Initial and Critical Heat Flux Densities Evaluated on the Basis of CFD Modeling and Experiments during Intensive Quenching

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Abstract: - Evaluation of initial heat flux densities during quenching is very important for the practice. They are needed to predict heat transfer modes appearing at the initial time of quenching. Initial heat flux densities were evaluated for cylindrical specimens on the basis of CFD modeling during intensive quenching. It is shown that initial heat flux densities are significantly less as compared with the critical heat flux densities. That is why there is no film boiling in these conditions. It was assumed that Fourier law is true after creation of boiling layer at the surface of steel parts. The duration of establishing of such layer is within 0.1 second. It was established in the previous experiments. It is underlined that true initial heat flux densities can be evaluated also on the basis of solving the inverse problem using hyperbolic heat conduction equation.

Key-Words: - Initial and critical heat flux densities, CFD modeling, Hyperbolic heat conduction equation, Databases.

1 Introduction

It is important to determine initial heat flux densities to predict heat transfer modes at steel quenching. As is well known, three modes of heat transfer on the surface of steel parts can be observed, which are connected with the first critical heat flux density q_{cr1}. Upon immersing of a heated steel part into the cold quenchant the initial heat flux density q can be in different ranges, namely [1]:

$$q >> q_{cr1};\; q \approx q_{cr1} \text{ or } q << q_{cr1}.$$

In the first case the full film boiling is observed, at $q \approx q_{cr1}$ transition boiling can be observed. In the last case at $q << q_{cr1}$ there is no film boiling and at once nucleate boiling begins. Due to the stated above, absolutely different values of $\alpha = f(T_{sf})$ can be obtained. As a rule, heat transfer coefficients are evaluated on the basis of solving the inverse problem and CFD modeling [2-8]. It follows that there is no unique dependence of a heat transfer coefficient α on temperature at the surface of a quenched part. To understand what chart we should use at making a concrete design, it is necessary to take into account the value of q_{cr1}. Therefore, it is important and necessary to determine first of all critical heat flux densities q_{cr1} and q_{cr2}, in order to perform engineering work highly competently.

2 Initial and Critical Heat Flux Densities

Critical heat flux density q_{cr1} for water flow can be evaluated from the equation (1) [1, 5-9]:

$$q_{cr1}^{uh} = 2.8\left(0.75W^{0.5} - 1\right) + 0.1(W^{0.35} - 1)\vartheta_{uh} \quad (1)$$

where W is water flow rate;
$\vartheta_{uh} = T_S - T_M$ is underheating temperature; T_s is boiling temperature; T_m is bath temperature.
Some results of calculations of q_{cr1} for water salt solutions of NaCl and water flow are presented in Table 1.and Table 2.

Table 1 Critical heat flux density q_{cr1} for water salt solutions NaCl at 20°C versus concentration in %

%	5	12	15	18
q_{cr1}, MW/m^2	9	15	8	7

There is optimal concentration for all salt solutions at which critical heat flux density has maximum value. To prevent film boiling, it is desired to quench steel parts in water salt solutions with the optimal concentration.

During intensive quenching film boiling should be eliminated. It means that initial heat flux density should be less then the first critical heat flux density q_{cr1} .
Results are fair for ring channels with the width of the clearance exceeding 1.2 mm.

Table 2 The first critical heat flux density versus water temperature and water flow velocity, MW/m^2.

W, m/s	20°C	30°C	40°C	60°C
5	7.94	7.18	6.43	4.91
6	9.32	8.44	7.57	5.83
7	10.57	9.59	8.62	6.66
8	11.7	10.63	9.56	7.42
9	12.76	11.6	10.44	8.13
10	13.74	12.51	11.27	8.79
15	17.97	16.39	14.81	11.65
20	21.4	19.56	17.71	14.00

Initial heat flux densities were calculated for semi-axles of 42-mm diameter and forgings of 44.5-mm diameter, which were cooled in ring channels where water flow was within 8 – 12 m/s (see Fig. 1 and Table 3).

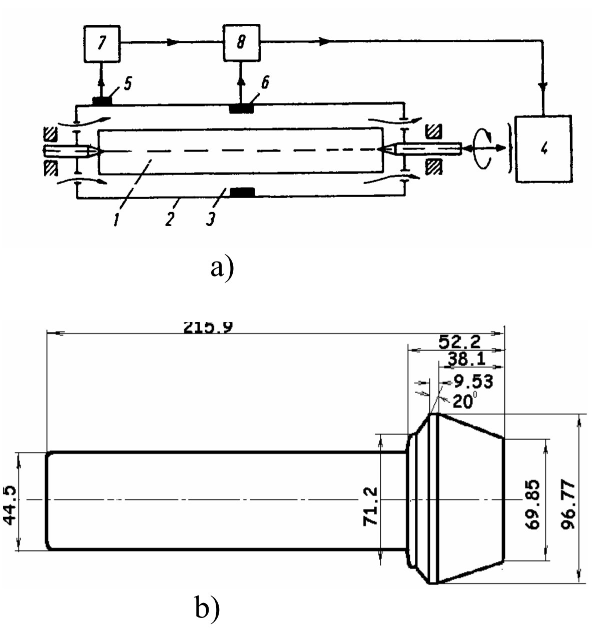

Fig. 1 Steel parts which were cooled in water flow and were investigated on the basis of CFD modeling: a) is semi-axle of cylindrical form; b) is forging.

Table 3 Initial heat flux density at the edges and along the semi-axle of 42-mm diameter and 600-mm length (at time of 0.1 s) when cooling in water flow of 10 m/s.

Distance along the specimen, m	Heat flux density, MW/m^2
	Side surface
0 (Edge)	11.5
0.1	10.14
0.2	10.11
0.3	10.07
0.4	9.95
0.5	9.77
0.6 (Edge)	9.78

3 CFD Modeling

As we can see from Fig. 2, difference in water flow velocity distribution .in the channel, evaluated through CFD modeling, is very big. It is very important to compare results of calculation with the precisely fulfilled experiments. At present time for this purpose laser technique is used. We are planning to use laser technique for further investigation of initial processes of quenching. Some results of investigations are published in Ref. [2].

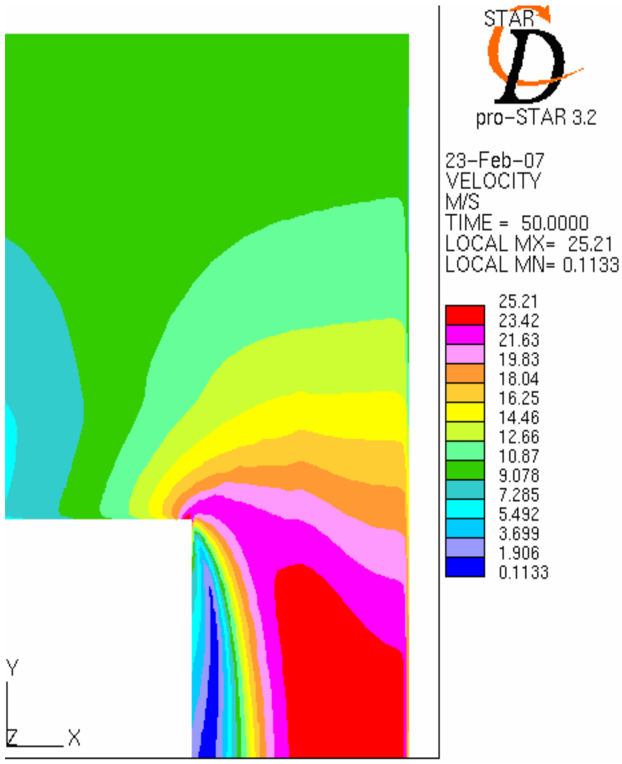

Fig. 2 Water flow velocities distribution during intensive quenching of the forging.

4 Hyperbolic Heat Conduction Equations

As is known, Fourier law at the initial time of immersing the heated part into the quenchant does not work [9- 12]. The initial heat flux tends to infinity. But actually it is finite. The modern intensive technologies require the determination of initial finite heat flux densities for their comparison with critical heat flux densities. This problem will be solved on the basis of solving hyperbolic thermal conductivity equation (2), which takes into account the finite speed of the heat propagation. The results of calculations will be compared with results of experiments made with Liscic probes [13].

$$c\rho\frac{\partial T}{\partial t}+\tau_0\frac{\partial^2 T}{\partial t^2}-div(\lambda\, grad\, T)=0, \qquad (2)$$

$$\frac{\partial T}{\partial r}+\frac{\beta^m}{\lambda}(T-T_S)^m\Big|_{r=R}=0, \qquad (3)$$

$$T(r,0)=T_0. \qquad (4)$$

Here $m=\frac{10}{3}$, $\beta\equiv const>0$. Solution should be suitable for any positive degree m.

Some hyperbolic heat conduction equations with non- linear boundary conditions were successfully solved by authors [9 – 12].

5 Discussions

During immersion of heated steel parts into cold quenchant the following processes are observed:

1. Cold quenchant at the surface of steel part firstly is heated to saturation temperature while the surface temperature of steel part drops very rapidly.
2. At the surface of steel part the formation and growth of nucleating centers are observed. At the beginning steam bubbles are very small, the frequency of their oscillations is much higher than at the established nucleate boiling.
3. The full film boiling or nucleate boiling is established depending on the value of initial heat flux density.
4. When $q>>q_{cr1}$ full film boiling is established. When $q<<q_{cr1}$ nucleate boiling is established.

When water flow velocity is very high full film boiling and even nucleate boiling can be prevented completely. Then convection is a main process. This investigation is fulfilled to discuss possible future projects (see: www.wseas.org/propose/project/wseas-project.html). The aim of investigation is to solve hyperbolic heat conduction equation with the non-linear boundary conditions. The results of investigations are used at the development of two step quenching of steel parts and tools. The technology is environmentally friendly and provides the following benefits:

- Increase of service life of tools;
- Elimination of oils and melting of alkali as a quenchant;
- The labor productivity increase for the account of reducing the time of heat treatment process.

It is expedient to start the research by join efforts on the creation of database on cooling capacities of various quenchants. These databases include

- initial heat flux densities;
- critical heat flux densities;
- heat flux densities and heat transfer coefficients for various heat transfer conditions.

These databases are of great scientific interest and they can be used by big companies dealing with the heat treating processes.

6 Conclusions

1. Initial process of quenching during immersion of steel parts into quenchant is not investigated deeply and widely enough.
2. Comparison of initial heat flux densities with the critical heat flux densities allows predicting heat transfer modes occurring during quenching.
3. There is optimal concentration of water salts solution which provides maximum critical heat flux density.
4. Solutions with the maximum critical heat flux densities are suitable quenchants for elimination of full film boiling.
5. Boundary boiling layer is established within 0.1 seconds and less when there is no film boiling.

6. Initial heat flux densities can be evaluated on the basis of CFD modeling or solving hyperbolic heat conduction equation with the non-linear boundary conditions.
7. A team of prominent scientists is organized to solve these problems in the frame of WSEAS, big Companies and academic institutions [14].
8. This paper deals with just some aspects of the problem and is supposed for the further discussion to outline the right way of the research. This discussion is necessary since different authors have different approaches.

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