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Shock-Wave Experiment with the Chelyabinsk LL5 Meteorite: Experimental Parameters and the Texture of the Shock-Affected Material

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Abstract—A spherical geometry shock experiment with the light-colored lithology material of the Chelyabinsk LL5 ordinary chondrite was carried out. The material was affected by shock and thermal metamorphism whose grade ranged from initial stage S3-4 to complete melting. The temperature and pressure were estimated at >2000°C and >90 GPa. The textural shock effects were studied by optical and electron microscopy. A single experimental impact has produced the whole the range of shock pressures and temperatures and, correspondingly, four zones identified by petrographic analysis: (1) a melt zone, (2) a zone of melting silicates, (3) a black ring zone, and (4) a zone of weakly shocked initial material. The following textural features of the material were identified: displacement of the metal and troilite phases from the central melt zone; the development of a zone of mixed lithology (light-colored fragments in silicate melt); the origin of a darkcolored lithology ring; and the generation of radiating shock veinlets. The experimental sample shows four textural zones that correspond to the different lithology types of the Chelyabinsk LL5 meteorite found in fragments of the meteoritic shower in the collection at the Ural Federal University. Our results prove that shock wave loading experiment can be successfully applied in modeling of space shocks and can be used to experimentally model processes at the small bodies of the solar system.

Keywords: Chelyabinsk meteorite, ordinary chondrite, shock experiment, spherical shock, texture, structure, shock metamorphism

INTRODUCTION

The Chelyabinsk meteorite shower fell on February 15, 2013, at approximately 9 : 20 a.m (UTC + 6) in the territory of Chelyabinsk oblast in Russia. The material of the meteorite was classified with LL ordinary chondrite of petrological type 5, grade of shock metamorphism 3/4, terrestrial weathering 0 (LL5 S3/4 W0) (Popova et al., 2013). Textural features of the material and the occurrence of different lithologies in it suggest that the light- and dark-colored lithologies of this ordinary chondrite have a practically identical chemical composition, which corresponds to LL chondrite (Galimov et al., 2013). The fabrics (textures and structures) of the light-colored and dark-colored lithologies are somewhat different. A number of hypotheses were put forth to explain processes that could transform the light-colored lithology into the dark one (Zaslavskaya et al., 1984; Migdisova et al., 1988; Kohout et al., 2014; Badyukov et al., 2015; Righter et al., 2015; Petrova et al., 2016a, 2016b; Danilenko et al., 2017; Trieloff et al., 2018).

The material of the different lithologies was found in large fragments of the Chelyabinsk LL5 meteorite and in its largest fragments recovered from Lake Chebarkul. However, most small fragments of the meteorite shower consist of any one lithology (light-colored, dark-colored, or impact melt). Relatively large sections (up to 150 cm^2) of the massive meteorite fragments resemble suevite, i.e., textures produced by massive impacts and found in rocks from impact craters, as those described in (Stoffler et al., 2013). It was hypothesized that the material of the Chelyabinsk meteorite was formed by a similar mechanism, when fragments of the target rocks are captured by the impact melt and are partly heated in it (Petrova et al., 2016; Trieloff et al., 2018).

Impact events are an inherent to the evolution of extraterrestrial material in space. When passing through an extraterrestrial material, a shock-wave front significantly affects the kinetics and mechanisms of phase transitions in the minerals. Experimental modeling of an impact event and corresponding transformations of the material within broad pressure and temperature ranges in a single sample is made possible by loading the sample with spherical converging shock waves, as was done in (Muftakhetdinova et al., 2018).

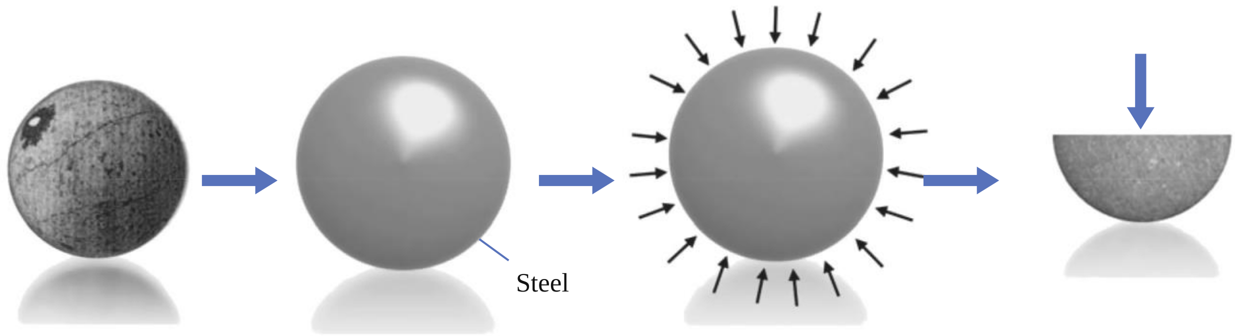

Fig. 1. Schematic diagram of the experiment with a spherical sample manufactured of the Chelyabinsk LL5 chondrite: the spherical sample is manufactured, placed in a hermetically sealed steel casing, loaded with spherically converging shock waves, extracted from the casing, and used to manufacture thin sections, which are then studied by various techniques.

Furthermore, it seems to be interesting to affect meteoritic material with shock transformations and then compare the texture with natural products of shock metamorphism produced in space. This is made possible to do with the material of the Chelyabinsk meteorite because of its brecciated texture and because the meteorite hosts fragments of material suitable for experiments.

This publication describes our experiment on intense shock loading of a sample of the light-colored lithology of the Chelyabinsk LL5 meteorite. Analogous experiments on shock loading were previously carried out with the material of the Saratov L4 ordinary chondrite (Bezaeva et al., 2010) and Tsarev L5 ordinary chondrite (Muftakhetdinova et al., 2017), as well as with the iron meteorites Sikhote-Alin and Chinga (Grokhovsky et al., 1999, 2000).

MATERIALS AND METHODS

Experiments on shock loading of the material of the Chelyabinsk LL5 meteorite with spherically converging shock waves were carried out at the Zababakhin Russian Federal Nuclear Center–All-Russia Scientific Research Institute of Technical Physics in the town of Snezhinsk. A sample for the experiment was cut off the light-colored lithology of the Chelyabinsk meteorite in the form of a sphere 39.99 ± 0.01 mm in diameter. The volume of the sphere was 33.49 ± 0.01 cm^3, and the average density of its material was 3.48 ± 0.01 g/cm^3. The homogeneity of the light-colored lithology of the material was tested, and the distribution of metal and sulfide phases was checked (to estimate material transfer) based on X-ray tomography data, which were acquired on an XT H 450 (X-Tek Nikon Metrology) industrial tomorgaph. After that the sample was placed into a hermetically sealed steel casing. Analogous estimates and measurements were made after the shock-loading experiment.

The design and layout of the experiment are schematically represented in Fig. 1.

As follows from the acquired 3D models of the original sphere made of the material of the Chelyabinsk meteorite, the texture of the sample varies over its volume. The content of inclusions of higher density (metal and sulfide phases) was estimated at 4.16% of the total volume of the sample. Detailed studies of sections of the 3D model allowed us to identify all zones of lower density: pores and small fractures.

The spherical sample was placed into a hermetically sealed casing (manufactured of KH18N9 steel, thickness 6 mm) in vacuum and was then loaded with spherically converging shock waves. The reader can find a detailed description of the experiment and its results in (Kozlov et al., 2015). This experimental method was previously applied in studying meteorites and other geological materials (Kozlov et al., 1994; Bezaeva et al., 2010). The geometry of the experiment implies that the shock pressure and temperature increase from sample periphery to its center. The spherical geometry of the shock loading makes it possible to acquire broad pressure and temperature ranges within a single experiment, and the single experimental sample consists of concentric zones, which enable the researcher to study how the structural and textural state of the material vary along the radius, from strong plastic deformations in a solid state to evaporation at pressure relieve in the shock-loaded melt and ensuing vapor condensation in the central cavity of the sample. The experimental pressure and temperature at the center of the sample were evaluated at >90 GPa and >2000°C (Kozlov et al., 2015). After the experiment, the sample was left to cool under natural gravity. Upon its full cooling, the sample was cut along its diameter and chords. The steel casing was preserved on the chondritic material because the matter was brittle and might have been broken if extracted. The sections were used to manufacture polished sections, and the chord section was utilized to make up a petrographic thin section.

The optical microscopy study was conducted under a Carl Zeiss Axiovert 40 MAT optical metallographic microscope and on a Carl Zeiss Jena Laboval 2 trans-

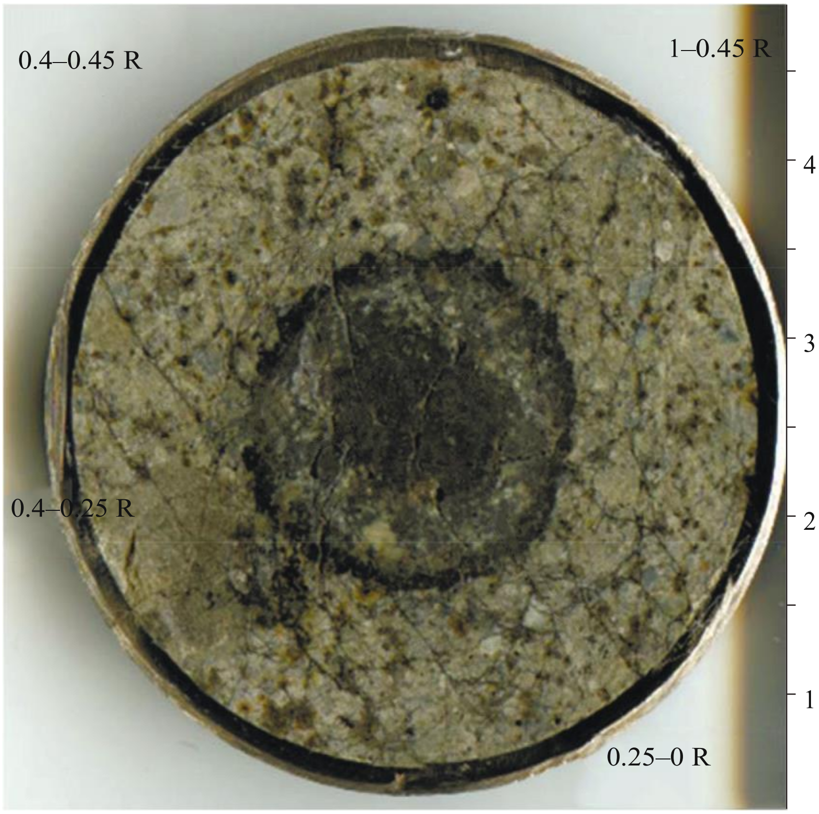

Fig. 2. Diametric section of the spherical sample of the shock material of the Chelyabinsk LL5 ordinary chondrite. Labels expressed the sizes of the regions as fractions of the radius of the sphere.

mitting optical microscope. The scanning electronmicroscopy study (SEM) was carried out on a Carl Zeiss Σigma VP electron microscope equipped with an analytical setup for conducting energy dispersive spectroscopy (EDS) and electron backscatter diffraction (EBSD) analysis.

RESULTS AND DISCUSSION

All principal features of the original texture of the light-colored and dark-colored lithologies and the impact melt of the Chelyabinsk chondrite are described in (Galimov et al., 2013; Kohout et al., 2014). The material of the different lithologies shows some differences that can be detected by, for example, Mössbauer spectroscopy (Oshtrakh et al., 2014, 2016), Raman spectroscopy (Kaeter et al., 2018), isotope analysis (Trieloff et al., 2018), etc. The experiment on loading the light-lithology material of the Chelyabinsk chondrite with a shock wave produced a gradient shock effect and the whole spectrum of impact textures in a single sample. Figure 2 shows a polished diametric section of the sphere after the experiment.

The pressure and temperature reached in the experiment in the central part of the sample are evaluated at >90 GPa and >2000°C. Textural shock effects in each of the zones of the gradient loading were studied using optical and electron microscopy. The experiment on loading with shock waves yielded pressure and temperature gradients corresponding to changes from the original material to its complete melting.

Petrographic analysis of thin sections of the shockmetamorphosed sample indicate that the sample after the experiment consists of the following four zones:

(1) melting zone in the central part of the sphere ata distance of 0 to 0.25 of the radius of the sample;

(2) zone of silicate melting, the next zone after themelting zone toward the sample periphery; the zone occurs as a ring at 0.25 to 0.4 of the radius of the sphere;

(3) zone of dark lithology-colored or dark-ringzone at 0.4 to 0.45 of the radius of the sphere;

(4) zone of additionally shock-loaded originalweakly shock-metamorphosed material of light-colored lithology of the Chelyabinsk LL5 chondrite at 0.45 of the radius of the sphere to the boundary between the chondrite material and metal.

Below the textures of each of the zones of shockmetamorphosed material are described in more detail, and hypotheses of the origin of the zones are discussed.

Zone1: Melting

The central zone of the shock-loaded sphere shows evidence of the complete melting of the chondritic material. Optical microscopy makes it possible to

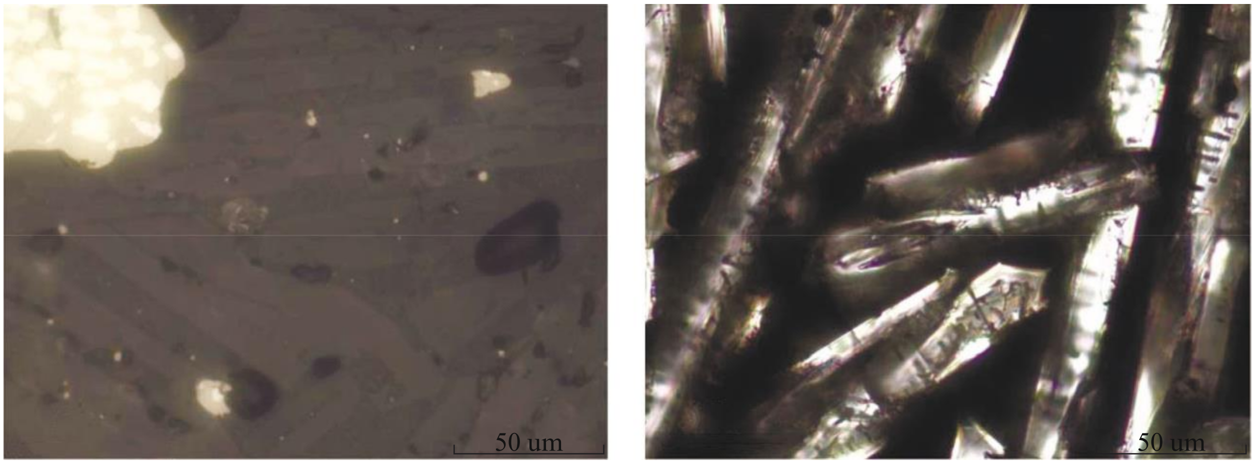

Fig. 3. Optical micrographs of the material produced by experimental shock melting the light-colored lithology of the Chelyabinsk ordinary chondrite: in reflected (left) and transmitted (right) light.

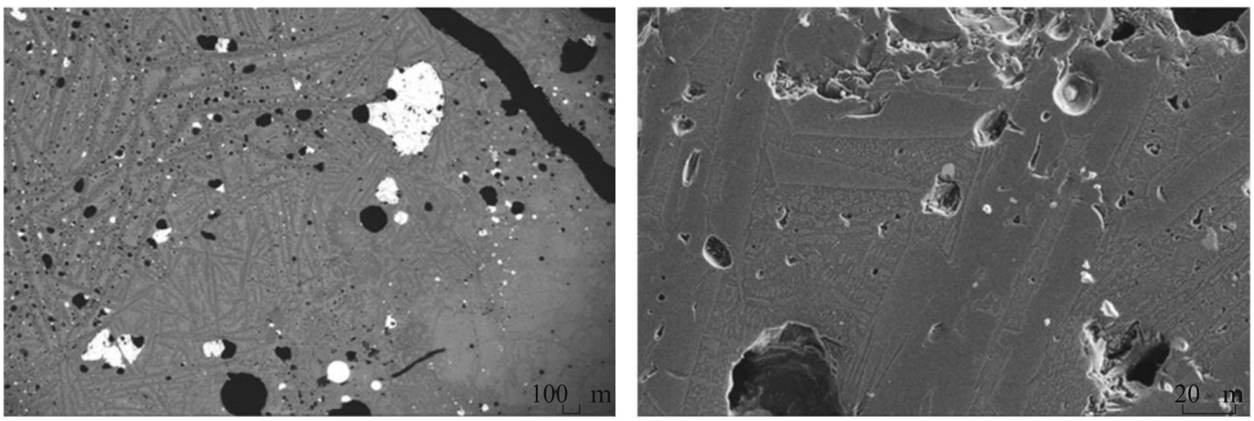

Fig. 4. BSE images of the experimental shock melt of the light-colored lithology of the Chelyabinsk ordinary chondrite

identify newly formed large bars of olivine crystals without traces of shock loading (Fig. 3). The zone consists of material that is dark in reflected light. The crystals show sharp optical extinction, and the intergranular space is filled with recrystallized glass with admixtures. It is interesting to mention that much of the metallic and sulfide phases were forced from the central (melting) zone to zone 2. Analogous phenomena were identified in the experiment (Bezaeva et al., 2010). The material of the zone contains preserved metal–troilite associations, which are found as eutectic textures in association with round pores (Fig. 4). The morphology of these textures suggests that shock melting was associated with gas release. The grade of the shock metamorphism of this zone is, according to (Stoffler et al., 1991), impact melt, with the pressure that affected the material being 90 GPa, and the temperature being >2000°C.

Comparison of the shock melting zones in the "natural" material of the Chelyabinsk ordinary chondrite and those reproduced experimentally reveals their following differences:

- olivine crystals in the shock-produced melt arelarger because of the lower cooling rate of impact melt on Earth than in space;
- the shock-produced melt hosts more pores thanthe natural melt does, which was also controlled by both the differences in cooling rates of the materials after shock loads and the differences in the pressures on these materials upon the passage of the shock wave front.

Zone 2: Melting of Silicates

The zone in which the shock-generated melt occurs is bounded by a zone of mixed lithology. It consists of round domains of light-colored lithology (chondrules, relics, and light-colored lithology fragments 1.5–3 mm in diameter) surrounded with silicate melt of darker color. Although the mixed lithology material is not widespread in samples of the shower of the Chelyabinsk ordinary chondrite, this lithology and data

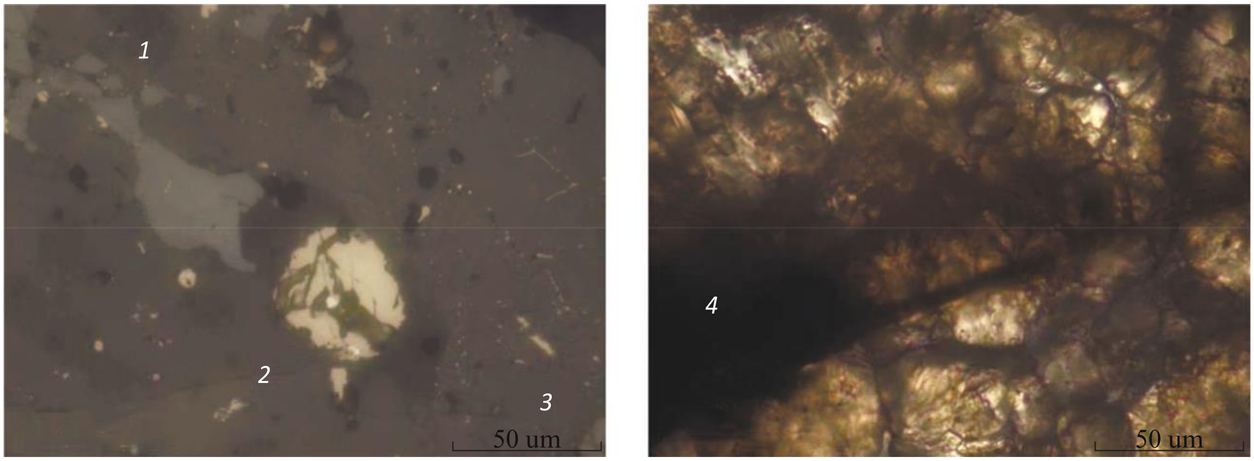

Fig. 5. Reflected-light (left) and transmitted-light (right) micrographs of the material of mixed lithology experimentally produced from the light-colored lithology of the Chelyabinsk ordinary chondrite. (*1*) Cr-spinel, (*2*) relict troilite grain, (*3*) veinlets filled with troilite, (*4*) opaque phases.

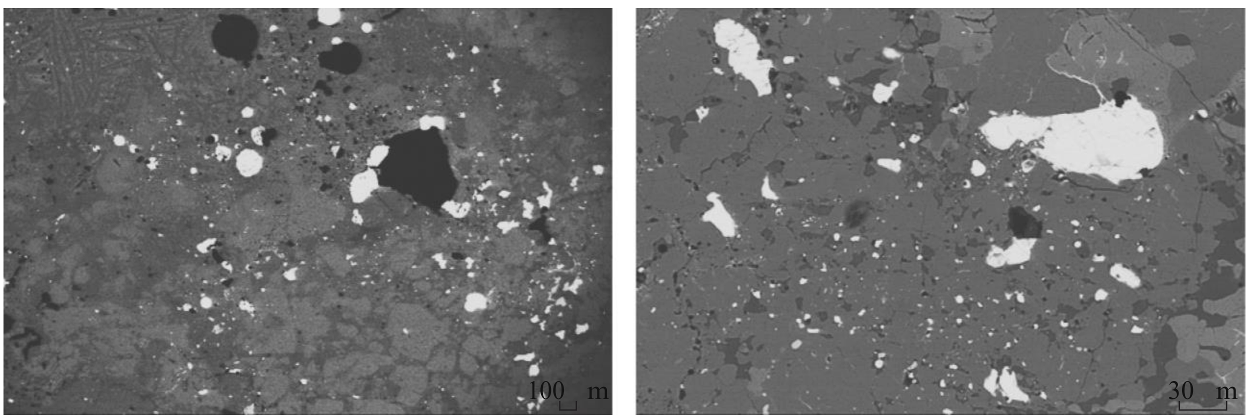

Fig. 6. BSE images of the texture of the of the material of mixed lithology experimentally produced from the light-colored lithology of the Chelyabinsk ordinary chondrite. The arrow points to the shock-melt zone.

obtained by studying it are reported in (Maksimova et al., 2015). The origin of this zone in the shock experiment is thus of undeniable interest.

The zone of mixed lithology (Figs. 5, 6) contains relict olivine grains, unaltered chromite grains, and troilite veinlets, which are fractures in silicates filled with melt. As seen under an optical microscope in transmitted light, the material consists of areas of opaque phases with transparent silicate crystals. It is also seen that metal and troilite melt is forced off the shock melt zone and, consequently, enriches the mixed lithology zone (Fig. 6). Estimates of the distribution of metal and troilite particles over the volume of the shock-metamorphosed sample of the Chelyabinsk LL5 chondrite based on data of X-ray tomography confirm that the metal phase was displaced from the central shock-melted region.

A model for the origin of the experimentally produced mixed lithology material was suggested in (Kohout et al., 2018). It involves the melting of the silicate matrix. The silicate melt protects the chondrules and unmelted silicate grains from injection of troilite and metal melt due to inmiscibility of these melts with silicate melt. The grade of shock metamorphism of this zone is S6, which corresponds to a shock pressure of 75 GPa and a temperature of 1500–1750°C (Stoffler et al., 1991).

Zone 3: Dark-colored Lithology

The zone of dark-colored lithology generated in the shock experiment has the lowest volume among all zones. Transmitted light microscopic observations (Fig. 7) indicate that the material of the zone contains much opaque phases, which is explained by that metal and troilite melt fills fractures in the silicate minerals and makes them opaque for transmitted light, up to the complete darkening of certain zones, which are seen in the polished section as a dark ring.

According to visual observations in the section of the sphere, most of the discernible fractures occur in

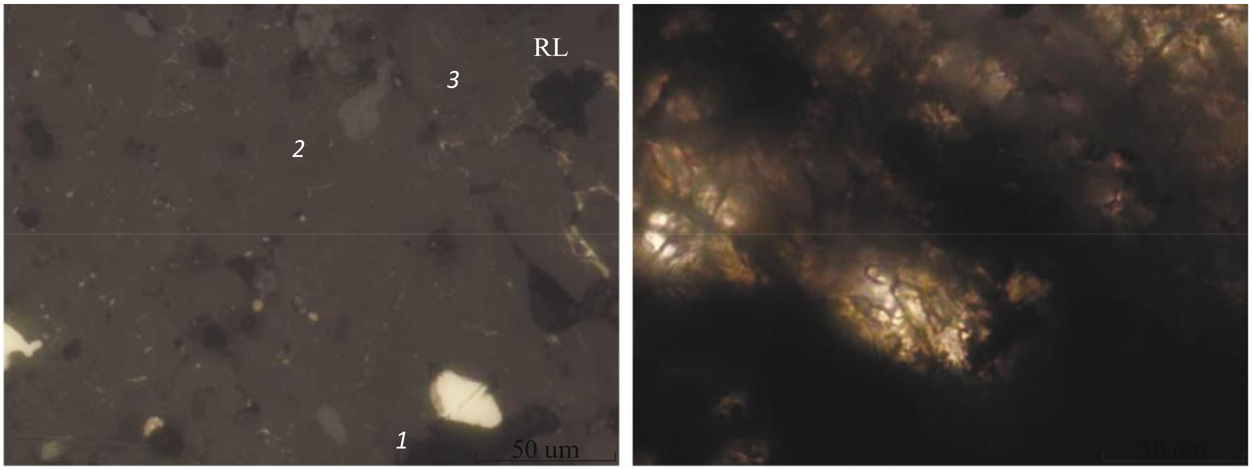

Fig. 7. Reflected-light (left) and transmitted-light (right) micrographs of the material of dark-colored lithology experimentally produced from the light-colored lithology of the Chelyabinsk ordinary chondrite. (*1*) Metal, (*2*) chromite, (*3*) metal and troilite melt.

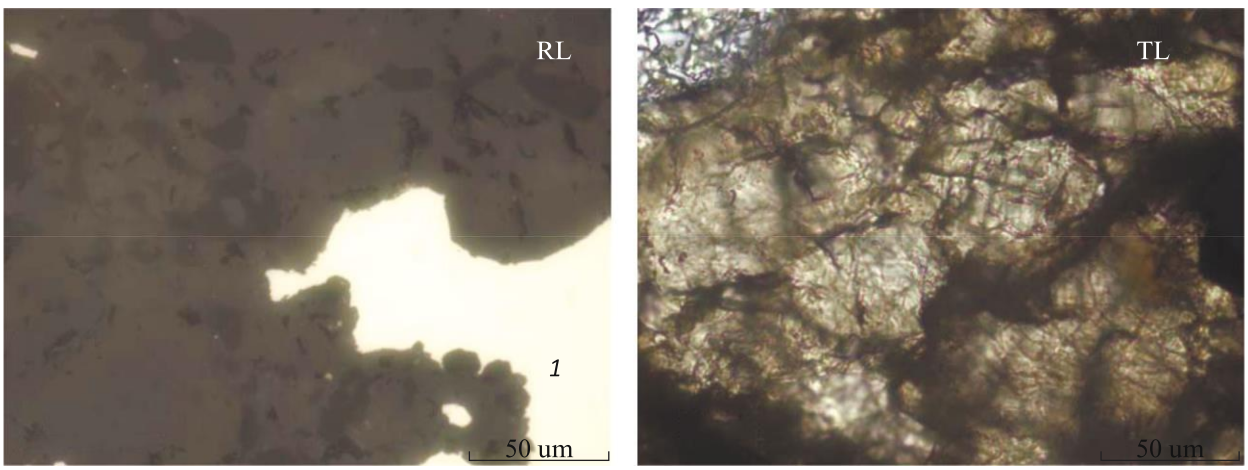

Fig. 8. Reflected-light (left) and transmitted-light (right) micrographs of the material of light-colored lithology experimentally produced from the light-colored lithology of the Chelyabinsk ordinary chondrite.

the central part and continue to the dark-colored lithology region. This is explained by the extensive plastic deformations of this zone.

The ring of dark lithology was likely produced by filling numerous small fractures in silicate crystals with metal and troilite melt. The texture of the experimentally produced zone of dark-colored lithology is absolutely analogous to that of the “natural” material of dark-colored lithology described in (Galimov et al., 2013a, 2013b; Kohout et al., 2014). The degree of shock metamorphism of the experimental dark-colored lithology material is S5, which corresponds to shock pressures of 45–55 GPa and temperatures of 600–

850°C (Stoffler et al., 1991).

Zone 4: Light-colored Lithology

This part of the sample correspond to the light-colored lithology (Fig. 8) and is characterized by the development of radiating shock-generated veinlets filled with melt (Fig. 9), but the texture of the dominant lithology is preserved: the shapes of the metal and sulfide grains, fracturing, and transparency of silicate crystals are as in the “natural” light-colored lithology. The undulatory optical extinction of the pyroxenes and the weak mosaicism of the olivine crystals correspond to grade S3/4 of shock metamorphism, which is typical of the original material. According to (Stoffler et al., 1991), the shock pressure was approximately 30 GPa, and the temperature increase was 350°C.

Experiments on loading the material of the Chelyabinsk ordinary chondrite with spherically converging shock waves have produced wide pressure and temperature ranges in the experimental sample, and they resulted in concentric zones of different texture in the spherical sample. The zones experimentally produced in the sample correspond to lithology types found in discrete fragments of the Chelyabinsk meteorite

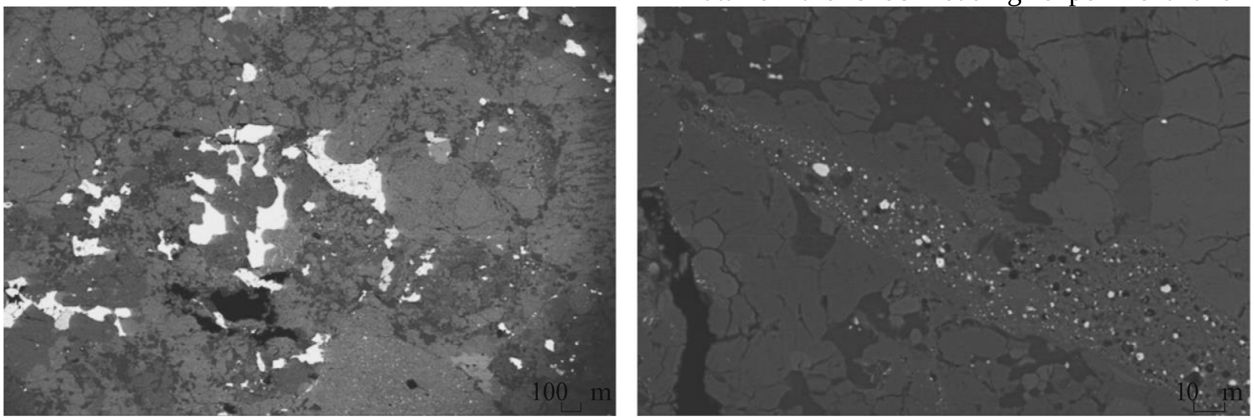

Fig. 9. BSE images of the texture of the material of mixed lithology experimentally produced from the light-colored lithology of the Chelyabinsk ordinary chondrite: individual metal and troilite grains in a silicate matrix (left) and shock-melted vein (right).

shower (in the collection of the Ural Federal University). Our data validate the model of the origin of different lithologies of the Chelyabinsk LL5 chondrite from the original material of light-colored lithology affected by an impact in the parent body.

CONCLUSIONS

The experiment on loading the light-colored lithology material of the Chelyabinsk LL5 ordinary chondrite has reproduced shock and thermal metamorphism of this material ranging from the original grade S3/4 to massive melting of the rock. The pressure and temperature at the center of the sample exceeded 90 GPa and 2000°C, with the whole spectrum of the P–T parameters reproduced in a single experiment.

Data on the experimentally shock-metamorphosed spherical sample confirm the following hypotheses:

- the material of dark-colored lithology and theimpact melt are the shock-modified light-lithology material;
- the distribution character of metal and troilite par-ticles in the original and experimentally modified materials vary depending on the lithology. In the material of dark-colored lithology, microfractures in silicate minerals are veinlets filled with troilite and metal melt. The texture of the dark-colored lithology experimentally produced in the shock-metamorphosed sample corresponds to the texture of the material of dark-colored lithology in the Chelyabinsk LL5 chondrite;
- the spherical experimental sample contains arare zone of mixed lithology, whose origin implies silicate melting;
- the texture of the experimentally generated shockmelt corresponds to shock pressures of >90 GPa;

Data of the shock-loading experiment and the comprehensive study of the texture of the Chelyabinsk LL5 meteorite confirm the model according to which the breccia texture was produced in the parent body of the Chelyabinsk meteoroid by a massive shock event. Our results indicate that the experiment can realistically reproduce an impact event analogous to those in space. This offers the possibility of modeling processes that occurred, or will occur, at small bodies of the solar system by loading corresponding samples with spherically converging shock waves.

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