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EFFECT OF CASTING AND ROLLING PROCESS PARAMETERS ON SOLIDIFICATION WELDING LINE OF MAGNESIUM ALLOY

Z.-Q. Huang [a], H.-Y. Lai [a,*], H.-B. Zhou [b], H. Guo [a]

[a] School of Mechanical Engineering, Taiyuan University of Science and Technology, Taiyuan, China
[b] State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha, China

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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 [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 [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 [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.

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 [8] analyzed the casting and rolling process of

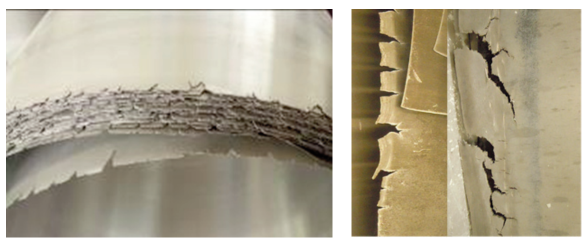

Figure 1. *Defects in magnesium alloy cast-rolled strip*

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 the process by optimizing some of the parameters. Zhang, JP [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 cannot be

* *Corresponding author: lai952339754@163.com*

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ignored, and position of solidification welding line has a decisive impact on rolling forming process [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 was selected for numerical study. Melt, paste, and solid were assumed to be incompressible nonlinear thermo-viscous materials. At the same time, influence of asymmetry caused by gravity was considered. Firstly, influence of casting and rolling process parameters on the position of solidification welding joint in casting and rolling area was analyzed, and then the key influencing factors of magnesium alloy casting rolling edge crack were 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), the expression of latent heat flow (Eq. 2), and the expression of the geometric relationship between solidification and welding point (Eq. 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 was finally derived (Eq. 4). Through the prediction model, it was learned that as the casting and rolling speed and the process parameters were determined, the location of the solidification welding point was also determined.

$$\Phi_1 = \frac{\lambda_m (T_l - T_s)}{\delta} \tag{1}$$

$$\Phi_2 = L_f \rho_m \frac{d\delta}{dt} \tag{2}$$

$$L_0 = \sqrt{(\delta_0 + R)^2 - (R + \frac{d}{2})^2} \tag{3}$$

$$v = \frac{2\pi K^2 R \arcsin(\frac{L}{R})}{2R^2 + Rd + \frac{d^2}{4} + l_0 - 2R\sqrt{l_0^2 + (R + \frac{d}{2})^2}} \tag{4}$$

where: λ_m - thermal conductivity of the billet shell; T_l - Liquid phase line temperature; T_s - Casting billet surface temperature; L_f - Latent heat of crystallization; L_o - Length of casting and rolling area; δ_o - Thickness of billet shell; R - Casting roller sleeve radius; ρ_m - Density and K - Coagulation coefficient.

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].

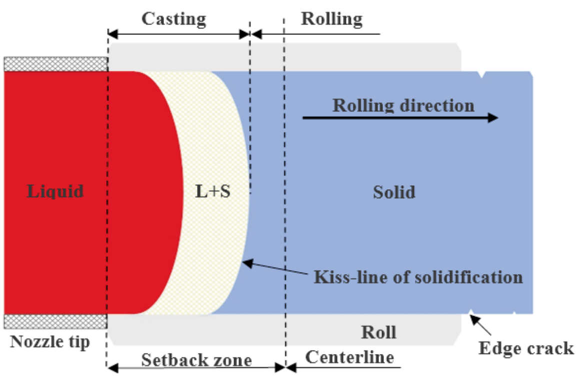

Figure 2. *Casting rolling process flow chart*

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

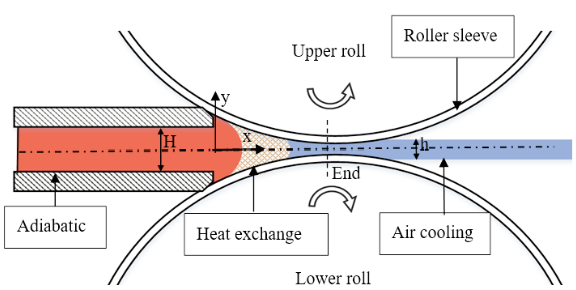

Figure 3. *Boundary of numerical analysis*

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 was assumed that AZ31 melts, pastes and solids were incompressible nonlinear thermo-viscous materials. Liquidus temperature was 898K and solidus temperature was 818K. Height of casting nozzle was 20 mm, total length of casting and rolling area was 81 mm, and thickness of production plate was 6 mm. 170,000 hexahedral meshes were evenly distributed in casting and rolling area. In the process of numerical analysis, commercial fluid finite element analysis software was used to calculate thermal fluid coupling field. Through finite element method, small time step iterative calculation was carried out in each cell, and convergent steady-state solution was 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 show 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 were taken as main casting and rolling process variables, and matching relationship between them and offset of solidification welding line was analyzed. According to previous literature research, it was found that maximum stress region of magnesium alloy plate rolling was 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 could be predicted, and then edge crack phenomenon could be effectively controlled. The setting of casting and rolling temperature depended on the liquid phase line temperature of AZ31 magnesium alloy, which was 898 K. Therefore, the temperature range was 900 K-950 K. The setting of casting and rolling speed needed to consider more factors. First step was to ensure that the solidification welding line was located in the casting and rolling zone, so the casting and rolling speed were not set too high. On the other hand, the casting speed was too low and could cause the phenomenon of rolling card. The heat transfer coefficient of the roll was set based on the heat transfer capacity of the copper alloy roll sleeve. Therefore, the set temperature range was 3200 W/(m^{2}K) -6000 W/(m^{2}K).

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

Table 1. *Simulation process grouping variable settings*

Serial number	Casting rolling temperature (T)	Heat transfer coefficient (H_e)	Casting rolling speed (V)
1	900-950 K	3200 W/(m^{2}K)	3 m/min
2	900 K	3000-6000 W/(m^{2}K)	3 m/min
3	900 K	3200 W/(m^{2}K)	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 (H_e), 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 were 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 lagged behind that of edge of cast-rolling zone. Moreover, temperature not only decreased along casting rolling direction, but also along width direction. With increase of casting and rolling temperature (900K - 950K), central position of solidification welding line moved from 66 mm to 75 mm. For every 10 K increase in temperature, offset was 2%. Edge position was shifted from 44.5 to 50.3 mm, and offset was 1.4% for every 10 K temperature rise. With increase of temperature, solidification welding line had characteristics of deviation to exit direction. Moreover, difference between middle and edge of solidification welding line along casting rolling direction increased from 21.5 mm to 24.7 mm, which showed a tensile trend.

As shown in Figure 4(b), with increase of casting rolling speed (V), shape and position of solidification welding line changed conspicuously. When casting speed was slow, solidification speed was relatively low. With increase of casting and rolling speed, slope of solidification welding line increased. Position of solidification welding line in center moved from 24 mm to 73 mm. The solidification line shifted 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 increased by 1 m/min, solidification line shifted by 17%. With increase of casting speed, solidification welding line had 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 had a tendency to shift towards entrance of casting and rolling zone and edge of solidification welding line tended 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 showed a linear trend. That is to say, with improvement of heat transfer capacity of roll, offset of solidification welding point decreased gradually. The reason was that solidification welding line was shifted to inlet, which increased distance of heat transfer from center of slab to heat exchange surface, which could not make cooling effect of casting rolling area improve significantly. Improvement of roll heat transfer capacity could reduce difference between middle and edge of solidification welding line along casting rolling direction, from 27.5 mm to 17.3 mm. It could reduce difference between edge rolling reduction and center rolling reduction.

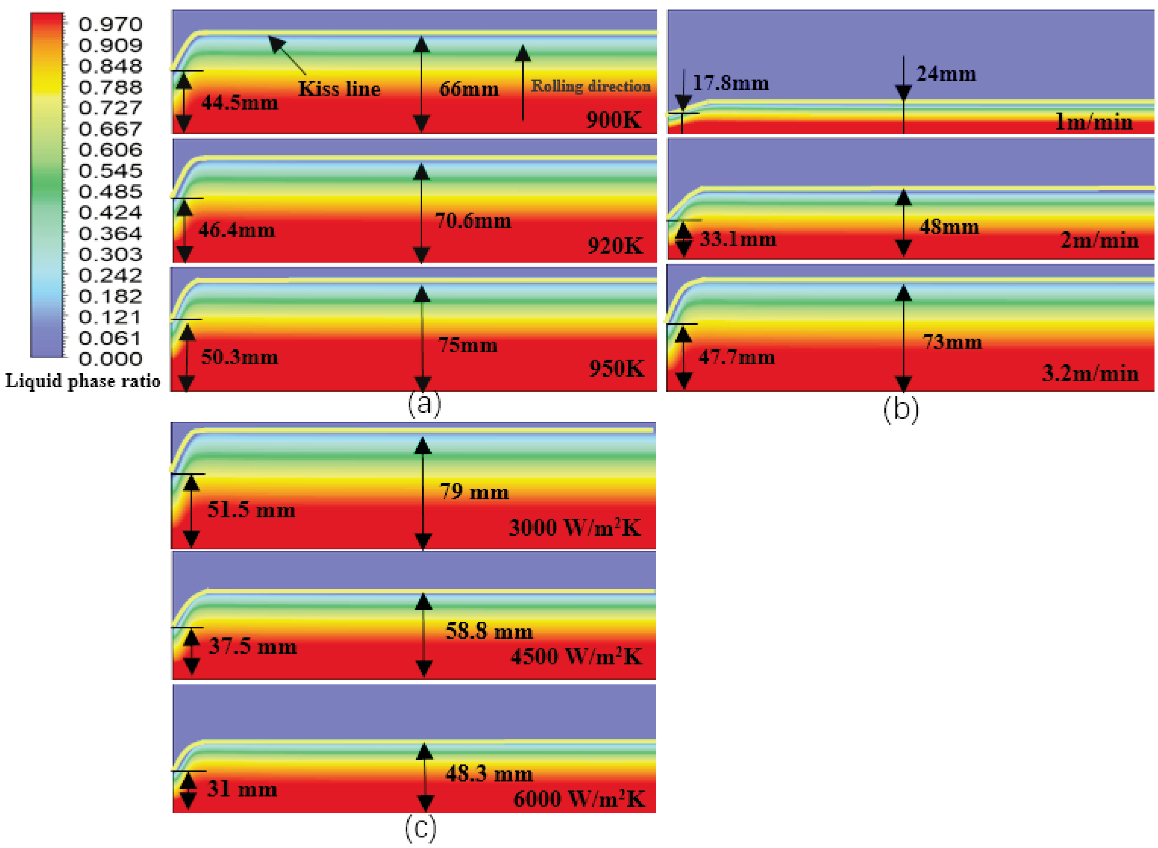

Figure 4. *Liquid fraction nephogram of casting and rolling zone with different process parameters: (a) Liquid fraction nephogram of different casting and rolling temperature; (b) Liquid fraction nephogram of different casting and rolling speed; (c) Liquid fraction nephogram of different heat transfer capacity*

In summary, with the casting and rolling process parameters continuous change, the solidification weld line edge position difference had also changed. It was obvious that the difference in the position of the center edge of the solidification weld line would 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 showed that flow velocity of melt decreased significantly, and melt presented two symmetrical cyclonic flows. After passing through vortex zone, melt velocity began to increase gradually.

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 decreased slightly and edge speed increased. Therefore, difference between center speed and side speed showed a decreasing trend, and difference decreased from 0.79 m/min to 0.29 m/min. The reason was that viscosity of magnesium alloy melt decreased with increase of casting temperature, which led 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 increased significantly. The increase rate of center velocity was higher than that of edge, so difference between center speed and edge speed increased, and difference increased from 0.1 m/min to 0.32 m/min. This happened because melt had a certain viscosity, edge velocity was always in a lower speed state under influence of wall. However, middle part kept 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 had no obvious effect on velocity field in casting rolling zone. The velocity of middle and edge corresponding to different heat transfer capacity of roller were kept in a certain range. The difference between the two was relatively stable, and difference was stable between 0.29 m/min-0.34 m/min. This was due to fact that only changing heat transfer capacity of roll could not effectively affect melt flow characteristics in casting and rolling area without changing melt viscosity and melt velocity.

As mentioned above, the primary reason for the tongue shape of the solidification weld line was the large difference between the middle and side velocities of the melt in the casting and rolling zone. The reason for this phenomenon was due to the uneven flow of melt in the casting and rolling area. It

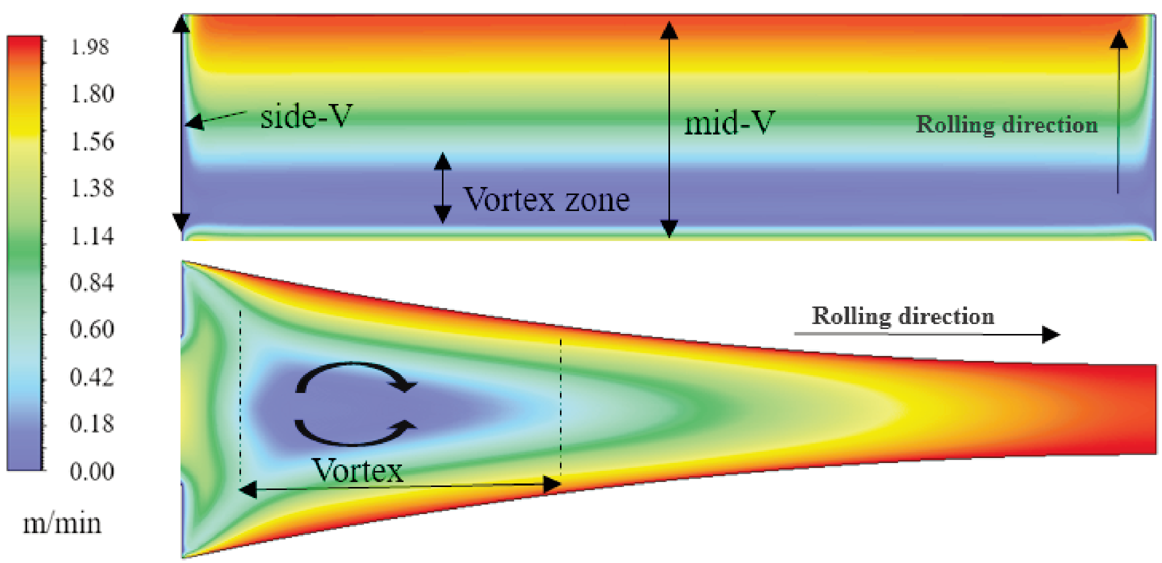

Figure 5. *Velocity field and eddy current in casting rolling area*

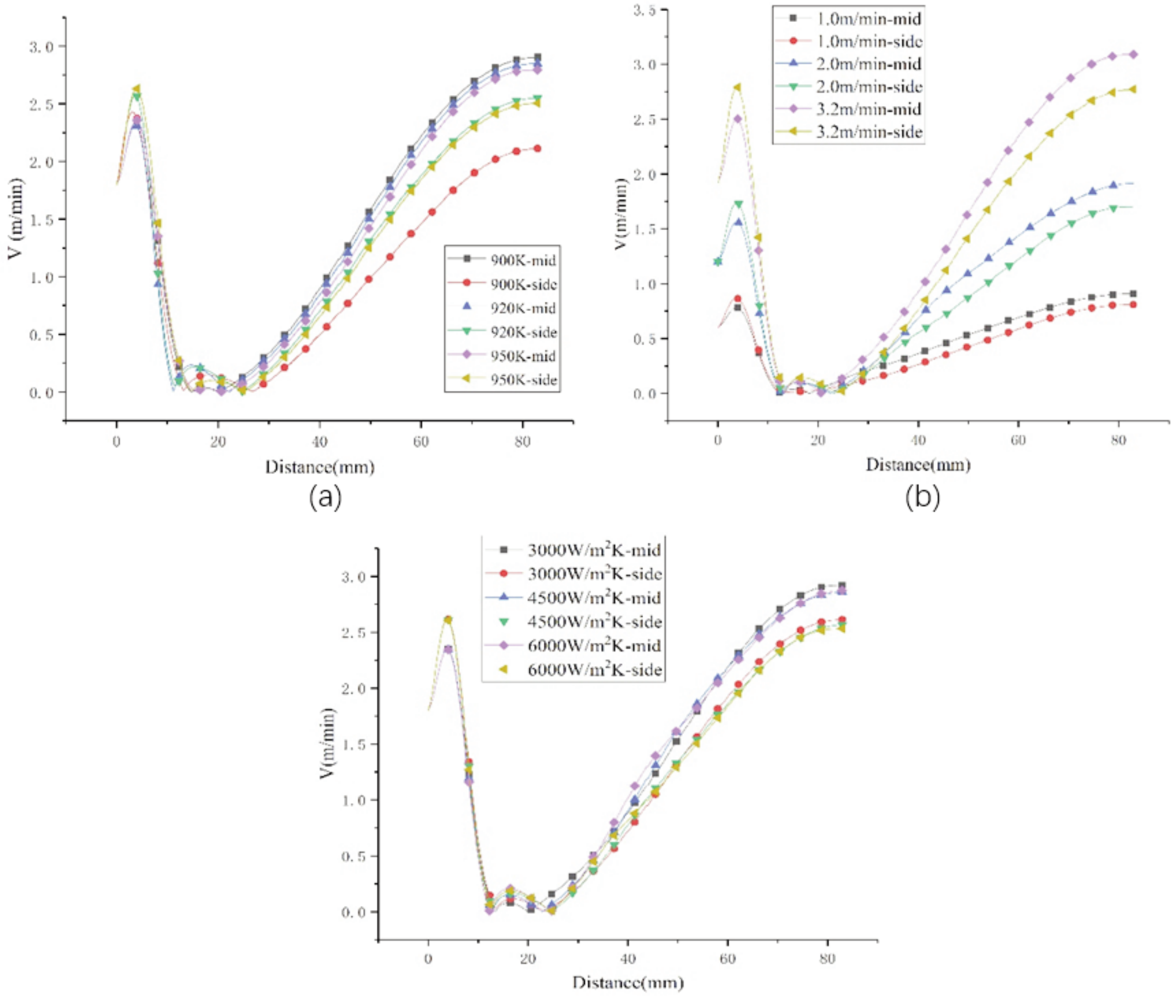

Figure 6. *Velocity diagram of center line and edge line in cast rolling area: (a) Different casting and rolling temperature velocity diagram; (b) Different casting and rolling speed diagram; (c) Different heat transfer capacity speed diagram*

was obvious that the flow of melt with certain viscosity in the casting and rolling zone was 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 was 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(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 presented characteristics of acute triangle. With increase of temperature, temperature difference between center of freezing point and heat transfer surface decreased from 58 K to 53 K. This happened due to the decrease of melt viscosity and more uniform melt flow in casting and rolling area, so that heat could 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 had a great impact on temperature distribution in casting rolling zone. When casting speed was low, melt in casting and rolling area were cooled sufficiently, so that it was at a lower temperature as a whole. When casting speed was 1 m/min, minimum temperature at exit of casting and rolling was as low as 380 K. With increase of casting speed, temperature difference between center of solidification point and heat transfer surface increased from 59 K to 68 K. This was due to the fact that the temperature of the heat exchange surface and the near heat exchange surface could be rapidly exported after the thickness of the slab was greatly reduced, while the melt in the center was affected by vortices and the cooling process was hindered.

Figure 7(c) shows 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 had a significant effect on temperature distribution in casting and rolling zone. Improvement of roll heat transfer capacity could greatly increase cooling rate of casting and rolling zone, but temperature difference between center of freezing point and heat transfer surface had an increasing trend, and difference increased from 51 K to 102 K. Reason was that solidification point shifted to entrance of casting and rolling zone, and heat transfer capacity of roll was enhanced at same time, which made central temperature and surface temperature of slab produce a large temperature gradient. Therefore, non-uniformity of heat distribution along direction of plate thickness increased.

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 was found that although the overall temperature field at the edge of the slab in the cast-rolled area was still at a higher temperature, the large temperature difference between the center and the edge was 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

According to the solidification weld joint prediction model above, its reasonableness was analyzed by comparing the results of finite element numerical simulation. This paper explains 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

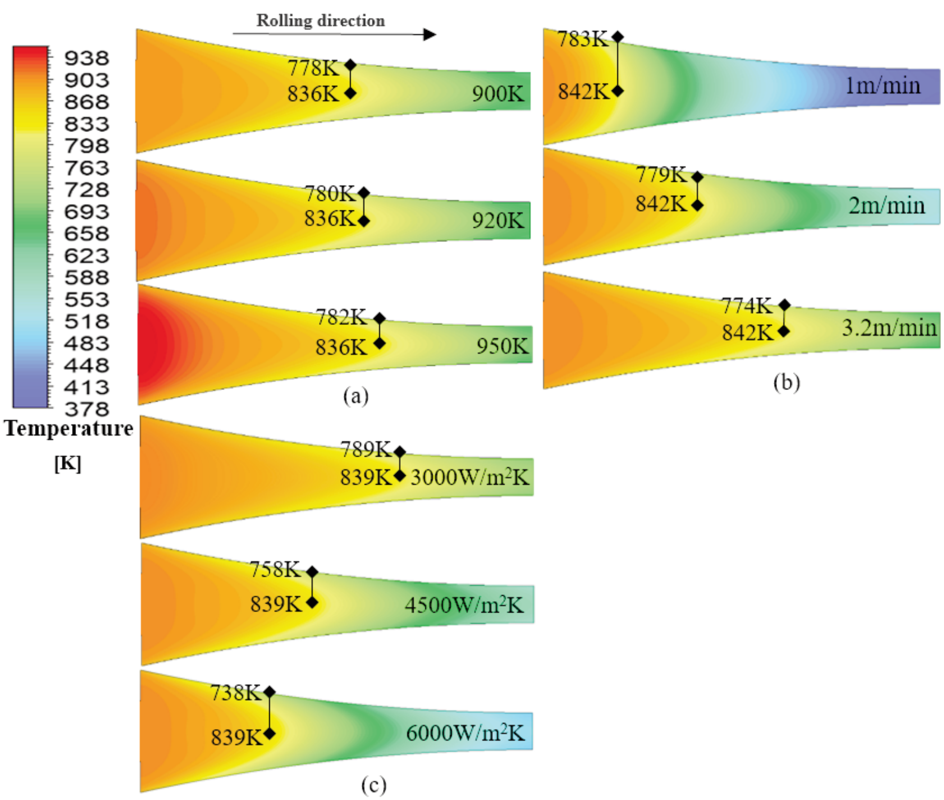

Figure 7. Temperature nephogram of casting and rolling area edge:(a) Edge temperature nephogram of different casting and rolling temperature; (b) Edge temperature nephogram of different casting and rolling speed; (c) Edge temperature nephogram of different heat transfer

simulation analysis results had less error compared to the prediction model. The simulated values of the solidified weld joint were 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 has not yet possible to experimentally observe the solidification weld line characteristics. However, the obtained data had a high fit compared to the theoretical model and other literature, so the numerical simulation process of this paper can be considered reasonable.

3.6. The best process plan

The AZ31 magnesium alloy cast rolling plate with thickness of 6 mm was taken as an example. It was obtained through the above simulation experiment. When casting temperature was 953K, heat transfer capacity of roll was 2500 W/(m2k), and the casting rolling speed was 2.2 m/min, optimal solidification welding line position was obtained, as shown in Figure 8. Central position of solidification welding

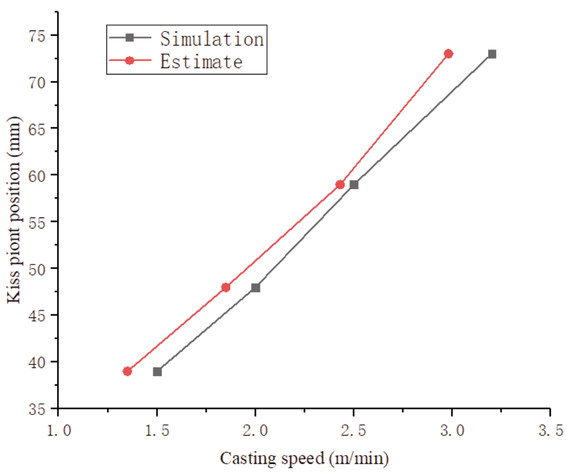

Figure 8. *Error detection chart*

line was 76 mm in casting rolling area, and difference between middle part and edge of solidification welding line along casting rolling direction was 23 mm. Temperature difference (ΔT) between center temperature and heat exchange surface temperature at edge solidification welding joint was 39 K. This

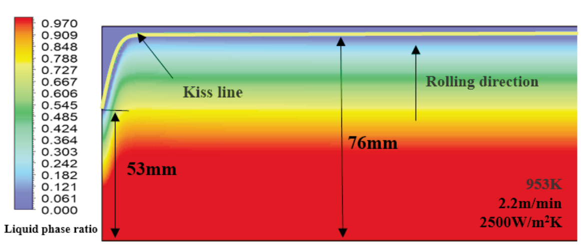

Figure 9. *Nephogram of liquid phase ratio of optimum process parameters*

ensured that small rolling reduction and uniform heat distribution in the thickness direction were obtained without liquid leakage. At this time, tendency of edge crack was least.

4. Conclusion

1) Casting and rolling process parameters had a decisive influence on the characteristics of solidification welding line. With increase of casting and rolling temperature, solidification welding line moved to exit of casting rolling zone in a small range. At same time, it changed fluid viscosity so that fluid flow in the casting and rolling area was more uniform, and temperature difference between slab center and heat exchange surface was kept at a low level. These characteristics could 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 were changed obviously. It significantly shifted to the exit of the cast-rolling zone. Moreover, increasing casting speed obviously increased the difference between middle and edge of the solidification welding line along casting direction. Too large position difference could have a negative effect on rolling. In addition, with the increase of casting and rolling speed and heat transfer capacity, both increased 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 was analyzed. The optimal production process (953 K; 2.2 m/min; 2500 W/m^{2}k) was obtained by adjusting and controlling the three process parameters. Position of solidification welding line tended to exit the casting rolling zone (75mm). At the same time, difference between middle and edge of solidification welding line along casting rolling direction was 23 mm. The temperature difference (ΔT) between central temperature and heat exchange surface temperature at edge solidification welding joint was 39 K. This can reduce probability of edge crack.

Author’s contributions

In this paper, each author has different contributions, jointly designed and participated in the research process, obtained the data through theoretical analysis and simulation experiments, and finally there is no conflict of interest. The author's contributions are as follows: Z.-Q. Huang：Formulation of overarching research goals and aims; H.-Y. Lai：Creation of models and conducting a research and investigation process. H.-B; Zhou：Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team; H. Guo：Conducting a research and investigation process.

Conflict of interest statement

We declare that all authors have no conflict of interest.

Data Availability Statement

The processed data needed to reproduce these findings cannot be shared at this time, as they also form part of an ongoing study, in accordance with the funder's data retention policy.

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UTICAJ PARAMETARA PROCESA LIVENJA I VALJANJA NA LINIJU SPAJANJA NASTALU PRILIKOM SOLIDIFIKACIJE KOD LEGURA MAGNEZIJUMA

Z.-Q. Huang [a], H.-Y. Lai [a,*], H.-B. Zhou [b], H. Guo [a]

[a] Fakultet za mašinsko inženjerstvo, Univerzitet za nauku i tehnologiju u Taijuanu, Taijuan, Kina
[b] Glavna državna laboratorija za proizvodnju složenih jedinjenja sa visokim performansama, Centralnojužni univerzitet, Čangša, Kina

Apstrakt

Numeričkom simulacijom analiziran je postupak horizontalnog livenja sa dva valjka. Linija spajanja nastala prilikom solidifikacije je analizirana i pažnja je usmerena na karakteristične promene koje su nastale zbog temperature livenja, brzine livenja i kapaciteta prenosa toplote valjka, kao i na njihov uticaj na postupak formiranja područja livenja sa dva valjka. Rezultati su pokazali da povećanje temperature livenja, brzine livenja ili smanjenje kapaciteta prenosa toplote valjka mogu dovesti do pomeranja linije spajanja do ivice zone livenja. Povećanje temperature i brzine livenja može prouzrokovati povećanje razlike između sredine i ivice linije spajanja duž smera livenja, a distribucija toplote cele ploče će biti ujednačenija. Međutim, poboljšanje kapaciteta prenosa toplote valjka imaće potpuno suprotan efekat. Prema tome, optimalni parametri procesa livenja i valjanja ploče debljine 6 mm od legure magnezijuma su primenjeni kako bi se smanjila verovatnoća pucanja ivica.

Ključne reči: *Legura magnezijuma; Horizontalno livenje sa dva valjka; Linija spajanja nastala prilikom solidifikacije; Oštećenje ivice*