Experimental investigation of the effect of nickel on the electrical resistivity of Fe-Ni and Fe-Ni-S alloys under pressure

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ABSTRACT

Electrical resistivity experiments were conducted on three alloys in the iron-rich side of the Fe-Ni(-S) system (Fe-5 wt% Ni, Fe-10 wt% Ni, Fe-10 wt% Ni-5 wt% S) at 4.5 and 8 GPa and up to 1900 K using the multi-anvil apparatus and the 4-electrode technique. For all samples, increasing temperature increases resistivity. At a specified temperature, Fe-Ni(-S) alloys are more resistive than Fe by a factor of about 3. Fe-Ni alloys containing 5 and 10 wt% Ni present comparable electrical resistivity values. The resistivity of Fe-Ni(-S) alloys is comparable to the one of Fe = 5 wt% S at 4.5 GPa and is about three times higher than the resistivity of Fe = 5 wt% S at 8 GPa, due to a different pressure dependence of electrical resistivity between Fe-Ni and Fe-S alloys. Based on these electrical results and experimentally determined thermal conductivity values from the literature, lower and upper bounds of thermal conductivity were calculated. For all Ni-bearing alloys, thermal conductivity estimates range between ~12 and 20 W/(m·K) over the considered pressure and temperature ranges. Adiabatic heat fluxes were computed for both Ganymede’s core and the Lunar core, and heat flux values suggest a significant dependence to both core composition and the adiabatic temperature. Comparison with previous thermochemical models of the cores of Ganymede and the Moon suggests that some studies may have overestimated the thermal conductivity and hence, the heat flux along the adiabat in these planetary cores.

Keywords: Iron-nickel alloys, metallic cores, electrical resistivity, multi-anvil apparatus, Ganymede, the Moon

INTRODUCTION

The metallic cores of terrestrial planets and moons are composed of iron-nickel alloy that contains different amounts of light elements (such as S, Si, and C). Several weight percentages of nickel are thought to be present in these planetary cores, based on mass balance calculations and on iron-rich meteorites geochemistry (e.g., McDonough and Sun 1995; Jarosewich 1990). For instance, geochemical models have suggested that about 5.5 wt% Ni is present in the Earth’s core (e.g., McDonough and Sun 1995), and an estimate of about 9 wt% Ni in the Lunar core has been suggested by Righter et al. (2017), assuming a bulk Moon Ni content of 2200 ppm, a core fraction of 2 mass% and using calculations of the metal–silicate partition coefficient of Ni. Meteorite geochemistry has indicated that the Martian core also likely contains several weight percentages Ni, with Fe, Ni, and S, possibly representing the major components of the planet’s core (e.g., Wänke and Dreibus 1988; Lodders and Fegley 1997).

Several investigations have been conducted to understand the effect of nickel on the chemical and physical properties of iron alloys, and therefore to determine the influence of Ni on the structure and dynamics of metallic cores. The effect of nickel on the phase diagram of iron is detectable but small (e.g., Lin et al. 2002), and in particular, Ni stabilizes the face-centered cubic (fcc) structure under high pressure and temperature (e.g., Côté et al. 2012). It was proposed that Ni does not affect significantly the melting curve of the Fe-rich side of the Fe-S system at the core conditions in small terrestrial bodies (less than 100 K of difference between Fe-S and (Fe,Ni)-S, Stewart et al. 2007), though it might be more significant at high pressure relevant to the Earth’s core (Komabayashi et al. 2019). This suggests that nickel, contrary to light-alloying components such as sulfur, is unlikely to affect the onset of core crystallization of small planets and moons. Nickel may have affected the partitioning behavior of heavy iron isotopes during core formation (Elardo and Shahar 2017), but no measurable effect of nickel concentration on the partitioning of siderophile elements has been observed under Earth’s core conditions (Ni, Cr, V; Huang and Badro 2017). Experimental studies of Fe-Ni alloys under pressure have demonstrated that Ni has a very small effect on several material properties, such as density, sound velocity, and compressibility (e.g., Mao et al. 1990; Lin et al. 2003; Kantor et al. 2007; Martorell et al. 2013, 2015; Kawaguchi et al. 2017; Wakamatsu et al. 2018; Morrison et al. 2019), justifying the use of Ni-free iron alloys as core analogues in mineral physics experiments.

The investigation of core dynamics requires constraining the superadiabatic heat flux, i.e., the heat that is available to drive convection, which depends strongly on the thermal resistivity of the core materials. Measurements of the thermal resistivity of Fe-Ni alloys under high temperature are scarce, but at atmospheric pressure and high temperature (~1673 K), experiments have suggested that Ni does not affect significantly the thermal resistivity.