Estimation of the heat transfer coefficient in melt spinning process

V I Tkatch¹, A M Grishin² and V V Maksimov¹
¹Donetsk Institute for Physics and Engineering NAS of Ukraine, R. Luxemburg 72, 83114 Donetsk, Ukraine
²Condensed Matter Physics, Royal Institute of Technology, Isafjordgatan 24, SE-16440 Stockholm-Kista, Sweden

Abstract. Effect of the quenching wheel velocity in the range 20.7–26.5 m/s on the cooling rate as well as on the structure and microtopology of the contact surfaces of the glass-forming FeNiPB melt-spun ribbons has been experimentally studied. Both the values of the cooling rate and heat transfer coefficient at the wheel-ribbon interface estimated from the temperature vs. time curves recorded during melt spinning runs are in the ranges (1.6–5.2) × 10⁶ K/s and (2.8–5.2) × 10⁵ Wm⁻²K⁻¹, respectively, for ribbon thicknesses of 31.4–22.0 μm. It was found that the density of the air pockets at the underside surface of ribbons decreases while its average depth remains essentially unchanged with the wheel velocity. Using the surface quality parameters the values of the heat transfer coefficient in the areas of direct ribbon-wheel contact were evaluated to be ranging from 5.75 to 6.65 × 10⁵ Wm⁻²K⁻¹.

1. Introduction
The melt spinning process is the most industrially important technique for fabrication of metallic alloys with highly non-equilibrium crystalline and amorphous structures. The advantage of this process is its relative simplicity and the effectiveness in rapid cooling, however, there is still exists a problem of obtaining reproducible physical properties of melt-spun ribbons. The variations in the properties of melt-spun ribbons are usually assumed to result from changes of cooling rate. The most important factors determining the cooling rate are the thickness of the ribbon and the heat transfer coefficient at the ribbon-wheel interface, h.

Many studies have been performed out attempting to evaluate the interfacial contact resistance [1-7]. In view, that the interfacial heat transfer coefficient is a function of many parameters [1] it appears that the most correct way of estimation of h is fitting of the solution of heat transfer problem to the measured temperature vs. time changes [4–7]. It has been established, in particular, that the values of h in the melt spinning process are typically in the range from 10⁴ to 10⁶ Wm⁻²s⁻¹ and tend to increase with the velocity of a quenching wheel, V, [2,3,5-7]. This effect is ascribed to lowering of the number of air pockets at the wheel-contact surfaces of melt-spun ribbons [2] which arise by air (gas) trapped between the melt puddle underside and the wheel [1,2]. The presence of these surface defects influences the surface roughness which is related, in particular, with magnetic properties of melt-spun ribbons [8]. A proper understanding of these effects, required for elaboration of high performance
ribbons, is still lacking and the aim of this paper is to gain additional information concerning the effect of the quenching wheel velocity on the quality of the thermal ribbon-wheel contact.

2. Experimental procedure
Three Fe_{40}Ni_{40}P_{14}B_{6} melt-spun amorphous ribbons were fabricated in open air using a laboratory scale single roller melt-spinner with a casting wheel made of commercial aluminum bronze [7]. The main casting parameters except the wheel velocity were kept constant. The casting runs were performed at the \( V_s \) values of 20.7, 24.2 and 26.5 m/s. The resultant ribbons (about 1 mm wide) were 31.4 ± 3.0 µm (A1), 25.7 ± 2.1 µm (A2) and 22.0 ± 1.2 µm (A3) thick, respectively.

The temperature at the bottom surface of the ribbons was measured using the thermocouple and the recording device described in Ref. [7]. The cooling rates at the alloy melting temperature (1173 K [10]) were calculated by numerical differentiation of the recorded "temperature-time" dependencies. The structure of the contact surfaces was examined by optical microscopy. The profiles of the wheel-side surfaces of the ribbons were measured with a Dektak 300 Stepmeter by scanning along (3 mm) and across the direction of the ribbon axis.

3. Results and discussion
A typical measured \( T(t) \) curve and its derivative, \( \dot{T} \), with respect to time, \( t \), are shown in figure 1 by dark and open symbols points, respectively. Evidently the cooling rate dependence on temperature is well approximated by a linear function. The similar \( T(t) \) and \( \dot{T}(T) \) curves were obtained at other \( V_s \) employed in this study and the cooling rates calculated at temperature 1173 K for the ribbons designated as A1, A2 and A3 were estimated to be 1.5×10^6, 3.1×10^6 and 5.2×10^6 K/s, respectively.

Comparison of the cooling rates measured at contact surfaces of the Fe_{40}Ni_{40}P_{14}B_{6} ribbons with the available results of direct measurements of \( \dot{T} \) shows that they are close to those for the Fe- and Ni-based alloys ribbons extrapolated to the same thicknesses [5,6] but somewhat lower than those measured for Cu and Cu-based alloys [3].

Figure 2 shows optical micrographs of the bottom surfaces of the melt-spun ribbons produced at various wheel velocities. These pictures clearly exhibit surface defects in the form of voids (air-pockets) where melt did not wet the wheel surface and regions of the direct wheel–ribbon contact. The air-pockets are originated by air entrapped between wheel and melt puddle [2] and in the ribbons obtained at lower wheel velocities they are elongated in a direction parallel of the ribbon axis.

The main difference among the structures presented is in the density and shape of the gas bubbles: increasing of \( V_s \) results in a decrease of the density of the voids and they become more equiaxed. Besides, it can be seen in figure 2(c) that the areas of melt–wheel contact reveal the scratches originating from the wheel surface treatment such indicating that the bottom surface of the ribbon replicates of the surface of the wheel.

In contrast to the density and shape of the gas bubbles the variations in the wheel velocity does not change essentially the roughness of the underside surfaces of the melt-spun ribbons as evident from the profilograms presented in figure 3, which contain small asperities and the relatively deep voids originating from the gas bubbles. Analysis of these data has shown that the number of large...
depressions (air pockets) at the wheel-side ribbon surface gradually decreases with the wheel velocity whereas its average depth, $l_p$, within the experimental error remains essentially unchanged (Table 1).

![Figure 2](image1)

**Figure 2** Photographs of contact surfaces of the ribbons A1 (a), A2 (b) and A3 (c). Casting direction is from top to bottom. The white lines correspond to 100 μm.

![Figure 3](image2)

**Figure 3** Microprofiles across the undersides of the Fe40Ni40P14B6 ribbons A1 (a), A2 (b) and A3 (c).

| Sample number | Average pocket depth, $l_p$ (μm) | Relative contact area, $S_c/S_t$ | Average heat transfer coefficient, $h_t$ (Wm⁻²K⁻¹) | Wheel-ribbon contact heat transfer coefficient, $h_{cc}$ (Wm⁻²K⁻¹) |
|---------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| A1            | 0.97 ± 0.6                      | 0.45 ± 0.02                     | $2.8 \times 10^5$             | $5.7 \times 10^5$             |
| A2            | 0.84 ± 0.4                      | 0.62 ± 0.02                     | $4.0 \times 10^5$             | $6.3 \times 10^5$             |
| A3            | 1.2 ± 0.5                       | 0.80 ± 0.01                     | $5.4 \times 10^5$             | $6.6 \times 10^5$             |

The linearity of the cooling rate against temperature implies that ribbon cooling occurs under Newtonian or intermediate mode [10], in which the $T(T)$ curves may be well approximated as [5,7]

$$T(T) = [h/(\rho c d)](T - T_2),$$  \hspace{1cm} (1)

where $\rho$ and $c$ are the density and the specific heat of the melt, respectively and $T_2$ is the temperature of the substrate [9]. Using the values of $\rho = 7500$ kg/m³ and $c = 544$ Jkg⁻¹K⁻¹ [10] the values of $h_t$ were calculated from Eq. (1) and listed in Table 1. Note that the estimated values of $h$ and their dependence on the wheel velocity are in general accordance with the available data [1-7].

Comparison of the changes in $h_t$ with the data presented in figure 2 suggests that growth of the heat transfer value is caused by an increase in area of direct contact between the melt and wheel in accordance with [2]. Using the elaborated software we have estimated the relative areas of the contact regions, $S_c/S_t$, from the micrographs shown in figure 2. The results of the treatment (Table 2) show that an increase of $V_s$ from 20.7 to 26.5 ms⁻¹ leads to approximately a twofold increase of $S_c/S_t$. The dependence of $h$ on $S_c/S_t$, plotted in figure 4, is close to linear. Extrapolation of this dependence to $S_c/S_t = 1$ gives the value of the heat transfer coefficient for full contact between the ribbon and wheel, $h_{cc}$.
about $6.9 \times 10^5$ Wm$^{-2}$K$^{-1}$. The relevant data ($h$ vs. $S_r/S$) reported in Ref. [2] for the Fe$_{40}$Ni$_{40}$P$_{14}$B$_6$ ribbons cooled on a chromium bronze wheel give the similar dependence but with a greater slope (figure 4) and the value of $h_c$ as large as $3.1 \times 10^6$ Wm$^{-2}$K$^{-1}$ [2]. This value is the highest one among the data reported and it is probably overestimated due to uncertainties of the model used in this study.

The above analysis ignores the heat transfer from a ribbon to a wheel through the areas of the gas bubbles. In fact, the thermal transfer through a gas layer with thickness $\delta$ is $h_g = \lambda_a/\delta$, where $\lambda_a$ is the thermal conductivity of the gas [1]. For the case considered, taking $\delta$ as the average air pocket depth, $l_p$ ($\approx 1 \mu$m) and the thermal conductivity of air $\lambda_a = 3.4 \times 10^{-2}$ Wm$^{-1}$K$^{-1}$ [11] the value of $h_g$ is $3.4 \times 10^5$ Wm$^{-2}$K$^{-1}$. To account the effect of the heat flow through the gas pockets we have re-estimated the values of the heat transfer coefficients at wheel-ribbon direct contact areas, $h_{cc}$, considering the total thermal transfer coefficient as a weighted sum:

$$h_t = h_{cc}(S_c/S_t) + (\lambda_a/l_p)(1-S_c/S_t). \quad (2)$$

Taking $h_t = h_c$ and substituting into Eq. 2 the values of $S_c/S_t$, and $l_p$ from Table 1, the values of $h_{cc}$ were calculated and listed in Table 1. As expected, the values of $h_{cc}$ are somewhat lower than that of $h_c$ obtained by direct extrapolation of the data in figure 4. Moreover, an increase of the calculated contact heat transfer coefficients with $V_s$ is observed. This tendency implies enhancement of mechanical tightness of the direct melt-wheel thermal contact with $V_s$ due to the greater impact between the wheel surface and the melt puddle [2]. The relatively low value of $h_g$ indicates that a decrease of air-pockets density at the underside ribbon surface plays the main role in enhancement of $T_v$, while the ribbon surface smoothness improvement is important for physical properties.

In conclusion, an increase of $V_s$ of the aluminum bronze wheel from 20.7 to 26.5 m/s resulted in a thickness decrease from 31.4 to 22.0 $\mu$m for the Fe$_{40}$Ni$_{40}$P$_{14}$B$_6$ ribbons and in an increase of both the cooling rate and the average heat transfer coefficient from $1.5 \times 10^5$ to $5.2 \times 10^5$ K/s and from $2.8 \times 10^5$ to $5.4 \times 10^5$ Wm$^{-2}$K$^{-1}$, respectively. The increase of the heat transfer coefficient is caused by lowering of the relative area of the air-pockets at the ribbons contact surfaces from 0.55 to 0.2 with the wheel velocity increase. The heat transfer coefficients of the regions of direct wheel-ribbon contact increase from $5.75 \times 10^5$ to $6.65 \times 10^5$ Wm$^{-2}$K$^{-1}$ with $V_s$ indicating enhancement of tightness of thermal contact.

References

[1] Cremer P, Wadier J.-F, 1985 in: Steeb S, Warlimont H (Eds.), Rapidly Quenched Metals V, North-Holland, Amsterdam:, Vol. 1. p. 83
[2] Huang S-C, Fiedler H C, 1981 Mater. Sci. Eng. 51 39
[3] Tenwic M J, Davies H A, see Ref. [1] p. 67
[4] Wang G-X, Matthys E F, 2002 Int. J. Heat Mass Transfer 45 4967
[5] Gillen A G, Cantor B, 1985 Acta Metall. 33 1813
[6] Bewlay B P, Cantor B, 1986 Intern. J. Rapid Solidification 2 107
[7] Tkatch V I, Denisenko S N, Beloshov O N, 1997 Acta Mater. 45 2821
[8] Haslar V, Kraus L, Janickowiec D, Svec P, Duhaj P, 1997 Mater. Sci. Eng. A226-A228 331
[9] Ruhl R C, 1967 Mater. Sci. and Eng. 1 313
[10] Anderson P M, Lord A E Jr., 1980 J. Non-Cryst. Solids 37 219
[11] Kuhling H, 1980 Physik.- (Leipzig: Veb Fachbuchverlag)