Steel Hardening in Low Concentration of Polyacrylamide Water Polymer Solutions

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Abstract - *The paper's idea is considering the possibility of using a low concentration of polyacrylamide water solutions as a quenchant for uniform and intensive hardening of machine components and tools. An advanced method of prediction microstructure and mechanical properties of steel in large hardened products are also considered. The idea consists of comparing cooling curves in small probes and large steel components during their quenching. It is assumed that cooling curves are the same if m exponent factors are equal between each other. This new approach provides more accurate prediction as compared with the existing method, which is based on a calculation cooling rate at a temperature 700^{o}C. It is underlined in the paper that primary attention should be paid to software development to govern correctly quenching process to receive essential benefits. The cost of polyacrylamide water solutions insignificantly prevails the cost of plain technical water due to deficient concentration and low cost of polyacrylamide. Customers can prepare polyacrylamide water solutions by themselves, providing appropriate control of quenching processes.*

I. INTRODUCTION

In 1983 – 1985, an extensive investigation was performed concerning water solutions of polyacrylamide used in the heat treating industry as a quenchant [1]. The authors [1, 2] performed investigations to evaluate experimentally critical heat flux densities responsible for the full film boiling process formation. These investigations showed a sharp decrease in the first critical heat flux density versus concentration polyacrylamide in water. Even a solution of 1% polyacrylamide in water results in a very stable film boiling process. Later it was noticed that a very low concentration of polyacrylamide in water eliminates the film boiling process creating a condition for uniform and intensive quenching [3]. The current paper aims to find out whether a low concentration of polyacrylamide water polymer solution can serve as a quenchant for intensive quenching processes.

II. FILM BOILING GENERATED BY POLYACRYLAMIDE

A widely distributed information concentration of polyacrylamide (0.001% – 0.003%) in cold water decreases hydrodynamic resistance by 70 %, almost two times [4, 5]. The mechanism of such behavior of a small amount of polyacrylamide in water is not investigated yet and understandable. However, this information can explain increase critical heat flux densities during quenching in solutions of 0.001%–0.003% polyacrylamide in water (see Fig. 1).

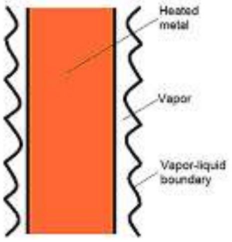

***Fig. 1**: Possible the full film boiling process destroying initiated by a decrease of a liquid's hydrodynamic resistance.*

Destroying a vapor blanket directly depends on the hydrodynamic resistance of a liquid. The lesser is hydrodynamic resistance; the higher is the probability of film boiling destroying, and the higher are critical heat flux densities. Accurate experiments performed by the author [3] support this hypothesis (see Fig. 2).

To guarantee the absence of quench crack formation during accelerated cooling of steel parts in low concentration of polyoxyethylene in cold water, accelerated cooling should be interrupted at the proper time. Thus, a simplified method of calculation and software are available from the Intensive Technologies Ltd, Kyiv, Ukraine [6].

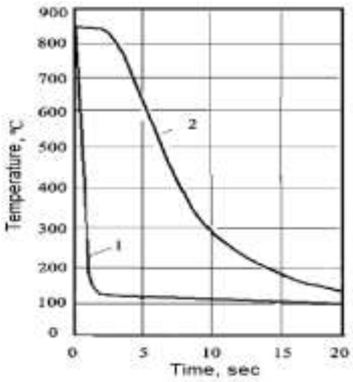

***Fig. 2**: Cooling curves versus time during quenching cylindrical probe 20 mm diameter and 80 mm long in a water solution of polyacrylamide (0.001 %) at 23 ºC: 1 is surface temperature; 2 is core temperature [1, 3].*

Fig. 2 shows the absence of a film boiling process during quenching cylindrical probe 20 mm diameter in very low concentration (0.001%) of polyacrylamide in the water at

23^{o}C. Fig. 2 is seen as the self – regulated thermal process. Its duration is approximately equal to 15 seconds. The duration of the self – the regulated thermal function is evaluated by equation (1) [7]:

$$\tau_{nb} = \overline{\Omega}\, k_F \frac{D^2}{a} \qquad (1)$$

Since the low concentration of polyacrylamide in water decreases hydrodynamic resistance, it results in slightly increase convective HTC during quenching in still solution at 23^{o}C. Its value is approximately equal to 1100 W/m^{2}K. It means that the convective Biot number is $Bi = \frac{1100W/m^2K}{23W/mK} \times 0.01m = 0.48$ similar to. According to Ref. [7], the parameter $\overline{\Omega}$ is equal to 4.8 when the convective Biot number is equal to 0.48. For the cylindrical shaped form coefficient $k_F = 0.0432$, the thermal diffusivity of steel is $a = 5.4 \times 10^{-6} m^2/s$; the sample's diameter is D = 0.02 m.

According to equation (1), the self's duration – the regulated thermal process τ_{nb} is equal to $\tau_{nb} = 4.8 \times 0.0432 \times \frac{4 \times 10^{-4} m^2}{5.4 \times 10^{-6} m^2/s} = 15.36s$ that coincides very well with the accurate experiments (see Fig. 2).

Increase the concentration of polyacrylamide to 1% in water results in forming the developed film boiling process (see Fig. 3).

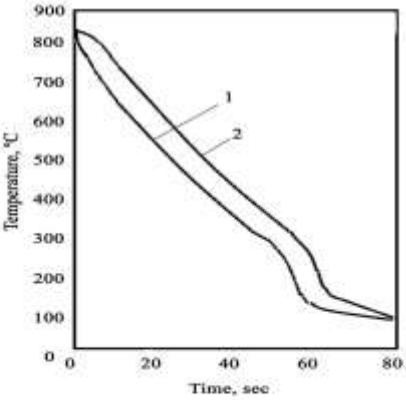

Fig. 3: Cooling curves versus time during quenching cylindrical probe 20 mm diameter and 80 mm length in a water solution of polyacrylamide (1 %) at 20 ºC: 1 is surface temperature; 2 is core temperature [1, 2].

As one can see from Fig. 3, 1% of polyacrylamide in cold water develops a stable full film boiling process. Heat transfer coefficient (HTC) can be easily evaluated here using universal correlation (2) that is used for calculating heating and cooling time of any steel part [6]:

$$\tau_{eq} = E_{eq} \frac{K}{aKn} \qquad (2)$$

According to Fig. 3, the dimensionless temperature at the core of a cylindrical probe 20 mm diameter decreases 3.75 times when in 60 seconds core temperature is 300^{o}C. Ref. [6] provides for this condition the value E_{eq}, which is $E_{eq} = 1.36$. Kondrat'ev form coefficient K for cylindrical probe 20 mm diameter is equal to $17.3 \times 10^{-6} m^2$.

The average thermal diffusivity of steel for a given temperature interval is equal to $5.4 \times 10^{-6} m^2/s$. When taken these data into account, Eq. (2) provides $Kn = 0.0726$, or $Bi_V = 0.079$. Knowing the generalized Biot number Bi_V, for cylindrical probe 20 mm in diameter, the HTC is evaluated as

$\alpha_F = \frac{23W/mK \times 0.079 \times 0{,}01m}{2 \times 17.3 \times 10^{-6} m^2} = 500W/m^2K$ that belongs to the developed full film boiling process.

As known, the HTC during film boiling is evaluated by equation (3) [2]:

$$\alpha_F = 0.25 \cdot \left[\frac{c_p g \lambda''(\rho' - \rho'')}{\nu''} \right]^{1/3} \qquad (3)$$

For waters at 20^{o}C (see Table 1 and Table 2)

$$\alpha_F = 0.25 \cdot \left[\frac{21.35 \times 9.81 \times 2.372 \times 997.6}{20.02 \times 10^{-6}} \right]^{1/3} = 728W/m^2K$$

that approximately coincides with experimental data. A small difference is explained by changing the thermal conductivity of water when polyacrylamide is dissolved in it.

Experiments support the obtained results of calculations (see Fig. 4 and Fig. 5).

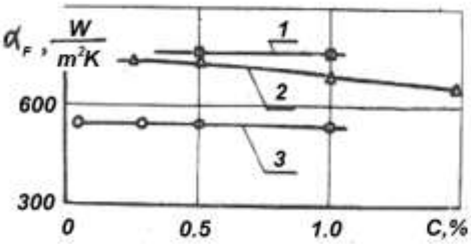

Fig. 4: Heat transfer coefficient during film boiling vs. concentration polymer in the water at 20^{o}C [1]: 1 is PK – 2 polymers tested by stainless cylindrical probe 20 mm in diameter; 2 is PK-2 polymer tested by spherical silver probe 20 mm in diameter; 3 is polyacrylamide water polymer solution tested by stainless cylindrical probe 20 mm in diameter.

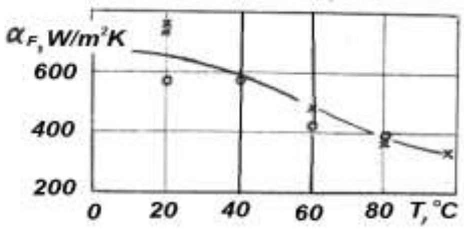

***Fig. 5**: **HTC during film boiling vs. bath temperature for 1% water polymer solutions: x is PK – 2 polymer; o is polyacrylamide**.*

TABLE I

Physical properties of water

T, °C	ρ, kg/m^3	c$_p$, kJ/(kg·°C)	λ, W/(m·K)	a·10^6, m^2/s	μ·10^6, Pa·s	ν·10^6, m^2/s	σ ·10^4, N/m	Pr
0	999.9	4.212	0.560	13.2	1788	1.789	756.4	13.5
10	999.7	4.191	0.580	13.8	1306	1.306	741.6	9.45
20	998.2	4.183	0.597	14.3	1004	1.996	726.9	7.03
30	995.7	4.174	0.612	14.7	801.5	0.805	712.2	5.45
40	992.2	4.174	0.627	15.1	653.3	0.659	696.5	4.36
50	988.1	4.174	0.640	15.5	549.4	0.556	676.9	3.59

TABLE II

Physical properties of vapor at normal pressure

T, °C	ρ'', kg/m^3	$r^\bullet$ kJ/kg	c$_p$, kJ/(kg·°C)	λ ·10^2, W/(m·K)	a·10^6, m^2/s	μ·10^6, Pa·s	ν·10^6, m^2/s	Pr
100	0.598	2256.8	2.135	2.372	18.58	11.97	20.02	1.08

III. CRITICAL HEAT FLUX DENSITIES

Critical heat flux densities are responsible for the absence of film boiling during quenching. It was shown by many experiments that equations govern the process of film boiling formation during quenching in polyacrylamide water solutions (4), (5), (6), which are supported by experiments (see Fig. 6 and Fig. 7) [8]:

$$q_{cr1}^{uh} = q_{cr1}\left[1 + 0.065\left(\frac{\rho'}{\rho''}\right)^{0.8}\frac{c_p\vartheta_{uh}}{r^\bullet}\right] \qquad (4)$$

$$q_{cr1} = 0.14r^\bullet\sqrt{\rho''}\sqrt[4]{g\sigma(\rho'-\rho'')} \qquad (5)$$

$$q_{cr1} = 7r^\bullet\sqrt{af\rho'\rho''} \qquad (6)$$

It should be noted here that data on temperature cooling curves and cooling rate, obtained by testing standard Inconel 600 probe, is not enough to correctly govern quenching processes taken place in polyacrylamide water solutions.

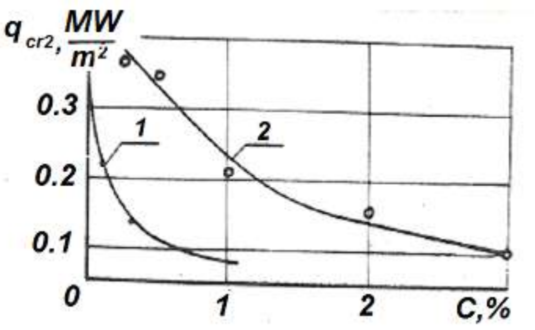

Fig. 6: Second critical heat flux density qcr2 versus the concentration of aqueous polymer solutions: 1, polyacrylamide; 2, polymer PK-2 [1].

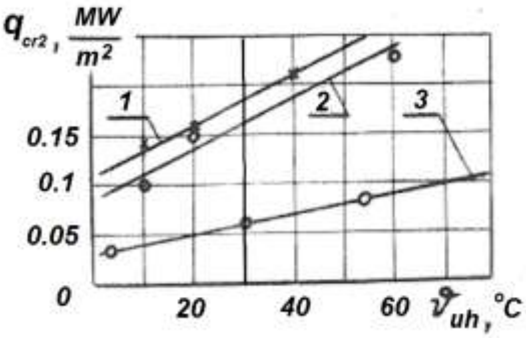

Fig. 7: Effect of underheating ϑ_{uh} on the second critical heat flux density q_{cr2} for polymer PK-2 and polyacrylamide: 1is polymer PK-2 when a spherical silver probe was used; 2 is a polymer PK-2, when a cylindrical steel probe was used, 3 is polyacrylamide [1].

TABLE III

Regular dimensionless temperature θ_{reg} for classical forms depending on conventional Biot number Bi when the accuracy of calculation is 3%

Biot number Bi	θ_{reg}	
	Plate	**Cylinder**
0.2	1	0.98
0.5	0.995	0.96
1.0	0.99	0.95
2.0	0.98	0.90
3.0	0.97	0.86
5.0	0.96	0.83
10	0.95	0.80
50	0.92	0.77
∞	0.90	0.75

IV. IMPROVED METHOD OF MICROSTRUCTURE PREDICTION

The mathematical model for computation of temperature fields during quenching in liquid media, when film boiling is absent, is written as [2, 9, 10]:

$$c\rho \frac{\partial T}{\partial \tau} = \lambda div(gradT) \quad (7)$$

$$\left[\frac{\partial T}{\partial r} + \frac{\beta^m}{\lambda}(T - T)^m \right]_{r=R} = 0 \quad (8)$$

$$T(r,0) = T_o \quad (9)$$

At establishing pure convection, the boundary conditions (8) transforms into normal form (10):

$$\left[\frac{\partial T}{\partial r} + \frac{\alpha}{\lambda}(T - T) \right]_{r=R} = 0 \quad (10)$$

The temperature field in the steel part at the end of the nucleate boiling process becomes an initial condition for convection mode:

$$T(r, \tau_{nb}) = \varphi(r) \quad (11)$$

The time of transition from transient nucleate boiling to convection is determined from equating heat flux densities q_{nb} and q_{conv} :

$$q_{nb} \cong q_{conv} \ , \quad (12)$$

It was shown by authors [9, 10] that for both parabolic and hyperbolic equations, the problem of finding an analytical solution is reduced to the finding of unknown function from the integral equation (13):

$$h(\varphi) = g(\varphi) \cdot \left[1 - \int_0^{\varphi} G(\varphi, \phi) \cdot h(\phi) d\phi \right]^m \quad (13)$$

Here $G(\varphi, \phi)$ is a classic Green function for the heat conductivity equation with Neumann boundary condition [9. 10]..

Assume that cooling curves 1. 2, and 3 for different steel parts are available (see Fig. 8). The below point of A_{c1} regular thermal condition is established for all three curves where the cooling process is governed by a simple exponent (14).

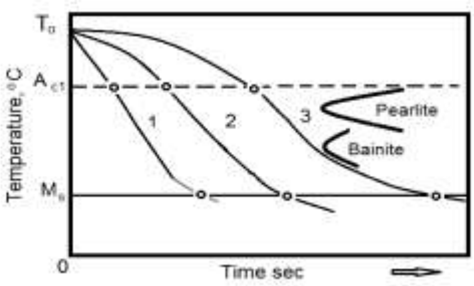

Fig. 8: CCT diagram explains the possibility of prediction microstructure and mechanical properties of steel in hardened machine components.

$$T = T_{reg} \exp(-m\tau) \quad (14)$$

According to the regular thermal condition theory of Kondra'ev m value in Eq. (14) is calculated as:

$$m = \frac{aKn}{K} \quad (15)$$

To simulate phase transformation at the core of the roller, shown in Fig. 9, in lab condition, one should provide the same value m for a small probe when quenching it in laboratory tank.

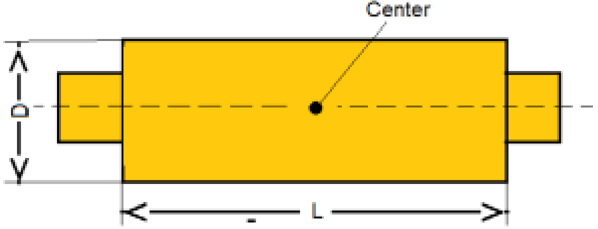

Fig. 9: Sketch of roller

It is known that during quenching of roller in a polyacrylamide water solution of low concentration, Kondrat'ev number Kn is equal to 0.72. Kondrat'ev K coefficient for different forms are collected in Table 4 [11., 12, 13].

TABLE IV

Kondratiev form coefficients K for bodies of a simple configuration (results of analytical calculations)

No.	**The shape of the part**	**Coefficient K, m^2**
1.	The slab of thickness L	$\frac{L^2}{\pi^2}$
2.	An infinite cylinder of radius R	$\frac{R^2}{5.784}$
3.	Square infinite prism with equal sides of L	$\frac{L^2}{2\pi^2}$
4.	The cylinder of radius R and height Z	
5.	Finite cylinder, R=Z	$\frac{R^2}{15 \cdot 65}$
6.	Finite cylinder 2R=Z	$\frac{R^2}{8.252}$
7.	Cube with a side of L	$\frac{L^2}{3\pi^2}$
8.	Finite square plate with sides of L_1, L_2, L_3	$\frac{1}{\pi^2\left(\frac{1}{L_1^2} + \frac{1}{L_2^2} + \frac{1}{L_3^2}\right)}$
9.	Sphere	$\frac{R^2}{\pi^2}$

Using the provided data, one should evaluate the value m for roller, which is calculated by Eq. (14). Then a small probe, made of the same steel, is slowly quenched in a water solution of elevated concentration of polyacrylamide in water to provide the same value m that is related to the small probe. For this purpose, experimental data are shown in Fig. 4 and Fig. 5, and the calculated data shown in Table 5 can be used.

Example: Calculated value m for roller 63 mm in diameter (see Fig. 9), that is quenched in condition Kn = 0.72, is equal to 0.0225s^{-1}. Find the same value m for small probe 10 mm in diameter that is quenched in 1% water solution of polyacrylamide at 90^{o}C (see Fig. 5). For such a condition of cooling, the HTC is equal to 270 W/m^{2}K. To find m value for a small probe, Kondrat'ev number Kn should be calculated first. It is equal to 0.019 if the small probe's diameter is 10 mm, and HTC is equal to 270 W/m^{2}K. According to Eq. (15),

$$m = \frac{5.30 \times 10^{-6} m^2 / s \times 0.019}{4.32 \times 10^{-6} m^2} = 0.023$$

The result of the calculation is approximately equal to value m that was calculated for roller. It means that microstructure and mechanical properties in small probe and microstructure at the roller's core should be similar.

More information on the temperature field calculation , on prediction microstructure and mechanical properties of steel are provided in the recently published papers and in the book [14, 15, and 16].

Note that during the calculation, the value m, the generalized Biot number Bi_V is calculated, and then Kondrat’ev number Kn is found from Table 5.

TABLE V

Universal correlation between generalized Biot number Bi_V and Kondratjev number Kn [2, 12, 13].

Bi_V	ψ	Kn		Bi_V	ψ	Kn
0.00	1.000	0.000		1.60	0.413	0.661
0.01	0.993	0.010		1.80	0.383	0.689
0.10	0.931	0.093		2.00	0.356	0.713
0.20	0.868	0.174		2.50	0.304	0.759
0.30	0.811	0.243		3.00	0.264	0.793
0.40	0.759	0.304		3.50	0.234	0.819
0.50	0.713	0.356		4.00	0.210	0.839
0.60	0.671	0.402		5.00	0.174	0.868
0.70	0.633	0.443		6.00	0.148	0.888
0.80	0.599	0.479		7.00	0.129	0.903
0.90	0.568	0.511		8.00	0.114	0.915
1.00	0.539	0.539		10.0	0.093	0.931
1.20	0.490	0.588		100	0.010	0.993
1.40	0.448	0.628		∞	0.000	1.000

More detailed information on universal correlation $Kn = \psi Bi_V$ via extended tables are available in the published literature [11 – 13].

V. CONCLUSIONS

1. Polyacrylamide water solutions of extremely low concentration can serve as a quenchant for uniform and intensive quenching of steel parts. Its cost differs insignificantly from the value of the technical water.

2. An improved method of microstructure and mechanical properties prediction in steel parts quenched in polyacrylamide water solutions is proposed, which can be used to optimize quenching processes.

3. The primary attention should be paid to the automation of quenchi9ng processes when polyacrylamide water solutions are used as a quenchant for intensive cooling of steel parts to obtain high surface compression residual stresses and super strengthened material.

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