B. KARPE, B. KOSEC, T. KOLENKO, M. BIZJAK

ISSN 0543-5846
METABK 50(1) 13-16 (2011)
UDC – UDK 621.746:672:536.21=111

HEAT TRANSFER ANALYSES OF CONTINUOUS CASTING BY FREE JET MELTSPINNING DEVICE

Received – Prispjelo: 2010-02-19
Accepted – Prihvaćeno: 2010-05-12
Original Scientific Paper – Izvorni znanstveni rad

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 molten material (melt puddle) and chilling wheel and enables cooling rate prediction before experiment execution. From the results can be concluded, that those process parameters which determine the thickness of the melt puddle in the downstream and consequently the ribbon thickness have major influence on cooling rate of the ribbon. 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.

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

Analiza prijelaza topline tijekom kontinuiranog lijevanja uređajem za brzo skrućivanje. Uvedena je nova metoda za određivanje kontaktne toplinske otpornosti pomoću varijabilnog koeficijenta prijelaza topline, koji uzima u obzir fizikalna svojstva lijevanog materijala, procesne parametre i vrijeme kontakta/duljine između rastaljenog djela materijala i rashladnog valjka, omogućavajući predviđanje brzine hlađenja prije provođenja eksperimenta. Iz navedenih se rezultata može se zaključiti, da oni procesni parametri koji određuju debljinu rastaljenog djela materijala u donjem toku, a posljedično i debljinu trake, imaju najveći utjecaj na brzinu hlađenja trake. U slučaju kontinuiranog lijevanja izračunata je toplinska bilanca valjka i analiziran je utjecaj načina hlađenja valjka na brzinu hlađenja metalne trake.

Ključne riječi: kontinuirano ljevanje, brzo skrućivanje, metalni materijali, toplinska bilanca, koeficijent prijelaza topline, numeričko 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- 4].

B. Karpe, B. Kosec, T. Kolenko, M. Bizjak, Faculty of Natural Science and Engineering, University of Ljubljana, Slovenia

HEAT TRANSFER CALCULATION

Because melt puddle is thin compare to its width and length an assumption of two dimensional (2D) transient heat transfer can be made. General partial differential equation for the melt is reduced to:

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

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

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

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

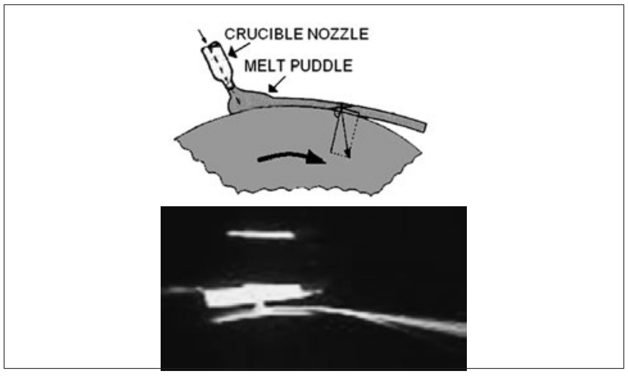

Figure 1 Melt puddle formation on the surface of the chill wheel at free jet melt-spinning process [2]

In situations where a detailed description of thermal physics is very complicated, such as in melt-spinning process, combined modes of heat exchange are usually taken in to account with the overall heat transfer coefficient (α)[5,6], which includes conduction and radiation of heat, as well as any convective effects. To simplify the mathematical model, numbers of assumptions were considered:

– The local heat transfer coefficient $\alpha(x)$ is calculated with the integral method for liquid metals flow over flat plate [7].
– No velocity gradient in the puddle and no slip conditions.
– Melt puddle thickness and consequently ribbon thicknesses are predicted by continuity and Bernoulli equations.
– Temperature of the melt in the puddle direct under the melt jet from the nozzle stays equal to casting temperature, because of strong turbulences in that region.

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

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

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

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 and constant contact resistance (10^{-6}(m^2·K)/W) [8] through entire contact time/length. Calculated cooling and heating rate is relatively much slower when some contact resistance is

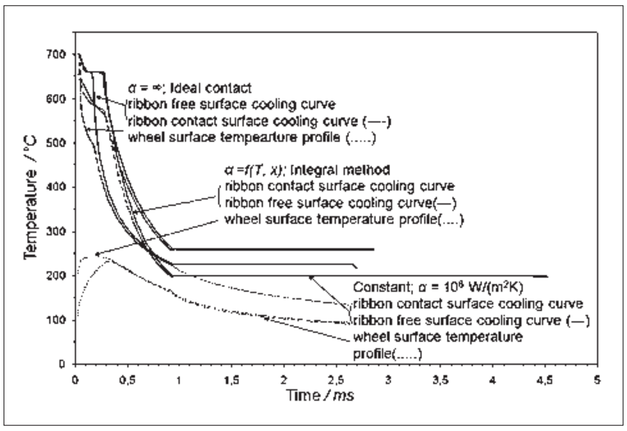

Figure 2 Cooling curves of free and contact surface of Al ribbon and contact surface temperature profile of copper wheel as a function of different contact resistance assumption (u_w=18,9m/s, ribbon thickness 66μm, contact time 0,923ms)

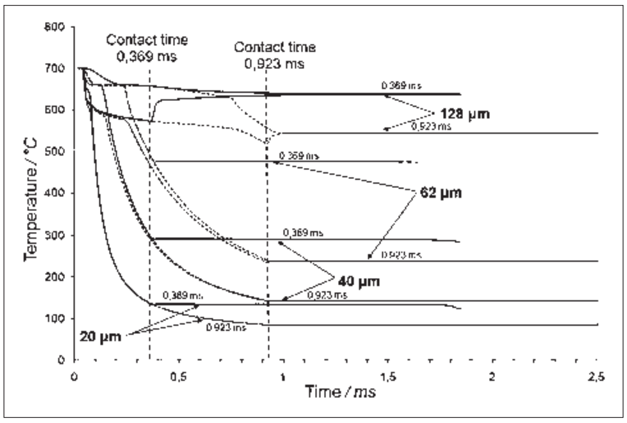

Figure 3 Cooling curves of contact and free surface of aluminium ribbon as a function of its thickness and contact time (u_w = 18,9 m/s, α = $f(x)$)

taken into account and must not be neglected even its value is very low.

Irrespective of contact resistance approximation, conduction heat transfer rate in the wheel is higher 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. Uniform cooling and solidifying rates through entire cross section of the ribbon can be achieved only when very thin (< 30μm) ribbons are cast (Figure 3).

Because of short duration of the contact (< 1 ms) and limited thermal diffusion in the wheel, the energy can penetrate only through a short distance in the wheel, which results in a higher temperature at the wheel surface. Figure 4 shows calculated temperature profiles in steel or copper wheel, at aluminum casting. 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 0,5mm. On contrary, the increase of copper wheel sur-

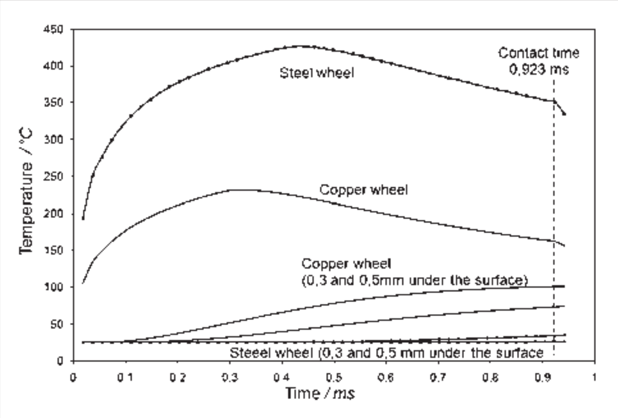

Figure 4 Steel and copper wheel temperature profile under melt puddle as a function of contact time (u_w = 18,9m/s, ribbon thickness 66μm, contact time 0,923 msec, α =10^{6}W/(m^2·K))

face temperature is about 200 °C and penetration depth twice as much. Nevertheless, after reaching its maximum the wheel surface temperature decreases, although it is in contact with hotter ribbon. This seems unlikely, but considering the wheel as a whole, its enthalpy rises constantly, since temperature of more than 0,3mm under the surface increases the entire contact time.

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 it is the best choice for the wheel material.

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. Figure 5 shows the effect of the initial wheel temperature on the temperature profiles calculated in the Al ribbon. Initial wheel temperature has considerable influence on ribbon free surface solidification time, which have further influence on puddle dynamic stability. When relatively thicker (> 60 μm) ribbons or materials with low thermal conductivity are cast, puddle instability prevent casting of ribbon with uniform thickness.

For continuous casting heat balance calculations, the following assumptions were considered:

- Wheel is cooled by convection heat transfer from the outside with surrounding atmosphere, and from the inside with water stream. Convective heat transfer coefficients were taken as constants and represents the average values calculated from forced convection correlation equations (α_{water} = 5000 W/(m^2·K), α_{air} = 50 W/(m^2·K) or limited value of 1000 W/(m^2·K)).

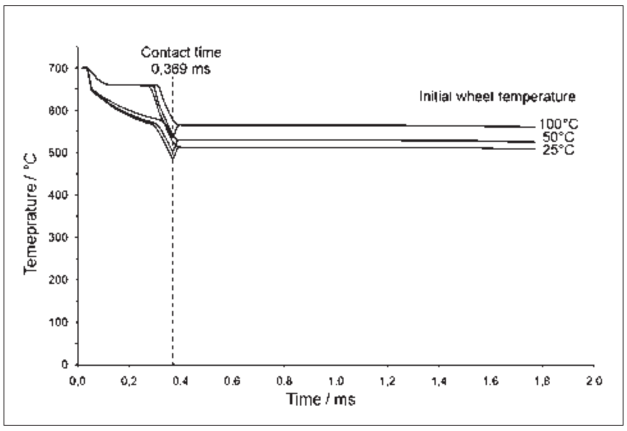

Figure 5 Cooling curves for 66 μm thick Al ribbon as a function of initial wheel temperature and contact time (u_w = 18,9 m/s, α = *f(x))*

- No radiation from the crucible is taken into account.

Internally water cooled wheel will reach the periodic steady state after few hundred of revolutions. But if the wheel casing is too thick, internal cooling will have no practical influence on wheel surface temperature, which can still increase significantly when high melting-point alloys are cast.

External gas convective cooling has also no significant influence on the wheel surface temperature even under assumption of exaggerated value of convective heat transfer coefficient α_{air} = 1000 W/(m^2·K), because duration of one revolution is too short. Conducting of heat into the wheel is much higher than external convective cooling with surrounding atmosphere.

If the wheel casing thickness is reduced down to 2 mm, internal water cooling will be more effective. Wheel surface temperature that melt will actually "see" at the beginning of the next pass of the wheel under the melt puddle, will be practically the same as at the first revolution, even if high melting temperature materials are cast. But with further reduction of the wheel casing, even beneath the heat penetration depth (Figure 6), con-

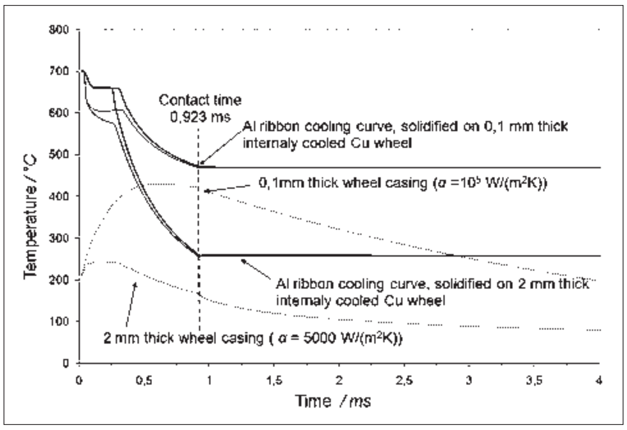

Figure 6 Internally cooled copper wheel surface temperature increase as a function of contact time and thickness of wheel casing for aluminum casting (R_w = 0,2 m, u_w = 18,9 m/s, ribbon thickness 66 μm, contact time 0,923 ms)

vective heat resistance on the inner side (wheel – water interface) becomes significant. Even if the heat transfer coefficient value on inner side of a casing is assumed as high as 100000 W/(m^2·K), which can be reached with high pressure impingement water jetsŠ9Ć, heat removal from the melt will be slower as in the case of bulk wheel. Reducing the thickness of the wheel casing under the heat penetration depth is unsuitable, because of rapid solidification and because 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 includes the effect of the conduction heat transfer mode within the chilling wheel and allowing to investigating the influence of heat contact resistance between the melt and the chill wheel, wheel material, and inner wheel cooling.

Calculations show that wheel surface temperature increase is considerable. Since copper has the highest thermal diffusivity between the all of commercially useful materials, we propose deoxidized copper for a wheel material. For continuous casting the 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 have no considerable influence on wheel surface temperature decrease. 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. Internal wheel cooling with liquids of room temperature does not increase cooling and solidifying rate of the ribbon, but only assures constant wheel surface temperature.

REFERENCES

[1] Bizjak M.: Temperaturna obstojnost hitro strjenih večkomponentnih aluminijevih zlitin, NTF, Ljubljana, 1999.
[2] Kosec B.: Euroteh, 3 (2004), 32-33.
[3] Praisner T.J., Chen J.S., Tseng A.: Metallurgical Transactions B26 (1995) 2, 1199-1208.
[4] Collins L.E.: Overview of rapid solidification technology, Canadian Metallurgy Quarterly, 25 (1986) 2, 59-71.
[5] Stefanescu D.M.: Science and Engineering of casting solidification, Kluwer Academic/Plenum Publishers, NY, 2005.
[6] Carpenter J.K., Steen P.H.: Metallurgical Transactions, B21 (1990) 2, 279-283.
[7] Özişik M.N.: Heat transfer: A Basic Approach, McGraw-Hill, NY, 1985.
[8] Wang G.X, Matthys. E.F.: Material Science and Engineering, A136 (1991), 85–97.
[9] Ciofalo M., Di Piazza I., Brucato V.: International Journal of Heat and Mass Transfer, 42 (1999), 1157-1175.
[10] Karpe B.: Idejni projekt hladilnega sistema na napravi za hitro strjevanje kovinskih materialov, NTF, Ljubljana, 2009.

Note: The responsible translator for English language is Urška Letonja, University of Ljubljana, Slovenia