Numerical simulation of the top side-pouring twin-roll casting of 6.5 wt.% Si steel process

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Abstract
Using the finite element software ProCAST to predict the temperature field, the flow field, the turbulent kinetic energy, and melt-pool outlet temperature of the top side-pouring twin-roll casting (TSTRC) of 6.5 wt.% Si steel process. The effect of different process conditions on the TSTRC process was investigated through numerical simulation, and a processing technique appropriate for the production of 6.5 wt.% Si steel was obtained. Meanwhile, the influence of violent stirring in the melt-pool on the microstructure under different process conditions was evaluated. The results showed that vigorous stirring in the melt-pool was conducive to formate the equiaxed crystal structure. We realized the near-final shape of the metal sheet and achieved the near-final shape of the microstructure. An appropriate process was selected to show good consistency with the experimental results.

Keywords Twin-roll casting · Numerical simulation · Microstructure · 6.5 wt.% Si steel

1 Introduction
Twin-roll strip casting (TRC) is a near-net-shape process that combines casting and rolling techniques to cast and roll liquid metal into thin strips of 1–4 mm [1]. TRC has been proven to be a kind of high-efficiency and energy-saving technology [2]. TRC has attracted extensive interest compared with traditional casting technology because of the advantages of a shorter production process, lower investment cost, and operating cost. Besides, the mechanical properties of metallic materials can be increased due to the rapid cooling in the casting process [3].

During the TRC process, the solidification, heat transfer, and possible plastic deformation of the metal are completed in a short time simultaneously. Additionally, the process parameters such as the pouring temperature, the casting speed, and the melt-pool height influence each other, making the TRC process very complicated to control. Therefore, the numerical simulation method can optimize the process parameters to reduce the cost and workload, which helps control the twin-roll casting process, product quality, and microstructure and properties.

Extensive research has been done on this technology, and many impressive results have been achieved. Tavares and Guthrie [4] systematically introduced the application of computational fluid dynamics in TRC, which provided tremendous help for later scholars in the study of TRC. Sahoo et al. [5] used FLUENT commercial software to model high-speed TRC and comprehensively verified the prediction results. Saitoh et al. [6] discussed the influence of various process parameters on the changing law of the solidified shell and analyzed the relationship between the kitting point and the process parameters. Hwang et al. [7] considered the fundamental transport phenomena of the TRC process and analyzed the flow field and temperature field in the melt-pool filling stage during the TRC process. Gupta and Sahai [8] developed a two-dimensional finite element model to research the influence of casting speed, heat transfer coefficient between melt-pool and roll, and molten steel superheat on strip thickness. Miao et al. [9] used a microsegregation model to probe the impact of the casting speed, the pouring temperature, and the roll gap on the flow field and temperature field. Bae et al. [10] investigated the flow field and
temperature distribution in the TRC process. They analyzed the influence of process parameters such as liquid level, casting speed, and nozzle size on the temperature distribution and velocity distribution in the melt-pool and its impact on the kissing point. Pei et al. [11] researched the temperature distribution in the melt-pool and the cooling rates under different casting conditions. He et al. [12] studied the relationship between cooling rate and microstructure evolution and mechanical properties under different casting methods. Their research believed that TRC has the potential to produce high-performance alloys. Zeng et al. [13] calculated the turbulent flow field for different steady-state casting points. They illustrated the influence of casting speed and roll gap width on the internal temperature field, flow field, and solidification structure. Li et al. [14] used thermal fluid and thermal-mechanical finite element methods to simulate the temperature field, flow field, and stress field of the TRC process. The effects of casting speed and pouring temperature on temperature field, fluid flow field, and stress field during the process were analyzed. According to the study of Guan et al. [15], as the casting temperature increases, the solid fraction increases from the inlet to the outlet of the roll gap. The average grain size of the product increases with the casting temperature, and the plastic deformation along the rolling direction occurs. Sun et al. [16] studied the influence of vibration parameters on twin-roll strip vibration cast-rolling. They found that mechanical vibration introduced during the casting process can optimize grains and suppress segregation. The perturbation effect of vibration on the flow field of the molten pool can increase the nucleation rate. Zhao et al. [17] obtained the temperature distribution and the flow field in the casting-rolling zone through the finite element method. They found that the casting temperature increase caused the rise of the strip temperature at the exit. Rodrigues et al. [18] minimized the macrosegregation deviations in the strip and predicted an optimal strip quality in the TRC process. To increase the casting speed and expand the applicable range of alloys, Wang and Zhou [19] proposed the TSTRC, which revealed the regular heat transfer pattern between the metal and the roll surface TSTRC process. Zhang et al. [20] adopted the method of combining numerical simulation and water simulation experiments with studying the influence of the flow distribution system on the TSTRC process, which provided stable flow conditions for the TSTRC process. The melt flow, heat transfer characteristics, and stability control during the molding process were probed. Concurrently, the influence of the primary process conditions on the melt flow stability and heat transfer characteristics in the TSTRC process was clarified [21]. Predecessors’ numerical simulation studies on the TRC process mainly focused on the flow, heat transfer, and solidification process in the melt-pool. The simulation results have particular guiding significance for subsequent research, but some problematic issues still need further study. In most numerical simulations, only a two-dimensional model was established to simulate the TRC process. However, the two-dimensional numerical simulation cannot accurately reflect the features of melt in the width direction. The majority of the numerical simulations treated the physical parameters of the material as constants for simulation. In fact, in the TRC process, different temperatures will inevitably cause changes in the material’s mechanical behavior and physical parameters. If the simulation uses constant physical parameters, the results will have significant effects and even fail to reflect the actual situation of the casting and rolling process. Simultaneously, the effect of stirring in the melt-pool on the solidification structure of the TRC process is rarely reported.

Regarding the issue above, the heat transfer, mass transfer, flow, and solidification processes were coupled, and a three-dimensional finite element model was established. Besides, the material thermophysical parameters that change with temperature were used for numerical simulation analysis. Based on the above conditions, the TSTRC process under different process parameters was simulated numerically. Meanwhile, a 2mm×2mm area was cut out at the melt-pool exit, and the microstructure was simulated by the CA-FE method.

2 Physical model and boundary conditions

Based on the casting and rolling equipment in our laboratory, a three-dimensional model as shown in Fig. 1a and a simulation calculation area as shown in Fig. 1b were established, and the following basic assumptions were made:

(1) The rolls are not deformable and rotate at a uniform speed.
(2) The contact surface of the melt and the roll has no slippage.
(3) The molten steel is regarded as an incompressible Newtonian fluid.
(4) Heat losses by radiation are negligible.
(5) Ignore the influence of natural convection caused by buoyancy.
(6) The environmental temperature is assumed as 25°C.
(7) The amount of molten metal in the simulation is 18.5kg.
(8) During the entire pouring process, the temperature of the twin rolls is constant at 25°C.

2.1 Physical model description

Figure 2a shows the schematic diagram of the TSTRC. Figure 2b is the partially enlarged view of the melt-pool. “V” is the casting speed, “H” is the melt-pool height, and
“the kissing point” is the point where two solidified shells meet. The TSTRC process is described as follows: melt the 6.5 wt.% Si steel (chemical compositions as shown in Table 1); the molten metal with certain superheat is delivered uniformly through the delivery system at a constant flow rate to the lower roll surface. After a period of cooling on the lower roll, the interface will form a thin shell of solidified metal, and then the molten metal will flow into the melt-pool formed by two rolls and side dams. Due to the “pre-cooling” effect on the lower roll surface, the melt is easier to solidify and form the other solidified shell when contacting the upper roll’s chilling surface. The two solidified metal shells have been meshed together before leaving the roll gap, and the solidified metal is rolled when it passes through the roll gap and becomes a strip.

2.2 Boundary conditions

\[ T = T_0 \quad (T_0: \text{inlet temperature}) \]
\[ u = u_0, v = v_0, w = 0 \quad (u_0, v_0, 0: \text{the initial velocity components in the } x, y, \text{ and } z \text{ directions}) \]
\[ Q_{in} = Q_{out} \quad (Q_{in}: \text{Inlet flow per second}, \ Q_{out}: \text{Outlet flow per second}) \]

In this paper’s simulation, the roll’s material is 5CrMnMo die steel, the density is 7830 Kg/m³, the thermal conductivity is 33 W/m°C, and the specific heat capacity is 460 J/Kg. °C. The value range of the heat transfer coefficient between the metal and the roller is between 0.8×10⁴~2.0×10⁴ W/m²°C [22], and the heat transfer coefficient in this paper is 1×10⁴ W/m²°C.

Table 2 shows the casting parameters and physical properties of 6.5 wt.% Si steel. In the numerical simulations, the parameters such as density, viscosity, enthalpy, and thermal conductivity are adjusted with temperature changes, as shown in Fig. 3, making the simulation more accurate, similar to the actual experiment.

3 Results and discussion

3.1 Effect of pouring temperatures

Jiang et al. [23] pointed out that the casting temperature has a greater impact on the expendable pattern shell casting with vacuum and low pressure (EPSC-VL). In the TSTRC process, the influence of the casting temperature also plays a predominant role. The simulation with a melt-pool height of 45 mm and the casting speed at 0.4 m/s was carried out, the initial pouring temperature varied from 1437 to 1477 °C, and all other parameters were kept constant.

To better reflect the effect of the flow field on the temperature field and turbulent flow energy, the central symmetry plane of the melt-pool is intercepted in the three-dimensional results to study and analyze the effect of the stirring effect.

Figure 4 a, b, and c show the melt-pool temperature and flow fields at different pouring temperatures. The arrow direction indicates the flow direction of the melt, and the length of the arrows represents the relative velocity value. As the pouring temperature increased, the melt-pool temperature was high and uneven. The solidus and liquidus position decreased, and the liquid phase area and the temperature gradient increased. This is because under other conditions unchanged, as the pouring temperature increases, the heat in the melt-pool increases, the cooling rate of the melt is slower, the solidified shell is thinner, and the heat exchange effect is poor. It can be seen from the flow field in Fig. 4 a, b, and c; the melt rushes into the wedge-shaped zone at a certain speed, and space is sharply reduced, and the squeeze effect of the twin rolls works together, a part of the melt is forced to flow back, while the upstream melt is still flowing at its original speed. At the intersection of the two melts, the melt flow in the direction of least resistance, that is, toward the liquid surface. After reaching the liquid level, the melt disperses under the action of gravity. When entering the area affected by the roll speed,
the rotating roll is driven forward to the roll gap so that the cycle repeats to form a vortex [24]. This forced convection has the benefit of improving the uniformity of temperature and composition [25]. The pouring temperature change did not significantly change the flow trend of the molten steel in the melt-pool. The vortex area inside the melt-pool did not change significantly, and the position of the vortex increased slightly with an increase in the pouring temperature. Because the temperature of the molten steel in the upper part of the melt-pool is relatively high, the viscosity of the molten steel changes less, and the temperature rise has little effect on the flow field in the melt-pool region.

As shown in Fig. 4 d, e, and f, the results showed that the solidified shell thickness decreased with the temperature change. Furthermore, it can be seen in Fig. 5c; the height of the kissing point was reduced from 21 to 10 mm. Generally speaking, as the pouring temperature increases, the superheat in the melt-pool increases, and the heat of the melt in the melt-pool is larger. The rolls take away less heat, allowing the liquid pocket to move to the melt-pool outlet, decreasing the length and thickness of the solidified shell, which will reduce the heat exchange effect between the roll and the melt.

As shown in Fig. 5 a and b, as the pouring temperature increased, the temperature increased at the melt-pool outlet, and the central temperature rose significantly. The results were consistent with the results obtained by Kim et al. [26]. The temperature difference between the surface and the center increased simultaneously. The temperature variation increased from 32 to 66 °C; the temperature at the centerline of the melt-pool outlet was distributed evenly across the width. When the pouring temperature is too high, the high-temperature area is more comprehensive. The viscosity in the upper part is low, and the central area is prone to incomplete solidification. It is easy to cause liquid leakage accidents, adversely affecting the continuity of the TSTRC process, and easy to oxidize the strip’s melt and surface. Zhang et al. [27] also believe that high casting temperatures are likely to oxidize the melt and thin strips, suggesting that the pouring temperature should be as low as possible. However, suppose the pouring temperature is too low. It is possible to cause the rolling force to be excessive, which can cause the thin strip to crack and negatively affect the continuity in the production process. More severe cases can trigger a rolling accident. So, it is crucial to choose a suitable temperature in the pouring process.

Figure 4 g, h, and i shows the turbulent kinetic energy and flow field distribution in the melt-pool at different pouring temperatures. As the pouring temperature increased, the turbulent kinetic energy in the liquid and solid-liquid two-phase regions in the melt-pool increased. When the pouring temperature was 1437 °C, the turbulent kinetic energy of the melt-pool was primarily distributed in 200~500 cm²/s². The pouring temperature was 1457 °C and 1477 °C; the turbulent kinetic energy in the melt-pool was distributed chiefly in 400~500 cm²/s². Due to the increase of the pouring temperature, the temperature in the melt-pool increases, and the

| Table 2  | Casting parameters and physical properties of 6.5 wt.% Si steel |
|----------|-------------------------------------------------------------------|
|          | Casting parameters                                                | Physical parameters                         |          |
|          | Values                                                             | Values                                      |          |
| Diameter of upper/lower roll (m) | 0.2/0.4                                                           | Liquidus temperature (°C)                  | 1422     |
| Width of upper/lower roll (m)    | 0.1                                                              | Solidus temperature (°C)                   | 1382     |
| Roll gap (mm)                    | 2                                                                | Latent heat of fusion (kJ/kg)              | 272      |
| The angle between rolls and horizontal line (°) | 45                                                                | Liquid heat capacity (J/kg°C)              | 784.3    |
| Pouring melt temperature (°C)    | 1437–1477                                                        | Solid heat capacity (J/kg°C)               | 790      |
| Casting speed (m/s)              | 0.4–1.2                                                          |                                            |          |
| Melt-pool height (mm)            | 25–45                                                            |                                            |          |

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Fig. 2  The schematic diagram of the TSTRC process (a) and enlarged view of the melt-pool (b)
velocity in the flow field also slightly increases, the viscosity of the liquid phase region and the solid-liquid two-phase region in the melt-pool decreases, and the vortex increases, so that the turbulence intensity in the melt-pool slightly increases, and the stirring in the melt-pool is also somewhat more intense.

Fig. 3 Thermal properties of 6.5 wt.% Si steel: a density, b viscosity, c enthalpy, and d thermal conductivity

Fig. 4 The temperature field and flow field (a–c), solidification field (d–f), and turbulent energy and flow field (g–i) in melt-pool at different pouring temperatures
Figure 6 shows the microstructure and grain size of the cross-section of the melt-pool outlet at different pouring temperatures. The structure in Fig. 6 a, b, and c is an equiaxed crystal structure, and with the increase of casting temperature, the size of grains increases significantly. This is caused by the difference in the contact time between the molten steel and rollers. The molten steel first contacts the surface of the lower roller. After the lower roller is pre-cooled, the superheat degree is reduced, so the solidification structure on the upper roll side is smaller, as shown in Fig. 9 a, b, and c, and Fig. 12 a, b, and c are also a similar result and reason. Figure 6 d, e, and f shows that the average grain size increases from 65 to 125 μm.

As the pouring temperature increases, the temperature in the melt-pool gradually increases. Higher temperatures cause dendrites to be re-melted, which is not conducive to the preservation of dendrites. Liu et al. [28] have reported that reverse flow exiting the TRC process can re-melt and break dendrite arms. Therefore, as the pouring temperature increases, the melt-pool nucleation rate decreases, and the grain size increases. Pirhayati and Aval [29] consider that a higher cooling rate will lead to fine grains. Wherefore, the cooling rate of the melt is fast, and the undercooling is large; the liquid phase at the front of the solid-liquid interface is more comfortable to nucleate, thereby easily forming a fine equiaxed crystal structure.
Fig. 9  The microstructure (a–c) and the grain size (d–f) at different casting speeds

Fig. 12  The microstructure (a–c) and the grain size (d–f) at different melt-pool heights
Moreover, Jiang [30] believes that the grain size can be refined through mechanical vibration. The violent stirring of the melt-pool during the TSTRC process also produced a similar effect. Wei and Li [31] believe that enormous turbulent kinetic energy can promote equiaxed crystal structures. Because the melt-pool flow field is relatively turbulent, the stirring is violent. The turbulent kinetic energy in the melt-pool is also considerable, breaking some dendritic arms based on heterogeneous nucleation. Under this stirring action, the crystal nucleus forms on the surface of the roller can be washed down, and the crystal nucleus forms on the surface of the roll can be swept down in the melt-pool under the action of the rotation and squeezing of the double rolls. At lower pouring temperature, the solidified shell in the melt-pool is thicker so that the heat transfer effect between the melt and the rolls is sufficient. The sizeable cooling rate and powerful stirring effect promote equiaxed crystals at the exit of the melt-pool.

### 3.2 Effect of casting speeds

Casting speed is closely related to the process of the TSTRC, as it is directly proportional to productivity. In the simulation process, the initial pouring temperature of 1457 °C and the melt-pool height of 45 mm maintained at a constant speed of 0.4~1.2 m/s, and other parameters unchanged.

Figure 7 a, b, and c show that the change in temperature field and flow field within the melt-pool is achieved at various speeds from 0.4 to 1.2 m/s. As the casting speed increased, the melt-pool temperature distribution changed considerably, and the temperature distribution became uneven. The melt-pool temperature generally rose, and the region of the liquid phase significantly increased with an increase in casting speed. The position of the solidus and liquidus decreased obviously with the rise in the casting speed. The rise in casting speed did not have a critical impact on improving the molten steel flow pattern in the melt-pool, and there was no apparent shift in the flow field vortex and location. With the increase of the casting speed, the vortex range increased, the flow velocity in the melt-pool increased, and the flow field was more turbulent. Since the faster the casting speed, the shorter the residence time of the molten steel in the melt-pool, and the faster the cooling time of the double rollers to the melt, the less sufficient heat exchange between the melt and the rolls in the melt-pool. As the casting speed increases, the linear speed of the roll speed also increases accordingly. In the sense of a constant roll gap, while keeping the melt-pool size unchanged, the inlet velocity of the melt increases simultaneously. The combined effect of the two causes the
As shown in the solidification field in Fig. 7 d, e, and f and the solidified shell thickness as shown in Fig. 8c, the kissing point’s height decreased from 16 to 3 mm with the casting speed increased. As the casting speed increases, the cooling time of the melt on the roll surface will decrease, which will cause the liquid pocket to move toward the outlet of the melt-pool, thereby reducing the length of the solidification section.

As shown in Fig. 8 a and b, when the casting speed rose, the temperature and the temperature fluctuation at the exit of the melt-pool increased. The temperature differential between the surface and the center rose from 50 to 83 °C. Significant temperature differences may increase the thermal stress of thin strips and increase the likelihood of surface cracking. The casting speed determines the melt-pool’s residence time and determines the cooling time of the melt. The casting speed increase makes the melt stay in the melt-pool shorter, resulting in a shorter cooling time of the melt, the heat loss of the melt decreases, which may cause the melt to flow out of the roll gap before it has cooled. Lee et al. [32] also consider that the melt’s heat loss through the cooling rolls decreases as the casting speed increases. Suppose the casting speed is faster than 1.2 m/s, most metal in the melt-pool is in the liquid and solid-liquid two-phase region, causing an incomplete solidification of the melt at the melt-pool outlet, then affect the quality of the thin strip, and may cause strip breakage or breakout accidents. When the casting speed is too slow, the kissing point is far from the melt-pool outlet, the temperature of the outlet region decreases, the solidifying region increases, and the rolling force increases may cause a production accident of the rolling card. Therefore, it is necessary to choose the right casting speed.

Figure 7 g, h, and i shows the turbulent kinetic energy in the melt-pool at different casting speeds. Jiang et al. [33] believe that during the metal filling process, as the fluid velocity increases, the turbulent flow of molten metal increases. As the casting speed increased, the turbulent kinetic energy in the liquid and solid-liquid two-phase regions in the melt-pool increased; the stirring was intense. When the rolling speed was 0.4 m/s, the turbulent kinetic energy in the melt-pool was mainly distributed in 400–500 cm²/s². When the rolling speed was 0.8 m/s, the turbulent kinetic energy in the melt-pool was mainly distributed in 400–600 cm²/s². When the casting speed was 1.2 m/s, the melt-pool turbulent flow energy was primarily distributed in 500–600 cm²/s². As the casting speed increased, the flow velocity and vortex of the molten steel in the melt-pool rose. Simultaneously, to maintain the dynamic balance of the melt-pool height, the inlet speed of the melt-pool needs to be increased, which directly leads to a significant increase in turbulent flow energy.

Figure 9 shows the microstructure and grain size at the exit of the melt-pool at different casting speeds. With the increase of the casting speed, the equiaxed crystal structure in the melt-pool outlet gradually coarsened, and the average grain size increased from 80 to 180 μm. Due to the increase of casting speed, the residence time of the molten steel in the melt-pool reduces, the convective heat exchange with the rolls is insufficient, resulting in a rise in the temperature in the melt-pool and a decrease of undercooling, and the solid-liquid two-phase region in the melt-pool decreases, resulting in the reduction of the nucleation rate. The turbulent kinetic energy inside the melt-pool is more significant when the casting speed is high and the stirring is intense; the crystal nuclei on the roll surface can be washed down, and some dendrite arms can be broken. Nevertheless, due to the high temperature in the melt-pool, it is easy to melt the crystal nucleus and the dendrite arms, leaving only a tiny part in the melt-pool as a base for heterogeneous nucleation. Therefore, the nucleation rate in the melt-pool decreases, and the microstructure at the melt-pool outlet increases.

### 3.3 Effect of melt-pool heights

The change in the melt-pool height directly affects the temperature field and the flow field in the melt-pool and then...
affects the quality of the thin strip. In the simulation, the initial casting temperature was 1457 °C, the casting speed was 0.4 m/s, the height of the melt-pool varied from 25 to 45 mm, and all other parameters remained constant.

Figure 10 a, b, and c indicates the melt-pool temperature and flow field distribution at various melt-pool heights. With the melt-pool height increased, the melt-pool temperature gradually decreased. The liquid phase region ratio in the melt-pool decreased. The solid phase region ratio and the solid-liquid two-phase region increased, and solidus and liquidus positions moved up obviously. When the melt-pool height increased, the vortex range and the melt-pool volume increased accordingly, and the vortex morphology was roughly similar. As the melt-pool height increases, the contact length between the melt and the rolls increases, enhancing the heat exchange effect between the melt and the rolls, so the cooling rate of the melt is fast, and the temperature field distribution in the melt-pool is more evenly. Besides, the vortex has sufficient reflux space, and the residence time increases so that the vortex in the melt-pool develops more fully. The full development of the vortex leads to a more uniform temperature distribution of the molten steel in the melt-pool. Also, it makes the temperature distribution in the width direction more uniform.

As shown in Fig. 10 d, e, and f and Fig. 11c, as the melt-pool height increased, the kissing point’s height increased from 4 to 16 mm, and the thickness of the solidified shell increased. The melt-pool height determines the continuous contact time of the melt with the two rolls and therefore determines the cooling time. When the stable melt-pool is less than 25 mm, the contact length between the melt and the upper roll is short. Most of the melt is in the two-phase region, and the solidified layer is thin. Until leaving the roll gap, the solidified layers on the upper and lower roll sides do not have enough thickness to complete the welding and cannot form the thin strip if the melt does not overflow the melt-pool. As the melt-pool height increases, the contact length between the melt and the upper roll increases. So the solidified layer becomes thicker, and the two solidified layers will be welded together before leaving the roll gap, and the quality of the thin strip will be better.

Figure 11 a and b are the temperatures from the surface to the center at the melt-pool outlet. As the melt-pool height increased, the temperature differential between the surface and the center of the melt-pool outlet decreased from 105 to 58 °C. As the melt-pool height increased, the temperature fluctuation of the centerline decreased, and the relative temperature distribution at the center of the melt-pool outlet became uniformly. The increase in the melt-pool height increases the contact length between the upper roll side melt and the roll surface. It enhances the double-sided cooling effect, thereby increasing the thickness of the solidified shell.

![Figure 10](image-url) The temperature field and flow field (a–c), solidification field (d–f), and turbulent energy and flow field (g–i) in melt-pool at different melt-pool heights

**Fig. 10** The temperature field and flow field (a–c), solidification field (d–f), and turbulent energy and flow field (g–i) in melt-pool at different melt-pool heights
The increase in the solidified shell thickness will enhance the heat exchange effect between the melt and the roll. Therefore, the increase in the melt-pool height enhances the heat exchange effect while increasing the solidified shell thickness. Therefore, when the melt does not overflow the melt-pool, the higher the melt-pool height, the better the surface quality of the strip.

Figure 10 g, h, and i show the turbulent kinetic energy at different heights of the melt-pool. As the melt-pool height increased, the liquid and solid-liquid two-phase regions’ turbulent kinetic energy decreased. When the melt-pool height was 25 mm, the liquid and solid-liquid two-phase regions’ turbulent kinetic energy was relatively large, and the part with considerable turbulent kinetic energy was distributed in 400–600 cm²/s². When the melt-pool height increased to 35 mm and 45 mm, the turbulent kinetic energy in the melt-pool was reduced, and the larger part of the turbulent kinetic energy was distributed in 200–500 cm²/s². In other words, under the condition of constant roll speed, the lower the melt-pool height, the greater the turbulent kinetic energy.

Figure 12 shows the distribution of the microstructure and the grain size at different melt-pool heights. It can be seen from Fig. 12 a, b, and c that the solidification structure at different heights of the melt-pool is a uniform equiaxed crystal structure. As the melt-pool height increased, the grain size in the melt-pool gradually decreased, and the average grain size decreased from 115 to 80 μm. Since the lower the melt-pool height, the worse the heat exchange effect between the molten steel and the roll’s surface, resulting in a higher temperature in the melt-pool, a smaller solid-liquid two-phase region, and a broader temperature gradient. Moreover, there are fewer crystal nuclei in the melt-pool, so when the melt-pool height is lower, it is easy to form a sizeable equiaxed crystal structure. When the melt-pool height is higher, the contact length between the melt and the roll is longer, the double-sided cooling effect is excellent, and the cooling rate is fast, so the undercooling and the nucleation rate is large. The solid-liquid two-phase region increases, and the temperature gradient decreases, and the liquid phase at the front of the solid-liquid interface is more comfortable to nucleate. Santos et al. [34] believe that the broader solid-liquid two-phase region is conducive to increasing nucleation rate. Furthermore, because more crystal nuclei in the melt-pool, the crystal nuclei contact each other under a lower temperature gradient and stop growing. The formation at the melt-pool exit is relatively uniform tiny equiaxed crystals.

4 Experimental verification

From the above simulation results, it could be seen that lower melt-pool height, too high or too low pouring temperature, and casting speed had a terrible influence on the quality of thin strips and the continuity of production. If the pouring temperature is too high, the casting speed is too fast, or if the melt-pool height is too low, it is easy to cause the thin strip to fracture or crack, as shown in the red wireframe in Fig. 13a. On the contrary, the stuck sample in the melt-pool shown in Fig. 13b is likely to cause rolling accidents, which is consistent with the prediction of the previous results. Therefore, it is imperative to select appropriate process parameters for experimentation. So, in the process of producing 6.5 wt.% Si steel by TSTRC, a melt-pool height of 45 mm, a pouring temperature of 1457 °C, and a casting speed of 0.4 m/s were selected to obtain the 6.5 wt.% Si steel strip.

Several experiments were carried out using the process described above. The raw materials used in the experiment are pure silicon and pure industrial iron with a purity of 99.99%. Put clean, pure iron and pure silicon into an induction heating furnace, and melt the raw materials under argon gas protection. When the molten steel is stirred evenly under electromagnetic action, use the AS852B infrared thermometer and disposable thermocouple to measure the molten metal’s temperature and pour when the temperature of the molten metal stabilizes at 1457°C, and a casting speed of 0.4 m/s were selected to obtain the 6.5 wt.% Si steel strip.
through the automatic control system, and then a thin strip is obtained. Use the AS852B infrared thermometer fixed on the bracket to measure the temperature on the centerline of the melt-pool outlet and the surface temperature of the melt-pool outlet, and transfer the data to the computer for record-keeping; the comparison between the melt-pool outlet temperature obtained through multiple experiments and measurements and the simulation results is shown in Fig. 14. The average temperature on the centerline of the exit of the melt-pool is 1285.25°C and 1285.41°C obtained by simulation and experiment. The average temperature of the exit surface of the melt-pool obtained by simulation and experiment is 1217.37°C and 1217.4°C, respectively. It can be seen from the comparison in the figure that the simulation and the experiment show good consistency. To quantify the error between the experimental and numerical results, root mean square error (RMSE) defined:

$$T_{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (T_{exp} - T_{sim})^2}$$

In the formula, $T_{exp}$ and $T_{sim}$ are the outlet temperature values of the melt-pool obtained by experimental measurement and simulation calculation, respectively, and $N$ is the number of test groups. According to the calculation of the equation, the $T_{RMSE}$ at the centerline of the melt-pool is 0.188, and the $T_{RMSE}$ at the exit surface of the melt-pool is 0.274. The results show that the simulation results have high accuracy.

Figure 15a shows the thin strip after cooling, and Fig. 15b shows the thickness of the thin strip. It can be seen from the figure that the surface quality of the thin strip was superior, and the edges of the strip were flush. The thickness of the thin strip is 2mm. Figure 16 shows the microstructure distribution obtained at the cross-section of the melt-pool exit through simulation and experiment. An area (1 mm×1 mm) was chosen at the central part of the cross-section in the melt-pool outlet to observe the microstructure of the simulation results. A metallographic sample (1 mm×1 mm) was cut at the central part of the cross-section of the thin strip, sanded with sandpaper and polished with a polishing machine, and etched with a mixed solution of 8% nitric acid and 92% ethanol for 48 s. Then conduct microstructure studies on an optical microscope. It also shows a good agreement between the simulation and experimental results, and the microstructure of 6.5 wt.% Si steel at the exit of melt-pool was 80μm equiaxed grain, which was beneficial to improve the quality and properties of the strip.

5 Conclusions

A three-dimensional finite element model was appropriately established based on the TSTRC process, and the casting
process of the 6.5 wt.% Si steel was numerically simulated fluently.

By analyzing the influence of different process parameters on the TSTRC process, the result shows that the casting process conditions profoundly impacted TSTRC processing. Simultaneously, it also had a meaningful impact on the continuity of production and the thin strip’s microstructure and quality.

Due to the melt-pool in the TSTRC process, the flow and stirring in the melt-pool were intense, and the turbulence intensity was high. While making the solute distribution in the melt-pool more uniform, it also made the heat exchange effect between the melt and the roll better, accelerated the cooling of the melt, and helped obtain a smaller equiaxed crystal structure. The thin strip structure was closer to the final structure of the finished plate and achieved the near-final formation of microstructure.

The TSTRC experiment was carried out under a pouring temperature of 1457 °C, a casting speed of 0.4 m/s, and a melt-pool height of 45 mm. High-quality thin strips were obtained through experiments. Comparing the microstructure obtained by simulation and experiment, the morphology, such as grain size, was also consistent with the experimental results, which not only verifies the correctness of the simulation but also verifies the feasibility of the experiment. Therefore, the TSTRC process can be reasonably predicted by numerical simulation.

**Author contribution** Cheng Zhou contributed to the conception of the study; Dongpo Xuan performed the experiment, contributed significantly to analysis and manuscript preparation, performed the data analyses, and wrote the manuscript; others helped perform the analysis with constructive discussions.

**Data availability** The data used to support the findings of this study are included within the article.

**Declarations**

**Ethics approval and consent to participate** Compliance with ethical standards. All authors agreed with the consent to participate.

**Consent for publication** The work described has not been published before (except in the form of an abstract or as part of a published lecture, review, or thesis). It is not under consideration for publication elsewhere; its publication has been approved by all co-authors, if any; its publication has been approved (tacitly or explicitly) by the responsible authorities at the institution where the work is carried out.

**Competing interests** The authors declare no competing interests.

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