OLIVINE MICROSTRUCTURES IN THE MILLER RANGE 99301 (LL6) ORDINARY CHONDRITE.
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Introduction: Miller Range 99301 (MIL 99301) was classified as an LL6 ordinary chondrite based on its recrystallized texture in thin section, chemical homogeneity of olivine and low-Ca pyroxene grains, and the presence of coarse (>50 µm) interstitial grains of plagioclase [1]. Determination of shock stage was problematic as various shock indicators gave contradictory information: olivine and plagioclase grains showed sharp optical extinction indicative of shock stage S1, whereas other indicators such as the presence of polycrystalline troilite and large grains of low-Ca clinopyroxene suggested a shock stage of S4 or higher [1]. To account for these observations, Rubin [1] proposed that MIL 99301 experienced a complex thermal history with metamorphism to petrographic type 6, a later shock event equivalent to shock stage S4 or higher, and annealing to metamorphic levels equivalent to petrographic type 4 to remove defects in olivine and plagioclase. Additionally, MIL 99301 records ^{39}Ar-^{40}Ar evidence for two impact events, one at ~4.52 and another at ~4.23 Ga ago [2].

We used transmission electron microscope (TEM) imaging to examine microstructures in MIL 99301 olivine grains in order to understand more fully this meteorite's deformation and thermal history.

Methods: A small bulk sample of MIL 99301 was lapped to ~100 µm thickness, cored and affixed to a 3 mm copper support grid. The sample was ion milled, with a milling angle of 5°, until a perforation was detected. The final TEM sample contained five perforations in an area approximately 500 µm x 500 µm, with electron transparent areas adjacent to these perforations. TEM work was done at Portland State University using an FEI Tecnai F-20 G2 TEM/STEM equipped with an EDAX energy dispersive detector (EDS) operated at 200 kV. Olivine grains were identified using EDS analysis.

Results: At present, ten olivine grains have been imaged. All of the grains contain very low dislocation densities. Figure 1 is typical of two of the areas studied, with grains that lack any evidence of dislocations. The remaining grains contain some dislocations, but also show evidence that more than one slip system was activated (Fig. 2). In two grains, dislocations are present in arrays (kink bands) (Fig. 2) which lack the regular spacing seen in subgrain boundaries. One area contained pinned and bowed dislocations (Fig. 3), while in another area 120° triple junctions were observed (Fig. 4).

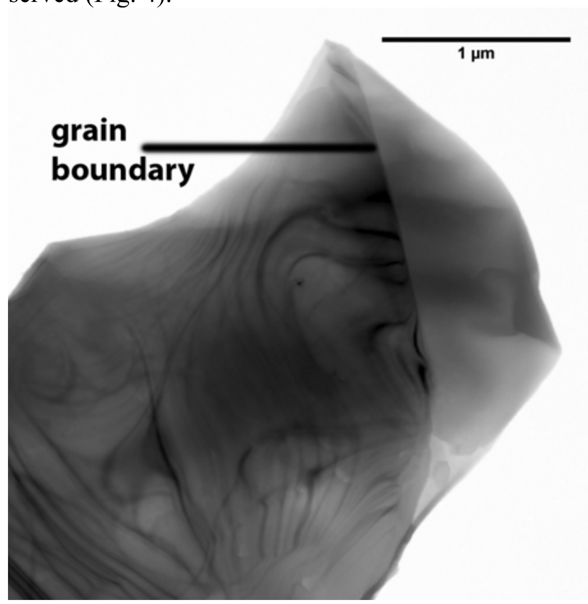

Fig. 1: Bright field image of two olivine grains lacking dislocations. Bend contours and a grain boundary are visible.

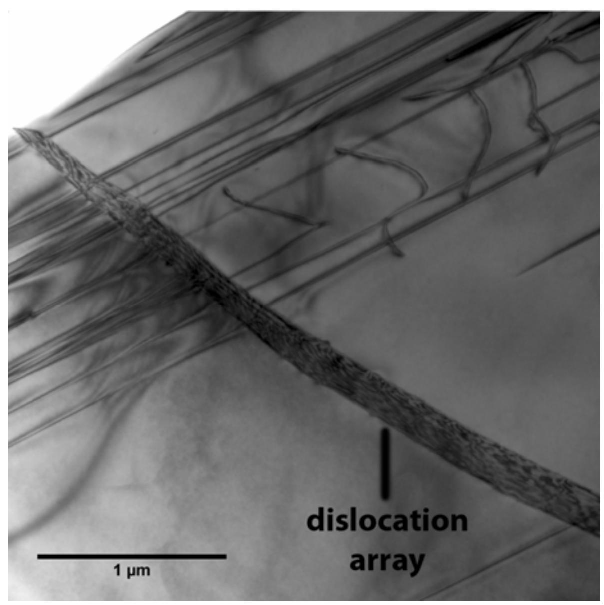

Fig. 2: Bright field image showing dislocations along different slip systems. The straight dislocations jog at the dilocations array, indicating that the array formed after the straight dislocations.

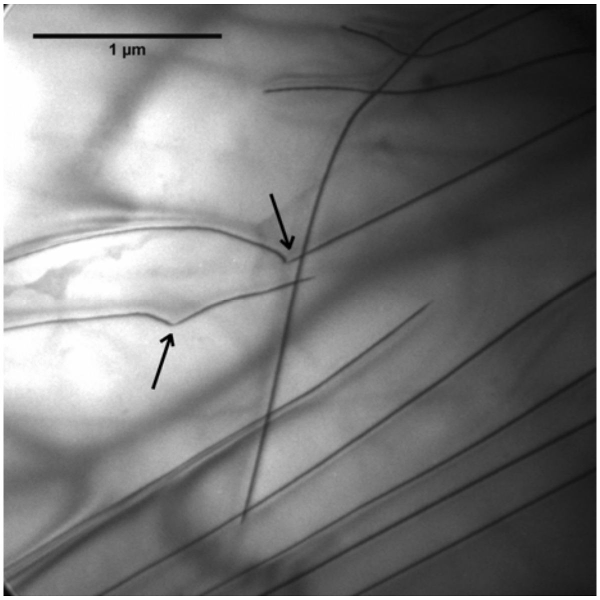

Fig. 3: Bright field image showing two sets of dislocations intersecting each other. Arrows point to dislocation jogs (pinning points) formed at prior dislocation intersections..

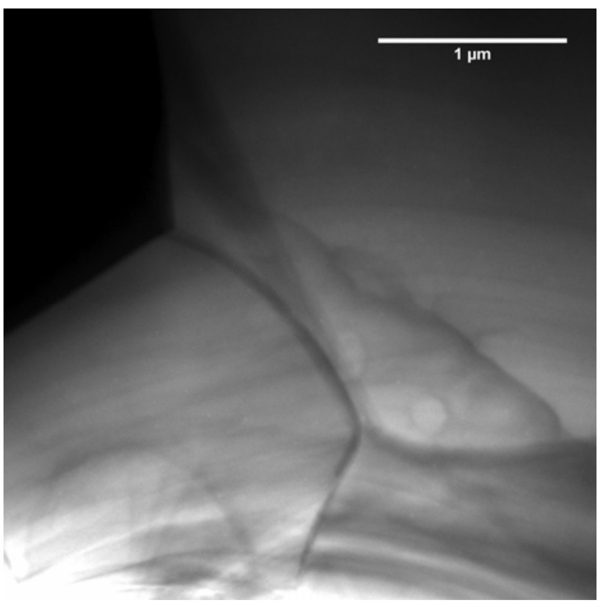

Fig. 4: Conical dark field image showing 120° triple junctions.

Discussion: Observational and experimental studies on olivine (e.g., [3, 4, 5, 6]) demonstate that the characteristics of microstructures that develop depend on strain rate and temperature of deformation. At low temperatures (below ~800° C) a single slip sytem is activated and there is a general increase in dislocation densities in olivine grains with increasing deformation. At higher temperatures (≥1000° C [3]), additional slip systems are activated. The presence of multiple slip systems in MIL 99301 (Fig. 2 and 3) and pinned dislocations that became bowed by movement from their intersection points (Fig. 3) provide clear evidence for deformation occurring at high temperatures.

The lack of well-defined subgrain boundaries in observed olivine grains implies that recovery during annealing was not significant in MIL 99301. Moreover, the overall low dislocation densities observed in MIL 99301 olivines (Fig. 1-4) and lack of dense tangles suggests that deformation of the meteorite was much less intense than has been proposed [1]. Annealing experiments for olivine show that with increasing recovery (promoted at higher temperatures), dislocations move into subgrain boundaries, decreasing the number of free dislocations [4]. However, even at 1000° C for annealing times up to 90 hours, a substantial number (>50%) of free dislocations remain outside of subgrain boundaries in olivine [7, 8].

The microstructures in MIL 99301 lead to the conclusion that the sample observed in this study experienced a weak shock event while the parent body was still undergoing thermal metamorphism. The 120° triple junctions most probably result from heating of the meteorite at temperatures corresponding to petrographic type 6. Similar features (multiple slip systems, dislocation arrays interpreted as kink bands, “curved and intersecting” dislocations indicative of climb) were observed in a TEM study of the Saint-Séverin (LL6) chondrite [9]. The authors concluded that Saint-Séverin had experienced “mild shock” during “gradual cooling” while undergoing thermal metamorphism to petrographic type 6 [9].

Conclusions: A preliminaryTEM examination of the MIL 99301 chondrite suggests that this meteorite experienced a slight shock event while still undergoing thermal metamorphism to petrographic type 6. This conceivably corresponds to the ~4.52 Ga thermal event recorded by ^{39}Ar-^{40}Ar [2]. However, we see no evidence for a significant later thermal event [2], and we have not resolved the obvious discrepancy between optical shock indicators in the meteorite [1].

References: [1] Rubin A. E. (2002) *Geochim. Cosmochim. Acta*, *66*, 3327-3337. [2] Dixon E. T. et al. (2004) *Geochim. Cosmochim. Acta*, *68*, 3779-3790. [3] Phakey P. et al. 1972. In Heard H.C. ed., *Flow and Fracture of Rocks*, 117-138. [4] Green H.W. (1976). In Wenk H.-R. ed., *Electron Microscopy in Mineralogy*, 443-464. [5] Ashworth J. R. (1985) *EPSL*, *73*, 17-32. [6] Sears D. W. et al. (1984) *Geochim. Cosmochim. Acta*, *48*, 343-360. [7] Goetze C. and Kohlstedt D. L. (1973) *JGR*, *78*, 5961-5971. [8] Ashworth J. R. and Mallinson L. G. (1985) *EPSL*, *73*, 33-40. [9] Ashworth J. R. and Barber D. J. (1977) *Phil. Trans. R. Soc. Lond.*, *A286*, 493-506,