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Article

Fluidity of Pure Aluminum in a Narrow Channel Die Gap during Die Casting

Toshio Haga [1,*] and Hiroshi Fuse [2]

[1] Department of Mechanical Engineering, Faculty of Engineering, Osaka Institute of Technology, Osaka 535-8585, Japan
[2] MOZUKURI Center, Faculty of Engineering, Osaka Institute of Technology, Osaka 535-8585, Japan; hiroshi.fusel@oit.ac.jp
* Correspondence: toshio.haga@oit.ac.jp

Abstract: Fluidity tests of 99.9%Al and 99.7%Al were conducted using a die casting machine equipped with a spiral die with a channel gap of 0.5 mm. The effects of die temperature and plunger speed on the fluidity were investigated. To clarify the flow length for these alloys, ADC12 and Al-X%Fe ($X \leq 1.1$) were also cast. A 1.0 mm channel gap was also used to compare the fluidity in a wider gap. The fluidity of 99.9%Al and 99.7%Al at a die temperature of 30 °C and a plunger speed of 0.2 m/s was superior to that at 150 °C and 0.8 m/s when the channel gap was 0.5 mm, and similar results were found for ADC12 and Al-X%Fe. When the die temperature was 30 °C, the fluidity of 99.9%Al and 99.7%Al decreased as the plunger speed increased when the channel gap was 0.5 mm, and similar results were also found for ADC12 and Al-X%Fe. These results did not align with conventional expectations. A discussion of the results based on the peeling and re-melting of the solidified layer was provided.

Keywords: pure aluminum; die casting; fluidity; narrow die gap; die temperature; plunger speed

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1. Introduction

Pure aluminum has higher thermal conductivity than the aluminum alloys commonly used for die casting, such as JIS ADC12 [1]. Heat sinks cast from pure aluminum may have excellent heat dissipation characteristics, and there is a strong demand for lightweight heat sinks with thin fins. However, the effect of casting conditions on the fluidity of the pure aluminum in a narrow die gap has not been fully clarified in die casting. The purpose of this study is to elucidate the effect of casting conditions on the fluidity of 99.9%Al and 99.7%Al in a narrow 0.5 mm die gap.

Many studies have examined factors that affect the fluidity of aluminum alloys, including solidification mode [2–7], metal composition [8–18], the superheating of molten metal [5,12–14,19–23], viscosity [3,24–26], surface tension [27–29], mold materials [30–32], mold temperature [33–40], plunger speed [13,34–38,40,41], mold gap [13,40,41], and mold vibration [42,43]. The fluidity of the aluminum alloy increases with die temperature, die gap, and plunger speed. However, in these studies, the fluidity of aluminum alloys was not investigated using a narrow die gap. It is therefore unclear whether similar results would be obtained for a narrow gap when die casting pure aluminum. In die casting, the plunger speed and die temperature are the typical casting conditions that influence the fluidity. In the present study, the effects of these conditions on the flow length of pure aluminum in a narrow gap were investigated. The flow length characteristics of pure aluminum were compared to those of ADC12 to elucidate the fluidity properties of pure aluminum in a narrow gap. It is unclear whether the reported relationship between the purity of aluminum and the flow length [2–6] holds or not for a narrow die gap. In the present study, the effects of Fe as an impurity on the flow length of pure aluminum in a narrow gap were investigated. The results are discussed in terms of peeling of the solidified layer from the die surface. Three types of roll casters were used to investigate the peeling of the solidified layer from the die.

2. Experimental Methods

A 500 kN cold chamber die casting machine (HC 50F, Hishinuma Machinery, Ranzan, Japan) with an injection force of 100 kN and a sleeve diameter of 45 mm was used in this study [44]. Various kinds of dies have been used for fluidity tests [13,14,22,42,45,46], with the spiral die being most common among them. A spiral die was therefore used in the present study to investigate the fluidity, as illustrated schematically in Figure 1. The width of the die channel was 7 mm, and the channel gap was set to 0.5 or 1.0 mm. A crimp was placed at the tip of the spiral test piece for the fluidity tests, and beyond this, the channel gap was not filled by the molten metal. The crimp and unfilled area were not considered part of the flow path [41]. Only portions of the path with a rectangular cross section were measured to determine the flow path length. Plunger speeds of 0.2, 0.4, 0.6, and 0.8 m/s and die temperatures of 30 and 150 °C were investigated to observe their effects on fluidity. A die temperature controller (TT-288, Hishinuma Machinery, Ranzan, Japan) was used to heat the spiral die [47]. The 99.7%Al, 99.9%Al, ADC12 and Al-X%Fe (X = 0.3, 0.5, 0.7, 0.9 and 1.1%) were used, and their chemical compositions are summarized in Table 1. Optical emission spectroscopy (PDA-500, SIMADZU, Kyoto, Japan) was used to obtain chemical compositions. The pouring temperature of the molten metal was 720 °C. The aluminum alloys were melted in an oxidizing atmosphere using a gas furnace. Twelve test pieces were cast for flow length measurements under each condition, and the average was used as the final value. Optical microscopy (ECLIPSE LV150, Nikon, Tokyo, Japan) was used to take photographs of the die and cast specimens.

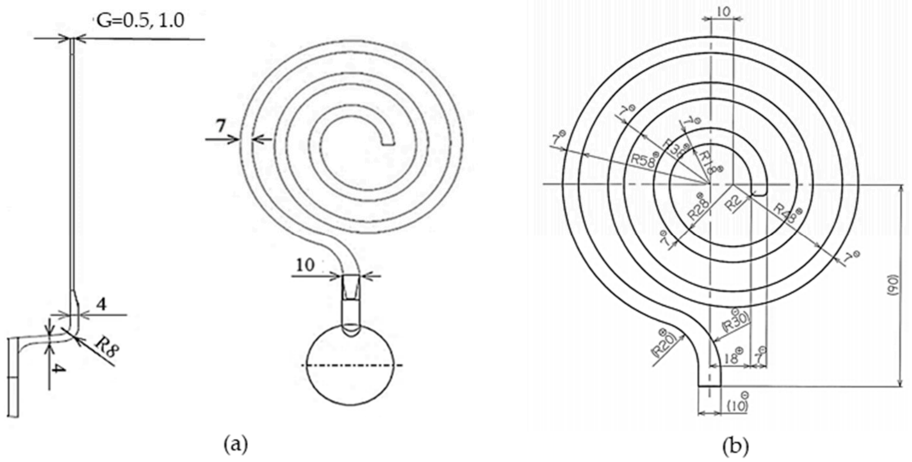


Figure 1. Schematic illustration of spiral die. Units: mm. (**a**) Shape, (**b**) dimensions.

Table 1. Chemical compositions of pure aluminum, Al-Fe alloys, and ADC12 (mass%).

Aluminum	Cu	Si	Mg	Fe	Zn	Mn	Ti	Bal.
99.9%Al	0.00	0.01	0.00	0.00	0.02	0.00	0.00	Al
99.7%Al	0.00	0.04	0.00	0.10	0.03	0.00	0.00	Al
Al-0.3%Fe	0.00	0.04	0.00	0.28	0.04	0.00	0.00	Al
Al-0.5%Fe	0.00	0.04	0.00	0.47	0.04	0.00	0.00	Al
Al-0.7%Fe	0.00	0.04	0.00	0.71	0.03	0.00	0.00	Al
Al-0.9%Fe	0.00	0.03	0.00	0.93	0.04	0.00	0.00	Al
Al-1.1%Fe	0.00	0.03	0.00	1.05	0.03	0.00	0.00	Al
ADC12	1.92	10.31	0.28	0.79	0.81	0.31	0.04	Al

Three types of roll casters, namely a melt-spinning caster [48], a melt-drag caster [49], and a twin-roll caster [50], were used to estimate the influence of plunger speed and die temperature on the peeling of the solidified layer from the die surface. These roll casters are shown in Figure 2. The roll diameter and width were 300 mm and 100 mm, respectively. In the melt-spinning caster shown in Figure 2a, a slit nozzle was used. The slit width was 50 mm, and the slit gaps were 0.2, 0.5, or 0.7 mm. The roll temperature was room temperature, 50, or 100 °C. In the melt-drag caster shown in Figure 2b, the nozzle width was 70 mm and the nozzle position was 50 mm. The melt-head height was 50 mm, and the roll temperature was room temperature. In the twin-roll caster shown in Figure 2c, the solidification length was 100 mm, the roll load per unit width was 100 N/mm, the roll temperature was room temperature, and the melt-head height was 100 mm.

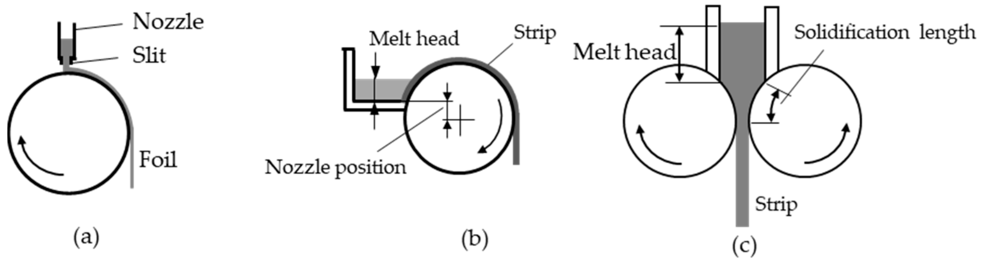


Figure 2. Schematic diagrams of casters used in this study. (**a**) Melt spinning single roll caster, (**b**) melt drag single roll caster, (**c**) vertical type high-speed twin roll caster.

3. Results

3.1. Effect of Plunger Speed and Die Temperature on Flow Length for Pure Aluminum with a 0.5 mm Die Gap

The effect of the plunger speed and die temperature on the flow length for a 0.5 mm die gap is shown in Figure 3. When the plunger speed and die temperature were the same, the flow length for 99.9%Al was longer than that for 99.7%Al. Thus, the fluidity increased with increasing purity, as has been shown in many reports.

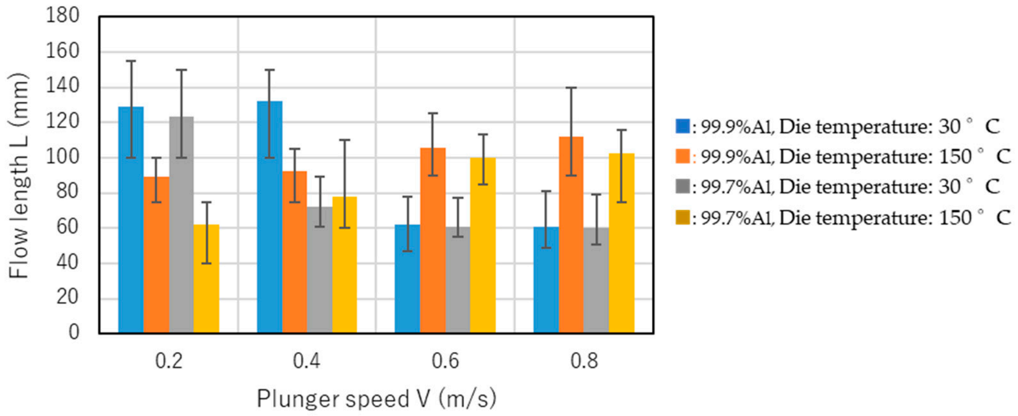


Figure 3. Effects of plunger speed and die temperature on flow length for 99.9%Al and 99.7%Al. Die gap: 0.5 mm.

When the die temperature was 30 °C, the flow length decreased as the plunger speed increased. The flow lengths for 99.9%Al and 99.7%Al decreased remarkably when the plunger speeds were higher than 0.4 m/s and 0.2 m/s, respectively. At a die temperature of 150 °C, the flow lengths for 99.7%Al and 99.9%Al increased with increasing plunger speed. In general, the flow length is expected to increase with increasing die temperature and plunger speed. However, this trend reversed for a die temperature of 30 °C. When the die temperature was 30 °C and the plunger speed was 0.2 m/s, the flow lengths for 99.7%Al and 99.9%Al were longer than those for other casting conditions. In other words, the flow length was longest under conditions that were expected to produce the shortest flow length. It is not clear whether this result was specific to pure aluminum, a 30 °C die temperature, or a 0.5 mm die gap, or a combination of these conditions.

3.2. Effect of Plunger Speed and Die Temperature on Flow Length for Pure Aluminum with a 1 mm Die Gap

For comparison, fluidity tests were conducted using a 1 mm gap spiral die to investigate the influence of the die gap on the fluidity of pure aluminum. As seen in Figure 4, the flow length increased with increasing plunger speed. When the die temperature was 30 °C, the flow length for 99.7%Al was shorter than that for 99.9%Al. These results are consistent with conventional understanding. The flow length for 99.9%Al was not influenced by the die temperature, but the flow length for 99.7%Al was longer for a die temperature of 150 °C than for 30 °C. When the die temperature was 150 °C, the flow lengths for 99.7%Al and 99.9%Al were almost the same. These results contradict conventional expectations. The tendency for the flow length to decrease with increasing plunger speed at a die temperature of 30 °C suggests that the 0.5 mm die gap may be the reason for the reduced flow length at low die temperature.

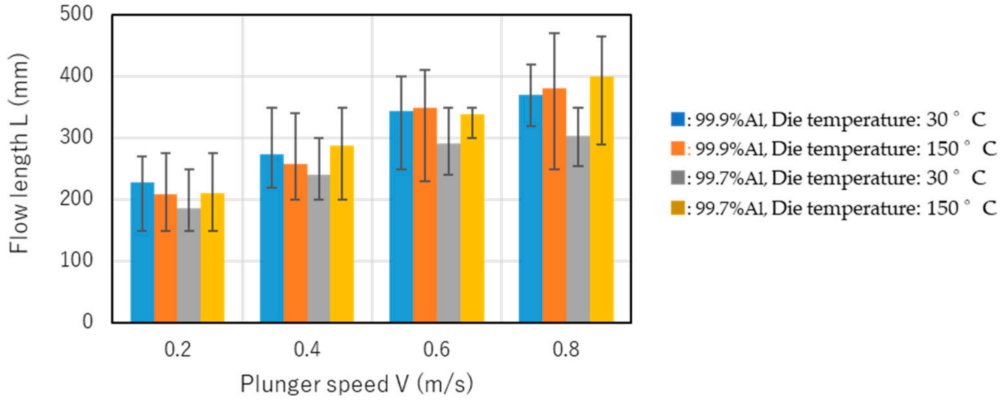
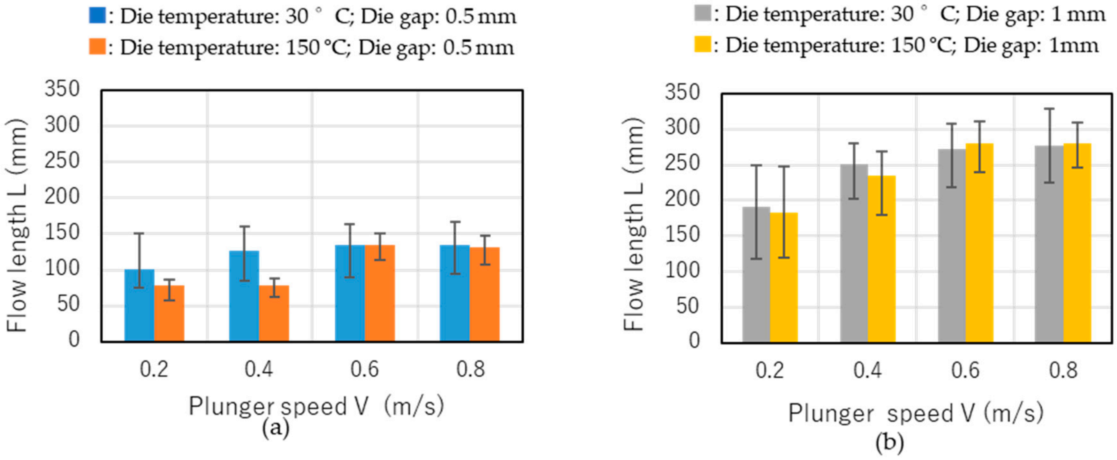


Figure 4. Effects of plunger speed and die temperature on flow length for 99.7%Al and 99.9%Al. Die gap: 1 mm.

3.3. Effect of Plunger Speed and Die Temperature on Flow Length for ADC12 with a 0.5 mm Die Gap

To compare the flow properties of pure aluminum for a 0.5 mm die gap, the flow length for ADC12 was also investigated using the 0.5 and 1 mm gap spiral dies. As seen in Figure 5, when the die gap was 0.5 mm and the plunger speed was 0.2 or 0.4 m/s, the flow length at a die temperature of 30 °C was longer than that at 150 °C. At higher plunger speeds of 0.6 and 0.8 m/s, the flow lengths at die temperatures of 30 and 150 °C were almost the same. The flow length did not increase with increasing plunger speed at a die temperature of 30 °C. Overall, the flow length at a higher die temperature was not longer than that at a lower die temperature. When the die gap was 1 mm, the die temperature did not influence the flow length, and the flow length only increased as the plunger speed increased. The results for the 0.5 mm die gap and a plunger speed of 0.2 or 0.4 m/s were different to what is expected in conventional die casting. Both pure aluminum and ADC12 exhibited superior fluidity at the lower die temperature of 30 °C, especially at a lower plunger speed of 0.2 m/s. It is thought that this is due to the narrow die gap of 0.5 mm.



(a)

(b)

Figure 5. Effects of plunger speed, die temperature, and die gap on flow length for JIS ADC12. (**a**) Die gap: 0.5 mm; die temperature: 30 and 150 °C. (**b**) Die gap: 1 mm; die temperature: 30 and 150 °C.

The effects of die temperature and plunger speed on the flow length were consistent between 99.7%Al and 99.9%Al, as shown in Figure 3. To investigate the effect of the impurity content on fluidity, Fe was added to pure aluminum, as summarized in Table 1. The effects of the Fe content, die temperature, and plunger speed on the flow length are shown in Figure 6.

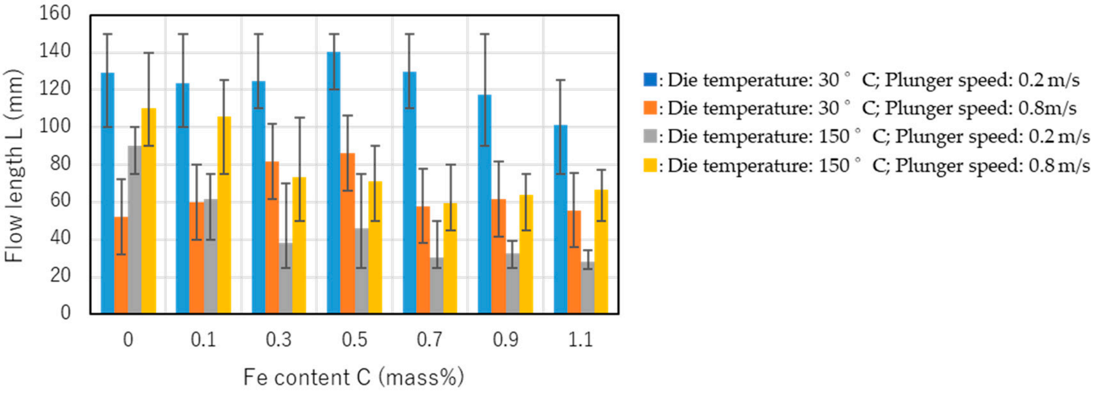


Figure 6. Effects of Fe content, plunger speed, and die temperature on flow length for pure aluminum and Al-Fe alloys listed in Table 1. Die gap is 0.5 mm.

The flow length at a die temperature of 30 °C and a plunger speed of 0.2 m/s was longer than that at other die temperatures and plunger speeds. This result is different from what is expected in conventional die casting. The flow length for a die temperature of 30 °C and a plunger speed of 0.8 m/s was shorter than that for other die temperatures and plunger speeds. When the die temperature was 30 °C and the plunger speed was 0.2 m/s, the flow lengths for Al-0.5%Fe and Al-0.7%Fe were longer than those for 99.9%Al and 99.7%Al. However, the flow lengths for 99.9%Al and 99.7%Al were longer than that for Al-X%Fe at other die temperatures and plunger speeds, and there was a tendency for the flow length for Al-X%Fe to decrease as the Fe content increased. This result matches what is expected in conventional die casting.

The effect of die temperature and plunger speed on the surfaces of die-cast spiral specimens of 99.7%Al was investigated. The die surface and specimen surfaces are shown in Figure 7. Machining marks are present on the die surface. When the plunger speed was 0.2 m/s and the die temperature was 30 °C, the presence of machining marks could not be confirmed, although such marks were observed under other conditions. When the plunger speed was 0.2 m/s and the die temperature was 30 °C, the molten metal may have solidified before fully coming into contact with the die surface. The contact between the solidified layer and the die surface was therefore poorer than for other conditions, and adhesion between the solidified layer and the die surface may have been weak. Alternatively, the solidified layer may have been heated to a semisolid condition by the molten metal, causing the machining marks to be erased. This may occur if the solidified layer peels from the die surface before the molten metal inside solidifies. These results suggest that there was poor contact between the molten metal and the die surface, and that peeling of the solidified layer may have occurred before the molten metal solidified when the plunger speed was 0.2 m/s and the die temperature was 30 °C.

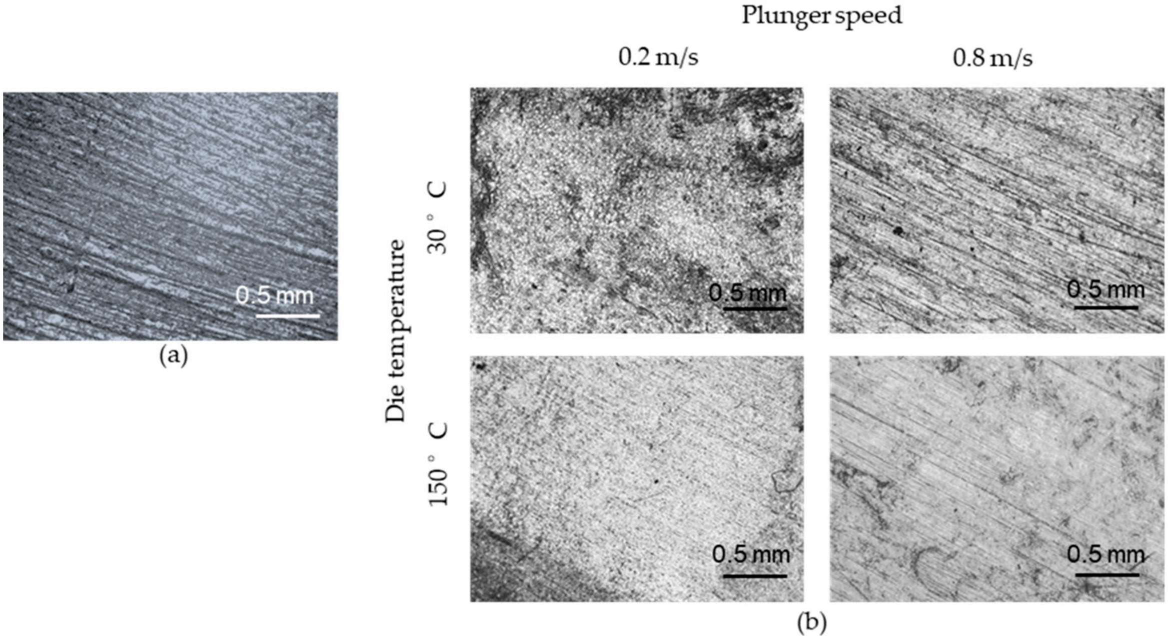


Figure 7. Effect of die temperature and plunger speed on surface conditions of spiral die-cast specimens of 99.7%Al. (**a**) Surface of spiral die, (**b**) surfaces of spiral die-cast specimens.

4. Discussion

Here, we discuss the effect of adhesion and the peeling of the solidified layer on the flow length during die casting based on the foil- or strip-to-roll adhesion conditions in roll casters. The influence of the roll temperature on the adhesion length for the 99.7%Al foil to the roll is shown in Figure 8. The adhesion length increased as the roll temperature increased. When the roll temperature was 150 °C, the foil adhered to the roll for more than one rotation. This indicates that there is a relationship between the thermal shrinkage of the foil and peeling. The contact conditions between the molten metal and the roll may be influenced by the roll temperature, and may improve as the roll temperature increases.

Slits with gaps of 0.2 and 0.7 mm were used to cast 99.7%Al foil of the same thickness of 32 μm at a roll speed of 55 m/s, and the adhesion length was measured. For the same foil thickness, the speed of the ejected molten metal was higher with a narrow gap than that with a wide gap. The results are shown in Figure 9. The adhesion length for the foil cast with a 0.2 mm gap was longer than that with a 0.7 mm gap. This shows that the contact between the molten metal and the roll improves as the speed at which molten metal is ejected from the slit increases.

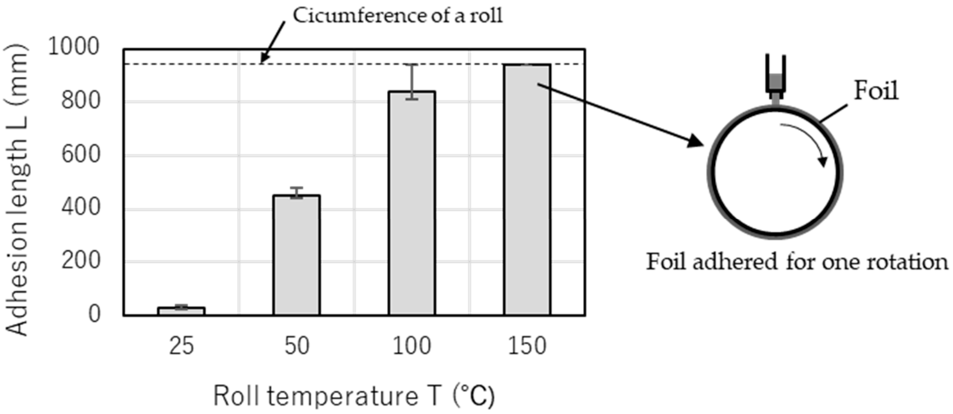


Figure 8. Effect of roll temperature on adhesion length for 99.9%Al to roll. Roll speed: 24 m/s.

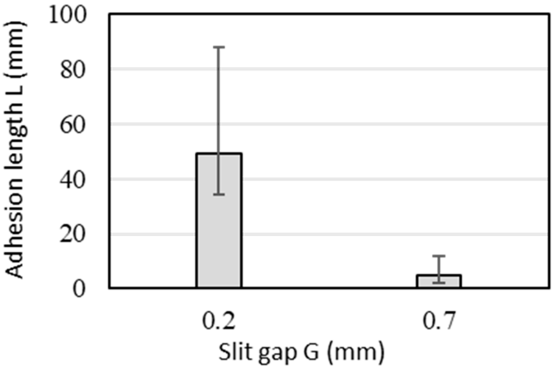


Figure 9. Effect of slit gap on adhesion length for 99.7%Al foil to roll for same foil thickness in melt-spinning single-roll caster. Roll speed: 55 m/s, foil thickness: 32 μm.

The influence of the roll temperature and the molten metal speed on the adhesion length is shown schematically in Figure 10. The adhesion length increased with increasing roll temperature and ejected molten metal speed, suggesting an effect on the adhesion condition. Peeling is thought to occur due to thermal contraction. When the adhesion force between the foil and the roll becomes weaker than the force due to thermal contraction, the foil peels from the roll. The adhesion force increases with increasing roll temperature and molten metal speed, resulting in a longer time for adhesion to occur.

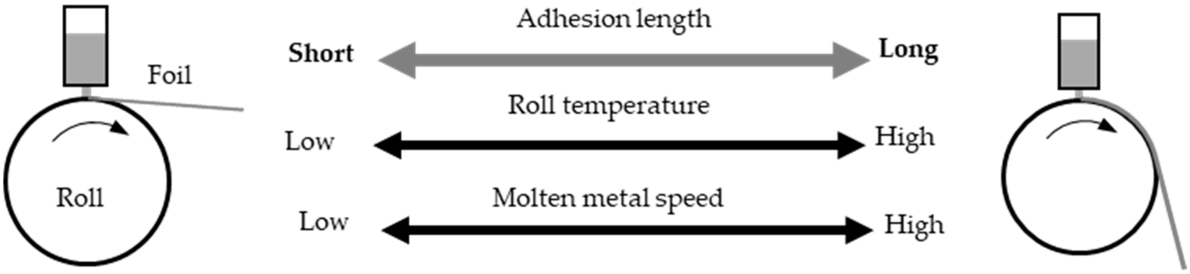


Figure 10. Effects of roll temperature and molten metal speed on adhesion length to roll during melt spinning.

Based on the finding that the adhesion length decreases with decreasing roll temperature and melt ejection speed, we will now discuss the flow length during die casting. As seen in Figure 3, when the die temperature was 30 °C and the plunger speed was 0.2 m/s, the flow length was longer than that under other casting conditions. The effects of the die temperature and plunger speed on the flow length are shown schematically in Figure 11.

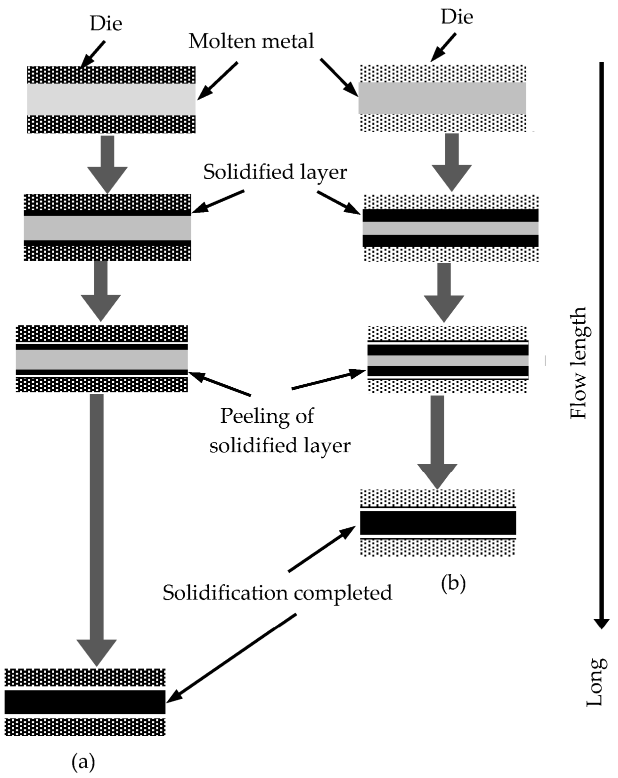


Figure 11. Schematic diagram showing the effects of die temperature and plunger speed on solidification and flow length for molten metal. (**a**) Die temperature: 30 °C, plunger speed: 0.2 m/s. (**b**) Die temperature: 150 °C; plunger speed: 0.8 m/s.

When the solidified layer peels from the die, heat transfer between the solidified layer and the die becomes smaller. When this occurs, the solidification rate decreases, resulting in a longer time until solidification is complete and an increased flow length. Under these conditions, the adhesion force becomes weaker and the adhesion time becomes shorter. Consequently, the flow length was longest for a die temperature of 30 °C and a plunger speed of 0.2 m/s. The influence of the die temperature on molten metal solidification inside the solidified layer may be smaller when the solidified layer peels from the die, as heat transfer between the solidified layer and the die decreases. As seen in Figure 3, when the die temperature was 30 °C, the flow length generally decreased with increasing plunger speed. The adhesion time for the solidified layer increased with increasing plunger speed, maintaining better heat transfer than when peeling occurred. The rate of increase of the solidified layer thickness was higher during this adhesion period, shortening the time until flow stopped. This is one cause for the decreased flow length with increasing plunger speed.

When the die gap was 1 mm, the flow length increased as the plunger speed increased, as shown in Figure 5. When the die gap was 1 mm, differences in the peeled solidified layer thickness for die temperatures of 30 and 150 °C were small compared to differences observed when varying the die gap, as shown schematically in Figure 12. Therefore, the flow length increased as the plunger speed increased.

As seen in Figures 3 and 4, at a die temperature of 150 °C, the flow length for 99.9%Al and 99.7%Al is seen to increase with increasing plunger speed. This is thought to be due to saturation of the solidified layer thickness increase rate as heat transfer between the solidified layer and the die became almost constant. Consequently, the flow length increased with increasing plunger speed.

Figure 12. Schematic diagram showing effects of die temperature and plunger speed on solidified layer thickness with 1 mm die gap. (**a**) Die temperature: 30 °C, plunger speed: 0.2 m/s. (**b**) Die temperature: 150 °C, plunger speed: 0.8 m/s.

As seen in Figure 5, the flow length for ADC12 at a die temperature of 30 °C was not influenced by the plunger speed, remaining almost constant. The influences of the rate of solidified layer thickness increase and the molten metal velocities on the flow length may offset one another. This is thought to result from increased heat transfer between the solidified layer and the die, and the increase in the solidified layer thickness rate with increasing plunger speed. In other words, the flow length increase rate decreased due to the offset of the solidified layer thickness increase rate and plunger speed increase.

The roll speed was 5 m/min. Strips of 99.9%Al and 99.7%Al could not be dragged from the tundish because they peeled from the roll. Al-0.3%Fe and ADC12 could be dragged from the tundish. This shows that the time during which adhesion occurred between the roll and 99.9%Al and 99.7%Al was shorter than that for Al-0.3%Fe and ADC12. In Figure 6, the flow length decreases as the Fe content increased. The adhesion time for the solidified layer increases with increasing Fe content, which may have caused the flow length to decrease. In Figure 6, the flow length for Al-0.5%Fe and Al-0.7%Fe is longer than that for 99.9%Al and 99.7%Al, but the cause of this is not clear.

The 99.9%Al molten metal did not solidify into a strip, and semisolid metal was ejected from the roll gap. It was thought that the semisolid layer with a low solid fraction peeled from the roll, or that the solid layer peeled and was heated into a semisolid condition, either of which resulted in the molten 99.9%Al failing to solidify. This may have occurred before the roll bite, since the 99.9%Al did not solidify. In contrast, the 99.7%Al strip could be cast successfully. Although the solid layer may have peeled from the roll, the molten metal solidified before the roll bite, allowing a strip to be cast. The contact time between the solid layer of 99.7%Al and the roll surface may be longer than that for 99.9%Al. These results clarify the mechanism responsible for the flow length for 99.9%Al being longer than that for 99.7%Al in Figures 3 and 6.

5. Conclusions

The effects of die temperature and plunger speed on the flow length for 99.9%Al and 99.7%Al were investigated using a spiral die with a 0.5 mm gap.

(1) Conventionally, the flow length is expected to increase with increasing die temperature, plunger speed, and aluminum purity. However, in the present study, it was found that when the plunger speed was 0.2 m/s, the flow length at a die temperature of 30 °C was longer than that at 150 °C. The results for the die temperature of 30 °C the plunger speed of 0.2 m/s are unique to the present study and are different from those conventionally expected for die casting. The narrow gap of 0.5 mm, low die temperature of 30 °C, and low plunger speed of 0.2 m/s are considered to be the reasons for this discrepancy.
(2) At a die temperature of 30 °C, the flow length decreased with increasing plunger speed, while at a die temperature of 150 °C, it increased with increasing plunger speed.
(3) The mechanism responsible for the results at a die temperature of 30 °C and a plunger speed of 0.2 m/s was discussed in terms of the peeling of the solidified layer from the die surface, and the unique results obtained in this study could be explained by a model that takes into account this peeling.

(4) At a die temperature of 30 °C and a plunger speed at 0.2 m/s, the flow length for Al-0.5%Fe and Al-0.7%Fe was longer than that for 99.9%Al and 99.7%Al, while at a die temperature of 150 °C, the flow length decreased with increasing Fe content.

When the die temperature is 30 °C and the plunger speed is 0.2 m/s, the adhesion force between the solidified layer and the die is weaker than at a higher die temperature and higher plunger speed, and the solidified layer peels easily from the die. As a result, the adhesion time becomes shorter.

Furthermore, when the solidified layer peels from the die, heat transfer between the solidified layer and the die becomes smaller. When this occurs, the solidification rate decreases, meaning there is a longer time until solidification is complete and an increased flow length. It is considered that for this reason, the flow length became longer at a die temperature of 30 °C and a plunger speed of 0.2 m/s.

The influence of the die temperature on molten metal solidification inside the solidified layer may be smaller when the solidified layer peels from the die, as heat transfer between the solidified layer and the die decreases. The adhesion time for the solidified layer increased with increasing plunger speed, maintaining better heat transfer than when peeling occurs The rate of increase in the solidified layer thickness is higher during this adhesion period, shortening the time until flow stops. This is considered to be the cause of the decrease in flow length with increasing plunger speed.

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