Thermal Deformation Analysis of the Rotating Roller in Planar Flow Casting Process

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(Received on May 6, 2010; accepted on June 15, 2010)

In planar flow casting (PFC) process for the manufacture of amorphous ribbon, the thermal deformation of the rotating roller is an important phenomenon that is not only for accuracy controlling the proper nozzle/substrate gap size to obtain the desired ribbon with uniform thickness and excellent quality, but also for stabilizing the manufacture and minimizing its cost. In this paper, by mapping and interpolating 2D temperature results (which are obtained by a conjugated solution of the thermal-fluid dynamics of the melt puddle zone and the heat transfer of rotating roller zone) into a 3D temperature distribution of the roller, the thermal behavior and the roller deformation features of rotating roller at a quasi-steady state and over a initial transient evolution in PFC process are analyzed. The effect of operating parameters and PFC configurations on the thermal and deformation behavior is theoretically examined. Results show that in PCF process, the plastic deformation of the roller occurs in a very thin surface layer under melt puddle, sharply decaying a lower value along the circumferential revolution. The thermal expansion is non-homogeneous on the roller surface and the location of the maximum roller expansion is beyond the coverage of the melt puddle due to the roller revolution. There is a rapid increase of the thermal expansion from the melt contact to ribbon separation. However, for the small melt puddle length, the fluctuation of the expansion along circumferential direction is very small (<10 μm) while the variation of the expansion along ribbon width direction is larger. With the evolution of the time, the thermal expansion rapidly increases at the beginning of the casting process and gradually increases, and the fluctuation of the roller surface expansion increases until a quasi-steady state when the heat balance is reached. The operating parameters and PFC configurations affect the magnitude and profile of roller thermal expansion. It is necessary to pay great attention to the effect of large roller deformation on the small nozzle/roller gap and thin ribbon thickness to avoid some qualities and operating problems in PFC process for the formation of amorphous ribbon.

KEY WORDS: planar flow casting; single roller; thermal stress; thermal deformation; amorphous alloy.

1. Introduction

In planar flow casting (PFC) process for the manufacture of amorphous alloy ribbon, the design of the rotating roller is very important because it largely determines the formation of the amorphous state and the qualities of the ribbon. First, the cooling channels within the roller for the design should be efficient to provide enough high cooling rates (usually >10⁶ K/s) for the rapid solidification process in order to avoid the appearance of crystallization in the ribbon. Secondly, the roller has to retain appropriate temperature distribution and thermal deformation to increase roll life and guarantee the desirable shape and qualities of the ribbon. As the cooling roller rotates, the roller surface is repeatedly heated up and cooled down from its cyclic contact with melt puddle. The continuous cycles of cooling and heating cause substantial variations in surface temperature of the roller and ultimately lead to the thermal expansion and the deformation of the roller. Because in PFC process the gap between the nozzle slit and the roller surface in PFC process is very small and the produced ribbon is very thin, the thermal deformation of the roller will cause the change of the gap between the nozzle slit and roller surface. If the nozzle slit has not been adjusted corresponding to the thermal expansion of the roller, this will affect the manufacture of the ribbon with uniform thickness, and more seriously, can lead to the nozzle slit in contact with the roller surface and cause the interruption of the casting practice. The large thermal stress variations on the roller surface also may cause wear of roll and reduce the roller life. In addition, the non-homogenous thermal expansion will change the roundness of the roller. It has been found that the periodic variations in ribbon thickness and the oscillations of the menisci in the melt puddle are associated with the non-homogeneity of the roller. Therefore, it is very necessary to evaluate roller stress and deformation behavior in planar flow casting process for amorphous ribbon formation.

Many studies have been done for investigating the deformation and thermal-mechanical behavior of the rotating roller in other processes, such as the roller in hot powder pressing, the roller in a cold rolling process, the work roll in hot strip rolling process, the cooling roller in twin-roll strip continuous casting. However, relatively little attention has been given to the evaluation of roll stresses and deformation behavior of the rotating roller in PFC process. Compared with the above-mentioned processes, PFC process involves large amounts of energy transferred over small periods of time and in small spatial
size of melt puddle. The interfacial heat transfer and the roller surface heating are strongly dependent on the flow and heat transfer behavior in the melt puddle. The narrow gap distance, the small puddle size and the desired high cooling rate in PFC process have limited process parameters to a narrow operating window for a stable casting, and thus the deformation of the roller has a more significant influence on the success of this process. Controlling a constant gap height adapted to the roller expansion is essential to obtain the uniform ribbon thickness and achieve a continuous casing, especially for the production of thinner and wider ribbon.

Using a high-speed photography of a run-out meter, Byrne et al. measured the time-dependent gap shrinkage due to thermal expansion of the roller for a melt-spinning process. However, due to the high-speed rotation of the cooling roller and the typical very small melt puddle, for the melt with higher temperature (>1500 K), it may be difficult and time-consuming to accurately investigate experimentally the roller thermal expansion underneath the melt puddle for casting operations with possible parameter variations and melt composition fluctuations in PFC process. Numerical method can provide an alternative to laboratory tests or plant trials to study the deformation behavior of rotating roller.

Previous numerical studies were mainly focused on flow and heat transfer behaviors in melt puddle without involving heat transfer in the rotating roller. Research activities have not been performed on numerical simulation of the deformation of the cooling roller and its effect on amorphous ribbon formation in PFC process although few work has involved in the conjugated heat transfer between the melt and the rotating roller.

The present paper is a follow-up to our previous work and focuses on the theoretical investigation of stresses distribution and deformation behavior of the rotating roller by a 3D elastic–plastic numerical method. It should be mentioned that the neglecting of thermal expansion in previous studies is valid for analyzing the flow and heat transfer behaviors in PFC process because in a realistic casing, a constant gap distance always is desirable by dynamically adjusting the location of the nozzle relative to the deformed roller surface. A sequential thermal-stress analysis is performed, similar as the numerical method from the work of Kang et al. The heat transfer and temperature fields in the rotating roller were first obtained by solving a two-dimensional conjugated heat transfer model between the melt puddle and the cooling roller and then were expanded to 3D results. The characteristics of the deformation and stresses distribution of rotating roller in PFC process are presented. The deformation behavior varying with time in the roll revolutions is discussed. The effect of operating parameters and PFC configurations on the thermal and deformation behavior are examined through numerical calculations. Several implications related to ribbon formation for avoiding some of the important problems resulting from the deformation of the rotating roller in PFC process are discussed.

2. Analysis Methods
2.1. Model Assumptions

For PFC process, which has a large-scale discrepancy between the microscopic melt puddle size and the macroscopic roller geometrical structures (e.g., length scale over 4 orders of magnitude from ribbon thickness to the roller diameter), it is a tough story to numerically describe the effect of flow and heat transfer in the melt puddle zone on temperature distribution of the whole roller by a conjugated fluid/solid heat transfer analysis and then a subsequent stress/deformation analysis. The deformation field doesn’t change the temperature distribution of the roller. This is a reasonable approximation in PFC process, because in reality the roller deformation is very small relative to the roller diameter and the roller layer thickness. The substantial temperature variation in the roller resulting from the different gap distances during the roller deformation process can be neglected.

(1) A sequential thermal-stress analysis method is used to predict the roller deformation, i.e., it is performed by a heat transfer analysis and then a subsequent stress/deformation analysis. The deformation field doesn’t change the temperature distribution of the roller. This is a reasonable approximation in PFC process, because in reality the roller deformation is very small relative to the roller diameter and the roller layer thickness. The substantial temperature variation in the roller resulting from the different gap distances during the roller deformation process can be neglected.

(2) The temperature fields of the roller were obtained by solving a two-dimensional model, which included the fluid flow with free surface and surface tension, heat transfer with phase transformation in the puddle zone and heat transfer in the roller zone. The 2D treatment is a reasonable approximation for the amorphous ribbon production with large ratio between ribbon width and ribbon thickness.

(3) In order to describe the dynamical process during the deformation of the rotating roller, an assumption of the relative constant gap distance between the nozzle slit and the deformed roller surface is used for parametrical studies. The constant value is relative to the deformed roller surface, which is maintained by adjusting the nozzle slit. The idealized assumption of the relative constant gap distance is from a realistic consideration that the gap distance is always kept constant by adjusting the location of the nozzle corresponding to the deformation of the roller in order to meet the requirements from the ribbon quality with uniform thickness and stable operations.

(4) The obtained 2D results of temperatures field of the roller are assumed to have the uniform distributions in the width direction of the formed amorphous ribbon and are expanded into 3D temperature field along the ribbon width by use of mapping and interpolation method from the nodal temperatures and geometrical data of 2D temperature results while the roller temperatures outside the ribbon width are assumed to remain at an ambient temperature. Then a sequential thermal stress analysis is performed by using a 3D FEM elastic–plastic model.

(5) The creep behavior of the roller is not taken into consideration.

(6) The physical external force caused by melt ejection pressure (the order of 10–40 kPa) is neglected because it seems to not have much contribution to the stress.
distribution in the roller.

In above assumptions, it should be noted that in a PFC process for amorphous ribbon manufacture, there exists an obvious interaction between the deformed roller surface and the melt puddle because the gap distance between the nozzle and the roller surface is too small (usually 0.2–0.4 mm at a quasi-steady state). If one imagines that the nozzle slit is fixed at an initial gap value, it is likely that the roller deformation value is over the gap distance (as shown in Chap. 3), which leads to draw a conclusion that the predicted results were meaningless. However, in a realistic casting, the gap distance is a relative value. The contact between the nozzle and the deformed roller surface and the large variation of gap distance are never expected to occur due to the requirement of stable operation and uniform ribbon thickness. The location of the nozzle slit is always dynamically adjusted corresponding to the deformation of roller but not fixed to keep a relative constant gap as soon as possible, especially at a quasi-steady state. Although it is very important to keep a constant the gap distance for success manufacture of the ribbon, the change of roller diameter resulting from roller expansion is very small compared with the dimension of roller diameter and roller layer thickness. Therefore, the substantial temperature variation can be neglected, and we can use the obtained temperature fields under a relative constant gap distance assumption to perform the deformation analysis of the rotating roller. Based on a realistic numerical consideration (i.e. the relative constant gap distance should be maintained by adjusting the location of the nozzle to obtain the temperature fields, and the deformation field doesn’t change the temperature distribution when roller thermal expansion occurs), the present study provides a simple and feasible method to theoretically analyze the deformation features of the rotating roller in PFC process.

2.2. Computational Conditions

Figure 1 shows the 3D simulation domain, mesh system and boundary conditions for thermal deformation analysis of the cooling roller. Due to a very high temperature gradient occurred in the surface layer of the roller and underneath the melt puddle, local fine mesh is employed. It is assumed that no deformation occurs at the fixed sides and a symmetrical boundary is used at Z=0 plane, shown in Fig. 1(b). The simulation conditions and material properties of the roller used are summarized in Table 1 and the others if not mentioned can be found elsewhere.14

3. Results and Discussion

3.1. Thermal and Deformation Characteristics of the Rotating Cooling Roller

A detailed description of the fluid flow and heat transfer behavior in the puddle zone and heat transfer in the rotating roller zone can be found elsewhere,14,15 but a brief summary of the important thermal characteristics of the roller in PFC process at a quasi-steady state in PFC process is given here for reference, as shown in Fig. 2. The melt heat conductivity is 21.0 W·m⁻²·K⁻¹. It can be seen from Fig. 2(a) that although there is a large local temperature variation in the surface layer of the roller, as a whole, the circumferential temperature distribution of the cooling roller shows a circular ring profile16 and the radial temperature from the outer to the inner shows a gradient decreasing dis-
Table 1. Simulation conditions and material properties used in the analysis.

| Items                                      | Values/Unit                      |
|--------------------------------------------|----------------------------------|
| (a) PFC configurations                     |                                  |
| Roller diameter                            | 0.60m, 0.70m                     |
| Copper thickness (DE)                      | 0.02m                            |
| Slit width of the nozzle                   | 0.0004m, 0.0006m, 0.0008m        |
| Gap distance                               | 0.0003m, 0.0004m, 0.0002m        |
| Cooling water channels (BC and CD)         | 25mm and 70mm, respectively     |
| Ribbon half width (EF)                     | 0.024m                           |
| Fixed sides of the roller (AB and AH)      | 0.03m and 0.025m, respectively   |
| (b) Operating parameters                   |                                  |
| Roller rotation speed                      | 20m s⁻¹, 25 m s⁻¹, 30 m s⁻¹       |
| Melt inlet temperature                     | 1533K, 1583K                     |
| Melt ejection velocity                     | 1.6 m s⁻¹, 1.8 m s⁻¹, 2.0 m s⁻¹   |
| Heat transfer coefficient between water wall and the roller | 22987.8 W m⁻² K⁻¹, 27000 W m⁻² K⁻¹ |
| Ambient temperature                        | 300K                             |
| (c) Material properties                    |                                  |
| Melt conductivity                          | 8.99 W m⁻² K⁻¹, 21.0 W m⁻² K⁻¹, 34.0 W m⁻² K⁻¹ |
| Density of the roller (copper)             | 8978 kg m⁻³                     |
| Specific heat of the roller (copper)       | 381 J kg⁻¹ K⁻¹                  |
| Heat conductivity of the roller            | 387.56 W m⁻² K⁻¹                 |
| Temperature-dependent elastic modulus of the roller | 135(GPa at 308K), 121(GPa at 373K), 114(GPa at 473K), 107(GPa at 573K) and 90(GPa at 673K) |
| Poisson ratio                              | 0.32                             |
| Thermal expansion coefficient (1/K)        | 1.461E-5 + 7.237E - 9 T (T is roller temperature, K) |
| Stress-strain curve for copper roller      | Ref. 16                          |

* The bolded parameters are used in a referenced case and other non-mentioned can be found in Ref. 14. The gap distance is a relative value between the adjusted nozzle slit and the deformed roller surface in this study.

Fig. 2. Typical thermal characteristics of the roller in PFC process at a quasi-steady state. (a) Temperature distribution of the roller; (b) local enlarged temperature distribution underneath the melt puddle zone; (c) streamlines in melt puddle zone and temperature distribution in roller zone; (d) Interpolated 3D temperature field of the roller.

Fig. 3. Von-Mises stress contours of the roller at a quasi-steady state (deformation scale factor: 100): (a) 3D roller surface; (b) XY plane (Z=0).
puddle, the equivalent plastic strain rapidly decays to lower values, which shows the plastic deformation of the roller only occurs in a short curve length and very thin layer region. The elastic deformation is dominant in the deformation of the roller in PFC process after the roller passes the melt puddle zone.

The difference between the local raised roller temperature along ribbon width direction and the ambient temperature in other portion of the roller leads to the compressive stress occurring at high temperature region during a casting process. The larger values of the compressive stress concentrate on the roller surface near the roller downstream meniscus, which is represented by minimum principal stress, shown in Fig. 5.

Figure 6 shows the thermal expansion of the roller surface at a quasi-steady state. The values are mirrored based on the $XY$ plane ($Z=0$ m). It can be found that the deformation of the rotating roller is non-uniform on the roller surface. Under the present roller construction and constraint, the maximum thermal expansion of the roller is about 0.32 mm. It means that in a realistic casting for this case, the location of the nozzle should be adjusted (about 0.32 mm) relative to an initial value to keep a constant gap distance. The predicted thermal expansion value provides an important reference to the adjusted magnitude of interference between the nozzle and the deformed roller surface in case the nozzle slit contacts with the rotating roller in the extreme by adjusting the location of the nozzle. The locations of the maximum roller deformation don’t occur under the melt puddle but develop away from the melt puddle along the circumferential direction. Furthermore, the roller appears to deform in such a way that the middle expansion of the roller is larger than the sides along the width direction of the ribbon (Z direction), and a roller crown can be observed on the surface of the roller (also see sliced $X=0$ plane). Figure 7 presents how irregular the roller deformation on the roller surface is in the circumferential and the ribbon width direction in PFC process. The thermal expansion values seem to have decreased significantly by the end of every revolution of the roller. The minimum value is located further away from the upstream of the melt puddle. When the roller surface contacts with the melt, the thermal expansion rapidly increases. It continues to increase out of the melt puddle because the heat from the melt is transferred along the circumferential and radial direction into the roller with the rotation of the roller. It decreases after ribbon separation (also see Fig. 6), followed by a relative smooth decrease in the roller expansion in the bottom half of the roll surface. The fluctuation between the maximum and the minimum thermal expansion on the roller surface is not large (only about 20–30 μm). This can be contributed to the high-speed rotation of the cooling roller (30 m/s), which makes the heat from the melt dissipated along roller surface rather than fully accumulated on the substrate under the
melt puddle. For the puddle length between the upstream \((X_u)\) and downstream detachment locations \((X_d)\), the variation of the deformation of the roller seems to be smaller \((<10 \mu m)\), as shown in Fig. 8(a). Relative to the small fluctuation of the roller thermal expansion in melt puddle length, the variation of the roller deformation along the ribbon width direction is larger, about 40 \(\mu m\) at \(X=0\) plane from the middle \((Z=0)\) to the edge of the ribbon \((Z=0.024 m)\). The closer to the edge of the ribbon the larger the variation of roller deformation is, shown in Fig. 8(b).

3.2. Initial Development of the Deformation of the Rotating Roller

Experimental results have demonstrated that smooth ribbon production is associated with the formation of a stable melt puddle at a quasi-steady state over a short initial transient time. In practical casting of amorphous ribbon, it is very important to perform the dynamical and fine tuning of the nozzle/roller gap during the periods from the initial state to the quasi-steady condition after the melt with high temperature impinges on the rotating roller. This is because in PFC process too large gap causes the nozzle no longer interacting with the flow region formed on the roller (free jet conditions), which will result in a disturbed and unconstrained melt puddle, and affect the qualities of the ribbon or the formation of thin and wide ribbon. Too small gap, if not adjusted according to the roller deformation, may cause the nozzle slit in contact with the roller surface and lead to the failure of casting operation, even a serious safety accident. Furthermore, the unstable gap adjustment will cause the variation in ribbon thickness. Therefore, it is necessary to evaluate the initial development in roller surface temperature and roller deformation in order to control a constant gap for the manufacture of the ribbon with uniform ribbon thickness.

The computational conditions for Fig. 9-13 are the same as those in Sec. 3.1 except that a lower melt heat conductivity of 8.99 \(W \cdot m^{-2} \cdot K^{-1}\) is used. Figure 9 shows temperature profiles inside a roller subject to melt impinging at \(X=\) 0 and \(X=5\) mm for different times. It can be found that the thermal penetration depth increases over time. By the end of the first revolution \((t=0.06345 \, s)\), the depth value hardly changes over time. However, the localized roller temperature under the puddle will keep increasing with the evolu-
tion of time as the roller heats up until a quasi-steady state. A larger localized temperature gradient only occurring on a very thin layer near the roller surface and an approximate uniform radial temperature gradient also can be observed from Fig. 9. This feature of temperature distribution leads to small fluctuation of thermal expansion around the circumferential direction.

Figure 10 shows the time history of roller surface temperature around the circumferential direction. Once the roller contacting with the melt, the surface temperature sharply rises at 0.202 ms. With the rotation of the roller, the heat is first circumferentially transferred into the roller, which leads to the temperature rise on roller surface further downstream of melt puddle (Label A through E). With the roller revolution, the surface temperature appears to have decreased significantly by the end of a revolution before the roller contacts with the melt next revolution. Although a quasi-steady melt puddle shape is formed within a very short period of time,14) in the subsequent revolutions, significant increases in roller surface temperature during continuous melt spinning take place until a quasi-steady state where the heat balance is reached.

The maximum and minimum thermal expansion of the rotating roller on the central cross-section \(Z=0\) according to the casting time is illustrated in Fig. 11. It is found that the thermal expansions rapidly increases at the beginning of the casting process and gradually increases in further process. The fluctuation of the roller surface expansion increases with time evolution. In this case, the thermal expansion of the roller increases up to about 0.30 mm after 69 revolutions. Therefore, it is required to adjust the nozzle/roller gap as the casting initial time increases in order to remain a constant gap distance.

Figure 12 shows the thermal expansion of the roller surface and cooling water wall with time evolution. It is found that the thermal expansion at the roller surface is larger than at the cooling water wall. With the evolution of time, the difference of thermal expansion between the roller surface and cooling water wall will increase. At \(t=0.202\) ms, only the roller surface is expanded and the thin thermal penetration layer may not be able to “see” much of the effect of the water cooling. With the increased time, the cooling water wall starts to deform. At \(t=0.533\) ms, when the melt puddle shape starts to form,14) the deformation of the roller under the puddle is only about 25 \(\mu\)m. Therefore, the subsequent major deformation is from the re-distribution of the roller temperature resulting from the rotation of the roller and the cooling of water (also see Fig. 10).

Figure 13 gives the equivalent plastic strain on the roller surface at different times. The plastic strain mainly occurs on the roller surface layer under the melt puddle and further downstream out of the puddle. The strain extends further downward of the puddle with the evolution of the time, but the maximum equivalent plastic strain doesn’t change much more. At \(t=0.202\) ms, when the melt in contact with the roller surface, the plastic deformation occurs. At a quasi-steady state, the plastic deformation extends only about 80 mm away from the nozzle slit.

3.3. Thermal Deformation Analysis According to Parameters Variations

Having understood the typical thermal and deformation behavior at a quasi-steady state and initial transient state, the effect of operating parameters and different PFC configuration is investigated. All parameters are held constant while only the studied condition is varied. The case which uses the bold parameters in Table 1 is considered as a referenced case.

3.3.1. Operating Parameters

Figure 14 shows a typical von-Mises stress and equivalent plastic strain at \(Z=0\) plane with various roller speeds. Larger plastic strain only appearing on a very thin layer can be observed. The profiles of von-Mises stress and equivalent plastic strain are similar for different roller speeds, but
lower roller speed causes the stress and strain distribution further away from the slit. It means that they are dependent on the melt puddle length (also see Table 2). The affected domain of roller plastic deformation under the puddle is larger due to the longer residence time. In addition, with the decrease of the roller speed, the thermal expansion decreases because the slower roller speed leads to an overall decrease of the roller temperature. There is about 30 \( \mu \)m reduction in present case at \( X=0 \) m when the roller speed varies from 30 to 20 m/s.

The comparison of thermal expansion at different section for different operating parameters is shown in Fig. 15. A large melt ejection velocity leads to a larger thermal expansion. The increase of the superheat, melt heat conductivity and roller speed cause an increase in thermal expansion at \( X=0 \) plane under the center of nozzle slit and \( Z=0 \) plane. Table 2 gives the qualified melt puddle length, the thermal expansion values at the selected points and the involved fluctuations for different parameters. It can be found that the rotating roller speed affects the fluctuation of the thermal expansion along circumferential direction. With the decrease of the roller speed, the fluctuation increases although the deformation reduces. Furthermore, the lower roller velocity leads to a longer melt puddle and thicker ribbon, which may reduce the cooling rate. Too high melt ejection velocity may not be desirable because it leads to an increase in ribbon thickness, melt puddle length, and roller deformation. It seems that strengthening water cooling will be favorable to reduce the thermal expansion, its fluctuation and melt puddle length. Although the lower melt heat conductivity can obviously reduce the roller deformation and the fluctuation of the deformation, it has a longer melt puddle, which may result in a low solidification rate and the appearance of partial crystallization. Therefore, it is necessary to seek out some compromise between the lower roller deformation and the desired ribbon quality when optimizing the various parameters.

### 3.3.2. PFC Configurations

Figure 16 shows the effect of different PFC configurations on the roller deformation. It can be observed that the roller deformation doesn’t change much with gap distance varying from 0.2 to 0.4 mm. However, the increase of slit width from 0.2 to 0.4 mm seems to cause a significant increase in roller expansion. The fluctuation between the middle (\( Z=0 \)) and the edge of ribbon (\( Z=0.024 \)) also increases with the increased slit width, shown in Fig. 16(a). The deformation of the roller with large diameter is relatively

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**Table 2.** Theoretical melt puddle length and thermal expansion values at selected points for different operating parameters.

| Variation of Operating Parameters | Melt puddle length | Expansion at \( Z=0 \) plane | Expansion at \( X=0 \) Plane |
|-----------------------------------|--------------------|-----------------------------|-----------------------------|
|                                   | Xu (mm)            | Xd (mm)                     | Xd-Xu (mm)                  | Min. (mm) | Max. (mm) | Fluctuation (Max.-Min.) \( (\mu m) \) | Middle of ribbon width (mm) | 1/4 of ribbon width (mm) | Edge of ribbon width (mm) | Fluctuation (Middle-Edge) \( (\mu m) \) |
| Roller speed 30 m s\(^{-1}\)      | -0.80              | 3.68                        | 4.48                        | 0.296      | 0.322      | 26                                        | 0.305                      | 0.296                      | 0.265                      | 40                             |
| Roller speed 25 m s\(^{-1}\)      | -0.94              | 4.23                        | 5.17                        | 0.274      | 0.306      | 32                                        | 0.284                      | 0.276                      | 0.247                      | 37                             |
| Roller speed 20 m s\(^{-1}\)      | -1.19              | 5.18                        | 6.37                        | 0.263      | 0.299      | 36                                        | 0.276                      | 0.267                      | 0.240                      | 36                             |
| Melt ejection velocity 1.8 m s\(^{-1}\) | -1.08              | 4.67                        | 5.75                        | 0.310      | 0.338      | 28                                        | 0.319                      | 0.310                      | 0.278                      | 41                             |
| Melt ejection velocity 2.0 m s\(^{-1}\) | -1.37              | 5.79                        | 7.16                        | 0.328      | 0.356      | 28                                        | 0.337                      | 0.327                      | 0.294                      | 43                             |
| Cooling water heat transfer coefficient 27000 W m\(^{-2}\) K\(^{-1}\) | -0.81              | 3.60                        | 4.41                        | 0.273      | 0.298      | 25                                        | 0.282                      | 0.273                      | 0.245                      | 37                             |
| Melt inlet temperature 1583K       | -0.87              | 3.96                        | 4.83                        | 0.303      | 0.330      | 27                                        | 0.312                      | 0.302                      | 0.271                      | 41                             |
| Melt heat conductivity 34.0 W m\(^{-1}\) K\(^{-1}\) | -0.68              | 2.74                        | 3.42                        | 0.298      | 0.324      | 26                                        | 0.307                      | 0.298                      | 0.268                      | 39                             |
| Melt heat conductivity 899 W m\(^{-1}\) K\(^{-1}\) | -1.04              | 6.70                        | 7.74                        | 0.261      | 0.286      | 25                                        | 0.269                      | 0.261                      | 0.235                      | 34                             |
lower than small roller diameter. The deformation behavior is associated with the features of temperature distribution of the rotating roller in different PFC configurations, which is given in Ref. 14).

3.4. Effect of Roller Deformation on the behavior of Melt Puddle and the Design of the Roller and Nozzle Slit

Although the size of melt puddle responsible for transferring the melt heat into the cooling roller is very small in PFC process, our numerical results show in PFC process the large roller deformation relative to the small nozzle/roller gap and the thin ribbon thickness should be paid great attention. The thermal deformation of the rotating roller in PFC process is an inevitable phenomenon. However, the amount of deformation may be controlled by operating conditions as well as the design of PFC configurations. The results of this model have several implications for avoiding some of the important problems related to physical behavior of melt puddle and the design issues of PFC configurations in planar flow casting.

3.4.1. Ribbon Thickness Variation and Gap Distance Adjustment

In PFC process, the ribbon thickness obviously affects the cooling rate, the amorphous microstructure and magnetic properties of the ribbon, so it is very important to control the ribbon thickness as a function of the process variables. Most studies have been done to investigate the effect of the gap size between the nozzle and the roller on the ribbon thickness.\textsuperscript{[19,20]} According to the work from Sung et al.,\textsuperscript{[20]} it is found that the strip thickness decreases rapidly as the gap becomes narrow due to the variation in the friction loss at the puddle area. Byrne et al. presented a profile of how the gap varies with the roller deformation throughout a cast.\textsuperscript{[19]} They concluded that the periodic variations in thickness are due to the out-of-roundness of the wheel. Therefore, in order to obtain the required ribbon thickness, careful analysis of roll deformation is the key because the non-uniform thermal expansion of the roller prevents precise measurement and control of the gap size.

Reducing the roller speed, strengthening the cooling and increasing the roller diameter will reduce the thermal deformation. The increase of the melt injection and nozzle slit width will obviously increase the roller thermal expansion. It is suggested that the gap distance is adjusted according to the thermal expansion of the roller from a large to the desired gap value, depending on the process parameters and PFC configurations. The gap size should remain a constant value at a quasi-steady state for the manufacture of the ribbon with desirable uniform thickness. The magnitude of interference between the nozzle and the deformed roller surface should be considered in case the nozzle slit contacts with the rotating roller in the extreme.

3.4.2. Melt Puddle Stabilization

It seems that the circumferential non-homogeneity on the roller surface is not large (about 25–36 μm) in the present variations of operating parameters due to the high-speed rotation of the roller. When covered in the melt puddle length, it is even smaller (<10 μm). However, for very thin ribbon production, the rapid increase of roller expansion under the melt puddle may lead to the disturbance of the melt puddle as the rotating roller moves through it. It has been found that a low frequency vibration of the menisci is related to the out-of-round of the roller, and the disturbance may be associated with a cross-stream defect of ribbon leading to a significant and undesirable reduction in the
local thickness of the ribbon. 1) A design issue that the front lip of nozzle slit is little higher than the back lip corresponding to the roller expansion may increase the stability of the puddle, but further study of the effect of roller deformation on melt puddle stability still should be done.

3.4.3. Design of the Roller and Nozzle Slit

The design of the rotating roller is very important because a good designing can considerably improves the cooling efficiency of the roller as well as the qualities of the amorphous ribbon. In PFC process, numerical results show the deformation of the roller shifts the original position of the cooling water channel. This will affect heat transfer between cooling water and the roller. In addition, the roller crown cannot be neglected. This is because that in reality, temperature distribution along the ribbon width direction is more non-uniform than the present temperature field obtained by theoretical mapping and interpolation of 2D temperature results, the roller crown may be more obvious. Increasing the heat input of the roller under the edge of the ribbon or designing a nozzle slit adapting to the roller deformation in width ribbon direction are possible methods to alleviate the roller crown.

In PFC process, it also is found that the yielding of the roller and plastic strain occurs over a very thin surface layer of the rotating roller. Rotating roller life is reduced by the re-machining needed to remove the effects of roller wear and non-resilient deformation. However, it can be expected that it is very difficult to minimize the plastic strain by lowering the roller surface temperature under melt puddle, because most heat from the melt should be extracted by the rotating roller to guarantee the desired high cooling rate.

Roll material which comes in contact with the melt puddle faces a continuous cycle of cooling and heating, fatigue analysis will help in predicting the actual roll life. Further extension of this work still involves the verification of the model from the plant measurements, accuracy constraint conditions and material properties in high temperature and the actual interfacial interaction between melt puddle and roller rotation.

4. Conclusions

A mathematical model has been developed to predict the thermal and deformation behavior of the rotating roller in planar flow casting for amorphous ribbon formation at a quasi-steady state and over an initial transient evolution. The effect of various operating parameters and PFC configurations on the roller deformation is theoretically examined and analyzed. Several implications for avoiding some of the important problems resulting from the roller deformation are discussed. The following conclusions can be drawn from numerical results:

(1) The roller deformation is non-uniform at a quasi-steady state. The thermal expansion value seems to have decreased significantly by the end of every revolution of the roller along circumferential direction. The plastic deformation of the roller occurs on contacting with the melt, which leads to the lower von-Mises stress underneath melt puddle. The thermal expansion of the roller rapidly increases and continues to increase out of the melt puddle. After ribbon separation, there is relative smooth decrease in the roller expansion in the bottom half of the roller surface.

(2) For the small puddle length over very short solidification time in PFC process, the variation of the deformation of the roller in the melt puddle length seems to be small. The fluctuation between the maximum and the minimum thermal expansion on the roller surface is not so much large due to the temperature distribution features of the rotating roller in PFC process. Relative to the small fluctuation along the circumferential direction in melt puddle length, a roll crown can be observed on the surface of the rotating roller, and the variation of the roller deformation along the ribbon width direction is larger.

(3) With the evolution of time, the difference of thermal expansion between the roller surface and cooling water wall will increase. The plastic strain extends further downward of the puddle with time. Significant increases in roller surface expansion during continuous melt spinning take place until a quasi-steady state where the heat balance is reached.

(4) The operating parameters and PFC configurations affects the magnitude and profile of roller thermal expansion. Reducing the roller speed, strengthening the cooling and increasing the roller diameter will reduce the thermal deformation. The increase of the melt injection velocity, the melt inlet temperature and nozzle slit width will increase the roller thermal expansion. It is necessary to seek out some compromise between the lower roller deformation and the desired ribbon quality when the parameters are optimized.

Acknowledgements

The authors would like to acknowledge gratefully the support of National Natural Science Foundation of China (NSFC) (Grant No. 50704014).

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