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TECHNICAL PAPER

# Comparison of Cooling Behaviour of Carbon Steels in Polymer, Oil and Carbonated Quench Media

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**Abstract** Cooling behaviour of steels in quench media is of great importance as this controls phase transformations, heat transfer and the stress evolution. The heat extraction ability of each quenchant is different because of varying thermophysical properties and wetting behaviour. The quenchants should be selected in such a way that they provide uniform cooling of steel. In the present investigation, quenching experiments were carried out with Inconel 600, EN19, EN24, EN31 steel grades in distilled water, servo oil, carbonated distilled water and 10% PAG. The cooling curve analysis of the quenching process was carried out with temperature data recorded during quenching. This measured temperature–time data were used to estimate the heat flux by inverse modelling without considering the effect of phase transformation. The crack propensity was quantified using the quench uniformity ratio. The hardness distribution observed during quenching in carbonated distilled water was observed to be more uniform compared to other quench media.

**Keywords** Quenching · Heat flux · Carbon steels · Phase transformation

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## 1 Introduction

The heat extraction process at the metal–quenchant interface is dependent on the chemical composition of steel, geometry, quench media and quenching condition. Among these factors, quenching medium plays a significant role in controlling heat transfer from quenched steel parts to obtain desired microstructure with minimum quench defects [1]. The selection of quench media should be based on the grade of steel being quenched and its section thickness.

Water, brine, mineral oil and water-soluble polymer quench media are widely used in industries to quench harden steel parts. Nayak et al. [2] proposed carbonated water quench media for quench hardening steel parts. Uniform hardness distribution was observed in low-carbon EN 8 steel probes quenched in carbonated water.

In the present work, the feasibility of distilled water, mineral oil, water-soluble polymer solution and carbonated water quench media for hardening medium and high-carbon steels was studied. The metal–quenchant interfacial heat flux during quenching of steel probes was estimated using inverse heat conduction method. Inconel probe was used to characterise the quench media as specified in ISO 9950 standard.

## 2 Experimental Details

Figure 1 shows schematic of steel probes used for quenching experiment. Table 1 shows composition of Inconel-600 alloy and EN19, EN24 and EN31 steel grades used for quenching experiments. The quench probe was fastened to the stainless steel rod, and 1-mm K-type Inconel-sheathed thermocouples were inserted into the

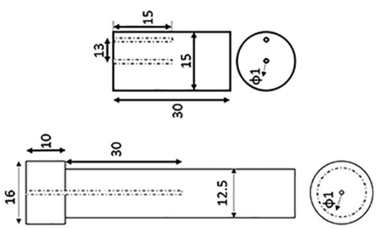

**Fig. 1** Schematic of **a** steel, **b** Inconel quench probe used for quenching experiment. All dimensions are in mm

holes drilled in these probes. The time–temperature measurements at the thermocouple locations were recorded using NI 9213 DAQ system connected to a personal computer. The stainless steel rod was used to support the thermocouple during quenching. The top and bottom faces of steel probe were insulated using zirconia insulating paste. The insulated probe with thermocouple was heated in a furnace to 860 °C and held for 20 min for austentization. The probe was then manually quenched in 2 lts of quenching medium at room temperature. The time–temperature data were acquired at an interval of 0.1 s.

Servo quench oil, distilled water, 10% PAG solution and carbonated water were used as quench media. Servo quench oil was procured from Indian Oil Corporation Ltd, Mangalore. Measured quantity of AquaQuench 20 bought from PSG International, Faridabad, was manually mixed with distilled water to prepare 10% PAG solution. Carbonated water was prepared by passing $CO_2$ gas at 50 bar pressure through distilled water.

TMMFE software (Thermet solutions Pvt Ltd, Bangalore) was used to estimate transient heat flux at the metal–quenchant interface. The estimation of heat flux was based on time–temperature curves obtained during quenching of steel probes. The axisymmetric model of the steel probe was discretised into 1000 rectangular elements of 0.375 × 0.6 mm. The top and bottom surfaces of the probe were assumed to be insulated. Thermophysical properties of the steel were obtained from Ref. [3]. A detailed description about the Beck's nonlinear method to solve inverse problem is available in Ref. [4].

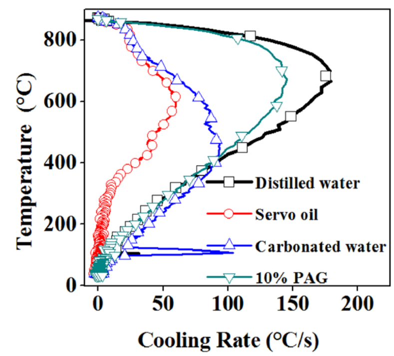


**Fig. 2** Cooling rate V/s temperature curve at geometric centre of Inconel probe

## 3 Results and Discussion

Figure 2 shows the variation of cooling rate with temperature measured by the thermocouple placed at the geometric centre of the Inconel probe quenched in different quench media. The maximum cooling rate attained in different quench media was arranged in the descending order as follows:

$$\text{Water}\ (177\,^{\circ}\text{C/s}) > 10\%\ \text{PAG}\ (145\,^{\circ}\text{C/s}) > \text{Carbonated water}\ (94\,^{\circ}\text{C/s}) > \text{Servo oil}\ (60\,^{\circ}\text{C/s}).$$

The lower peak cooling rate observed in servo oil and carbonated water was due to the presence of vapour blanket stage. The heat energy was extracted at a low rate during vapour blanket stage. The portion of heat energy extracted during vapour blanket stage in carbonated water and servo oil was significantly higher compared to that observed in water and PAG quench media. This resulted in lower peak cooling rate during subsequent nucleate boiling stage.

The cooling rate at 300 °C and 200 °C was observed to be maximum in carbonated water (66 °C/s and 39 °C/s, respectively) and minimum in servo oil (8 °C/s and 4 °C/s, respectively). The low cooling rate in this temperature range was desirable to ensure lower residual stress, distortion and avoid quench cracks in the quenched steel part.

The time–temperature data measured at different locations of EN19, EN24 and EN31 steel probes during quenching in different quench media were used to estimate heat flux at the metal–quenchant interface. Figure 3 shows

**Table 1** Composition of Inconel 600 and steel probes used for quenching experiment

| Material | %Fe | %C | %Ni | %Cr | %Mn | %Cu | %Si | %S | %P | %Co | %Mo |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inconel 600 | 8.77 | 0.006 | 75.67 | 15.22 | 0.027 | 0.26 | 0.012 | 0.002 | – | – | – |
| EN 19 | 97.3 | 0.366 | 0.017 | 1.04 | 0.760 | 0.007 | 0.240 | 0.024 | 0.017 | 0.0047 | 0.211 |
| EN24 | 95.8 | 0.350 | 1.29 | 1.12 | 0.570 | 0.111 | 0.318 | 0.015 | 0.018 | 0.021 | 0.251 |
| EN 31 | 96.9 | 0.950 | 0.069 | 1.07 | 0.463 | 0.047 | 0.299 | 0.075 | 0.042 | 0.0087 | 0.033 |

estimated heat flux transients. The vapour blanket stage observed during quenching of Inconel probe was not observed during quenching of steel probes in servo oil.

The peak heat flux observed during vapour blanket stage during quenching in carbonated water was significantly high and comparable with peak heat flux in nucleate boiling stage. This was in sharp contrast with traditional quench media, wherein the peak heat flux during nucleate boiling stage was at least 2.5 times greater than peak heat flux during vapour blanket stage.

Quench cracks were observed in EN31 probes quenched in water and carbonated water quench media (Fig. 4). The cracks were observed to run along the surface and originate from the hole drilled for the thermocouple. The quench media seeped through the crack and came in contact with the thermocouple tip. Accurate measurement of temperature data was therefore not possible during quenching of EN31 steel probe in distilled water and carbonated water.

Vs and Vc are defined as average cooling rate between $M_s$ and $M_f$ of the steel grade at centre and surface of the part, respectively. The ratio Vs/Vc determines the propensity of a quenchant to produce distortion cracking and residual stress in the quenched steel part [5]. The uniformity of cooling is said to improve when the uniformity parameter approaches 1. Table 2 shows that as $M_s$ and $M_f$ of the steel decreased, the uniformity parameter approached unity for carbonated water, distilled water and PAG quench media. Despite uniform cooling, the high cooling rates resulted in cracking of EN31 steel probes quenched in water and carbonated water.

The quenched steel probes were sectioned at 15 mm depth, and Vickers hardness was measured in this plane. Figure 5 shows hardness distribution in steel probes quenched in various quench media. The uniformity in hardness distribution in EN19 and EN24 steel probes quenched in carbonated water was observed to be similar to

**Fig. 4** Crack propagation in EN31 steel probe quenched in water

that observed in servo oil. The uniformity in hardness distribution in EN19 and EN24 steel probes quenched in carbonated water was observed to be more uniform compared to that observed in polymer solution and water. The average hardness in EN19 and EN24 probes quenched in water and polymer quench media was about 10% higher than that observed in servo oil and carbonated water quench media.

## 4 Conclusions

- The cooling performance of quench media was arranged in the following descending order. This was based on Inconel cooling curve parameters, quench heat flux transients estimated for steel probes and the measured hardness.

Distilled water > 10% PAG > Carbonated water > servo oil

- Carbonated water was found to be an effective replacement for mineral oil to quench hardend medium-carbon steel parts to obtain uniform hardness distribution across the cross section.
- The propensity of quench defects in steel parts hardened in carbonated water, water and PAG media decreased with decrease in $M_s$ temperature. The high

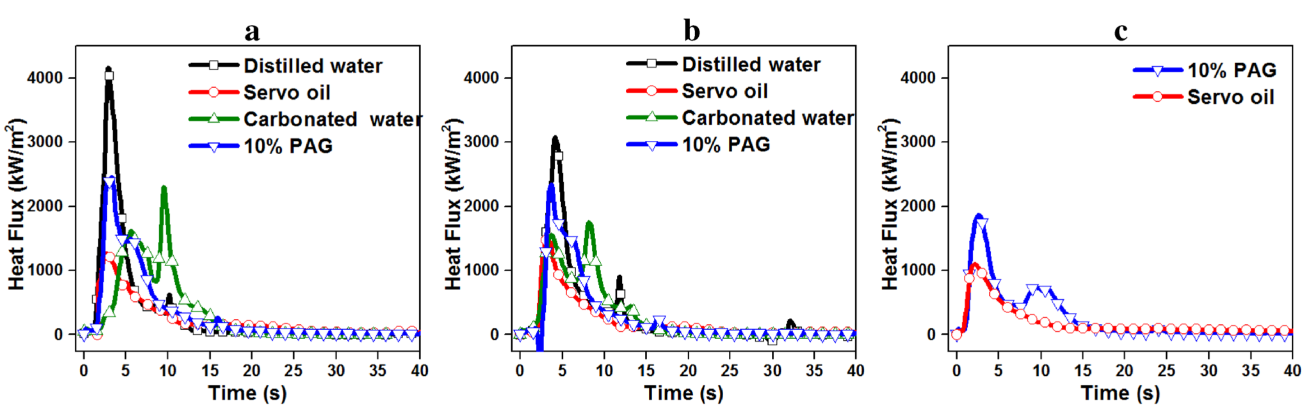


**Fig. 3** Transient variation of metal–quenchant interfacial estimated for **a** EN19, **b** EN24, **c** EN31 steel probe quenched in different quench media

**Table 2** Uniformity parameter for steel probes quenched in different quench media

| Steel grade | $M_s$ (°C) | $M_f$ (°C) | Vs/Vc | | | |
|---|---|---|---|---|---|---|
| | | | Distilled water | Servo oil | Carbonated water | 10% PAG |
| EN 19 | 375.01 | 230.34 | 1.41 | 1.01 | 1.91 | 1.36 |
| EN 24 | 327.96 | 210.41 | 1.05 | 1.01 | 1.55 | 1.28 |
| EN 31 | 166.96 | 29.46 | – | 1.01 | – | 1.13 |

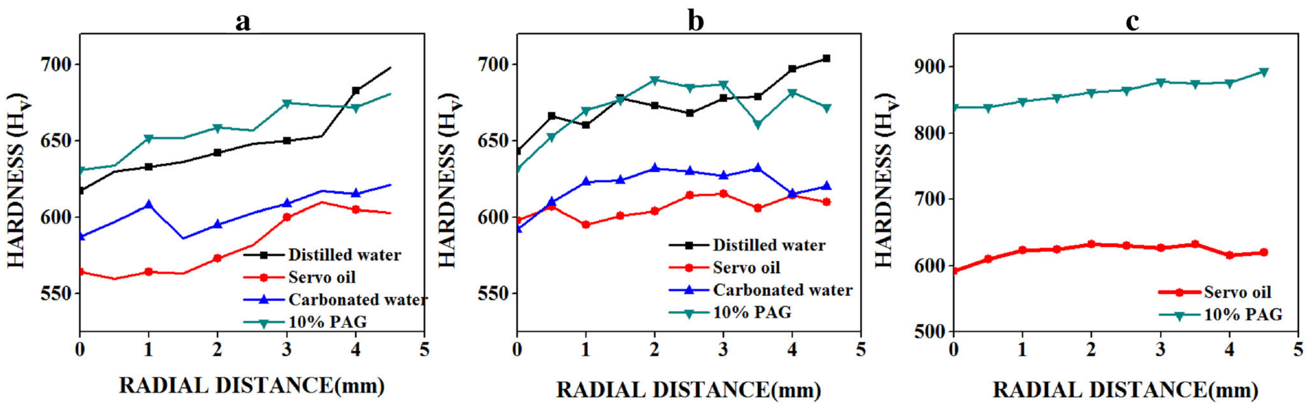


**Fig. 5** Hardness distribution in **a** EN19, **b** EN24, **c** EN31 steel probe quenched in different quench media

cooling rates offered by water and carbonated water below $M_s$ of steels often resulted in cracking and higher residual stress in high-carbon and medium-carbon steel parts.

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