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# MOLD FILLING ABILITY AND HOT CRACKING SUSCEPTIBILITY OF AL-FE-NI ALLOYS FOR HIGH CONDUCTIVITY APPLICATIONS

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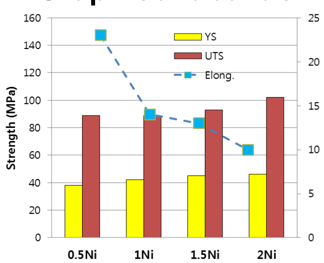
**Graphical abstract**




**Abstract**

Newly developed high conductivity Al-Fe-Ni alloys are expected to be used for various electronic and electrical applications instead of conventional low conductivity Al casting alloys. In this research, influence of Ni content on the mold filling ability and hot cracking susceptibility of Al-Fe-Ni alloys was investigated. The cast microstructure of Al-0.5Fe-xNi alloys mainly consists of primary aluminum and 2$^{nd}$ phases, and the kind of the 2$^{nd}$ phases is dependent on the Ni content. As the Ni content was increased, $Al_3Ni$ phase became dominant as the 2$^{nd}$ phase. Although the Ni additions reduced the conductivity a little, Al-0.5Fe-xNi alloys with nickel ranging from 0.5 to 2% showed significantly higher electrical conductivity than conventional Al-Si based alloys. The mold filling ability measured by fluidity serpentine test of Al-Fe-Ni alloys decreased significantly when more than 1%Ni was added. The mold filling ability measured by using a pressure die-casting method showed the similar results with respect to the Ni content. Meanwhile, hot cracking susceptibility was increased remarkably when more than 0.5%Ni was added.

*Keywords*: Aluminum, nickel, conductivity, solidification, mold filling, hot cracking



## 1.0 INTRODUCTION

Aluminum-silicon based casting alloys have been the most widely used for various industrial applications because of their excellent casting capabilities and good mechanical properties. The excellent castabilities of aluminum-silicon alloys are partly due to the characteristic of silicon that releases a lot of heat of fusion during solidification, hence prolongs the solidification time. Although silicon as an alloying element to aluminum is beneficial for castabilities and many other properties, it significantly reduces the conductivity. The typical thermal conductivity of conventional Al-Si die-casting alloys is about only 70% of that of pure aluminum [1]. So, Al-Si alloys are not suitable for high conductivity demanding applications, and recently, high conductivity aluminum alloys containing no or very limited silicon content have been paid much attention.

Nickel as an alloying element to aluminum appears to be promising because the solubility of Ni on Al matrix is very low (~0.05wt.%) so that the conductivity of aluminum is not remarkably reduced by Ni additions as compared to other alloying elements such as Si [2]. To be used as a casting alloy, good casting abilities such as mold filling ability and hot tear resistance are indispensible, therefore new high conductivity aluminum alloys should possess at least fairly good casting capabilities. However, there is a lack in the literature about the effect of Ni content on the castabilities of aluminum alloys.

The mold filling ability or often called as fluidity is one of the most important castabilites and it is related to diverse metallurgical and test variables [3]. Metallurgical variables are the inherent ones influencing the fluidity of each alloy system. Degree of superheat, solidificatin mode, surface tension, and heat of fusion are included in the variables. Pure aluminum possess a high fluidity, but this excellent fluidity tends to drop sharply with alloying element additions owing to expanded solidification range and changed solidification mode from a planar to a pasty one. The fluidity is then significantly enhanced near the eutectic composition by further alloying element additions. It has been known that the fluidity is generally inversely proportional to the solidification range for a constant superheat. Surface tension can be also very influencing on the fluidity, especially when the fluidity test channel is very narrow. The effect of grain size refining on the fluidity is still controversial even though a little enhancement seems to occur in many cases.

The mold filling phenomenon that occurs under external pressure can be quite different from the case of ordinary fluidity test using a gravity to fill the test channel. It was reported that the fluidity under high pressure die-casting condition was not inversely proportional to the solidification range of an alloy, and the fluidity length increased with decreasing solidus temperature [4]. It was suggested that a liquid alloy could still flow even at high solidification fraction under a high pressure. Therefore, the flow was stopped at a temperature closer to the solidus of the alloy. The mold filling ability under external pressure conditions is also in need of investigation.

Another important castability, hot cracking resistance is to hinder the occurrence of hot cracking that occurs at a certain position of casting during a relatively late solidification stage when the solidification contraction is so severe that cracks take place easily. Hot cracking susceptibility (HCS) also tends to be proportional to the freezing range. And it can be reduced if dendrite coherency point (DCP) is delayed with respect to the given solidus and enough residual liquid remains at the late solidification stage [5-6]. The residual liquid at the late solidification can be very influential [7] and significant grain refining is often found to be effective in reducing the hot tear susceptibility [8-9]. This article aims to investigate the mold filling ability measured by two different methods and hot cracking susceptibility of Al-Fe-Ni alloys that can be applied to high conductivity parts.

## 2.0 EXPERIMENTAL

Al-0.5%Fe-xNi alloy specimens were fabricated by a permanent mold gravity casting method. The liquid metal was prepared in a coreless induction furnace, and poured into a metallic mold to produce small plates with a thickness of 10mm. The actual chemical compositions of the investigated alloys are indicated in Table 1. The electrical conductivity of the as-cast alloys was evaluated by using a contact-type tester (Fischer, Sigmascope SMP10) and tensile tests with cast specimens were carried out at room temperature according to ASTM B 557M. The microstructural analyses were performed using optical microscope, scanning electron microscope (SEM, JEOL, JSM-5610) equipped with energy dispersive X-ray spectrometer (EDS), and X-ray diffractometer (XRD, Rigaku, Smartlab).

Thermal analysis was carried out using a differential scanning calorimeter (DSC, TA instrument, Q20) at a heating rate of 5$^{o}$C/min. under a protective argon atmosphere. To investigate the solidification characteristics of actual castings with a relatively high cooling rate, the quantitative cooling curve analysis method was also utilized [10]. Liquid metal was poured into the cylindrical graphite mold with 100mm diameter, and the temperatures were measured at the center and near the mold wall during the cooling. In addition to the start and end temperatures of solidification, the dendrite coherency point (DCP) were measured by the cooling curve analysis [10]. The dendrite coherency point is defined as a certain temperature when dendritic networks begin to gain strength. And DCP was determined from the cooling curves when the temperature difference between the center and mold wall reached to the maximum. An example of DCP measurement for Al-0.5Fe-1Ni alloy is shown in Figure 1. Thermo-physical modeling using the commercial software JMatPro 5.0 was also performed to compare with the experimental observations.

**Table 1** Chemical compositions of investigated alloys (wt%)

| Alloy | Fe | Ni | Al |
|---|---|---|---|
| 0.5Ni | 0.52 | 0.53 | Balance |
| 1Ni | 0.52 | 1.03 | “ |
| 1.5Ni | 0.34 | 1.55 | “ |
| 2Ni | 0.34 | 2.06 | “ |

In order to measure the mold filling ability, liquid alloys were poured into a fluidity serpentine metallic mold that was isothermally heated to 200°C. The test mold spiral had a cross section of 5 x 5mm and the superheat for melt was kept as 50°C. Pressure die-casting type casting experiments were also conducted to investigate the mold filling ability of alloys. A ceramic-coated steel mold with multi channels and a pressure casting machine under an inert gas atmosphere to prevent melt oxidation were applied for tests. Figure 2 illustrates the parting plane of the test mold, of which flow channels were 100 mm long with various diameters of 8, 4, 2, and 1 mm. Because liquid metal hardly entered the flow channel with 1mm diameter and it could easily filled the channels with 4 and 8 diameters, the average distance that metal flow occurred in the 2mm channel was taken as the mold filling ability. The test mold temperature, the superheat and casting pressure were 180°C, 100°C, and 14,710Pa, respectively. Hot cracking susceptibility was tested by using a steel mold with a 5mm wide ring-shaped open cavity. The melt was poured into the open cavity for producing ring-type castings, and hot cracking susceptibility (HCS) was quantified by measuring the total length of cracks on the test casting. The mold temperature and the superheat for melt were 350 and 100°C, respectively.

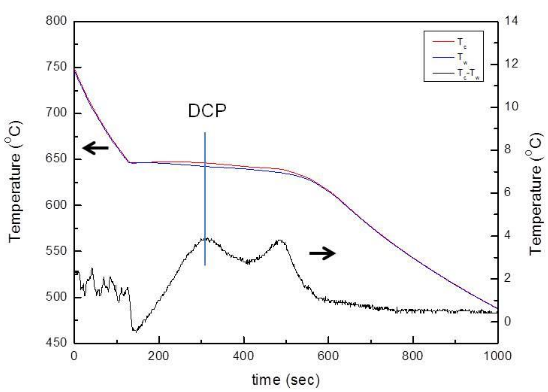



**Figure 1** Typical cooling curve obtained for Al-0.5Fe-1Ni alloy showing DCP (dendrite coherency point) measurement

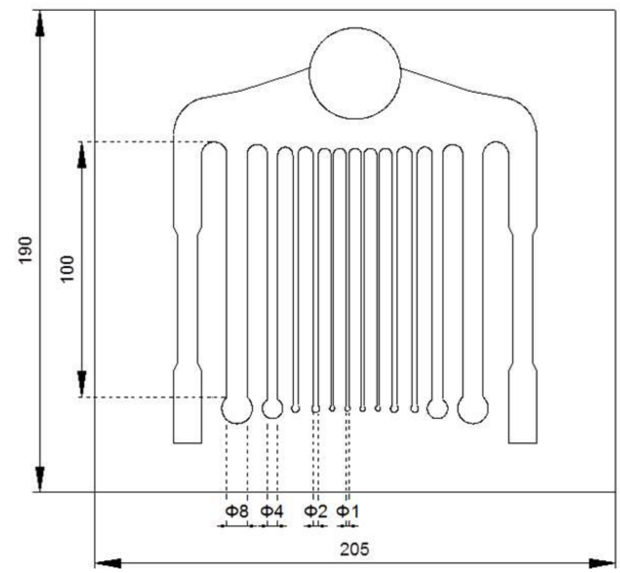



**Figure 2** Schematic diagram of metallic mold for mold filling test used for pressure casting process

## 3.0 RESULTS AND DISCUSSION

As shown in Figures 3 and 4, the typical cast microstructure of Al-0.5Fe-xNi alloys mainly consists of primary aluminum (matrix) and 2nd phases at interdendritic and grain boundary areas. The secondary arm spacing at the identical postion of castings appears to become a little finer with increasing the Ni content due to solute enrichment. The kind of the 2nd phases was observed to vary depending on the Ni content. SEM-EDS analysis results indicated that mainly $Al_9FeNi$ phase was formed as the 2nd phase in the 0.5%Ni alloy, while $Al_3Ni$ phase was found as well as the $Al_9FeNi$ phase in the 1%Ni alloy. The majority of 2nd phases were $Al_3Ni$ in the higher Ni content alloys.

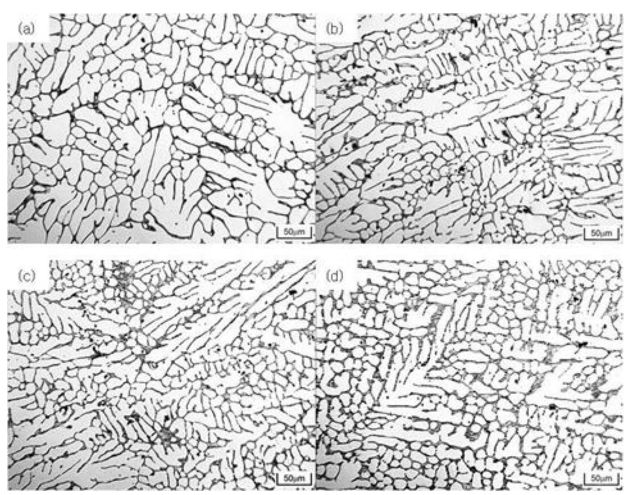



**Figure 3** Typical microstructure of as-cast Al-0.5Fe-xNi alloys: (a) 0.5, (b) 1, (c) 1.5, (d) 2%

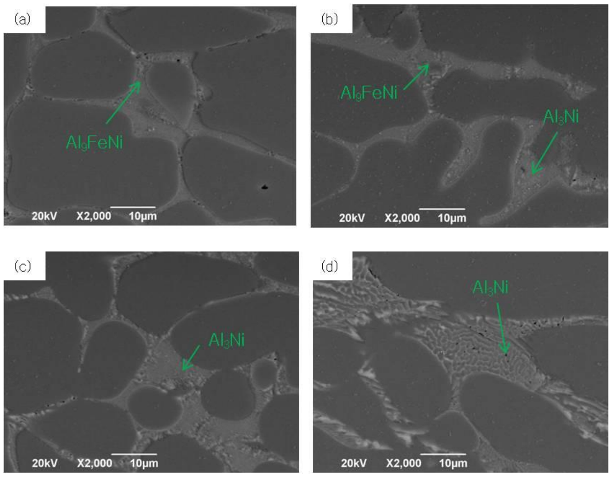



**Figure 4** SEM micrographs of as-cast Al-0.5Fe-xNi alloys: (a) 0.5, (b) 1, (c) 1.5, (d) 2%

Figure 5 shows phase formation during the solidification of AlFeNi alloys calculated by JMatPro. Like the microstructural observations, only primary aluminum and $Al_9FeNi$ phases are predicted to form for the 0.5%Ni alloy. $Al_3Ni$ phase starts to form when 1%Ni is added to Al-0.5%Fe, and the amounts of both $Al_9FeNi$ and $Al_3Ni$ phases tend to increase gradually with further increasing the Ni content. The last phase that is predicted to form during the solidification is $Al_3Ni$ phase so that this phase may be the most influential on the hot cracking phenomena. Phases formed in the Ni added cast alloys were also investigated by XRD analysis, as indicated in Figure 6. Although there is a little inconsistency between XRD and SEM-EDS analysis results, it is apparent that the larger amount of $Al_3Ni$ phase is formed as the Ni content is increased [11]. AlFe phases such as $Al_3Fe$ and $Al_6Fe$ that were typically formed in iron containing Al alloys were not observed in the present investigation probably owing to the relatively low Fe content [12].

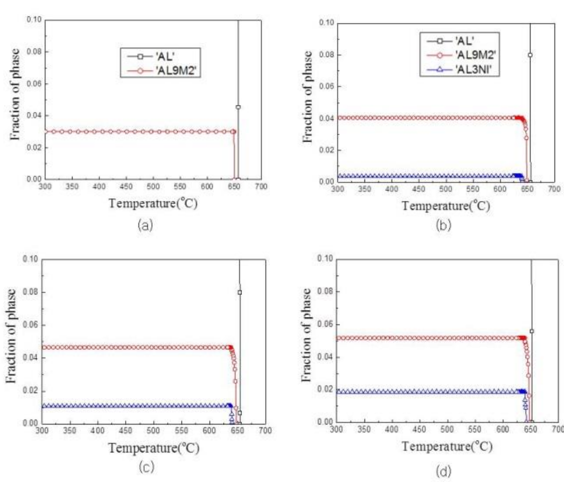



**Figure 5** Phase equilibria calculated by by JMatPro: (a) Al-0.5Fe-0.5Ni, (b) Al-0.5Fe-1Ni, (c) Al-0.5Fe-1.5Ni, (d) Al-0.5Fe-2Ni

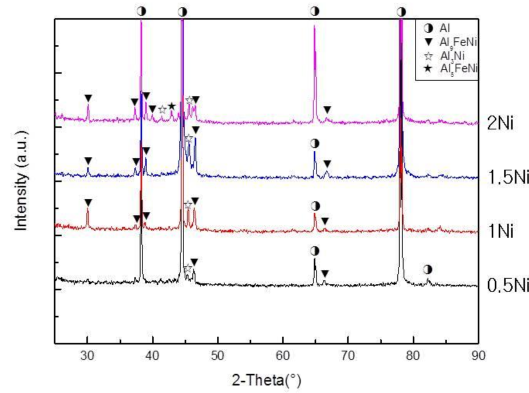



**Figure 6** XRD analysis results of Al-0.5Fe-xNi alloys

The effect of Ni content on the electrical conductivity of investigated alloys is indicated in Figure 7. Although the conductivity is reduced gradually by the Ni additions, the lowest conductivity of 53%IACS at 2%Ni is still much higher than those of conventional Al-Si die-casting alloys that typically possess about 30%IACS [13]. The electrical conductivity of alloy is continuously reduced when the alloying element is dissolved into the matrix, but the conductivity is less significantly decreased if the element is further added over its solubility limit [14]. The solubility of Ni on aluminum matrix is comparatively limited at room temperature, and this explains the smaller reduction of conductivity with increasing Ni content ranging from 1 to 2%, as compared to the initial conductivity drop.

Figure 8 indicates that tensile properties of cast Al-0.5Fe-xNi alloys. The tensile strength tended to improve with increasing the Ni content, while the elongation initially sharply dropped and then slowly decreased. The strength increase and elongation reduction should be attributed to the increased amount of the 2$^{nd}$ phases. Since the amount of $Al_9FeNi$ is gradually increased with the Ni content, the remarkable elongation reduction at 1%Ni seems mainly owing to the formation of $Al_3Ni$ phase. It may be worthwhile to mention that the tensile elongation of all the investigated alloys in this research is comparatively high considering they are in as-cast state.

The mold filling ability as measured by using the fluidity serpentine was observed to decrease as the Ni content was increased (Figure 9). The solidification ranges for high Ni alloys are remarkably wider than those for low Ni alloys, as indicated in Table 2. Because the fluidity is generally inversely proportional to the solidification range, relatively low fluidity for high Ni alloys is understandable.

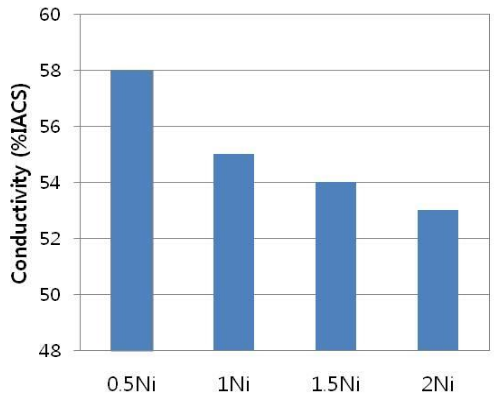



**Figure 7** Electrical conductivity of cast Al-0.5Fe-xNi alloys

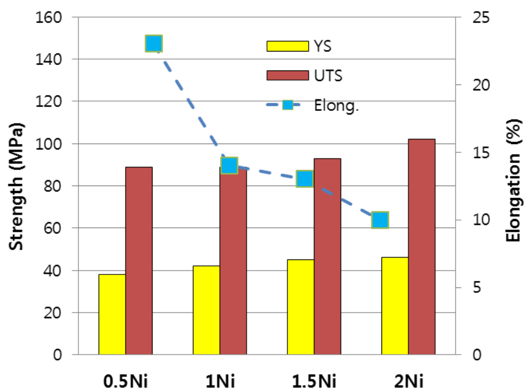



**Figure 8** Tensile properties of as-cast Al-0.5Fe-xSi alloys

Figure 10 shows that the mold filling ability determined via a pressure die-casting type test showed a similar trend with the fluidity serpentine test result. Namely, clearly higher fillability was obtained for low Ni alloys. Han *et al*. [4] suggested that the mold filling ability under high pressure die-casting conditions is related to not the solidification range, but the solidus temperature. However, the mold filling ability of investigated alloys in this study did not follow the relationship because high Ni alloys possess much lower solidus temperature as compared to low Ni alloys. This discrepancy might be partly due to the different applied pressure. The pressure utilized in the high pressure die-casting was 13.8MPa which is significantly higher than the pressure used in the present test (~0.015MPa).

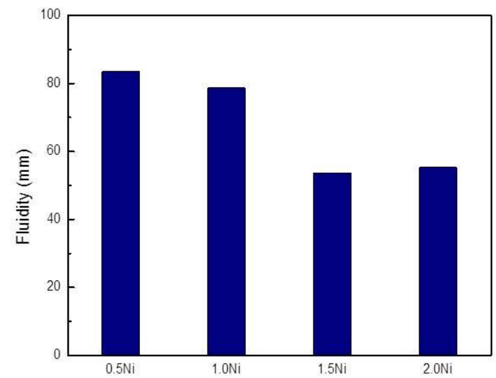



**Figure 9** Fluidity serpentine results of Al-0.5%Fe-xNi alloys poured at 50°C superheat

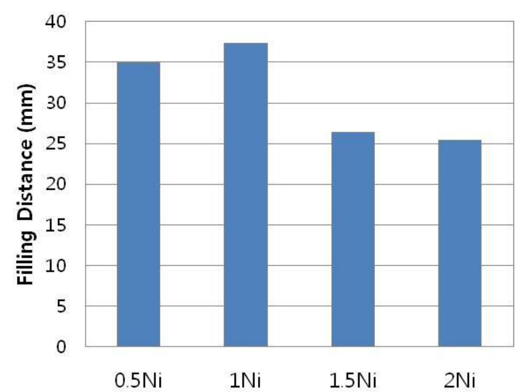



**Figure 10** Average Mold filling distance in the ϕ2mm channel of Al-0.5Fe-xNi alloys measured by using a pressure casting method

The mold filling test results indicated that liquid metal could hardly enter the flow channel with 1mm diameter under the given process condition. Using a below equation, obtained approximate surface tension is about 7.3N/m, and this calculated surface tension is apparently much higher than the generally known value of about 1N/m [15].

$$P = \frac{2\gamma}{r} \quad (1)$$

Where P is pressure due to surface tension, λ is surface tension, and r is channel radius. It is postulated that the presence of a strong oxide film on the liquid metal surface increased the surface tension to a degree. And the effect of modulus over surface tension seems to be dominant in this narrow channel under a moderate pressure.

Hot cracking susceptibility variations with respect to the Ni content are shown in Figure 11. The susceptibility was clearly increased by the Ni addition. Table 2 implies that HCS tended to increase with increasing the solidification range, especially for 1.5 and 2%Ni alloys. But 1%Ni added alloy showed also high susceptibility even though its solidification range is similar with that for 0.5%Ni alloy. 'Critical temperature range' between DCP and the end temperature of solidification appears to be more closely related to HCS than the total solidification range. This critical temperature range expands if more than 0.5%Ni is added, as indicated in Table 2. The residual liquid at the end of solidification is observed to increase with the Ni content from the cooling curve analyses. This effect can be beneficial for fluidity of high Ni alloys. Grain size can also influence the susceptibility, but average grain size was not changed remarkably according to the Ni content (not shown here). Considering the critical temperature range, residual liquid fraction, and grain size, HCS seems to be mainly affected by the critical temperature range in this research.

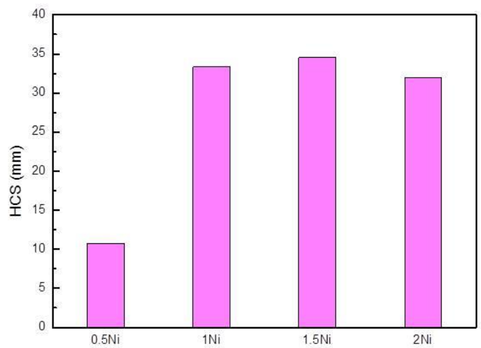



**Figure 11** Hot cracking susceptibility of Al-0.5Fe-xNi alloys

**Table 2** Solidification characteristics of investigated alloys (°C)

| Alloy | Start | End | Solidification range | Temp. (DCP) | Range (DCP~T(end)) |
|---|---|---|---|---|---|
| 0.5Ni | 652 | 638 | 14 | 647 | 9 |
| 1Ni | 649 | 635 | 14 | 646 | 11 |
| 1.5Ni | 646 | 624 | 22 | 636 | 12 |
| 2Ni | 640 | 623 | 17 | 635 | 12 |

## 4.0 CONCLUSION

1. As-cast microstructure of Al-0.5Fe-xNi alloys is mainly composed of Al matrix and $Al_9FeNi$ and/or $Al_3Ni$ second phases, depending on the Ni content. With increasing the Ni content $Al_3Ni$ phase becomes dominant as the second phase.
2. The tensile strength was gradually enhanced with Ni content, while the electrical conductivity and the ductility were reduced. Comparatively high conductivity was measured for all the investigated alloys, regardless of the Ni content.
3. The relationship between solidification characteristics and castabilities of high conductivity Al-1Fe-0.5Ni alloys was also investigated. Both the fluidity serpentine and the mold filling ability showed the similar trend of significantly reduced values for high Ni alloys, mainly attributed to expanded solidification range. The hot tear susceptibility of the alloys was significantly increased at 1%Ni and then remained almost unchanged up to 2%Ni.

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