates through a medium with a velocity $U_s$, which is higher than the sound velocity $c$. There are two principal mechanisms of shock wave generation.

The first one is a wave source moving with a velocity at least as high as, or higher than, the velocity of the waves it produces. This leads to the superposition of generated waves and a so-called Mach cone arises. Another example of a Mach cone is the bang produced by an airplane flying at supersonic speed that can be heard on the ground. The second mechanism is wave dispersion. The wave velocity is not constant, but grows with increasing density if a medium has a nonlinear compression curve such that the pressure rise from a relative volume change increases with increasing
density. This is the case for practically all materials. The influence becomes remarkable in the very high-pressure region, i.e., above about a few GPa. For example, the velocity of a longitudinal wave in pure iron rises by 23% when the pressure is increased from 0 to 10 GPa (Meyers 1994a). In such materials, a rapidly growing load generates waves with increasing pressure and density, which build a wave front. In the vicinity of the source, the width (or steepness) of the front is determined by the loading time. At some distance from the source, provided that the above-mentioned condition is fulfilled, the faster high-pressure wave components catch up with the low-pressure components, and the wave front becomes steeper and thinner until a shock wave has been formed. The shape of the shock front is spherical for point loads, whereas a plane wave front is produced by planar loads.

In the case of a meteorite impact on Earth, both mechanisms occur. In the first impact phase, wave superposition is dominant; the shock wave front has a conical shape. In the second phase, when the meteorite mass decelerates, wave dispersion becomes the more important mechanism, and the shock wave’s shape becomes more and more spherical. Due to the spherical shape, the wave energy is spread over a rapidly growing surface in increasing distance from the source such that pressure amplitude and velocity decrease.

Mathematical Description

Shock waves can be described by means of the so-called Rankine-Hugoniot equations. They are derived from mass, momentum, and energy balances established for the material states in front of and behind a shock wave. They will be explained for the case of a 1-D shock wave in the following. The 1-D idealization is representative of plane waves and implies that no movement of material in the direction normal to the shock front occurs. Several pertinent references include Zel’dovich and Raizer (2002), Nicholas and Recht (1990), and Meyers (1994b). Figure 17 shows a schematic representation of a propagating shock front. The indices 0 and 1 represent the states in front of and behind the shock wave, respectively. The material has an initial velocity $u_0$ and is in a state characterized by density $\rho_0$, pressure $p_0$, and energy $e_0$. As the shock wave encounters a particle within the material, a transition from the initial state to the state behind the wave, represented by the state variables $\rho_1$, $p_1$, and $e_1$, takes place. A balance of the mass flow in and out of the moving shock front with constant thickness leads to the following equation (here, velocity differences are used to represent the relative velocities of material and shock wave):

$$\rho_1(U_s - u_1) = \rho_0(U_s - u_0)$$  (1)

Similarly, the momentum flow in and out of the shock front must be equal, which leads to an equation for the conservation of momentum:

$$p_1 - p_0 = \rho_0(U_s - u_0)(u_1 - u_0)$$  (2)

Finally, conservation of energy must be maintained and can be formulated as

$$e_1 - e_0 = \frac{1}{2} \left( p_1 + p_0 \right) \left( \frac{1}{\rho_0} - \frac{1}{\rho_1} \right)$$  (3)

In these three conservation equations, given that one condition behind the shock front must be prescribed by boundary conditions, four unknown variables are left. If the particle velocity $u_1$ is given, for example, by the loading conditions, the state variables behind the shock $\rho_1$, $p_1$, and $e_1$, and the shock wave velocity $U_s$ are not known. The missing equation is given by the EOS of the material, which generally describes the dependency between pressure, density, and internal energy. Figure 18 generalizes the equation of state as a plane in $p$-$\rho$-$e$ space. During a shock event, the material undergoes a transition from state A to B, thereby reaching a state on the Hugoniot curve, which is principally the intersection of two planes: the EOS and the plane defined by the Rankine-Hugoniot equations. The Hugoniot curve defines all states that can possibly be reached from a specific starting state. The actual state transition takes place along a straight line, called the Rayleigh line. Because not all of the internal energy accumulated during the shock is stored in a reversible
form, energy is dispersed during these state transitions, leading to shock heating of the material.

The derivation of a representative equation EOS and its parameters is normally accomplished experimentally. In order to obtain data for the high-pressure region, which is most interesting in the case of shock waves, special accelerators such as air or light gas guns and explosive devices have to be used, as do elaborate measurement techniques, as explained in the “Experimental Methods of Shock Wave Generation” section. Numerical simulation has recently reached a stage where it can be employed for the derivation of EOS parameters for composite materials. This approach takes the known EOS parameters of the constituents, such as the major oxides or minerals in rocks, and a representative geometry, into account and simulates the behavior of the mixture. Depending on the size of the grains, fabrics, and so forth, the length scale that has to be considered might range from centimeters to millimeters, or down to a few micrometers or even smaller.

The method is illustrated in Fig. 19 (Riedel 2000) for the case of concrete. On the left side of the figure, the 3-D Finite Element Model is shown. The cement matrix is blue and the idealized spherical pebbles are orange. A velocity boundary condition (600 m/sec) is applied. Calculated absolute velocities, pressure, and effective plastic strain in a cross-section of the specimen are shown on the right side of Fig. 19. For the moment shown, the shock wave has nearly reached the middle of the specimen. The contour colors range from blue (lowest values) to red (highest values). The shock wave is obviously dispersed by the inhomogeneous microstructure, and strain localizations at grain boundaries occur. These effects can be represented by a numerical simulation that takes microstructure and nonlinear material behavior into account. It would not be possible to represent them using classical mixture theory. By applying different boundary velocities, that kind of simulation has been used to generate EOS data for a specific concrete by Riedel (2000).

Methods for Numerical Simulation of Shock Wave Phenomena

Increasing computer power in combination with continuous development of numerical methods as well as input and verification data from experiments has led to elaborate numerical methods for the simulation of shock wave phenomena. Increasingly more complex, real systems can be simulated with high accuracy. Different methods are available in commercial codes as well as in proprietary software used and are developed by diverse institutions and workers. They all rely on some kind of discretization of the problem, which means that the original, in space and time continuous, problem is solved by either using a mathematical representation of regularly or irregularly spaced points, combined with a method for interpolation between points and for the integration of small volumes, or directly by employing balance equations for discrete volumes. The first approach is used in Finite Element methods, the second in Finite Volume methods. Both of them can be formulated using a computational grid or mesh or by using alternative techniques, the so-called mesh-free methods. Furthermore, there are two ways of describing the movement of material, either by fixed points in space (Eulerian description) or by describing the movement of material points through space (Lagrangian description). In the first case, if a grid-based method is used, the grid stays fixed with respect to space. This allows unlimited deformation, but material interfaces are difficult to track. Lagrangian methods use a mesh that deforms with the material, thereby limiting the degree of deformation that can be described before the mesh has to be re-zoned, because the accuracy of the approximation depends on a well-defined grid. An ideal and efficient method that accommodates unlimited, large deformations and at the same time preserves material interfaces is still a subject of ongoing research in the numerical simulation community. Mesh-free Lagrangian methods, which do not rely on a fixed topological connectivity between points, seem to be one possible solution that is currently under development. Meanwhile, for a specific problem, one has to carefully choose the most suitable method to be employed. The numerical methods mentioned above are used to solve the conservation equations given below, either in Lagrangian (above) or Eulerian (below) description.

Conservation of mass:

\[
\frac{D \rho}{Dt} + \rho \frac{\partial v_i}{\partial x_i} = 0
\]  

(4)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_i)}{\partial x_i} = 0
\]  

(5)

Conservation of momentum:

\[
\frac{D v_i}{Dt} = f_i + \frac{1}{\rho} \frac{\partial \sigma_{ij}}{\partial x_j}
\]  

(6)

\[
\frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j} = f_i + \frac{1}{\rho} \frac{\partial \sigma_{ij}}{\partial x_j}
\]  

(7)

Conservation of energy:

\[
\frac{D e}{Dt} = f_i v_i + \frac{1}{\rho} \frac{\partial (\sigma_{ij} v_i)}{\partial x_j}
\]  

(8)

\[
\frac{\partial e}{\partial t} + v_i \frac{\partial e}{\partial x_i} = f_i v_i + \frac{1}{\rho} \frac{\partial (\sigma_{ij} v_i)}{\partial x_j}
\]  

(9)
In the equations, \( \partial \) denotes the partial derivative, \( D(\cdot)/Dt \) is the total (Lagrangian) time derivative, \( v_i \) is the velocity vector, \( x_i \) the spatial coordinate vector, \( \sigma_{ij} \) the Cauchy stress tensor, and \( f_i \) the vector of body forces (e.g., gravity). In most methods used for shock wave simulation, the equations solved are the general conservation equations. An explicit time-integration scheme with a small time-step limit given by the Courant-Friedrichs-Lewy criterion (Courant et al. 1967) allows subsequent evaluation of the individual equations and, in contrast to methods for quasi-static problems, no system of equations has to be solved. This makes this type of computation very efficient. In principle, one can calculate the equations has to be solved. This makes this type of contrast to methods for quasi-static problems, no system of equations has to be solved. This makes this type of computation very efficient. In principle, one can calculate the equations has to be solved. This makes this type of computation very efficient. In principle, one can calculate the equations has to be solved. This makes this type of computation very efficient. In principle, one can calculate

Numerical viscosities like the von Neumann-Richtmeyer viscosity (von Neumann and Richtmeyer 1950) are used to distribute the steep shock front over a few computational cells. This is done in order to smooth the discontinuity and avoid spurious oscillations that would otherwise be generated by the underlying approximation methods. Alternatives to the use of numerical viscosities, which are frequently employed in Eulerian descriptions, are the so-called Godunov schemes (Godunov 1959). Instead of solving the conservation equations in their differential or integral form, the Rankine-Hugoniot jump conditions (for example, Meyers 1994b) at the shock front can be solved. This allows an improved resolution of shock waves.

Application of Numerical Simulation for Meteorite Impact

Two examples of numerical simulation of shock wave phenomena in meteorite impact will be shown in this section. The first is taken from a paper by Heider and Kenkmann (2003), who investigated shock metamorphism at the interfaces of inhomogeneous targets such as rocks or meteorites. The formation of melt veins and high-pressure polymorphs that form after a shock wave passes through the inhomogeneous medium could be explained by observations in experiment and simulation. The size of the melt veins investigated by Heider and Kenkmann is on the order of 10 \( \mu m \). In the simulation, which was done with the commercial hydrocode AUTODYN (Century Dynamics 1999), a steel plate was launched into a steel cylinder at a velocity of 2500 m/sec. Two different geologic materials, dunite and quartzite, were placed within the steel cylinder (Fig. 20). The same configuration has been used in experiments carried out by Kenkmann et al. (2000). The steel plate produces a shock wave in the cylinder, which then traverses quartzite and dunite. It could be shown in the simulation that, due to the different material properties of quartzite and dunite, the initially horizontal shock front does not stay in a horizontal straight line, but runs faster through dunite, thereby generating material movement from left to right at the interface. High temperatures occurred in a small region on the right side of the interface, which explains the melt veins found in the experiment and, by implication, in natural geological samples (Fig. 21). By varying the geometry, it was shown that the temperature increase in geologic materials due to shock wave passage strongly depends on the geometry of interfaces and cracks.

The second example is taken from the large-scale modelling of the Ries-Steinheim event, already mentioned above (Stöffler et al. 2002). With the hydrocode SOVA, coupled with ANEAS-derived EOS tables, the formation of the Ries crater and the related melt production and ejection were modeled. For the first time, the production of different types of melt and their deposition on the surface could be reproduced in one simulation (Fig. 22). This was achieved by coupling the Eulerian hydrocode with a module that estimated ejecta flow through the atmosphere, which is governed by interaction with gas. This interaction could not have been modeled with the hydrocode at the same scale as the impact event, as there are more than ten thousand orders of magnitude between both phenomena.

EXPERIMENTAL METHODS OF SHOCK WAVE GENERATION

There are essentially two methods of experimentally producing shock waves in solid matter: hypervelocity impact of projectiles (Schneider et al. 1999) and high explosive detonation processes.

Major Acceleration Principles and Facilities for Projectile Launch

Electrostatic Dust Accelerators

The principle of this type of accelerator is based on a high-voltage potential acting on electrostatically charged microparticles. As an example, Fig. 23 shows the 2 MV Van-de-Graaff dust accelerator at the Max-Planck-Institut für Kernphysik in Germany (Fechtig et al. 1972). An electronic mass and velocity pre-selecting system detects the desired particles and deflects them toward the target by switching a static high voltage at a deflector electrode. Depending on masses, particle velocities of up to 60 km/sec can be obtained. The mass range is between \( 10^{-15} \) and \( 10^{-9} \) g. Only electrically conducting particles, either pure metals or metal-coated particles, can be accelerated. Such devices are routinely used to simulate micrometeoroid and space debris micro-impact phenomena on spacecraft and planetary surface samples.

Plasma Drag Accelerators

This mechanism uses plasma drag forces to accelerate particles with masses between \( 10^{-8} \) and \( 10^{-4} \) g to velocities of up to 20 km/sec. Figure 24 shows a coaxial magnetodynamic...
Fig. 19. A mesomechanical model for the generation of equation of state data for concrete (Riedel 2000). The left shows a model with boundary conditions. The right shows simulated deformation and shock propagation.

Fig. 20. A simulation model used by Heider and Kenkmann (2003).

Fig. 21. Pressure and temperature distribution in the simulation after 3 µsec (Heider and Kenkmann 2003).

Fig. 22. Tektite ejection model results for the Ries event, from Stöffler et al. (2002). Impact angle was 30°; projectile speed 20 km/sec. The picture shows material distribution at 3.94 sec after impact; the numbers are km (Red = molten upper layer material; yellow = molten target material; black = solid target material).
accelerator with a plasma compression coil, which is used at the Technical University of Munich in Germany (Igenbergs 1973). By means of discharging a capacitor bank, plasma is produced between concentric electrodes. Due to the strong current flow, a concentric magnetic field around the center electrode accelerates the plasma toward the compression coil, where it is compressed and subsequently impinges on a thin Mylar foil with glass projectiles attached to it. The latter are then drag-accelerated by the dense and fast plasma. Due to intense radiation of the hot plasma, the projectile material is restricted to non-absorbing transparent substances (mainly glasses). Nevertheless, this type of accelerator is widely used to cover a mass and velocity range that is relevant and important for micrometeoroid and orbital debris simulation.

**Light Gas Guns**

Besides compressed gas guns and conventional powder guns used for accelerating particles and bodies in a wide mass range, as well as for the performance of planar impact experiments, light gas guns are used especially for the realization of higher impact velocities. As an example of light gas acceleration principles, the operation of a two-stage light gas gun as the most versatile accelerator will be described here. By means of a compression piston, energy produced by combustion of a propellant combustion is transferred to a light gas (H₂ or He) in a so-called pump tube (Fig. 25). High pressures (order of GPa) are produced in the light gas until the burst pressure of a diaphragm is reached. Now the compressed hot gas can expand into a launch tube, where a projectile housed in a plastic casing, the “sabot,” is accelerated by the expanding gas. After exiting the launch tube, the sabot parts separate from the projectile and the free-flying projectile passes a velocity measurement system and finally hits a target. Flash X-ray diagnostic equipment and high-speed camera techniques may be applied to record the projectile’s free-flight and impact phases. This method takes advantage of the fact that at any given energy a “light” gas (with a low molecular weight) has a high expansion velocity, especially in comparison to conventional combustion propellants. Projectile velocities of up to about 10 km/sec are thus attainable (Stilp 1987).

An interesting extension of this type of accelerator expanding the velocity range beyond 12 km/sec has been described by Chhabildas (1993). It is the so-called three-stage light gas gun or “shock accelerator” (Fig. 26). A graded density planar impactor is accelerated in a two-stage gun and hits a planar target arrangement consisting of a buffer and a flyer plate. The flyer plate is accelerated by a planar pressure pulse induced during the impact. Velocities of up to a factor of 2–3 times the primary impact velocity (maximum about 16 km/sec) can be reached for flyer plates with masses of several hundred mg.

**Shaped Charge Acceleration**

Other methods that also yield projectile velocities exceeding 10 km/sec are based on specially shaped charge techniques. An example is given in Fig. 27 (Walker et al. 1993). A so-called inhibitor is mounted within a conically shaped charge with cylindrical tip. After ignition, a short cylindrical projectile is formed as tip particle of the developing jet. The properties and geometry of the inhibitor
are adjusted in such a manner that it allows passage of the tip particle, but inhibits further jet development by blocking the material flow immediately behind the tip particle (projectile). By applying such methods, projectile velocities of up to 12 km/sec have been obtained for projectile masses of several grams (e.g., Bol and Fücke 1997).

**Exploding Wire (Foil) Acceleration**

There are various acceleration techniques that take advantage of the energy produced by electrically exploded wires or foils. Figures 28 and 29 demonstrate two principles applied at the TNO Prins Mauritz Laboratory (Rijswijk, The Netherlands). Figure 28 shows a Li wire arrangement, which is exploded by a high voltage shortage pulse between two electrodes. The vapor/plasma energy that is produced is used to accelerate small particles that stick to a plastic foil. Velocities in the order of 5 km/sec can be reached for particles of about 100 mg. Figure 29 is a schematic of an arrangement in which aluminium foil is electrically exploded. During the explosion a circular piece of a Kapton foil is punched out in the direction of a cylindrical hole within a steel plate that acts as launch tube. Thus, a planar Kapton projectile with masses in the order of 50 mg can be accelerated up to about 7 km/sec. The figure shows a simplified cross-section of the apparatus.

**Electrical Rail Guns**

For completeness of this survey, the principle of electrical rail guns will also be illustrated, despite the fact that this type of accelerator has not yet reached a significant application status. Figure 30 shows a schematic of the operation principle. A conductive projectile is mounted with electrical contact between two rails. By means of a controlled capacitor discharge currents up to MAmp magnitude are flowing through the rails and the projectile. A circular magnetic field builds up around the rails and the projectile is driven downrange by electromagnetic forces. In principle, very high speeds could be produced by applying this method;
however, due to technical constraints that are mainly related to limited material properties, the velocities achieved for substantial projectile masses (in the gram range) are currently limited to some km/sec.

**High Explosive Detonation Methods**

Laboratory shock-loading experiments on minerals and rocks are an essential tool in interpreting natural shock wave effects in meteorite impact craters. For instance, the shock effects in silicate minerals were used as shock wave barometers, giving a better understanding of crater formation on the Earth’s surface. Recovery experiments based on planar impacts are the most widely used technique for shock loading of rock materials. Compared with other techniques, the advantage is that the equation of state data sets—principally determined by the same method—can be directly applied to the experimental set-ups. In addition, encapsulated samples can be recovered after shock loading without any loss of mass in the initial position to the shock wave direction. It can be assumed that many impact craters were formed in hot or partly molten rocks at the surfaces of planetary bodies. High-temperature shock metamorphism is different from that generated in cold rocks. The Ernst-Mach-Institut has therefore developed a technique to perform shock-loading experiments of heated samples.

**High Explosive Devices**

Several charge configurations have been developed to carry out shock-loading experiments with steel plates accelerated to high velocities by high explosives. One of them has a caliber of 64 mm and an explosive mass of 300 g. It is initiated at the top end and generates a modestly spherical detonation wave causing a slight curvature in the central part of the accelerated flyer plate. After a free flight of 10 mm, the steel plate strikes the sample container. Another frequently used charge type has a diameter of 80 mm, an explosive mass of 810 g, and involves a plane wave generator (Fig. 31). This configuration guarantees a plane acceleration of the flyer plates. The form of the detonation waves and the curvature of the flyer plates are monitored by flash X-ray photography. In both charge types, the velocity of the steel plate can be varied by using different high explosives and plate masses.

**Sample Container**

The mineral or rock samples are placed and tightly fitted into the borehole (diameter 10–20 mm) of a cylindrical steel container (length 50 mm, diameter 40 mm). The container and the flyer plate are made from pure iron (ARMCO steel) of known EOS. It is surrounded by rectangular steel blocks (mild steel) in order to reduce the effects of rarefaction waves generated at the outer surfaces and, thus, to protect the container against destruction. The samples are 0.5 to 2.0 mm thick flat disks or up to 30 mm thick cylinders. Small grains can be embedded in pressed NaBr of similar acoustic impedance to that of the target material. After impact, the sample container is slightly deformed in the upper part, whereas the upper steel block can be destroyed by tension cracks. Figure 32 shows a cross section of a sample container shocked to 85 GPa.

**Shock Wave Measurements**

The shock wave generated by the impacting flyer plate of thickness \( d \) travels through the upper container wall and is transmitted to the sample. The peak pressure of the sample can be varied by changing the velocity \( v \) and the distance \( D \) between the impacted surface and the sample interface. The shock pressure is determined in separate calibration tests using the same flyer plate system as that used for the recovery
experiments. The calibration curves give the shock pressure in steel at the depth of the sample interface as a function of the test parameters, \( p = f(v, d, D) \).

From the conservation conditions of mass and impulse for a 1-D steady flow behind a shock front the equation \( p = \rho_o u U \) can be derived. This equation relates the shock pressure \( p \) to the material density \( \rho_o \), the particle velocity \( u \), and the shock wave velocity \( U \). The loci of all states that can be reached from an initial state by shock compression in the \( p, u \)-plane is called the experimental Hugoniot curve of a material. The Hugoniot curve for ARMCO steel is available from the literature. Therefore, it is sufficient to measure \( U \) or \( u \) to calculate \( p \). For our applications, the particle velocity was determined because \( du/dp > dU/dp \). Thus, for the same accuracy of measurement in \( U \) and \( u \), the pressure \( p \) will be obtained more precisely.

The particle velocity is measured indirectly by the “free surface method.” Conservation of momentum implies that the velocity imparted to a free surface \( V_{fs} \) by a shock wave is twice the particle velocity \( u \), and thus \( V_{fs} = 2u \). The container-sample interface represents this free surface. The velocity of the free surface can be measured by electrical contact pins, flash X-ray photography, or laser interferometer technique. Figure 33 shows the shock pressure in steel at the interface container sample as a function of distance \( D \) and flyer plate thickness \( d \) for the 64 mm explosive devices. The thinner the flyer plates, the higher the pressures reached, because the same explosive energy accelerates a smaller mass to higher velocities. The calibration curves show breaks, which move to higher values of \( D \) with increasing flyer plate thicknesses \( (d) \). The pressure decay on the left side of a break is caused by shock absorption and a slight divergence of the shock wave.

The break itself marks the distance inside the driver plate where the rarefaction wave from the back side of the flyer plate overtakes the shock wave. Therefore, the pressure decay is much steeper on the right side of the break.

The shock pressures of the samples are calculated by either the impedance match or reflection method, depending on sample geometry. The impedance match method is used for thick cylindrical samples of known or assumed EOS. Figure 34 shows a graphical solution to estimate the sample pressure using the measured projectile or particle velocity and the Hugoniot curves for ARMCO and the sample material. Most of the experiments are made with thin discs to reach higher sample pressures than are achievable by the impedance match method. The samples are encapsulated in steel, a material of high shock impedance. At the upper and lower interfaces of the sample, the shock wave reflects and increases the pressure. After multiple reflections, the sample pressure reaches the pressure of the incoming shock wave at the container-sample interface. However, this model requires that the sample is under continuous compression; thus, the time needed for all shock reverberations must be shorter than the pulse duration of the initial shock, which is a function of flyer plate thickness \( d \). The advantage of this method is that the knowledge of the sample Hugoniot curve is not required.
Shock Experiments at High Temperatures

To carry out shock recovery experiments at high temperatures using high explosives, substantial safety precautions have to be taken into consideration. The sample container and the surrounding steel blocks are heated in a muffle furnace. The temperature is measured with thermocouples in a separate, identical steel block heated up simultaneously. After reaching the desired temperature, the steel blocks are carried to the test site and the experimental arrangement including the explosive charge is installed (Fig. 35). The explosive and the flyer plate are thermally isolated from the hot container steel block by a combination of aluminium and Kapton foils. The time between removing the container block from the muffle furnace and detonation of the explosive is about 30 sec. The cooling history of the test block is measured separately, so that the actual temperature during shock loading can be determined. The accuracy of the temperature estimation is about ±1%. There are no major issues in recovering the samples after shock loading at room temperature.

Figure 36 shows the P/T-parameter areas for shock recovery experiments with the above described acceleration techniques. T represents the initial temperature of the sample or sample container. The dashed lines represent the limits not yet established by tests. In the past, shock experiments were carried out up to temperatures of 900 °C and pressures of 85 GPa.

CONCLUSIONS

The various examples of shock wave phenomena and respective research results reported in this paper demonstrate how an interdisciplinary cooperation in the fields of fundamental and applied research can be extremely fruitful. In the past, the experimental and numerical techniques that are reviewed in this paper allowed us to explain phenomena in the field of meteorite impact cratering and associated shock wave effects on Earth. Progress in these techniques will extend the spectrum of relevant processes that can be analyzed.

Acknowledgments—The authors would like to thank Dieter Stöffler for giving them the opportunity to cooperate with him for many years, a cooperation which was interesting and successful in many aspects. We are indebted to F. Hörz and W. U. Reimold for helpful and constructive reviews.

Editorial Handling—Dr. Wolf Uwe Reimold

REFERENCES


