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Mechanism of Film Boiling Elimination when Intensively Quenching Steel Parts in Water Polymer Solutions of Low Concentration

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Abstract- The paper considers a mechanism of the elimination of the film boiling process during intensive quenching (IQ) of steel parts in water polymer solutions of low concentration. The use of the IQ process results in improvement of material mechanical properties and steel part performance characteristics. Evaluation of ways of eliminating of the film boiling process using a modern physics point of view allows significant improvement of the IQ equipment making it less costly and more efficient. All of this cardinally simplifies the implementation of the IQ technology in heat treat practice. The paper shows how creation of a thin insulating surface layer during quenching of steel parts in low concentration of inverse solubility polymers results in eliminating of film boiling processes that makes the quench process intensive. Historically in heat treating industry, an effective heat transfer coefficient was widely used for evaluating of the nucleate boiling process. And quenching during the nucleate boiling mode of heat transfer was considered as slow cooling. That is why powerful quenching systems were recommended for performing IQ processes. It is shown that the absence of the film boiling process makes quenching intensive. Quenching parts made of optimal hardenability steel under such condition results in the development of high surface compressive residual stresses and in material super-strengthening that, in turn, increases a quality and service life of steel parts. The paper can be useful for engineers, scientists and college students.

Keywords: IQ process; mass production; new approach; insulating layer; film boiling elimination; service life; low cost.

I. INTRODUCTION

Conventional quenching of steel parts and tools in heat treating industry is performed in oils, water polymer solutions of high concentration and water. As a rule, parts made of alloy steels are quenched in oils or water polymer solutions of high concentration while parts made of plain carbon steels are quenched in water. To control quenching process, cooling curves and cooling rate curves are widely used in practice. In contrast to conventional quenching methods, intensive quenching (IQ) processes are conducted in plain water or water polymer solutions of low concentration and are applicable to all types of steel. Implementing of the IQ methods requires interruption of the cooling process at a proper time based on consideration of the quench process physics. As known [1], five possible scenarios of the heat transfer process are considered during quenching parts in liquid media:

a) Full film boiling and nucleate boiling processes are present at the same time on the part surface. The area of nucleate boiling moves up along the part surface replacing film boiling. A wetting process of a cylindrical Cr-Ni steel sample of Ø15mm by 45mm long quenched in still water of 60°C is discussed in the book [1].

b) A film boiling process takes place throughout the entire part surface area at the beginning of the quench. At a certain point in time, a nucleate boiling process followed by a convection mode of heat transfer replaces film boiling (this is a well known classical consideration [1, 2]).

c) Some local areas of the part surface are covered by the vapor blanket, while at the same time, other areas experience nucleate boiling. These local areas do not move and their presence is one of the major reasons for significant distortion of steel parts during quenching in liquid media[1,3].

d) The boiling process takes place on some local areas of the part surface. Film boiling and nucleate boiling processes appear periodically in these areas, replacing each other (see Fig. 2) [1, 4].

e) The film boiling process is completely absent from the very beginning of quenching and only a transient nucleate boiling process followed by convection take place [5].

When the IQ process is designed correctly, the film boiling process is completely absent during quenching. For developing quenching processes in liquid media, engineers used to use a parabolic heat conductivity equation considering the following three classical modes of heat transfer: film boiling, nucleate boiling and convection. Later modified law of Fourier was taken into account and a hyperbolic heat conductivity equation was used for calculating an initial heat flux density which, in this case, is a final value and, in many cases, is below the critical value q_{cr1} [6]. It means that any film boiling is completely absent. In this

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paper, it is shown that the absence of the film boiling results in establishing of the intensive quenching process. The use of the IQ processes for steel parts has been explored extensively during the last several decades by IQ Technologies, Inc. of Cleveland, Ohio (established in 1999) and Intensive Technologies Ltd. of Kyiv, Ukraine (founded in 2000) [7, 8].

This paper discusses the physics of accelerated cooling in water polymer solutions of low concentration when thin insulating surface layer is formed during quenching of steel.

II. Intense Quenching when Film Boiling is Completely Absent

As known, the real heat transfer coefficient (HTC) during a transient nucleate boiling process is calculated as a ratio of the heat flux density produced by bubbles to the overheat of the boundary layer [3, 5], *i.e.*

$$\alpha_{nb} = \frac{q}{T_{sf} - T_s}. \quad (1)$$

In heat treating industry, historically, the HTC during transient a nucleate boiling process is calculated as:

$$\alpha_{ef} = \frac{q}{T_{sf} - T_m}, \; T_m << T_s. \quad (2)$$

Here α_{nb} is a real HTC during the transient nucleate boiling process; α_{ef} is an effective HTC; q is a heat flux density; T_{sf} is a part surface temperature; T_s is a quenchant saturation temperature; T_m is a bath temperature.

The effective HTC cannot be used for calculating of the temperature gradient throughout the part thickness during transient nucleate boiling process. Fig. 1 presents a qualitatively difference between temperature gradients calculated using the real and affective HTC (TG_{effc} and TG_{real} accordingly). As seen, the temperature gradient calculated using the real HTC is much greater compared to that calculated using the effective HTC. Note that the part surface temperature is below the martensite start temperature M_S when using the real HTC.

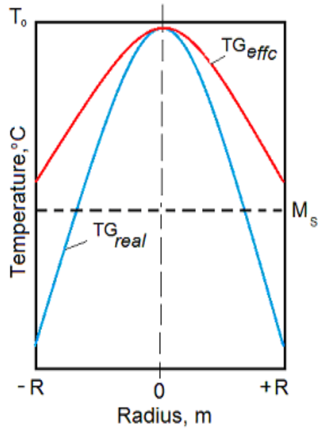

Fig. 1: Temperature gradients calculated using real and effective HTC.

As seen from Table 1 and Fig. 2, values of the real HTCs are very large as compared with that of the effective HTC [3, 9].

Table 1: Real HTCs in W/m^{2}K during nucleate boiling process depending on the temperature of water solution when heat flux density is 15 MW/m^2 [9].

Temperature of water solution	Tolubinsky	Shekriladze	Average
10	152248	176546	164397
20	193929	243641	218785
40	224989	241615	233302
60	271273	271323	271298

The real HTCs were calculated using well known dimensionless equations of authors [10 - 12] who considered HTC as a ratio of heat flux to overheat $T_{sf} - T_s$ (see Eq. (1).

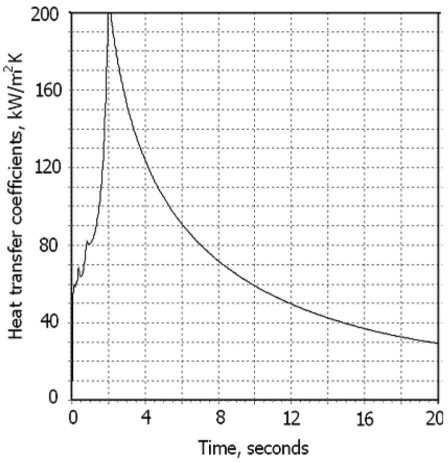

Fig. 2: Shock and nucleate boiling heat transfer coefficients versus time for a sphere of Ø38.1mm quenched from 875°C in a 5 % aqueous NaOH solution at 20°C [3].

As one can see from Table 1 and Fig. 2, nucleate boiling is an intensively forced process which lasts for a relatively long time (see Table 2).

Table 2: Conventional Bi and generalized Bi_V Biot numbers vs time during quenching spherical probe Ø 38.1mm from 875°C in a 5 % aqueous NaOH solution at 20°C.

Time, s	2	4	6	8	10	12	14	16	18
HTC, kW/m^2K	200	120	90	70	60	50	43	37	33
Bi	405	240	180	140	120	100	86	74	66
Bi_V	123	73	55	43	36	30	26	22	20

Using Eq. (3), it is possible to see what temperature gradients appear during quenching versus time (see Table 3).

$$\psi = \frac{\overline{T}_{sf} - T_s}{\overline{T}_V - T_s} = \frac{1}{\left(Bi_V^{\ 2} + 1.437 Bi_V + 1\right)^{0.5}} \tag{3}$$

Table 3: Smoothness criterion ψ and generalized Biot number Bi_V vs time during quenching spherical probe Ø 38.1mm from 875°C in a 5 % aqueous NaOH solution at 20°C

Time, s	2	4	6	8	10	12	14	16	18
Bi_V	123	73	55	43	36	30	26	22	20
ψ	0.008	0.013	0.018	0.020	0.027	0.033	0.037	0.044	0.048

The following conclusion can be made. If any film boiling during quenching in liquid media (water and water solutions) is completely absent, the cooling process is very intensive and uniform in the interval of temperatures T_o and T_s without powerful agitation of the liquid (see Fig. 2 and Table 3).

A value of the HTC during nucleate boiling is evaluated as a ratio (1) because the nucleation depends on $\Delta T = T_{sf} - T_S$ and doesn't visibly depends on the bath temperature in the quench tank (see Eq. (4)) [10].

$$R_{cr} = \frac{2\sigma T_S}{r^* \rho'' \Delta T} \tag{4}$$

$$\Delta T = T_{sf} - T_S$$

According to Tolubinsky [10], during an established nucleate boiling process, the heat flux density is proportional to the cube of the wall overheating (Eq. (5)) while the HTC is proportional to the squared overheat $\Delta T = T_{sf} - T_S$ (see Eq. (6)).

$$q \propto (\Delta T)^3 \tag{5}$$

$$\alpha_{nb} \propto (\Delta T)^2 \tag{6}$$

Due to this fact, after the probe immersion into cold liquid, its surface temperature drops immediately close to the saturation temperature T_S of the liquid (see Eq. (7)) and maintains at this level for a relatively long time [3].

$$T_{sf} \approx T_S + \Delta\bar{\xi} \approx Const \qquad (7)$$

Duration of the transient nucleate boiling process τ_{nb} is proportional to the squared thickness D of the probe, inversely proportional to the material thermal diffusivity and depends on the probe shape k_F and liquid physical characteristics (included into $\bar{\Omega}$) if the initial temperature T_o and the bath temperature T_m are fixed (see Eq. (8)) [14]:

$$\tau_{nb} = \bar{\Omega} k_F \frac{D^2}{a} \qquad (8)$$

During this period of time, the cooling process is very intensive even in the still cold water or water solution if any film boiling is completely absent. When a pure nucleate boiling process is realized, there is no need in the use of powerful pumps or powerful motors with propellers for providing heat transfer conditions required by the IQ process. According to Kutateladze [12], a liquid agitation process affects insignificantly the HTC during nucleate boiling. In many cases, powerful pumps and propellers are used for destroying of film boiling processes, especially during batch quenching where film boiling appears inside the load.

Often, investigators use effective HTC (see Eq. (2)) which is almost ten times lesser as compared with the real HTC. In this case, the part cooling rate during the nucleate boiling mode of heat transfer appears to slow. Even in the scientific literature, a method for testing quenchants was developed where effective HTC was used to check condition $Bi \le 0.2$. As a result, incorrectness appears in many practical situations. This problem was widely discussed in Ref [9].

In Ref. [15] effective HTC was calculated using silver spherical probe 20 mm in diameter (see Fig. 3).

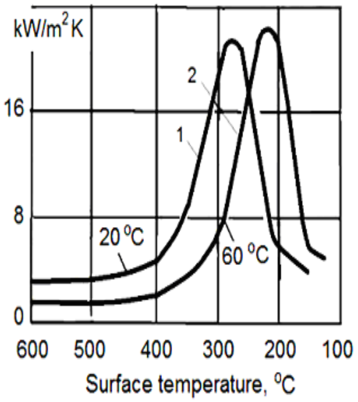

Fig. 3: Effective heat transfer coefficients versus surface temperature of silver spherical probe 20 mm in diameter during quenching in water at different temperatures: first curve 1 is true for water at 20°C; the second curve 2 is true for water at 60°C [15]

Fig. 4 shows incorrect surface temperature calculation in cylindrical probe when using HTC from Fig. 3.

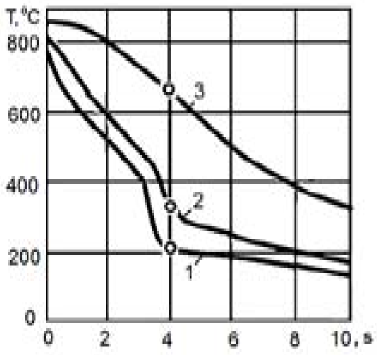

Fig. 4: Calculated temperature cooling curves for 20 mm cylindrical probe made of AISI 304 steel versus time when HTC was taken from Fig. 1 [16]: 1 is surface temperature; 2 is average volumer temperature; 3 is temperature at the center of cylindrical probe; o is transition time from film to nucleate boiling process.

It looks like saturation temperature of water is 200°C instead of 100°C that creates 100% error (see Fig. 4). Moreover, duration of film boiling is too long. In fact, surface temperature of probe during quenching in cold water and water solutions drops immediately close to 100°C as shown in Table 4.

III. Consequences Linked with Consideration of Effective HTCs

According to French [13], the time for establishing of the self-regulating thermal process (SRTP) is almost the same for different sizes and forms of steel components (see Table 4) and its duration is 1 – 2 seconds if any film boiling is completely absent. This phenomenon can be explained by an extremely fast cooling during the immersion of hot steel parts into cold liquid. At the very beginning of intense cooling, independently on form and size of the part the part surface is considered as a semi – infinite because only a very thin surface layer of the material is firstly activated. Further, when a transient nucleate boiling process is established, the cooling time depends on the form and dimensions of steel parts.

Table 4: Time required for the surface of steel spheres of different sizes to cool to different temperatures when quenched from 875 °C in 5 % water solution of NaOH at 20 °C agitated with 0.914 m/s (French, 1930) [13].

Size, Inches, (mm)	Time, sec							
	700°C	600°C	500°C	400°C	300°C	250°C	200°C	150°C
0.25" (6.35)	0.027	0.037	0.043	0.051	0.09	0.15	0.29	0.69
0.5" (12.7)	0.028	0.042	0.058	0.071	0.11	0.15	0.26	0.60
4.75" (120.6)	0.043	0.066	0.09	0.12	0.17	0.21	0.29	0.95
7.15" (181.6)	0.040	0.070	0.100	0.140	0.240	0.310	0.42	1.15
11.25" (285.8)	0.043	0.120	0.190	0.330	0.570	0.960	1.26	2.18

Since $\alpha_{ef} << \alpha_{real}$, incorrect temperature gradient appears during computer calculation as is shown on Fig. 1 above. Such incorrectness can generate other problems which are listed below:

- Large errors when calculating temperature gradients under condition of $Bi = \frac{\alpha_{ef}}{\lambda} R \leq 0.2$.
- Incorrect calculation of the quenchant agitation rate in IQ tanks required for implementing of the IQ process.
- Some error appears when calculating of residual stresses when using effective HTCs.
- Delaying of the implementation of the IQ technology due to the high cost and complexity of IQ equipment.

It follows from the above considerations that the transient nucleate boiling process taking place during quenching of steel parts in water and water solutions provides uniform and intensive cooling if any film boiling is completely absent. In heat treating practice, powerful pumps and propellers are usually used for eliminating an undesirable film boiling process. More effective and less costly ways for eliminating the film boiling process are discussed in the paper [17].

IV. Elimination of Any Film Boiling Process by Creation of a Thin Polymeric Surface Layer

A possibility of providing of the intensive quenching process during hardening of steel parts in 1% water PAG polymer solution was discussed in Ref. [18]. For the first time, a mechanism of the elimination of the film boiling process during quenching of a cylindrical probe in a low concentration of water polymer solution was explained by the creation of a thin insulating surface layer in Ref. [9]. Further this idea was supported by results of many experiments including quenching of standard probes in mineral oils [19, 20]. An absence of any film boiling process during quenching of probes in low concentration of water polymer solutions is explained by the decrease of the initial heat flux density q_o which is calculated by Eq. (9) [9]:

$$q_{in} = \frac{q_o}{\left(1 + 2\frac{\delta}{R}\frac{\lambda}{\lambda_{coat}}\right)} \qquad (9)$$

$$\Delta l = \left(1 + 2\frac{\delta}{R}\frac{\lambda}{\lambda_{coat}}\right) \qquad (9a)$$

Where $\lambda_{coat} = 0.2W/mK$ and $\lambda_{sl} = 20W/mK$ then $\frac{\lambda_{sl}}{\lambda_{coat}} = 100$. When thickness of insulating layer is 100 μm

and 2R = 0.020 m then $\frac{\delta}{R}=\frac{100\times10^{-6}m}{10\times10^{-3}m}=0.01$. In this case $\Delta l=\left(1+2\times0.01\times100\right)=3$. It means that the initial heat flux density during quenching of a given sample can be reduced by 3 times that eliminates completely any film boiling process since $q_{in}<q_{cr1}$. More data on the value of Δl are provided in Table 5.

Table 5: Possible values Δl during quenching in low concentration of water PAG polymer solutions

No.	$\frac{\delta}{R}$	$\frac{\lambda_{sl}}{\lambda_{coat}}$	Δl
1	0.001	100	1.2
2	0.005	100	2
3	0.01	100	3
4	0.001	200	1.4
5	0.005	200	3
6	0.01	200	5

Poly Alkylene Glycol(PAG) polymers of the optimal concentrations provide an ideal uniform cooling for minimizing distortion and preventing the crack formation during hardening of machine components and tools due to their inverse solubility that is a reason for the polymeric surface layer formation [9, 21]. More information on the use of water PAG solutions as a quenchant is provided in book [22].

Now, let's consider initial heat flux densities during conventional quenching. For this purpose, a set of accurate experimental data of French from Table 4 were used for solving inverse problem with the first type of boundary condition. Results of heat flux densities calculations are shown in Fig. 5 a) and Fig. 5 b). Maximal heat flux densities on graphs are considered as initial heat flux densities. They are 17.7 MW/m^2 and 14.7 W/m^2 for spherical probes of Ø12.7mm and Ø120.6mm accordingly. According to Table 5, initial heat flux densities can be reduced by three times by creating a surface insulating layer. The initial heat flux densities became 5.9 MW/m^2 and 4.9 MW/m^2 accordingly For still water without any agitation at 20°C, the first critical heat flux density is 5.9 MW/m^2 [10]. For a slow cooling process, the following ratio is true :

$$\frac{q_{cr2}}{q_{cr1}}=0.2$$

According to Tolubinsky [10], this ratio for the extremely fast cooling is the following:

$$\frac{q_{cr2}}{q_{cr1}}=0.05 \qquad (10)$$

It means that the critical heat flux density q_{cr1} during fast cooling can be four times greater. Moreover, a slow agitation of water or even an insignificant resonance effect generated by a hydrodynamic emitter can increase essentially the first critical heat flux density q_{cr1}.

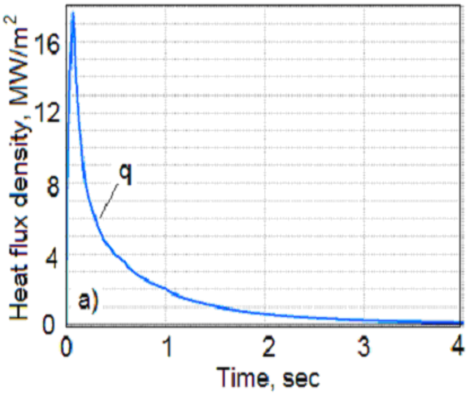

Fig. 5 a

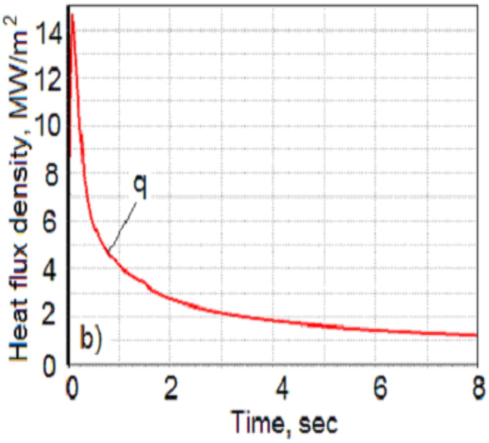

Fig. 5 b

Fig. 5: Heat flux density versus time when quenching spherical steel samples in 5 % water NaOH solution at 20°C agitated with 0.914 m/s: *a* – 12.7 mm in diameter; *b* – 120.6 mm in diameter.

Thus, combining all together, it is possible to design an intensive and uniform cooling process in water PAG solutions of low concentration. More information one can get from Refs [23, 24].

Similar calculations were performed for mineral oils with and without a polymer addition. As seen from Fig. 6, the addition of polyisobutylene (PIB) to mineral oil decreases or completely eliminates a full film boiling process [20].

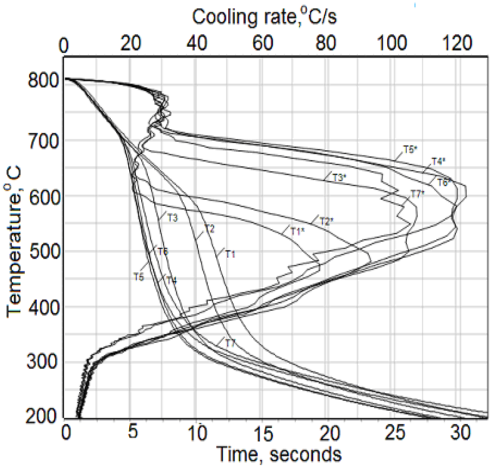

Fig. 6: Temperature T and cooling rate T^* versus time at the core of Inconel 600 probe during quenching in solution of PIB-2400 in oil I-8A at 50°oC, % wt: 1 – 0; 2 – 0.5; 3 – 1.0; 4 – 2.0; 5 – 3.5; 6 – 10; 7 – 14

For more information see Refs [19, 20].

V. Intensively Quenched Optimal Hardenability Steel

a) The bell – shaped curve

A bell – shaped curve was discovered by authors [25 - 27] in 1964 (see Fig. 7). It says that distortion and quench crack formation of steel parts is minimal when performing slow cooling or extremely high cooling of steel parts during hardening.

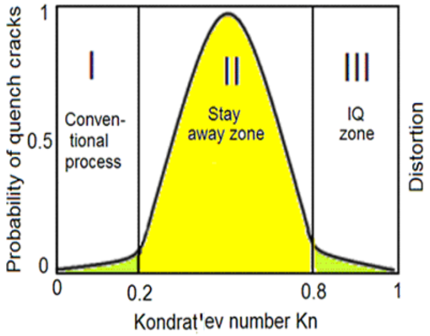

Fig. 7: Probability of quench crack formation and distortion versus Kondrat'ev number Kn.

As known, a cooling rate of any steel part is a linear function of the dimensionless number Kn which changes within the range of 0 and 1 [3, 28].

There is a linear correlation between Kondrat'ev number Kn and the core cooling rate of steel parts during quenching (see Eq. (11) and Eq. (12)) [3, 28]:

$$v = \frac{aKn}{K}\left(T - T_m\right) \qquad (11)$$

$$v = \frac{aKn\left(T - T_m\right)}{K\left(1 + 2\dfrac{\delta}{R}\dfrac{\lambda_l}{\lambda_{coat}}\right)} \qquad (12)$$

When the surface of steel parts is covered by an insulating layer having the thickness δ, the part core cooling rate slightly decreases (see Eq. (12)).

As a rule, alloy and high alloy steels are quenched slowly in oils or in the air flow for obtaining minimal distortion and for avoiding the crack formation [22]. However, slow cooling in zone I ($0 < Kn < 0.2$) (see Fig. 7) requires more alloy elements in steel for providing a required hardened layer [3]. Absence of the quench crack formation in zone I is explained by an insignificant temperature gradient throughout the part cross section that results in neutral or low surface tensile stresses. In zone III, distortion is minimal, high surface compressive stresses are formed during intensive quenching preventing the quench crack formation (see Fig. 8) [29].

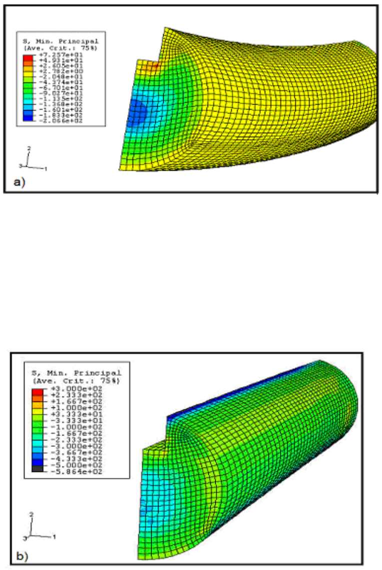

Fig. 8: Minimum principal residual stresses in keyway shaft after quenching in oil (a) and after IQ process (b) according to author [29].

As seen from Fig. 8, the IQ process generates high surface compressive residual stresses and minimal distortion, while quenching in oil results in visible distortion and tensile surface residual stresses in keyway shaft [29]. Also, additional strengthening (superstrengthening) of material is observed in condition of intensive quenching that all together increases significantly service life of hardened machine components and tools [3, 30 - 32].

b) Compressive surface residual stresses and super-strengthened material

It was discovered in 1983 [33, 34] that there is an optimal depth of the hardened layer which provides a formation of high surface compressive current and residual stresses in quenched specimens after intensive cooling. In 2013 [35, 36], a following correlation between steel chemical composition, part size and shape and optimal hardened layer was obtained based on numerous calculations and results of experiments:

$$\frac{DI \cdot Kn^{0.5}}{D_{opt}} = 0.35 \pm 0.095 \qquad (13)$$

Here DI is a part critical diameter in m which depends on chemical composition of steel and is calculated using well known Grossmann's equation [37]; D_{opt} is thickness of steel part. More information is available in Ukrainian patent [35]. A procedure for using the above correlation is as follows:

- A steel grade with certain chemical composition is chosen.
- The ideal critical size for this steel is determined.
- The ratio DI/D_{opt} for specific steel part is evaluated and alloy elements are reduced two or three times to satisfy ratio (13) which must be in a range of 0.2 – 0.5.
- The part is quenched under a condition of $0.8 \le Kn \le 1$.
- Intensive quenching is interrupted to provide self – tempering.
- The part is tempered at the temperature of Ms or higher.

If ratio (13) is satisfied, a residual hoop stress distribution in the steel component is optimal which is shown in Fig. 9. More information related to optimal hardenability steel is available in book [36] issued by Lambert Academic Publishing in 2018.

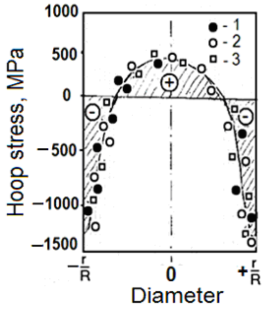

Fig. 9: Residual stress distribution in cylindrical specimens when quenching intensively in water flow in condition 0.8 < Kn < 1 [36].

The patented technology allows decrease a content of the alloy elements in steel, increase a service life of machine components and tools, make the environment cleaner and significantly reduce a cost of the technological process.

Optimal hardenability (OH) steel differs from low hardenability (LH) steel [38 – 41] by its application to any size and form of steel parts and it can be an already existing conventional grade if correlation (13) is satisfied by the existing chemical composition of steel. Some differences between LH, OH, and high alloy steel are shown schematically in Fig 10.

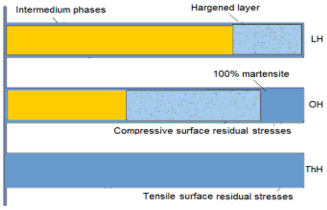

Fig. 10: Optimal depth of hardened layer corresponding to the maximum surface compressive residual stresses: LH, low hardenability steel; OH, optimal hardenability; ThH, through hardening [36].

Fig. 11 explains a mechanism of the superstrengthening phenomenon taking place in the part surface hardened layer [3]. The plates of martensite deform the supercooled austenite that is between them, creating a high density of dislocations that are responsible for a high strength of material.

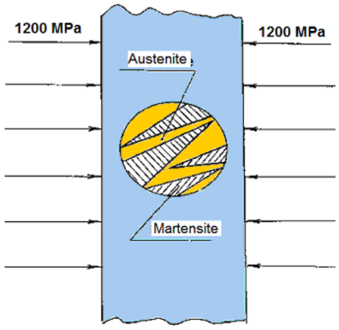

Fig. 11: The transformation scheme of austenite into martensite in the compressed layer, illustrating the effect of additional strengthening (super-strengthening) of the material [36].

More information regarding additional strengthening of steel is available in Refs. [30, 36].

c) Cooling time interruption during IQ process

The IQ process implemented in low concentration of water polymer solutions should be interrupted at a proper time for the following three main reasons:

1. To provide immediate self – tempering of the part quenched layer.
2. To achieve a fine or nano – bainitic microstructure at the core of steel parts.
3. To prevent dissolving of the surface polymeric layer that can result in a big distortion and crack formation during quenching.

The first two reasons were widely discussed in Refs [3, 26]. The last reason is new one and relates to dissolving of the polymeric layer at the bottom of the load being quenched (see Fig. 12).

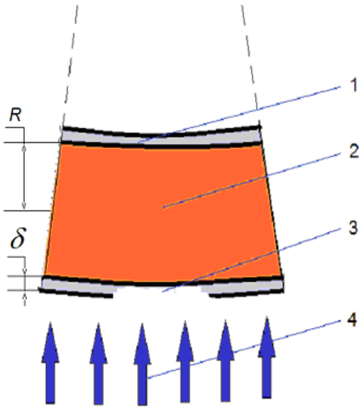

Fig. 12: Schematic explaining why a big distortion takes place during quenching in water PAG polymers solutions: 1 – polymer coating; 2 – quenched steel part; 3 – locally dissolved by water flow polymer coating; 4 – water flow [42].

In area 3 in Fig. 12, a non – uniform cooling process takes place that results in big distortion and can be a reason for the quench crack formation. That is why the cooling process should be interrupted before the insulated surface temperature reaches 72ºC where dissolving of the polymeric layer starts [42]. The cooling time interruption can be calculated approximately using generalized equation (14), Table 6 and Fig. 13 [26]:

$$\tau = \left[\frac{kBi_V}{2.095 + 3.87\,Bi_V} + \ln\frac{T_o - T_m}{T - T_n} \right] \frac{K}{aKn} \tag{14}$$

Table 6: Kondrat'ev coefficients K depending on different shapes and sizes of solid bodies [16]

Shape	Kondrat'ev coefficient K, m^2
Slab of thickness L	$\frac{L^2}{\pi^2}$
Infinite cylinder of radius R	$\frac{R^2}{5.784}$
Infinite square bar with sides of L	$\frac{L^2}{2\pi^2}$
Cylinder of radius R and height Z	$\frac{1}{\frac{5.784}{R^2}+\frac{\pi^2}{Z^2}}$
Plate with sides L_1, L_2, L_3	$\frac{1}{\pi^2\left(\frac{1}{L_1^2}+\frac{1}{L_2^2}+\frac{1}{L_3^2}\right)}$
Sphere	$\frac{R^2}{\pi^2}$

Note: R is radius, L is thickness, Z is height.

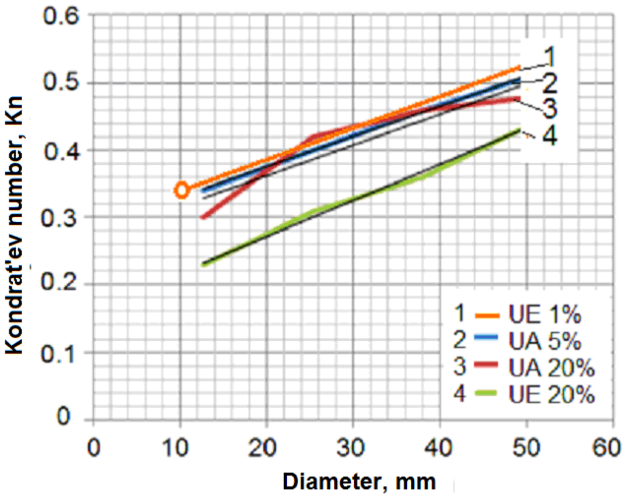

Fig. 13: Effective Kondrat'ev numbers Kn for inverse solubility water solutions of polymers depending on their concentrations and size of product: 1 is 1 % of UCON E in water; 2 is 5 % of UCON A in water; 3 is 20 % of UCON A in water; 4 is 20 % of UCON E in water at 20°C [43].

Fig. 13 provides effective Kondrat'ev numbers Kn used for calculating of the cooling time. However, obtained data are true only for calculating of the part core and cannot be used for evaluating of the part temperature field as discussed above [9].

VI. BENEFITS AND EQUIPMENT FOR PERFORMING OF IQ PROCESSES

Benefits of IQ processes and equipment for their implementation are widely discussed in published books [3, 44, 45]. A possibility of combining of the IQ process (that makes a difference in the surface hardened layer) with a possibility of achieving a fine bainitic microstructure at the core of intensively quenched steel parts is underlined below. After interrupting of the IQ process, there is enough room at the core of steel parts to maximize strength and plastic properties of bainite [46]. The first trial was conducted in 1989 that showed amazing results presented in Table 7 [47].

Table 7: Mechanical properties at the core of cylindrical probes of Ø50mm made of different steels and quenched in oil and water salt solutions [47]

Steel grade	Quenchant	R_m (MPa)	$R_{p0.2}$ (MPa)	A (%)	Z (%)	a_k (J/cm^2)	HB
AISI 4135 (35KhM)	Oil	950	775	14	53	54	285
	Water salt solution	970	820	17	63	150	285
AISI 4140 (40Kh)	Oil	770	575	23	64	13.8	217
	Water salt solution	860	695	16.5	65	168	269

As known, equipment for performing of IQ processes was firstly designed and manufactured in Former Soviet Union (FSU) for quenching of truck semi – axles in water flow moving with a speed of w > 12 m/s [26, 40, 48]. Further accurate investigations dealing with cooling steel samples in a high speed water flow was made in the USA and Germany [3, 49 – 52]. Also, for performing IQ processes, conventional continuous technological lines were used filled with the water salt solutions of optimal concentration to maximize critical heat flux densities in order to eliminate completely any film boiling process [26]. Quenching in such condition provided a uniform and intensive cooling of steel parts, such as bearing rings, rollers, *etc.* [3, 26]. As mentioned above, two companies were established later in 1999 (IQT) and in 2000 (ITL) dealing with IQ processes with the aim to start implementation of the IQ processes in the heat treating industry for a mass production of steel parts in America, Europe and Asia [3, 7, 8]. In the USA, two types of IQ equipment were designed and manufactured: for batch quenching (an IQ – 2 process) and for single part quencjing (an IQ – 3 process) [3]. In a production IQ – 2 model of a 91 by 91 by 182- cm (36 by 36 by 72-in.) A first integral quench atmosphere 91x91x182cm (36x36x72") furnace equipped with an IQ water quench tank of 41.6 m3 (11,000 gallons) was manufactured by AFC-Holcroft Co. of Wixom, Michigan, USA and was installed at the Euclid Heat Treating Co. (EHT) of Cleveland, Ohio, USA. The furnace is equipped with an intermediate chamber connecting the heating chamber with the IQ tank. One of single-part processing high-velocity systems for implementing of the IQ – 3 process developed and built by IQt is also installed at EHT. The system includes a water tank, powerful pump, stationary upper section of the vertical quench chamber, movable lower loading table of the quench chamber, air cylinders, three-way valve, control valves, flow meters, *etc* [3, 45]. Unique experimental results obtained in both above IQ systems were widely discussed in the literature [3, 26, 45] showing a possibility of the part service life increase by up to 8 times. Despite the results obtained, until now the IQ processes are not in mass production in all continents of our Globe. The reason for restricted use of IQ technology in production is its rather high cost, complicated design, and lack of different kinds of software for controlling and governing of the new technology. This paper discusses how to solve this problem to make IQ processes as a mass production around our Globe. Fig. 14 illustrates one of such possibilities.

Table 8 shows a difference in the cooling temperature curves vs time at the core of cylindrical probes of Ø50mm made of stainless AISI 304 steel and quenched in 14% NaCl water solution at 23°C and in 1% of water polymer solution (PAG) [27]. A more useful information on quenching of steel in water polymer solutions one can find in published literature "[24, 27]. Table 8 supports an idea on the possibility performing intensive quenching in 1% water PAG polymer solution [18, 27].

Table 8: Comparison of temperature cooling curves vs time at the core of cylindrical probes of Ø50mm made of stainless AISI 304 steel and quenched in 14% NaCl water solution at 23°C and 1% of water polymer solution (PAG) [27]

Time, sec	0	10	20	30	40	50	60
Core temperature during quenching in 14% NaCl water solution at 23°C	800	780	650	505	380	250	212
Core temperature during quenching in 1% of PAG at 23°C	800	780	650	500	470	320	210

As follows from experiments conducted, intensity of cooling in water salt solution and in 1% of PAG at 23°C are similar (see Table 8) [27].

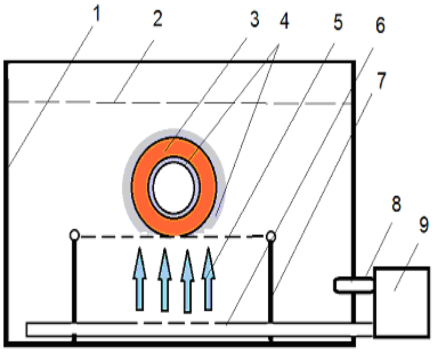

Fig. 14: Prinsipal scheme of performing IQ -2 process using of low concentration polymers: 1 is quench tank; 2 is level quenchant in a tank; 3 is steel parft (large gear or large bearing ring); 4 is surface polymeric layer; 5 is liquid stream; 6 is perforated tube or hydrodynamic emitters; 7 is holder; 8 is outlet tube; 9 is pump

If so, no costly intensive and uniform cooling of steel parts can be easily performed by designing and manufacturing a simple quench tank filled with a low concentration of PAG water polymer solution that is shown on Fig. 14. It differs insignificantly from existing conventional tanks used worldwide in the mass production. Quench tanks or continuous technological lines are equipped with hydrodynamic emitters which generate resonance waves with the frequency equal to frequency of vapor film oscillation. Simultaneously, emitters create agitation of a liquid that increases the first critical heat flux density q_{cr1}. Listed measures (a thin insulating surface layer formed during quenching in water PAG solutions, resonance effect and slow agitation of the liquid guarantee an absence of any film boiling process that makes cooling intensive. A proposed new approach for designing of the IQ processes for mass production doesn't compete with already existing IQ systems. This is because, based on a current consideration of the transient nucleate boiling, batch quench systems designed for implementing of the IQ -2 process will be suitable for conducting of the IQ- 3 process too. IQ – 3 systems will be used for carburized steel parts where martensite start temperature Ms is below 100°C.

VII. DISCUSSION

In this short overview, the main early published results of investigations are discussed by author of the paper. A more detail information can be found in the published literature cited below. Based on a careful consideration of the given subject, one can conclude that the physics of the quench process during hardening of steel parts in liquid media is not investigated deep enough due to a very complicated problem that requires essential investment and time. As known, all handbooks consider three classical phases of the quench process that include film boiling, transient nucleate boiling and convection. It was firmly accepted by worldwide community that during quenching from high temperatures in liquid media the film boiling process always takes place which, as a rule, is a slow cooling. Such opinion is based on the conventional heat conductivity law of Fourier (15). During the immersion of probes heated to a high temperature into a cold liquid $\partial x \to 0$, and it means that $q \to \infty$. That is why, even among the thermal scientists an opinion that the film boiling must be present during quenching was accepted. However, at the beginning of the 20th century, very costly and painstaking experiments were performed in the USA by French who published his very accurate investigation in his book [13]. It was shown by French that during quenching of steel spheres of different sizes from 875 °C in 5 % water solution of NaOH at 20 °C agitated with 0.914 m/s any film boiling was completely absent (French, 1930) [13]. A long time, nobody paid any attention to these very costly and important experimental results since they contradicted the theory and investigators could see that the film boiling process was present during quenching.

$$q = -\lambda \frac{\partial T}{\partial x} \tag{15}$$

Scientists and engineers started to explore parabolic heat conductivity equation (16) which is based on the conventional law of Fourier (15) and must include certain boundary conditions related to film boiling, nucleate boiling and convection and initial condition to obtain a specific solution for the considered specific object.

$$c\rho \frac{\partial T}{\partial \tau} = \lambda div(gradT) \tag{16}$$

Later, the conventional law of Fourier (15) was modified and rewritten as shown by Eq. (17) to make an initial heat flux density the final value during cooling of solid objects in any thermo - dynamical closed system [6]

$$q = -\lambda \frac{\partial T}{\partial x} - \tau_r \frac{\partial q}{\partial \tau} \qquad (17)$$

Here τ_r is relaxation time which is very small value. Eq. (17) generates hyperbolic Eq. (18) which can be used to solve the problem of calculating more accurately initial heat flux densities during quenching.

$$c\rho \frac{\partial T}{\partial \tau} + \frac{1}{w_r^{\,2}} \frac{\partial^2 T}{\partial \tau^2} = \lambda div(gradT) \qquad (18)$$

Here $w_r = \sqrt{\frac{a}{\tau_r}}$ is a speed of thermal wave distribution in m/s [6]. The initial heat flux density q_{in} in this case is always a finite value which can be $q_{in} < q_{cr1}$ that provides the absence of the film boiling process. It was shown by author [53] that the thermal diffusivity of steel a and relaxation time τ_r can be measured experimentally by measuring a speed of the thermal wave distribution.

If the speed of thermal wave distribution is infinity $(w_r \to \infty)$, hyperbolic heat conductivity Eq. (18) become parabolic where the initial heat flux density is infinity and, as a result, the developed film boiling process during quenching from high temperatures in liquid media should be always present. To fix such incorrectness, a contemporary modern physics should consider hyperbolic heat conductivity Eq. (18) with the boundary and initial condition that correctly describe the transient nucleate boiling process that later passes to convection. In the last decade, mathematicians and physicists developed original methods for solving the hyperbolic heat conductivity equation with different kinds of the boundary condition which can be used as a tool for investigating of the IQ processes [54 - 58]. However, solutions are too complicated for engineers working in the heat treating industry. That is why an appropriate software should be designed to simplify developing recipes for IQ processes. Anyway, the most important result of our consideration is a theoretical explanation of the film boiling absence during quenching in liquid media when the initial heat flux density q_{in} is below the first critical heat flux density q_{cr1}, *i.e.* $q_{in} < q_{cr1}$. In this case, the cooling process is very intensive from the very beginning of quenching and there is no need to use very powerful propellers and costly pumps to eliminate the undesirable film boiling mode during hardening of steel with the martensite start temperature M_S > 100°C. As discussed above, the initial heat flux density q_{in} can be significantly reduced by creating of the thin surface insulating layer that is automatically formed during quenching in water polymer solutions of low concentration. During a very fast cooling, the critical heat flux density q_{cr1} increases and it means that the insulating layer can eliminate easily the film boiling process. However, another problem arises here . The point is that big companies, which manufacture polymers for quenching processes, are interested in custometers who use 10%, and 20% solutions not a 1% water polymer solution because of the decreased revenue. The problem can be compromised if manufactures and designers of the costly software for governing of quenching technological processes will work together to sell packages to heat treating industry that will increase the cost of polymers due to investments from big companies for physical investigations and software developments. The considered technology can reduce not only water polymer concentration, but also can cardinally reduce a content of the alloy elements in steel, make the IQ processes and equipment less costly, save materials, and make environment green. All of these are very important for the future generation to live safely on our Globe.

VIII. CONCLUSIONS

1. The less costly IQ process can be designed using low concentration of water PAG polymer solution that creates a thin surface polymeric layer during cooling and reduces the initial heat flux density below its critical value q_{cr1}.
2. There is a belief that the IQ process can become as a mass production globally when it is introduced in the heat treating practice as a package that includes a low concentration water polymer solution, hydrodynamic emitters for slow quenchant agitation, appropriate software for controlling and governing of the technological process based on already available equipment or equipment to be simply designed and manufactured.
3. The proposed technology can be successfully combined with the patented optimal hardenability steel (if its martensite start temperature $M_S > T_s$) that results in formation of high surface compression residual stresses and provides superstrengthening of material in the part surface layer.
4. Achievements in the field of IQ processes and in the field of bainitic transformations can be put together via interrupting of the cooling process at a proper time.
5. To perform correctly the cooling time interruption, an effective dimensionless Kondrat'ev number Kn for inverse solubility polymers can be used which depends on the polymer solution concentration and thickness of quenched components and is true only for core cooling time calculation.

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Nomenclature

Bi	Biot number
Bi_V	Generalized Biot number
Kn	Kondrat'ev number
α_{nb}	Heat transfer coefficient (real) during nucleate boiling in W/m ^{2}K
α_{ef}	Effective heat transfer coefficient (for restricted use) during nucleate boiling in W/m^{2}K
Δ	Overheat of a boundary layer
$\Delta\overline{\xi}$	Average overheat of a boundary layer within the nucleate boiling process
a	Thermal diffusivity of solid material in m ^{2}/s
ψ	Criterion as a characteristic for temperature gradient through section of sample
c	Specific heat capacity
Ω	Parameter depending on convective Biot number, initial and bath temperature
λ	Thermal conductivity of a solid material in W/mK
λ_{coat}	Thermal conductivity of an insulating layer in W/mK
ρ	Density of solid material in kg/m^3
ρ''	Vapor density in kg/m^3
R_{cr}	Critical radius of growing vapor bubble
$r^{\bullet}$	Latent heat of evaporation in J/kg
v	Cooling rate during quenching steel parts in liquid media
σ	Surface tension in N/m
D	Diameter or thickness in m
w_r	Speed of thermal wave distribution
R	Radius in m
τ	Time in seconds
τ_r	Relaxation time
δ	Thickness of insulating layer in m
K	Kondrat'ev size factor in m^2
k_F	Form coefficient
q	Heat flux density in W/m^2
q_{in}	Initial heat flux density W/m^2
q_{cr1}	First critical heat flux density in W/m^2
q_{cr2}	Second critical heat flux density in W/m^2
T_{sf}	Surface temperature in °C
$\overline{T}_{sf}$	Average surface temperature in °C
$\overline{T}_V$	Average volume temperature in °C
R_m	Ultimate strength in MPa
$R_{p0.2}$	Yield strength in MPa
$A(\%)$	Elongation in %
$Z(\%)$	Contraction in %
a_k	Impact strength in J/cm^2

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