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Magnetic properties of liquid Ti–Si, V–Si and Cr–Si alloys

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Abstract

The magnetic susceptibilities of liquid Ti–Si, V–Si and Cr–Si alloys have been measured as a function of composition and temperature. The magnetic susceptibilities were found to be almost independent of temperature, which suggests that transition metal solutes in liquid Si are in the non-magnetic state. The impurity susceptibilities were estimated under the assumption that the solute atoms are monovalent in liquid Si. The general trend obtained for the whole series of 3d solutes in liquid Si shows a sharp peak around Mn solute which is considerably less pronounced than that reported in liquid In or Sn. The results are discussed in terms of Anderson's model of localized impurity states.

Keywords: Magnetic susceptibility; Transition metal; Liquid Si; Impurity susceptibility; Anderson model

1. Introduction

When a transition metal (TM) solute is dissolved into liquid Si, the 3d electron states of the solute are strongly hybridized with the conduction electron states in liquid Si. The width of virtual bound 3d states depends upon the density of states of conduction electrons at the Fermi level (E_F) and the strength of sp–d mixing [1]. Because of the large density of states of liquid Si at E_F, the TM solutes in liquid Si have a considerably large width of the virtual bound 3d states. It suggests that the whole of liquid TM–Si alloys may be in a non-magnetic state on the Si-rich side.

In the paper submitted [2], we have already obtained the magnetic susceptibility of liquid TM–Si alloys (TM = Mn, Fe, Co, Ni). There are few accurate data of magnetic susceptibility of Ti, V and Cr solutes in liquid metals. It is interesting to compare the behavior of Fe, Co and Ni solutes to those of Cr, V and Ti solutes. In this paper, the impurity susceptibility of the whole series of 3d metals in liquid Si will be studied. The trend of the impurity susceptibility obtained in liquid Si will be compared with those obtained in liquid Al, In and Sn [3–5]. The model of Anderson will be used to estimate the density of 3d states at E_F and the width of virtual bound 3d states.

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2. Experimental procedure

Magnetic susceptibility measurements were made using a standard Faraday method with a torsion balance [2,5]. The field strength of the electromagnet was approximately 10 kOe with a 6 cm gap between the pole pieces. The constant value of $H(dH/dx)$ was 6.10 ± 0.15 $(kOe)^2$/cm. Mohr's salt with a room temperature susceptibility of 1.26×10^{-2} emu/mol was employed as a standard sample. Alloys of 0.5 g were put into alumina cells and were heated in a silicon carbide furnace in an atmosphere of high purity helium. The measurements were carried out during heating from the melting point up to a maximum temperature of around 1600 °C and also during the subsequent cooling process.

3. Results

Fig. 1 shows the magnetic susceptibility of liquid Ti–Si alloys as a function of temperature. For all composition up to 35 at.% Ti the magnetic susceptibilities were almost independent of temperature, which suggests that the Ti ions in the liquid alloys are in the non-magnetic state. The observed discontinuities on the low temperature side are due to solidification and are in accordance with the melting point given in literature (1480 °C at 35 at.% Ti) [6].

The magnetic susceptibilities as a function of temperature of liquid V–Si (up to 20 at.% V) and liquid Cr–Si (up to 50 at.% Cr) are shown in Figs. 2 and 3, respectively. As observed for the alloys of Ti–Si, the discontinuities of data are due to the onset of solidification and are again in accordance with the literature

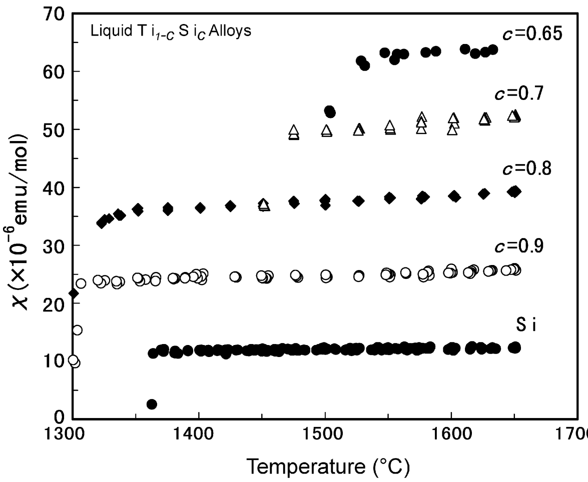

Fig. 1. Magnetic susceptibility of liquid Ti–Si alloys as a function of temperature.

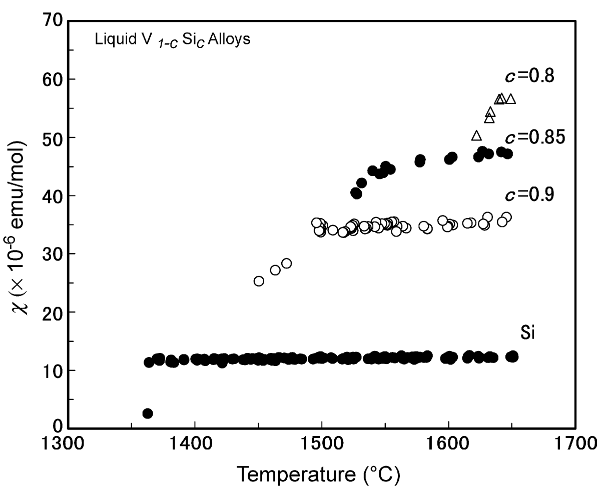

Fig. 2. Magnetic susceptibility of liquid V–Si alloys as a function of temperature.

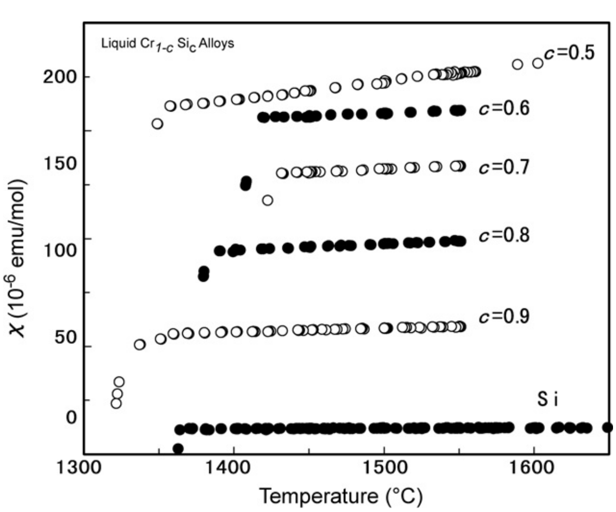

Fig. 3. Magnetic susceptibility of liquid Cr–Si alloys as a function of temperature.

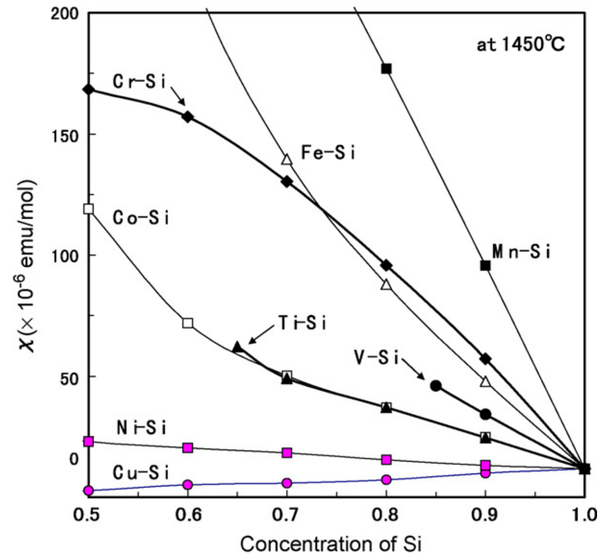

Fig. 4. Composition dependence of magnetic susceptibility in liquid 3d transition metal–Si alloys at 1450 °C. The values of liquid Mn, Fe, Co and Ni were taken from [2].

(1630 °C at 20 at.% V, 1350 °C at 50 at.% Cr) [6]. Similar to Ti–Si, the magnetic susceptibilities of both systems show a weak and positive temperature dependence of magnetic susceptibility, which suggests that both V and Cr ions in liquid Si are in a non-magnetic state.

Fig. 4 shows the composition dependence of susceptibility for the entire series of 3d metals at 1450 °C. The data of liquid TM–Si (TM = Mn, Fe, Co, Ni, Cu) were taken from the previous paper [2]. The increase in χ observed for small additions of less than half filled metals (10 at.% Cr, V, Ti) are larger than that for the corresponding more than half filled metals (10 at.% Fe, Co, Ni), respectively. That is, $\chi(\mathrm{Cr}) > \chi(\mathrm{Fe})$, $\chi(\mathrm{V}) > \chi(\mathrm{Co})$ and $\chi(\mathrm{Ti}) > \chi(\mathrm{Ni})$.

4. Discussion

The magnetic susceptibilities of liquid TM–Si alloys are given by [7]:

$$\chi = \chi_{3d}(\mathrm{TM}^+) + \chi_{para} + \{(1-c)\chi_{dia}(\mathrm{TM}^+) + c\chi_{dia}(\mathrm{Si}^{4+})\}, \quad (1)$$

where $\chi_{3d}(\mathrm{TM}^+)$ is the paramagnetic susceptibility due to the localized 3d electron states, and $\chi_{dia}(\mathrm{TM}^+)$ and $\chi_{dia}(\mathrm{Si}^{4+})$ are the diamagnetic susceptibilities of the TM^+ and Si^{4+} ion cores, respectively. It is known that Cu ions are monovalent in liquid metals. The assumption of TM^+ ions is based upon the conclusions drawn from the alloying behavior of electronic properties of liquid TM–Ge (TM = Mn, Fe, Co, Ni, Cu) [8]. The diamagnetic value of Si^{4+} is -2.3×10^{-6} emu/mol [9], those of TM^+ ions were interpolated from the trend of $\chi_{dia}(\mathrm{TM}^{n+})$ as reported by [9]. The total values of diamagnetic susceptibility are shown in Table 1. The decrease in χ_{dia} due to the addition of 10 at.% TM solute lies in the range between -1.8 and -2.5×10^{-6} emu/mol.