

Heat transfer in the single roller quenching methods

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Abstract

The heat transfer coefficient between the roller and the melt has been estimated from the melt pool length and ribbon thickness data of the literature using the boundary layer theory to model the momentum and thermal transport in the melt pool. The results are correlated with the casting conditions and wetting properties.

1. Introduction

As a result of the high cooling rate (10^6 – 10^7 K s^{-1}) characteristic of the single roller rapid quenching methods (melt spinning, planar flow casting, etc.) these techniques are widely applied for the preparation of non-equilibrium materials (metallic glasses, quasi-crystals and microcrystalline alloys).

A characteristic feature of these methods is a melt pool produced in contact with a moving chill roller. A thin melt layer is accelerated by the roller which solidifies downstream forming a 10–100 μm thick ribbon or foil.

One of the important factors determining the quenching rate is the heat transfer coefficient h , describing the heat contact between the roller and the melt. This quantity has been estimated from the temperature distribution on the top of the ribbon measured by photocalorimetry, with fast pyrometers or from the microstructure of crystalline ribbons. The value of h determined by different methods varies from approximately 10^5 W m^{-2} K^{-1} to a few times 10^6 W m^{-2} K^{-1} [1]. It is found that the value of h is related to the formation of air bubbles at the melt–roller interface [2, 3].

Some results indicate that the heat transfer under melt pool is far better than between the solidified ribbon and the wheel [2]. This conclusion is based on the extrapolation of the temperature distribution on the free surface into the melt

pool. An alternative estimate of h could be obtained by the method of Huang and Fiedler [3] who pointed out that the heat and momentum transport are coupled, thus h can be determined from the relation between the melt pool length l and the ribbon thickness δ .

In the present work the heat transfer coefficient is estimated on this basis. The results are correlated with the casting conditions and the wetting properties.

2. Determination of the heat transfer coefficient

The heat and momentum transport in the melt pool is modelled by the Falkner–Skan type formulation of the boundary layer theory as described in ref. 4. To extend the model's applicability for the formation of crystalline ribbons, a heat release at the solidification front is included as an option. The heat transfer at the melt–roller interface is modelled as suggested by Anestiev [5].

The heat transfer coefficient corresponding to a δ – l pair was determined by varying h at fixed l until the calculated ribbon thickness reached the experimental value.

3. Physical properties and casting conditions

The casting conditions, melt pool length and ribbon thickness data reported for aluminium [6],

$\text{Fe}_{40}\text{Ni}_{40}\text{P}_{14}\text{B}_6$ [7], $\text{Fe}_{81.5}\text{B}_{14.5}\text{Si}_4$ [3], $\text{Ni}_{81}\text{P}_{19}$ [2], AMS 4777, 4778 and 4778L [8] have been used. When possible the expressions $\delta = a \cdot V_0^b$ and $l = c \cdot V_0^d$ (V_0 = roller velocity) have been fitted to the experimental data to remove the statistical error. The relevant properties (viscosity, thermal diffusivity, etc.) were taken from refs. 2, 9 and 10. The viscosity of the AMS alloys and $\text{Fe}_{81.5}\text{B}_{14.5}\text{Si}_4$ was approximated by that of $\text{Ni}_{75}\text{Si}_8\text{B}_{17}$ and $\text{Fe}_{79}\text{B}_{11}\text{Si}_{10}$ [9], respectively.

4. Testing the method

Analysis of the method shows that if the heat contact is nearly perfect or very poor, small changes of δ may result in order of magnitude change in h . The data used in this work are far from these limits. The typical variation of h with l and δ in our case is shown in Fig. 1. While δ can be measured with sufficient accuracy, the error of l is usually large ($\approx 20\%$), thus only averages of a large number of experiments are considered suitable for the determination of h . Another source of uncertainty is the viscosity function in the supercooled range. In the case of $\text{Fe}_{40}\text{Ni}_{40}\text{P}_{14}\text{B}_6$, about a 40% difference of h has been found for viscosity functions of different origin.

5. Results and discussion

It has been reported that the heat transfer coefficient increases with the roller velocity owing to a reduction of the size and density of the air bubbles formed between the roller and the melt

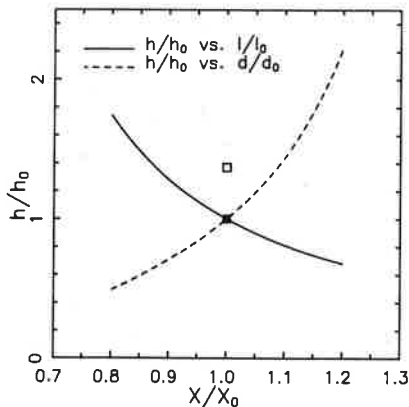


Fig. 1. Sensitivity of the calculated heat transfer coefficient to the ribbon thickness, the melt pool length, and the viscosity function. (Notation. ■ and ◊: values calculated for $\text{Fe}_{40}\text{Ni}_{40}\text{P}_{14}\text{B}_6$ with viscosity functions from different experiments.)

[1–3]. The heat transfer coefficients calculated for a few alloys are shown as a function of roller velocity in Fig. 2. Our results indicate that this trend is valid under the melt pool as well. The h values obtained for $\text{Ni}_{81}\text{P}_{19}$ are in good agreement with those determined from the temperature distribution on the free surface (■) [2].

Huang and Fiedler reported that h increases steeply with V_0 for $\text{Fe}_{81.5}\text{B}_{14.5}\text{Si}_4$ [3], a trend which could not be explained by the variation of the contact area due to air bubbles. (This result has been considered as an artefact [2] since the momentum transport was neglected in ref. 3.) Our results confirm the existence of a steep increase. A possible explanation could be the variation of the density of microbubbles not resolved in the contact area measurements.

The bubble formation is expected to vary with the wetting conditions, which can be influenced by, for example, the melt temperature. The influence of superheating is studied in the case of aluminium cast on copper. It is found that h is increasing with the superheating (see Fig. 3). This trend could be interpreted by the decreasing surface energy of the melt, which improves the wetting of the roller.

The wetting conditions can be changed by applying different melt/roller combinations. The h values we obtained for the ASM 4777 alloy cast on different rollers are given in Table 1. The qualitative differences of the bubble structure described by Adler and Hus [8] correlate well with our data.

The wetting of the roller by the melt can be characterized by the wetting angle ϕ decreasing

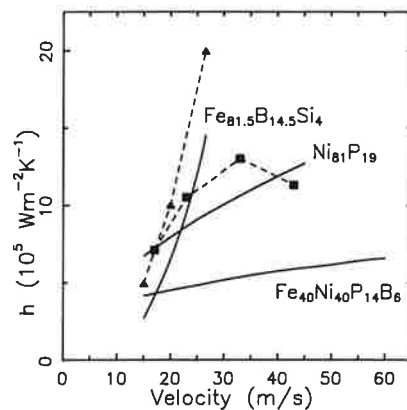


Fig. 2. The heat transfer coefficient vs. roller velocity for different alloys. (Notation. Solid line: present calculations; ■: data for $\text{Ni}_{81}\text{P}_{19}$ from [2]; ▲: data for $\text{Fe}_{81.5}\text{B}_{14.5}\text{Si}_4$ from [3].)

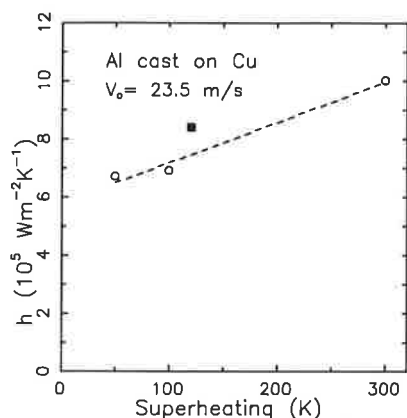


Fig. 3. The heat transfer coefficient vs. melt superheating at $V_0 = 23.5 \text{ m s}^{-1}$ (○: present calculations; ■: from [11]).

TABLE 1

Heat transfer coefficients calculated for ASM 4777 cast on different rollers

Roller	Al	Cr/Cu	Cu	Fe	Ni/Cu
$h (10^5 \text{ W m}^{-2} \text{ K}^{-1})$	1.1	2.0	2.6	4.1	5.1

Cr/Cu and Ni/Cu stand for a copper roller electroplated by chromium and nickel.

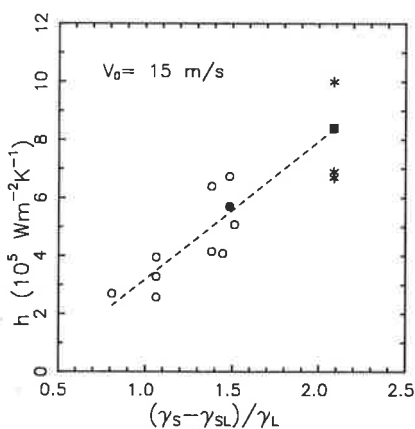


Fig. 4. The heat transfer coefficient vs. $(\gamma_s - \gamma_{SL})/\gamma_L$ at $V_0 = 15 \text{ m s}^{-1}$. (Notations. ○: present results; ■: aluminium cast on copper [11]; ●: $\text{Ni}_{81}\text{P}_{19}$ cast on copper, extrapolation of data from [2] for 15 m s^{-1} ; *: present results, aluminium cast on copper, $V_0 = 23.5 \text{ m s}^{-1}$.)

with improving wetting, where $\cos \phi = (\gamma_s - \gamma_{SL})/\gamma_L$, while γ_s , γ_L and γ_{SL} are the surface energy of the melt, the roller and the roller-melt interface. Owing to the lack of experimental data for the alloys, γ_L has been approximated by $3.6 \cdot T_m / v^{2/3}$ [12] (T_m and v are the melting point and the

molar volume), while γ_{SL} has been calculated using the model of Miedema [13]. The results obtained with the assumption of chemically clean surfaces suggest an ideal wetting ($(\gamma_s - \gamma_{SL})/\gamma_L > 1$) for almost all the cases studied here. The presence of oxides on the surfaces, however, could reduce the wetting of the roller by the melt.

The heat transfer coefficient derived for several melt/roller combinations is presented for $V_0 = 15 \text{ m s}^{-1}$ as a function of $(\gamma_s - \gamma_{SL})/\gamma_L$ in Fig. 4. Despite a considerable scatter, which can be attributed to conditions different in the experiments (super-heating, surface roughness, etc.), a tendency-like correlation can be seen between h and $(\gamma_s - \gamma_{SL})/\gamma_L$: the heat transfer becomes more efficient when the wetting is improved.

6. Conclusions

(1) The heat transfer coefficient *under the melt pool* can be estimated with an acceptable accuracy from the melt pool length and ribbon thickness data using the present model.

(2) The heat transfer coefficient increases with roller velocity, with the superheating of the melt, and with improved wetting.

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