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Abnormal expansion during the ferro- to para-magnetic transition in pure iron

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ABSTRACT

The strain change near the Curie temperature was investigated during continuous heating of pure iron using two different types of dilatometers with and without a radio frequency (RF) field. Contrary to the well-known fact that the ferro- to para-magnetic transition accompanies volumetric contraction, abnormal expansion was observed near the Curie temperature only when the quench dilatometer employing the RF field for heating was used. The abnormal expansion was caused primarily by the change in electron–phonon interaction under the RF field.

1. Introduction

A quench dilatometer equipped with an induction-heating system has been widely utilized to investigate the behavior of thermal expansion [1,2], phase transformations [2,3], and magnetic transitions [4] in various metallic materials because of precise control of heating and cooling rates. Mohapatra et al. [1], Benedicks [2], and Verma et al. [4] investigated the thermal expansion behavior of pure iron using quench dilatometers. The dilatational change near the Curie temperature (T_C, 1043 K) measured during continuous heating was differently described according to researchers [1,2,4]. Benedicks [2] and Verma et al. [4] reported contraction or a dip near T_C on a dilatational curve measured as a function of temperature using pure iron. On the other hand, Mohapatra et al. [1] observed a hump near T_C on a thermal expansion coefficient vs. temperature curve. However, if we carefully observe the strain curves measured by these researchers [1,2,4], the strain curves commonly exhibit slight contraction followed by expansion near T_C. Therefore, inconsistent descriptions of the strain change near T_C among researchers [1,2,4] seem to stem from a simple difference in viewpoint on the curve shape.

The more important result on the strain variation near T_C in pure iron is the fact that strain curves measured using quench dilatometers are different from those measured using high-temperature X-ray diffractometers (XRDs) and normal dilatometers without an induction-heating system. Strain curves measured using an XRD [5] and a normal dilatometer [6] show only lattice contraction without subsequent expansion near T_C (Fig. 1). This lattice contraction has been explained by dissipation of the electronic exchange interaction during the ferro- to para-magnetic transition [7].

An interesting point is that abrupt expansion appears after contraction near T_C on the strain curves measured using quench dilatometers. This abnormal expansion is considered to be related to an electromagnetic field with a radio frequency (the RF field) employed for the induction-heating system. However, until now there are few reports on the relationship between the RF field and the strain change near T_C. Therefore, we investigated the effect of the RF field on the strain change occurring during the ferro- to para-magnetic transition in pure iron.

2. Experimental procedures

In the present study, the strain change near T_C was measured during continuous heating using two different types of dilatometers; a quench dilatometer using an induction-heating system with a RF field of 1 MHz (Theta, Dilatronic III) and a normal dilatometer using a furnace-heating system (Netzsch, DIL 402C). The heating rate was varied from 0.1 K/s to 100 K/s to examine the effect of the RF field strength on strain variation. The higher heating rate requires the higher input energy, which is generated

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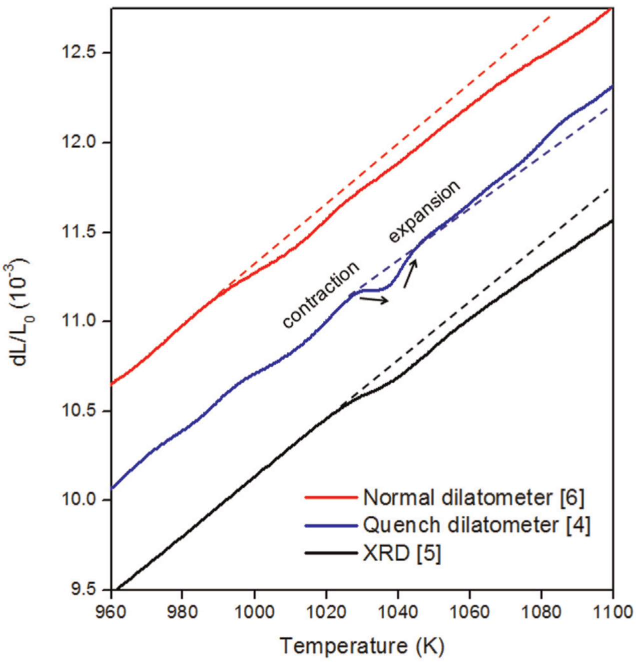

Fig. 1. Variation in strain (dL/L_0) measured during continuous heating of pure iron using quench [4] and normal [6] dilatometers and an X-ray diffractometer (XRD) [5]. For the XRD, the strain was converted from the lattice parameters of pure iron measured at various temperatures. The heating rate was 5 K/min for the normal dilatometer and 10 K/min for the quench dilatometer, respectively.

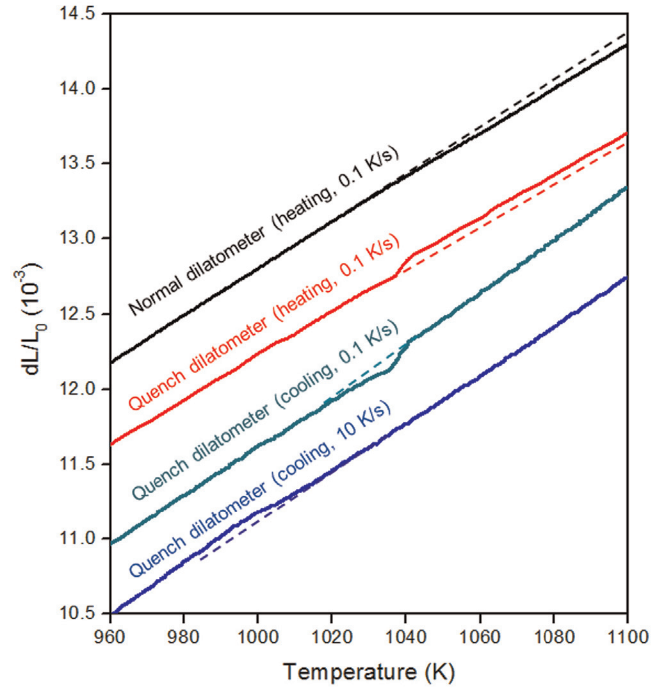

Fig. 2. Variation in strain measured during continuous heating and cooling of pure iron. Continuous heating was performed at a constant rate of 0.1 K/s using both quench and normal dilatometers. Continuous cooling was carried out at two different rates of 0.1 K/s and 10 K/s using only the quench dilatometer. The RF field was turned off only in the case of a cooling rate of 10 K/s.

by the stronger RF field. The induction heating was performed in a vacuum chamber of approximately 10^{-5} Torr. The furnace heating was carried out under a nitrogen atmosphere.

Two kinds of pure iron samples were used for the present study; a rod of high-purity iron (99.995%) measuring 2 mm in diameter and 250 mm in length [8] and a rod of pure iron (99.4%) measuring 12 mm in diameter and 100 mm in length. Dilatometric samples measuring 2 mm in diameter and 8 mm in length were machined from the high-purity iron (99.995%) to investigate the effects of the dilatometer type and the heating rate on thermal strain. To elucidate the effect of thermal stress, caused by the skin effect under the RF field, on abnormal expansion, dilatometric samples with two different shapes, rod and hollow specimens, were fabricated using the pure iron (99.4%). The size of the rod specimen was 10 mm in length and 3 mm in diameter. The hollow specimen was made by drilling the rod specimen and its wall thickness was approximately 0.2 mm. The reason why the rod of high-purity iron was not used was because its diameter (2 mm) is too small to be drilled to make the hollow specimen and thermal stress was also expected to be small.

3. Results and discussion

Fig. 2 shows strain change with temperature in pure iron. The strain change was measured during continuous heating at a rate of 0.1 K/s using both quench and normal dilatometers. Pure iron specimens were almost linearly expanded with increasing temperature from 960 K to approximately 1030 K, regardless of the type of dilatometers. At high temperatures of over 1030 K, whereas the strain curve measured using the normal dilatometer was contracted, the strain curve measured using the quench dilatometer exhibited subtle contraction followed by rapid expansion. These dilatometric results show good agreement with previous results shown in Fig. 1.

If abnormal expansion near T_C measured during continuous heating using the quench dilatometer was caused by the RF field, on the contrary abnormal contraction was expected during continuous cooling under the RF field. Thus, strain changes during continuous cooling were measured at two different rates of 10 K/s and 0.1 K/s from 1100 K, and are also plotted in Fig. 2. The RF field was applied only for the slow cooling rate (0.1 K/s) and turned off for the fast cooling rate (10 K/s).

Strain curves measured during cooling linearly decreased at the temperature range from 1100 K to approximately 1040 K, regardless of the cooling rate. Abnormal contraction occurred at around 1040 K for the cooling rate of 0.1 K/s. The abnormal contraction is an opposite result to the abnormal expansion measured during continuous heating at the same rate of 0.1 K/s using the identical quench dilatometer. Meanwhile, when the cooling rate was 10 K/s, the strain curve was linearly contracted until approximately 1020 K, and then was slightly expanded. This result shows good agreement with previous results measured using the XRD [5] and the normal dilatometer without the RF field [6]. Abnormal contraction measured during continuous cooling using the quench dilatometer confirmed that abnormal expansion near T_C measured during continuous heating was caused by the RF field.

This abnormal expansion near T_C may be caused by the relative change in thermal expansion coefficients of ferromagnetic and paramagnetic irons under the RF field. If the thermal expansion coefficient of the ferromagnetic iron (α_{FM}) decreases under the RF field, the atomic volume of the ferromagnetic iron becomes smaller near T_C than the atomic volume without the RF field, resulting in expansion near T_C. In contrast, if the thermal expansion coefficient of the paramagnetic iron (α_{PM}) increases under the RF field, the large thermal expansion of the paramagnetic iron compensates for lattice contraction during the ferro- to para-magnetic transition to cause abnormal expansion near T_C.

Therefore, the α_{FM} was measured at the temperature range from 950 K to 1000 K and the α_{PM} at the temperature range from