Effect of casting and rolling process parameters on solidification welding line of magnesium alloy

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Abstract: Process of horizontal twin roll casting magnesium alloy was analyzed by numerical simulation. Taking solidification welding line in cast rolling area as research object, the characteristic change of solidification welding line caused by casting rolling temperature, casting rolling speed and roll heat transfer capacity and its influence on the forming process of casting rolling area were analyzed. The results show that increasing casting temperature, casting speed or reducing heat transfer capacity of roll can make solidification welding line shift to exit of casting rolling zone. Increasing casting temperature and casting speed will increase difference between middle and edge of the solidification welding line along casting direction. And heat distribution of whole slab is more uniform. However, effect of improving heat transfer capacity of roll is completely opposite. According to this, optimum process parameters of casting and rolling magnesium alloy with plate thickness of 6 mm are put forward to reduce probability of edge crack.

Keywords: magnesium alloy; horizontal twin roll casting; solidification welding line; edge damage;
1. Introduction

Magnesium alloys are widely used in lightweight engineering because of their excellent properties\cite{1,2}. However, due to its poor temperature sensitivity and low-temperature plasticity, repeated reheating and multi-pass reciprocating rolling are required in blooming rolling process, and serious edge cracks are very easy to appear\cite{3,4,5}, as shown in Figure 1, which is more prominent in large reduction rolling. Compared with traditional blooming rolling, twin roll casting rolling technology combines casting and rolling into one, realizing short process production\cite{6,7}. Although double roll casting technology can save temperature and greatly reduce rolling pass, yield is greatly improved and production cost is effectively controlled. However, it is still impossible to eliminate edge cracks completely. Therefore, it is of great significance for development of magnesium alloy sheet and strip to explore a reliable and effective production process to restrain edge crack of magnesium alloy casting and rolling.

![Figure 1 Defects in magnesium alloy cast-rolled strip](image)

In recent research, many scholars have paid great attention to the effect of casting rolling magnesium alloy solidification process and plate quality. P. Jong-Jin \cite{8} analyzed the casting and rolling process of AA3003 alloy by means of numerical simulation, and found that the melt flow in the casting and rolling area showed inhomogeneous characteristics, while the melt contact with the roll surface showed irregular characteristics, and finally the scholar proposed to regulate by optimizing some process parameters. Zhang, JP \cite{9} proposed a prediction model for the casting and rolling force during the casting and rolling process based on the two-roll casting and rolling model. After verification by numerical simulation, it was found that there was an obvious mapping relationship between the solidification weld point and the casting and rolling force.

However, influence of rolling forming stage in casting rolling process on plate quality can not be ignored, and position of solidification welding line has a decisive impact on rolling forming process\cite{10,11}. Solidification welding line (kiss line) is comprehensive embodiment of key process parameters of cast rolling, and has chain effect with solidification structure and forming defects of slab. From the perspective of metal plastic forming, change of solidification welding line position will affect rolling process from two dimensions, including rolling deformation and temperature distribution in solid phase zone. In this study, horizontal twin roll casting method is
selected for numerical study. Melt, paste and solid are assumed to be incompressible nonlinear thermo-viscous materials. At the same time, influence of asymmetry caused by gravity is considered. Firstly, influence of casting and rolling process parameters on the position of solidification welding joint in casting and rolling area is analyzed, and then the key influencing factors of magnesium alloy casting rolling edge crack are explored based on influence of casting and rolling process parameters on position of solidification welding line and temperature distribution.

2. Numerical Analysis

2.1 Solidification prediction model

According to the group’s preliminary research on the heat balance and rotational speed of casting and rolling, a prediction model for the position of the solidification welding point of the two-roll casting and the rolling process was derived. Based on the expression of heat derived from the solidification of billet shell in the casting and rolling process (Eq. 1-1), the expression of latent heat flow (Eq. 1-2), and the expression of the geometric relationship between solidification and welding point (Eq. 1-3). Through the internal thermal equilibrium conditions in the casting and rolling process as well as the geometric boundary conditions, a prediction model for the location of the solidification point within the casting and rolling zone can finally be derived (Eq. 1-4). Through the prediction model, it can be learned that as the casting and rolling speed and the process parameters are determined, the location of the solidification welding point will also be determined.

\[
\Phi_1 = \frac{\lambda_m(T_1-T_2)}{\delta} \quad (1-1)
\]

\[
\Phi_2 = L_f \rho_m \frac{d\delta}{dt} \quad (1-2)
\]

\[
L_0 = \sqrt{(\delta_0 + R)^2 - (R + \frac{d}{2})^2} \quad (1-3)
\]

\[
\nu = \frac{2\pi R^2 \arcsin \left(\frac{\delta}{R}\right)}{2R^2 + \pi R \delta - 4R^2 \sqrt{R^2 + \delta^2}} \quad (1-4)
\]

where: 
\(\lambda_m\)—thermal conductivity of the billet shell; 
\(T_1\)—Liquid phase line temperature;  
\(T_2\)—Casting billet surface temperature;  
\(L_f\)—Latent heat of crystallization;  
\(L_0\)—Length of casting and rolling area;
Thickness of billet shell: \( \delta_0 \);
Casting roller sleeve radius: \( R \);
Density: \( \rho_m \);
Coagulation coefficient: \( K \).

2.2 Boundary conditions

Normal direction of horizontal twin roll casting rolling is shown in Figure 2. After molten magnesium alloy flows out of nozzle outlet, it enters casting rolling area and solidifies under the cooling effect of roller. According to different melts, casting and rolling can be divided into liquid, paste and solid regions. The boundary line between mushy zone and solid zone is defined as solidification layer welding line. Solidified magnesium alloy is rolled by roller to form required magnesium alloy sheet\[8,12,13,14]\.

![Casting rolling process flow chart](image)

Taking horizontal twin-roll casting as research object, boundary conditions of numerical analysis are shown in figure 3. Taking exit of casting nozzle as origin of coordinate system, center line of roll is end point of casting rolling, positive direction of X axis is direction of casting rolling, and direction of Y axis is direction of plate thickness. Since nozzle is made of insulating material, it is assumed that heat of molten magnesium alloy is not lost at nozzle. Temperature in nozzle is defined as casting rolling temperature \( T \), and inner wall height of nozzle is \( H_1 \). Casting roll is usually composed of roll sleeve and roll. Roller sleeve is made of material with good heat conduction capacity, and roller has a special cooling system inside. Therefore, it is considered that in the process of contact and heat transfer between molten magnesium alloy and roll, roll has sufficient heat transfer capacity and can keep constant temperature. Thickness of molten magnesium alloy sheet is \( H_2 \) after cooling and rolling\[15,16]\.
In this study, AZ31 magnesium alloy was used. It is assumed that AZ31 melts, pastes and solids are incompressible nonlinear thermo-viscous materials. Liquidus temperature is 898K and solidus temperature is 818K. Height of casting nozzle is 20 mm, total length of casting and rolling area is 81 mm, and thickness of production plate is 6 mm. 170000 hexahedral meshes are evenly distributed in casting and rolling area. In process of numerical analysis, commercial fluid finite element analysis software is used to calculate thermal fluid coupling field. Through finite element method, small time step iterative calculation is carried out in each cell, and convergent steady-state solution is finally obtained.

2.3 Data grouping

Position of solidification welding line is comprehensive embodiment of roll-casting process parameters, which is affected by many factors. Previous findings that position and shape of solidification welding line are affected by casting temperature, casting speed and roll heat transfer capacity. Therefore, factors such as casting temperature, rolling speed and roll heat transfer capacity are taken as main casting and rolling process variables, and matching relationship between them and offset of solidification welding line is analyzed. According to previous literature research, it is found that maximum stress region of magnesium alloy plate rolling is concentrated on edge of plate due to stress characteristics, resulting in edge crack. Based on simulation results of mapping relationship between the above key process parameters and solidification welding line, internal causes of edge crack of magnesium alloy casting and rolling were analyzed. According to the simulation results, maximum stress and stress distribution of plate edge under different process parameters can be predicted, and then edge crack phenomenon can be effectively controlled. The setting of casting and rolling temperature depends on the liquid phase line temperature of AZ31 magnesium alloy, which is 898 K. Therefore, the temperature range is 900 K-950 K. The setting of casting and rolling speed needs to consider more factors. First, to ensure that the solidification welding line is located in the casting and rolling zone, so the casting and rolling speed should not be set too high. On the other hand, the casting speed is too low and will cause the phenomenon
of rolling card. The heat transfer coefficient of the roll is set based on the heat transfer capacity of the copper alloy roll sleeve. Therefore, the set temperature range is 3200 W/(m²K) - 6000 W/(m²K).

The different process variables used in the numerical simulation are shown in Table 1.

| Serial number | Casting rolling temperature (T) | Heat transfer coefficient (Hₑ) | Casting rolling speed (V) |
|---------------|---------------------------------|-------------------------------|--------------------------|
| 1             | 900-950 K                       | 3200 W/(m²K)                 | 3 m/min                  |
| 2             | 900 K                           | 3000-6000 W/(m²K)            | 3 m/min                  |
| 3             | 900 K                           | 3200 W/(m²K)                 | 1-3.2 m/min              |

3. Results and Discussion

3.1 Control mode of three process parameters

(1) Casting and rolling temperature (T): temperature of casting and rolling can be controlled by regulating temperature of front box.

(2) Roll casting speed (V): it is defined as horizontal speed of plate at exit of casting roll. According to principle of equal flow rate per second, melt outflow velocity of nozzle can be obtained. Roll casting speed can be adjusted by adjusting nozzle exit speed and roll speed.

(3) The heat transfer capacity of roll is defined as heat transfer coefficient (Hₑ), and heat transfer coefficient of different roller sleeves is different. For different conditions of cast rolling, roll sleeve of different materials can be replaced to adjust casting and rolling area.

In this paper, position change of solidification welding line and temperature distribution along thickness direction in cast rolling area under different process parameters are analyzed.

3.2 Effect of process parameters on solidification welding line

As shown in Figure 4(a), temperature distribution cloud of central plane in normal direction of casting and rolling area is like a tongue, and yellow line is solidification welding line. It can be seen from figure that cooling rate of central part lags behind that of edge of cast-rolling zone. Moreover, temperature not only decreases along casting rolling direction, but also along width direction. With increase of casting and rolling temperature (900K-950K), central position of solidification welding line moves from 66 mm to 75 mm. For every 10K increase in temperature, offset is 2%. Edge position is shifted from 44.5 to 50.3 mm, and offset is 1.4% for every 10K temperature rise. With increase of temperature, solidification welding line has characteristics of deviation to exit direction. Moreover, difference between middle and edge of solidification welding line along casting rolling direction increases from 21.5mm to 24.7mm, which shows a tensile trend.

As shown in Figure 4(b), with increase of casting rolling speed (V), shape and position of solidification welding line have changed conspicuously. When casting
speed is slow, solidification speed is relatively low. With increase of casting and rolling speed, slope of solidification welding line increases. Position of solidification welding line in center moved from 24 mm to 73 mm. The solidification line shifts 28% for every 1 m/min increase of casting speed. The position of edge solidification welding line moved from 17.8 mm to 47.7 mm. When casting speed is increased by 1 m/min, solidification line will shift by 17%. With increase of casting speed, solidification welding line has characteristics of large deviation to exit of casting rolling zone. The difference between middle and edge of solidification welding line along casting rolling direction increased from 6.2 mm to 25.3 mm.

As shown in Figure 4(c), with improvement of heat transfer capacity of roll, solidification welding line has a tendency to shift towards entrance of casting and rolling zone. And edge of solidification welding line tends to be smooth. With continuous improvement of heat transfer capacity of roll, position of solidification welding line in center moved from 79 mm to 48.3 mm. The position of edge solidification welding line moved from 51.5 mm to 31 mm. Neither rate of change shows a linear trend. That is to say, with improvement of heat transfer capacity of roll, offset of solidification welding point decreases gradually. The reason is that solidification welding line is shifted to inlet, which increases distance of heat transfer from center of slab to heat exchange surface, which cannot make cooling effect of casting rolling area improve significantly. Improvement of roll heat transfer capacity can reduce difference between middle and edge of solidification welding line along casting rolling direction, from 27.5 mm to 17.3 mm. It can reduce difference between edge rolling reduction and center rolling reduction.

![Figure 4 Liquid fraction nephogram of casting and rolling zone with different process parameters](image-url)
In summary, with the casting and rolling process parameters continue to change, the solidification weld line edge position difference is also changing. It is obvious that the difference in the position of the center edge of the solidification weld line will have a direct impact on the amount of depression in the rolling process. It is known that as the amount of depression increases within a certain range, the tissue grain will be more refined and the sheet properties will rise [17,18]. At the same time, with the increase of depression, the plate edges are subjected to more rolling deformation stress, and the very poor plastic forming ability of magnesium alloy will lead to edge cracking [19]. To ensure better slab quality, so the solidification weld line should be located at the exit of the casting and rolling zone as a whole as much as possible, while reducing the solidification weld line position difference.

### 3.3 Effect of process parameters on flow field in casting rolling zone

The velocity field and eddy current phenomenon in casting and rolling area are shown in Figure 5. Because of non-uniformity of melt flow, eddy current appears at entrance side of casting rolling zone. The results show that flow velocity of melt decreases significantly, and melt presents two symmetrical cyclonic flows. After passing through vortex zone, melt velocity begin to increase gradually.

![Figure 5 Velocity field and eddy current in casting rolling area](image)

Figure 6(a) shows center and edge velocity lines at different temperatures. It can be seen from figure that with increase of casting and rolling temperature, center speed decreases slightly and edge speed increases. Therefore, difference between center speed and side speed shows a decreasing trend, and difference decreases from 0.79 m/min to 0.29 m/min. The reason is that viscosity of magnesium alloy melt decreases with increase of casting temperature, which leads to more uniform fluid movement in direction of plate width.

Figure 6(b) shows center and edge velocity lines at different casting and rolling speeds. It can be seen from figure that with increase of casting and rolling speed, center speed and edge speed increase significantly. Increase rate of center velocity is higher than that of edge, so difference between center speed and edge speed increases,
and difference increases from 0.1 m/min to 0.32 m/min. This is because melt has a certain viscosity, edge velocity is always in a lower speed state under influence of wall. But middle part can keep high speed.

Figure 6(c) shows velocity lines of center and edge under different heat transfer coefficients. It can be seen from figure that change of roll heat transfer capacity has no obvious effect on velocity field in casting rolling zone. The velocity of middle and edge corresponding to different heat transfer capacity of roller are kept in a certain range. And difference between the two is relatively stable, difference is stable between 0.29 m/min-0.34 m/min. This is due to fact that only changing heat transfer capacity of roll cannot effectively affect melt flow characteristics in casting and rolling area without changing melt viscosity and melt velocity.

Figure 6 Velocity diagram of center line and edge line in cast rolling area
(a) Different casting and rolling temperature velocity diagram (b) Different casting and rolling speed diagram (c) Different heat transfer capacity speed diagram

As mentioned above, the primary reason for the tongue shape of the solidification weld line is the large difference between the middle and side velocities of the melt in the casting and rolling zone. The reason for this phenomenon is due to the uneven flow of melt in the casting and rolling area. It is obvious that the flow of melt with certain viscosity in the casting and rolling zone is not only influenced by the pressure of the casting nozzle, but also by the rotation of the two sets of casting and rolling rolls [20]. The most intuitive manifestation of this is the vortex phenomenon in the casting zone [8,21]. In order to improve the shape of the solidification line, the variability of the melt velocity in the casting zone should be reduced as much as possible.
3.4 Effect of process parameters on temperature of plate edge

Figure 7 Temperature nephogram of casting and rolling area edge

(a) Edge temperature nephogram of different casting and rolling temperature (b) Edge temperature nephogram of different casting and rolling speed (c) Edge temperature nephogram of different heat transfer

Figure 7(a) shows temperature nephogram of edge casting and rolling area corresponding to different casting and rolling temperatures. It can be seen from figure that temperature nephogram of casting and rolling area presents characteristics of acute triangle. With increase of temperature, temperature difference between center of freezing point and heat transfer surface decreases, from 58K to 53K. This is due to decrease of melt viscosity and more uniform melt flow in casting and rolling area, so that heat can be transferred to heat exchange surface synchronously.

Figure 7(b) shows temperature nephogram of edge casting zone corresponding to different casting and rolling speeds. It can be seen from figure that change of casting rolling speed will have a great impact on temperature distribution in casting rolling zone. When casting speed is low, melt in casting and rolling area can be cooled sufficiently, so that it is at a lower temperature as a whole. When casting speed is 1 m/min, minimum temperature at exit of casting and rolling is as low as 380K. With increase of casting speed, temperature difference between center of solidification point and heat transfer surface increases, from 59K to 68K. This is due to the fact that the temperature of the heat exchange surface and the near heat exchange surface can be rapidly exported after the thickness of the slab is greatly reduced, while the melt in the center is affected by vortices and the cooling process is hindered.

Figure 7(c) is temperature nephogram of edge casting rolling zone corresponding
to different roll heat transfer capacity. It can be seen from figure that roll heat transfer capacity has a significant effect on temperature distribution in casting and rolling zone. Improvement of roll heat transfer capacity can greatly increase cooling rate of casting and rolling zone, but temperature difference between center of freezing point and heat transfer surface has an increasing trend, and difference increases from 51K to 102K. Reason is that solidification point shifts to entrance of casting and rolling zone, and heat transfer capacity of roll is enhanced at same time, which makes central temperature and surface temperature of slab produce a large temperature gradient. Therefore, non-uniformity of heat distribution along direction of plate thickness increases.

It is well known that temperature will play a crucial role in the metal forming process. In particular, during the forming of magnesium alloys, the grain organization as well as the mechanical properties of the sheet will change significantly with the change in temperature [22]. Other scholars have found that the activation of dynamic recovery, continuous dynamic recrystallization, grain boundary sliding and additional slip systems lead to improved ductility of magnesium alloys at high temperatures [23]. In this study, it can be found that although the overall temperature field at the edge of the slab in the cast-rolled area is still at a higher temperature, the large temperature difference between the center and the edge is a potential factor for the occurrence of edge cracking [24]. Therefore, in order to ensure the quality of cast and rolled magnesium alloy slabs, the high temperature state should be satisfied while the temperature difference between the slab sides should be reduced as much as possible.

3.5 Model Validation

![Figure 8. Error detection chart](image)

According to the solidification weld joint prediction model above, its reasonableness is analyzed by comparing the results of finite element numerical simulation. This paper takes the effect of casting and rolling speed change on the
solidification weld joint as the object of verification. As shown in Figure 8, it can be learned that the simulation analysis results have less error compared to the prediction model. The simulated values of the solidified weld joint are within 8 mm of the predicted values. There are few reports on the means of detecting the internal temperature of the casting and rolling area, so it is not yet possible to experimentally observe the solidification weld line characteristics. However, the obtained data have a high fit compared to the theoretical model and other scholars' literature, so the numerical simulation process of this paper can be considered reasonable.

3.6 The best process plan

Taking AZ31 magnesium alloy cast rolling plate with thickness of 6 mm as an example. Which is obtained through the above simulation experiment. When casting temperature is 953K, heat transfer capacity of roll is 2500 W/(m²k), and the casting rolling speed is 2.2 m/min, optimal solidification welding line position can be obtained, as shown in Figure 8. Central position of solidification welding line is 76 mm in casting rolling area, and difference between middle part and edge of solidification welding line along casting rolling direction is 23 mm. Temperature difference (ΔT) between center temperature and heat exchange surface temperature at edge solidification welding joint is 39K. This can ensure that small rolling reduction and uniform heat distribution in the thickness direction can be obtained without liquid leakage. At this time, tendency of edge crack is least.

![Nephogram of liquid phase ratio of optimum process parameters](image)

Figure 9 Nephogram of liquid phase ratio of optimum process parameters

4. Conclusion

1) Casting and rolling process parameters have a decisive influence on the characteristics of solidification welding line. With increase of casting and rolling temperature, solidification welding line moves to exit of casting rolling zone in a small range. At same time, it can change fluid viscosity so that fluid flow in the casting and rolling area is more uniform, and temperature difference between slab center and heat exchange surface is kept at a low level. These characteristics can improve the edge stress of slab.

2) With increase of casting speed or decrease of heat transfer capacity of roll, position and shape of solidification welding line can be changed obviously. It significantly
shifts to the exit of the cast-rolling zone. Moreover, increasing casting speed will obviously increase difference between middle and edge of the solidification welding line along casting direction. Too large position difference will have a negative effect on rolling. In addition, with the increase of casting and rolling speed and heat transfer capacity, both will increase the unevenness of heat distribution in the plate thickness direction.

3) Production process of casting rolling plate of AZ31 magnesium alloy with thickness of 6 mm. The optimal production process (953K; 2.2 m/min; 2500 W/m²k) can be obtained by adjusting and controlling the three process parameters. Position of solidification welding line tends to exit of casting rolling zone (75mm). At the same time, difference between middle and edge of solidification welding line along casting rolling direction is 23mm. And temperature difference (ΔT) between central temperature and heat exchange surface temperature at edge solidification welding joint is 39K. This can reduce probability of edge crack.

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