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The effects of microstructure and growth rate on microhardness, tensile strength, and electrical resistivity for directionally solidified Al–Ni–Fe alloys

Sevda Engin [a,*], Uğur Büyük [b], Necmettin Maraşlı [c]

[a] Department of Energy Systems Engineering, Faculty of Technology, Dumlupınar University, Kütahya, Turkey
[b] Department of Science Education, Faculty of Education, Erciyes University, Kayseri, Turkey
[c] Department of Metallurgical and Materials Engineering, Faculty of Chemical and Metallurgical Engineering, Yıldız Technical University, İstanbul, Turkey

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Directional solidification of eutectic alloys attracts considerable attention because of microhardness, tensile strength, and electrical resistivity influenced by eutectic structures. In this research, we examined processing of Al–Ni–Fe (Al–6.5wt.%Ni–1.5wt.%Fe) eutectic by directional solidification. The alloy was prepared by vacuum furnace and directionally solidified in Bridgman-type equipment. During the directional solidification process, the growth rates utilized varied from 8.25 μm/s to 164.80 μm/s. The Al–Ni–Fe system showed a eutectic transformation, which resulted in the matrix Al, rod Al_3Ni, and plates Al_9NiFe phases. The eutectic spacing between $(\lambda_{Al_3Ni} - \lambda_{Al_3Ni}, \lambda_{Al_9NiFe} - \lambda_{Al_9NiFe})$was measured. Additionally, the microhardness, tensile strength, and electrical resistivity of the alloy were determined using directionally solidified samples. The effects of growth rates on microhardness, tensile strength, and electrical resistivity for directionally solidified Al–Ni–Fe eutectic alloy were investigated, and the relationships between them were experimentally obtained. It was found that the microhardness, tensile strength, and electrical resistivity were affected by both eutectic spacing and the solidification parameter.

1. Introduction

Aluminum and aluminum alloys are used in industry because of their resistance characteristics, corrosion resistance, low specific weight, conductance of electricity, and heat and flexibility. These properties make them valuable for use in various industrial applications, and researchers have been actively exploring new application for these alloys [1–4].

The most prominent feature of aluminum in engineering applications and everyday life is its lightness. In addition, alloying elements in aluminum improve its strength and stiffness, properties which are superior compared to other metals. The alloying of iron into aluminum is especially effective at improving its strength and stiffness properties. Another important element in aluminum alloys is nickel. Alloying nickel in aluminum improves its high temperature mechanical strength and increases its modulus of elasticity. For these reasons, research studies on Al–Ni, Al–Fe, and Al–Ni–Fe alloys are of great interest [2,5–8].

In the literature, there are many studies on eutectic composition [9,10]. Eutectic composition has a lower melting point than the melting point of the other elements in the alloy and obtains two separate solid phases from a single liquid phase. Because of these properties, industrial applications of the material have become widespread.

The mechanical and thermo physical properties of a material depend on not only the selection of alloying elements but also the production technique employed. The directional solidification technique by Bridgman-type equipment is one of the most important techniques for producing crystal growth that is widely utilized in engineering. Aluminum and aluminum alloys, more so than other alloys, are prone to having possible casting errors, such as cracks and distortions, due to volume shrinkage depressions. These errors can be minimized by using Bridgman's technique as known The Controlled Solidification Technique. When eutectic alloys are directionally solidified in Bridgman-type equipment, the solidification results in two or more phases aligned in growth direction. This microstructure morphology of eutectic alloys affects their mechanical and thermo physical properties.

* Corresponding author. Tel.: +90 274 513 79 17x171; fax: +90 274 513 79 14.
E-mail address: sevda.engin@dpu.edu.tr (S. Engin).

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In this study, the dependence of the eutectic spacing ($\lambda_{Al_3Ni} - \lambda_{Al_3Ni}$, $\lambda_{Al_9NiFe} - \lambda_{Al_9NiFe}$) on the growth rate ($V$) in the eutectic composition of the Al–Ni–Fe alloy was experimentally investigated and the results were compared with the previous experimental results for binary Al–Ni, Al–Fe and ternary Al–Ni–Si eutectic alloys. The relationship between the eutectic spacing and the growth rate was experimentally obtained by using regression analysis. Additionally, the dependencies of eutectic spacing (λ), Vickers microhardness (HV), ultimate tensile strength (σ_{uts}), and electrical resistivity (ρ) on the growth rate of directionally solidified Al–Ni–Fe eutectic alloy were investigated. The relationships between them were experimentally obtained by using both regression analysis and Hall–Petch type correlations.

2. Experimental procedure

2.1. Alloy preparation, directional solidification and metallography

In the present work, the composition of the Al–Ni–Fe ternary alloy was chosen as Al–6.5wt.%Ni–1.5wt.%Fe to grow eutectic phases from ternary liquid. After sufficient homogenization, the melted Al–Ni–Fe alloy under the vacuum by using 99.99% pure aluminum, 99.95% pure nickel and 99.97% pure iron was poured into 10 graphite crucibles (200 mm in length 4 mm ID and 6.35 mm OD). Each sample was then positioned in a Bridgman type furnace. Solidification of the samples was carried out with different growth rates (V = 8.25–164.80 μm/s) at a constant temperature gradient (G = 4.48 K/mm) by synchronous motors running at different speeds. Details of the Bridgman–type directional solidification furnace and experimental procedures pertaining to it are given in References [[11–16]].

The quenched sample was removed from the graphite crucible and typically cut into lengths of 10 mm each. After smoothing each sample with SiC paper (180, 500, 1000, 2500 grit), we mounted them with epoxy–resin and polished them with diamond paste using a ***Struers TegraPol–15*** polishing machine. The samples were etched with 5 ml Hydrofluoric acid (*HF*) in 95 ml distilled water for 10–15 s in order to reveal each sample's microstructures.

2.2. Microstructure observation and identification of phases

The microstructures of the samples were photographed in both transverse and longitudinal sections with a ***LEO*** model Scanning Electron Microscope (SEM). The microstructures of samples were produced with different growth rates. The quantitative chemical composition analyses of the phases in the sample were carried out by using energy dispersive X–ray analysis (EDX).

2.3. Measurement of solidification parameters and eutectic spacing

The temperature in the specimen was measured using three K–type 0.25 mm in diameter insulated thermocouples, which were positioned inside the sample with spacing of 10–20 mm. The cooling rates were recorded with a data–logger via computer during the solidification process. The temperature gradient ($G = \Delta T/\Delta X$) in the liquid phase and the value of the growth rate ($V = \Delta X/\Delta t$) for each sample were determined using the measured values of ΔT, ΔX, and Δt. Details of the measurements of ΔT, ΔX, and Δt are given in References [[11–16]].

The values of eutectic spacing were measured with a linear intercept method using transverse sections of the samples [17].

2.4. Measurement of microhardness

One of the goals of this research was to learn the relationships between the solidification processing parameters and microhardness for directionally solidified Al–Ni–Fe eutectic alloy. Vickers microhardness measurements in this study were performed with a ***Future–Tech FM–700*** model hardness measuring test device using a 500 g load and a dwell time of 10 s giving a typical indentation depth of about 40–60 μm. Our measure of microhardness is the average of at least 10 measurements on the transverse sections.

2.5. Measurement of tensile strength

Uniaxial tensile tests were performed at room temperature at a strain rate of 10^{-3} s^{-1} with a ***Shimadzu Universal Testing Instrument*** (Type AG–10KNG). The samples with diameter of 4 mm and gage length of 50 mm were prepared using directionally solidified rod samples with different solidification parameters. The tensile axis was chosen parallel to the growth direction of the sample, and the tests were repeated three times.

2.6. Measurement of electrical properties

Electrical measurements of the samples were taken using the four–point probe technique on samples with 4 mm diameter [18]. The four–point probe technique has been used to measure electrical resistivity of different materials such as powder metallurgy or metallic alloy [19–21]. A ***Keithley 2400*** sourcemeter was used to provide constant current, and potential drop was measured by a ***Keithley 2700*** multimeter through an interface card, which was controlled by a computer. Platinum wires with a diameter of 0.5 mm were used as current and potential probes. Voltage drop was detected, and the electrical resistivity and conductivity were determined using a standard conversion method. Also, the electrical resistivity dependence of the solidification processing parameters of Al–Ni–Fe eutectic alloy was determined.

3. Results and discussion

3.1. Effect of growth rate on the eutectic spacing

The Al–Ni–Fe alloy at eutectic composition indicates the existence of multiphase microstructure $Al + Al_3Ni + Al_9FeNi$ and shown in Fig. 1. This existence are defined as nonvariant growth that in a ternary alloy involves three solid phase growing simultaneously from the liquid [22]. The quantitative chemical composition analyses of the solid matrix Al, rod Al_3Ni and plates Al_9NiFe intermetallic phases in the sample were carried out by using energy dispersive X–ray analysis (EDX) and given in Fig. 2.

Solid solubility of nickel in aluminum is very low and it is about 0.05% at the eutectic temperature (640 °C). Additionally, solid solubility of iron in aluminum is very low, and it is about 0.03% at the eutectic temperature (655 °C) [23]. The maximum solubilities of both Fe and Ni in Al phase are determined to be extremely small, about 0.58 at.% for both elements [11]. According to the EDX results shown in Fig. 2, the solubility of components in each phase (plate phase, rod phase, and matrix phase) was identified as Al_3Ni, Al_9NiFe intermetallic phases, and Al matrix phase, respectively.

For eutectics with a small amount of ternary impurities, eutectic colonies form. The Al_3Ni phase forms as regular rod during unidirectional solidification of the binary A1–Ni eutectic [24]. However, during unidirectional solidification of ternary A1–Ni–Fe eutectic, Al_3Ni phases appear as irregularly colony rod between needle–like Al_9FeNi intermetallic plate phases, as we have been seen in the transverse sections shown in Fig. 1. For a more detailed review on solidification in multicomponent alloys in Ref. [22].

In this study, formations of the microstructures vary with the growth rates. As the growth rate is increased, the eutectic spacing