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Experimental grain growth of forsterite and nickel in melt-free and melt-bearing systems: implications for meteorite parent-body processes.

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Abstract

The grain growth kinetics and microstructural evolution of olivine (forsterite) and metal (nickel) have been experimentally quantified in the presence and absence of a silicate melt. Experiments of variable duration have been performed at 1bar pressure, a temperature of ~1440°C, and an oxygen fugacity (fO_2) approximately 3.5 log units below the NiNiO buffer. In melt-free systems, grain growth was measured for four binary mixtures, containing 95, 80, 30, and 10 vol% Ol, covering geometries for each phase varying from an interconnected matrix to isolated grains. In all aggregates, the grain growth exponent *n* is found to have a value of 4-5. Despite this common value, consideration of the distribution of grain sizes points to variable grain growth mechanisms, from grain boundary migration for forsterite and nickel when they form an interconnected matrix, to grain growth by coalescence for nickel when the latter occurs as isolated grains. For melt-bearing systems a fixed Fo/Ni ratio was used (95:5) to which 5 and 20 vol% of melt was added. Five olivine-saturated liquid compositions from the forsterite-anorthite-diopside ternary were tested (liquids containing 0 to 24 wt% Al_2O_3). In all cases, grain growth of both Fo and Ni is faster than under "dry" conditions. Grain growth of Fo is controlled by Ostwald ripening (*n*~2-3) while that of Ni appears to remain controlled by coalescence (*n*~4-5). For 20% melt, an effect of melt composition is also observed. Finally, comparisons between experimental data and natural observations (in chondrites and achondrites) have been made with the aim of constraining the thermal history of their parent bodies.

1. Introduction

Many meteorites come from parent bodies thought to have accreted early in the history of the solar system (typically in the first ten million years). At that time, short lived radioactive elements *[1]* such as ^{26}Al ($T_{1/2}$~730ky) and ^{60}Fe ($T_{1/2}$=1.5 Ma) were potentially present in non-negligible amounts, providing a source of heat. Depending on the size of the object and its accretion time, heating was modest (e.g. thermal metamorphism in H-chondrites), or more extensive (e.g. partial melting seen by primitive achondrites). Of all the processes that take place at that time, segregation of metallic iron is one of the most important. With the aim of quantifying the textural consequences of heating observed in natural meteorites, including in the presence of a silicate melt, experiments of grain growth have been performed on a simplified analogue system composed of Forsterite (Fo) + Nickel (Ni) ± Silicate melt. Two sets of experiments have been performed: (i) silicate melt free samples with different amounts of forsterite and nickel and (ii) experiments with various amounts and various compositions of silicate melt (and thus of different viscosity).

2. Experimental procedure

Polycrystalline aggregates have been prepared from commercial powders of Forsterite and Nickel sintered by Spark Plasma Sintering (SPS) *[2]*. Five melts saturated in Fo near 1450°C have been synthesized from reagent grade oxides. Four melt-free mixtures have been synthesized with phase proportions from $Fo_{95}+Ni_5$ to $Fo_{10}+Ni_{90}$. In addition, ten melt-bearing starting products have been made: $Fo_{90}+Ni_5+Melt^{(c)}_5$ and $Fo_{76}+Ni_4+Melt^{(c)}_{20}$. (c) represents the five different compositions of the silicate melt in equilibrium with the forsterite. Annealing experiments have been performed in a controlled atmosphere vertical furnace at high temperature (1440°C) under reducing conditions ($fO_2=10^{-8.8}$atm) and between 2 hours and 21 days.

3. Results and Discussion

Evolution of grain size of Fo and Ni in almost all samples (with 2 or 3 phases) shows features of

Normal Grain Growth (NGG), i.e, the grain size distributions reach a steady state *(Fig.1)*.

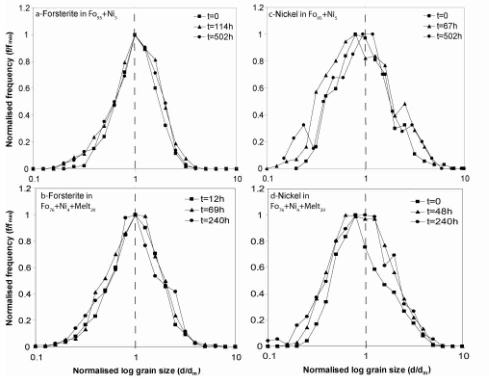

Fig.1: **Normalized grain size distribution as a function of annealing time and sample compositions. Note that a steady-state distribution is reached for both phases Fo and Ni in dry (a & c) and wet conditions (b & d).**

The grain growth law $d^n\text{-}d_0^n=kt$ is considered here, where d is the mean grain size at time t, d_0 is the initial mean grain size, n is the grain growth exponent and k is the grain growth rate. Normalized Grain Size Distribution (NGSD) is also considered, as peak frequency and maximum grain size are useful parameters to constrain grain growth mechanisms. In silicate melt free systems, grain growth (GG) of Fo is found to be a function of its proportion in the mixture, occurring by grain boundary migration. On the other hand, GG of Ni occurs through coalescence limited by the growth of olivine grains when Ni is not interconnected. Such mechanisms have been described in other experiments *[3]* (olivine + pores). In the presence of a silicate melt, grain growth rates of both Fo and Ni are 2-3 times larger than in the melt-free case *(fig.2)*, with a dependence on the proportion of silicate melt (5 or 20 vol%). In these cases, GG of Fo occurs by Ostwald ripening while GG of Ni remains limited by that of Fo. Composition (and thus viscosity) of the silicate melt is also found to control the grain growth rate of Fo *(fig.2)* (and indirectly Ni).

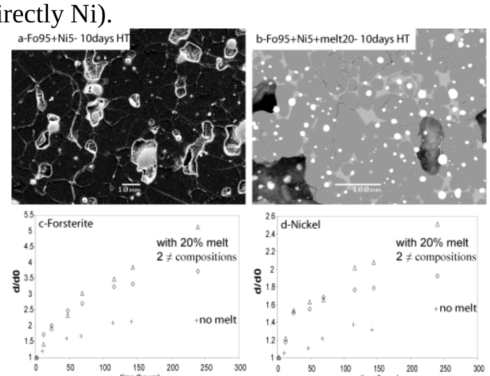

Fig2: **(a & b) SEM images showing the evolution of the microstructures between samples without (a) and with silicate melt (b). Note that the scale is one order of magnitude different between the two pictures. (c &d) Evolution of the grain size with time and sample compositions. In both phases, grain growth is faster in the presence of silicate melt. Finally, note the influence of the composition of the silicate melt on grain growth.**

Despite H-type ordinary chondrites having experienced lower temperatures (800-1200K) and longer annealing times (few Ma), textures in natural and experimental samples (without silicate melt) show similar features, including the shape of the NGSD and the same value of grain growth exponent, suggesting that processes of coalescence of metal also occur inside their parent body. By extrapolation (in time and temperature) and combination of a thermal model constrained by geochemical age determinations and our experimental laws, we calculate the evolution with time of grain size of metal in several H-chondrites. Very good agreement is observed between observed and calculated values of mean grain size. This approach will now be applied to bodies which have experienced a degree of partial melting such as the parent body of the Acapulcoites-Lodranites, with the aim of better understanding the earliest stages of core formation.

4. Conclusion

In this study, we show that experiments can provide new constraints in the understanding of processes which occurred on early accreted bodies in the solar system and provide new information on the early stages of the metal/silicate segregation, i.e, proportion of each phase, nature of silicate melt…

References

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