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Transient contact behavior of aqueous polymer solution droplets with transparent hot solid

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ABSTRACT

In the metal forming industry, quench hardening is commonly used to strengthen steel products by rapidly cooling hot materials. One of the typical coolants used in the quench hardening process is an aqueous polymer solution. During the hardening process, several phenomena occur simultaneously, namely, coolant boiling, separation of the polymer from the aqueous solution, and formation of a polymer-enriched layer on the solid surface. The hydrodynamics and heat transfer characteristics of the coolant during the cooling process are complex in nature and remain unclear. The main objective of this study is to develop an experimental understanding of the collision and contact behavior of aqueous polymer solution droplets with a hot substrate. This research will serve as a fundamental reference work for the process of quench hardening using spray cooling. To fulfill this objective, a three-directional flash photography technique was developed. A transparent sapphire prism was used to observe the transient contact behavior of droplets with a hot solid, whose temperature was varied from 300 to 600 °C. A solution of 10 wt% polyoxyethylene-polyoxypropylene glycol with an average molecular weight of approximately 20,000 was used as the test liquid. At a substrate temperature of 300 °C, jellylike polymer residue remained on the substrate. At 400 and 500 °C, a wet area appeared temporarily on the solid substrate soon after the droplet collision, but this area eventually disappeared because of the thermal decomposition of the polymer. At 600 °C, no wet area was seen. The lifetime of the temporary wet area decreased with an increase in the temperature of the solid but was almost independent of the impact inertia of droplets. In addition, in the case of the polymer solution droplet, the upper limit of the surface temperature for forming the wet area was around 580 °C, which was considerably higher than that in the case of a water droplet.

1. Introduction

Aqueous polymer solutions are widely utilized as a cooling medium in quench hardening processes to strengthen hot carbon steels [1–6]. Hot materials are rapidly cooled from approximately 750–900 °C to a certain specific temperature to induce martensitic transformation, and then, a moderate cooling rate is imposed on the materials to prevent unwanted quench-crack initiations or distortion of products. During the cooling process, the polymer separates from the aqueous solution and adheres to the material surface, resulting in the formation of a polymer-enriched layer [2], which is a characteristic feature of this coolant and inhibits rapid heat reduction from the solid substrate.

Several previous works [2–6] have focused on the cooling process in industrial heat-treatment applications using aqueous polymer solutions. The main interests of these studies were the measurement of the temperature histories of materials and the determination of the heat transfer coefficient. Various parameters were found to influence the heat transfer characteristics, including the polymer component, its concentration, and the cooling conditions. However, less attention has been paid to understanding the underlying physical mechanism. In general, actual cooling operation conditions are determined empirically without an understanding of the underlying physical mechanism. Indeed, to find better cooling operation conditions, it would be useful to have a fundamental understanding of the hydrodynamics and boiling phenomena of polymer quenchants, and the formation process of the polymer-enriched layer. The present study was not aimed at obtaining practical data for an actual cooling system design, but rather at an exploration of the fundamental physics of the phenomena through simple laboratory-scale experiments.

Spray cooling methods are commonly employed in induction hardening applications [5,6], in which steel products are heated by induction heating, followed by immediate quenching. The collision of individual liquid droplets with a solid is a basic process of spray cooling applications [7,8]. Several excellent review papers concerning the collision of individual liquid droplets with a solid have been published [9–15]. In most previous works, a single-component liquid such as

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Nomenclature

c_p	specific heat, J/(kg K)
d	preimpact diameter of droplets, m
t	elapsed time after a droplet touches the solid surface, s
T_w	temperature of the solid substrate, °C
T_i	interfacial temperature at the moment of droplet impact, °C
v	impact velocity of the droplet, m/s
We	Weber number, –

Greek symbols

λ	thermal conductivity, W/(m K)
ρ	material density, kg/m^3
σ	surface tension, N/m

water or fuel was used. However, the deformation behavior of aqueous solution droplets with polymer additives has been less studied. Rozhkov et al. [16] studied the collision behavior of aqueous polymer solutions with small nonheated targets made of stainless steel by employing a high-speed photography technique. The test liquids were aqueous water solutions of polyethylene oxide at concentrations of 10, 100, and 1000 wt ppm. The droplet impacted the target, and a liquid lamella was formed. Polymeric additives were shown to prevent the rupture of the liquid lamella. Bertola [17] studied a droplet impacting a hot solid heated at 120–180 °C. The test liquids were water and a water solution with 0.02 wt% polyethylene oxide additives. The Weber number, which ranged from 20 to 220, is the ratio of the impact inertia to the surface tension force and is defined as

$$We = \frac{\rho v^2 d}{\sigma} \tag{1}$$

where ρ, v, d, and σ represent the liquid density, impact velocity, droplet diameter, and surface tension coefficient of droplets, respectively. They reported the additive inhibited droplet splashing, secondary droplet ejection, and mist formation.

Bertola and Sefiane [18] studied the effects of minute amounts of polyethylene oxide in water on the occurrence of secondary atomization when a liquid drop impacted a heated surface at 150–350 °C. The additive was found to oppose the scattering of secondary droplets from the free surface of the liquid. Zang et al. [19] studied the impact dynamics of droplets on a superhydrophobic surface with a dendritic structure by using a high-speed camera. The test liquid contained silica nanoparticles and/or polyethylene oxide additives. They showed that both the particles and polymer additives constrain the instability behavior of the liquid.

The abovementioned works reported useful data from a scientific perspective, but the experimental conditions used in these studies, including the polymer type, its concentration, and the temperature range of the solid substrate, were different from those in actual hardening processes of steel products. Therefore, we studied the hydrodynamic behavior of droplets of an aqueous polymer solution impinging on a hot sapphire substrate by employing a flash photography technique [20]. An aqueous solution of 10 wt% polyoxyethylene-polyoxypropylene glycol with an average molecular weight of approximately 20,000 was used as the test liquid. When the Weber number was small and the substrate temperature was 500 °C, the droplet impacted the solid, deformed into a disc, and recoiled and rebounded off the solid. Some empirical formulae for predicting the spreading diameter of droplets and the resident time were built as functions of the Weber number. More interestingly, a polymer-enriched layer was found to form temporarily on the hot substrate and eventually disappear because of the thermal decomposition of the polymer. This finding indicates that a polymer-enriched layer might be present even at a substrate temperature that is higher than the temperatures at which the test polymer is thermally decomposed. This is also interesting from an industrial perspective, because the polymer-enriched layer influences the transient temperature profile of materials during spray cooling. However, the process by which the polymer layer forms and disappears remains unclear, because the flow visualization technique used in the above study was inappropriate for observing the phenomenon.

To address this problem, the present study was planned as a part of a series of studies. The main objective of the present study was to understand the transient liquid–solid interfacial phenomena, which involve the boiling of water, the separation of the polymer from the aqueous solution, and the formation of a polymer-enriched layer on the solid surface. A new flash photography technique was developed to investigate the collision and contact behavior of droplets with a hot substrate simultaneously by expanding the flow visualization technique used in our previous studies [21]. A transparent rectangular prism made of sapphire was employed as the test substrate to observe the physics of the phenomena directly at the liquid–substrate interface during droplet impact. We used sapphire because its thermal conductivity and thermal diffusivity are comparable to those of some steel alloys like stainless steel.

The test polymer solution was the same as that used in our previous study [20]. Water was also used as a test liquid for reference. The effects of varying the substrate temperature and the Weber number on the contact behavior of the aqueous polymer solution droplets with the solid substrate were investigated. We found that at 300 °C, some polymer residue remained on the substrate. At 400 and 500 °C, a polymer-enriched layer temporarily appeared on the solid substrate and then disappeared because of the thermal decomposition of the polymer. At 600 °C, no wet area was seen. The lifetime of the temporary polymer-enriched layer depended on the substrate temperature but was almost independent of the Weber number. The physics of these phenomena will be discussed in detail, from both scientific and industrial perspectives.

2. Experiments

2.1. Test polymer and test solution

In the present study, polyoxyethylene-polyoxypropylene glycol (chemical formula: $HO–(C_2H_4O)_a–(C_3H_6O)_b–(C_2H_4O)_c–H$) was used as the test polymer. The measured molecular weight of the test polymer was approximately 20,000, and the measured ratio of $(a + c)$:b was 75:25. Fig. 1 presents the thermogravimetric curve showing the relationship between the temperature of the test polymer and its weight

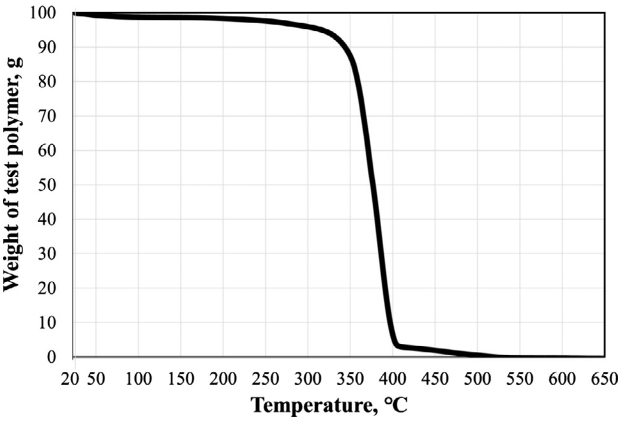

Fig. 1. Thermogravimetric curve of test polymer.