Experimental Thermal and Fluid Science 76 (2016) 211–220

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

The effects of spray characteristic on heat transfer during spray quenching of aluminum alloy 2024

Ruichao Guo, Jianjun Wu *, He Fan, Xuepeng Zhan

School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China

ARTICLE INFO

Article history:
Received 2 January 2016
Received in revised form 9 March 2016
Accepted 26 March 2016
Available online 30 March 2016

Keywords:
Heat transfer
Spray quenching
Critical heat flux
Aluminum alloy

ABSTRACT

A spray quenching apparatus was performed and hot aluminum alloy 2024 thin sheets were spray quenched by two symmetrically arranged nozzles. The influence of spray nozzle distance on heat transfer was experimentally investigated. The results show that there is no film boiling regime and Leidenfrost point at different nozzle distance. Both critical heat flux (CHF) value and surface temperature at which CHF occurs first decrease to the minimum value with increased nozzle distance, and then increase until reach the maximum value. Finally, CHF value and surface temperature decrease with further increase of nozzle distance. However, the maximum CHF value is observed when nozzle distance is 70 mm, and the highest surface temperature at which CHF occurs is obtained at nozzle distance of 80 mm. A nozzle distance of 80 mm is better since there exists a longer nucleate boiling regime and a relatively higher CHF value. This phenomenon may have guiding significance for industrial production.

1. Introduction

With the development of the aviation industry and in order to satisfy weight requirements of large size aircraft parts, more and more metal honeycomb bonding composites have been applied to the design of aircraft structures, such as aircraft radome, spoiler, aileron, rudder, side wall and hatch door. The aluminum alloy 2024 thin sheets (0.30–0.50 mm thickness), because of their good forming ability and machinability [1,2], are widely used as preferred materials for aircraft metal honeycomb panels.

In order to obtain the required mechanical properties of structures, the aluminum alloy 2024 thin sheets, after heated above the solution temperature (approximately 500 °C), are usually quenched by water, oil or other liquids [3]. The spraying quenching, compared with other quenching techniques, has been extensively used in aluminum alloy quenching due to its ability of higher removal of heat flux [4,5]. However, a significant amount of residual stresses will be produced by the thermal gradients which occur during spray quenching. And the existence of residual stresses can have a significant impact on structures properties. The magnitude of residual stresses mainly depends on the quenching rate which is directly related to the spray quenching factors [6].

In spray quenching process, the primary spray parameters, which have the significant influence on heat transfer performance, are volumetric flux, Sauter mean diameter and mean droplet velocity [7]. The volumetric flux, compared with other parameters, is the most important parameter which has the strongest effects on the determination of Leidenfrost point, critical heat flux and its temperature [8]. Wendelstorf et al. [9] studied the heat transfer at different mass fluxes during spray quenching. They indicated that the heat transfer coefficient increased with the increasing of mass flux in film boiling regime, and also they found that the temperature may have an influence on heat transfer coefficient (HTC). A similar result, where heat transfer coefficient increased with volumetric flux, was found by Puschmann et al. [10]. Estes and Mudawar [11] found that low volumetric flux had a significant increase in the slope of the boiling curve between the single-phase and nucleate boiling regime. However, this influence was not pronounced at high volumetric flux. Lin and Ponnappan [12] studied different liquids (FC-87, FC-72, methanol and water) for the cooling of high heat flux heat sources. They presented that for a given surface superheat, the heat flux increased with the volumetric flux and critical heat flux increased with the volumetric flux. Rybicki and Mudawar [13] also indicated that volumetric flux and Sauter mean diameter were the key parameters that influenced spray quenching performance.

The spray quenching of aluminum alloys were widely investigated in previous literatures. However, many research results were focused on the spray quenching of aluminum alloy castings and plates. Few research was studied on spray quenching of thin sheets. Mascarenhas and Mudawar [14] studied quenching aluminum alloy 2024 cylinder using full-cone pressure sprays. They

* Corresponding author at: Northwestern Polytechnical University, 127 West Youyi Road, Xi'an, Shaanxi 710072, PR China.

E-mail address: wujj@nwpu.edu.cn (J. Wu).

http://dx.doi.org/10.1016/j.expthermflusci.2016.03.025
0894-1777/

Nomenclature

B	matrix of coefficient
c	specific heat capacity, J/(kg °C)
CHF	critical heat flux, W/m^2
d_{32}	Sauter mean diameter, mm
D	the interval
d_0	nozzle orifice diameter, mm
D_N	nozzle distance, mm
h	heat transfer coefficient, W/(m^2 K)
HTC	heat transfer coefficient, W/(m^2 K)
L	the heated surface area relative to length
k	smoothing parameter
m	an integer which defines the length of interval D
n	an integer which defines the number of time–temperature data
N	the normalized uniform B-spline elements
P_N	nozzle pressure, bar
q	heat flux, W/m^2
Q	spray flow rate, L/min
Q''_{sp}	volumetric spray flux, m^3/(s m^2)
s_i	time fraction of discrete temperature data, s
t	time, s
T	temperature, °C
T_s	surface temperature of specimens, °C
T_w	water temperature, °C
ΔT	difference between surface and water temperature temperatures, °C
$y(t)$	B-spline smoothed temperature, °C

Greek symbols

α	thermal diffusivity, m^2/s
δ	thickness of sheets, mm
η	heat transfer efficiency
λ	thermal conductivity, W/(m °C)
θ	spray angle, °
ρ	density, kg/m^3
$\boldsymbol{\tau}$	control point vector

indicated that increasing nozzle pressure drop or decreasing orifice-to-surface distance may increase the heat transfer performance. Xu et al. [15] focused on 6082 aluminum alloy. The influence of spray pressure and surface roughness on heat transfer was investigated. They found that both the heat flux and heat transfer coefficient increased with spray pressure. Golovko et al. [16] examined quenching EN AW-6082 aluminum alloy by lumped heat capacitance method. The influence of spraying distance, inclination angle and flow rate on the heat transfer coefficients was discussed. They indicated that neither spraying distance nor inclination angle had significant influence on heat transfer coefficient. Mascarenhas and Mudawar [17] experimentally studied the parametric influence of spray quenching for thick-walled aluminum alloy 2024 tube. Three parameters including spray pressure, orifice-to-surface distance and thermal properties on temperature response during spray quenching were investigated. The results showed that increasing spray pressure or decreasing orifice-to-surface distance hastened the onset of rapid cooling stages of quench as well as improved overall cooling effectiveness.

In an earlier investigation [18] we demonstrated that the water temperature and nozzle pressure had a significant influence on heat transfer of aluminum 2024. However, in industrial production, the two parameters are difficult to perform and may need higher cost. The volumetric flux is the ratio of volume flow rate and it can be changed by spray nozzle distance or spray pressures for identical spray nozzles. Unlike nozzle pressure or water temperature, nozzle distance is easier to operate in industry. Therefore, the present study is concerned with the influences of practical spray parameter (nozzle distance) on heat transfer during spray quenching. These influences are used to predict residual stresses during practical spray quenching in future work. In this paper, a spray quenching apparatus is performed to obtain time–temperature data. The surface temperatures and surface heat fluxes of thin sheets are inversely determined from smoothing time–temperature curves by B-spline approximation.

2. Experimental procedure

2.1. Spray quenching system and specimens

Schematic diagrams and the photo of the spray quenching experimental system are shown in Fig. 1 and it has been descried in detail elsewhere [18]. Basically, the system consists of four sections: the tank system, the spray quenching system, the furnace system and the data acquisition system. The water is adjusted inside the tank and then, water at room temperature (approximately 25 °C) is pumped from the tank to the spray nozzles. Nozzle pressure (P_N), varying from 1 bar to 5 bar, can be regulated by the inverter. And the nozzle pressure is to be set at 3 bar in present condition. Two commercial full-cone spray nozzles (Spraying Systems, Co., Ltd) are used at nozzle distance (D_N) ranging from 50 mm to 90 mm. In this work, the spray angle is 45° and nozzle orifice diameter (d_0) is 2.4 mm. The Sauter mean diameter (d_{32}) is approximately 0.3 mm obtained from the manufacture. Locations of nozzles are shown in Fig. 2. The dimensions of specimens are 60 mm × 60 mm, and all the specimens have a normal thickness of 0.508 mm. The materials of the specimens are 2024-O aluminum sheets from Kaiser Aluminum, Co., Ltd, USA. And chemical composition of aluminum alloy 2024 are listed in Table 1. The density of aluminum alloy 2024 is assumed to be constant (2780 kg/m^3). The thermal conductivity and specific heat capacity of aluminum alloy 2024 obey the following temperature dependent equations, respectively [19]:

$$\lambda = 167.7 + 0.108 \times T\ (^{\circ}\mathrm{C}) \quad \text{unit}: \mathrm{W/(m\ ^{\circ}C)} \tag{1}$$

$$c = 856.7 + 0.891 \times T\ (^{\circ}\mathrm{C}) \quad \text{unit}: \mathrm{J/(kg\ ^{\circ}C)} \tag{2}$$

Eqs. (1) and (2) are effective for the temperature varied from 0 °C to 500 °C.

2.2. Heat transfer procedure

Characteristics of spray quenching are listed in Table 2. The method of investigation is based on the measurement in the middle of two specimens. A CHROMEGA®–ALOMEGA® thermocouple (CO2-K, OMEGA, USA) is sandwiched between the two specimens. And high temperature air set cement (OMEGABOND® 400) is applied to thermocouples to ensure good contact between surface of specimens and thermocouples (see Fig. 3). The thermocouple is about 0.013 mm in diameter. After installing the specimens in the furnace, they are heated to 495 °C by resistive heaters and retained for 30 min when reaching the test temperature. Then the specimens are quickly moved from furnace to the spraying position. In this position, two surfaces of specimens are symmetrically quenched with sprays when two valves are simultaneously opened on water circuit. Supported by the evaluation of heat flux, there are