Materials Science and Engineering A 449–451 (2007) 430–434

MATERIALS SCIENCE & ENGINEERING A

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Effect of Si addition on the magnetic properties of melt-quenched Ni–Fe alloy strip

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Received 23 August 2005; received in revised form 6 March 2006; accepted 21 March 2006

Abstract

A sheet manufacturing technology for 79Ni–Fe alloy, which is highly permeable and has soft magnetic properties, was developed based on the melt drag casting method. Melt drag strip was manufactured using the new 79Ni–Fe–Si alloy designed considering the strip forming ability and soft magnetic properties in the single-roll casting method. The microstructure and soft magnetic properties were measured based on following casting and heat treatment processes. Oxygen concentration within the air-heated molten 79Ni–Fe alloy decreased rapidly following the addition of a small quantity of Si to the existing 79Ni–Fe alloy. Moreover, the effect of enhancing the strip-forming ability was determined by increasing the liquidus line temperature and solidus line temperature interval of 79Ni–Fe alloy with the additional Si concentration. As a result of cold processing and proper heat treatment, the melt drag cast 79Ni–19Fe–2Si alloy exhibited excellent soft magnetic properties compared with the 79Ni–Fe alloy strip. Therefore, the forming ability of melt drag strip can be enhanced by adding a small quantity of Si to the traditional 79Ni–Fe alloy. Likewise, soft magnetic properties can be enhanced by reducing oxygen concentration within the molten metal.

Keywords: Melt drag; Melt-quenched; Ni–Fe–Si alloy; Permalloy; Magnetic property; Si addition

1. Introduction

Following the recent boom of the electronic and telecommunication industry, the use of 79Ni–Fe alloy with high permeability and soft magnetic properties has been increasing [1–5]. A 0.2–0.5 mm thick sheet is used in the electronic and telecommunications sectors. Traditionally, functional Ni alloy sheets such as 79Ni–Fe alloy have been manufactured through hot and cold rolling processes where ingots are produced through mold casting. Recent studies on the manufacturing technology of various alloy sheets have reported using the single-roll casting method that enables manufacturing products in small quantities from many kinds of steel. This process has the advantage of streamlining the manufacturing process of metal sheets [6–10].

To form a smooth strip in molten metal by casting alloy using the melt drag casting method, which forms the metal strip through contact between the molten metal and the surface of the rotating casting roll in the horizontal direction, the following conditions may be established. First, contact between the molten metal and casting roll should be easy. Second, the molten alloy should form a coagulation shell easily through the cooling power of the casting roll. Finally, the surface of the formed coagulation shell should maintain friction force with the surface of the rotating casting roll. Continuous dragging should also be possible.

In the Ni–Fe binary alloy, the liquidus line temperature and solidus line temperature are known to be only 2–3 °C in most composition ranges. Likewise, shrinkage following coagulation occurs heavily in Ni among metal elements [11]. Therefore, many difficulties occur when forming metal sheet materials continuously and stably from the 79Ni–Fe alloy using the melt drag casting method. Moreover, since Ni has high oxygen solubility and high affinity in its molten state, it has been cast in vacuum melting to avoid oxygen contamination. When continuous metal sheet casting using the melt drag method is conducted under an atmosphere of common air melting; however, the soft magnetic properties may decrease due to oxygen impurity [12–14].

This study investigated the effect of the addition of a small quantity of Si to 79Ni–Fe alloy, which is known to be a highly permeable and soft magnetic alloy, on the formation of melt

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0921-5093/$ – see front matter
doi:10.1016/j.msea.2006.03.146

drag strip. The relationship between variations in the concentration of residual oxygen and permeability properties in the air-melted 79Ni–Fe alloy following the addition of Si was also investigated.

2. Experimental procedure

To predict the melt drag continuous casting ability of 79Ni–Fe alloy, the variation in the temperature domain for the coexistence of solid and liquid, which may affect continuous casting ability, was investigated based on the calculated phase diagram following variations in Si concentration. The calculation of phase diagram was carried out with CALPHAD (CALuation of PHAse diagram method) [15,16]. Specifically, the Si concentration that causes the biggest difference between the liquidus line temperature and solidus line temperature was determined.

The melt drag casting equipment (melting furnace, casting roll, and nozzle) was briefly delineated as shown in Fig. 1. Mass production equipment consists of strip transfer and winding equipment. When manufacturing 79Ni–Fe–Si alloy strip utilizing the melt drag casting method, 99.9% electrolytic iron, electrolytic nickel, and metal silicone are induction-melted in air in the magnesia (MgO) crucible. Its temperature is also increased to approximately 1520 °C, and molten metal is fed to the caster. To feed molten metal to the casting roll, molten metal is fed to the nozzle after preheating to about 1200 °C and made to come into contact with the surface of the casting roll; thus allowing the formation of an alloy strip. It is continuously dragged and manufactured like this. At this time, the nozzle is made of alumina (Al_2O_3) material and is in constant contact with the surface of the casting roll of the chrome (Cr) plated surface of the Cu–Cr material. For the measurement of the molten metal temperature of 79Ni–Fe alloy and concentration of residual oxygen following the Si addition, three small ingots weighing about 300 g were taken from the molten steel in each condition by utilizing the quartz tube. The material was then cold rolled until a thickness of about 3 mm was achieved. In addition, three specimens about L4 mm × W4 mm × T3 mm were then prepared, and the concentration of oxygen and nitrogen was measured. To compare and evaluate the soft magnetic properties of these specimens, cold rolled sheet was prepared through blanking and machining to an outer diameter of 30 mm, an inner diameter of 15 mm, and a thickness of 3 mm. Recrystallization heat treatment was conducted for 1h at 1000–1200 °C in a hydrogen atmosphere, and the effective permeability property was measured at 10 Hz.

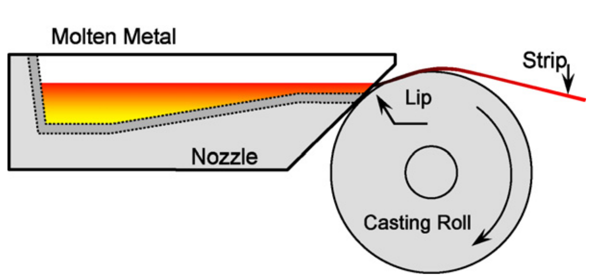

Fig. 1. Schematic view of the melt drag caster.

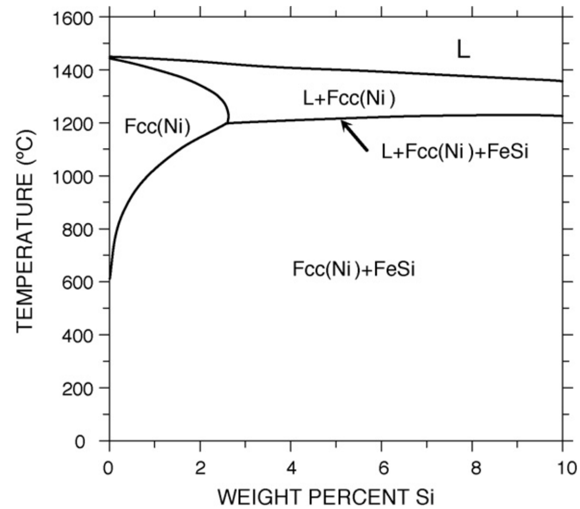

Fig. 2. Calculated phase diagram of 79Ni–Fe alloy with silicon concentration.

3. Results and discussion

3.1. Melt drag 79Ni–Fe–Si alloy strip

As a result of having added Si to improve the melt drag casting ability of 79Ni–Fe–Si alloy, the temperature range of the domain for the coexistence of solid and liquid increased from the existing 2–3 °C to up to about 200 °C following the Si addition as shown in the calculated phase diagram of Fig. 2. Moreover, since the solidus line temperature of alloy decreased in accordance with the Si addition, it can serve as an advantage in the casting process. For the molten metal of 79Ni–19Fe–2Si alloy, a strip about 450 μm thick could be manufactured stably utilizing the casting roll of Cu–Cr material with excellent heat transfer. Thus, a strip about 200 μm thick manufactured through the application of an adiabatic coating such as alumina on the casting roll to overcome the melt drag casting problem of the existing alloy was obtained. Fig. 3 shows the melt drag casting of 79Ni–19Fe–2Si alloy manufactured continuously and wound strip in cast state with a width of 110 mm and a length of 15 m.

The thickness of the formed melt drag strip is determined based on the contact time of the molten metal fed into the nozzle, with the casting roll used for cooling. For the 79Ni–19Fe–2Si strip, the relationship between the thickness of the strip formed given a melt casting temperature of about 1520 °C and contact time is shown in Fig. 4. Here, strip thickness is indicated in the equation $t\ (\mu\text{m}) = K[T\ (\text{s})]^{1/2}$. At this time, K is a constant depending on the physical properties of molten metal and heat transfer characteristics of the casting roll. Fig. 5 indicates the variation of constant K affecting strip thickness in the same casting process condition following the temperature variation of molten metal. Since constant K decreases with a constant slope as the temperature of molten metal increases, the decrease in the thickness of the formed strip can be predicted easily. Generally, constant K is believed to increase as the viscosity of molten metal increases and the cooling power of the casting roll and wetting ability between the molten metal and casting roll improve; thus increasing heat transfer efficiency.