Analysis of Heat Transfer Processes during Intensive Quenching of Cylinder-Shaped Forgings on the Basis of CFD Simulation

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Abstract: - The analysis of heat transfer during quenching in intensive water streams has been made on the basis of CFD simulation. The analysis has allowed to detect special zones at the surface at which the condition of no non-stationary nucleate boiling is not met and for this reason the requirements for the creation of high compressive stresses at the surface and additional strengthening of material are not met. Such zones are related to the quench crack probability and not big effect of superstrengthening of material. The results can be used at the design of quench equipment and development of new ecologically pure and energy-saving technologies.

Key-words: Intensive quenching process, Heat transfer, CFD simulation, Energy-saving technologies, Ecology.

1 Introduction

This paper deals with the intensive quenching (IQ) process called IQ-3 technology. The specific feature of this process is the absence of both film and nucleate boiling. From the very beginning at all the surface of the part to be quenched, very intensive heat transfer is established, which provides the formation of martensite structure uniformly at all the surface [1, 2].

The formation of the martensite shell creates high compressive stresses at the surface of the part, and the high cooling rate within the martensite range results in additional strengthening of material [1]. At present time CFD simulation is used at quench process analysis. For example, authors [3] have used CFD simulation on the basis of program STAR – CD [4] to study process of quenching semi- axles. At such modeling there is no need to use heat transfer coefficients; they can be evaluated after modeling just to compare results of calculations.

If at all the surface of the part to be quenched the convection is observed, program STAR-CD must produce calculated data well agreed with the results of experiment. If at some points at the surface for any reason the condition of no nucleate boiling is not met, let us call these points special or special zones. To eliminate special zones, it is required to take additional engineering measures connected with the design of quench equipment. On the basis of CFD simulation, the paper discusses quenching process for a part of cylinder shape and having different diameters along its length. The part is cooled in O-shaped channel of the complex configuration to provide condition for IQ-3 process [5]. CFD simulation allowed detecting special zones at the surface of the part and analyzing the water flow vectors in the O-shaped channel of the complex configuration.

2 Configurations of the Part and Quench Equipment

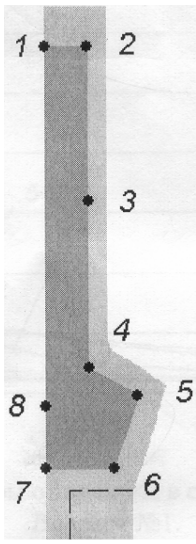


Fig. 1 The part in the quench fixture.

The configuration of the part and quench equipment is presented in Fig. 1. All the system consists of 16000 cells. The time spacing is 0.001 s. The cooling process has been calculated for 50 s. The water flow rate at the entrance was 10 m/s. To simulate the heat transfer processes we used the numerical methods of control volume described in program STAR –CD [4]. The study of heat transfer processes during quenching has been performed on the basis of numerical solving of the full system of Navier – Stokes equations, determined by Reynolds and differential equations for two-layer k - ε turbulence model [6, 7].

3 Results of CFD Simulation

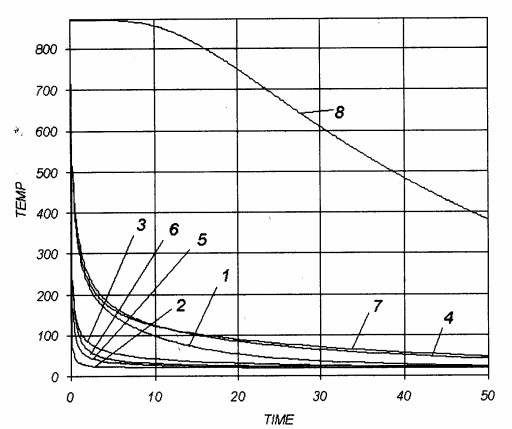


Fig. 2 Calculated temperatures versus time at points 1….8 received on the basis of solving the conjugate problem.

The results of CFD simulation are as follows: function of temperature versus time at points 1-8, heat flux densities at the same points at time of 0.1 s, water flow rate at the mentioned time points. Some results of calculations are presented in Table 1.

Table 1 Computational data for time of 0.1 s.

Parameter	Points at the surface part.						
	1	2	3	4	5	6	7
Water temperature, °C	34	26	45	44	35	35	43
Surface temperature, °C	638	161	366	613	292	391	622
Water flow rate, m/s (1 mm from the surface)	1.5	22	13	1.2	22	5.2	0.9
Heat flux density, MW/m^2	14	6.5	14	0.7	15	14	9.3

4 Discussions

CFD simulation is of great practical interest since it allows observing the full picture of changes in water flows, which has effect upon the heat flux densities and heating transfer coefficients in the steel quenching process. In criterion dependencies it is assumed that the water flow rate is preset and is not changed during the time. This assumption is used in the calculation of the condition when there is no non-stationary nucleate boiling on the basis of the criterion as follows:

$$Bi = \frac{2(\vartheta_0 - \vartheta_I)}{\vartheta_I + \vartheta_{uh}}, \qquad (1)$$

where

$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3}$. For water at 20°C: β=7.36. $\vartheta_0 = T_0 - T_s$; T_o *is* initial temperature of steel part at the moment of immersion into quenchant, for example T_o = 870°C; T_s *is* saturation (boiling) temperature; T_m is medium temperature; T_m = 20°C; $\vartheta_{uh} = T_s - T_m = 100^0 C - 20^0 C = 80^0 C$, λ is thermal conductivity; λ = 22 W/mK. R is radius. In the left and right side of the equation (5) ϑ_I is the same symbol. It can be evaluated step by step calculation.

In the O-shaped channel of the complex configuration the water flow rate at the surface of steel parts to be cooled can drastically change and in stagnation zones it can decrease significantly. Of course, in these zones condition (1) is not met, therefore it is possible that the nucleate and even film boiling arises. In turn, it results in the discrepancy in the computation results obtained from solving the conjugate problem on the basis of STAR-CD program with regard to true values. As is known, STAR-CD is not able yet to simulate the process of nucleate and film boiling. At the points where the process of non-stationary nucleate boiling is observed, STAR-CD will give higher values of temperature at the surface of the part. Thus, Fig. 2 presents the results of computing the temperature at the surface of the part at its various points as well as in the core of the part (point 8). At points 1, 4 and 7 the condition of criterion (1) was broken, and therefore CFD simulation produced higher surface temperature by 2-3 times. Actually when there is nucleate boiling and no film boiling, the surface temperature rapidly drops to the saturation temperature Ts, being a little higher (by 10-20 °C).

The calculations, for example, at point 1 at time of 1 s produce the surface temperature of 300 °C, however, actually the surface temperature at that time must be within 110-120 °C. The increase in the temperature is observed just at some points, which cannot significantly change the cooling rate in the core (in our case, this is point 8).

To prove it, let us compare the cooling time from austenitizing temperature T_0=870 °C to temperature of 500 °C at point 8. The cooling time can be calculated by the generalized dependence of the author [1]

$$Fo_v\ Kn = \left[\frac{k\,Bi_v}{2.095+3.867\,Bi_v}+\ln\theta\right], \quad (2)$$

or

$$t = \left[\frac{kBi_v}{2.095+3.867Bi_v}+\ln\frac{T_0-T_C}{T-T_C}\right]\frac{K}{aKn}. \qquad (2a)$$

Here t is time of heating and cooling of the steel parts;

Bi_v is generalized Biot number;

K is Kondratjev form factor (Table 2);

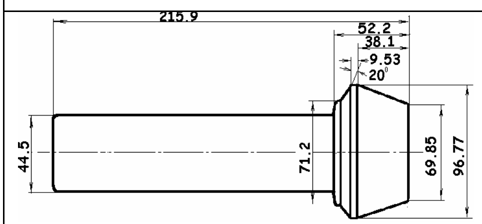
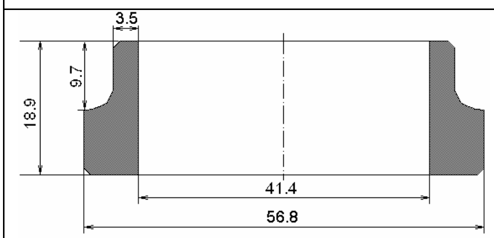
Kn is Kondratjev number;

T_o is initial temperature before cooling;

T_c is quenchant temperature.

K depends on form and size of steel part.

Table 2 Kondratjev form factors for different kind of steel parts

Drawings of steel parts	*K, m²*
	171·10⁻⁶
	3.94·10⁻⁶

Let us calculate the time by the mentioned formula:

$$t = \left(0.48+\ln\left(\frac{870-20}{500-20}\right)\right)\frac{171\times10^{-6}\,m^2}{5.36\times10^{-6}\,m^2/s\times0.9}\approx 37s$$

By Kobasko equation (2) the core's cooling time from 870 °C till 500 °C is equal to 37 s. The cooling time in the same range obtained on the basis of CFD simulation is 38 s, which agrees well with each other. Some increase in the cooling time is explained by the reduced heat transfer at (zones) points 1, 4 and 7. In the whole, excluding points 1, 4 and 7, the CFD simulation gives the right picture of the process of non-stationary heat transfer during steel quenching in the O-shaped channel of quite complex configuration.

The CFD simulation performed allowed to detect special zones which can have unfavorable effect upon the distribution of current and residual stresses in the part quenched and result in quench crack formation due to non-uniform martensite shell at all the surface of the part.

Non-uniformity of heat transfer at the surface is connected with the non-uniform distribution of water flow rates and appearance of special zones the analysis of which is given below and presented in Fig.3, Fig.4, Fig.5 and Fig.6.

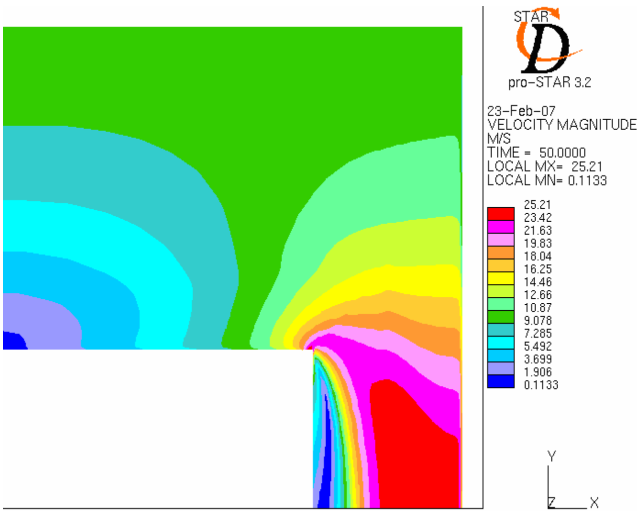


Fig. 3 Distribution of water flow at the upper edge of the cylinder and at the entrance to the O-shaped channel at time of 50 s.

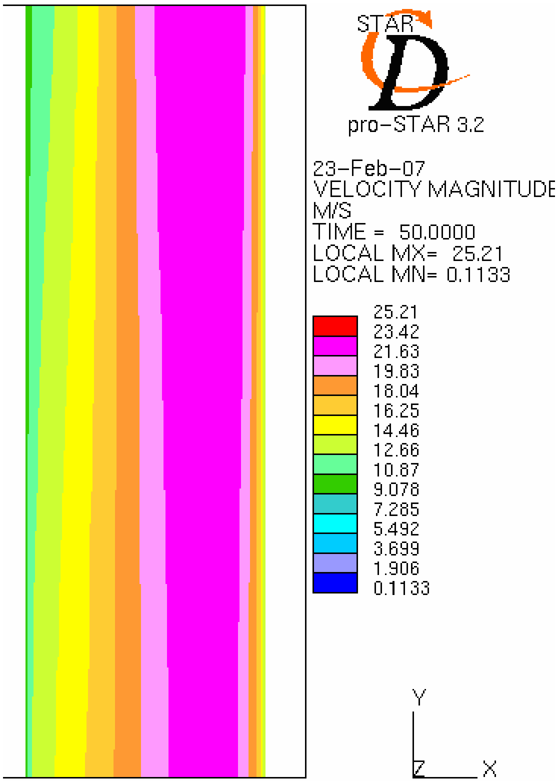


Fig.4 Distribution of water flow rates in the O-shaped channel (point 3) at time of 50 s.

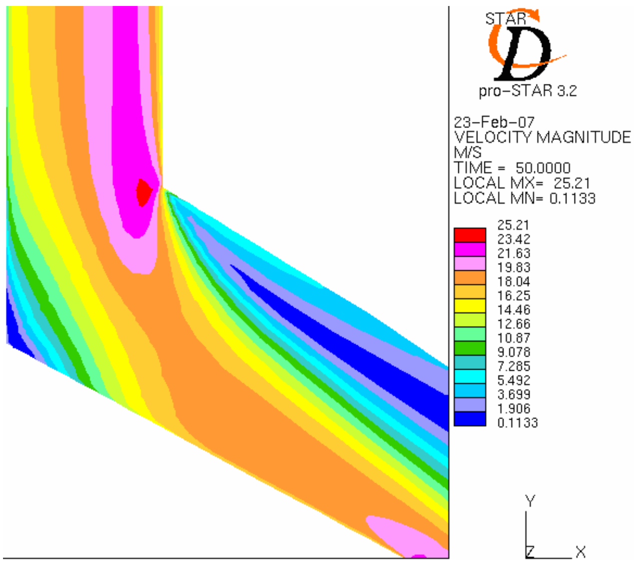


Fig. 5 Distribution of water flow rates at the fold at point 4 at time of 50 s.

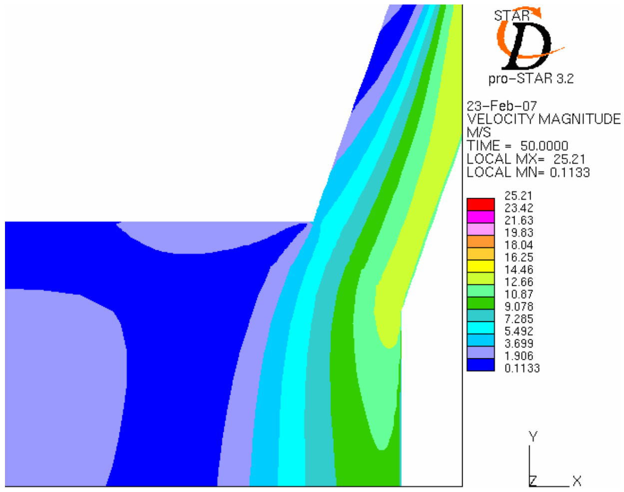


Fig. 6 Distribution of water flow rates at the opposite edge of forging (point 7) at time of 50 s.

Fig.3 shows the distribution of water flow rates at the edge of the cylinder and at the entrance to the U-shaped channel formed by cylinder-shaped part and quench equipment. The distribution of rates is quite non-uniform. At the cylinder's axis the water rate is obviously insufficient to suppress the process of non-stationary nucleate boiling. The same is observed also at points 4 and 7. At these points the nucleate boiling prevails, and STAR-CD, which does not regard boiling, yields the higher temperatures at the surface of the part.

Using an appropriate design one can eliminate the stagnation zones and provide very intensive and uniform cooling of the part to be quenched. The final purpose of such design is the creation of high compressive residual stresses at the surface and superstrengthening of material. Both factors allows to save energy resources and expensive materials.

5 Conclusions

1. The CFD simulation can be applied in the research of heat transfer processes by IQ-3 technology, at which there is neither film nor nucleate boiling and the prevailing process is one-phase convection during all the period of cooling.
2. During quenching parts in the flow of water moved at the rate of 10 m/s in the O-shaped channels of the complex configuration there are zones of slow water flows and there can be special zones where the condition of no non-stationary nucleate boiling is not met.
3. The CFD simulation is a very useful tool in the design of the quench equipment.

4. When there is no nucleate boiling at all the surface, the CFD simulation agrees well with the experimental data.
5. The research of heat transfer processes during quenching was performed on the basis of numerical solving the full system of Navier-Stokes differential equations, determined by Reynolds, and differential equations for two-layer k - ε - turbulence model [6, 7].
6. It is need in further investigations of the conjugate problem to verify its applicability to the intensive quenching processes.

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