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Review

Twin Roll Caster for Clad Strip

Toshio Haga

Department of Mechanical Engineering, Faculty of Engineering, Osaka Institute of Technology, 5-16-1 Omiya Asahi-Ku, Osaka 535-8585, Japan; toshio.haga@oit.ac.jp

Abstract: Production of aluminum alloy clad strips requires many processes, and a reduction in the number of processes has long been demanded. A method to cast clad strips directly from molten metal using a twin roll caster with copper rolls is proposed in this work. Two types of twin roll casters were designed and tested. One was a vertical-type tandem twin roll caster and the other was a twin roll caster equipped with a scraper. The casting of the clad strips was conducted in an oxidizing atmosphere. The clad strips were cast at speeds higher than 15 m/min. This casting speed is much higher than that of conventional twin roll casters for aluminum alloys. The roll load was smaller than 0.2 kN/mm. This small roll load means that strips were not bonded by hot rolling. The clad strips had a clear interface between strips, and elements in each strip did not diffuse into other strips. The clad strips did not fracture at the interface in a tension shear test. This means that the clad strips were strongly bonded.

Keywords: clad strip; high-speed twin roll caster; scraper; aluminum alloy; interface

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1. Introduction

Production of aluminum alloy clad strips requires a great many processes such as DC casting, scalping of the slab, homogenization, and hot and cold rolling to make each strip. Moreover, cleaning, edge-welding, and hot rolling are conducted to bond the strips. A reduction in the number of processes needed to cast clad strips has long been demanded. Clad strips of hard or brittle aluminum alloys cannot be made by hot rolling. A process that can make clad strips consisting of hard or brittle aluminum is needed. The Novelis Fusion process can directly cast clad ingots from molten metal [1–4], so that a cladding process by hot rolling is not necessary. In this process, the many rolling processes needed to make thin strips cannot be eliminated. Moreover, hot rolling of ingots of hard or brittle aluminum alloys may be difficult.

The casting of a clad strip from an aluminum strip and aluminum alloy molten metal using a conventional twin roll caster was investigated [5]. Using similar methods, the castings of a clad strip between an aluminum alloy strip and magnesium alloy molten metal, between aluminum alloy molten metal and a steel strip, and between a copper alloy strip and molten metal of cast iron were investigated [6–9]. In these studies, one or two layers of the clad strip were not molten metal, but rather a solid strip, and the clad strip was not cast directly from two molten metals.

In the past 20 years, the design and testing of twin roll casters to cast clad strips has been conducted at the Osaka Institute of Technology (O.I.T.) to resolve these problems [10–29]. Two types of twin roll casters for clad strips were designed, assembled, and used to cast clad strips in an oxidizing atmosphere. One is a vertical-type tandem twin roll caster and the other a twin roll caster equipped with a scraper [13–23]. The vertical-type twin roll caster can cast three- and five-layer clad strips. The twin roll caster equipped with a scraper can cast clad strips without the bonding surface coming in contact with the oxidizing atmosphere [24–29]. The twin roll caster equipped with a scraper can cast clad strips consisting of magnesium alloy strips. These twin roll casters can cast clad strips at speeds higher than 15 m/min due to the use of a copper alloy roll, and because a parting material is not needed. The molten metal is rapidly solidified, and the solidification layer is cooled rapidly due to the high thermal conductivity of the copper alloy roll. In the conventional twin roll caster used for aluminum alloy, a steel roll is used, and the casting speed is slower than 5 m/min [30–39]. The roll load of these two types of twin roll casters designed by the O.I.T. is smaller than 0.2 kN/mm. This means that the cast strips are not bonded by the hot rolling, and a clear interface exists between the strips. Thus, melting of the strips occurs in a much thinner layer; for example, thinner than 1 μm.

In this paper, the properties of the two types of twin roll casters to cast clad strips proposed by the Material Processing Laboratory at the O.I.T. and the properties of the clad strips are presented.

2. Vertical-Type Tandem Twin Roll Caster

2.1. Overview of Vertical-Type Tandem Twin Roll Caster

A schematic illustration of a vertical-type tandem twin roll caster (VTTRC) is shown in Figure 1 [13–23]. Casting is conducted in an oxidizing atmosphere. The strip cast by the first twin roll caster is called a base strip, and the strip cast by the second twin roll caster is called an overlay strip. The molten metal of the overlay strip is poured after the base strip has gone through the roll gap of the lower twin roll caster. The roll speed of the upper twin roll caster and that of the lower twin roll caster are almost the same. The contact length between the aluminum alloy and the roll is called the solidification length, which is set by the position of the back dam plate. The thickness can be set by the solidification length [13–15]. This means that the thickness ratio between the base strip and the overlay strip can be controlled by the solidification length. Copper rolls were used to increase the cooling speed and casting speed. The roll speed of the VTTRC was much higher than that of the conventional twin roll caster for aluminum alloy (CTRCA), and the roll load was much smaller than that of the CTRCA. A parting material is not sprayed on the roll because the strip does not stick to the roll. The parting material creates heat resistance between the roll and the molten metal. Therefore, when a parting material is not used, rapid solidification occurs, and it is possible to increase the roll speed.

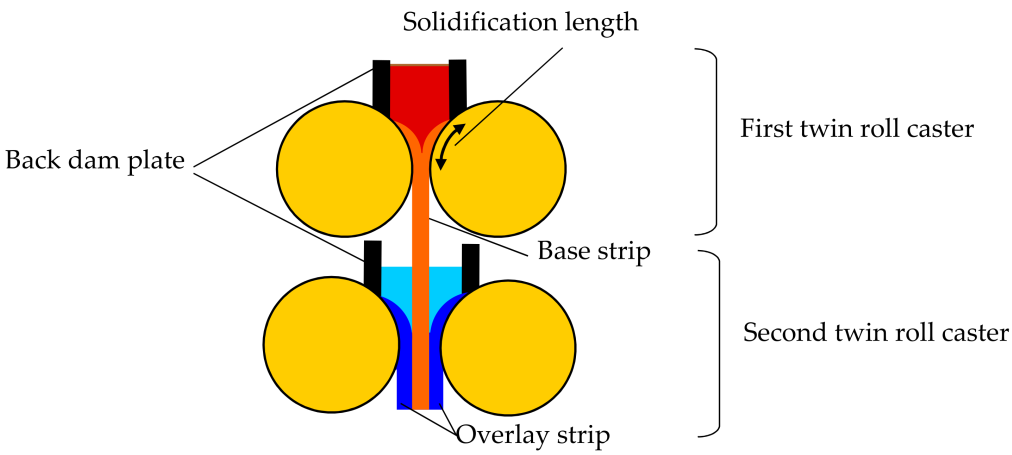

Figure 1. Schematic illustration of a vertical-type tandem twin roll caster.

2.2. Factors Affecting Bonding

2.2.1. Base Strip Temperature

Factors affecting the bonding were investigated [17–19]. The effect of the temperature of the base strip on bonding between the base strip and the overlay strip was investigated [20]. The experimental procedure is shown in Figure 2. The roll diameter of the twin roll casters was 300 mm, the roll load was 88 N/mm, the solidification length was 100 mm, and the roll speed was 30 m/min. The base strip was 3004 alloy and the overlay strip was 4045 alloy. This combination is the same as in the brazing sheet used for an automotive heat exchanger. The pouring temperatures for the 3004 and 4045 alloys were 680 °C and 620 °C, respectively. The roll-cast 3004 strip was cooled down to a designated temperature, and then inserted into the roll caster to cast the clad strip. The temperature of the 3004 base strip was set at 200, 300, 400, 450, 500, and 550 °C. The relationship between the time the strip was released from the first caster and the temperature of the base strip is shown in Figure 3. A tensile shear test was conducted on the as-cast clad strip, with the results shown in Figure 4. The shear stress increased as the temperature of the 3004 base strip increased to 550 °C, and reached a peak when the temperature of the 3004 base strip was higher than 450 °C.

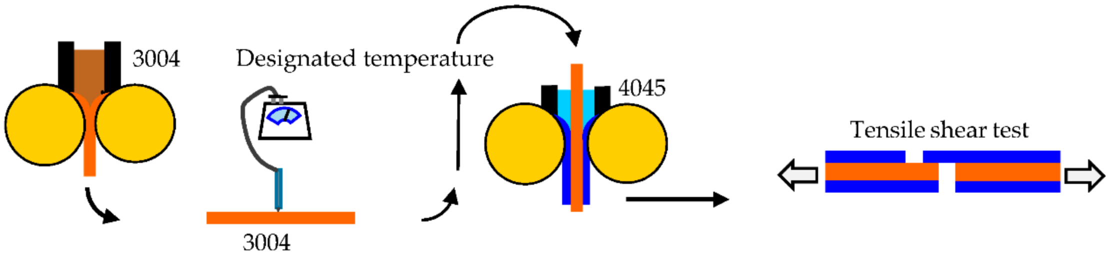

Figure 2. Experimental procedure to investigate the effect of the base strip temperature on bonding.

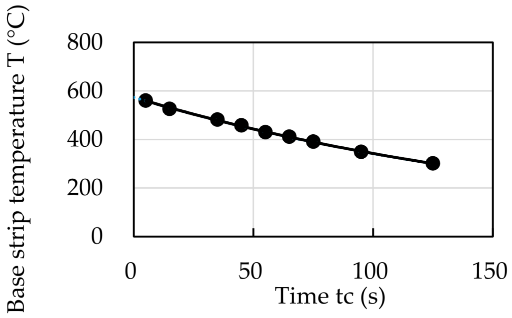

Figure 3. Relationship between the time after the base strip was released from the first caster and the temperature of the strip.

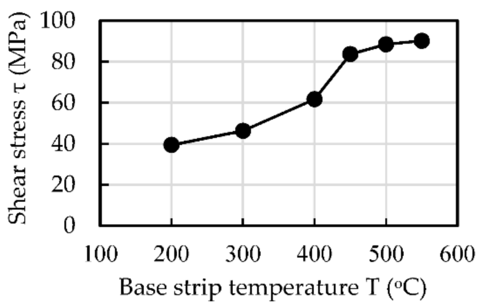

Figure 4. Effect of base strip temperature on bonding force at the interface between the base and overlay strips.

Cold rolling was conducted on the as-cast strip, and a bending-fracture test was conducted on the cold-rolled strip to investigate the bonding characteristics. When the temperature of the base strip was 200 °C or 300 °C, the overlay strip peeled from the base strip. Overlay strips peeled by cold rolling are shown in Figure 5. The clad strip could be cold rolled down to a thickness of 1 mm at base strip temperatures ranging from 400 °C to 550 °C.

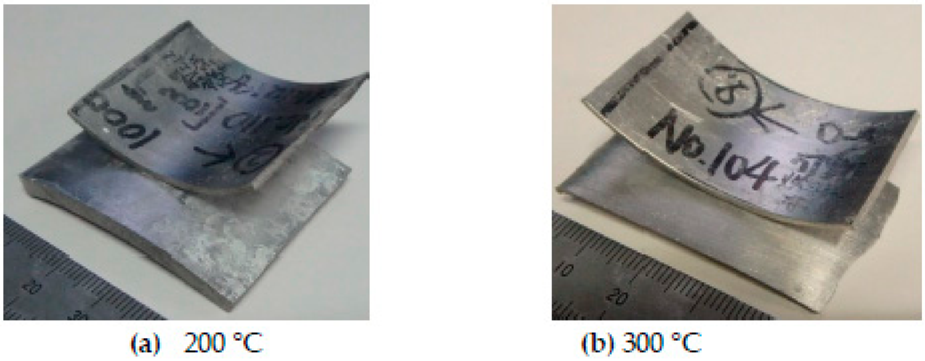

Figure 5. Peeling of the overlay strip from the base strip. Base strip temperature: (**a**) 200 °C, (**b**) 300 °C.

A schematic illustration of the bending-fracture test and cross-sectional images of the fracture areas are shown in Figure 6. The bending-fracture test was conducted on cold-rolled 1 mm-thick clad strip. The overlay strip did not peel from the base strip in the bending-fracture test. It appeared that the overlay strip was strongly bonded to the base strip when the temperature of the base strip was higher than 400 °C.

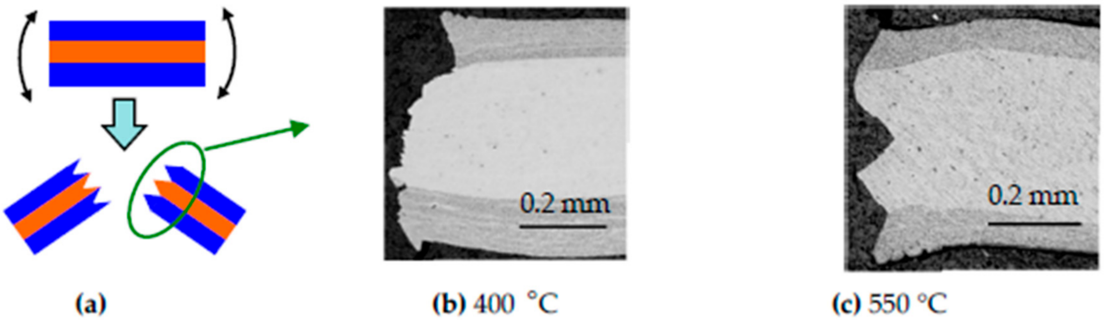

Figure 6. Schematic illustration of bending-fracture test and cross-section of fractured area of the cold-rolled 1 mm-thick clad strip. (**a**) Bending-fracture test. Base strip temperature: (**b**) 400 °C, (**c**) 550 °C.

When the temperature of the base strip was higher than 450 °C, the overlay strip was strongly bonded to the base strip. It is clear from Figure 3 that it took about 40 s to reduce the temperature of the base strip to 450 °C. When the roll diameter was 200 mm and 300 mm, the distance of the roll bite between the first and the second twin roll caster shown in Figure 1 was 500 mm and 600 mm, respectively. The roll speed for this type of clad caster ranges from 20 to 40 m/min. When the roll diameter was 300 mm, the distance between the roll bite of the first and the second roll caster was 600 mm and the roll speed was 20 m/min, and the base strip took 1.8 s to travel to the roll bite of the second roll caster. This shows that the temperature of the base strip was within the range in which strong bonding is obtained at any roll speed.

2.2.2. Roll Speed

The effect of the roll speed on bonding was investigated [21]. The base strip was 3003 alloy and the overlay strip was 4045 alloy. The roll load was 22 N/mm, the roll diameter was 200 mm, and roll speeds of 20, 30, and 40 m/min were investigated. The pouring temperatures for the base strip and the overlay strip were 670 °C and 700 °C, respectively. The solidification length was 80 mm, and the as-cast clad strip was cold. The overlay strip did not peel from the base strip. A cross-section of the cold-rolled strip is shown in Figure 7. The base strip and the overlay strip were strongly bonded. The roll speed had no influence on the condition of the interface between the base strip and the overlay strip. This result was considered to be due to the effect of the base strip temperature on the bonding shown above. When the roll speed becomes higher, it is thought that the contact time between the base strip and the overlay strip at the roll bite becomes shorter. The roll speed did not affect bonding within the investigated roll speeds until peeling of the overlay strip occurred.

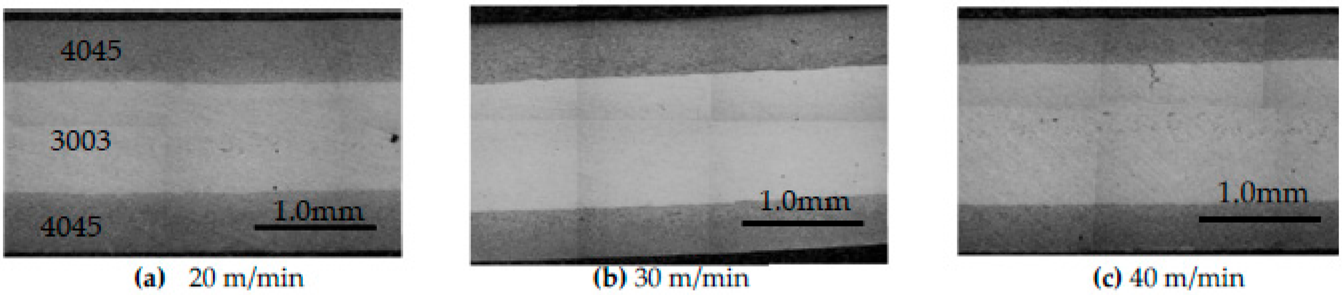

Figure 7. Cross-sections of cold rolled clad strips cast at different roll speeds. Base strip is 3003 and over lay strip is 4045. Roll speed: (**a**) 20 m/min, (**b**) 30 m/min, (**c**) 40 m/min.

2.2.3. Molten Metal Temperature of Overlay Strip

The effect of the molten metal temperature of the overlay strip on bonding was investigated [21,22]. The base strip was 3003 alloy and the overlay strip was 4045 alloy. The conditions were a solidification length of 80 mm, a roll diameter of 200 mm, a roll load of 22 N/mm, and a roll speed of 40 m/min. The pouring temperature for the base strip was 670 °C. Pouring temperatures of 610 °C, 630 °C, and 700 °C were investigated for the overlay strip, and the extents of superheating were 15 °C, 30 °C, and 105 °C, respectively. The solidus line for the 3003 alloy was at 643 °C. When the pouring temperature for the overlay strip was 610 °C or 630 °C, they were lower than the solidus line for the 3003 base strip, and the overlay strip bonded to the base strip. The 4045 alloy bonded to the 3003 alloy under all superheating conditions. The interface between the base strip and the overlay strip for an as-cast clad strip is shown in Figure 8. The pouring temperature for the molten metal for the overlay strip did not influence the interface between the base strip and the overlay strip. The clad strip in which the molten metal of the overlay strip was cast at 610 °C was cold-rolled, and a bending-fracture test was conducted. A cross-section of the fracture area is also shown in Figure 8. No peeling occurred between the base strip and the overlay strip. This shows that whether the pouring temperature for the overlay strip was higher or lower than the solidus line for the base strip was not a dominant factor in bonding. The superheating of the molten metal of the overlay strip had no influence on bonding.

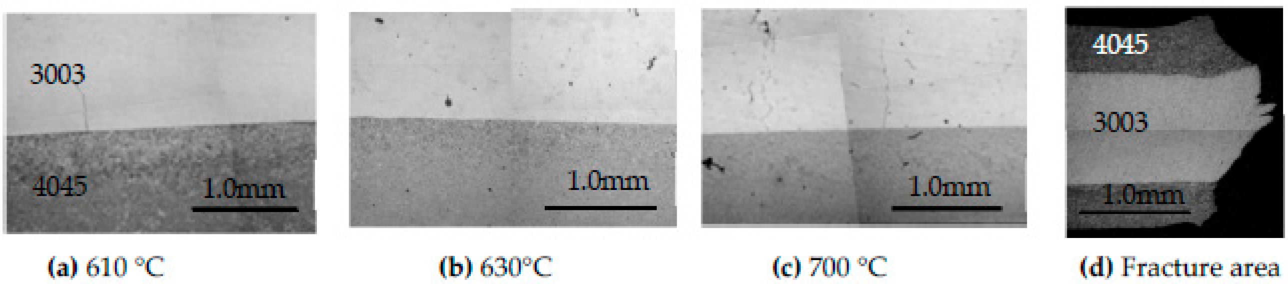

Figure 8. Cross-section near interface between base and overlay strips of as-cast strip, and fracture area after bending-fracture test of cold-rolled strip. Molten metal of overlay strip: (**a**) 610 °C, (**b**) 670 °C, (**c**) 700 °C, (**d**) Fracture area of clad strip of (**a**) after cold-rolling and bending-fracture test.

2.2.4. Roll Load

A two-layer clad strip can be cast using a single-roll caster [40]. This means that the roll load is not an essential factor in the bonding of strips. The clad strip was cast at roll loads of 10, 88, and 176 N/mm, and the bonding and interface conditions were investigated [21]. The base strip was 3003 alloy and the overlay strip was 4045 alloy. The roll diameter was 200 mm, the solidification length was 80 mm, and the roll speed was 40 m/min. The pouring temperatures for the molten metals for the base strip and the overlay strip were 670 °C and 610 °C, respectively. Cross-sections near the interface between the base strip and the overlay strip of the as-cast clad strips cast are shown in Figure 9. There were no differences between the interfaces of the clad strips cast under the different roll loads. These as-cast strips could be cold-rolled without peeling at the interface. Thus, it appeared that the roll load did not affect the interface and bonding conditions. These roll loads were very small compared to the load employed during hot rolling to make the clad strip, and the difference in the roll loads was not large enough to affect the interface or the bonding.

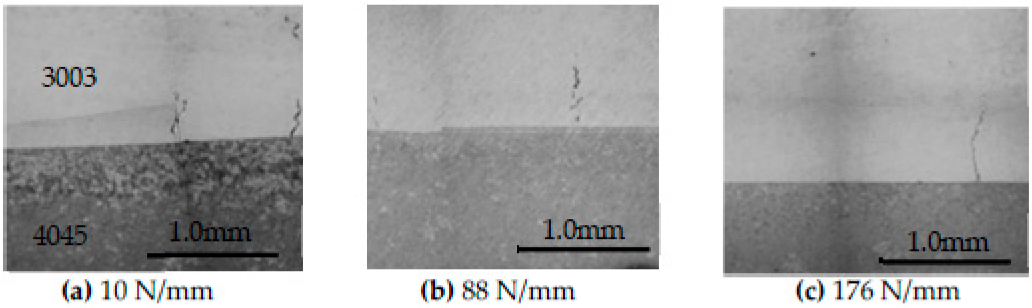

Figure 9. Cross-section near interface of as-cast clad strip cast at different roll loads. Roll load: (**a**) 10 N/mm, (**b**) 88 N/mm, (**c**) 176 N/mm.

2.2.5. Thickness of Overlay Strip

The influence of the thickness of the overlay strip on the bonding between the base strip and the overlay strip was investigated. The experimental procedure is shown in Figure 10. The casting speed was 30 m/min and the roll load was 55 N/mm. As shown in Figure 10a, the roll diameter of the first and the second twin roll casters was 200 mm. The solidification length of the base strip was 60 mm, and that of the overlay strip was 80 mm. As shown in Figure 10b, the roll diameters of the first and second twin roll casters were 300 mm and 100 mm, respectively. The solidification length of the base strip was 120 mm, and that of the overlay strip was 25 mm. The pouring temperatures for the 3003 and 4045 alloys were 670 °C and 625 °C, respectively. The overlay strip in Figure 10a was thicker than that in Figure 10b, as the solidification length in Figure 10a was greater. In Figure 10b, a smaller diameter roll was used to make the overlay strip thinner. It is easy to make the solidification length shorter when the roll diameter is smaller [14].

A bending-fracture test was conducted on the as-cast clad strips in Figure 10a,b, and the results are shown in Figure 11a,b. No peeling occurred between the base strip and the overlay strip for either of the clad strips. There was no difference between the interfaces of the clad strips shown in Figure 11a,b. The clad strip in Figure 10b was cold-rolled down to 1 mm without peeling, as shown in Figure 11c. Thus, it appeared that the thickness of the overlay strip did not influence the condition of the interface or the bonding. The temperature of the free solidified surface of the overlay strip is the liquidus line, and this temperature does not depend on the thickness of the overlay strip. The interface and bonding were not influenced by the thickness of the overlay strip.

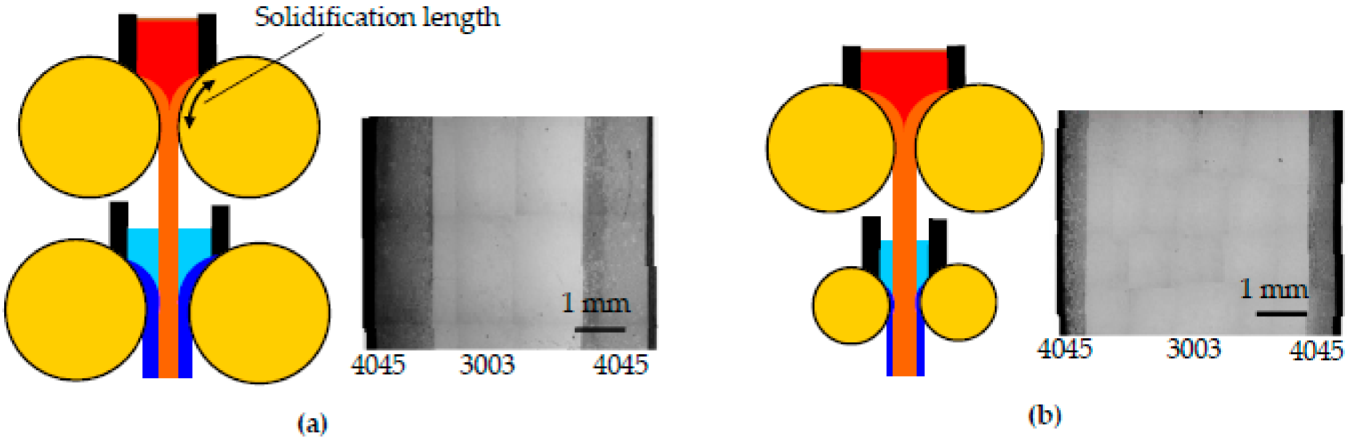

Figure 10. Control of strip thickness by solidification length and cross-section of as-cast clad strip. (**a**) The roll diameter of both the upper and lower twin roll casters was 200 mm. The solidification length of the base strip was 60 mm, and that of the overlay strip was 80 mm. (**b**) The roll diameters of the upper and lower twin roll casters were 300 mm and 100 mm, respectively. The solidification length of the base strip was 120 mm, and that of the overlay strip was 25 mm.

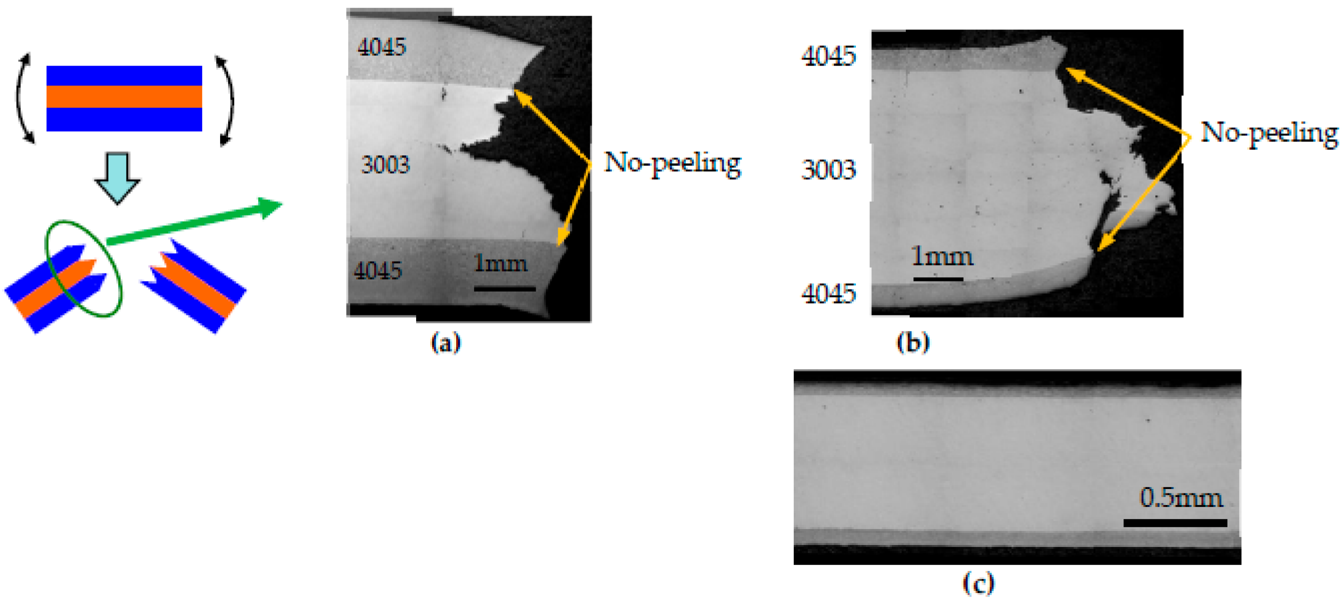

Figure 11. Cross-section of fracture area after bending-fracture test and after cold rolling. (**a**) Strip shown in Figure 10a; (**b**) strip shown in Figure 10b; (**c**) cold-rolled strip shown in Figure 10b.

2.2.6. Latent Heat of Overlay Strip

The effect of the latent heat of the overlay strip on the bonding was investigated. In Figure 12, the base strip is 3003 alloy, and one overlay strip is 4045 alloy and the other is Al-4%Si or Al-2%Mg alloy [16]. The roll diameter was 300 mm, the roll load was 88 N/mm, the solidification length was 100 mm, and the roll speed was 30 m/min. The solidus lines, liquidus lines, and pouring temperatures for these aluminum alloys are shown in Table 1. The 4045 overlay strip was bonded to the 3003 base strip without a gap at the interface. When Al-4%Si or Al-2%Mg was used as the overlay strip, it did not bond to the 3003 base strip. The pouring temperature for the 4045 alloy was lower than that of Al-4%Si and Al-2%Mg. The pouring temperatures for Al-4%Si and Al-2%Mg were higher than the liquidus line of the 3003 alloy, while the pouring temperature for the 4045 alloy was 630 °C, which was lower than the solidus line for the 3003 alloy. The solidus and liquidus lines for the 4045 alloy were lower than those for Al-4%Si and Al-2%Mg. This shows that the solidus line, liquidus line, and pouring temperature for the overlay strip were not dominant factors in bonding. When the pouring temperature for the 4045 overlay strip was lower than solidus line for the 3003 base strip, the 4045 overlay bonded to the 3003 base strip as shown above.

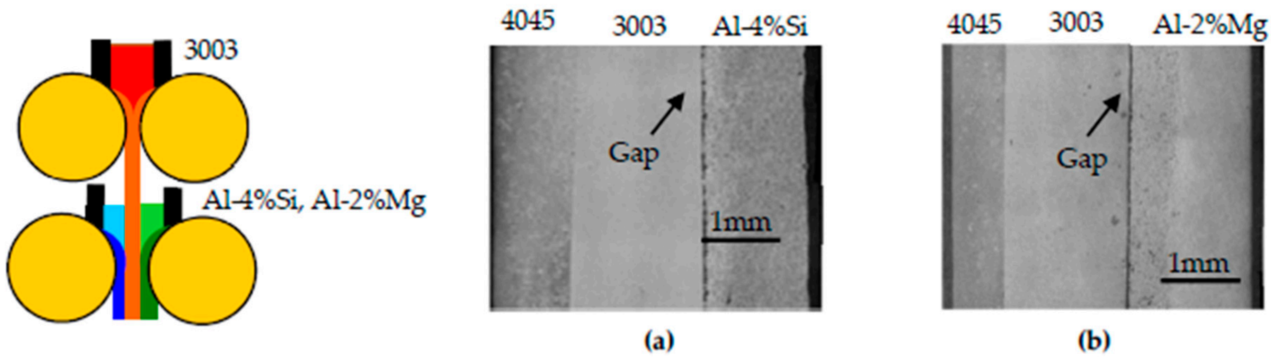

Figure 12. Cross-section of as-cast clad strips. (**a**) 4045/3003/Al-4%Si clad strip, (**b**) 4045/3003/Al-2%Mg clad strip.

Table 1. Solidus lines, liquidus lines, and pouring temperatures.

Material	Solidus Line (°C)	Liquidus Line (°C)	Pouring Temperature (°C)
3003	643	655	670
3003 + 2% Mg	625	655	670
4045	575	595	610, 630, 700
Al-4% Si	577	624	660
Al-2% Mg	620	650	680
5182	577	638	670

Usually, the latent heat is greater than the specific heat. The latent heat of aluminum alloys is affected by additive elements. The latent heat of Si is larger than that of Al, while that of Mg is smaller. In the Al-Si alloy, the latent heat became larger as the content of Si became greater. In the Al-Mg alloy, the latent heat was smaller than that of the Al or Al-Si alloys. It was estimated that the latent heat of the 4045 alloy was larger than that of Al-4%Si and Al-2%Mg. The latent heat of the 4045 alloy was large enough to enable it to be bonded to the 3003 base strip. The surface of the 3003 base strip was heated to the temperature at which bonding became feasible. The effects of roll speed and roll load on bonding were smaller than that of the latent heat.

In Figure 13, cross-sections of two kinds of clad strips are shown [16]. The casting conditions were a roll diameter of 300 mm, a roll load of 210 N/mm, a solidification length of 100 mm, and a roll speed of 30 m/min. The overlay strip for both clad strips was 5182 alloy, while one base strip was 3003 alloy and the other was 3003 + 2% Mg. The solidus line for 3003 + 2% Mg was 18 °C lower than that for the 3003 alloy, and the latent heat of the 3003 + 2% Mg alloy was smaller than that of the 3003 alloy. When the base strip was the 3003 alloy, a gap existed at the interface between the 3003 base strip and the 5182 overlay strip, while a gap did not exist when the base strip was 3003 + 2% Mg. This means that the bonding conditions were better when the 3003 + 2% Mg alloy was the base strip. The 3003 + 2% Mg base strip ruptured at the inside of the strip. This shows that the 3003 + 2% Mg strip was heated up to semisolid conditions. It is estimated that when the surface of the 3003 + 2% Mg base strip was semisolid, firm bonding was realized.

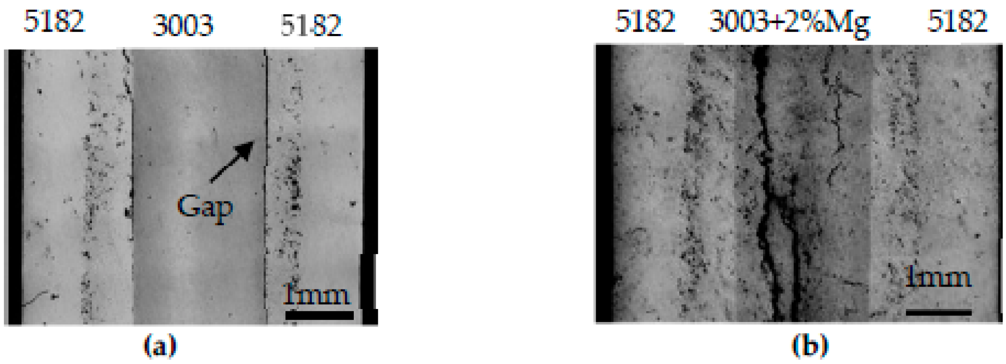

Figure 13. Cross-section of as-cast clad strips. (**a**) 5182/3003/5182 clad strip, (**b**) 5182/3003 + 2% Mg/5182 clad strip.

2.2.7. Effect of Oxide Film

The base strip of the VTTRC was in contact with an oxidizing atmosphere. It was assumed that an oxide film formed at the surfaces of the base strip, but the base strip bonded to the overlay strips. It appears that that a strong and thick oxide film did not exist at the interfaces between the strips of the cladding and base metal, because these strips bonded successfully. To investigate the differences between the oxide films for the single strip and the interface of the clad strip, the experiment shown in Figure 14 was conducted. Two A356 single strips were placed together and heated up to a semisolid temperature of 580 °C with compression. The strips did not bond. It was considered that an oxide film existed on the strip surface, and this oxide film was not broken; as a result, the semisolid strips did not bond. It is clear that heating the strips to a semisolid condition caused the primary crystals to become globular. The A356 strip was very soft at 580 °C, which corresponded to a semisolid condition. The oxide film was strong enough to prevent breakage by compression. In contrast, in the clad strip cast by the VTTRC, the interface, which existed in the as-cast condition, disappeared when the clad strip was heated to a semisolid condition. There was a difference in the size of primary crystals at the position of the interface, and a clear interface did not exist as in the as-cast clad strip. This result shows that a strong oxide film did not exist at the interface of the clad strip. The clad strip could be cast using a single roll caster [24,40]. This shows that the roll load at the roll bite did not break the oxide film. It appeared that the oxide film on the base strip was thin and weak enough to enable bonding between the base and the overlay strips when the molten metal of the overlay strip contacted the base strip. An electron diffraction pattern obtained by TEM did not show a halo pattern, indicating the existence of an oxide film [23]. It is possible that the oxide film on the base strip might be finely dispersed and exist within the overlay strip. In a three-layer clad strip consisting of a 3003 base strip and 4045 overlay strip, the base strip took 0.5 s to travel to the second roll caster, and the temperature of the base strip at the position of the second caster was about 560 °C. Figures 3 and 4 show that the bonding strength plateaued when the base strip temperature was higher than 500 °C, and the casting using VTTRC was in this range. The influence of the oxide film on the bonding force between the base and the overlay strips may depend on the base strip temperature. The oxide film may become thin and weak when the base strip temperature is higher than 500 °C.

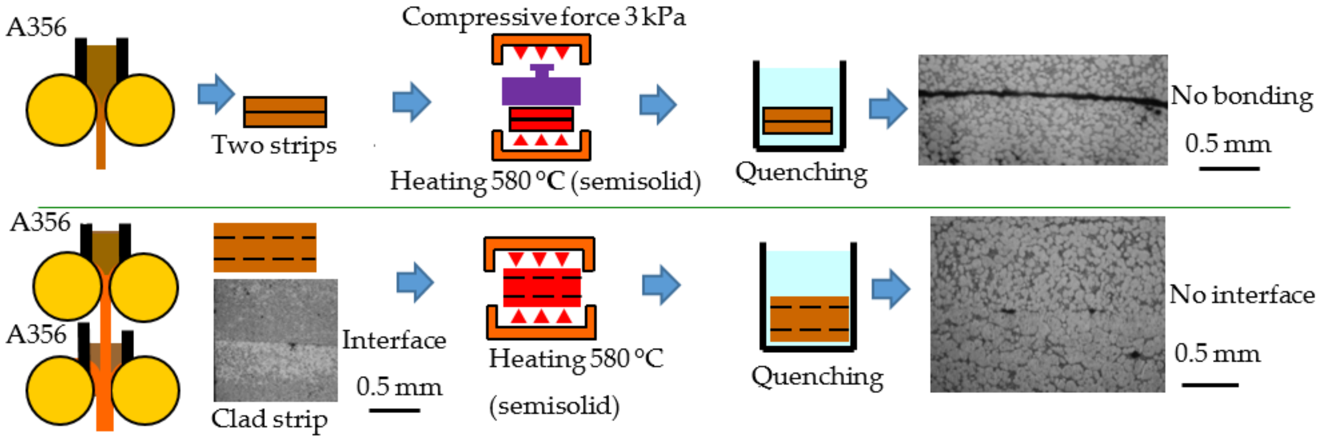

Figure 14. Heating of two stacked A356 strips with compression and three-layer A356 clad strips under semisolid conditions, and images of interfaces between strips.

2.3. Base Strip with Lower Solidification Temperature than Overlay Strip

When the solidification temperature of the base strip was higher than that of the overlay strip, the base strip was not melted, and a clear interface between the base and overlay strips could be observed, as shown in Figure 15a. In Figure 15b, the positions of the aluminum alloys in the base strip and the overlay strip are reversed. When the solidification temperature of the base strip was lower than that of the overlay strip, the base strip was melted by heating from both sides of the overlay strip, and the Si from the 4045 alloy entered into the 3003 overlay by diffusion, as shown in Figure 15b. When the 3003 overlay strips were bonded one by one as shown in Figure 15c, the base strip was not melted. When the 3003 overlay strip was bonded to one side of the 4045 base strip, the other side contacted the roll, so the 4045 base strip was not heated from both sides. The base strip did not melt, and a sound clad strip could be cast [13,14,22].

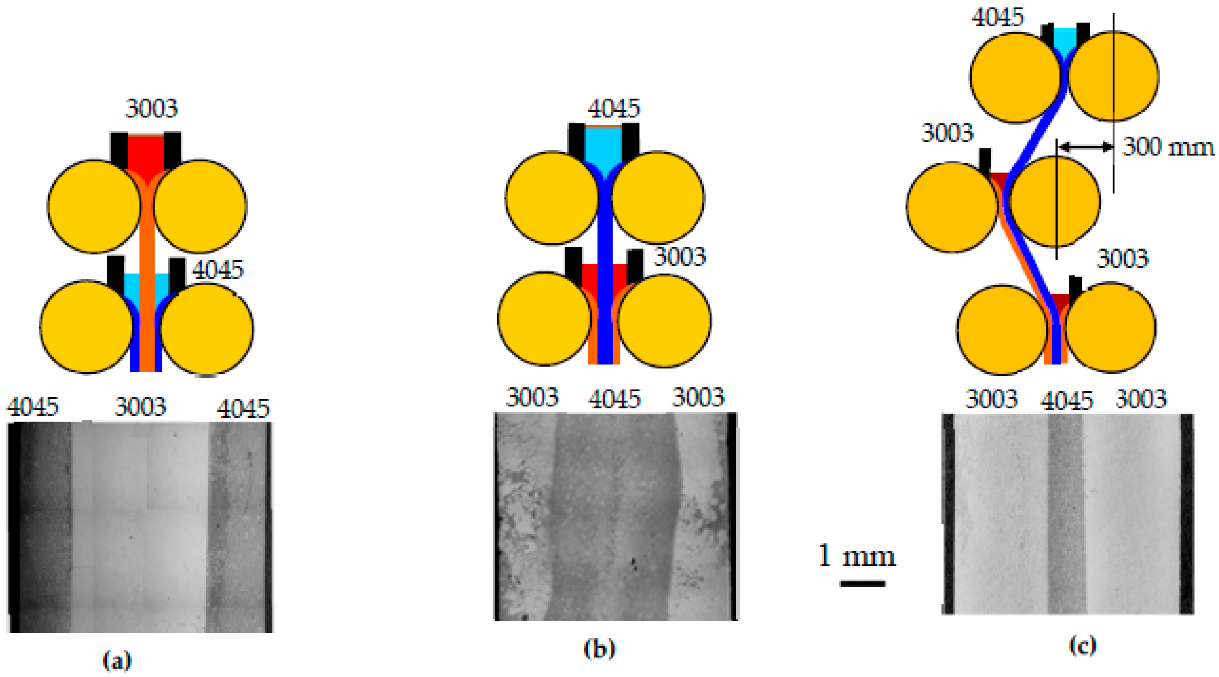

Figure 15. Schematic illustration of vertical-type tandem twin roll casters and cross-sections of clad strips. (**a**) 4045/3003/4045 clad strip, (**b**) 3003/4045/3003 clad strip, (**c**) 3003/4045/3003 clad strip.

2.4. Different Aluminum Alloy Overlay Strips

In a three-layer clad strip, different aluminum alloys can be used for the two overlay strips. As shown in Figure 16, the liquidus line for the Type A alloy was lower than the solidus line for the Type B alloy. Solidus lines and liquidus lines for the Type A and Type B alloys are shown in Table 2. When the solidification length was 25 mm as shown in Figure 16a, the Type A alloy was re-melted after release from the second roll caster. When the solidification length was 70 mm, the overlay strip of the Type A alloy was not re-melted. It was thought that when the solidification length was 25 mm, the temperature of the Type B alloy was not reduced to lower than the solidus line for the Type A alloy. The temperature of the overlay strip of the Type A alloy was increased by heating from the overlay strip of the Type B alloy, and the overlay strip of the Type A alloy was heated to a semisolid condition. As shown in Figure 16b, the temperature of the base strip of the Type B alloy was lower than the solidus line for the Type A alloy, and the Type A alloy was not re-melted [15].

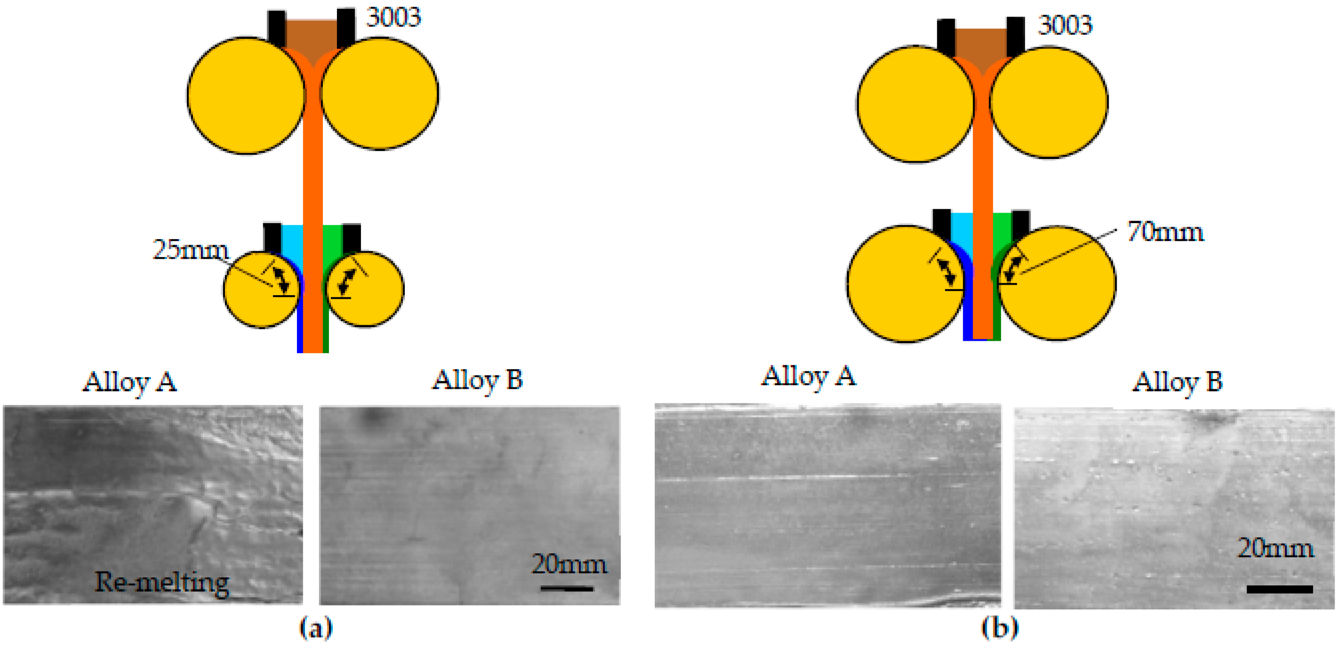

Figure 16. Surface of clad strips for which overlay strips were different aluminum alloys. The solidification length of the overlay strip in (**a**) was 25 mm, and in (**b**) was 70 mm. The solidus and liquidus lines of Alloy A and Alloy B are shown in Table 2.

Table 2. Solidus and liquidus lines of Alloys A and B in Figure 16.

Aluminum Alloy	Solidus Line (°C)	Liquidus Line (°C)
Alloy A	575	590
Alloy B	627	643

When the solidification temperatures for the overlay strips are different, the solidification temperature for the overlay strip with the higher solidification temperature must be lowered until it becomes lower than that of the overlay strip whose solidification temperature is lower. Alternatively, the method shown in Figure 15c is suitable for this condition.

2.5. Diffusion of Element of Base Strip and Overlay Strip Near the Interface

Line analyses at the interface between the base strip and the overlay strip for two kinds of three-layer clad strips are shown in Figure 17. As shown in Figure 17a, the base strip was 3003 alloy and the overlay strip was 4045 alloy. Si, an element of the 4045 alloy overlay strip, did not diffuse into the base strip [13–15,23]. As shown in Figure 17b, the base strip was 8079 alloy and the overlay strip was 6022 alloy, and the Fe in the 8079 alloy base strip did not diffuse into the overlay strip [17,19]. There was no diffusion of elements between the base and overlay strips. A clear interface was formed, as shown in Figure 17a,b. These results mean that if the base strip was melted by the molten metal of the overlay strip, the melted area was very thin, and a clear interface was formed.

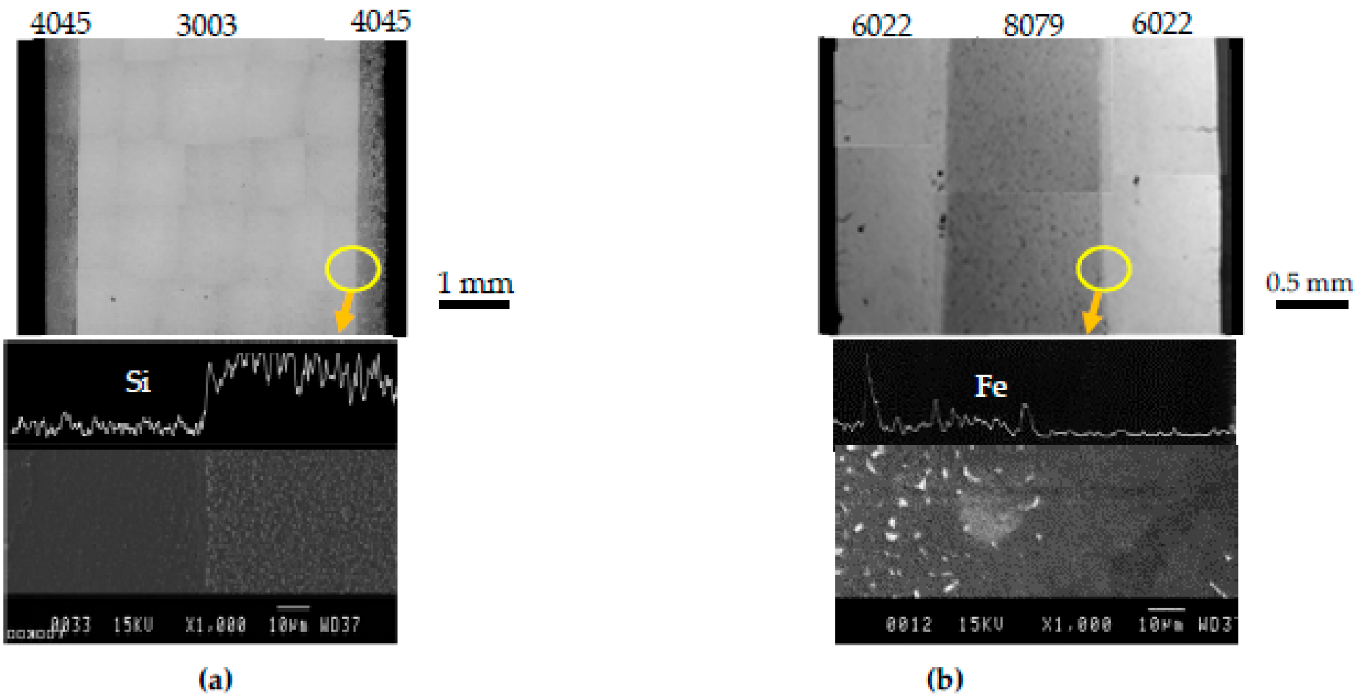

Figure 17. Line analysis at interface between base strip and overlay strip. (**a**) 4045/3003/4045 clad strip, (**b**) 6022/8079/6022 clad strip.

2.6. Five-Layer Clad Strip

A five-layer clad strip can be cast using three tandem-type twin roll casters [15]. A photograph and a schematic illustration of the three tandem-type twin roll casters and cross-sections of five-layer clad strips are shown in Figure 18. The solidification temperature for the alloys was set from higher to lower from the upper twin roll caster to the lower twin roll caster. This means that the solidification temperature for the outer strip must be lower than the solidification temperature of the inner strip. When the same alloy was used at the 1st and 2nd twin roll casters, the base strip could be thicker. When different alloys were used at each twin roll caster, a functionally gradient metal could be cast. When a thicker strip was needed, the same alloy was used in the 1st, 2nd, and 3rd twin casters.

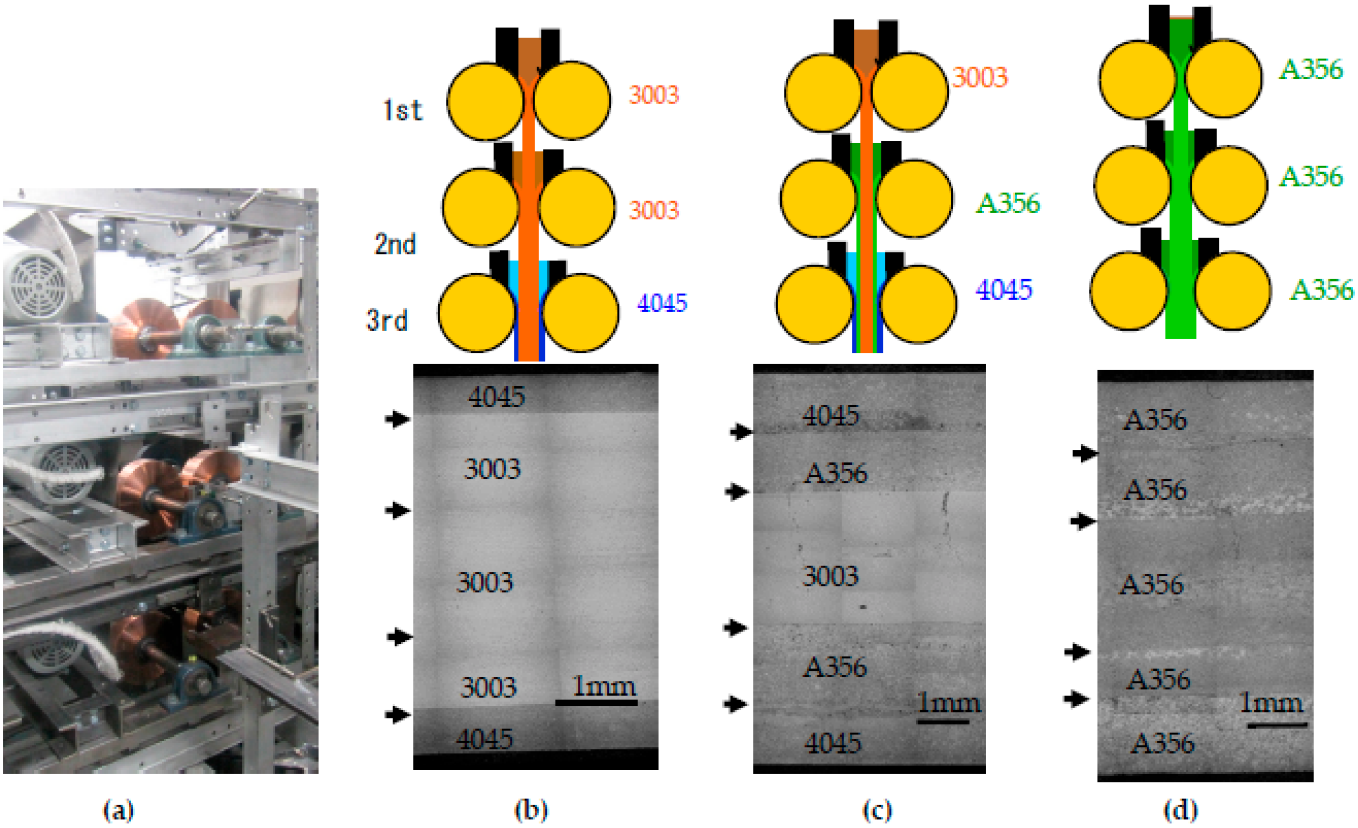

Figure 18. Photograph and schematic illustrations of vertical-type tandem twin roll casters to cast five-layer clad strips, and cross-sections of the five-layer clad strips. Arrows show the interfaces between the strips. (**a**) Photograph of rolls of a triple tandem-type twin roll caster. (**b**) The same alloy was used in the 1st and 2nd twin roll casters. (**c**) Different alloys used in each twin roll caster. (**d**) The same alloy was used in the 1st, 2nd, and 3rd twin roll casters.

2.7. Bonding Time

When the free solidified surface of the overlay strip contacts the base strip, the free solidified surface temperature is the liquidus line. The latent heat of the semisolid metal in the overlay strip heats the base strip and bonding occurs. The latent heat is usually larger than the specific heat. The base strip is heated by the latent heat. The results shown in Figure 12 support this. The bonding time for the strips was estimated from measurement of the metal temperature between the rolls using a thermocouple. The experimental method is shown in Figure 19. A thermocouple with a 0.1 mm diameter was dragged by a lead wire into the melt pool and embedded in a strip of the 4045 alloy. The positions of the liquidus line and solidus line were 40 mm and 5 mm from the roll bite, respectively. It took 0.07 s to travel from the liquidus line point to the solidus line point when the roll speed was 30 m/min. Bonding between the base strip and the overlay strip occurred only within this 0.07 s timeframe. Thus, the bonding between strips was estimated to occur over a very short time.

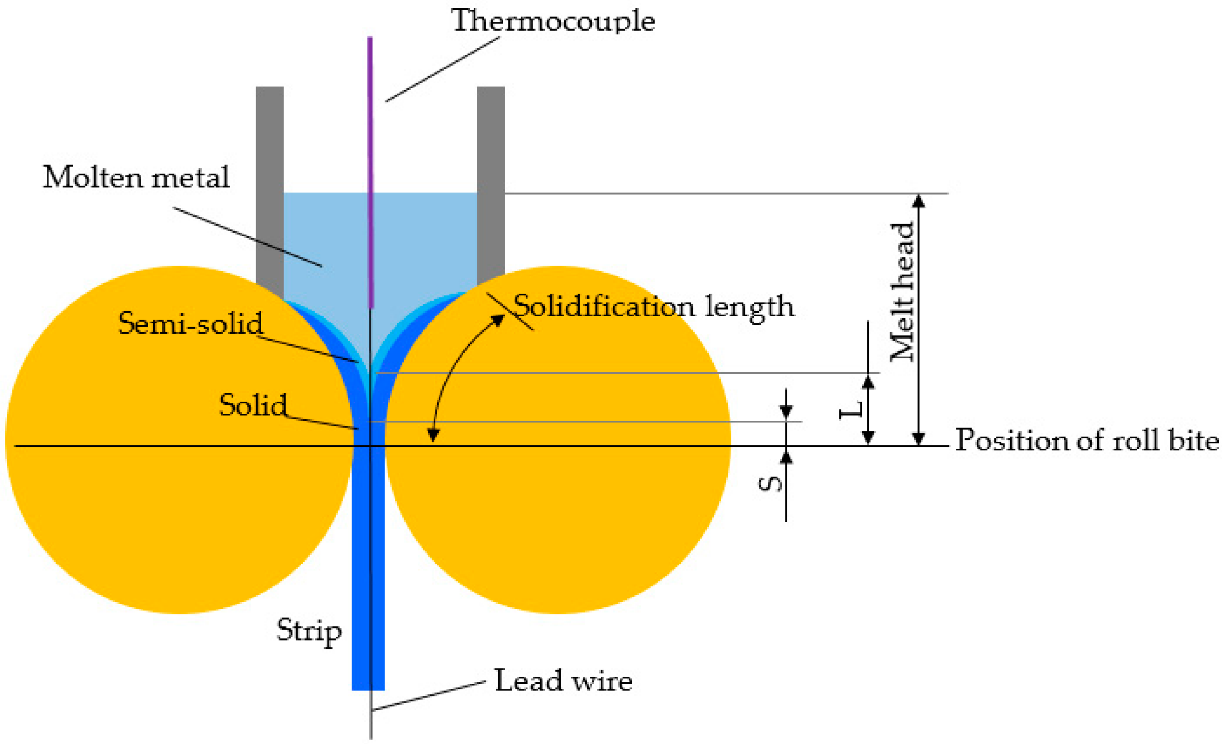

Figure 19. Schematic illustration showing measurement of the temperature of the metal solidified by the twin roll caster. L: position of liquidus line; S: position of solidus line.

2.8. *Starting Point of Cladding*

Figure 20 shows the contact-start point between the base strip of the 3003 alloy and the overlay strip of the 4045 alloy. The overlay strip was immediately bonded to the base strip after pouring the molten metal of the overlay strip [16]. The transition length of the overlay strip depended on the time it took for the melt head of the overlay strip to reach the position of the back dam plate contacting the roll.

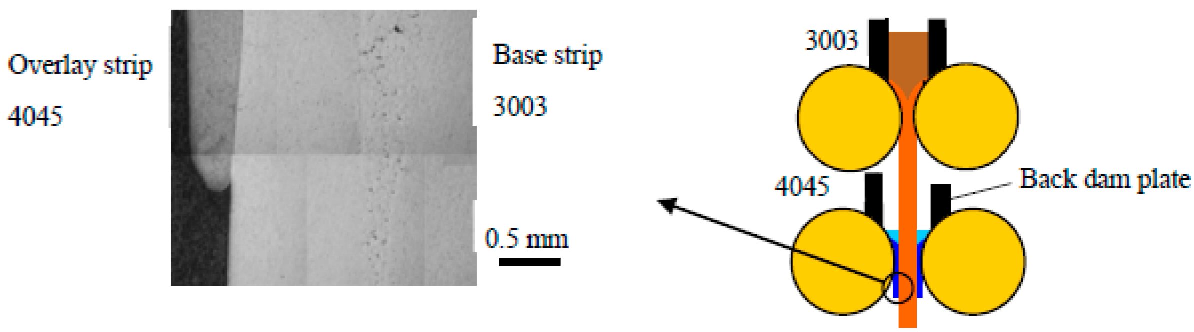

Figure 20. Starting point of cladding between the base strip and the overlay strip.

3. Twin Roll Caster Equipped with a Scraper

3.1. *Overview of Twin Roll Caster Equipped with a Scraper*

A scraper has two roles. One is separation of two kinds of molten metal, and the other is to make the surface of the base strip a semisolid of high solid fraction [24–29]. Figure 21 shows two kinds of twin roll casters equipped with a scraper and a close-up of the scraper. The scraper was attached to the vertical-type twin roll caster and an unequal-diameter twin roll caster, and these are shown in Figure 21a,b, respectively [24–29]. The unequal-diameter twin roll caster is suitable for a mounting a scraper because there is enough space. The alloy for which the solidification temperature is higher is used as the base strip. The side of the base strip not contacting the roll is scribed by the scraper. The molten metal of the overlay strip is poured on the base strip and is solidified by a small upper roll. The scribed surface of the base strip contacts the molten metal of the overlay strip without coming in contact with the oxidizing atmosphere by the effect of the scraper. Thus, an oxide film is not formed. The scribed surface of the base strip is in semisolid condition at high solid fraction. In this way, the scribed surface is formed in an appropriate condition for cladding. The other useful point is that an alloy whose latent heat is small can be used for the overlay strip.

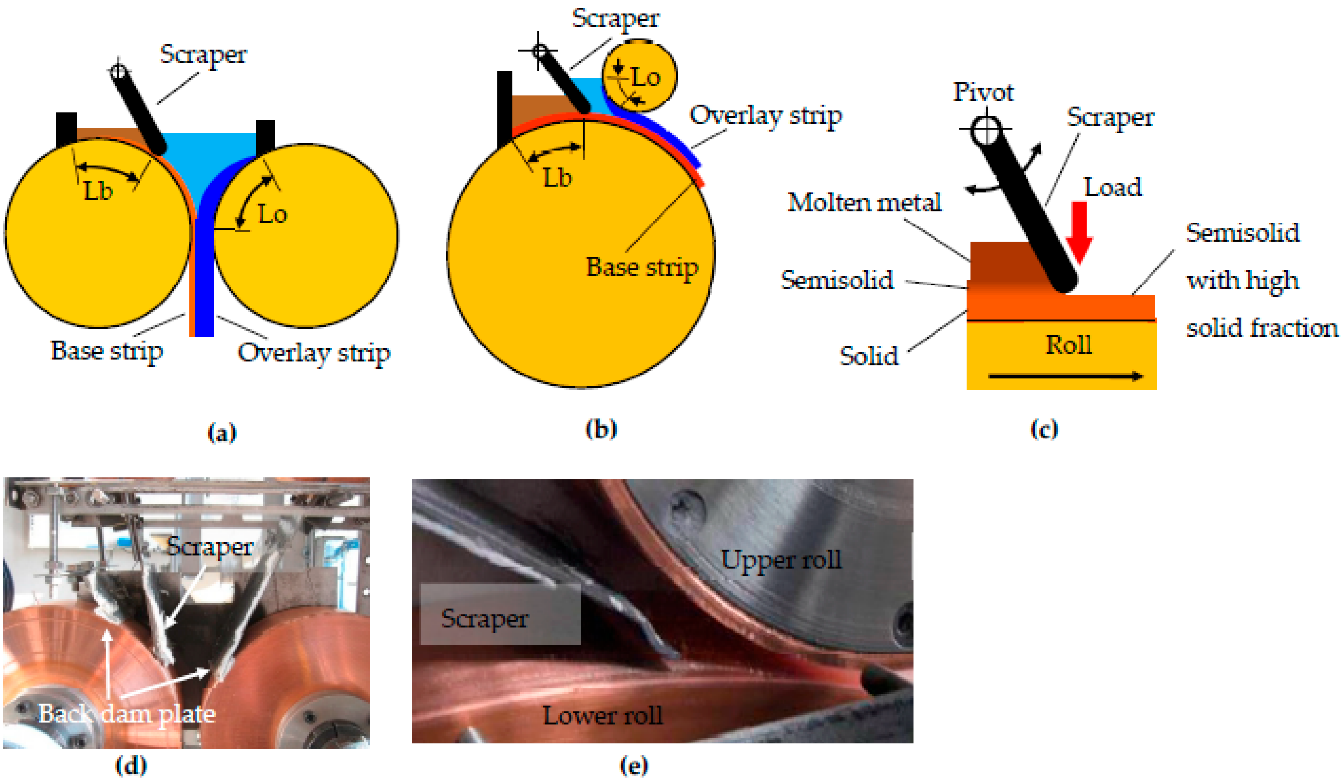

Figure 21. Schematic illustrations of two types of twin-roll casters equipped with a scraper, and enlarged view and photographs of the scraper. (**a**) Vertical-type twin roll caster equipped with a scraper. (**b**) Unequal-diameter twin roll caster equipped with a scraper. (**c**) Enlarged view of the scraper. (**d**,**e**) Close-up photographs near scrapers of type (**a**) and type (**b**), respectively. Lb: solidification length of a base strip; Lo: solidification length of an overlay strip.

The scraper was supported by a pivot and rotated around the pivot, as shown in Figure 21c [28]. The scraper was pushed against the solidification layer on the lower roll by a constant load. In Figure 12, a dead weight was used for the scraper load. The scraper moved along the thickness of the solidification layer. The molten metal of the base strip did not leak between the scraper and the solidification layer. The scraper load was very small (0.2 N/mm), so the solidified alloy did not stick to the scraper. The scraper was made of a mild steel plate with a thickness of 3.2 mm. The plate was covered by a 2 mm-thick insulator sheet. Figure 21d,e are close-up photographs near the scraper of a vertical-type twin roll caster equipped with a scraper and an unequal-diameter twin roll caster equipped with a scraper, respectively.

3.2. Vertical-Type Twin Roll Caster Equipped with a Scraper

3.2.1. Al-Mg Alloy Clad Strip

Figure 22a shows a cross-section of a clad strip consisting of 3003 and 5182 aluminum alloys cast using the vertical-type twin roll caster equipped with a scraper. The roll speed was 30 m/min, the roll load was 88 N/mm, and the scraper load was 1 N/mm. The solidification lengths of the base and overlay strips were 50 mm and 100 mm, respectively. When a clad strip consisting of 3003 and 5182 alloys was cast using the vertical-type tandem twin roll caster, a gap existed at the interface between the 3003 alloy strip and 5182 alloy strip, as shown in Figure 13a. There was no gap at the interface between the 3003 alloy strip and the 5182 alloy strip for the strip cast using the vertical-type twin roll caster equipped with the scraper, as shown in Figure 22b [25]. The scribed surface of the 3003 alloy strip was semisolid with a high solid fraction, which was appropriate for bonding, and a gap did not occur at the interface between strips. The results of a bending-fracture test are shown in Figure 22c. The bending-fracture test was conducted as an easy test to estimate the bonding conditions at the interface. After the test, no cracks were observed at the interface. This shows that the 3003 alloy base strip and the 5182 alloy overlay strip were bonded strongly.

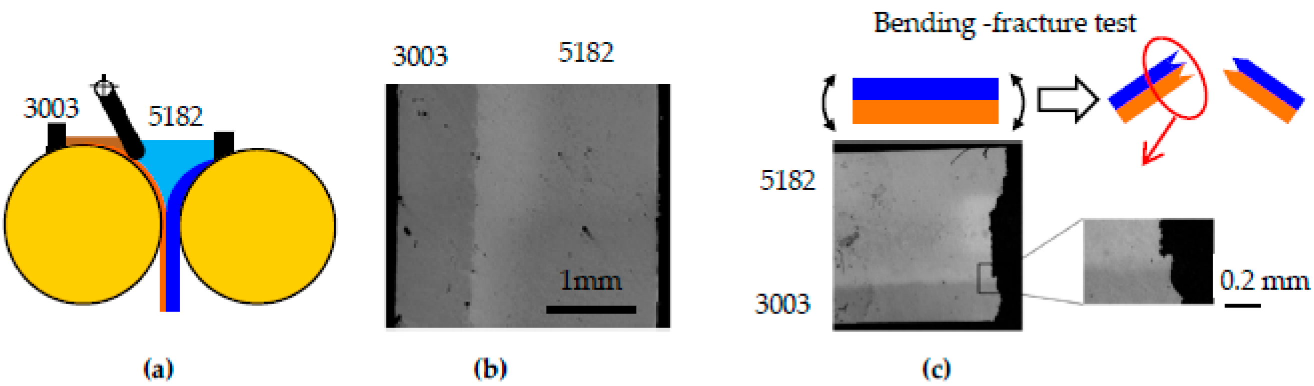

Figure 22. Cross-section of clad strip consisting of 3003 and 5182 aluminum alloys. (**a**) Schematic illustration showing the 3003 alloy as the base strip and the 5182 alloy as the overlay strip. (**b**) Cross-section of clad strip. (**c**) Result of bending-fracture test.

3.2.2. Hard and Brittle Composite Aluminum Alloy

A cross-sectional image of a clad strip consisting of a 1070 base strip and a particle dispersed composite of Al-30vol%SiC_p overlay strip, and the results of a line analysis for Si at the interface are shown in Figure 23a,b, respectively [26]. The scraper load was 80 N/mm, the roll load was 0.2 kN/mm, and the roll speed was 30 m/min. The solidification lengths of the base and overlay strips were 50 mm and 100 mm, respectively. Al-30vol%SiC_p is very hard and brittle. It is difficult to make clad strips of this alloy by hot rolling, because it breaks due to its low ductility. A clad strip consisting of 1070 and Al-30vol%SiC_p alloys could be cast using the vertical-type twin roll caster equipped with a scraper. This was possible since plastic deformation of the Al-30vol%SiC_p strip did not occur, because of the small roll load. The 1070 base strip and the Al-30vol%SiC_p overlay strip were bonded without breakage of the Al-30vol%SiC_p strip and without a gap at the interface, as shown in Figure 23a. Si is an element of the Al-Si base aluminum alloy of the Al-30vol%SiC_p composite. Figure 23b, which presents the results of a line analysis of Si at the interface, shows that the Si did not diffuse into the 1070 alloy from the Al-30vol%SiC_p. This means that the semisolid layer on the scribed surface of the 1070 base strip was very thin and its solid fraction was very high.

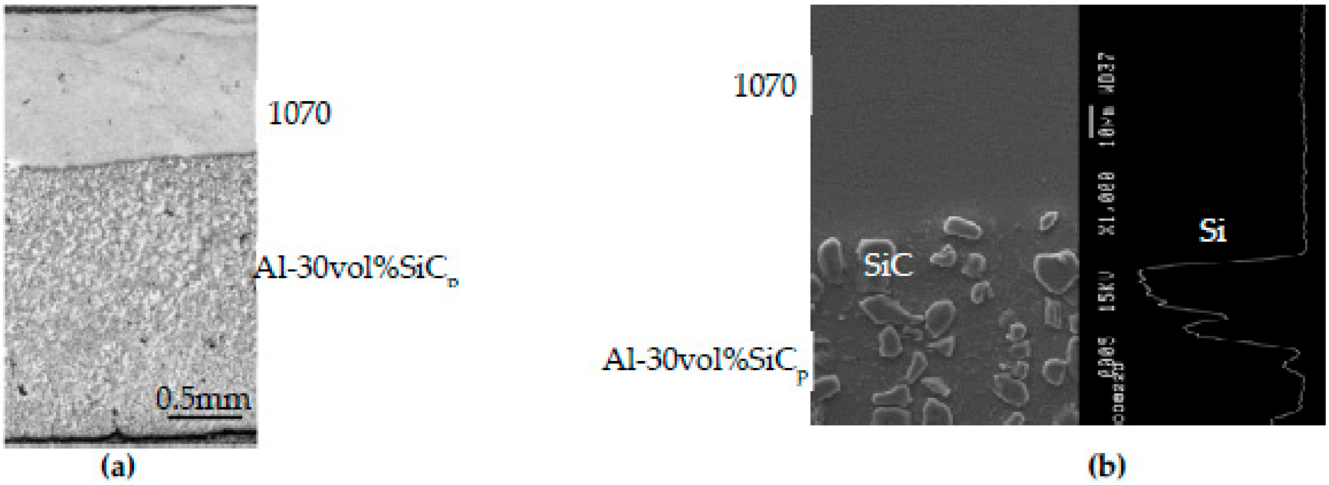

Figure 23. Cross-section of clad strip consisting of a 1070 base strip and an Al-30vol%SiC$_p$ overlay strip, and the result of a line analysis of Si at the interface between strips. (**a**) Cross-section of clad strip. (**b**) Line analysis of Si.

3.3. Unequal-Diameter Twin Roll Caster Equipped with a Scraper

3.3.1. Magnesium Alloy Clad Strip

Casting of clad strips consisting of magnesium alloys was tried using an unequal-diameter twin roll caster equipped with a scraper [27]. Casting was conducted in an oxidizing atmosphere. The upper and lower roll diameters were 300 mm and 1000 mm, respectively, and the roll and scraper loads were 50 N/mm and 0.5 N/mm, respectively. The roll speed was 30 m/min, and the solidification lengths of the base and overlay strips were 100 mm and 60 mm, respectively. The cross-section of a strip consisting of an AM60 alloy base strip and Mg-12%Al-1%Zn alloy overlay and the results of a bending-fracture test are shown in Figure 24. The unequal-diameter twin roll caster equipped with a scraper and the positions of the molten metals of the AM60 alloy base strip and Mg-12%Al-1%Zn alloy overlay strip are shown in Figure 24a. The interface between the AM60 alloy base strip and Mg-12%Al-1%Zn alloy overlay strip was clear, and a gap did not exist at the interface, as shown in Figure 24b. No cracks occurred at the interface in the bending-fracture test, as shown in Figure 24c. The results of the bending-fracture test showed that the magnesium strips were strongly bonded. Magnesium is easily oxidized in an oxidizing atmosphere; however, the bonding surfaces of the strips were not exposed to the oxidizing atmosphere when the clad strip was cast using the twin roll caster equipped with a scraper, and the strips were strongly bonded.

Hot rolling of a clad strip consisting of an AM60 alloy strip and Mg-12%Al-1%Zn alloy strip was conducted by the cold-roll method (room temperature). The clad strip was heated, while the rolls were not heated. The clad strip was not peeled off at the interface by the hot rolling. The surfaces of the clad strip after hot rolling are shown in Figure 25. No cracks occurred at the surfaces without edges.

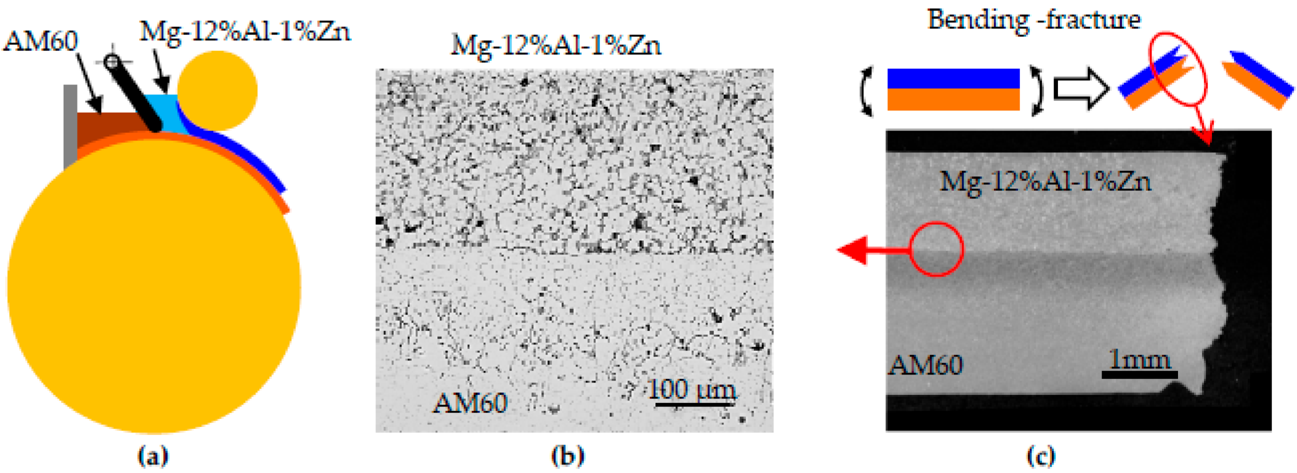

Figure 24. Cross-section of clad strip consisting of AM60 base strip and Mg-12%Al-1%Zn overlay strip cast using an unequal-diameter twin roll caster equipped with a scraper, and result of the bending-fracture test. (**a**) Unequal-diameter twin roll caster equipped with a scraper used to cast the clad strip. (**b**) Interface between the AM60 base strip and the Mg-12%Al-1%Zn overlay strip. (**c**) Cross-section of fracture area after the bending-fracture test.

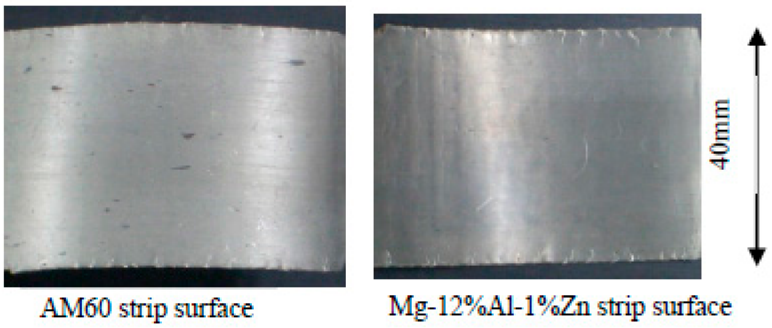

Figure 25. Surfaces of hot-rolled clad strip consisting of an AM60 strip and a Mg-12%Al-1%Zn strip.

3.3.2. Aluminum Alloy with Wide Solidification Temperature

Casting of a clad strip for which the overlay strip had a wide solidification temperature range was attempted [28]. The base strip was 1050 and the overlay strip was Al-40%Sn-1%Cu alloy. The Al-40%Sn-1%Cu alloy is used as a sliding bearing; for example, in the engines of large ships. The solidification temperatures and pouring temperatures for 1050 and Al-40%Sn-1%Cu alloy are shown in Table 3. The solidification temperature range for Al-40%Sn-1%Cu alloy is very wide, at 382 °C. The liquidus line for Al-40%Sn-1%Cu alloy is lower than the solidus line for 1050. The clad strip was cast using the unequal-diameter twin roll caster equipped with a scraper, as shown in Figure 26a. The upper and lower roll diameters were 300 mm and 1000 mm, respectively; The roll load was 50 N/mm, the scraper load was 0.1 N/mm, and the roll speed was 15 m/min. The solidification lengths for the base and overlay strips were 190 mm and 120 mm, respectively. The molten metal of the Al-40%Sn-1%Cu alloy was poured after the 1050 base strip went through the roll gap. The forward part of the strip was a single strip of 1050 base strip, as shown in Figure 26b. The poured Al-40%Sn-1%Cu became a strip, and this overlay strip was immediately bonded to the 1050 base strip. The length of unsteady state Al-40%Sn-1%Cu alloy was less than 100 mm. After cladding started, the clad strip casting was steady, as shown in Figure 26c.

Table 3. Solidus lines, liquidus lines, and pouring temperatures of 1050 and Al-40%Sn-1%Cu.

Alloy	Solidus Line (°C)	Liquidus Line (°C)	Pouring Temperature (°C)
1050	646	657	700
Al-40%Sn-1%Cu	228	610	640

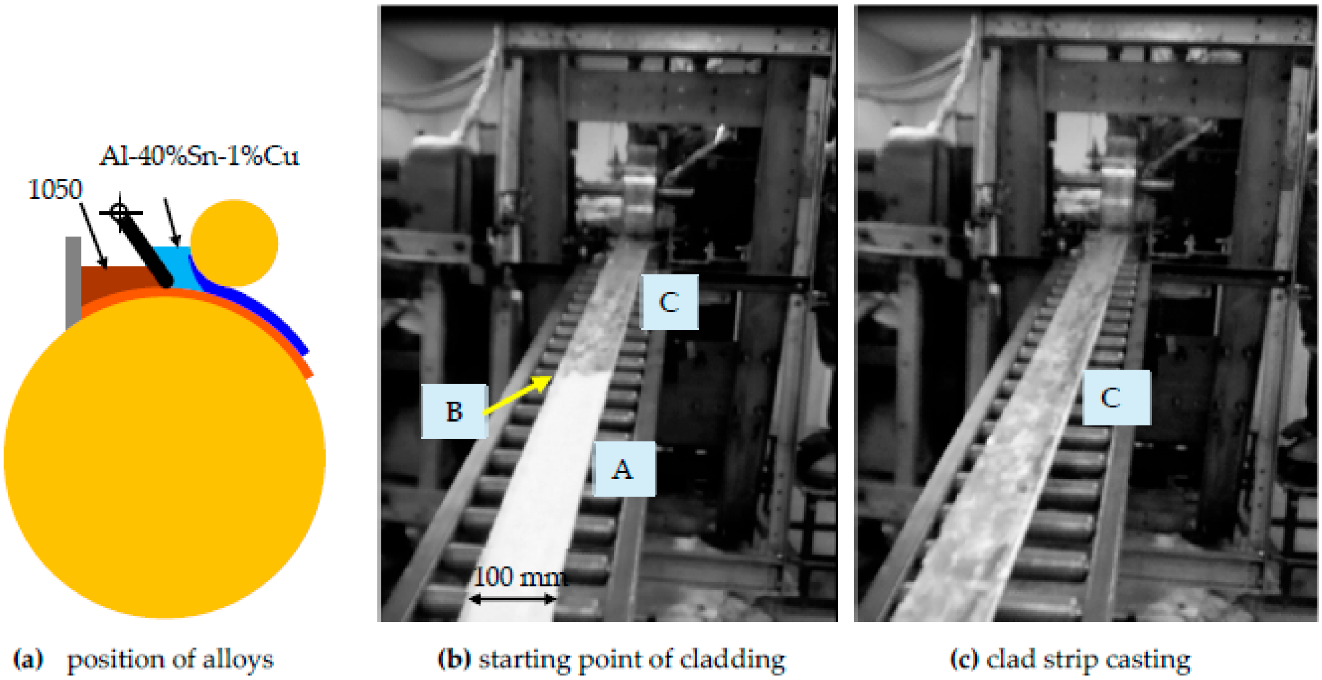

Figure 26. Casting of clad strip consisting of 1050 and Al-40%Sn-1%Cu. (**a**) Position of alloys, (**b**) starting point of cladding, (**c**) clad strip casting. A: 1050 base strip only, B: starting point of cladding, C: clad strip of 1050 and Al-40%Sn-1%Cu.

The temperature of the Al-40%Sn-1%Cu alloy overlay strip of the clad strip was about 550 °C when it released from the upper roll. It took more than 5 min for the temperature of the Al-40%Sn-1%Cu alloy overlay strip to become lower than the solidus line of 228 °C, so that the Al-40%Sn-1%Cu overlay strip was in a semisolid condition for more than 5 min. Figure 27 shows the results of a line analysis for Sn at the interface between the 1050 base strip and the Al-40%Sn-1%Cu alloy overlay strip. Sn, which was an element of the Al-40%Sn-1%Cu alloy overlay strip, did not diffuse into the 1050 base strip. The scribed surface of the 1050 base strip was semisolid with a high solid fraction when the molten metal of the Al-40%Sn-1%Cu alloy started contacting the 1050 base strip, and the Al-40%Sn-1%Cu alloy overlay strip was semisolid for more than 5 min. In spite of these conditions, diffusion of Sn did not occur.

The broken tensile-shear test piece after testing is shown in Figure 28. The break position was not at the interface, but within the Al-40%Sn-1%Cu alloy overlay strip. This shows that the bonding force at the interface was stronger than the Al-40%Sn-1%Cu alloy overlay strip, and that the strips were bonded strongly. It was considered that shrinkage of the Al-40%Sn-1%Cu alloy overlay strip must have occurred after bonding, because the Al-40%Sn-1%Cu alloy was in a semisolid condition for more than 5 min after bonding. The bonding force was stronger than the shear stress created by the shrinkage of the Al-40%Sn-1%Cu alloy overlay strip.

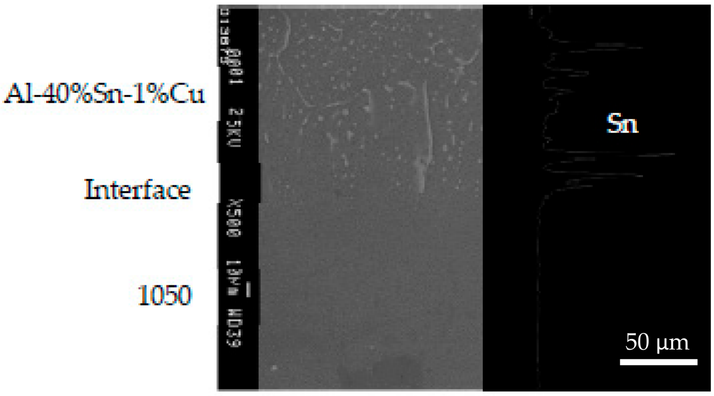

Figure 27. Result of the line analysis of Sn at the interface between the 1050 base strip and the Al-40%Sn-1%Cu overlay strip.

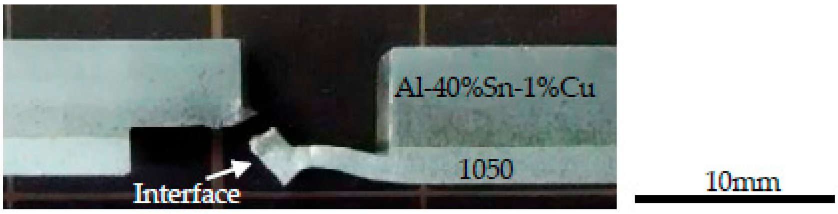

Figure 28. Test piece of tensile-shear test after test.

3.3.3. Wide Clad Strip

The influence of the width of the clad strip on bonding was investigated [29]. Casting of a 400 mm-wide clad strip consisting of a 1070 base strip and an Al-40%Sn-1%Cu alloy overlay strip was tried using the unequal-diameter twin roll caster equipped with a scraper. The diameters of the upper and lower rolls were 300 mm and 1000 mm, respectively, and the roll width was 400 mm. The roll load was 50 N/mm and the scraper load was 0.4 N/mm. The roll speed was 10 m/min, and the solidification lengths of the base and overlay strips were 250 mm and 50 mm, respectively. The as-cast clad strip, surface of 1070 base strip, and the surface of the Al-40%Sn-1%Cu alloy overlay strip are shown in Figure 29a–c, respectively. The 400 mm-wide clad strip could be cast, and the surface conditions of the base and overlay strips were uniform. Figure 29d shows a cross-section of the fully bent as-cast clad strip. It is clear that the base strip did not peel from the overlay strip. The strips were strongly bonded for the 400 mm-wide clad strip. These results show that a wide clad strip could be cast by the unequal-diameter twin roll caster equipped with a scraper.

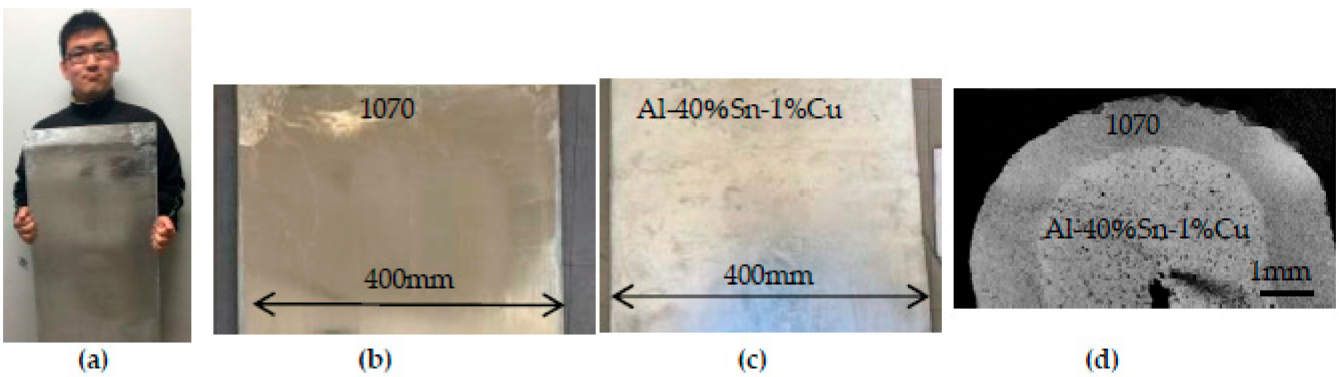

Figure 29. 400 mm clad strip consisting of a 1070 base strip and an Al-40%Sn-1%Cu overlay strip. (**a**) As-cast strip, (**b**) surface of the 1070 base strip, (**c**) surface of the Al-40%Sn-1%Cu overlay strip, (**d**) cross-section of the full-bent clad strip.

4. Conclusions

Two types of twin roll casters that could cast a clad strip from molten metals in an oxidizing atmosphere with a small roll load were designed. One was a vertical-type tandem twin roll caster, and the other was a twin roll caster equipped with a scraper. Features common to both the twin roll casters for clad strips were a higher casting speed and a smaller roll load than conventional twin roll casters for aluminum alloy. Bonding between the strips was strong enough that the clad strip was not peeled by cold rolling or during the bending-fracture test. Aluminum alloys were not mixed at the interface between the strips, and the interface was clear.

4.1. Vertical-Type Tandem Twin Roll Caster

(1) In the vertical-type tandem twin roll caster, when the solidification temperature for the base strip was higher than that for the overlay strip, and the latent heat of the overlay strip was large enough to heat the surface of the base strip, bonding of the strips easily occurred. When the latent heat of the overlay strip was not large enough to heat the surface of the base strip, the overlay strip did not bond to the base strip.
(2) The roll speed, pouring temperature of the molten metal of the overlay strip, and the roll load did not affect the bonding of the strips, or the extent of the effects was very small.
(3) Under the condition that the solidification temperature for the overlay strip is higher than that of the base strip, the overlay strip must be bonded to the base strip one side at a time to prevent the re-melting of the base strip.
(4) It was estimated that the oxide film on the base strip was very thin and weak when the overlay strip came in contact.
(5) Assuming that bonding occurred between the liquidus line and solidus line for the base-strip-contacting surface of the overlay strip, the bonding time was shorter than 0.1 s.

4.2. Twin Roll Caster Equipped with a Scraper

The scraper could be attached to the vertical-type twin roll caster and an unequal-diameter twin roll caster.

(1) The twin roll caster equipped with a scraper could bond an aluminum alloy whose latent heat was small; for example, an Al-Mg alloy, to other aluminum alloys that could not be bonded using the vertical-type tandem twin roll caster.
(2) The twin roll caster equipped with a scraper enabled cladding of easily oxidized alloys such as magnesium alloy in an oxidizing atmosphere, as the bonding surfaces did not come in contact with the oxidizing atmosphere.
(3) A clad strip for which the overlay strip had a wide solidification temperature range; for example, about 400 °C, could be cast using the twin roll caster equipped with a scraper.

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