Effect of the chill wheel cooling during continuous free jet melt-spinning

Vpliv hlajenja valja med kontinuirnim litjem na napravi za hitro strjevanje

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Abstract: New method for determining contact resistance through variable heat transfer coefficient is introduced which takes into account physical properties of the casting material, process parameters and contact time/length between metal melt or metal ribbon and substrate and enables cooling and solidifying rate prediction before the experiment execution. The calculations show that contact resistance between metal melt and chilling wheel has a great influence on melt cooling and wheel heating rate, and must not be neglected in numerical calculations, even if its value is very low.

Influence of process parameters on cooling and solidifying rate and consequently on microstructure development over ribbon thickness are outlined. It can be concluded from the results, that process parameters which determine the thickness of the melt puddle in the downstream have major influence on cooling and solidifying rate of the ribbon. Among thermal properties, the thermal diffusivity of the metallic melt, solidified ribbon and wheel material has major influence on cooling and solidifying rate of the melt and solidified ribbon respectively.

In the case of continuous casting, heat balance of the wheel is calculated and influence of the chill wheel cooling mode on cooling rate of metallic ribbon is analyzed.

Original scientific paper

Izvleček: V delu je uporabljen numerični model izračunavanja kontaktne upornosti z uporabo variabilnega koeficienta toplotne prestopnosti, ki vključuje fizikalne lastnosti litega materiala, procesne parametre in kontaktni čas/dolžino med kovinsko talino oziroma trakom in hladilno podlago ter omogoča predvidevanje hitrosti ohlajanja in strjevanja pred izvedbo poskusa. Izračuni nakazujejo, da ima kontaktna upornosti med kovinsko talino in hladilnim valjem zelo velik vpliv na hitrost ohlajanja in strjevanja taline in se je v numeričnih izračunih ne sme zanemariti, tudi v primeru, ko je njena vrednost zelo majhna.

Analiziran je vpliv procesnih parametrov na hitrost ohlajanja ter strjevanja taline in posledično razvoj mikrostrukture po debelini traku. Iz izračunov lahko sklenemo, da imajo procesni parametri, ki določajo debelino talinske pete v spodnjem toku, največji vpliv na hitrost ohlajanja in strjevanja traku. Med toplotnimi lastnostmi imajo največji vpliv na hitrost ohlajanja in strjevanja temperaturna prevodnost kovinske taline, strjenega traku in materiala valja.

Izračunana je toplotna bilanca v primeru kontinuirnega litja in analiziran vpliv različnih načinov hlajenja valja na hitrost ohlajanja taline oziroma traku.

Key words: rapid solidification, metallic materials, heat transfer balance, heat transfer coefficient, numerical modeling

Ključne besede: hitro strjevanje, kovinski materiali, toplotna bilanca, koeficienta toplotne prestopnosti, numerično modeliranje

INTRODUCTION

Single roll melt spinning is the most commonly used process for the production of rapidly solidified thin metal foils or ribbons with amorphous, microcrystalline or even combined microstructure. In this type of a process, a molten material is introduced onto a surface of the spinning wheel, where melt puddle is formed (Figure 1). Material is then dragged out from the puddle by relative motion of the wheel. Usually thin ribbons are produced which can leave the wheel surface in solidified, semi-solidified or fully liquid form, depending on the contact resistance between the melt and substrate, heat transfer in the melt and wheel respectively, process parameters, and nucleation and crystal growth characteristics of the particular casting material.[1] The most important advantages of rapid solidification, which can be made with this process are extended solubility, refined microstructure, thermal stability at elevated temperatures, and improved magnetic and electrical properties.[1, 2, 3]

Heat transfer calculation

Primary objective of our work was to calculate the temperature field inside the chilling wheel and to ascertain the influence of the chill wheel cooling on metal ribbon cooling and solidification velocity. Because melt puddle is thin compare to its width and length we can make an assumption of two-dimensional (2D) transient heat transfer. Assuming 2D transient heat transfer with variable thermal properties and internal heat generation (latent heat of crystallization), general partial differential equation for the melt is reduced to:

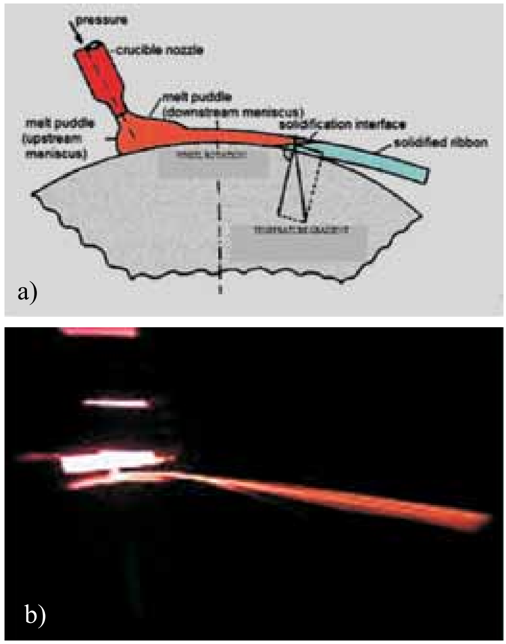

Figure 1. Melt puddle development on the surface of the wheel at free jet melt-spinning process Sheme (a), Snap shot[4] (b)

$$\frac{1}{r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{\partial}{\partial r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{1}{r^2}\cdot\frac{\partial}{\partial\varphi}\cdot(\lambda\cdot\frac{\partial T}{\partial\varphi})+q'''=\rho\cdot c\cdot\frac{\partial T}{\partial t} \quad (1)$$

And for chill wheel, where no heat is released by wheel material:

$$\frac{1}{r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{\partial}{\partial r}\cdot(\lambda\cdot\frac{\partial T}{\partial r})+\frac{1}{r^2}\cdot\frac{\partial}{\partial\varphi}\cdot(\lambda\cdot\frac{\partial T}{\partial\varphi})=\rho\cdot c\cdot\frac{\partial T}{\partial t} \quad (2)$$

Where:

r, φ, z	cylindrical coordinate system [m; rad; m]
T	temperature [K]
$\rho = \rho(T)$	density [kg/m^3]
$\lambda = \lambda(T)$	thermal conductivity [W/(m · K)]
$c = c(T)$	specific heat [J/(kg · K)]
q'''	volumetric heat generation rate [W/m^3]

For calculation of temperature distribution inside the melt puddle and chill wheel, we used explicit finite difference method (FDM) with cylindrical coordinate system. Thermal properties of the melt and wheel material ($\lambda(T)$, $c(T)$) are temperature dependant and are calculated for each iteration step with linear interpolation from tabulated values. Density in solidification interval of the casting material is changing linearly or parabolic, depending of the alloy solidification type (eutectic, dendritic),[5] whereas density of the wheel material is approximated as constant.

In situations where a detailed description of thermal physics is very complicated, such as in melt-spinning process, where heat transfer between melt and substrate (wheel) is coupled with fluid flow which is further complicated by the presence of solidified region, combined modes of heat exchange are usually taken in to account with the overall heat transfer coefficient.[5, 6] This coefficient (α) includes conduction and radiation of heat, as well as any convective effects and is defined as the ratio of the heat flux (q) from the liquid metal and solid ribbon across the interface with the wheel, to the temperature difference between molten metal or ribbon and wheel.

Because the temperatures of the casting material and chill wheel are changing along contact length, numerical modeling of the heat transfer with constant heat transfer coefficient and nominal chill wheel temperature is not realistic. Actually, heat transfer coefficient is dependant by many factors which include physical and thermal properties of the melt and chill substrate, fluid velocity, state and geometry of the chill surface and its temperature. Moreover, molten material solidifies and shrinks, which changes the physical contact from liquid/solid to solid/solid or (solid + gas)/solid.[5] Consequently, value of heat transfer coefficient over entire contact length can vary in wide range.

Furthermore, values of the heat transfer coefficient are difficult to measure with confidence. In literature you can find different techniques. From those based on pyrometric, photocalorimetric or wheel surface temperature measurements with embedded thermocouples, to those based on dendrite arm or interlamellar spacing, but none of them can predict the value of the local heat transfer coefficient particularly accurate.[6]

To simplify the mathematical model, we considered number of assumptions. The local heat transfer coefficient $\alpha(x)$ is calculated with the integral method for liquid metals flow over flat plate. The approximation of the flat plate is reasonable, because of the large aspect ratio between puddle length and radius of the wheel. Another assumption in our model is to consider that there is no velocity gradient in the puddle. This is not completely true in the actual case, but when metallic materials are cast, we believe that velocity gradient can be neglected for thermal field calculation inside the chill wheel and melt puddle. Namely, metal melts have very low Prandtl number and consequently thermal boundary layer much thicker than velocity boundary layer.[7] Ribbon thickness is also found to be proportional to circumferential velocity of the chill wheel (u_w^{-1}) and the pressure in the crucible ($p^{0,5}$), as predicted by continuity and Bernoulli equations.[1] Next assumption is that temperature of the melt in the puddle direct under the impinging jet stays equal to casting temperature, because strong turbulences in that region.

The equation for local heat transfer coefficient $\alpha(x)$ calculation, included in the numerical scheme is:

Results and discussion

Figure 2 represents calculated cooling curves in Al ribbon and heating curves for Cu wheel surface, considering different modes of contact resistance: ideal contact, variable contact resistance (*α(x) = integral method*) and constant contact resistance through entire contact time/length (*α(x)* = 10^6W/(m^2 · K)). Value for constant average heat transfer coefficient for aluminum was obtained with subsequent microstructure analyses and reported by other authors.[8]

By applying different modes of contact resistance, calculations revealed that cooling and heating rates of the ribbon and the wheel diverse considerably. Calculated cooling and heating rate is relatively much slower when some contact resistance is considered. Although the contact resistance value is very low (≈ 10^{-6}(m^2 · K)/W), it should not be neglected.

$$\alpha(x) = \alpha(R, \varphi_j) = \lambda \frac{\partial \theta}{\partial y}\Big|_{y=0} = \frac{3 \cdot \lambda}{2\delta_t} = \frac{3 \cdot \lambda}{2 \cdot \sqrt{8}} \cdot \sqrt{\frac{u_w}{a \cdot x}} \tag{3}$$

u_w	circumferential velocity of the wheel [m/s]
λ	thermal conductivity of the casting material (temperature dependant) [W/(m · K)]
δ	thermal boundary layer thickness [m]
a	thermal diffusivity [m^2/s]
x	distance from the initial contact point to the actual calculation point [m]

Integral method calculation of the heat transfer coefficient gives the most logical results for entire duration of the contact. Calculated solidification time is practically the same to those obtained by overall (constant) heat transfer coefficient, but final temperature of the ribbon at the detachment point is much greater, especially for longer contact time. Constant contact resistance approximation ($10^{-6}(m^2 \cdot K)/W$) for longer contact time predicts even lower ribbon temperature then ideal contact calculation, which is physical unlikely. Irrespective of contact resistance approximation, the wheel surface temperature after reaching its maximum decrease, although it is in contact with hotter ribbon. By considering the wheel as a whole, its enthalpy is constantly rising, since temperature more than 0.3 mm under the surface, is increasing the entire contact time (Figure 4 a). Namely, conduction heat transfer rate in the wheel is faster than the heat transfer rate across ribbon/wheel interface and through solidified ribbon.

When thicker ribbons are cast or materials with lower thermal conductivity, thermal resistance in already solidified region of the ribbon becomes the limiting factor of the heat transfer. High cooling and solidifying rates, through entire cross section of the ribbon, especially on its free surface, can be achieved only when very thin (<30 μm) ribbons are cast (Figure 3).

We also analyzed influence of the wheel material on the solidification characteristics. Figure 4 shows calculated temperature profiles in steel or copper wheel, when aluminum melt is cast. As we can see, surface temperature will increase significantly, especially for a wheel of low thermal diffusivity. Because short duration of the contact (<1 ms) and limited thermal diffusion in the wheel, the energy can penetrate only a short distance in the wheel, which results in a higher temperature at the wheel surface. The magnitude of temperature increase depends on the wheel material. For steel wheel, which has much lower thermal diffusivity than copper, an increase of surface temperature is over 400 °C, and heat penetration depth about 0.5 mm. On contrary, copper wheel surface temperature increase is about 200 °C and penetration depth twice as much. When materials with higher melting point are cast, surface temperature will increase much higher. Obviously, such a large deviation in surface temperature should not be neglected in calculation of cooling and solidification rate of the melt. Importance of wheel material selection is evident. Pure deoxidized copper has the highest thermal diffusivity between all commercially useful materials and therefore is the best choice for the wheel material.

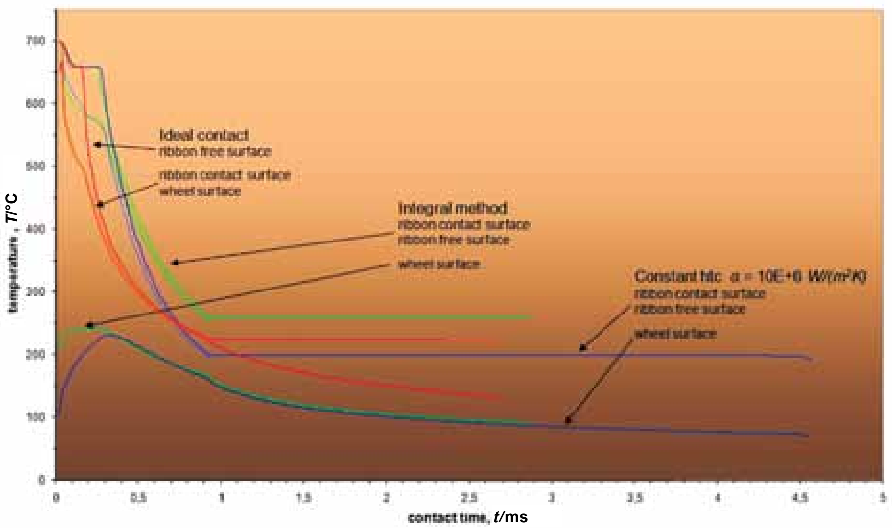

Figure 2. Cooling curves of free and contact surface of Al ribbon and contact surface of the Cu wheel as a function of different contact resistance. (u_w = 18.9 m/s, ribbon thickness 66 µm, contact time 0.923 ms)

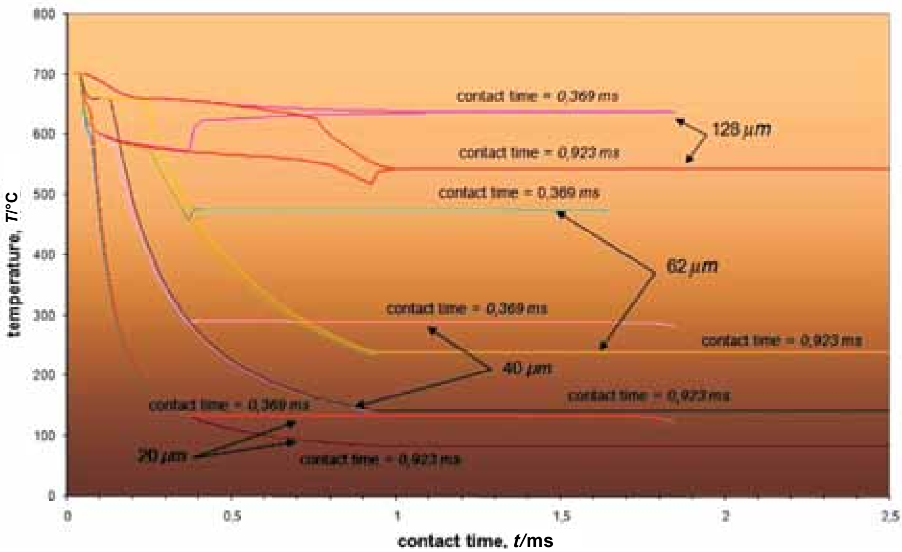

Figure 3. Cooling curves of contact and free surface of the Al ribbon as a function of its thickness and contact time (u_w = 18.9 m/s, $\alpha(x)$ = integral method)

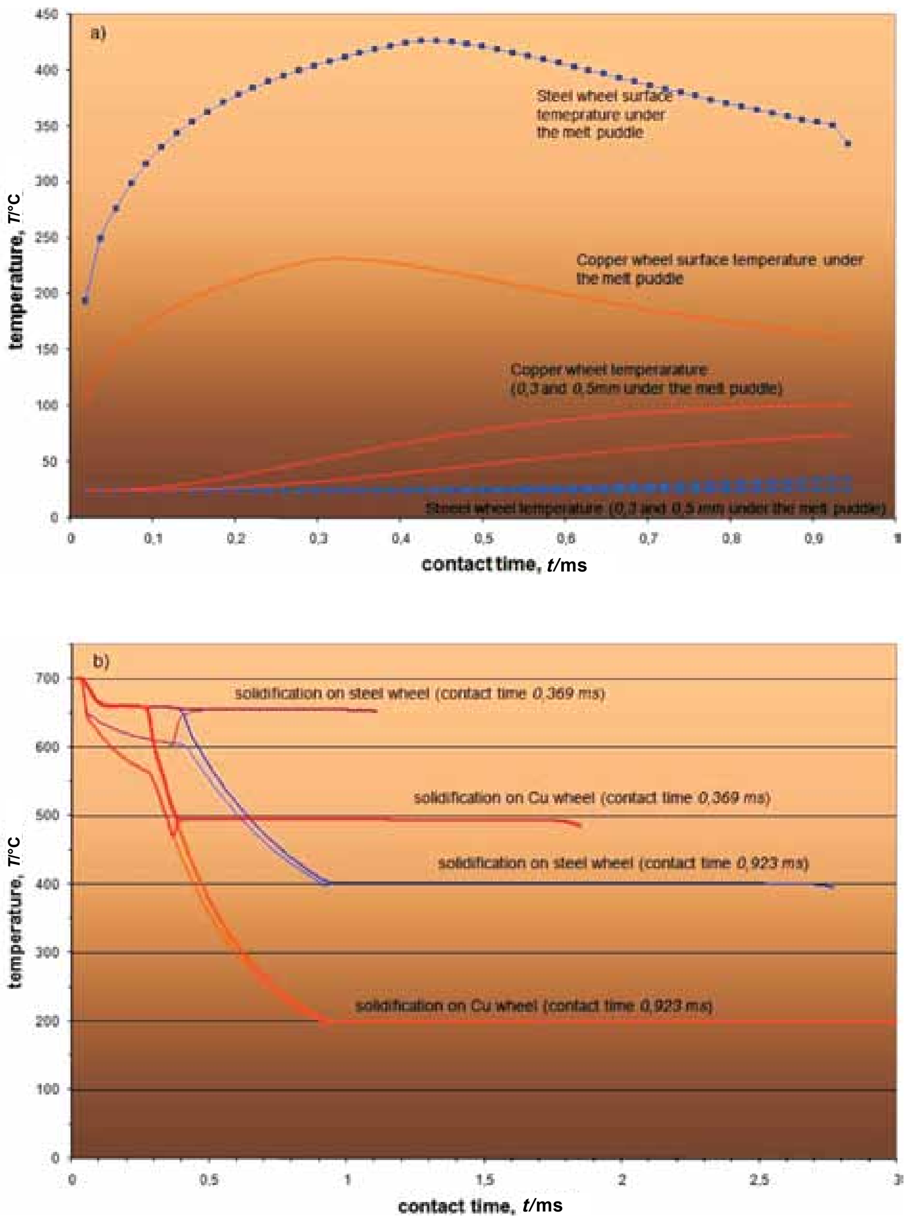

Figure 4. a) Steel and copper wheel temperature increase as a function of contact time
b) Cooling curves of Al ribbon as a function of wheel material and contact time (u_w = 18.9 m/s, ribbon thickness 66 μm, contact time 0.923 ms, $\alpha = 10^6$ W/(m$^2 \cdot$ K))

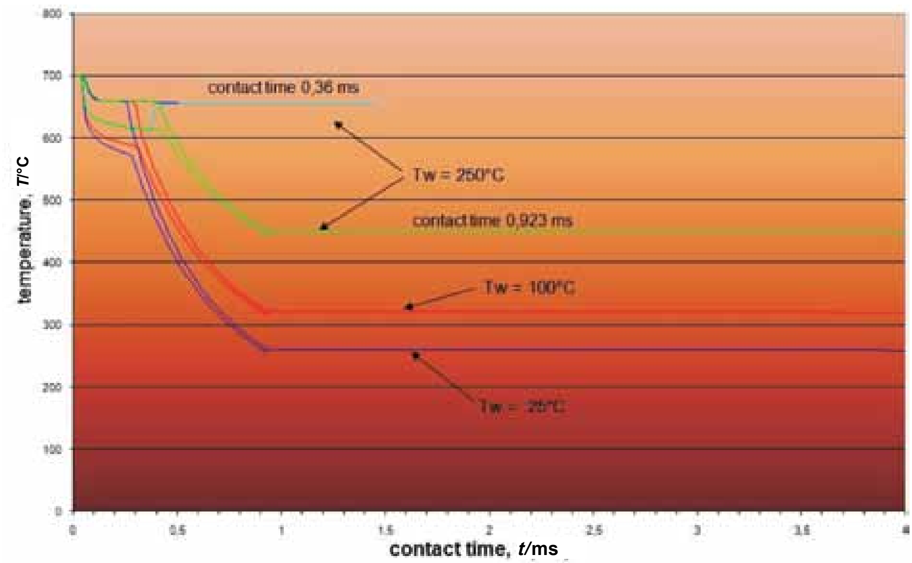

Figure 5. Cooling curves for 66 μm thick Al ribbon as a function of initial wheel temperature and contact time (u_w = 18.9 m/s, $\alpha(x)$ = integral method)

During continuous casting process, the wheel is not subjected only to heat transfer from the solidifying material, but also to radiation and convection heat transfer from the crucible. In that case, significant "long term" surface temperature increase may take place, if the wheel in not externally or internally cooled. In calculations discussed above, we have assumed that the wheel surface is at room temperature at the beginning of the contact. For first ten to hundred revolutions surface temperature increase may indeed not be insignificant, but when continuous casting is performed, especially when materials with high melting point are cast, surface temperature of the wheel can increase in such an extent, that formation of the ribbon will be disturbed, because of decreased cooling and solidifying rate in the melt puddle. Figure 5 shows the effect of the initial wheel temperature on calculated temperature profiles in the Al ribbon. . As we can see, initial wheel temperature has substantial influence on ribbon cooling rate especially if the contact time is short (high wheel speed).

For the purpose of the continuous casting, we calculated temperature profiles in inner water cooled wheel (R_w = 0.2 m) as a function of casing thickness. From the outside, wheel is convectively cooled with surrounding atmosphere, because its rotation, and from the inside with water stream. For simplicity of the mathematical model, convective heat transfer coefficients are taken as constants (α_{water} = 5000 W/(m^2 · K) and α_{air} = 50 W/(m^2 · K)) and represent average values, calculated from forced convection correlation equations. No radiation from the crucible is taking into account. To ascertain influence of external cooling, we also make an assumption of exaggerated value for convective heat transfer coefficient (α_{air} = 1000 W/(m^2 · K)). The calculated surface temperatures for 10 mm thick wheel casing are shown in Figure 6. Each saw tooth spike corresponds to the temperature of the wheel surface being underneath the puddle. As we can see, internally water cooled wheel will reach the periodic steady state after few revolutions. But still, surface temperature can increase significantly when iron is cast (>200 °C), although we assume exaggerated value (α_{air} = 1000 W/(m^2 · K)) for convective heat transfer coefficient. Namely, duration of one revolution of the wheel is so short that external gas convective cooling would have no significant influence on the wheel surface temperature. Conducting of heat into the wheel and cooling of the inner casing surface with water stream is much faster than external convective cooling with surrounding atmosphere.

If we reduce wheel casing thickness up to 2 mm, internal water cooling will be more effective, and wheel surface temperature that melt will effectively "see" at the beginning of the next pass of the wheel under the puddle, will be practically the same as at the first revolution, even if high melting temperature materials are cast (Figure 7).

But if we reduce wheel casing even further, beneath the heat penetration depth under the melt puddle, convective heat resistance on the inner side (wheel – water interface) becomes significant. Even if we assume heat transfer coefficient value on inner side of a casing as high as 100 000 W/(m^2 · K), which can be reached with high pressure impingement water jets,[9] heat removal from the melt will be slower as in the case of full or internally water cooled wheel with 10 mm thick casing (Figure 8). Reducing the thickness of the wheel casing is unsuitable, from rapid solidification and from steadiness point of view.[10]

CONCLUSIONS

An improved FDM method with variable heat transfer coefficient was used to calculate the heat balance of free jet melt-spinning process.

The mathematical model developed, includes the effect of the conduction heat transfer within the chilling wheel and allows us to investigate the influence of heat contact resistance between the melt and the chill wheel, wheel material, and inner wheel cooling. The fact that the wheel surface temperature is increasing significantly under the solidification melt puddle, selection of the wheel material is important. Because copper has the highest thermal diffusivity between all commercially

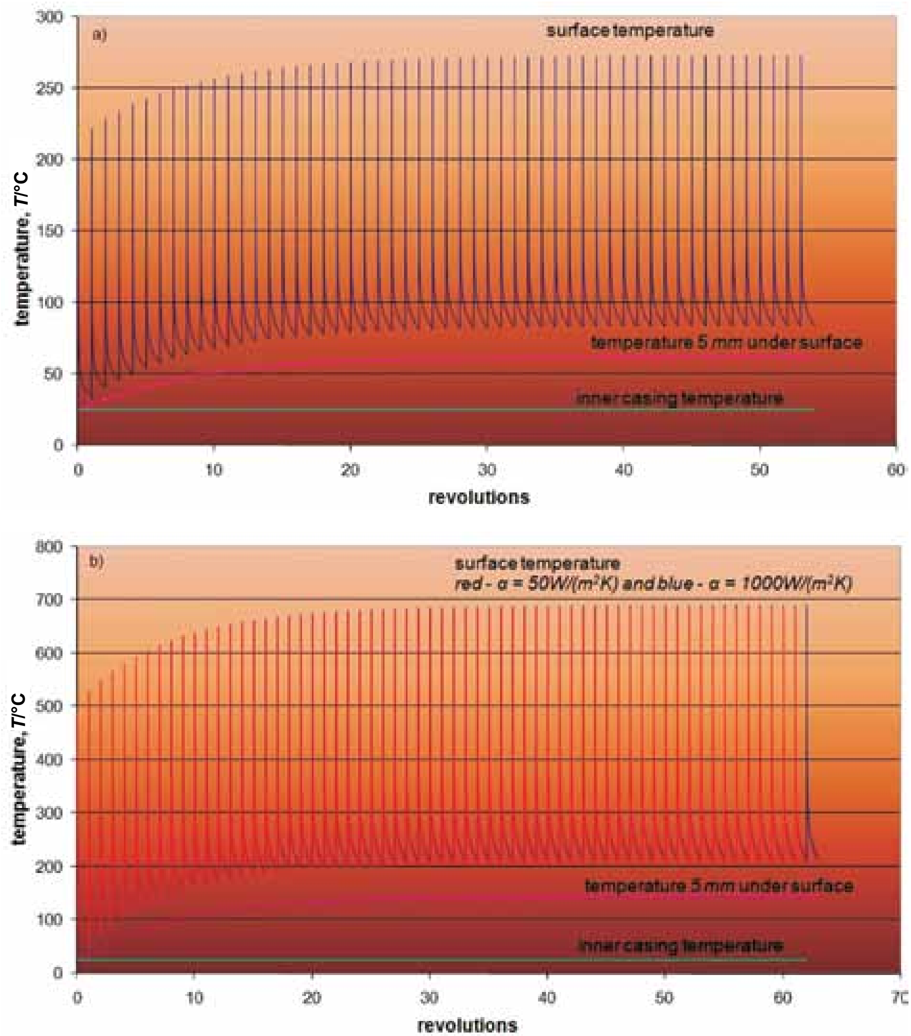

Figure 6. Surface temperature of the internally water cooled wheel with casing thickness 10 mm and wheel radius 0.2 m a) aluminum casting; b) iron casting (u_w = 18.9 m/s, α_{water} = 5000 W/(m^2 · K) and α_{air} = 50W/(m^2 · K) and (α_{air} = 1000 W/(m^2 · K))

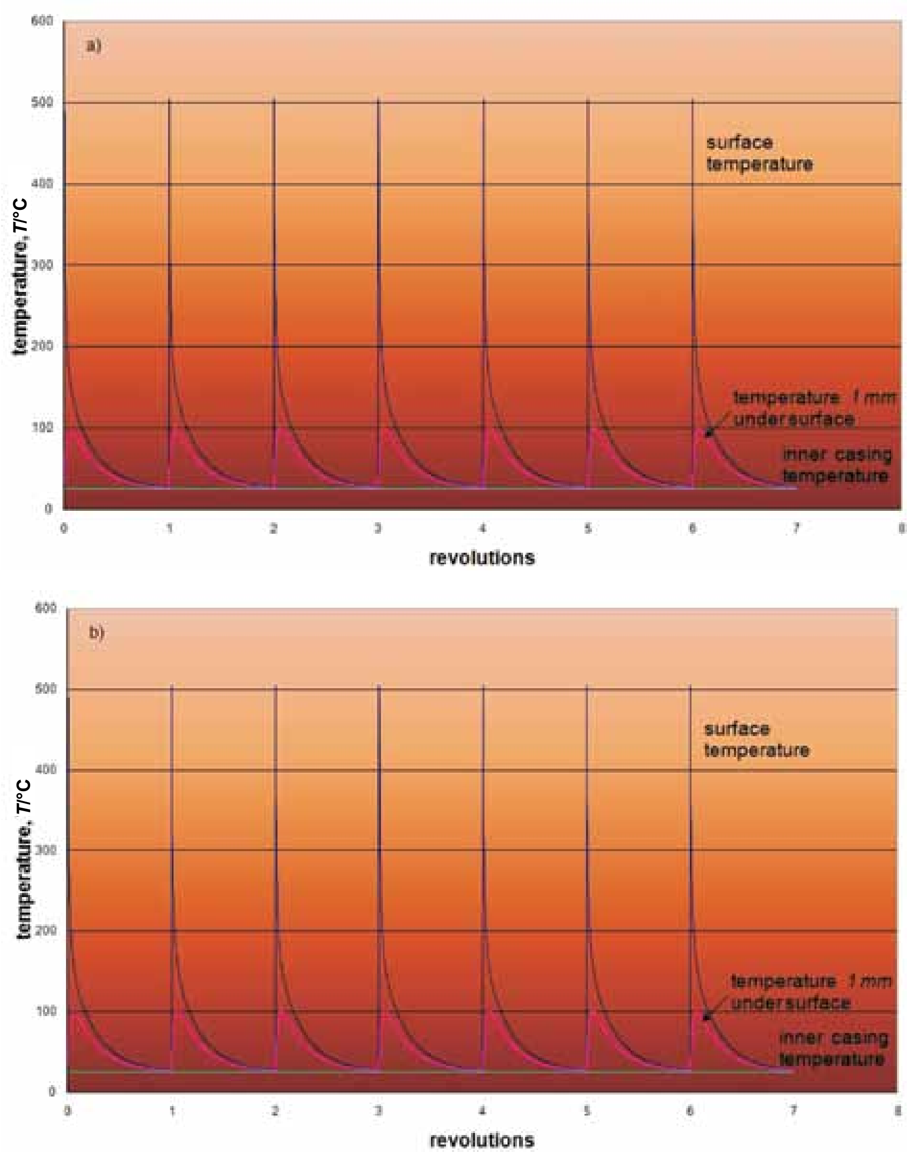

Figure 7. Surface temperature of the internally water cooled wheel with casing thickness 2 mm and wheel radius 0.2 m a) aluminum casting b) iron casting (u_w = 18.9 m/s, α_{water} = 5000W/(m^2 · K) and α_{air} = 50 W/(m^2 · K))

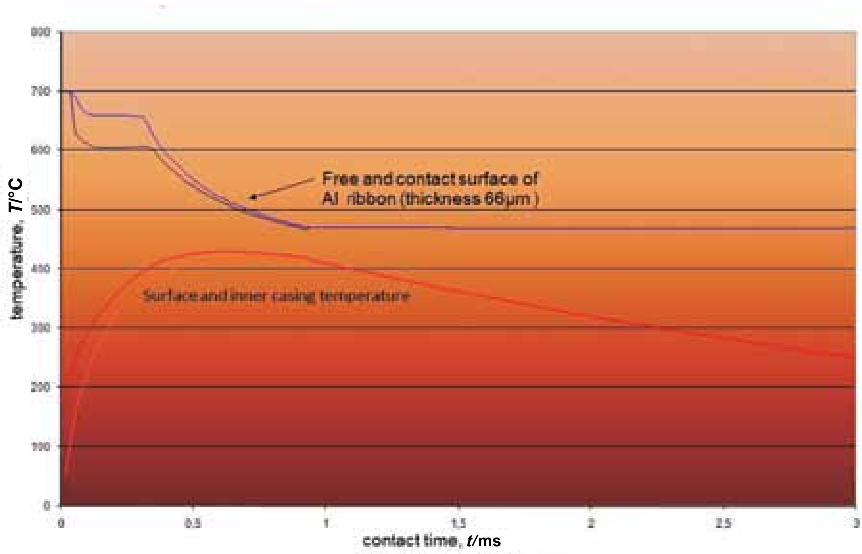

Figure 8. Internally cooled copper wheel surface temperature increase as a function of contact time and thickness of wheel casing for aluminum casting. (R_w = 0.2 m, u_w = 18.9 m/s, ribbon thickness 66 µm, contact time 0.923 ms, htc on wheel-water side 100 000 W/(m^2 · K))

useful materials, we propose deoxidized copper for a wheel material.

For continuous casting internally cooled wheel is preferable, but only in the case when wheel casing thickness is correctly selected. When too thick casing is applied, water cooling will not have adequate influence on wheel surface temperature increase. When the casing of the wheel is too thin, thermal resistance on the cooling side (wheel-water interface) becomes the limiting factor, which reduces the heat transfer from the melt and consequently its cooling and solidifying rate.

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