AN EVALUATION OF QUANTITATIVE METHODS OF DETERMINING THE DEGREE OF MELTING EXPERIENCED BY A CHONDRULE.

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Introduction. Many workers have considered the degree to which partial melting occurred in chondrules they have studied, and this has led to attempts to find reliable methods of determining the degree of melting. At least two quantitative methods have been used in the literature: a convolution index (CVI), which is a ratio of the perimeter of the chondrule as seen in thin section divided by the perimeter of a circle with the same area as the chondrule [1], and nominal grain size (NGS), which is the inverse square root of the number density of olivines and pyroxenes in a chondrule (again, as seen in thin section)[2].

We have evaluated both nominal grain size and convolution index as melting indicators. Nominal grain size was measured on the results of a set of dynamic crystallization experiments previously described in [3], where aliquots of LEW97008(L3.4) were heated to peak temperatures of 1250, 1350, 1370, and 1450 ºC, representing varying degrees of partial melting of the starting material. Nominal grain size numbers should correlate with peak temperature (and therefore degree of partial melting) if it is a good melting indicator. The convolution index is not directly testable with these experiments because the experiments do not actually create chondrules (and therefore they have no outline on which to measure a CVI). Thus we had no means to directly test how well the CVI predicted different degrees of melting. Therefore, we discuss the use of the CVI measurement and support the discussion with X-ray Computed Tomography (CT) data.

Methods: *Nominal Grain Size (NGS).* As noted above, NGS is the inverse square root of the number of olivines and pyroxenes (excluding dendrites) per unit area in a chondrule. Its basis as a use as a melting indicator is that this number should reflect the number of nucleation sites remaining when cooling of the partially melted chondrule began. A matrix of twelve dynamic crystallization experiments was used to test how well NGS predicts degree of melting in a chondrule. We varied both peak temperature and cooling rate in the experiments so that cooling rate effects could be separated from melting effects on the experimental products. The sample matrix is shown in table 1. For a more complete description of the experiments, see [3]. Backscatter electron (BSE) images of the experimental products served as the basis for the NGS measurements. All NGS measurements were made on images with the same scale (FOV = 1000µm).

Table 1. Crystallization experiment matrix showing sample numbers along with their peak temperatures and cooling rates.

Cooling Rate (°C/Hr)	Maximum Temperature (°C)			
	1250	1350	1370	1450
Quench	Que285			Que277
1000	Que286		Que278	Que290
100	Que287	Que283	Que279	Que289
10	Que288	Que284		Que280

Convolution Index(CVI). The CVI ratio, defined earlier in the abstract, is a measure of the outline of a chondrule as seen in thin section. The premise behind the use of the CVI is that, as melting progresses, the chondrule should behave more like a liquid droplet, and thus become spherical. Therefore a CVI of 1 would represent high degrees of partial melting (or complete melting), and higher CVI's would represent lower degrees of melting. [1] found a correlation between CVI and olivine Fa content and the Ni and P content of metal and concluded that these compositional trends were related to the degrees of partial melting in the chondrules they analyzed. [4] noted that the CVI, like any measurement of an object in thin-section, has the problem of being a two-dimensional measurement of a three-dimensional object. Since X-ray CT scanning is a way to measure the shape of an object in three-dimensions, it provides a way to evaluate how much bias the two-dimensional thin section measurements introduce.

X-ray CT works by acquiring a sequence of two-dimensional slices through the object being measured. X-rays are passed through the sample, and the sample is rotated 360º, acquiring a two-dimensional image that resembles a BSE image. The gray scale in the image is related to the density of the object being imaged. Stacking the slices creates a three-dimensional image volume of the object. For a more complete description of X-ray CT methodology, see [5]. We used scans with an in-slice resolution of 9.8 µm/pixel, and a slice thickness of 13.8 µm. The Semarkona scans were acquired at the University of Texas at Austin's High Resolution X-ray CT Facility.

[4] measured CVI's of individual slices of Renazzo chondrules in CT scans and found that each successive slice of the same chondrule can have a significantly different CVI (the range of CVI's in a single chondrule was about 0.28). But the slices used in that study were the slices of the CT data volume itself, meaning that each slice had the same orientation and thus does not truly represent the way thin sections are made, where the orientation of objects being captured in thin section is truly random. We wrote a software routine in the IDL language to extract 193 slices from a CT scan of a Semarkona chondrule at random orientations, thus more faithfully reproducing the kinds of orientations that are found in thin sections. This gives us a way to best evaluate how a CVI for a single chondrule might change simply by virtue of the way it was cut to make a thin section. We then measured the CVI using the outline of the chondrule as captured in each of the random slices.

Results and Discussion: *Nominal Grain Size.* Figure 1 is a plot of NGS versus peak temperature for each cooling rate in the experiment matrix. For each cooling rate, there is a positive correlation of NGS with peak temperature, and thus with degree of partial melting. It was our expectation that NGS would be unable to distinguish cooling rate effects from melting effects on grain size, since with slow cooling, crystals have time to grow larger, and thus one might expect a modestly melted chondrule that cooled relatively slowly to have grain sizes similar to a chondrule significantly melted but that cooled more rapidly. However, the NGS parameter does a surprisingly good job at separating the two effects. There is no overlap between the nominal grain sizes of experiments with 1250 ºC and 1450 ºC peak temperatures, and very little overlap between the 1350/1370 ºC experiments with the other groups. Clearly, NGS has some use as a melting indicator.

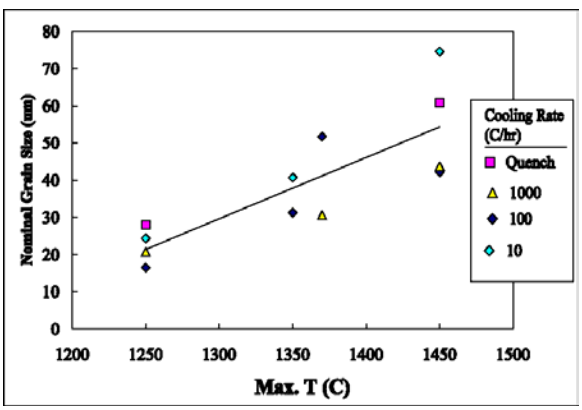

Figure 1. Nominal Grain Sizes of experimental charges as a function of peak melting temperature for four different cooling rates.

Convolution Index. Figure 2 shows some examples of the random slices through the Semarkona chondrule from which CVI measurements were made. A histogram of the entire set of CVI measurements is shown in Figure 3. Most of the CVI measurements fall within the range of ~1.5 – 2.2. Thus we might expect the CVI for a chondrule to vary by about 0.7 simply by virtue of the way the thin section was cut. This is at least equal to the 0.68 variation in CVI attributed to variation due to degrees in partial melting found by [1]. If the entire range of the histogram in Figure 3 is considered, the random slice variation is much greater. This suggests that NGS might be a better melting indicator than CVI.

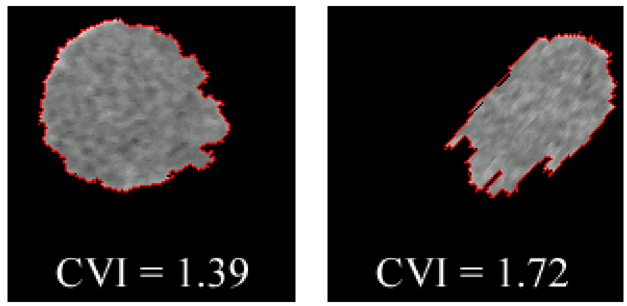

Figure 2. Examples of chondrule outlines created by randomly taking slices through a CT data volume of a single chondrule.

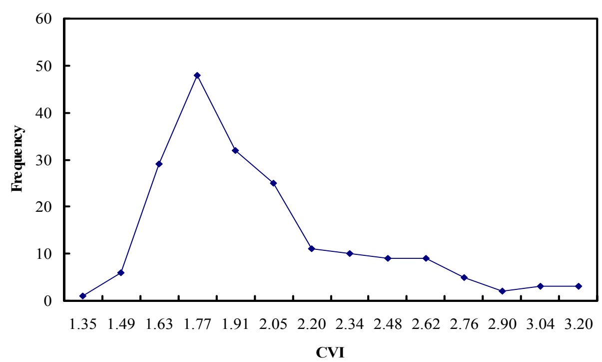

Figure 3. Histogram of CVI values obtained from random slices.

References. [1] Zanda B. et al. (2002), LPSC XXXIII, Abs. #1852. [2] Hewins R. H. et al. (1997) *Ant. Met. Res.*, 10, 275-298. [3] Nettles J. W. et al. (2003) LPSC XXXIV, Abs. #1823. [4] Hertz J. et al. (2003) LPSC XXXIV, Abs. #1959. [5] Ketcham R. A. and Carlson W. D. (2001) *Comp. and Geosci.* 27, 381-400.