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Shock experiments in range of 10-45 GPa with small multidomain magnetite in porous targets

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Abstract

Physical properties of multidomain magnetite bearing porous pellets shocked up to 45 GPa were measured. The results show general magnetic softening as a result of shock. However, relative magnetic hardening trend and slight magnetic susceptibility decrease is observed with increasing pressure among shocked samples. Initially, the shock also seems to cause a slight decrease of porosity, but at higher shock pressures macroscopic porosity increase progressively in our pellets. The microscopic porosity remains almost unchanged. Since our samples have distinctly higher porosity compared to samples used in previous studies our results may be representative for impacts into highly porous magnetite bearing sedimentary or volcanic rocks and are relevant to impacts into such target rocks on Earth and Mars.

1. Introduction

Impact cratering is one of the most important geological processes in our Solar System and is responsible for evolution and resurfacing of most Solar System bodies. The current Earth Impact Database (http://www.passc.net/EarthImpactDatabase/index.html) reveal over 180 confirmed impact structures of which more than 30\% are located in crystalline target rocks, and another 33\% in a mixed sedimentary- crystalline target. The terrestrial impact structures (Pilkington and Grieve 1992; Plado et al. 1996; Pesonen et al. 1999a, 1999b; Pesonen 2011, and references therein) as well
as those on Moon (Halekas et al. 2003) and Mars (Hood et al. 2003; Kletetschka et al. 2004b) are often associated with magnetic anomalies related either to shock or and post-impact heating (e.g. Hargraves and Perkins 1969; Wasilewski 1973; Pohl et al. 1975; Cisowski et al. 1976; Cisowski and Fuller 1978; Cisowski and Fuller 1982; Pesonen et al. 1997; Kontny et al. 2007; Gattacceca et al. 2010) or and to post-impact hydrothermal mineralization (Elbra and Pesonen 2011).

In order to construct feasible geophysical models of the magnetic anomalies of impact structures it is essential to understand the changes of magnetic properties of various minerals as a result of the shock process or the development of new magnetic phases in impactites. To clarify the effects of shock on physical properties of rocks and meteorites, laboratory shock experiments on controlled target material with well characterized lithological and physical properties are required (e.g. Pesonen et al. 1997; Gattacceca et al. 2007; 2010).

This work focuses on shock experiments with synthetic magnetite pellets with small multidomain (MD) to pseudo-single domain (PSD) grain size (Argyle and Dunlop 1990). Magnetite is one of the most common iron-bearing ferrimagnetic oxides in rocks forming the Earth’s crust. Typically, the igneous rocks contain up to few percent (titano-)magnetite as accessory mineral. Magnetite is also a common magnetic mineral in impactites, either derived directly from the target rocks or appearing as a newly impact-generated oxide. Such newly grown magnetite can form either from the melt (Deutsch et al. 2012) or under the influence of hydrothermal fluids circulating in impactite layers or within the fractured target rocks (Elbra and Pesonen 2011). Magnetite is also reported to be present in some Martian meteorites (Rochette et al. 2005) and, thus, most likely exists in the Martian crust.

In this study we present rock magnetic properties of artificial pellets that contain synthetic multidomain (MD) to pseudo-single domain (PSD) magnetite shocked in a series of experiments at nominal peak pressures up to 45 GPa, and compare the results to similar experiments done with magnetite bearing rocks (e.g. diabase – Pesonen et al. 1997; microdiorite – Gattacceca et al. 2007).

2. Methods

Physical properties of the pellets were measured at the Department of Physics, University of Helsinki. Bulk density was determined through the Archimedean method based on weighing the sample in air and suspended in liquid (ethanol or acetone). The mass of the pellets was determined using an AND HF-300G digital scale with 0.001 g resolution. Grain density and macro-porosity was determined using liquid immersion (ethanol or acetone) method. This method allows detection of macro-porosity represented by open pores only. The additional micro-porosity represented by
closed sub-µm inter- and intra-grain space was determined through comparison of calculated mineralogical density (4000 kg/m³) of the pellets major (95%) constituent, corundum Al₂O₃, to the grain density and porosity measured by water immersion methods. Physical properties of the pellets are summarized in Table 1.

The characterization of the pellets on the µm-scale was done at the IfP using a JEOL-SEM JSM-6610 LV scanning electron microscope (SEM) in backscattered electron mode (BSE) at 20 kV acceleration voltage.

Magnetic measurements were done at the Department of Physics, University of Helsinki. Bulk susceptibility measurements were done using a RISTO 5 kappa-bridge (operating at 1025 Hz frequency and 48 A/m rms field intensity) and an AGICO KLY3S Kappa-bridge (operating at 875 Hz frequency and 300 A/m rms field intensity). For remanence measurements an AGICO JR-6 spinner and a 2G Model 755 superconducting rock magnetometer (SRM) were used. The hysteresis parameters were measured using a Princeton Measurements Model 3900 VSM (Vibrating Sample Magnetometer) and a Lakeshore 735 VSM (at NASA Goddard Space Flight Center). Temperature dependence of magnetic susceptibility was measured using a KLY-3S Kappa-bridge equipped with CS-3 and CS-L temperature control units. Isothermal remanent magnetization (IRM) acquisition was done using a Princeton Measurements Model 3900 VSM. Anhysteretic remanent magnetization (ARM) was imparted to the samples using AGICO LDA-3 apparatus with a DC-field of 50 µT and AF of 100 mT. Alternating field demagnetizations (AFD) of the M_r (saturation isothermal remanent magnetization) and ARM were done using an AGICO LDA-3 or and 2G Model 600 demagnetizers.

After the complete characterization of the samples, a series of shock recovery experiments was conducted using a conventional high-explosive set-up (composition B or TNT) with an ARMCO steel sample container, surrounded by a momentum trap of the identical material (Fig. 1; Langenhorst and Deutsch 1994; Langenhorst and Hornemann 2005). The pressure given in Table 1, 10 to 45 GPa, is a nominal pressure corresponding to the pressure that is reached in identical experiments using single crystal quartz disks (cf. Langenhorst and Deutsch 1994). For our porous corundum-magnetite pellets Hugoniot data are unknown. Hence, straight forward calculation of the maximum pressure in the pellets using the graphical impedance match method (Langenhorst and Hornemann 2005) is impossible. The experiment at 25 GPa was repeated to allow a more detailed mineralogical study. The samples were shocked inside the steel container where the prevailing magnetic field was roughly five times higher (~300 µT) than the ambient geomagnetic field. After the shock, the containers cooled down to ambient temperatures slowly.
The shock experiments were accompanied by numerical modeling. We used the iSALE shock physics code (Ivanov et al. 1997; Wünnemann et al. 2006 and references therein) to simulate shock compression in the porous sample material to estimate peak shock pressure variations and temperatures. iSALE is based on the SALE (Simplified Arbitrary Lagrangian-Eulerian) code (Amsden et al. 1980), and has been developed by a number of authors. Further details on the iSALE code are provided in Wünnemann et al. (2006). Due to the cylindrical geometry of the experimental setup the models were carried out on a 2D cylindrically symmetric Eulerian grid. The computational domain covers the ARMCO steel container with the embedded sample, the driver plate, and the flyer plate. The total grid size is 500 x 1300 cells. The sample is resolved by 133 x 80 cells in radial and vertical direction, respectively. We use Tillotson equation of state (EoS) for iron (approximating steel) and corundum (composition of the grains) combined with the HD- porosity compaction model (Wünnemann et al. 2006) including the extension for highly porous materials (Collins et al., 2011) to simulate the thermodynamic behavior of the container and the sample during shock compression. The Tillotson parameter for corundum was obtained by fitting the Hugoniot curve generated by the Tillotson EoS to experimental data from the literature (Trunin et al., 2001). The minor amount of synthetic magnetite (1%) in the pellets justifies neglecting this material in the calculation. We considered only the strength of the steel container by a Johnson-Cook model and neglect any resistance against plastic deformation of the sample pellet. Peak shock pressures and temperatures were recorded by mass-less Lagrangian particles (tracers) that were initially located in the center of each cell of the sample and in close proximity in the steel container.

3. Samples

Hysteresis properties of the magnetite powder used for sample preparation indicate small MD to pseudo-single domain (PSD) state. The properties of the magnetite powder used during sample preparation are in detail described in Argyle and Dunlop (1990).

The magnetite samples were prepared for experiments into pellets as follows. One weight percent of magnetite (Fe₃O₄) was mixed with 99% of Al₂O₃ mixture, containing 94.5% Al₂O₃ (Degussa, Germany), 5% SiO₂ and about 0.5% organic binder. Water-glass was then used to produce solid disk shaped pellets. The paste was inserted tightly (to avoid bubbles) into plexi-glass moulds of desired dimensions (height 0.4 mm, diameter ~10 mm) and allowed to dry in air at room temperature for a couple of days. After drying, the disks were carefully extracted from the moulds and were sintered at 1200°C for 12 h under an atmosphere of CO + CO₂ to produce the oxygen partial pressure (P_{O₂} about 10^{-4}) necessary for preventing oxidation or reduction of the magnetite.
BSE micrographs of an unshocked pellet (Fig. 2) show magnetite grains varying in grain size from ~1 µm up to over 100 µm within the homogeneously grained Al₂O₃ matrix. Thus, some of the fine magnetite powder sintered into larger grain aggregates. The pore space, however, is rather homogeneously distributed within the sample.

Prior to the shock experiments the faces of the pellets were polished and the following physical properties were determined: bulk and grain density, micro- and macro-porosity, magnetic susceptibility, hysteresis properties, and AF (Alternating Field) demagnetization curves of the ARM and Mₘ. The initial measured bulk density of the pellets was ~2100 kg/m³, measured grain density ~2700 kg/m³ and calculated mineralogical density ~4000 kg/m³. This data results in total porosity of 48% subdivided into 15% of macro-porosity and 33% of micro-porosity. The initial magnetic susceptibility was~ 4.3 x 10⁻⁶ m³/kg.

4. Results

4.1 Shock simulations

A series of snapshots from the numerical model of shock wave propagation is shown in Fig. 3 for the 25 GPa case assuming an initial porosity of 48%. We do not distinguish between macro- and micro-porosity in the models. Due to the impedance contrast between the steel container and the porous aluminum sample the shock pressure is reduced at the interface and a shock wave of lower amplitude propagates into the sample. Superposition of reflections from the interface with the surrounding steel container ramps up the pressure of the primary wave to approximately the shock pressure of the initial wave in the steel container. The initial porosity in the sample is completely crushed up by shock compression; however, rarefaction causes tensile stresses resulting in a significant increase in porosity after unloading from shock pressure. The opening of flaws and cracks during shock release is not included in the numerical models. The compaction of pore space significantly contributes to the rise in temperature that is achieved during the shock compression in the sample (Wünnemann et al. 2008). The modeled estimates for peak temperatures in each experiment are given in Table 1.

4.2 Texture

Figs. 4-6 illustrate shock-induced changes in the macroscopic and microscopic texture of the pellets. At macro-scale (Fig. 4a) the pellet shocked at 10 GPa nominal pressure appears rather
compact which is also supported by decrease in pellet porosity (as discussed in detail in following section).

At 25 G shock pressure fracturing related to unloading rather than compaction prevails (Fig. 4b). The pellet is partly cracked, the perimeter is crushed, and an open gap between sample and container indicates tensile movement during unloading. At micro-scale, the pellet shows the compaction of the original texture into solid clusters with areas of just minor reduced pore space in between (Fig. 5a). We have observed intrusion of container material at the rim of the pellet (Fig. 5bc) which, however, seems to affect only the surface of the pellet (~100 µm). No traces of container material occur in pellet cross-sections (Fig. 6ab). The distribution of macro-porosity is more irregular (Fig. 6a) compared to unshocked samples with fractures appearing also within corundum grains (Fig. 6b). Magnetite grains (Fig. 6c), in contrast, do not show any microscopically visible shock features (at scale ~1 µm).

At 45 GPa the strong tensile stress during unloading results in open fractures, and shock heating is causing molten apophyges of the ARMCO container to intrude the surface of the pellet. Several welding spots are seen at the perimeter (Fig. 4c; example shown by red arrows).

### 4.3 Physical properties

Pre- and post-shock physical properties of the pellets are summarized in Table 1 and Figs. 7-8. Several trends can be seen as a result of the shock. Initially, the bulk density slightly increases and macro-porosity decreases at low (10 GPa) pressure (compaction as observed also in Fig. 4). However, at higher pressures the opposite trend is observed (most likely an effect of rapid unloading). Bulk density progressively decreases and macro-porosity increases if shock pressure is raised. The grain density, however, remains almost unchanged as does the mineralogical density (no mineralogical changes are observed within the pellets on µm-scale). Thus, the shock related changes in porosity within the bulk of the sample seem to be related mainly to macro-porosity with micro-porosity remaining unchanged within most of the sample volume.

Overall, the shock had “softened” the magnetic properties of the samples which can be observed as a decrease of the median destructive field (MDF) values of ARM and $M_r$ as a function of shock (Fig. 7). However, a relative hardening trend of post-shock ARM and $M_r$ is observed with increasing shock pressure (Fig. 7, down) which is also similar to the behavior of the magnetic susceptibility as described above. The overall shock softening can be observed also on the hysteresis parameters as a decrease of coercivities ($H_c$, $H_{cr}$) and shift further into the PSD field of the Day plot (Fig. 8) (Day et al. 1977) compared to pre-shocked values. There is no relative trend
with increasing shock observed among the shock samples in their hysteresis properties. The magnetic susceptibility tends to slightly decrease with increasing shock.

The sample (S2-5) shocked at 45 GPa is showing off-trend behavior. As will be discussed in the following section this may be possible due to an extensive contamination from the steel container.

Prior the shock experiments the samples were given $M_r$ (at 1.2 T field) in the shock direction. The ambient magnetic field inside the container was roughly 250 $\mu$T. The post-shock remanence (labeled here as SRM – Shock Remanent Magnetization) values reveal a progressive demagnetization of the pre-shock $M_r$ as the result of the shock (Table 1).

5. Discussion

While interpreting our results, one has to consider the differences between pellets used in this study and natural magnetite bearing rocks used in earlier studies (e.g. diabase – Pesonen et al. 1997, or microdiorite – Gattacceca et al. 2007). The pellets have on the average 15% initial macro-porosity compared to the typically much lower porosity (~1%) in diabase or microdiorite. The larger amount of porosity causes much higher peak temperatures in the samples as a result of pore crushing which deposits additional heat in the material due to the extra plastic work the material experiences during compression. Thus, partial melting and recrystallization of the samples may occur as discussed in the previous section. The presence of the pore space also allows melt to migrate within the pellet. In contrast, low porosity samples experience much lower peak temperatures during the shock wave propagation and lower melt generation, and migration within the samples. The effect of porosity on the generation of shock-melting is discussed in detail in Wünnemann et al. (2008).

The high porosity of our samples does not need to be considered as disadvantage while evaluating shock effects. According to Consolmagno et al. (2008) it resembles more closely some magnetite bearing meteorites of higher porosity such as carbonaceous chondrites (typical porosity in range of 10-35%) or SNC meteorites (with some Shergottites containing porosity over 20%). In a similar way, the higher peak temperature and partial melting experienced by our samples due to their higher porosity is a natural phenomenon and would occur also in natural targets of similar porosity. The temperature effects are a consequence of the shock and target porosity and can’t be omitted when interpreting shock effects in porous targets. Thus, in the following discussion “shock” is considered to include both shock pressure and temperature effects.

As described in the previous section, macro-porosity slightly decreases (compaction) initially, but increases at higher shock pressures (effect of unloading). The micro-porosity remains almost
unchanged. This observation suggests that the effective porosity crushed during the shock experiments is only part of the total porosity (mainly macro-porosity) and thus heating effects within the bulk pellet are in fact lower than predicted by the modeling. The modeled peak shock temperatures (Table 1) are rather representative for the hotspots around sample boundaries and not to sample interior itself. This is also supported by the observation of local melt formation along pellet-container interfaces (Figs 4 and 5) and absence of complete melting within the interior of the 25 GPa-pellet (Fig. 6).

The overall magnetic softening of our samples seen as reduction of MDF of ARM and Mr (Fig. 7) and softening of hysteresis parameters (Fig. 8) is in contrast to previous experiments using nearly pure magnetite bearing rocks such as diabase (Pesonen et al. 1997) or microdiorite (Gattacceca et al. 2007) where magnetic hardening was observed as the result of shock. The main factor causing the difference is most likely the higher initial porosity causing higher shock temperatures accompanied by partial or, even locally complete melting of the sample, melt migration and possibly recrystallization of magnetite aggregates into larger grains. However, as described in the previous section and as seen from Fig. 7, despite the overall softening of the magnetic parameters as a result of the shock, there is a trend of relative hardening observed among the pellets as function of increasing shock which is consistent with results by Pesonen et al. (1997) and Gattacceca et al. (2007). A tentative explanation of this trend is fracturing and/or origin of dislocations within the magnetite grains at scales below 1 μm. Alternatively, it can be the result of different post-shock cooling rates of the samples causing a faster growth (higher cooling rates) of new sub-μm magnetite grains (resulting in smaller grain size) in molten regions of samples shocked (and heated) to higher level.

Localized melting of the steel container and related contamination, however, can’t explain completely the overall magnetic softening. As seen on Fig. 4 and 5 of a sample shocked to 25 GPa pressure such contamination is localized to the pellet boundary only, and the observed level of iron contamination in the boundary zone is minor; no traces of steel contamination have been found within interior of the pellets. Magnetic susceptibility vs. temperature measurements of the pellets reveal a dominant magnetite composition (Curie temperature ~560°C) with only traces of iron present (minor Curie temperature peak ~780°C almost at noise level) in some bulk samples which is consistent with overall iron contamination of less than 1%.

The above described steel contamination could, however, partly explain the sudden off-trend behavior of sample S2-5 that was shocked at 45 GPa. As seen from Fig. 4 melting of the container material as well as of the sample is more extensive at this shock pressure. The presence of
additional iron may also explain sudden increase in magnetic susceptibility of this sample. Another factor contributing to the soft behavior of this sample may be the enhanced magnetite migration and recrystallization.

The systematic decrease of pre-impact remanence with increasing shock is called shock demagnetization, a process often speculated to take place in impact structures on Earth (Pilkington and Grieve 1992) or on Mars (e.g. Rochette et al. 2005; Kletetschka et al. 2004b). As the pre-shock remanence was equal to $M_r$, demagnetization rather than new shock remanent magnetization acquisition was observed. Gattacceca et al. (2010) estimated the SRM acquisition efficiency in lunar rocks. Their results indicate that the SRM acquisition efficiency is roughly four times lower than that of the Thermo-Remanent Magnetization (TRM). The TRM acquisition efficiency expressed as REM ratio ($TRM/M_r$) of magnetite is roughly 0.02 in the geomagnetic field (Kletetschka et al. 2004a). As mentioned earlier, the field inside the sample container was around 250 $\mu$T (five times higher than geomagnetic field). Thus the SRM efficiency in our experimental setup (expressed as SRM/$M_r$ ratio) is expected to be $0.02 \times 0.25 \times 5 = 0.025$. This explains why the pre-shock remanence ($=M_r$) and its shock related demagnetization dominates over acquisition of new SRM.

6. Conclusions

The shock effect on density and porosity of our corundum pellets doped with synthetic magnetite seems to be pressure dependent and affecting predominantly macro-porosity. Initially, the increase in bulk density and decrease in macro-porosity is observed. This is most likely related to compaction of the pellet samples. Subsequently, at higher shock pressures a decrease in bulk density and increase in macro-porosity is observed which most likely is the result of rapid unloading and tensile failure of sample material. The micro-porosity surprisingly remains almost unchanged.

Magnetic results of our shock experiments on small MD magnetite in porous pellets show overall magnetic softening as a result of shock. This is in contrast to previous observations (Pesonen et al. 1997, 2011; Gattacceca et al. 2010) in low porosity mafic to intermediate rocks where shock related magnetic hardening usually appears. However, a relative magnetic hardening trend is observed with increasing shock. The magnetic susceptibility tends to slightly decrease with increasing shock.

Pesonen (2011) has recently demonstrated that susceptibility of fractured target rocks will be distinctly lower compared to unshocked target rocks while the susceptibility of the impactites may
be slightly enhanced compared to unshocked target rock values. The very low susceptibilities of the fractured target rocks explain the circular weak magnetic reliefs over impact structures within crystalline targets. The spot magnetic “bull-eye” highs (e.g. Pesonen et al. 1996) in such impact structures are due to enhanced NRM values and increased Q-values. Several Finnish impact structures on crystalline target rocks have such anomaly patterns, notably the Suvasvesi North (Pesonen et al. 1996), Pääljäkkä (Pesonen et al. 1999a), Lumpsarn (Abels et al. 2001), and Lappajärvi (Pesonen et al. 1992) structures.

Since our samples have distinctly higher porosity compared to samples used in previous studies our results may be representative for impacts into highly porous magnetite bearing sedimentary or volcanic rocks and are probably more relevant to impact processes into these types of target rocks on Earth and Mars.

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Table 1. Comparison of pre- and post-shock physical properties of the pellets.

| Sample | p<sub>s</sub> (GPa) / T<sub>s max</sub> (K) | δ<sub>p</sub> | δ<sub>k</sub> | δ<sub>m</sub> | p<sub>macro</sub> | p<sub>micro</sub> | p<sub>total</sub> | k<sub>m</sub> / 10<sup>-6</sup> m<sup>3</sup>/kg | ARM / mAm<sup>2</sup>/kg | M<sub>r</sub> / mAm<sup>2</sup>/kg | H<sub>c</sub> / mT | H<sub>cr</sub> / mT | M<sub>r</sub>/M<sub>s</sub> | M<sub>s</sub>/H<sub>c</sub> | δ<sub>p</sub> | δ<sub>k</sub> | δ<sub>m</sub> | p<sub>macro</sub> | p<sub>micro</sub> | p<sub>total</sub> | k<sub>m</sub> / 10<sup>-6</sup> m<sup>3</sup>/kg | ARM / mAm<sup>2</sup>/kg | M<sub>r</sub> / mAm<sup>2</sup>/kg | H<sub>c</sub> / mT | H<sub>cr</sub> / mT | M<sub>r</sub>/M<sub>s</sub> | M<sub>s</sub>/H<sub>c</sub> | SRM / mAm<sup>2</sup>/kg |
|--------|----------------------------------|------|------|-------|-------|-------|-------|-------------------|----------------|
| S2-1   | 10 / 1500                        | 2100 | 2700 | 4000  | 15    | 33    | 48    | 0.286             | 251            |
|        |                                  |      |      |       |       |       |       | 0.36              | 1.6            |
|        |                                  |      |      |       |       |       |       | 2500             | 4000           |
|        |                                  |      |      |       |       |       |       | 5                | 33             |
|        |                                  |      |      |       |       |       |       | 38               | 5.9            |
|        |                                  |      |      |       |       |       |       | 0.466            | 234            |
|        |                                  |      |      |       |       |       |       | 860              | 28             |
|        |                                  |      |      |       |       |       |       | 58               | 0.26           |
|        |                                  |      |      |       |       |       |       | 2.0              |                |
| S2-2   | 15 / 1900                        | 2100 | 2700 | 4000  | 15    | 33    | 48    | 0.282             | 262            |
|        |                                  |      |      |       |       |       |       | 0.36              | 1.6            |
|        |                                  |      |      |       |       |       |       | 2000             | 4000           |
|        |                                  |      |      |       |       |       |       | 17               | 33             |
|        |                                  |      |      |       |       |       |       | 50               | 5.3            |
|        |                                  |      |      |       |       |       |       | 0.451            | 202            |
|        |                                  |      |      |       |       |       |       | 934              | 26             |
|        |                                  |      |      |       |       |       |       | 53               | 0.26           |
|        |                                  |      |      |       |       |       |       | 2.0              |                |
| S2-3   | 25 / 2860                        | 2100 | 2700 | 4000  | 15    | 33    | 48    | 0.259             | 236            |
|        |                                  |      |      |       |       |       |       | 0.36              | 1.6            |
|        |                                  |      |      |       |       |       |       | 1900             | 4000           |
|        |                                  |      |      |       |       |       |       | 20               | 33             |
|        |                                  |      |      |       |       |       |       | 53               | 4.1            |
|        |                                  |      |      |       |       |       |       | 0.395            | 154            |
|        |                                  |      |      |       |       |       |       | 605              | 26             |
|        |                                  |      |      |       |       |       |       | 50               | 0.23           |
|        |                                  |      |      |       |       |       |       | 1.9              |                |
| S2-4   | 35 / 3180                        | 2100 | 2700 | 4000  | 15    | 33    | 48    | 0.318             | 273            |
|        |                                  |      |      |       |       |       |       | 0.36              | 1.6            |
|        |                                  |      |      |       |       |       |       | 1700             | 4000           |
|        |                                  |      |      |       |       |       |       | 25               | 33             |
|        |                                  |      |      |       |       |       |       | 57               | 3.5            |
|        |                                  |      |      |       |       |       |       | 0.322            | 135            |
|        |                                  |      |      |       |       |       |       | 638              | 27             |
|        |                                  |      |      |       |       |       |       | 53               | 0.19           |
|        |                                  |      |      |       |       |       |       | 1.9              |                |
| S2-5   | 45 / 3550                        | 2100 | 2700 | 4000  | 15    | 33    | 48    | 0.252             | 262            |
|        |                                  |      |      |       |       |       |       | 0.36              | 1.6            |
|        |                                  |      |      |       |       |       |       | 1100             | 4000           |
|        |                                  |      |      |       |       |       |       | 43               | 30             |
|        |                                  |      |      |       |       |       |       | 73               | 11.0           |
|        |                                  |      |      |       |       |       |       | 0.434            | 128            |
|        |                                  |      |      |       |       |       |       | 1072             | 43             |
|        |                                  |      |      |       |       |       |       | 3.3              |                |

p<sub>s</sub>, nominal shock pressure, T<sub>s max</sub> modeled peak shock temperature, δ<sub>p</sub> bulk density, δ<sub>k</sub> grain density, δ<sub>m</sub> calculated mineralogical density, p<sub>macro</sub> macro-porosity (open pores), p<sub>micro</sub> micro-porosity (closed pores), p<sub>total</sub> total porosity, k<sub>m</sub> mass susceptibility, ARM anhysteretic remanent magnetization, M<sub>r</sub> = saturation isothermal remanent magnetization, M<sub>s</sub> saturation magnetization, H<sub>c</sub> coercivity, H<sub>cr</sub> coercivity of remanence, SRM shock remanent magnetization (magnetization after the shock).
Figure 1. Fully assembled set-up of the shock recovery experiments; modified after Langenhorst and Deutsch (1994) and Langenhorst and Hornemann (2005). Left: Photgraph. Right: schematic drawing. The steel blocks (10 cm in length) serve as a momentum trap.
Figure 2. BSE (Back Scattered Electrons) micrographs of an unshocked pellet. a: Overview showing voids (dark) and magnetite grains (white) that vary in grain size from ~1 µm up to over 100 µm within the homogeneously grained Al₂O₃ matrix (gray). b: High resolution image shows the large amount of pore space which is rather homogeneously distributed within the sample.
Figure 3. Snapshot series of the numerical model of shock wave propagation during an experiment at 25 GPa nominal shock pressure. The left side of each panel shows shock pressure, the right side depicts the peak temperature the material has experienced until the given point in time. Due to reflections the shock pressure within the sample can be locally amplified up to 50 GPa. The compaction of pore space significantly contributes to the increase in peak shock temperature that is achieved during and after the shock compression. While the overall peak shock temperature within the sample is in the range of 2500-3000 K, local hotspots with temperature up to 5000 K may occur.
Figure 4. Photograph of shocked pellets in plain view after removal of the driver plate (steel cap topping the sample). A: solid pellet at the low shock pressure of 10 GPa lacks fracturing. B: At 25 GPa the pellet is partly cracked and the perimeter is crushed. C: At 45 GPa the strong tensile stress during unloading results in open fractures, and molten apophysys of the ARMCO container intruded the surface of the pellet. Several welding spots are seen at the perimeter (example shown by red arrows).
Figure 5. BSE micrographs of the surface of the pellet shocked at 25 GPa. A: The original texture is compacted into solid clusters with areas of just minor reduced pore space in between. The contrast of this micrograph was enhanced but still the discrimination between mineral grains and voids on a binary scale is occasionally dubious. B: Intrusion of container material at the rim of the pellet (right edge). C: enlargement of B. Globule of the ARMCO container steel at the edge of the molten pellet.
Figure 6. BSE micrographs of the thin section cut across (perpendicular to the upper surface) the pellet shocked at 25 GPa. A: Porosity (black) in the shocked sample obviously consists of three components, (i) the original pores, (ii) the internal fractures of the grains, and (iii) fractures transecting grains. The large black areas are artifacts of the sample preparation. B: Fracture patterns in single grains and in the whole matrix are mostly parallel, probably indicating tensile stress. C: Compared to Fig. 2, pore space is more irregular, partly filled with very fine-grained matrix but the magnetite grain (white) is devoid of any visible shock features (at scale ~1 μm).
Figure 7. Comparison of the pre- and post-shock stability of the ARM (Anhysteretic Remanent Magnetization) (left) and $M_r$ (Saturation Isothermal Remanent Magnetization) (right). $J_m$ magnetization, $J_0$ initial magnetization (at 0 mT).
Figure 8. Comparison of the pre- and post-shock hysteresis properties. $M_r$ saturation isothermal remanent magnetization, $M_s$ saturation magnetization, $H_c$ coercivity, $H_{cr}$ coercivity of remanence.