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Nanoquenchants for Industrial Heat Treatment

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The present work outlines the possibility of using nanofluids for industrial heat treatment. Development of nanoquenchants having (i) high quench severity for enhancement of heat transfer for thick sections with low quench sensitivity and (ii) low cooling severity for thin sections with high quench sensitivity would be extremely useful to the heat treating community. The temperature dependent heat transfer coefficient and the wettability of the medium are the two important parameters that can be used to characterize a nanoquenchant to assess its suitability for industrial heat treatment.

Keywords heat treatment, nanoquenchant

1. Introduction

A quench medium must extract heat from the metal at a rate rapid enough to produce the desired microstructure and properties. The rate of cooling of the work-piece depends on its size, thermophysical properties, surface characteristics, and the initial temperature prior to quenching. Water, brine, water, polymers, oils, salts, and gases having different cooling characteristics are some of the commonly used quench media. Judicious selection of quench medium is critical for obtaining optimum mechanical properties, avoiding quench cracks, minimizing distortion, and improving reproducibility in hardening. Generally low cooling rates are employed on critical components with variation in section thickness to reduce residual stresses. Petroleum-based oils having low severity of quenching are more suitable for this purpose. However, petroleum-based products are nonrenewable and can contribute to air and water pollution. Modern nanotechnology provides new opportunities to process and produce quench media having varying severities of quenching. Fluids incorporating nanoparticles with average crystallite sizes below 50 nm suspended in them are called nanofluids (Ref 1). Nanofluids can be considered to be the next generation heat transfer fluids as they offer exciting new possibilities to enhance heat transfer performance compared to pure liquids. They are expected to have superior properties compared to conventional heat transfer fluids. Nanofluids used for quenching can be called as nanoquenchants.

In the present work, the severity of quenching of water and water-based nanofluid containing 20 wt.% alumina particles having size 50 nm is assessed using lumped heat capacitance method. The wetting behavior of both the media on stainless steel substrate is compared. Wettability can be defined as the tendency of a liquid to spread on a solid substrate. If a liquid spreads spontaneously on a given solid surface, it is said to be wetting the solid. If the liquid beads up into a droplet on a surface, then it is considered as nonwetting the solid surface (Ref 2). Wettability can be characterized by the degree and the rate of wetting (Ref 3, 4).

2. Assessment of Heat Transfer Coefficients

The lumped heat capacitance method was used to assess heat transfer during quenching. This method can efficiently model the unsteady cooling of a small object with an assumption of uniform probe temperature during quenching process (Ref 5, 6). If the temperature of the probe is uniform during cooling process, the heat loss from the probe 'Q' is equal to the decrease in internal energy of the probe. Thus

$$Q = hA(T_\mathrm{p} - T_\mathrm{q}) = -Cp\rho V\left(\frac{dTp}{dt}\right) \qquad \text{(Eq 1)}$$

where Q is the heat flow rate, W; h the heat transfer coefficient on the probe surface, W/m^2 K; A the surface area of the probe, m^2; T_p the temperature of the probe, K; T_q the temperature of the quenchant, K; C_p the specific heat of the probe material, J/ kg K; ρ the specific density of the probe material, kg/m^3; V the volume of the probe, m^3; t the time, s; (dT_p/dt) the cooling rate of the probe.

The heat transfer coefficient (h) can be calculated from the cooling rate (dT_p/dt) as

$$h = C_p\rho\,\frac{V}{A}\left(\frac{dT_\mathrm{p}/dt}{(T_\mathrm{p} - T_\mathrm{q})}\right) \qquad \text{(Eq 2)}$$

3. Experimental Details

The experimental setup for assessment of wetting behavior consists of a dynamic contact angle analyzer (Model: FTA 200—First Ten Ångstroms, Virginia, USA). A droplet of test liquid was dispensed using a surgical syringe with a precision

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flow control valve on to the steel substrate and spreading phenomena was recorded at 60 images per second. Captured images were analyzed using FTA software to determine the contact angle of the droplet on the substrate. The experimental setup for the quenching treatment consisted of a vertical tubular electric resistance furnace open at both the ends. A quench tank containing the quenching medium was placed directly underneath the furnace so that the heated work-piece could be transferred quickly to the quench medium. Cylindrical quench probe having 12 mm diameter and 60 mm height was prepared from Type 304 stainless steel. The probe was instrumented with K-type thermocouples of 0.45 mm diameter and was connected by means of compensating cable to a data-logger interfaced with a PC. The probe was heated to about 850 °C in the furnace and held vertically inside the furnace using a nichrome wire for 10 min and was quickly transferred to the quench tank containing 1500 mL of quench medium. The temperature of the quench medium was also measured during the experiment. The temperature data acquired during quenching of specimen was used as an input to the lumped heat capacitance model for estimating heat transfer coefficients.

4. Results and Discussion

The thermal history during immersion quenching of the stainless steel probe in quench media is shown in Fig. 1. The three stages of quenching namely vapor blanket, nucleate boiling, and convective cooling stages were observed for both water and nanoquenchant. However, the transition from the vapor phase stage to the nucleate boiling stage was gradual for the nanomedium. Figure 2 shows the variation of heat transfer coefficients (*h*) with temperature for both the quench media. Although the peak heat transfer coefficient for water ($h_{\max}$ = 1365 W/m^2 K) was slightly higher than the nanoquenchant ($h_{\max}$ = 1241 W/m^2 K), the significant difference between the two media lies in the time of occurrence of the peak. The time of occurrence of peak heat transfer coefficient was about 10 s for water and 26 s for the nanomedium. The probe temperatures corresponding to the peak heat transfer coefficients were 560 and 460 °C for water and the nanomedium, respectively. The occurrence of the peak is delayed in the nanomedium because of the prolonged vapor phase and the peak occurred at lower probe temperatures. This significantly decreases the severity of quenching of the medium. Figure 3 shows the integral heat flux curves for the quench media. The plot clearly shows that the amount of heat extracted is considerably lower for the nanomedium particularly during the initial stages of quenching. The longer vapor phase stage and the delayed mucleate boiling in the nanomedium can be explained on the basis of its wetting behavior on the stainless steel substrate. Figure 4 shows the relaxation of contact angles of water and nanoquenchant on the stainless steel substrate at 27 °C. A comparison of the spreading behavior indicated that the spreading was almost complete for water at about 200 ms. However, the nanomedium continued to spread on the substrate even after 1000 ms. The contact angle for water stabilized at about 83°. For the nanomedium, the contact angle did not stabilize even below 68°. The good wettability of the quench medium with the substrate improves the probe/quench medium

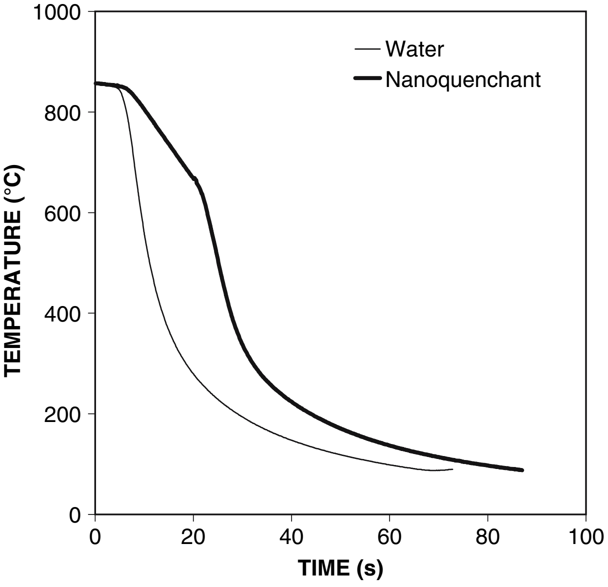

Fig. 1 Cooling curves during quenching of stainless steel probe in quench media

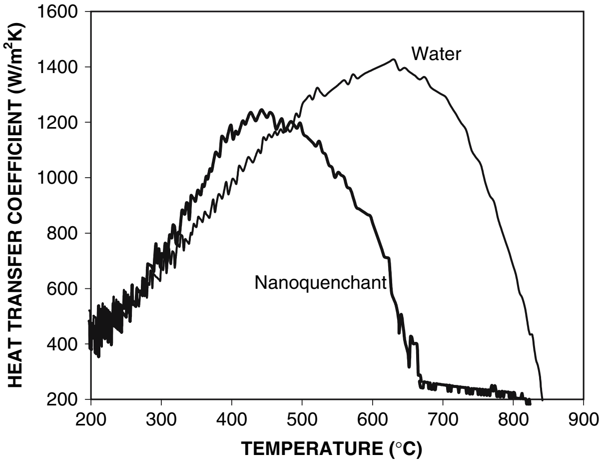

Fig. 2 Estimated heat transfer coefficients for water and nanoquenchant

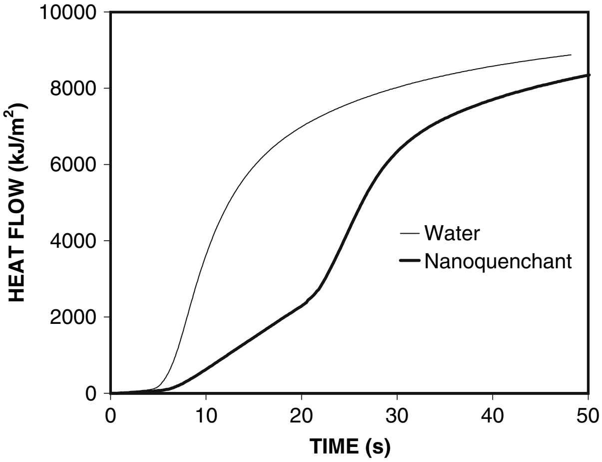

Fig. 3 Integral heat flow curves for water and nanoquenchant

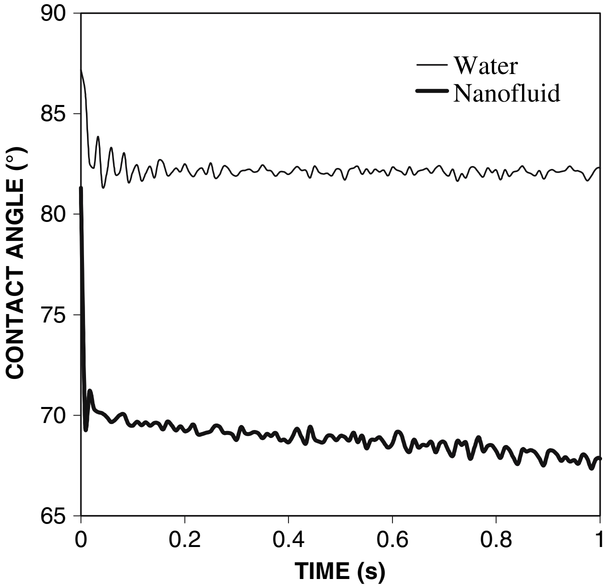

Fig. 4 Contact angle as a function of time for water and nanoquenchant in contact with a stainless steel substrate

contact and promotes the formation of a stable vapor film at the surface in the initial period of quenching. The temperature dependent heat transfer coefficient and the wettability of the medium are thus very important parameters to characterize a nanoquenchant to assess its suitability for industrial heat treatment. These nanoquenchants could be utilized in quenching heat treatment in two ways either to promote or decrease the rate of heat transfer depending upon the section thickness of the part to be heat treated and the desired microstructure. Hence there is a need for development of nanofluids having (i) high quench severity for enhancement of heat transfer for thick sections with low quench sensitivity and (ii) low cooling severity for thin sections with high quench sensitivity. The development of the water-based nanoquenchants having varying cooling severity would be extremely useful to the heat treating community. The concept is novel since it totally eliminates the dependence on mineral oil which is nonrenewable.

5. Conclusions

The transition from the vapor phase stage to the nucleate boiling stage was gradual for the nanoquench medium used in the present investigation. The magnitude of peak heat transfer coefficient for the nanoquench medium was about 10% lower compared to water. The significant difference between the two media lies in the time of occurrence of the peak heat transfer coefficient. The longer vapor phase stage and the delayed mucleate boiling associated with lower quench severity of the nanomedium are attributed to its better wettability on the stainless steel substrate.

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