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Effect of CNT concentration and agitation on surface heat flux during quenching in CNT nanofluids

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ABSTRACT

In this article, the effect of Carbon Nanotube (CNT) concentration and agitation on the heat transfer rate has been studied during immersion quenching in CNT nanofluids. For this purpose, CNT nanofluids were prepared by suspending chemically treated CNTs (TCNT) at four different concentrations in deionized (D.I) water without using any surfactant. Quench probes with a diameter of 20 mm and a length of 50 mm were machined from 304L stainless steel (SS) and quenched in water and CNT nanofluids with the CNT concentration ranging from 0.25 to 1.0 wt.%. The heat flux and temperature at the quenched surface were estimated based on the Inverse Heat Conduction (IHC) method using the temperature data recorded at 2 mm below the probe surface during quenching. The computation results showed that the peak heat flux increased with an increase in the CNT concentration up to 0.50 wt.% and started decreasing with further increase in the CNT concentration. The enhanced heat transfer performance of CNT nanofluids during quenching at lower concentration of CNTs is attributed to their higher effective thermal conductivity. The reduced heat transfer performance of CNT nanofluids having higher concentration of CNTs is due to the increased viscosity of CNT nanofluids. The effect of agitation on heat transfer rate during quenching has also been studied in this work by stirring the CNT nanofluid prepared with 0.50 wt.% of CNTs which recorded the maximum peak heat flux among the four concentrations. The effect of CNT nanofluid agitation was counter-intuitive and resulted in decreased heat transfer rate with the increase in agitation rate.

1. Introduction

Quenching is one of the important industrial processes in which the rate of heat transfer plays a vital role in the development of microstructure and mechanical properties of the quenched product. Immersion quenching is one of the most widely used processes for achieving martensitic and bainitic structure, where the rate of cooling has a decisive influence on the mechanical properties. Heat transfer during quenching is complex and is controlled by different cooling mechanisms. Quenching of steel in water consists of three distinct stages of cooling: (i) the vapor phase (ii) nucleate boiling and (iii) the convective stage. The parameters that affect the heat transfer during quenching may include surface temperature, surface condition of the specimen, agitation of the quenchant, thermo-physical properties of the quenchant and materials being quenched. The literature concerned with these various quenching parameters can be found in plenty in the open literature. The heat transfer at the surface during quenching is characterized by the heat flux or heat transfer coefficient of the quenching medium. The heat flux at the quenched surface is unknown during quenching and is calculated with the help of measured temperature data at an interior location in the part being quenched.

Estimation of the surface heat flux or heat transfer coefficient of the quenchant from the measured temperature data during quenching is based on the Inverse Heat Conduction (IHC) method. Babu and Prasanna Kumar [1] estimated the surface heat flux and temperature using the IHC method for different initial soaking temperatures during quenching and modeled the surface heat flux as a function of dimensionless parameters. Various algorithms for solving the IHC problems have been well-documented by Beck et al. [2] and successfully implemented by many researchers [1–7]. Prasanna Kumar [3] described a serial solution method for a 2-D IHC problem to estimate the surface heat flux and used it to estimate the heat flux components at the metal/mold interface during casting [4]. The same algorithm was used by Arunkumar et al. [5] to study the spatial variation of heat flux at the metal–mold interface in gravity die casting. Sarmiento et al. [6] estimated the temperature dependent heat transfer coefficient during quenching from the measured cooling curves based on the IHC method and compared the results of two computer programs developed for the computation. The heat flux transients obtained through the inverse technique were found to be more accurate than Grossmann technique in determining the quench severity of various quenchants by Narayan Prabhu and Prasad [7] and was

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Nomenclature

q	surface heat flux in W/m^2	ρ	density in kg/m^3
T	temperature in °C	c	specific heat in J/kg K
t	time in s	$n_x,\ n_y$	direction cosines of the outward normal vector
k	thermal conductivity in W/m K		

stated that it could be used for heat transfer modeling during quenching.

Intensive Quenching (IQ) [8,9], known as IntensiQuench^{SM}, developed by Nikolai Kobasko is an alternate way of hardening steel parts. IntensiQuench^{SM} process can be defined as cooling at a rate several times higher than the rate of normal or conventional quenching. In contrast to the conventional quenching practices, Intensive Quenching calls for very high cooling rates for parts within the martensite phase. Kobasko's research showed that very fast and uniform part cooling actually reduced the probability of part cracking and distortion, while improving the surface hardness and durability of steel parts. With this perception, we wanted to achieve higher cooling rate during quenching possibly by the use of nanofluids. Nanofluids are the new class of engineering fluids and have attracted many researchers because of their better heat transfer performance [10–25]. Nanoparticles are suspended in the base fluids usually at a very low concentration to improve their heat transfer performance. By suspending nanosized metallic particles, whose thermal conductivities are many folds higher than conventional liquids in the cooling or heating media, the resultant thermal conductivity of the base fluids is improved. It was thought that the use of nanofluids for quenching might evolve as an alternate quenching technique and yield the benefits of Intensive Quenching process.

Choi [10] has projected the possibility of using nanofluids for different practical applications which include quenching. Narayan Prabhu and Peter Fernades [11] used water and water based nanofluid containing 20 wt.% alumina nanoparticles as quenchants and reported that the peak heat transfer coefficient of the nanoquenchant was 10% lower as compared to water. Kim et al. [12] quenched small metallic spheres in water and water based nanofluids having alumina, silica and diamond nanoparticles and showed that the quenching behavior of nanofluids was nearly identical with that of pure water. Lotfi and Shafii [13] investigated the boiling heat transfer characteristics of nanofluids by quenching a silver sphere in water based nanofluids at 90 °C prepared with Ag and TiO_2 nanoparticles and reported a considerable reduction in the quenching ability of nanofluids as compared to that of pure water. These results on the use of nanofluids for quenching were not encouraging. However, Chopkar et al. [14,15] reported the higher quenching efficiency of water and ethylene glycol based nanofluids prepared with nanoparticles of aluminium, copper and silver alloys and their results were encouraging. The quenching experiments conducted with the hot copper block in these nanofluids could not be treated as practical quenching applications, because Chopkar et al. quenched from 300 °C to demonstrate the higher heat transfer rates in nanofluids. They also studied the effect of particle size and concentration on the effective thermal conductivity of nanofluids [15].

Choi [10] stated that CNTs, the most thermally conductive material known, yielded the highest heat transfer enhancement ever achieved in liquids. CNTs have attracted many researchers due to their higher thermal conductivity and very high aspect ratio, for preparing nanofluids. Park and Jung [16] showed that the presence of CNTs improved the nucleate boiling heat transfer coefficient of water and a refrigerant, R22. Ding et al. [17] reported that CNT nanofluids produced a maximum heat transfer enhancement of 350% by considering the flow conditions through a horizontal tube and studied the effect of CNT concentration on the thermal conductivity and viscosity of CNT nanofluids at different temperatures. Xie et al. [18] measured the thermal conductivities of nanofluids containing treated CNTs and proved that the thermal conductivity of nanofluids increased with an increase in the CNT concentration. The different mechanisms for the improved heat transfer performance of nanofluids were elaborated by Keblinski et al. [19]. The effects of various parameters like nanoparticle size, concentration, temperature, pH value of base fluid, ultrasonication on the heat transfer performance and stability of nanofluids were thoroughly investigated by several researchers [20–26]. The use of nanofluids for a practical quenching application reporting the improved heat transfer during quenching is not available in the literature yet.

The objective of this work is to use CNT nanofluids as quenchants to improve the heat transfer rate during quenching of steel parts and study the effect of CNT concentration in CNT nanofluids and agitation during quenching. Multi-walled CNTs were synthesized through arc discharge method. CNTs after chemical treatment were dispersed in D.I water at four different concentrations. Quench probes with a diameter of 20 mm and length of 50 mm were machined from SS 304L with a deep hole drilled at 2 mm below the probe surface to fix a thermocouple. The probes were then quenched in water and CNT nanofluids and time–temperature data were recorded during quenching. To study the effect of agitation on heat transfer rate during quenching in CNT nanofluid, the CNT nanofluid was stirred during the immersion quenching. The recorded temperature data were then used as input for the IHC algorithm to compute the heat flux and temperature at the quenched surface. The results of the computation showed that CNT nanofluid has increased the quenching heat transfer significantly. The peak heat flux increased with an increase in the CNT concentration up to 0.5 wt.%, but started decreasing with further increase in the CNT loadings. The agitation effect was not as expected and the peak heat flux decreased with an increase in the agitation rate.

2. Preparation of water based CNT nanofluids

Nanofluids refer to the fluids with suspended nanoparticles. By suspending nanoparticles at very low concentration, usually 2 vol.% or less in heating or cooling fluids, the heat transfer performance is proved to have significant improvement by the researchers. The basic idea is to increase the effective thermal conductivity of the heat transfer fluids to improve their heat transfer performance. The primary reason for the better heat transfer performance of nanofluids is attributed to the higher effective thermal conductivity of nanofluids than that of their base fluids. The nanoparticles that were used to produce nanofluids in the open literature include: aluminum oxide, copper, copper oxide, silver, silica and CNTs. CNT nanofluids have been reported to have higher heat transfer performance [10] because of the unique properties of CNTs such as higher thermal conductivity which is in the order of ~3000 W/mK (multi-walled CNT) and very high aspect ratio [17].