

Article

Casting of Al-1%Si Strip Using Single-Roll Caster Equipped with Scraper

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Abstract

The high-speed, low-load twin-roll casting of Al-Si alloys with a Si content of approximately 1 at% is needed to prevent the occurrence of cracks. In twin-roll casting, however, the roll load reaches the lower limit required for the sufficient solidification of the aluminum alloy. In this study, a single-roll caster equipped with a scraper was used to cast strips without cracks. The semi-solid forming of the free-solidified surface of an Al-1%Si strip during casting using a single-roll caster was attempted with a scraper under a very small load at a high roll speed of 30 m/min. The effects of the scraper angle and the scraper load on the condition of the scraped surface were investigated. The roll-contact surface and scraped surface of the strips cast under the appropriate conditions were compared by bending and deep drawing tests. After cold-rolling and annealing, no differences were observed between the roll-contact surface and the scraped surface. A sound Al-1%Si strip without cracks can be cast using a single-roll caster equipped with a scraper at a speed of 30 m/min.

Keywords: single-roll caster; semi-solid; free solidified surface; scraper; center segregation; surface crack

1. Introduction

The roll speed of a conventional twin-roll caster for an aluminum alloy (CTRCA) is usually lower than 2 m/min [1–7]. A vertical-type high-speed twin-roll caster (VHSTRC) [8] and an unequal-diameter twin-roll caster (UDTRC) [9] can cast aluminum alloy strips at speeds higher than 20 m/min. The VHSTRC and UDTRC therefore have an advantage in roll speed over the CTRCA. When an aluminum alloy strip with a Si content of about 1–2% is cast using the VHSTRC or UDTRC, a band zone is clearly observed in the cross section of the as-cast strip [10,11]. When the roll load is not appropriate, alligator cracks occur at the edge of the band zone [12]. When bending or deep drawing is conducted on a cold-rolled and annealed strip with a Si content of about 1–2% cast using the VHSTRC or UDTRC, surface cracks oriented in the rolling direction occur. The alligator cracks and surface cracks tend to become more severe as the roll load increases [12]. Additionally, the roll load of a twin-roll caster has a lower limit of 5 N/mm. If the roll load is lower than this limit, the strip does not solidify sufficiently, the strip breaks, and continuous casting cannot be achieved. Therefore, it is not easy to cast strips without cracks using the VHSTRC or UDTRC. The band zone does not exist in strips cast using a single-roll caster (SRC), because the solidification of the strip proceeds from the roll-contact side to the free-solidified surface. No roll load is applied. Therefore, alligator cracks and surface cracks do not occur in strips cast using the SRC. However, the SRC has a disadvantage: the



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thickness distribution in the width direction of strips cast using the SRC is less uniform than that of strips cast using a twin-roll caster (TRC) [13]. In the TRC, the cooling of the strip increases at the roll bite because the roll load improves the contact condition and heat transfer between the strip and the rolls. The cooling of strips cast using the SRC is insufficient because the strip is not pushed against the roll, and heat transfer between the strip and the roll of the SRC may be lower than that of the TRC. The contact length between the strip and the roll of the SRC is longer than that of the TRC. However, strips cast using the SRC cannot be cooled as sufficiently as strips cast using the TRC. A scraper was developed and mounted on the SRC in order to flatten the semi-solid layer that exists on the free-solidified surface and to improve the contact condition between the strip and the roll. A single-roll caster equipped with a scraper (SRCS) was used in this study. The scraper load was much smaller than the roll load of the VHSTRC and UDTRC. Therefore, the SRCS is thought to be suitable for reducing alligator cracks and surface cracks. Al-1%Si was used because alligator cracks and surface cracks are pronounced in this alloy. Al-1%Si has a quasi-solidification line [14], and its viscosity in the semi-solid state may be higher than that of alloys without a quasi-solidification line, such as Al-7%Si. This may be one of the causes of alligator cracks and surface cracks in Al-1%Si. It was not clear whether the scraper was effective for flattening the free-solidified surface. First, the effects of the scraper angle and the scraper load on the condition of the scraped surface, especially its flatness, were investigated. The difference between the roll-contact surface and the scraped surface was investigated by bending and deep drawing tests. The microstructure of the cross section was observed by optical microscopy to confirm that the band zone did not exist. Mechanical properties were investigated by tensile testing. This study evaluated the usefulness of the SRCS for reducing alligator cracks and surface cracks.

2. Experimental Conditions

Schematic diagrams of the SRCS (Osaka Institute of Technology, Osaka city 535-8585, Japan) and the region near the scraper tip, together with a photograph showing the scraper, back dam plate, side dam plate, launder, and roll, are shown in Figure 1. A copper roll was used for rapid solidification and high-speed roll casting. The diameter and width of the roll were 1000 mm and 100 mm, respectively. The parting material was not used on the roll surface, because the strip did not adhere to the roll in the SRCS. The reason for the non-sticking of the strip is considered as follows. The roll surface temperature did not reach the temperature at which the aluminum alloy and copper react, and the small scraper load did not cause the sticking of the strip. The roll speed of the SRCS was 30 m/min. The roll of the CTRCA is usually made of hot-work tool steel to withstand a heavy roll load, and a parting material is used to prevent the adhesion of the strip to the roll. The thermal conductivity of copper is higher than that of steel. The parting material introduces thermal resistance between the molten aluminum alloy and the roll surface. Using a copper roll and omitting the parting material are effective for increasing the heat transfer between Al-1%Si and the roll, thus allowing the roll speed to be increased. The roll speed of the CTRCA is usually lower than 2 m/min, but the roll speed of the SRCS was much higher than that of the CTRCA. Molten metal was poured from the crucible through the launder onto the roll, which was rotating at the designated roll speed. The molten metal pool was formed on the roll by the side dam plates, the back dam plate, and the scraper, as shown in Figure 1a. The solidification length, which is the distance from the back dam plate to the scraper, was 200 mm. A schematic diagram of the region near the scraper is shown in Figure 1b. The scraper was made of 2.3 mm thick mild steel and covered with a 2 mm thick insulating sheet. The scraper could rotate around the pivot. The side dam plates and back dam plate were also made from a mild steel plate and covered with an

insulating sheet. The scraper, side dam plates, and back dam plate were not preheated. Boron nitride was sprayed as a parting material on the scraper, side dam plates, and back dam plate. The effects of the scraper angle and the scraper load on the scraped surface were investigated. The scraper angle, which is the angle between the scraper and the roll surface, is shown in Figure 1b. The scraper angles were 30°, 60°, and 90°. The initial gap between the scraper and the roll was 1 mm. The scraper load was adjusted using a dead weight and was measured at the scraper tip. The scraper load ranged from 0.05 N/mm to 1.25 N/mm. The appropriate scraper angle and scraper load were investigated. The roll loads of the VHSTRC and UDTRC ranged from 10 N/mm to 0.5 kN/mm. The roll load of the CTRCA was from 4 kN/mm to 20 kN/mm [15–18]. The roll loads of the VHSTRC and UDTRC were smaller than that of the CTRCA. The scraper load of the SRCS was much smaller than the roll load of the VHSTRC and UDTRC. A highly rigid scraper was therefore not necessary, and the load on the roll was considered to be very small.

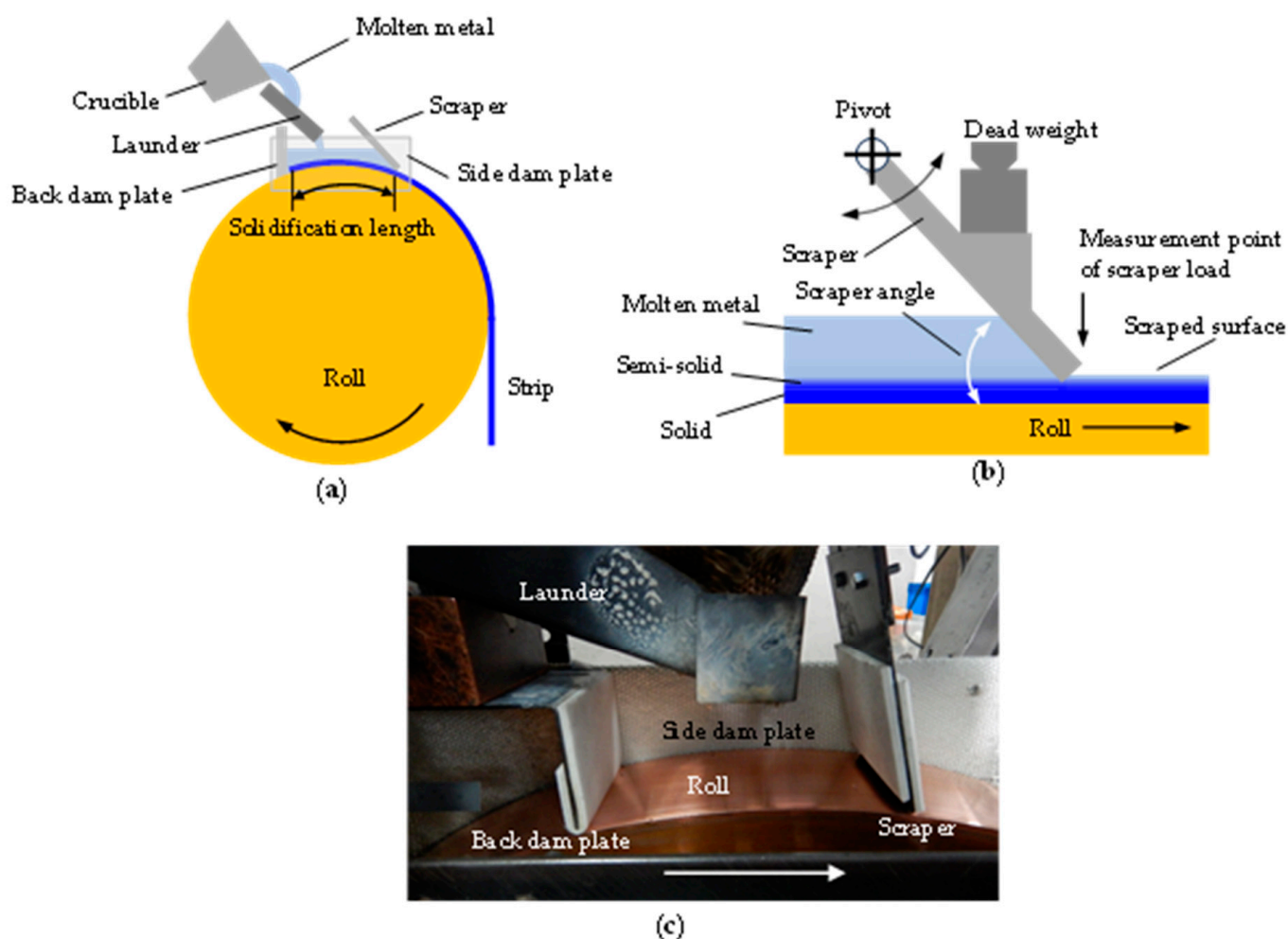


Figure 1. Schematic diagram of the single-roll caster equipped with a scraper. (a) Overview of the single-roll caster equipped with a scraper. (b) Region near the scraper. (c) Photograph showing the scraper, back dam plate, side dam plate, launder and roll.

Al-1%Si was used in this study. The temperature of the molten metal in the crucible at the time of pouring was 670 °C. When the Al-1%Si strip was cast using the VHSTRC or UDTRC, cracks tended to occur easily. This study investigated whether the SRCS could cast Al-1%Si strips without cracks. Optical microscopy (ECLIPSE LV150N, Nikon, Shinagawa-ku, Tokyo, Japan) was conducted to investigate the occurrence of the band zone and alligator cracks. Penetrant testing was conducted on the roll-contact surface and the

scraped surface of the cast strip to investigate the occurrence of surface cracks caused by the use of the scraper. Bending and deep drawing tests were conducted on cold-rolled and annealed strips to investigate crack occurrence. Annealing was conducted at 400 °C for 1 h. The bending angle was 180°. In the deep drawing test, the punch diameter was 32 mm, and the blank holder force was 1.5 kN. Tensile testing was performed on cold-rolled and annealed 1 mm thick plate in both the casting and lateral directions using a universal testing machine (AG-I/100 kN, Shimadzu, Nakagyo-ku, Kyoto, Japan). The gauge length, width, and thickness of the tensile test pieces were 25 mm, 12.5 mm, and 1 mm, respectively. Five test pieces were tested in each direction.

3. Results

The casting of the strip using the SRCS and the tip of the as-cast strip are shown in Figure 2. Figure 2a shows the strip being drawn between the roll and the scraper. The strip could be cast continuously. The tips of the cast strip, which correspond to the start of strip casting, are shown in Figure 2b–d. Figure 2c is an enlarged view of Figure 2b. When pouring started, there was not enough molten metal to reach the back dam plate. Therefore, the roll-contact surface was in an unsteady state and was not flat, as shown in Figure 2d. The length of the unsteady state of the roll-contact surface was about 200 mm. The roll-contact surface reached a steady state after this unsteady state. The scraped surface was not uniform in the width direction where the roll-contact surface was in the unsteady state, as shown in Figure 2b. Even after the roll-contact surface had reached a steady state, as shown in Figure 2d, the scraped surface was still in an unsteady state. A non-scraped area and scratch marks were present, as shown in Figure 2d. The length of the unsteady state of the scraped surface was about 600 mm.

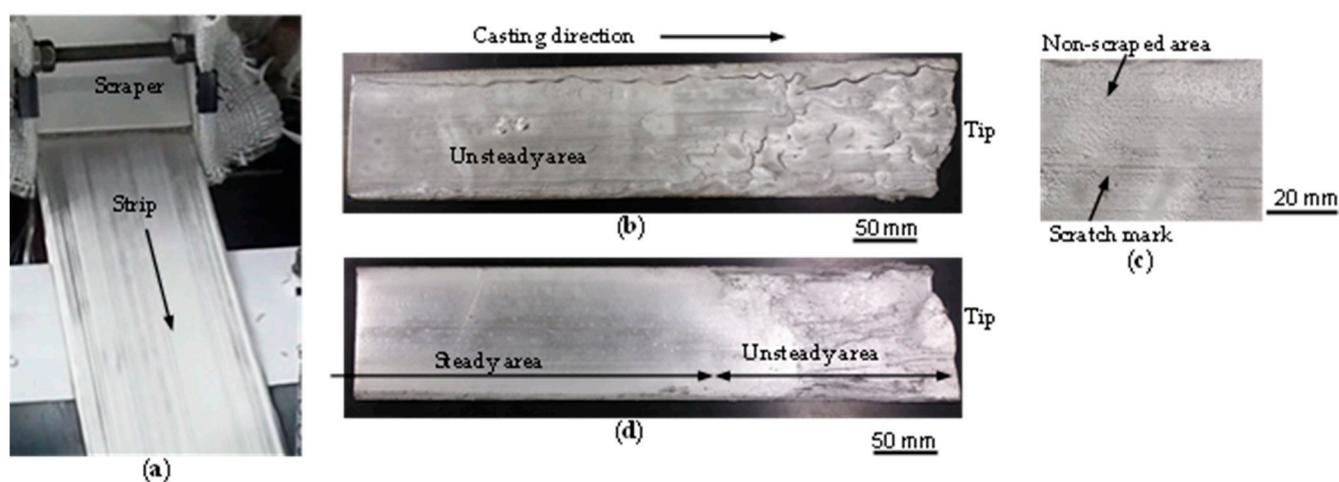


Figure 2. Casting of a strip using the SRCS and the tip of the cast strip. (a) Casting in operation. (b) Scraped surface near the tip of the as-cast strip. (c) Enlarged view of (b). (d) Roll-contact surface near the tip of the as-cast strip.

The effects of the scraper angle and the scraper load on the scraped surface were investigated, and the results are shown in Figure 3. Figure 4 shows the typical scraped surfaces for scraper angles of 30°, 60°, and 90°. The conditions of the scraped surface in Figure 3 are shown in Figure 4. In Figures 3 and 4, the white circles show a sound condition, the black circles show the leakage of molten metal from the scraper tip, and the red circles show bulge occurrence. The surface conditions were classified as sound, leakage, or bulging by visual inspection. The scraped surface was considered sound when neither molten-metal leakage nor the bulging of semi-solid metal occurred. The scraper load at which molten metal leakage occurred increased as the scraper angle decreased.

Bulging occurred only when the scraper angle was 90° and the scraper load was larger than 0.14 N/mm . Figure 3 shows that, as the scraper load increased, the scraped surface changed from a condition with molten-metal leakage to a sound condition and then to a condition with bulging. At insufficient scraper loads, molten metal leaked through the gap formed between the solidified layer and the scraper when the scraper was pushed upward.

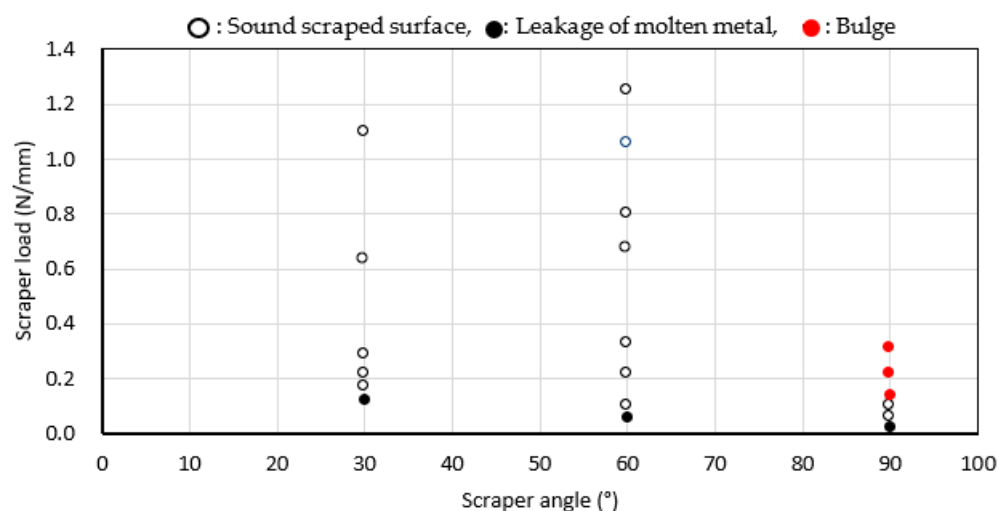


Figure 3. Classification of scraped surfaces. The conditions for Figures 2 and 3 are the same.

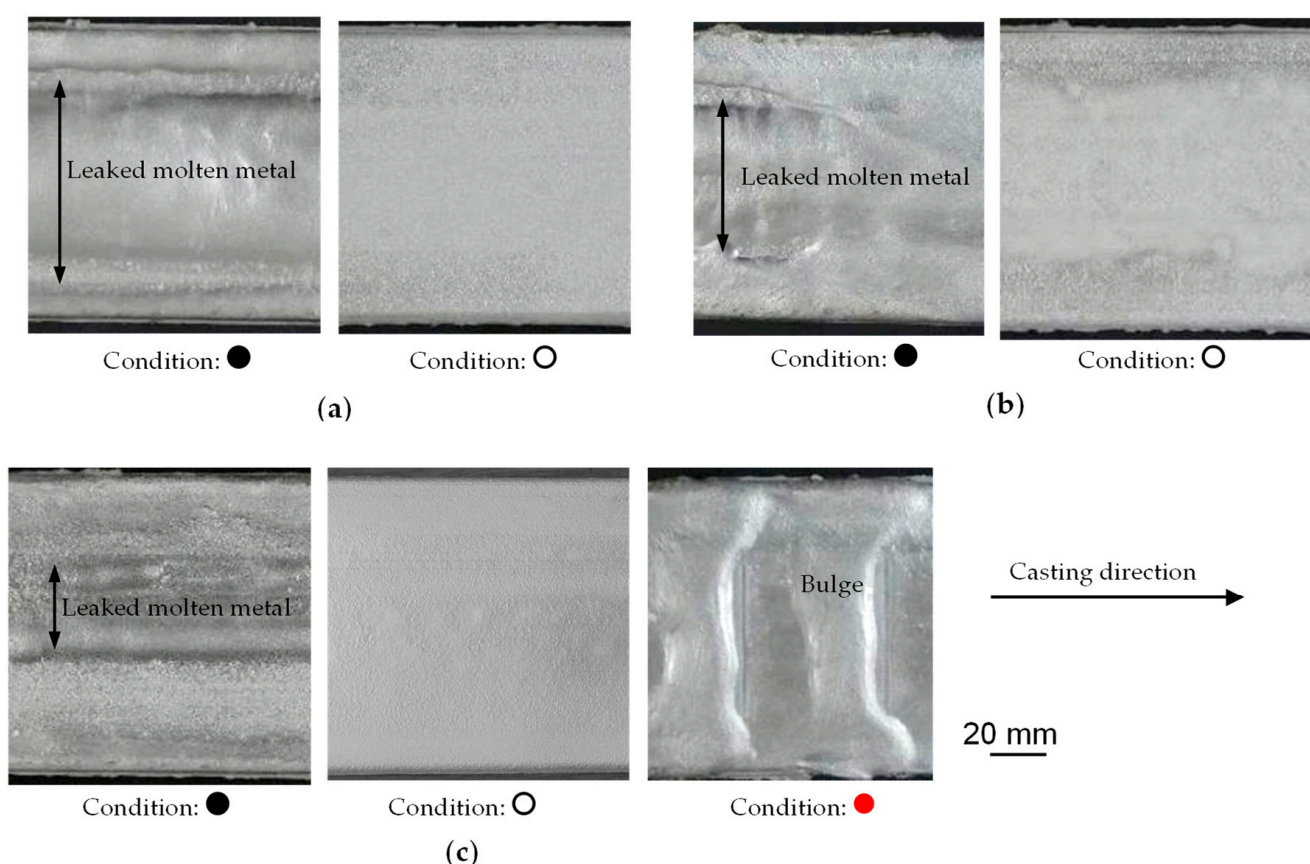


Figure 4. Classification of scraped surfaces. The scraper angles of (a–c) are 30° , 60° and 90° . The conditions for Figures 2 and 4 are the same. Red circle: Sound scraped surface, White circle: Leakage of molten metal, Black circle: Bulge.

The effect of the scraper angle on bulge occurrence was investigated. The scraper load was set at 0.31 N/mm. This scraper load was sufficiently large to cause bulging when the scraper angle was 90°, as judged from Figure 3. The scraped surfaces for each scraper angle are shown in Figure 5. The largest bulges occurred at a scraper angle of 80°. An appropriate scraper load can maintain a balance between the outflow of semi-solid metal under the scraper and the accumulation of semi-solid metal behind the scraper.

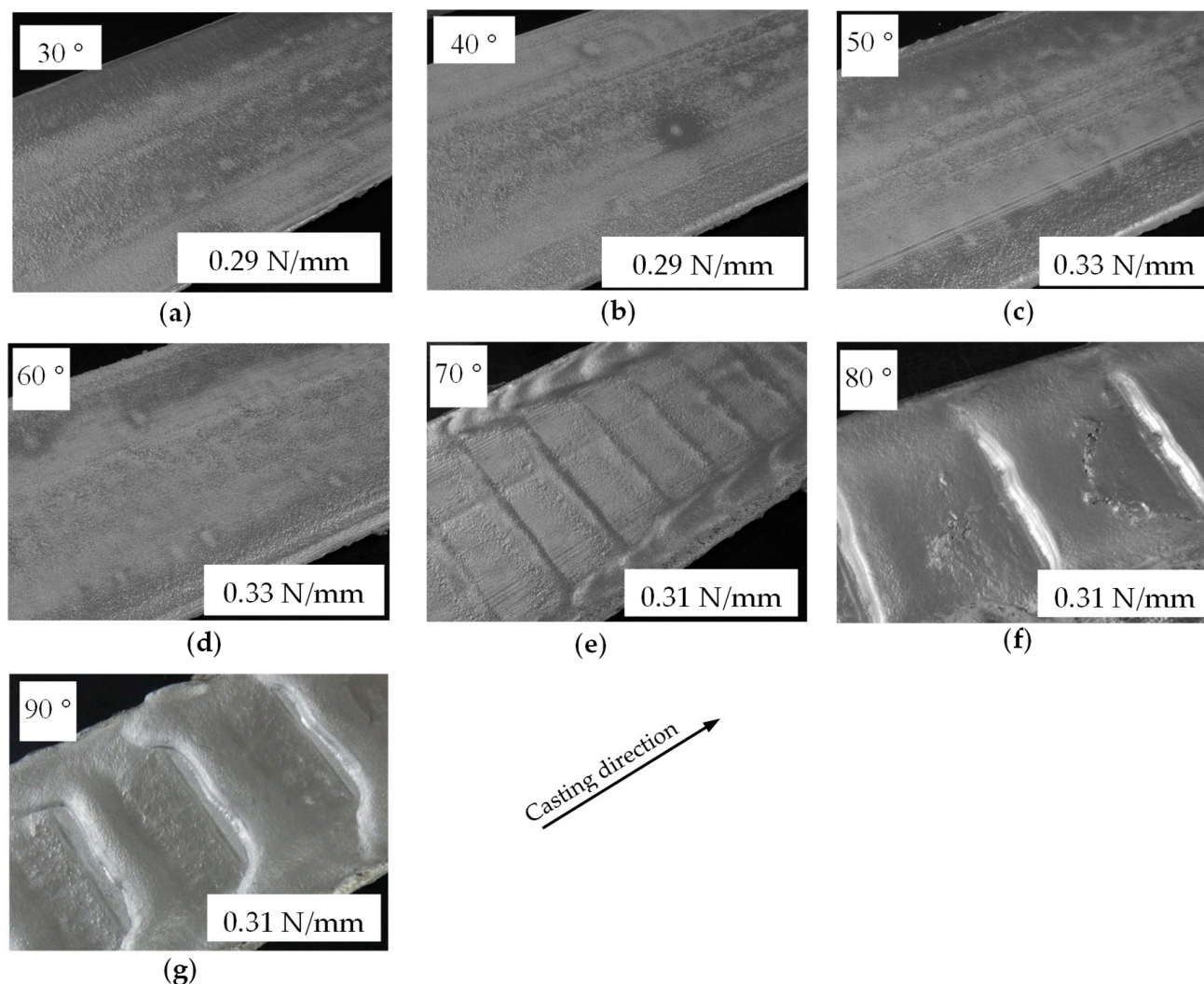


Figure 5. Effect of the scraper angle on the occurrence of bulges. Scraper angle: (a) 30°, (b) 40°, (c) 50°, (d) 60°, (e) 70°, (f) 80°, and (g) 90°. Scraper load: (a,b), 0.29 N/mm; (c,d), 0.33 N/mm; and (e–g) 0.31 N/mm.

Figure 6 shows the thickness distribution of the bulges in the casting direction. The measurement was conducted at the center in the width direction. The scraper angles were 70°, 80°, and 90°, and the scraper load was 0.31 N/mm. The volume and length of the bulge increased in the order of 70°, 90°, and 80°. The heights of the bulges at scraper angles of 80° and 90° were remarkably higher than that at a scraper angle of 70°. The highest point of the bulge was at the front of the bulge when the scraper angle was 70°, and it was at the back of the bulge when the scraper angles were 80° or 90°. Both the scraper angle and the scraper load are thought to influence the bulge shape. It is not clear why the bulge was largest when the scraper angle was 80°.

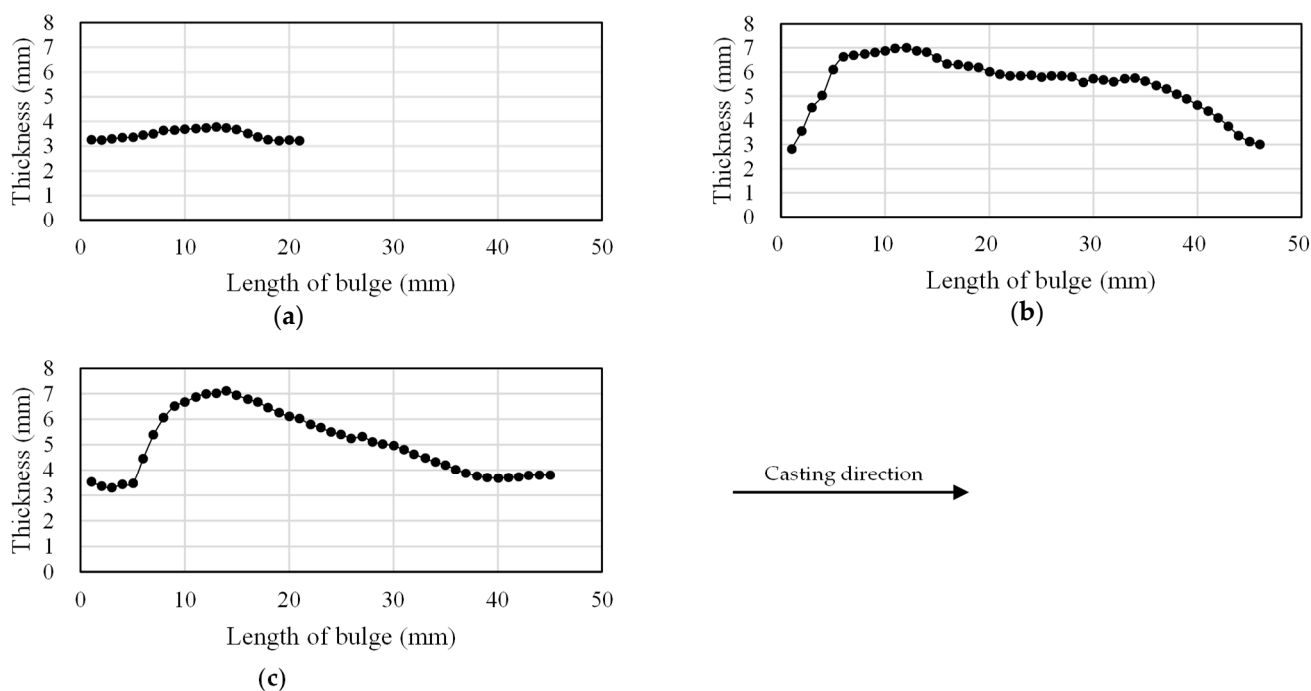


Figure 6. Effect of scraper angle on bulge shape. Scraper angle: (a) 70°, (b) 80°, (c) 90°. Scraper load was 0.31 N/mm.

The outflow of semi-solid metal below the scraper may become more difficult as the scraper angle increases. When the scraper angle was greater than 70°, the balance between the semi-solid metal flowing under the scraper and that accumulating behind it may not be maintained. The amount of accumulated semi-solid metal increased as the scraper angle increased to 80°, resulting in a larger bulge. For a given amount of accumulated metal, the contact area between the scraper and the bulge decreased as the scraper angle increased. The bulge grew until the upward force against the scraper was sufficient to lift it. When the scraper angle was 90°, however, the bulge was smaller than that at 80°. This may show that the mechanism of bulge formation at 90° may be different from that at scraper angles of 80° or less.

When the scraper angle is 90°, the outflow of semi-solid metal may be easily stopped because the scraper is perpendicular to the flow direction of the semi-solid metal, causing the metal to accumulate behind the scraper. As the solid fraction of the accumulated semi-solid metal increases, the accumulated metal eventually moves with the strip (solidified layer) once it reaches a certain solid fraction. In this case, the accumulated metal may push the scraper outward rather than upward. The period from the start of accumulation to the passage of the bulge under the scraper at a scraper angle of 90° was shorter than that at 80°, and the length of the bulge at 90° was also shorter than that at 80°.

The growth of the bulge when the scraper angle was greater than 60° is shown in Figure 7b. Only a thin semi-solid layer existed on the scraped surface because most of the semi-solid metal was scraped. The scraper was gradually pushed upward as the amount of accumulated metal increased. When the accumulated metal reached a certain size, it passed under the scraper and became a bulge.

The thickness distributions in the width direction at scraper angles of 30°, 60°, and 90° are shown in Figure 8. All strips had sound surfaces, as shown in Figure 4. There was no particular trend in the thickness distribution with the scraper angle. The edges were thinner than the inside. This might be due to sliding between the solidified layer and the side dam plates. The thickness at the center in the width direction was also slightly thinner. The cause of this is not clear.

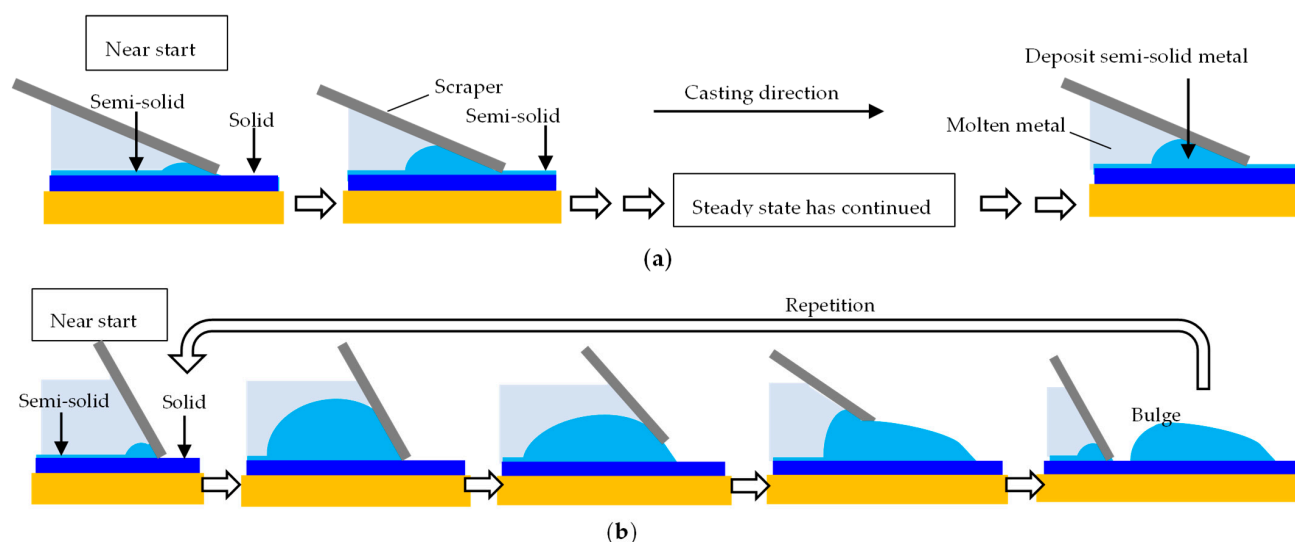


Figure 7. Schematic diagram showing the effect of the slope angle on the deposition of semi-solid metal under the scraper. (a) The scraper angle is smaller than 60° . (b) The scraper angle is greater than 60° , and a bulge occurs.

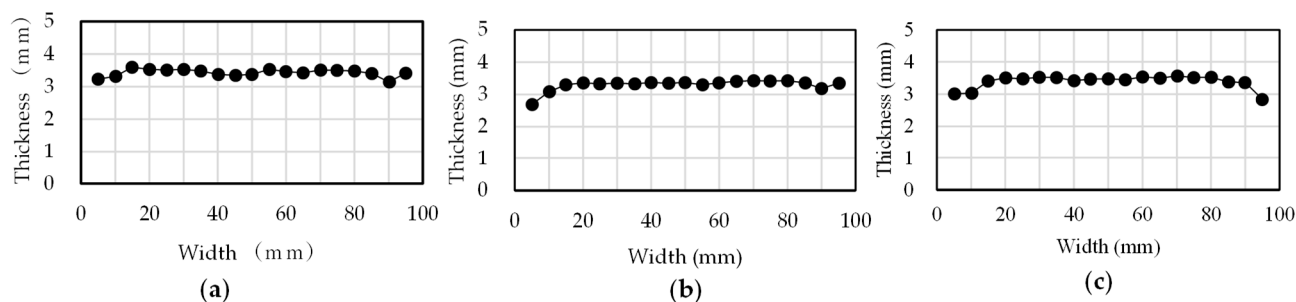


Figure 8. Thickness distribution in the width direction of the as-cast strip. (a) Scraper angle: 30° , scraper load: 1.10 N/mm. (b) Scraper angle: 60° , scraper load: 1.09 N/mm. (c) Scraper angle: 90° , scraper load: 0.10 N/mm.

The effects of the scraper angle and the scraper load on the average thickness of the strips with sound surfaces are shown in Figure 9. It appears that the scraper load and scraper angle did not influence the strip thickness when the surface condition was sound. The strip thickness may consist of the thicknesses of the solidified layer and the semi-solid layer. The thickness of the solidified layer may be constant because the roll speed and solidification length were the same. The thickness of the semi-solid layer after scraping was thinner than that of the solidified layer, and the strip thickness may therefore not have been significantly influenced by the scraper load or scraper angle.

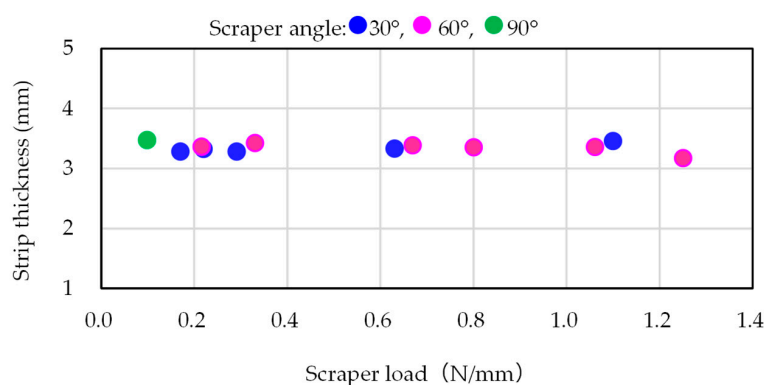


Figure 9. Effect of scraper angle and scraper load on average strip thickness.

When the scraper angle was 60° or less, the range of scraper loads that produced a sound scraped surface was wide. The effect of the scraper load on the thickness distribution in the width direction at a scraper angle of 60° was investigated, and the result is shown in Figure 10. There was a tendency for the thickness in the center area to be thinner than that on both sides. This tendency was remarkable when the scraper load was smaller than 0.33 N/mm . This might be due to the scraping of the semi-solid layer. When the scraper load was greater than 0.67 N/mm , the thickness distribution was not remarkably influenced by the scraper load.

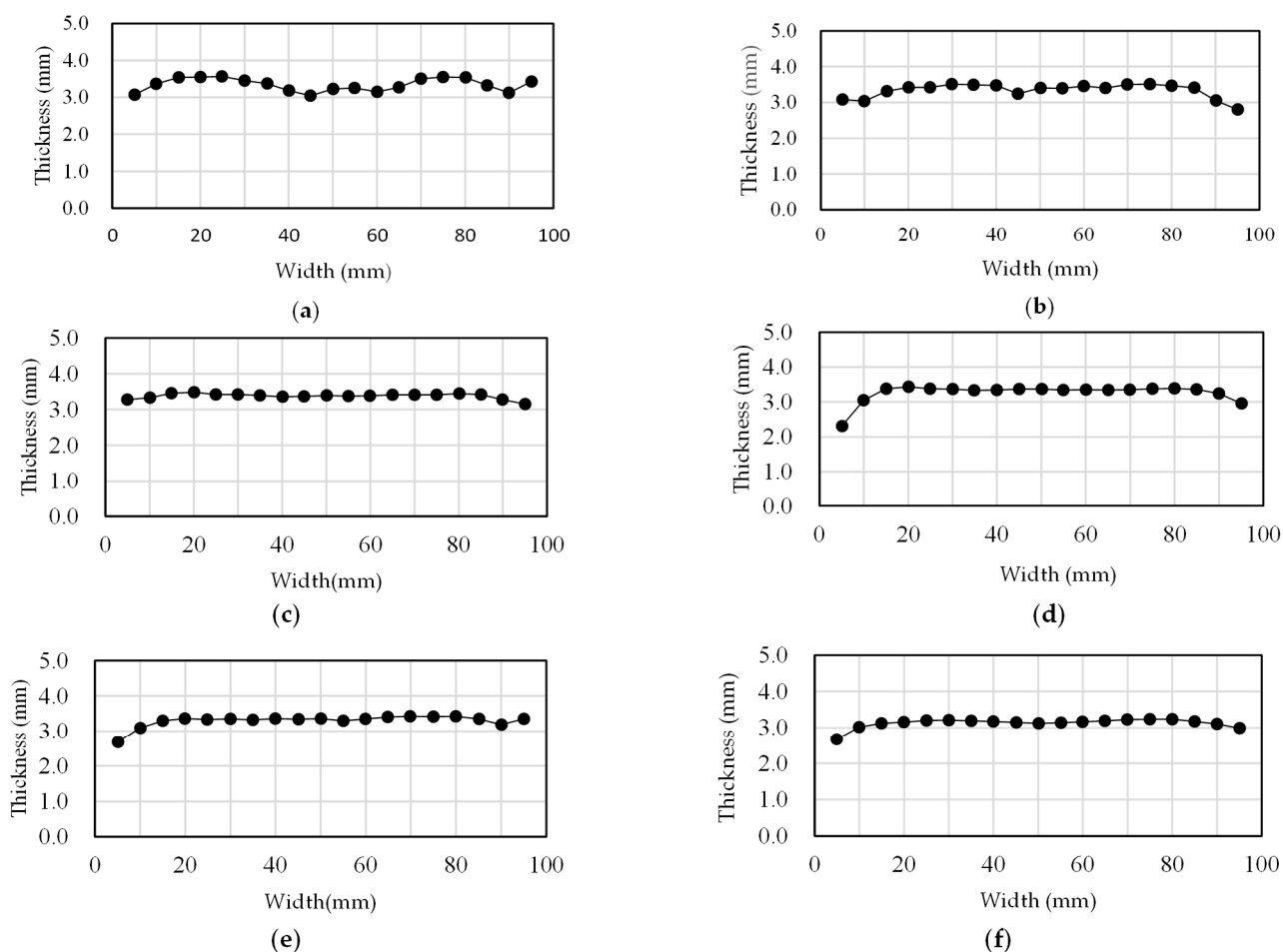


Figure 10. Effect of scraper load on thickness distribution in the width direction when the scraper angle was 60° . Scraper loads; (a) 0.22 N/mm , (b) 0.33 N/mm , (c) 0.67 N/mm , (d) 0.80 N/mm , (e) 1.06 N/mm , (f) 1.25 N/mm .

The molten metal was poured onto the center of the roll width, and the molten-metal flow was about 40 mm wide. The poured molten metal spread toward both sides in the width direction. The temperature of the molten metal in the central region of the roll width might have been higher than that in the regions on either side. This might explain why the strip was thinner in the center than on both sides. The strip was also thinner at most edges. The edge of the solidified layer rubbed against the side dam plate. This might have worsened the contact condition between the solidified layer and the roll and reduced heat transfer, resulting in a thinner edge. Alternatively, the semi-solid metal with a low solid fraction might have been abraded by the side dam plate. In Figure 10a,e, one edge of the strip was raised. This might have resulted from molten metal flowing into the gap between the scraper and the side dam plate.

The existence of cracks in the strips cast using the SRCS was investigated by penetrant testing, and the result is shown in Figure 11. Cracks were observed on the surface of the strips cast using the VHSTRC. No cracks were observed on either the scraped surface or the roll-contact surface of the strips cast at scraper angles of 30°, 60°, and 90°. Scraping the semi-solid layer did not cause cracks. The scraper load of the SRCS was smaller than the roll load of the VHSTRC, and this may be why no cracks occurred on the surface of the strips cast using the SRCS.

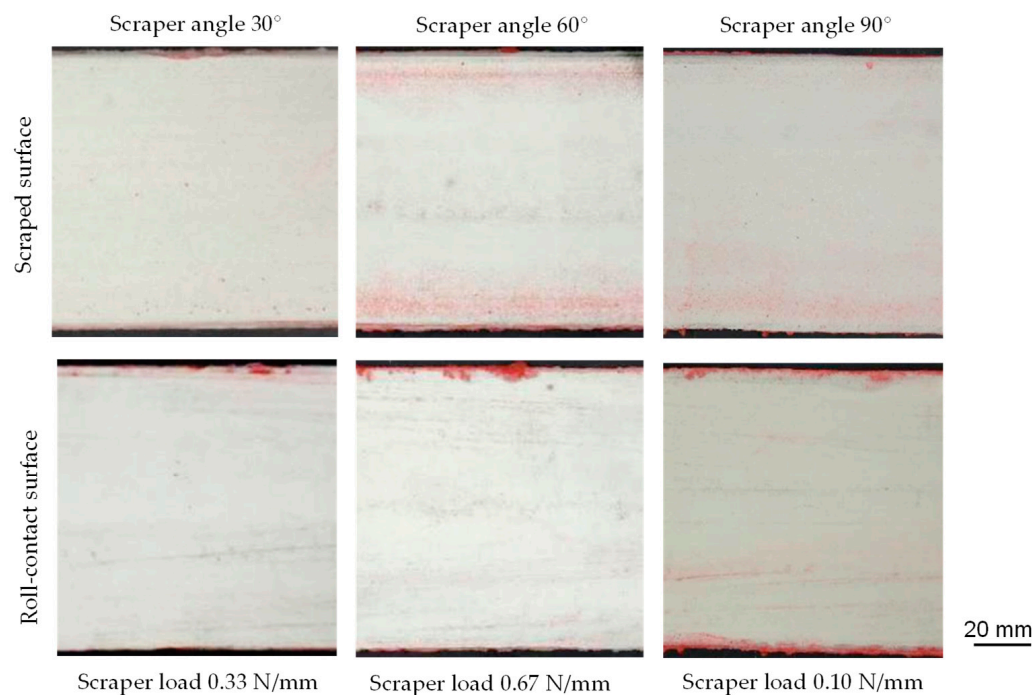


Figure 11. Results of penetrant testing of as-cast strips cast using SRCS.

Cross sections of the as-cast strips produced using the SRCS are shown in Figure 12a. The cast strip was cold-rolled down to 1 mm and annealed at 400 °C for 1 h, and the cross section of this plate is also shown in Figure 12b. Segregation in the strips cast using the VHSTRC and UDTRC occurred in the band zone. The band zone did not exist in the strips cast using the SRCS, as shown in Figure 12a. The cause is as follows. In the VHSTRC and UDTRC, the strip solidifies from both roll sides, and the band zone, which is a semi-solid area, is formed between the solidification fronts. In other words, the band zone is a semi-solid layer between the solidified layers. In the SRCS, the strip is solidified from one roll side toward the free-solidified surface, and only one solidification layer exists. Therefore, the band zone does not occur in the SRCS. A scraper-affected zone existed at the scraped surface and had a finer appearance than the other areas. The semi-solid metal may have been mechanically crushed. The grain size was not uniform in the thickness direction, and it increased from the roll-contact surface toward the scraped surface as the cooling rate decreased. The microstructure in Figure 12b was almost uniform in the thickness direction. There was little difference in the microstructure between the roll-contact surface and the scraped surface.

The strip that was cast at a scraper load of 1.06 N/mm and a scraper angle of 60° was cold-rolled down to 1 mm. The surfaces are shown in Figure 13. There was no remarkable difference between the roll-contact surface and the scraped surface. The difference between the roll-contact surface and the scraped surface could be reduced by cold-rolling.

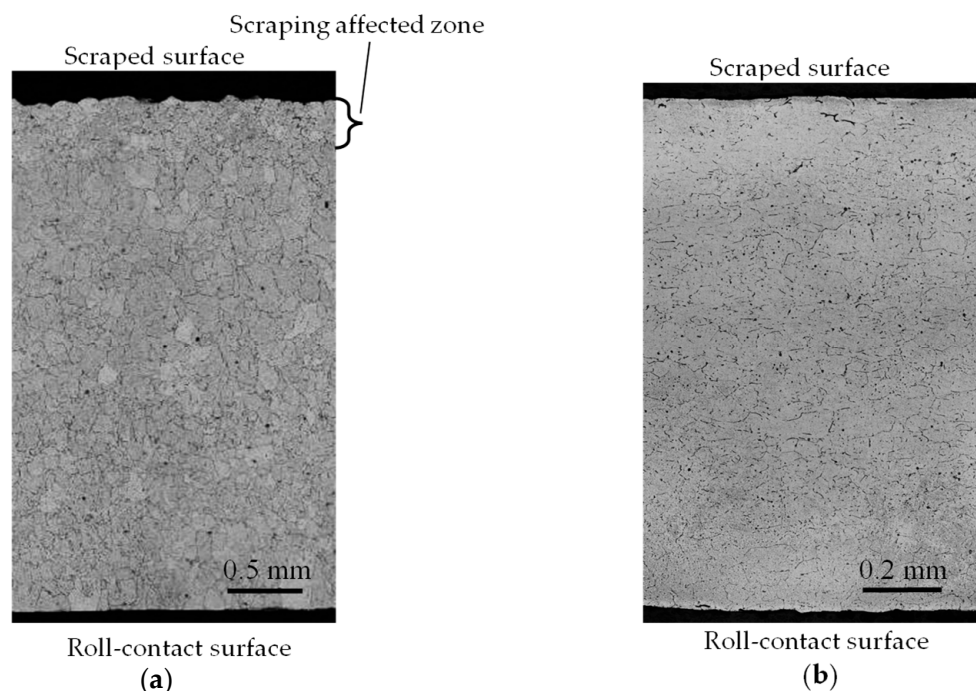


Figure 12. Cross sections of strips and plate. (a) As-cast strip cast using SRCS. (b) Strip after cold-rolling down to 1 mm and annealing at 400 °C for 1 h.

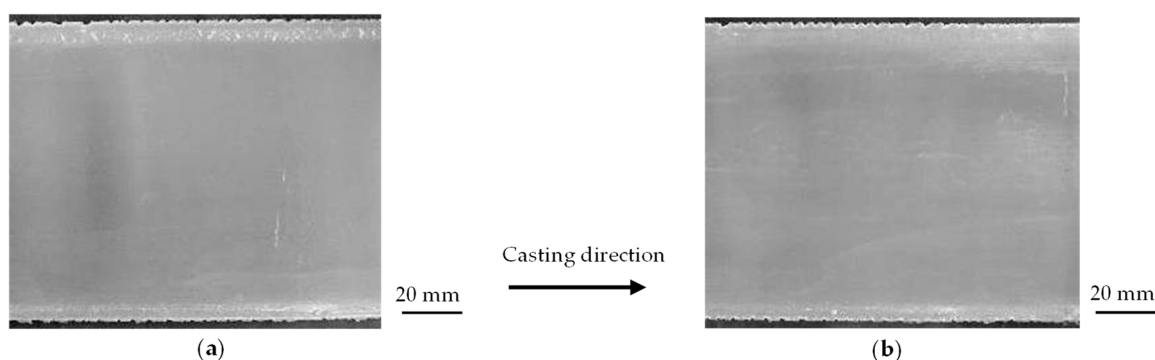


Figure 13. Surfaces of strip after cold-rolling down to 1 mm. Strip was cast at a scraper load of 1.06 N/mm and a scraper angle of 60°. (a) Roll-contact surface, (b) scraped surface.

A 180° bending test was conducted to investigate the difference in ductility between the scraped surface and the roll-contact surface. The cast strip was cold-rolled down to 1 mm and annealed at 400 °C for 1 h, and this plate was then bent in a direction perpendicular to either the width direction or the casting direction. The results of the bending test are shown in Figure 14. When the plate made from a strip cast using the VHSTRC was bent, cracks parallel to the casting direction occurred [12]. These cracks became more severe as the roll load increased. One cause of crack occurrence is thought to be the roll load. Cracks parallel to the casting direction did not occur on either the scraped surface or the roll-contact surface. No other types of cracks occurred on either the scraped surface or the roll-contact surface, as shown in Figure 14. It became apparent that there was no difference in crack occurrence between the scraped surface and the roll-contact surface during bending.

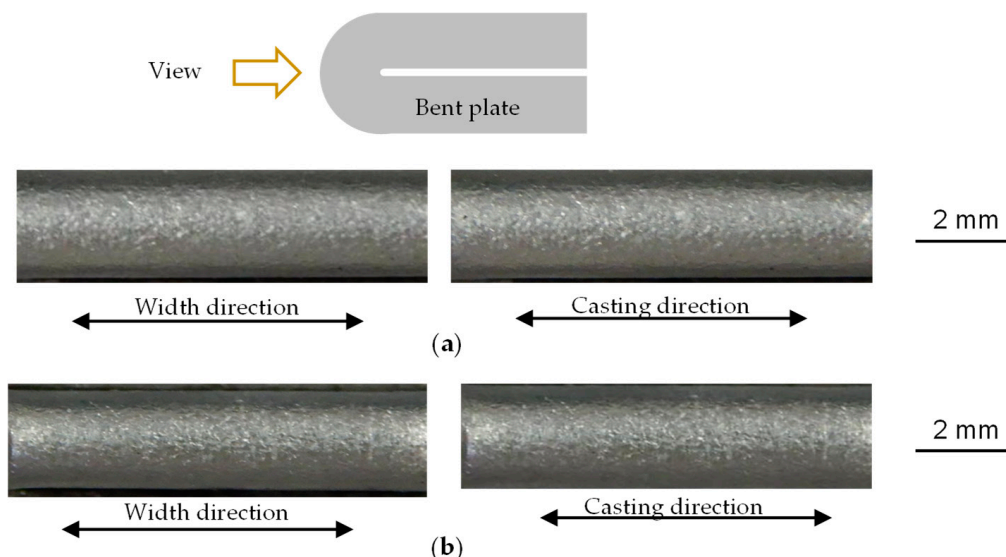


Figure 14. Outer surfaces of bent plate. Cast strip was cold-rolled down to 1 mm and was annealed at 400 °C for 1 h. (a) Scraped surface of strip cast using SRCS. (b) Roll-contact surface of strip cast using SRCS.

The result of the deep drawing of the strips cast using the SRCS is shown in Figure 15. The cast strip was cold-rolled down to 1 mm and annealed at 400 °C for 1 h. In the strips cast using the VHSTRC, cracks occurred at the corner of the cup [12]. The cracks were oriented in the casting direction. The cause of these cracks might be the same as that in bending. In Figure 15, cracks did not occur under either condition: when the scraped surface was on the outer side or when the roll-contact surface was on the outer side. The limiting drawing ratio (LDR) was 2.0. According to the results shown in Figures 12–15, there was no remarkable difference between the scraped surface and the roll-contact surface when the cast strip was cold-rolled and annealed. The very small scraper load may have helped prevent crack formation.

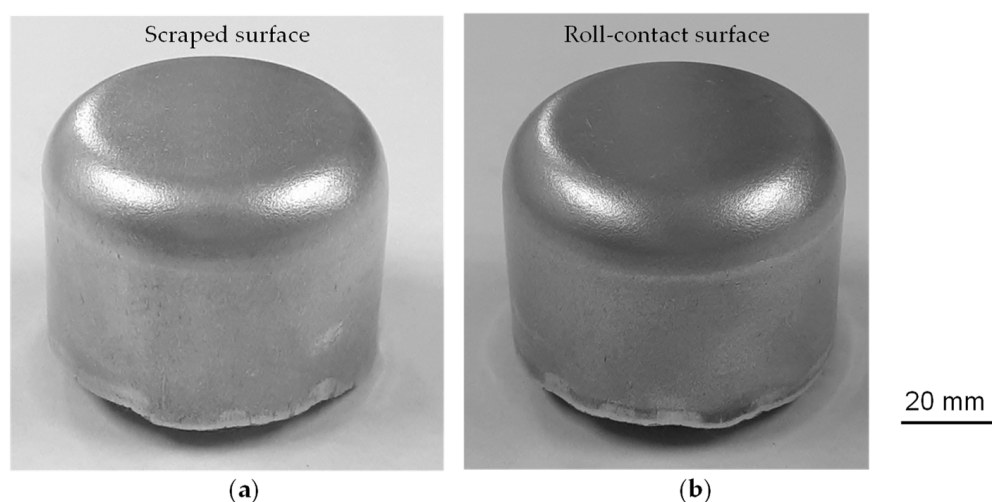


Figure 15. Result of deep drawing test. The punch diameter was 32 mm. The cast strip was cold-rolled down to 1 mm and annealed at 400 °C for 1 h, and used for deep drawing. (a) The scraped surface is the outer surface, LDR: 2.0. (b) The roll-contact surface is the outer surface, LDR: 2.0.

The results of tensile testing are shown in Figure 16. The tensile strength and proof stress in the casting direction were greater than those in the width direction. In contrast, the elongation in the width direction was greater than that in the casting direction. The reasons for these differences are not clear.

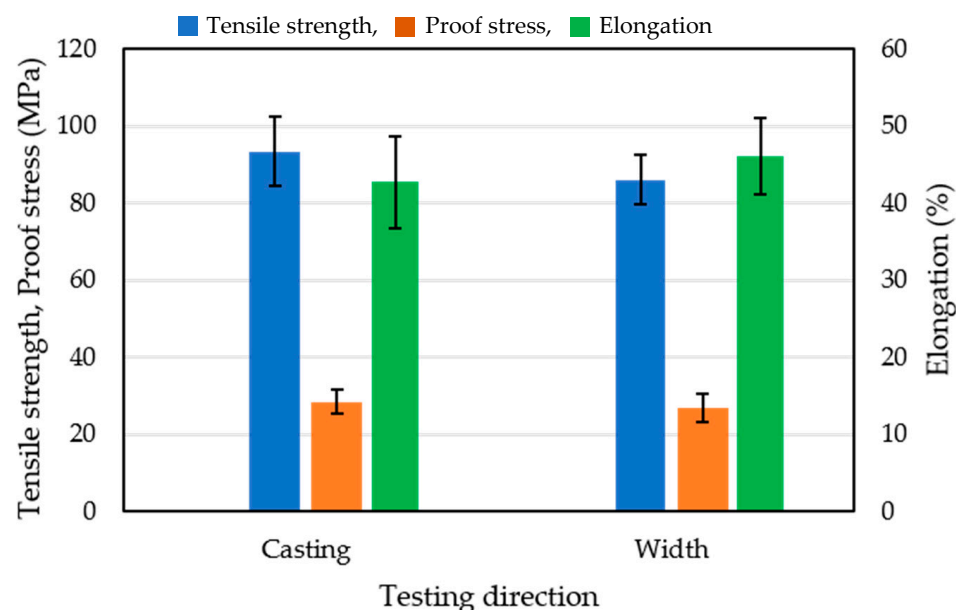


Figure 16. Result of tensile testing. The cast strip was cold-rolled down to 1 mm and annealed at 400 °C for 1 h, and used for tensile testing. Test piece; gage length: 25 mm, width: 10 mm, thickness: 1 mm.

The tensile strengths in the casting and width directions were 93.3 MPa and 86.0 MPa, respectively. The difference was 7.3 MPa. This value was within the experimental scatter of the tensile strength in the casting direction, but outside the experimental scatter of the tensile strength in the width direction. The proof stresses in the casting and width directions were 28.4 MPa and 26.8 MPa, respectively. The difference was 1.6 MPa, which was within the experimental scatter of the proof stresses in both directions. The elongations in the casting and width directions were 42.7% and 46.1%, respectively. The difference was 3.4%, which was within the experimental scatter of the elongation in both directions. These results show that the differences in the mechanical properties between the casting and width directions were small. The results shown in Figures 15 and 16 indicate that the strips cast using the SRCS had sufficient mechanical properties for conventional use.

4. Conclusions

Alligator cracks and surface cracks are characteristic cracks in strips cast using the vertical-type high-speed twin-roll caster and the unequal-diameter twin-roll caster. Surface cracks occur after 180° bending and deep drawing. In Al-Si alloys with a Si content of 1–2%, these cracks become more severe. The use of a single-roll caster equipped with a scraper was attempted to eliminate alligator cracks and surface cracks in Al-1%Si alloys.

(1) Al-1%Si strips could be cast continuously at a speed of 30 m/min using the single-roll caster equipped with a scraper.

(2) The scraped surface was different from the roll-contact surface in the as-cast strip. The scraped surface became almost the same as the roll-contact surface after cold-rolling.

(3) When the scraper angle was larger than 70°, a bulge formed on the scraped surface.

(4) The scraped surface was sound when neither molten-metal leakage nor the bulging of semi-solid metal occurred. At scraper angles from 30° to 60°, scraper loads from 0.2 N/mm to 1.1 N/mm produced a sound scraped surface.

(5) The microstructure of the cast strip was not uniform in the thickness direction, and the band zone did not exist. The microstructure became almost uniform in the thickness direction after cold-rolling and annealing.

(6) In 180° bending, cracks did not occur when either the scraped surface or the roll-contact surface was the outer surface.

(7) In deep drawing, when either the scraped surface or the roll-contact surface was the outer surface, cracks did not occur. The limiting drawing ratio reached 2.0.

(8) Tensile testing was conducted on cold-rolled and annealed strips. The mechanical properties in the casting direction and width direction were almost the same. Scraping did not cause the anisotropy of the mechanical properties of the cast strips.

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