Quantitative determination of the shock stage of L6 ordinary chondrites using X-ray diffraction

NAOYA IMAE1,2,* AND MAKOTO KIMURA1

1National Institute of Polar Research, 10-3 Midori-cho, Tachikawa-shi, Tokyo 190-8518, Japan
2SOKENDAI, 10-3 Midori-cho, Tachikawa-shi, Tokyo 190-8518, Japan

ABSTRACT

The shock stages of 14 L6 ordinary chondrites are estimated using the random X-ray diffraction patterns of polished thin section samples and the in-plane rotation method. The mean lattice strains and grain size factors for olivine and orthopyroxene are determined from the analyses based on the Williamson–Hall plots, which depict the tangent Bragg angle and integral breadth β. The lattice strain in olivine, ε^Ol, is distributed from ~0.05% to ~0.25%, where that in orthopyroxene, ε^Opx, is distributed from ~0.1 to ~0.4%, where we selected the isolated peaks of olivine and orthopyroxene. The olivine peaks have Miller indices of (130), (211), (222), and (322), while the orthopyroxene peaks have Miller indices of (610), (511), (421), (631), and (12.1.2). The intercept for integral breadth β^Ol and β^Opx for the Williamson–Hall plots correlates with the grain size of the constituent minerals. The grain size is proportional to the inverse of β, since the β intercept increases with the shock stage. Introducing a new parameter, −ε/ log β, for olivine (0.04–0.16) and orthopyroxene (0.07–0.32) reveals a clear relationship between them: −ε^Ol/ log β^Ol = −0.01 + 2.0 (−ε^Opx/ log β^Opx) (R > 0.9). In addition, the isolated peak of plagioclase (201) systematically changes as the shock stage increases, suggesting the progress of amorphization (maskelynitization). Another parameter, (I/FWHM)_{201} reveals additional relationships: −ε^Ol/ log β^Ol = 0.14±(0.01) − 5.2 × 10^{-5} (±5.7 × 10^{-5}) × (I/FWHM)_{201}, and −ε^Opx/ log β^Opx = 0.25±(0.04) − 8.9 × 10^{-5} (±2.6 × 10^{-5}) × 10^{-5} × (I/FWHM)_{201}. These three parameters systematically change with the shock stage, suggesting that they are suitable shock barometers. The present method is useful to evaluate the shock stage of L6 chondrites and potentially enables quantitative shock stage classification for stony meteorites.

Keywords: Olivine, orthopyroxene, ordinary chondrites, X-ray diffraction, lattice strain, shock metamorphism

INTRODUCTION

Laboratory X-ray diffraction (XRD) methods are useful tools to characterize extraterrestrial materials. Some studies have macroscopically examined powder samples (e.g., Howard et al., 2009, 2010; Dunn et al., 2010) and polished thin sections (Imae and Nakamuta, 2018; Imae et al., 2019), while others have microscopically investigated submillimeter grains (Imae and Kimura, 2021) and ~50 μm sized grains (Uchizono et al., 1999; Nakamuta and Motomura, 1999; Nakamuta et al., 2001; Nakamuta et al., 2006; Flemming et al., 2007; Jenkins et al., 2019). These approaches can identify the constituent phases, their chemical composition (e.g., Mg-Fe in olivine), the shock stage, the shock metamorphism (Uchizono et al., 1999; Jenkins et al., 2019; Imae et al., 2019), and thermal metamorphism (Imae and Nakamuta, 2018; Imae et al., 2019) as well as determine the modal abundance of the constituent minerals (Howard et al., 2009; Dunn et al., 2010).

Stöffler et al. (1991) established a shock stage classification of ordinary chondrites by textural observations and shock recovery experimental results. The results are defined on a scale of S1 to S6, where the shock peak pressure increases from S1 (<3 GPa) to S6 (>50 GPa). The classification of the degree of shock in chondrites is somewhat descriptive (Stöffler et al., 1991, 2018; Schmitt, 2000). Chondrites exhibit diverse shock effects, which can be observed under an optical microscope, such as undulatory extinction, mosaic texture, planar deformation features (PDF), brecciation, shock melt vein formation, recrystallization, and annealing after shock (Stöffler et al., 1991, 2018). However, a quantitative analytical technique to measure shock effects on ordinary chondrites has yet to be established.

Crystal defects such as dislocations, which originate from subgrain or subdomain micro-orientations, form both undulatory extinctions and mosaic textures. Undulatory extinctions are correlated with the lattice strain due to the deviation of the unit cell and are detected as broadening of the XRD diffraction peaks. In contrast, mosaic textures are due the organization of dislocations into discrete arrays and are detected as a grain size factor under XRD as a function of the tangent of the Bragg angle. Additionally, they may be detected as dislocation densities under a transmission electron microscope (TEM). Jenkins et al. (2019) identified the mosaic texture by a streak of the Laue spot along the Debye ring (strain-related mosaicity) using a two-dimensional (2D) detector.

Among the shock effects in extraterrestrial materials, strain can be evaluated using macroscopic X-ray diffraction. Imae et al. (2019) recently found that the full-width at half maximum (FWHM) of the olivine (Ol) (130) lattice plane measured in 11 L6 chondrites shows a positive correlation with the shock stages (S1–S5) defined by Stöffler et al. (1991, 2018, 2019). However, the relationship for the FWHM of the diffraction peaks from orthopyroxene is less distinct than that of olivine (Imae et al., 2019). The FWHM is correlated with the lattice strain that formed during the shock processes and can be observed as diffraction line broadening. However, these works did not consider the strain-related mosaicity.