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Effect of section size and agitation on heat transfer during quenching of AISI 1040 steel

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Abstract

In the present work an attempt has been made to determine the heat flux transients during quenching of Ø28 mm × 56 mm height and Ø44 mm × 88 mm height AISI 1040 steel specimens during lateral quenching in brine, water, palm oil and mineral oil. The heat flux transients were estimated by inverse modeling of heat conduction. The variation of heat flux transients with surface temperature for different quenching media is investigated. Higher peak heat flux transients are obtained for 28 mm diameter specimen than 44 mm diameter specimen during quenching in aqueous media. However quenching with oil media shows opposite results. Agitation of quenching medium increases the peak heat flux during the quenching of steel specimen in all the quenching media. Peak hardness is obtained at the surface and with smaller diameter specimens during agitation.

Keywords: Quenching; Section thickness; Heat flux transients; Inverse modeling

1. Introduction

Quenching is one of the important processes of heat treatment to improve the performance of steel. During quenching, the steel is rapidly cooled in a quenching medium from the austenetising temperature, typically in the range of 845–870 °C. Quenching is performed to prevent ferrite or pearlite formation and allow bainite or martensite to be formed. Quenching of steel in liquid medium consists of three distinct stages of cooling: the vapour phase; nucleate boiling; and the convective stage. In the initial stage, a vapour blanket is formed immediately upon quenching. This vapour blanket has an insulating effect, and heat transfer in this stage is low since it is mostly through radiation. As the temperature drops, the vapour blanket becomes unstable and collapses, initiating the nucleate boiling stage. Heat removal is the fastest in this stage, due to the heat of vapourisation and continues until the surface temperature drops below the boiling point of the quenching medium. Further cooling takes place mostly through convection and some conduction [1,2].

Lumped heat capacity method is only an approximate technique to determine the heat transfer coefficients as this method assumes a constant work piece temperature. Kobasko et al. experimentally determined the first and second critical heat flux densities to characterize the quenching process [3]. The right method for getting the realistic metal/quenchant interfacial heat transfer properties is inverse modeling and this method allows the determination of boundary conditions by the coupling of numerical methods with simple temperature measurements inside the quench probe [4]. A two-dimensional inverse method combined with the lumped heat capacity method was adopted by Naarasaki et al. [5] to estimate the heat transfer coefficients.

When a work piece of large section size is quenched, the surface cools more rapidly than the centre. The surface of the component cooled at the critical cooling rate and hence fully hardened, whereas the centre cools more slowly and forms soft structure. Variation in the section size of the component will lead to different cooling rates, and that will influence the critical cooling rate required for full hardening. This variation in cooling rate across component sections has influence on the formation of microstructures and properties. When a heavy section component quenched in a liquid medium the cooling rate is limited by the rate of heat conduction from the interior to the surface. Rapid cooling of centre of an extremely large section

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is impossible because of the mass effect. Generally low cooling rates are employed on components having large changes in section thickness in order to reduce the variation in hardness from surface to core. When deep hardening a heavy section it is necessary to use an alloy steel with higher hardenability. Parts with high ratio of surface area to volume increase the fire hazard because they transfer heat more rapidly to the oil, and requires low quenching oil temperatures, large volume of oil with higher flash point [1,2].

Gur [6] studied the influence of specimen geometry on the evolution of stress and microstructure analysis during quenching of solid and hollow cylinders. The percentage of martensite increased from core to the surface during quenching of C60 steel due to different cooling rates. Serajzadeh [7] showed that the cooling rate and the ferrite phase change kinetics were not uniform in the radial direction which leads to non uniform distribution of ferrite grain size and phase transformation during quenching of low carbon steel. Chen et al. [8] have investigated that the influence of variable physical properties and shape effect on the distribution of transient temperature. They concluded that these factors retard the cooling velocity during quenching of eutectoid steel and also quantity of transformed martensite distribution over the different radii.

Heming et al. [9] investigated the surface heat transfer coefficients and surface temperature of the two different diameter cylinders during quenching in water. They found that maximum value of heat transfer coefficient was obtained for the larger diameter specimen than smaller diameter.

Most of the work carried on heat transfer during quenching has been devoted to the estimation of cooling power of the quench media and not much attention is given to the heat transfer–structure–property correlation during quenching of steel specimens. In the present investigation, an attempt has been made to determine the heat flux transients during lateral quenching of AISI 1040 steel specimens. The effect of section size on heat transfer during quenching in brine, water, palm oil and mineral oil was investigated.

1.1. Estimation of heat flux

The one dimensional transient heat conduction equation in cylindrical coordinates given below,

$$\rho C_p \frac{\partial T}{\partial t} = \frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \quad (1)$$

has been solved inversely. The details of the inverse analysis are given in references [10,11]. In Eq. (1), k, ρ and C_p are the thermal conductivity, density and specific heat of the quench specimen respectively. In the inverse technique, the surface heat flux density is estimated from the knowledge of the measured temperature inside a heat-conducting solid. This is done by minimizing the function,

$$F(q) = \sum_{i=1}^{Ms} (T_{n+1} - Y_{n+i})^2 \quad (2)$$

where $M = \Delta\theta/\Delta t$ (s = a small integer) at regular finite different intervals. T_n and Y_n are the calculated and the measured temperatures at a location close to the metal/quenchant interface respectively. $\Delta\theta$ and Δt are the time steps for the estimation of heat flux and temperature respectively. Applying the condition for minimization, the correction for the heat flux (∇q) at each iteration step is estimated. This procedure is continued until the ratio ($\nabla q/q$) becomes less than 0.005. This procedure simultaneously yields the temperature of the specimen surface in contact with the quench medium and the interfacial heat flux.

2. Experimental work

The experimental set-up consisted of a vertical tubular electric resistance furnace open at both 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 quenching medium at 30 °C. The experimental set-up was also designed for agitation using a mechanical stirrer with three vanes. The stirring speed was 20 m/min. Experiments were carried out to determine the effect of size, rate of agitation, and the type of quenching medium on heat transfer during lateral quenching. Quench specimens having dimensions of Ø28 mm × 56 mm height and Ø44 mm × 88 mm were prepared from AISI 1040 steel. All the specimens were instrumented with K-type thermocouples. The thermocouple wires were protected using twin bored ceramic beads. The location of thermocouples for lateral quenching is shown in Fig. 1. The test specimens were heated to 870 °C in the electric resistance furnace and were quickly transferred to a quench tank containing 31 and 121 of the quench medium respectively. Lateral quenching of two different size specimens were carried out in 10 pct brine, water, palm oil and mineral oils with and without agitation. A mechanical stirrer was used for agitation of the quench medium. The top and bottom ends of the specimens were coated with alumina based coating material to ensure radial heat transfer. The composition of the coating material used is given in Table 1. The composition of AISI 1040 steel specimens used is given in Table 2. The thermocouples were connected by means of compensating cables to a data logger interfaced with the computer.

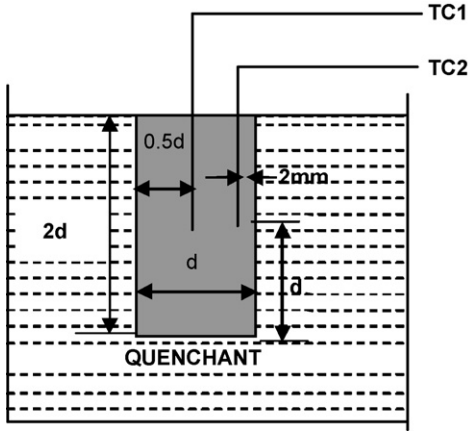

Fig. 1. Schematic sketch of lateral quenching set up.

Table 1
Composition of coating materials

Component	wt.%
Alumina	17
Sodium silicate	11
Water	72

Table 2
Composition of AISI 1040 steel specimen

Component	wt.%
C	0.41
Mn	0.67
Si	0.11
P	0.026
S	0.025
Cr	0.011
Ni	<0.013
Mo	<0.007
Fe	Balance

3. Results and discussion

Fig. 2 shows the typical thermal history and cooling rates measured at the centre and 2 mm from the interface of AISI 1040 steel specimens subjected to lateral quenching in still water.

The measured temperature history was used as an input to an inverse heat conduction model to estimate the heat flux transients at the metal/quenchant interface. The inverse analysis yielded the temperature of the specimen surface in contact with the quench medium. Figs. 3–6 show the relationship between the estimated heat flux and the surface temperature of AISI 1040 steel specimens during lateral quenching in various quenching media with and without agitation. The heat flux value is low in the initial period during quenching. This might be due to the vapour film formed at the surface of the steel specimen. The vapour film offers the resistance to heat transfer due to its insulation effect and low thermal conductivity. This is observed in all the quenching media with and without agitation. With progress in quenching, the vapour film collapses and heat transfer rate increases significantly. The duration of vapour blanket stage is decreased during agitation of quenching media. The heat flux transients increased rapidly due to the enhanced convective heat transfer between the specimen and quenching media. The heat flux transients showed a peak during nucleate boiling stage in all the quenching media and the occurrence of peak in the heat flux associated with the peak thermal gradient existing inside the quenched specimen with complete collapse of the vapour film. Peak heat flux value is obtained for aqueous media with 28 mm diameter specimen whereas peak heat flux value is obtained for larger diameter specimen with oil quenchants. Table 3 gives the

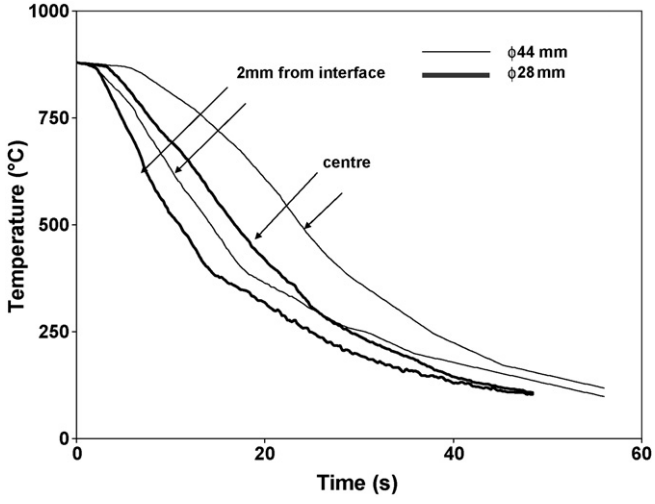

Fig. 2. Specimen thermal history during lateral quenching in water (without agitation).

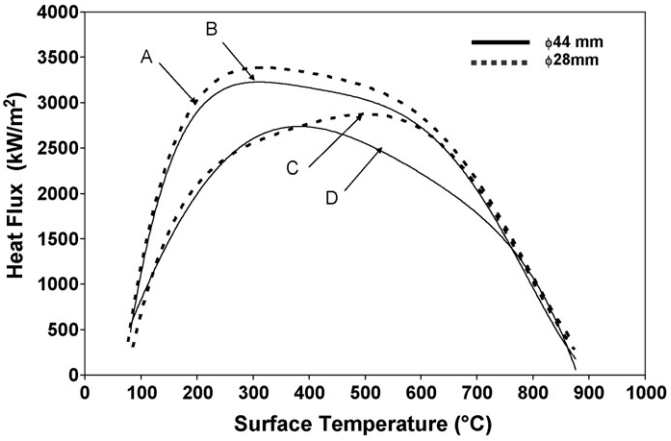

Fig. 3. Effect of section thickness on heat flux vs. surface temperature during quenching in brine. (A and B) agitation; (C and D) still.

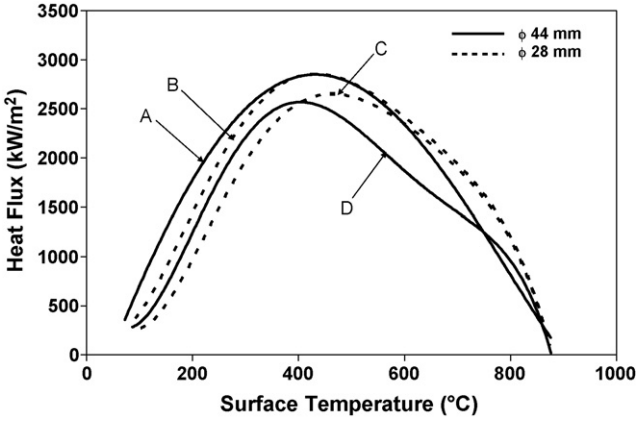

Fig. 4. Effect of section thickness on heat flux vs. surface temperature during quenching in water. (A and B) agitation; (C and D) still.

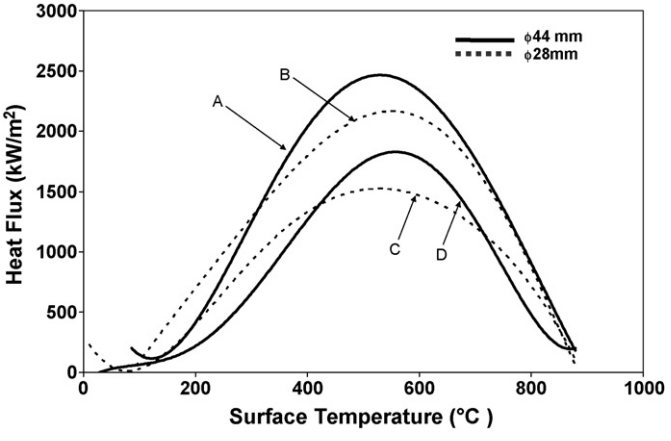

Fig. 5. Effect of section thickness on heat flux vs. surface temperature during quenching in palm oil. (A and B) agitation; (C and D) still.

Table 3
Peak heat flux (q_{max}) and corresponding surface temperature (T_{surf}) of different diameters with still and agitated quenchants

Quenchant	Section size							
	28 mm diameter				44 mm diameter			
	Still quenchant[a]		Agitated quenchant[a]		Still quenchant		Agitated quenchant	
	q_{max} (kW/m^2)	T_{surf} (°C)	q_{max} (kW/m^2)	T_{surf} (°C)	q_{max} (kW/m^2)	T_{surf} (°C)	q_{max} (kW/m^2)	T_{surf} (°C)
Brine	2939	442	3446	363	2806	364	3372	341
Water	2883	437	3021	391	2662	390	2948	362
Palm oil	1750	443	2256	438	1996	442	2369	427
Mineral oil	1435	562	2109	515	1774	491	2147	411

[a] Condition.

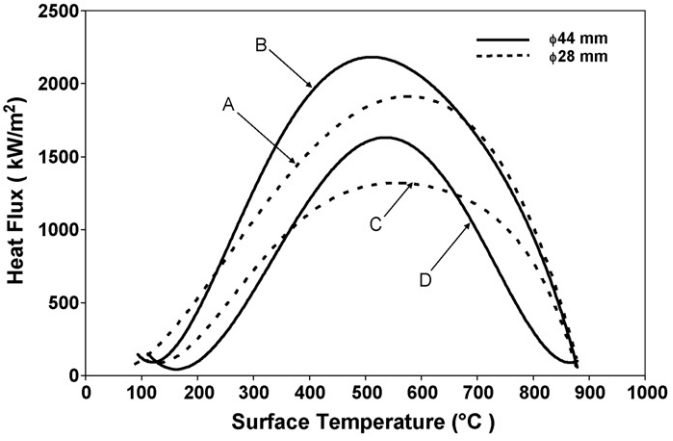

Fig. 6. Effect of section thickness on heat flux vs. surface temperature during quenching in mineral oil. (A and B) agitation; (C and D) still.

effect of section thickness and quench medium on peak heat flux.

Fig. 7 shows the effect of section thickness and agitation on heat flux transients during quenching in palm oil. The agitation of quenching media increases the rate of heat transfer and is reflected in the occurrence of peak heat flux early compared to the quenching medium in still condition. A peak heat flux of 2256 kW/m^2 is obtained for 28 mm diameter specimen at 14 s during agitation of palm oil. The corresponding heat flux for palm oil (still) is 1750 kW/m^2 and is obtained at 18.4 s (Fig. 7). It is observed that with increase in diameter, the time required to reach the peak value also increases. With increase in diameter to 44 mm, the peak flux increases to 1996 kW/m^2. However the peak flux is obtained at about 22 s as shown in Fig. 7. Similar results are also obtained with other quenching media in still and agitated conditions. This is due to the stability of the vapour film for a longer period of time in larger diameter specimen. After the collapse of vapour film, the heat flux transients increased quickly in 44 mm diameter specimen than 28 mm diameter specimen in oil quenchants as shown in Figs. 5 and 6. The occurrence of peak was followed by a sharp decrease in the heat flux transients at the specimen/quenchant interface indicating negligible thermal gradients inside the specimen at later stages of cooling.

The peak heat flux value was obtained at lower surface temperature for larger diameter specimens and agitation of quenching media. Peak heat flux value occurred for 28 mm diameter specimen at surface temperatures of 363 and 442 °C with and without agitation of 10 pct brine, respectively. For 44 mm diameter specimen, the corresponding temperatures were 341 and 364 °C, respectively.

Peak heat flux value occurs at lower surface temperatures for more severe quench media. Maximum peak heat flux is obtained in 10 pct brine and minimum peak heat flux is obtained in mineral oil for both 28 mm diameter and 44 mm diameter AISI 1040 steel specimens in still condition as shown in Fig. 8. A peak heat flux

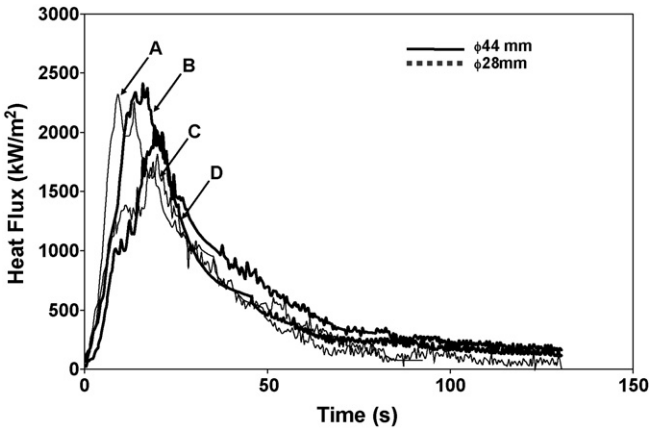

Fig. 7. Effect of section thickness on heat flux vs. time during quenching in palm oil. (A and B) agitation; (C and D) still.

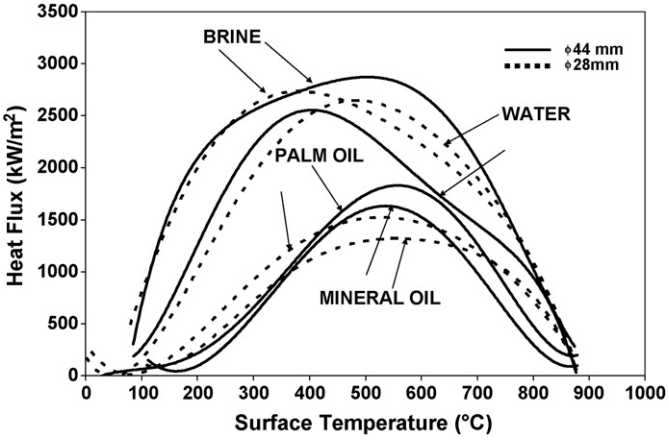

Fig. 8. Effect of section thickness on heat flux vs. surface temperature quenching in various quenching medium without agitation.

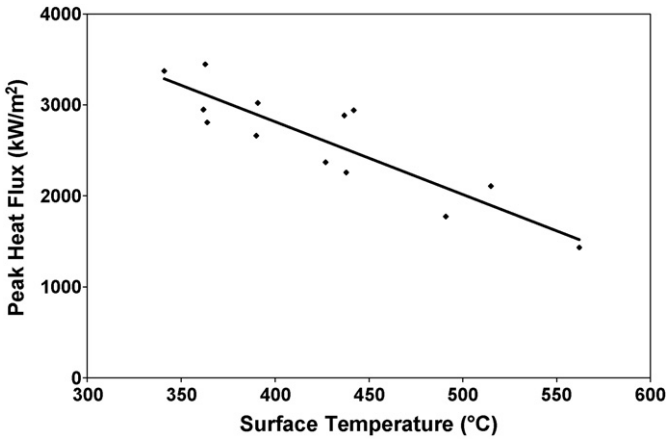

Fig. 9. Effect of surface temperature on peak heat flux for various quenching conditions for both specimens.

value of 2939 kW/m^2 is obtained for 28 mm diameter specimen at surface temperature of 442 °C in 10 pct still brine and peak heat flux value of 1435 kW/m^2 is obtained for 28 mm diameter specimen at the surface temperature of 562 °C in still mineral oil. Similar results are obtained during agitation of quenching media. This is due to the severity of heat removal characteristics of the brine than other quenching media.

Fig. 9 shows the effect of surface temperature on the peak heat flux for all quenching conditions for both specimens quenched in still and agitated media. It is observed that peak heat flux decreases linearly with increase in surface temperature. However, the surface temperature of the specimen depends upon section thickness and severity of the quench media. From the data given in Table 3, it is evident that the peak heat flux occurs at higher temperatures for low severity quench media. Increase in section thickness and agitation of quench medium results in occurrence of peak heat flux significantly at lower surface temperatures.

The hardness (VHN) data obtained at the centre of specimens and at locations closer to the surface for smaller and larger diameter steel specimens quenched in water and mineral oil is given in Table 4. Peak hardness is obtained for smaller diameter specimens during agitation at locations close to the metal/quenchant interface.

Table 4
Vickers Hardness of the AISI 1040 steel specimen

Quenching media	Location	Ø28 mm		Ø44 mm	
		Still	Agitated	Still	Agitated
Water	Surface	524	644	366	385
	Centre	362	412	244	348
Mineral oil	Surface	348	386	321	348
	Centre	232	271	216	244

4. Conclusions

Based on the results and discussion the following conclusions were drawn:

1. Agitation of quenching medium increases the peak heat flux during quenching of steel specimen in all the quenching media.
2. The time required to obtain the peak heat transfer rate increases with increase in diameter.
3. Higher peak heat flux transients are obtained for 28 mm diameter specimen than 44mm diameter specimen during quenching in aqueous media. However quenching with oil media shows opposite results.
4. Nucleate boiling stage is delayed in 44 mm diameter specimen compared to 28mm diameter specimen.
5. Peak heat transfer occurred at lower surface temperature with larger diameter specimens and more severe quenching media.
6. Hardness data obtained on the surfaces of quenched specimens are in good agreement with the results of the heat transfer analysis.

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