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Influence of pressure and surface roughness on the heat transfer efficiency during water spray quenching of 6082 aluminum alloy

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A B S T R A C T

The heat flux (q) and heat transfer coefficient (h) at the interface between hot aluminum surface and spray water were determined by using an inverse heat conduction method. Good agreements between numerically calculated temperatures with the inverse identified h and experimentally measurements demonstrate that the method is valid for solving the q and h of spray quenching process. The estimated heat flux consists of three main stages of transition boiling, nucleate boiling and single-phase cooling. The results show that both the heat flux and heat transfer coefficient increase with the increasing of spray pressure. When the surface temperature is lower than 170 °C, the q, h and the maximum heat transfer coefficient (h_{max}) decrease and then increase as surface roughness increases. However, when the surface temperature is higher than 170 °C, the influence of surface is insignificant. This phenomenon may be attributed to the variation of nucleation site density with surface roughness.

1. Introduction

Spray quenching is an effective heat treatment method to improve the material performance due to its ability of high heat removal rate. The final mechanical properties of metal workpiece highly depend on the heat transfer efficiency at the metal-quenchant interface during spray quenching process. There are many factors that can influence the heat transfer efficiency, such as the properties of metal workpiece and quenchant, nozzle type, spray pressure, spray distance, spray angle, surface roughness. Therefore, quantitative characterization of the heat transfer coefficient in the simple mathematical model is still very difficult. The previous investigation were mainly focused on a few parameters that can be isolated and easily changed in practice, such as spray pressure and surface roughness.

Xu and Mohamed (2006) developed an iterative and sequential inverse heat transfer analysis procedure to obtain the heat fluxes at the stagnation points of stationary hot steel plates cooled by impingement water jet and studied the effects of water flow rate on heat transfer at different water temperature levels. They concluded that the water flow rate generally has little effect on the heat fluxes of the stagnation points at all water temperature levers. Wang et al. (2012) investigated the heat transfer phenomena of stationary hot steel plate under multiple top circular jets and also found that the cooling water flow rate in the range of 15–35 L/min has no effect on h within 70 mm distance from stagnation line. Mozumder et al. (2006) studied the quenching of hot cylindrical blocks made of copper, brass and steel with initial block temperature 250–400 °C by a subcooled water jet. They suggested that jet velocity was one of predominant parameters and the maximum heat flux (q_{max}) increased gradually with increasing jet velocity. Mascarenhas and Mudawar (2010) examined the quenching a solid alloy cylinder using a full-cone plain-orifice spray nozzles with a cone angle of 45° and found that the increasing of nozzle pressure drop or the decreasing of orifice-to-surface distance could cause the transitions to the initiation of lower temperature boiling regimes to occur at higher surface temperatures and hasten the exit from the poor film boiling regime to the more efficient transition boiling regime.

There are also several studies involving the effect of surface roughness on the interfacial heat transfer over the past two decades. Prabhu and Fernandes (2007) prepared three identical stainless steel specimens with three different surface roughness (R_a = 1.0, 3.0 μm and a groove) at the bottom surface to study the effect of surface roughness on heat transfer rates in various

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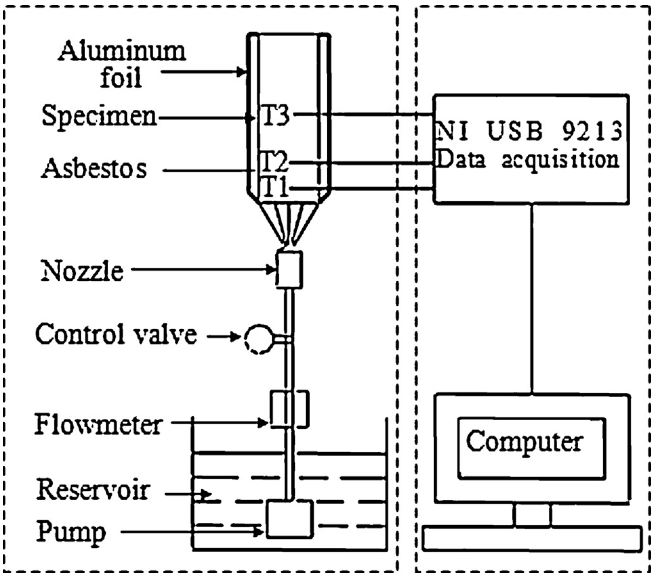

Fig. 1. Schematic diagram of quenching experimental set-up.

quenchants during end quenching. The results indicated that the specimens were found to be very sensitive to surface roughness and the interfacial heat transfer increased with increasing the surface roughness during quenching in water and brine. Luke (1997) investigated the effect of the surface roughness (11.3, 1.00 and 0.16 μm) on the heat transfer coefficient by experiments with propane boiling on copper and steel tubes and observed that increase of surface roughness could increase the nucleation sites which resulted in the increase of heat transfer. Park et al. (2004) found that the wettability in rough surface with a roughness of 6.97 μm was more than that of smooth surface with a roughness of 0.39 μm. The enhancement of wettability on the heated surface directly improved the heat transfer rate. Pais et al. (1992) studied the effects of surface roughness (values ranged 0.3–22.0 μm) on heat transfer during spray cooling and found that the 0.3 μm rough surface achieved higher heat fluxes over the temperature domain sampled.

According to the above literature, research on the effects of spray pressure and surface roughness on the heat transfer is still not systematic, different researchers obtained inconsistent results under different experimental conditions. The present study is aimed to investigate the effects of spray pressure and surface roughness on the heat flux and heat transfer coefficient at the interface between a heated aluminum surface and spray cooling water, to simulate the quenching process of aluminum alloys. The q and h are determined by inverse heat conduction method.

2. Experimental apparatus and procedure

2.1. Experimental set-up

The schematic diagram of quenching experimental set-up is shown in Fig. 1. It consists of water spray quenching system (left dash box in Fig. 1), specimen and data acquisition system (right dash box in Fig. 1). A tank containing quenchant was placed in the bottom of the set-up. Circulating cooling water was used as quenching medium. A pump located in the tank was used to pump the water through a nozzle of diameter 10 mm. A flowmeter and a control valve were mounted in the middle of the pump and the nozzle in order to adjust the spray water flow as needed. Quench specimen was placed directly above the nozzle. All specimens were instrumented with three K-type thermocouples. The side face of the specimen was wrapped with an asbestos layer tighten by aluminum foil, to ensure the water flow only contacts the bottom end of the specimen. All the experimental conditions employed in the present study are displayed in Table 1. The temperature of the water spray (T_w) is 8 °C. Spray pressure (P) is the water pressure at the outlet of the nozzle. The value of the spray pressure was calculated by using the measured total flow rate and nozzle diameter and varies from 0.6 to 3.1 kPa. The distance from the outlet of the nozzle to the specimen was about 80 mm.

2.2. Specimen preparation and data acquisition

Cylindrical specimens were used to study the interaction between water and hot aluminum alloy specimens during quenching and particularly to determine q and h in different quenching conditions. The chemical composition of the cylindrical specimens is illustrated in Table 2. Aiming to measure the evolution of temperature, three K-type thermocouples labeled by T1, T2 and T3 with the diameter of 0.2 mm were centrally positioned in the lateral surface of each specimen. The distances between the surface and the three thermocouples are 3 mm, 10 mm and 20 mm, respectively. The dimensions of specimens and the location of thermocouples are shown in Fig. 2. Three specimens with different milled surface roughness (R_a = 0.6, 7.6, 40.2 μm) at the quench end were prepared to study the effect of surface roughness on the interfacial heat transfer coefficients. The specimens were heated to 520 °C and soaked for 3 hours in the electric resistance furnace, and then quickly transferred to the operating position within 10 s.

NI USB 9213 data acquisition instrument (National Instruments, Inc., Austin, Texas, US) was used to collect temperature data at a rate of 100 Hz. This is a 16 channel, 24 bit data acquisition instrument with a sampling rate of 1200 samples/sec. It has built-in cold junction compensation. The uncertainty of the temperature measurement is less than 0.25 °C for K-type thermocouple, while the uncertainty of the placement of the thermocouples is estimated to be ±0.2 mm.

3. Results and discussion

3.1. Inverse identification of the heat flux

As shown in Fig. 2, the length of the specimen is far greater than its diameter. Thus the quenching process can be approximately considered as one-dimensional heat transfer in order to simplify the data processing. The measured temperature data at the location T1 in Fig. 2 is used as the known temperature history for estimating the interfacial heat flux and the metal surface temperature at the quenching interface using an inverse heat conduction method as described in Zhang and Li (2013). The one dimensional transient heat conduction equation is defined as follows:

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2}\right) \tag{1}$$

where ρ, C_p and k are the density, specific heat and thermal conductivity of the specimen. T is the temperature of the specimen, t is the time. The surface heat flux density is estimated from the T1 temperature by minimizing the objective function:

$$F(q^i) = \frac{1}{M}\sum_{n=1}^{M}(T_n^{i+R\Delta\theta} - Y_n^{i+R\Delta\theta})^2 \tag{2}$$

where M is the number of the heat fluxes to be predicted, $T_n^{i+R\Delta\theta}$ and $Y_n^{i+R\Delta\theta}$ are the calculated and measured temperature at time $i + R\Delta\theta$, R is the number of future time steps to compensate for the heat difference and $\Delta\theta$ is a discrete time interval. The objective function is minimized through iterations. At each iteration step,