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Investigation of heat transfer on 2024 aluminum alloy thin sheets by water spray quenching

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ABSTRACT

In this paper, the hot 2024 aluminum alloy thin sheets at 495 °C were quenched by two spray nozzles with different pressures and water temperatures. The heat fluxes were determined using an inverse heat conduction method, and time–temperature curves were smoothed by B-spline approximation. The results indicate that there exists a film boiling regime and Leidenfrost point when water temperature is 70 °C. The critical heat flux first increases and then decreases with increasing nozzle pressure. The critical heat flux decreases when water temperature increases from 25 °C to 60 °C. However, the critical heat flux increases when water temperature varies from 60 °C to 70 °C.

1. Introduction

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

In order to satisfy the required mechanical properties of structures, the 2024 aluminum alloy thin sheets are usually heated above the solution temperature (approximately 500 °C), and then cooled in a cold medium [3]. The cooling process is generally carried out either by putting the components into water, oil or other liquids, or by spraying them with liquids. The spraying quenching, compared with other quenching techniques, has the higher heat fluxes and heat transfer efficiency. Therefore it is widely used in steel and aluminum alloy quenching [4,5].

The spray quenching of aluminum alloys were widely discussed in the literature, however, mainly about aluminum alloy castings and plates. Mascarenhas and Mudawar [6] studied quenching 2024 aluminum alloy cylinder by full-cone pressure sprays. The results showed that the increasing nozzle pressure drop or the decreasing orifice-to-surface distance caused the transitions to the lower temperature boiling regimes to occur at higher surface temperatures and also it could accelerate the exit from poor film boiling regime to more efficient transition boiling regime. Cheung et al. [7] investigated the metal/mold heat transfer coefficient during solidification about 6101 aluminum casting. Finite difference method was used to obtained time-dependent temperature distribution and then the heat transfer coefficient was based on the inverse heat conduction problem. Xu et al. [8] focused on the influence of spray pressure and surface roughness on heat transfer about 6082 aluminum alloy. They found that the both heat flux and heat transfer coefficient increased with increasing of spray pressure. However, the influence of surface roughness was insignificant when surface temperature was higher than 170 °C. Zhang et al. [9] studied the influence of latent heat and thermocouples distance on heat transfer coefficient about A356 aluminum casting. Inverse methods were used and the results showed that thermocouples should be placed less than 2 mm from interface. Golovko et al. [10] investigated the impact of spraying distance, inclination angle and flow rate on the heat transfer coefficients about EN AW-6082 aluminum alloy by lumped heat capacitance method. They found that neither spraying distance nor inclination angle had significant influence on heat transfer coefficient. Mascarenhas and Mudawar [11] examined the influence of spray pressure, orifice-to-surface distance and thermal properties on temperature response during spray quenching for thick-walled aluminum alloy 2024 tube. The results showed that the cooling effectiveness improved with the increasing spray pressure and the decreasing orifice-to-surface distance.

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Nomenclature

$\mathbf{B}$	matrix of coefficient
c	specific heat capacity, J/(kg °C)
CHF	critical heat flux, W/m^2
d	thickness of sheets, mm
d_{32}	Sauter mean diameter, mm
D	the interval
d_0	nozzle orifice diameter, mm
D_N	nozzle distance, mm
F	the force required to rupture a liquid in tension, N
h	heat transfer coefficient, W/(m^2 K)
HTC	heat transfer coefficient, W/(m^2 K)
IHCP	inverse heat conduction problem
k	thermal conductivity, W/(m °C)
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	flow rate, L/min
$\mathbf{Q}$	matrix with dimensions of $(m+3) \times (m+3)$

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
$\mathbf{T}$	temperature vector
T_s	surface temperature of specimens, °C
T_w	water temperature, °C
ΔT	difference between surface and water temperature temperatures, °C
x	coordinate defined in Fig. 4
$y(t)$	B-spline smoothed temperature, °C

Greek symbols

α	thermal diffusivity, m^2/s
λ	smoothing parameter
θ	spray angle, °
ρ	density, kg/m^3
σ	surface tension, N/m
$\boldsymbol{\tau}$	control point vector
ω	a constant for scaling the interval

According to the above references, research on the aluminum alloys is not systematic. Due to different experimental conditions, the obtained results are inconsistent. The heat transfer coefficient (HTC) or heat flux is the most decisive factor in influencing the quenching results, compared with other data such as material property, process parameter and other conditions [12,13]. In spray quenching, the heat transfer is a complicated process which depends on many factors such as water temperature and nozzle pressure. Therefore, in this paper, to fully understand the influence of quenching conditions on heat transfer during water spray quenching, a spray quenching apparatus is built to conduct water quenching experiments for 2024 aluminum thin sheets. The surface heat fluxes of thin sheets are inversely determined from the smoothing time–temperature curves by B-spline approximation.

2. Experimental procedure

2.1. Spray quenching system

Schematic diagram and photo of the water spray quenching system are shown in Fig. 1. The system has the following sections: the tank zone, the water spray quenching zone, the furnace zone and the data acquisition system zone. At first, the water is adjusted inside the tank varying from the room temperature to 95 °C by temperature controller, resistive heater and temperature sensor. Then, water is pumped by pump which is located above the tank. A bottom valve, located in the tank, is used to avoid water backflow. Nozzle pressure, varying from 1 bar to 5 bar, can be regulated by the inverter. Two commercial full-cone spray nozzles (Spraying Systems, Co., Ltd., 1/4HH-SS6.5) are located on both sides of the quenching tank and the distance between the nozzles is 140 mm, and in this study the spray angle is 65° and nozzle orifice diameter is 2.4 mm. Locations of nozzles and thermocouple are shown in Fig. 2. The Sauter mean diameter d_{32} of droplets, obtained from manufacturer, is approximately 0.3 mm. The volumetric spray flux Q''_{SP} is assumed uniform over the spherical surface area and it can be defined as [14]:

$$Q''_{sp} = \frac{Q}{2\pi D_N^2 (1 - \cos(\theta/2))} \tag{1}$$

The volumetric spray flux is obtained by the data in Table 1. The influence of water temperature and nozzle pressure will be investigated, and characteristics of water spray quenching are listed in Table 1.

2.2. Heat transfer process

The method of investigation is based on the measurement carried out at the middle of two sheets. A CHROMEGA® – ALOMEGA® thermocouple (CO2-K, OMEGA, USA) is sandwiched between two sheets, and the thermocouple is around 0.013 mm in diameter. High temperature air set cement (OMEGABOND® 400) is applied to thermocouples to ensure good contact between surface of specimens and thermocouples (shown in Fig. 2b). The aluminum sheets are 60 mm × 60 mm × 0.508 mm in dimensions which are made of 2024-O aluminum alloy from Kaiser Aluminum, Co., USA. Chemical limits of 2024 aluminum alloy is illustrated in Table 2. The specimens are heated to 495 °C by resistive heaters and retained for 30 min in furnace, and then quickly transferred to the spraying position. Two valves are simultaneously opened on water circuit, thus, two surfaces of specimens are symmetrically quenched. Output signals are recorded by a high DC data acquisition system (OM-DAQ-USB-2401, USA) at high frequencies of 100 Hz when specimens are transferred to the spraying position.

2.3. Uncertainty analysis

The dimensions of the specimens are determined by a water jet cutting machine which has an repeated accuracy of ±0.050 mm according to the manufacturer. The CO2-K thermocouples have the uncertainty of ±0.75% full scale. The accuracy of temperature measurement is approximately ±1.2 °C for K-type thermocouples. The nozzle pressure is obtained with an error of ±0.05 bar by pressure controller. And water temperature has an uncertainty of ±0.05 °C. The percentage of conductivity and heat capacity error is about 5%. The precision of the heated temperature of specimens is estimated as ±1 °C based on performance data of digital temperature controller in furnace. The uncertainty of surface temperature and heat flux are calculated by a root summary square method of