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Nikolai I. Kobasko

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In the paper an overview on elimination of any film boiling process during quenching in Poly(Alkilene) Glycol (PAG) solutions is widely discussed. Such elimination is possible due to formation an insulating polymeric layer on the surface of quenched steel parts which decreases initial heat flux density below its critical value. An insulating polymeric layer accelerates cooling process making it uniform and very stable. In such condition, physics and mathematical interpretation of quenching technologies is reliable and creates a basis for automation and software design. The main attention in the paper is paid to mechanism of polymeric layer formation to accelerate hardening of optimal hardenability steel. All of this creates high surface compression residual stresses, makes material ductile and super strengthened, decreases steel alloying and makes possible to switch from oils and melted alkalis to low concentration of water PAG solutions. Along with quenching optimal hardenability steel, it is shown that low and high temperature mechanical treatment combined with PAG solutions as a quenchant makes environment green.

Keywords: insulating layer, film boiling elimination, accelerated cooling, strength increase, environment.

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I. INTRODUCTION

As known, all machine components including cars, trucks and other small and heavy machines are heated to high temperatures and quenched in oils or water polymer solutions to provide appropriate their strength and increase service life of designed machines. In average machine components are heated to 800°C – 900°C and cooled in oils or cold-water solutions at 20°C - 30°C. The problems which arise during quenching are quench cracks, distortion, unsmooth hardness, environment pollution and so on. To prevent quench crack formation and decrease distortion, engineers in heat treating industry use slow cooling in warm and hot oils. However, slow cooling requires more alloy elements in steel to provide hardness at the core of steel parts according to required specification. The main rule in heat treating industry is hardening alloy steel in oil while plain carbon steel can be hardened in water, except high carbon steels used for special tools and dies. So, heat treating industry relates to environment pollution. During producing alloy elements from minerals needed for steel alloying additional pollution takes place. To solve this problem, in last decades intensive quenching was used [1]. It is shown that intensive quenching decreases alloying, increases service life of quenched steel parts, due to high surface compressive residual stresses super strengthening effect, reduces pollution and increases productivity [2]. However, intensive quenching productions lines are still expensive since they require powerful motors with propellers and pumps to provide sever agitation of quenchants [1]. In this paper an alternative way of performing accelerated quenching process in liquid media is discussed. Due to forming an insulating layer on the surface of hardened steel, any film boiling is eliminated that accelerates cooling process. Thus, for performing accelerated quenching in water and water solutions, several requirements should be strongly fulfilled.

- Any film boiling process during quenching in liquid medium should be absent.
- Moderate agitation of liquid should be used during quenching to provide developed transient nucleate boiling process.
- Developed transient nucleate boiling process should drop surface temperature to boiling point of a liquid within 1 – 2 seconds.

The first requirement is fulfilled if initial heat flux density during quenching is below the first critical value q_{cr1}. When initial heat flux density prevails critical value, developed film boiling takes place. When initial heat flux density q_{in} is equal to the first critical value, local film boiling process could take place that causes big distortion [3, 4]. The last is the most undesirable since local film boiling results not only in big distortion but in non-uniform hardness and crack formation.

The second requirement, moderate agitation, can be effectively fulfilled using hydrodynamic emitters that destroy film boiling via resonance effect [5].

The third requirement is fulfilled if water solutions are used to maximize critical heat flux densities [3].

Based on Provided short discussion, an accelerated and uniform cooling is designed using inverse solubility polymers [6].

II. ELIMINATION FILM BOILING BY CREATING SURFACE INSULATING LAYER

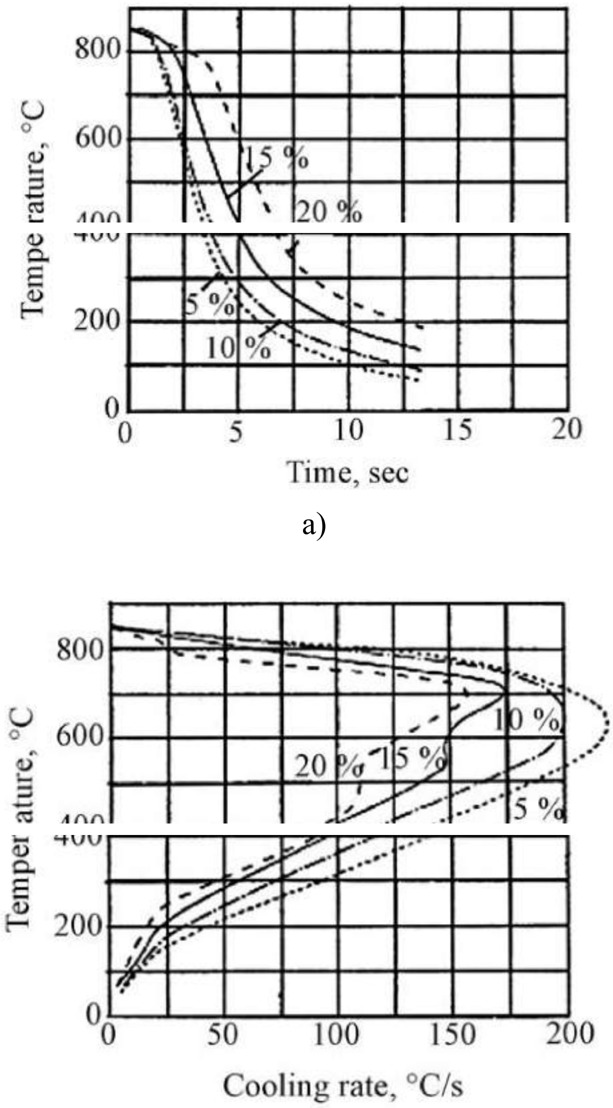
2.1 Experimental Methodology

The method for determination cooling characteristics of aqueous polymer quenchants was proposed by ASTM Standard D 6482 – 06 [7]. This test method covers the equipment and the procedure for evaluation of quenching characteristics of a quenching fluid by cooling rate determination. It is design to eexamine quenching fluids with agitation, using the Tensi agitation apparatus [7]. Very accurate experimental data are provided by standard which are used by author of current paper to study mechanism of surface polymeric layer formation. As a liquid quenchant is used Poly(Alkylene) Glycol (PAG) inverse solubility polymer that creates stable polymeric surface layer during quenching. The proposed method explores standard cylindrical probe 12.5 mm in diameter and 80 mm long and is made of Inconel 600 material [1, 6]. Thermal diffusivity and thermal conductivity of Inconel 600 material versus temperature are provided in Table 1.

Table 1: Thermal diffusiyit and thermal conductiyit of Inconel 600 material versus temp erature.

T, °C	$a \cdot 10^{-6} m^2 / s$	$\bar{a} \cdot 10^{-6} m^2 / s$	λ . W/m K	λ . W/m K
100	3.7	3.7	14.2	14.2
200	4.1	3.9	16	15.1
300	4.5	4.1	17.8	16
400	4.8	4.28	19.7	17
500	5.1	4.44	21.7	17.8
600	5.4	4.6	23.7	18.8
700	5.6	4.74	25.9	20
800	5.8	4.88	26.3	20.06
900	6.0	5	28	21

Fig. 1 present accurate experimental cooling curves and cooling rates for Inconel 600 standard probe 12.5 mm diameter. These accurate experiments are used to see how dimensionless number Kn changes versus time. The aim of such recalculations is to get knowledge on polymeric surface layer behavior during quenching.



a)

b)

Fig. 1: Illustration of the effect of quenchant concentration on cooling curve performance for PAG solutions at 30 °C and agitation 0.5 m/s [7]: *a* – cooling curves versus time; *b* – cooling rate versus time

As well known, presented cooling characteristics allow comparing experiments between each other and cannot be used directly to calculate cooling time and cooling rate the real steel parts during quenching. The goal of investigation is establishing correlation between standard Inconel 600 probe and real steel parts of different sizes and forms to have mathematical tool for recipes development. As known cooling rate of any form of steel parts is calculated as [1, 8]:

$$v = \frac{aKn}{K}\left(T - T_m\right) \tag{1}$$

or

$$Kn = \frac{vK}{a\left(T - T_m\right)} \tag{2}$$

$$Kn = \Psi \cdot Bi_V \tag{3}$$

$$\Psi = \frac{\overline{T}_{sf} - T_m}{\overline{T}_V - T_m} = \frac{1}{\left(Bi_V^{\,2} + 1.437\,Bi_V + 1\right)^{0.5}} \tag{4}$$

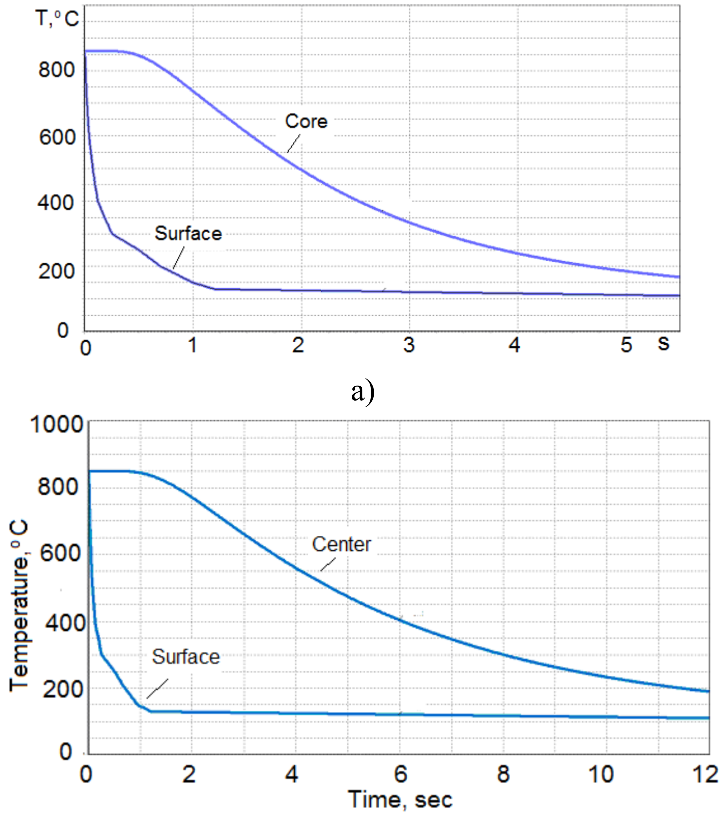
Here v is core cooling rate of steel part during quenching in °C/s; a is thermal diffusivity of material in m²/s; Kn is dimensionless Kondrat'ev number; K is Kondrat'ev form factor in m²; T_m is bath temperature; Bi_V is generalized Biot number; $\bar{T}_{sf}$ is average surface temperature; $\bar{T}_V$ is average volume temperature; Ψ is non-smoothness temperature in steel part.

Note that dimensionless number Kn varies within $0 \le Kn \le 1$ (see Table 2) and can adequately indicate intensity of cooling. When Kn = 1, cooling is ideal and depends only on thermal diffusivity of material and form and size of steel parts. This condition is called $Bi_V \to \infty$

Table 2: Kondrat'ev number Kn versus generalized Biot number Bi_V [8].

Bi_V	ψ	Kn	Bi_V	ψ	Kn
0.00	1	0.00	6	0.14	0.888
0.1	0.93	0.093	7	0.129	0.903
0.2	0.87	0.174	8	0.114	0.915
0.4	0.76	0.304	9	0.103	0.924
0.6	0.67	0.402	10	0.093	0.931
0.8	0.60	0.479	15	0.064	0.953
1	0.54	0.539	20	0.048	0.965
2	0.36	0.713	30	0.033	0.976
3	0.264	0.793	40	0.025	0.982
4	0.21	0.839	50	0.018	0.096
5	0.174	0.868	100	0.010	0.99
5.5	0.16	0.879	∞	0	1

To see physical meaning of dimensionless number Kn, let's analyze experimental data received during quenching in 5% water solution NaOH which was tested by French [9]. This solution provides extremely fast cooling and tends to ideal condition (see Fig. 2 and Fig. 3).



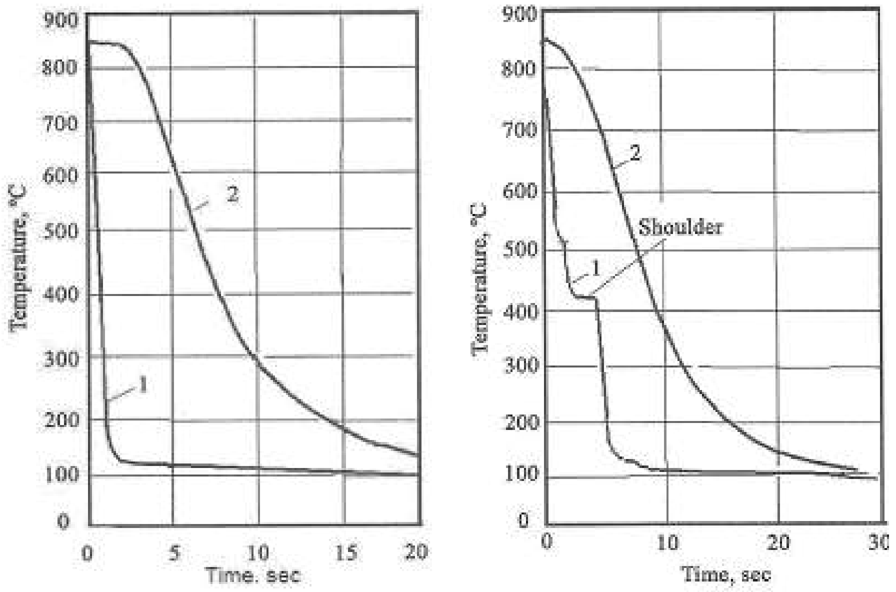
a)

b)

Fig. 2: Surface and core cooling curves versus time during quenching cylindrical specimens in 5% Water solution NaOH at 20°C: a – standard probe. 12.5 mm diameter; b – cylindrical probe 20 mm.

Early scientists established three principles to be successfully used for quench process design [10].

They include possibility to explore the same surface cooling curves for different sizes and forms of steel part quenched in liquid where any film boiling is absent. Evaluation the duration of transient nucleate boiling process during quenching steel in liquid media. And possibility to evaluate surface temperature of any steel part during transient nucleate boiling.



a) b)

Fig. 3: Surface and core cooling curves versus time during quenching cylindrical specimens (20 mm diameter) in low concentration (< 1%) polyoxyethylene at 20°C [11]: a – normal cooling curves; b – surface cooling curve with a shoulder formation.

All three principles are seen from Fig. 2. Surface temperature in all tests drops from 850°C to 150°C within one second independently of size of probe. Surface temperature during nucleate boiling maintains on the level of boiling point of a liquid.

Duration of nucleate boiling is evaluated by established correlation on laws of quenching process [10]. It became clear that the real and effective dimensionless numbers Kn are linear function versus time (see Fig. 4) [12].

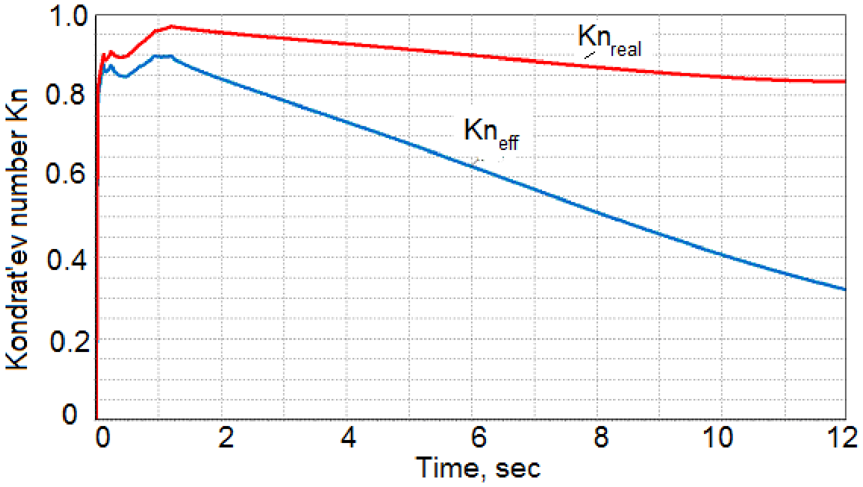


Fig. 4: Real and effective Kondrat'ev numbers versus time during quenching cylindrical specimens (20 mm diameter) in 5% water solution NaOH.

Average real dimensionless number is equal to 0.9. Average effective dimensionless number is equal to 0.65 (see Fig. 4). Real Kn number is responsible for temperature gradient formation. Effective Kn number can be used only for core cooling time and core cooling rate evaluation [1, 12].

According to the patented technology [1, 13], intense cooling process is considered when $0.8 < Kn < 1$. It means that 5% water solution of NaOH solution provides intensive quenching during transient nucleate boiling process. Cooling process during convection is slow. Further these data will be used to compare them with the water PAG solutions data.

Cooling curves on Fig. 3 are similar, however, cooling process a little bit decreases due to surface polymeric layer formation that creates thermal resistance [14].

2.2 Surface polymeric layer eliminates any film boiling process

For the first time intensive quenching process during quenching in low concentration of PAG solution was observed by authors [1]. It was not clear why that is happening. Author [12] explained uniform and accelerated cooling by surface polymeric layer formation that decreases initial heat flux density below its critical value (see Fig. 5 , Fig. 6, and Eq. 5).

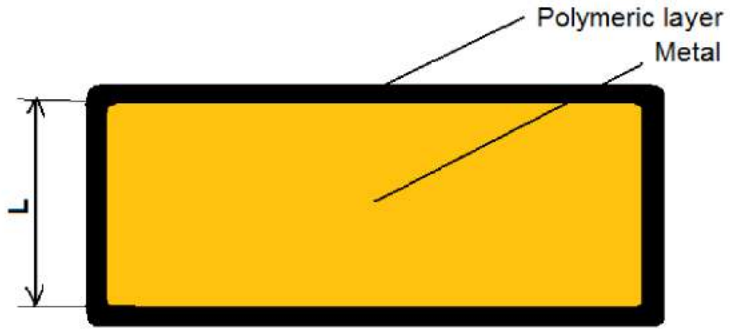


Fig. 5: Steel part covered by insulating layer.

As seen from Fig. 6, initial heat flux density during quenching in water NaOH solution is equal to 14 MW/m^2.

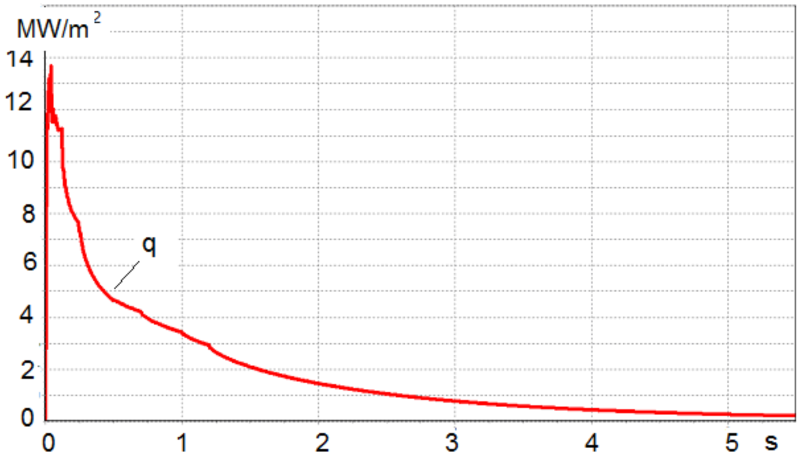


Fig. 6: Heat flux density versus time during quenching standard probe in 5% water NaOH solution.

Let see how much we can reduce it if thickness of insulating layer is 0.1 mm or 10 x 10^{-6}m. Radius of standard probe is 0.00625 m. Average thermal conductivity of Inconel 600 material is 20 W/mK while thermal conductivity of insulating layer is 0.2 W/mK. Using equation (5), calculate heat flux density reduced by formation of insulating layer. This simple calculation show that initial heat flux density reduces from 14 MW/m² to 4.1 MW/m². According to authors [3, 4], the first critical heat flus density for water at 20°C is equal 5.8 MW/m². It means that film boiling is absent since initial heat flux density is below its critical value q_{cr1}.

$$q_{in} = \frac{q_0}{1 + 2\frac{\delta}{R}\cdot\frac{\lambda}{\lambda_{coat}}} \qquad (5)$$

It was established by author [15] that during immersion probe into water PAG solution surface polymeric layer forms immediately (see Fig. 7). If film boiling is absent, polymeric surface layer is formed within 0.05 s – 0.25 s [15, 16].

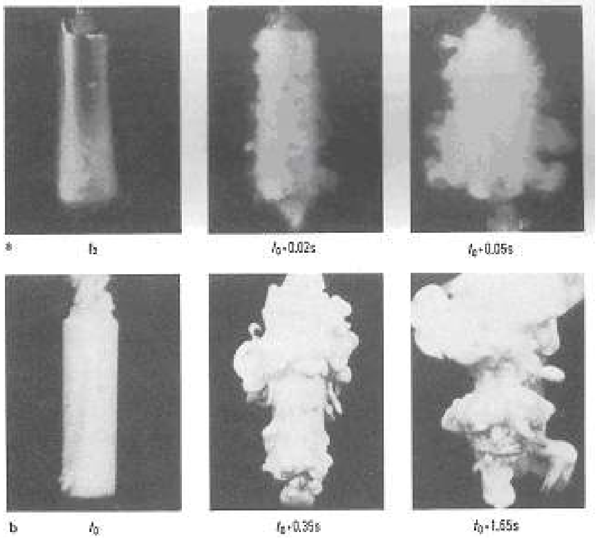


Fig. 7: Formation of surface polymeric layer during queching cylindrical probe 15 mm diameter in water solution of 10% of polymer at 29°C [15, 16]: a) start of polymeric layer formation 20 sec; b) start of polymeric layer formation 6 sec.

It should be noted here that currently polymeric layer is used also for the film boiling elimination during quenching in oils (see Fig. 8). Authors [17, 18] dissolved polyisobutelene (PIB) in mineral oil (3%) to provide uniform hardness, decrease distortion of hardened steel parts and decrease emission due to absence of film boiling process. Solution with 3% PIB in oil is currently used in heat treating industry [18].

Fig. 8: Polymeric surface layer formation during quenching standard probe in oil [17, 18].

New quenchant was introduced for hardening bearing rings and rollers where problem with distortion often arises [17, 18].

III. COOLING CURVES ANALYSIS TO OBSERVE VARYING THICKNESS OF SURFACE INSULATING LAYER

As known, the real heat transfer coefficient (HTC) during 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] that is a realistic indicator of temperature gradient value. Here we have to use effective Kn_{eff} as a tool for intensity process investigation because there were no enough experimental data for real Kn evaluation. For this purpose Eq. 2 was used.

As already known, the coating (insulating layer) forms immediately after immersion probe into water polymer solution. Coating starts decrease its thickness due to dissolving polymer with passing time. It means that dimensionless number Kn slightly increases because decreases thermal resistance. When insulating layer is completely dissolved and convection mode starts, dimensionless number decreases since heat transfer coefficient during convention is low and decreases with time. Detail results of calculations are presented in Fig. 9, Fig. 10, and Fig. 11.

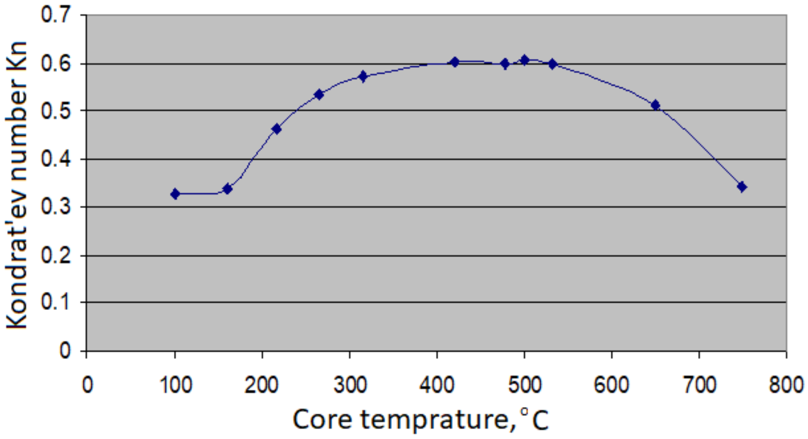


Fig. 9: Dimensionless effective number Kn versus core temperature of standard probe during its quenching in 5% PAG solution at 30°C and 0.5 m/s agitation

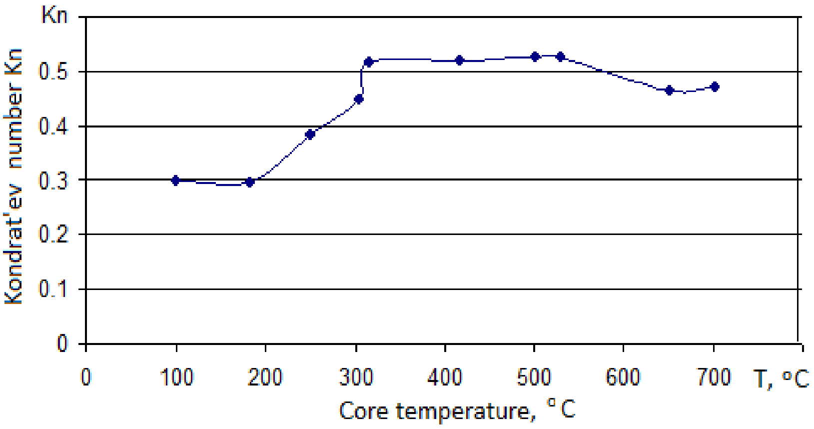


Fig. 10: Dimensionless effective number Kn versus core temperature of standard probe during its quenching in 10% PAG solution at 30°C and 0.5 m/s agitation

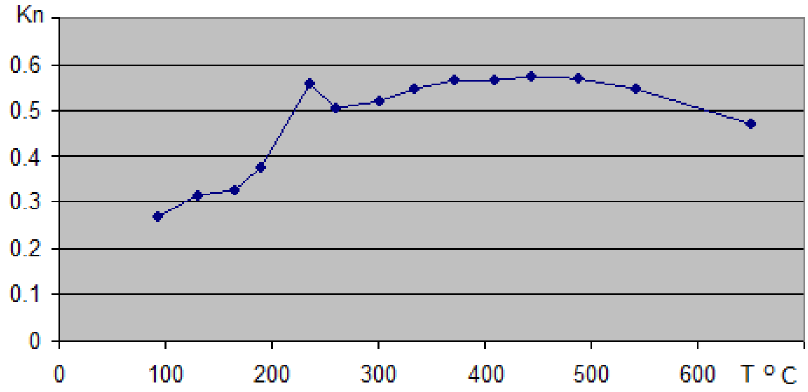


Fig. 11: Dimensionless number Kn versus core temperature of standard probe during its quenching in 3% Aqua-quench 365 water polymer solution at 38°C and moderate agitation

Comparison of dimensionless effective Kn numbers for different polymeric quenchants is provided in Table 3.

Table 3: Comparison of dimensionless effective Kn numbers for different polymeric quenchants

Quenchant	Kn	Comments
PAG , 5%	0.58	Thickness of insulating layer is not proportional
PAG, 10%	0.50	to water polymer solution
Aqua-quench 365, 5%	0.53	Differs insignificantly from PAG solution

More useful information on cooling intensity of polymer water solutions can be provided by testing Liscic probe [19]. Some results of test are shown on Fig. 12.

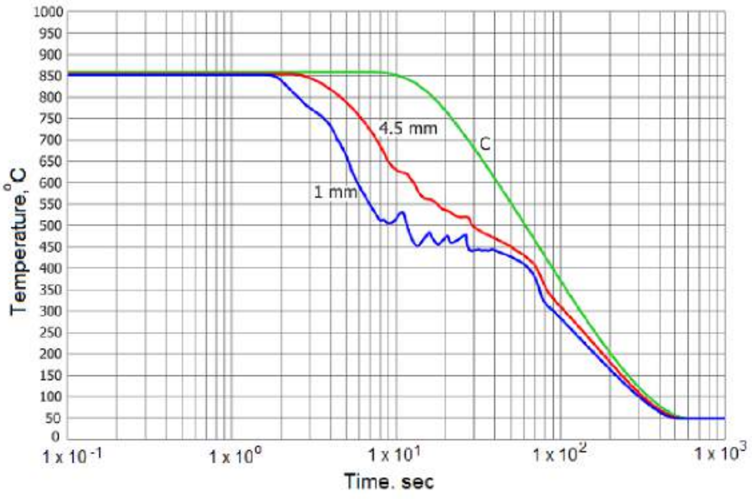


Fig. 12: Cooling curves measured by the Liscic probe (50 mm diameter) quenched in polymer solution at 35 °C, with agitation [19, 20].

On the cooling curve depicted on a distance 1 mm below surface, one can see shoulder formation reminding shelf. Further investigations in this area were fulfilled by team of scientists from Germany [21]. They tested huge shaft 150 mm in diameter and 450 mm long. Three thermocouples were welded on the surface of shaft and one thermocouple was welded on the bottom end of shaft. All three surface thermocouples showed "shoulder" formation at 350°C. Authors explained shoulder formation by film boiling process development [21]. However, by solving inverse problem, is clear that heat transfer coefficient (HTC) at the area of shelf formation significantly prevails HTC at film boiling process. Author [22] came to conclusion that shoulder formation is caused by varying surface polymeric layer during quenching probes in water PAG solutions.

As one can see from Fig. 13, dimensionless effective number Kn_{eff} during quenching in 5% water solution of NaOH gradually decreases versus core temperature of standard probe while effective number during quenching probe in 10% water PAG solution, in contrary.   increases significantly. There is no contradiction here, just almost instantly formed thick polymeric surface layer starts to dissolve by vapor bubbles. At normal atmospheric pressure diameter of vapor bubble is 2.3 mm, and release frequency is 76 Hz [3]. Number of active bubbles depend on developed heat flux density. The higher is the heat flux density, the higher are numbers of active bubbles which start to dissolve insulating layer. Mechanism of polymeric layer dissolving is caused by pumping mechanism of bubbles release. Vapor bubble push away hot water from hot boundary layer replacing it by cold water.

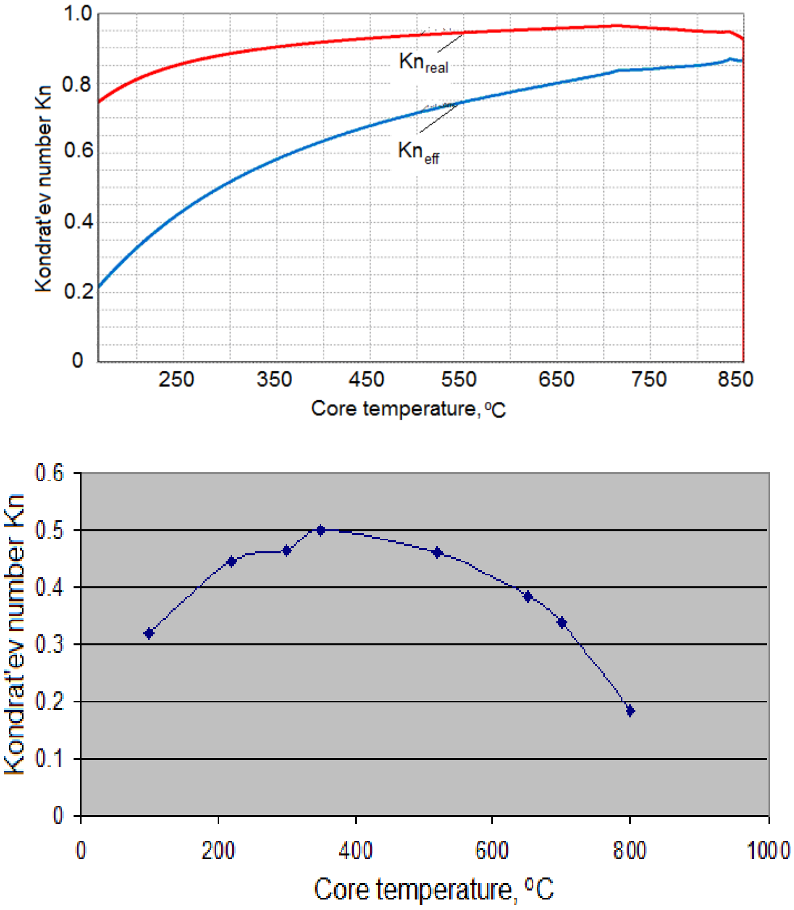


Fig. 13: Real and effective dimensionless numbers Kn versus core temperature of standard probe 12.5 mm: a – quenching in 5% solution odf NaOH; b – quenching in 10% water solution of PAG 27ºC and agitation 15 L/min.

Cold water dissolves surface polymeric layer. However, heat flux density decreases with passing time resulting in decrease active bubbles which cannot more compete with depositing of surface polymeric layer. Beginning from this point of time thickness of polymeric layer gradually increases. Especially such effect is taking place when quenching in PAG polymer solutions of large steel parts.

Such simple and very interesting mechanism of dissolving surface polymeric layer is used to explain shoulder formation on the cooling curve during quenching (see Fig. 3. b)).

IV. BENEFITS CAUSED BY OPTIMIZING INSULATED POLYMERIC SURFACE LAYER DURING QUENCHING

4.1 Optimal hardenability steel quenched in low concentration of PAG solutions

Quenching in water polymer solution of low concentration provides maximal intensity of steel parts cooling. According to accurate data of author [23], accelerated steel quenching in water polymers solutions of inverse solubility results in surface compressive residual stresses formation and superstrengthening of material. These phenomena take place when surface hardened layer is optimal or cooling is interrupted at proper time to create such hardened layer [24, 25]. Optimal hardened layer in optimal hardenbility steel (OHS) is formed if correlations (6 and 7) are true:

$$\frac{DI}{D_{opt}} \cdot Kn^{0.5} = 0.35 \pm 0.095 \tag{6}$$

$$DI = 25.4 \cdot k_{Fe} \cdot k_{Mn} \cdot k_{Si} \cdot k_{Cr} \cdot k_{Ni} \cdot k_{Mo} \ldots \tag{7}$$

In heat treating industry is used low hardenability steel containing minimum alloy elements. Intensive quenching of low hardenability (LH) steel results in increasing service life of machine components, in saving energy and materials [26]. The LH steel can serve as an optimal hardenability steel for small gears and shafts. Its chemical composition is provided below in wt % [26]: C: 0.40 - 0.85; Mn: ≤ 0.20 ; Si: ≤ 0.20; Cr: ≤ 0.10 ; Ni: ≤ 0.10 ; Cu: ≤ 0.10 ; Al: 0.03 - 0.10; Ti: 0.06 - 0.12 ; V: ≤ 0.40 . Proposed steel chemistry is used for manufacturing small gears and shafts. Unfortunately, there is no a method for its chemistry optimizing depending on size and form of quenched samples. As the next step in optimizing quenching processes is optimal hardenability steel. It provides optimal hardened layer for any size and form of machine component and its chemical composition is (in wt, %) [24]: C: 0.30 - 1.20; Mn ≤ 0.20; Si: ≤ 0.20 ; Cr: ≤ 0.50 ; Ni: ≤ 1.6; Mo: ≤ 0.25 ; Cu: ≤ 0,20; Al: 0.03 - 0.10; Ti: 0.06 - 0.12; V: ≤ 0.40; S: ≤ 0,035; P: ≤ 0.035 . Both steels provide fine microstructure due to containing small amount of aluminum; vanadium and titanium. Proposed steel chemistry is used for manufacturing different sizes and forms machine components. There is a method for its chemistry optimizing depending on size and form of quenched samples which was tested in the practice. In contrast to LH steel, OH steel can be quenched in low concentration of water polymer solutions that significancy extends its use.

4.2 Alloy steel quenched in low concentration of PAG solutions

If alloy steel is through hardened, it develops in many cases tensile surface residual stresses after quenching. To create compression residual stresses for such steel, cooling rate should be interrupted at a temperature within interval 400°C – 500°C [1]. Let s consider an example proposed technology.

A squares plate 150 mm long and 15 mm thickness is quenched from 860°C in low concentration of water PAG solution at 30°C. Plate is made of AISI 4340 steel. It should be provided compressive residual stresses at the surface of plate after quenching. Some initial data are known. Dimensionless number Kn is equal to 0.54 (see Fig. 9). Average thermal diffusivity of steel is $5.4 \times 10^{-6} m^2/s$. Kondrat'ev form factor K is $K = l^2/\pi^2 = (0.015m)^2/9.87 = 22.8 \times 10^{-6} m^2$

Calculate core cooling time from 860°C to 300°C and provide immediate tempering of the plate at a temperature 300°C.

For cooling time calculation generalized equation (8) is used [1]:

$$\tau = \left[\frac{kBi_V}{2.095 + 3.867 Bi_V} + \ln \frac{T_o - T_m}{T - T_m} \right] \cdot \frac{K}{aKn} \tag{8}$$

Knowing Kn it is possible to get generalized Biot numberBi_V from Table 3 which is equal 1.

According to Eq. (8), duration of quenching in water polymer solution is:

$$\tau = \left[\frac{2 \times 1}{2.095 + 3.867 \times 1} + \ln \frac{860^{o}C - 30^{o}C}{300 - 30^{o}C} \right] \cdot \frac{22.8 \times 10^{-6} m^{2}}{5.4 \times 10^{-6} m^{2} / s \times 0.54} = 11.4 \sec$$

For water polymer solution of normal and elevated concentration, dimensionless numbers Kn can be used from Fig. 14.

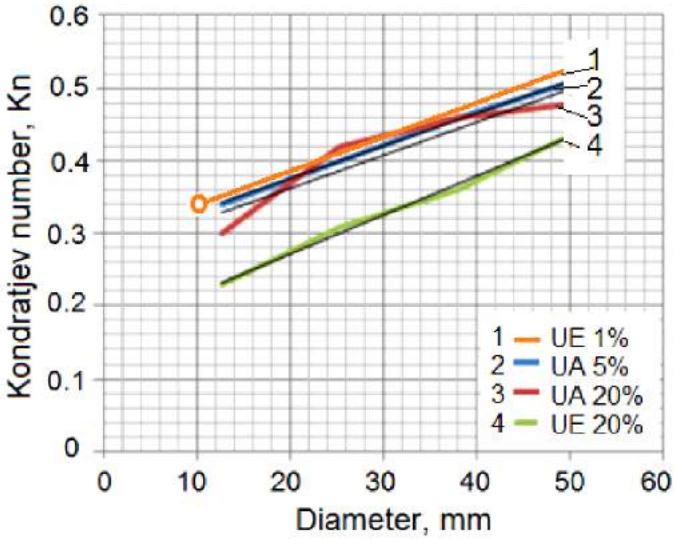


Fig. 14: Dimensionless number Kn versus diameter of tested probes during quenching in PAG solutions at 38°C [23].

4.3 High and low temperature mechanical treatment

The installation shown on Fig. 15, was discussed in literature [1]. This time, there is an opportunity for combining two effects together: increase the first critical heat flux density of liquid and decrease initial heat flux density of quenched steel part. This combination creates uniform and intensive quenching since film boiling cannot appear at all. To be more specific, let's quench a plate. The plate (L_1 = 20 mm; L_2 = 60 mm; L_3 = 80 mm) after forging with intensity of deformation 35% is quenched in low concentration (3%) of PAG water solution under pressure 0.3 MPa. Quenchant saturation temperature is 134°C. Martensite starts temperature for high carbon steel U12A is 130°C. Kondrat'ev form factor K for plate is

$$K = \frac{1}{\pi^{2}\left(\frac{1}{L_1^2} + \frac{1}{L_2^2} + \frac{1}{L_3^2}\right)}$$ [1]. Average thermal diffusivity of steel is $a = 5.4 \times 10^{-6} m^{2}$; Dimensionless number Kn = 0.54. Taking all into account, core cooling time was calculated for interval of temperatures: from 900°C to 600°C which is equal 28 sec. So, specimen was quenched in the installation (see Fig. 15) under pressure 0.3 MPa for 28 seconds and then forged again to form cutting tool and put into liquid nitrogen for 30 minutes for deep cold treatment. The technology allowed using plain carbon steel instead of alloy high carbon steel and increases service life of cutting tool. High and low temperature thermomechanical treatment (further we'll call it mechanical treatment) was investigated by many leading researchers [27, 28, and 29]. Thermomechanical treatment was used mainly for condition of slow cooling that

significantly decreases strengthening effect. This issue was discussed by authors [30, 31]. It has been shown by authors [31] that thermomechanical treatment combined with accelerated quenching further increases mechanical properties of material. Also promising idea is combining the surface martensitic microstructure with the fine bainitic microstructure at the core of quenched steel parts [32, 33].

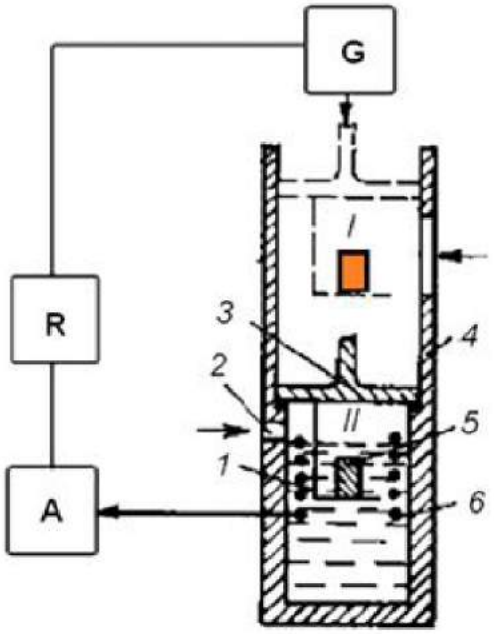


Fig. 15: Basic scheme of the automated process of steel quenching in water and aqueous solutions under pressure [1]: 1, tray; 2, aperture for pumping in compressed air; 3, mobile piston (cover); 4, case of the quench tank; 5, the part to be quenched; 6, solenoid for fixing the initial time of transformation of austenite into martensite; A, the amplifier of a signal of the martensite start; R, relay of current; G, driving mechanism; I, starting position; II, work position.

The considered process is shown schematically on Fig. 16.

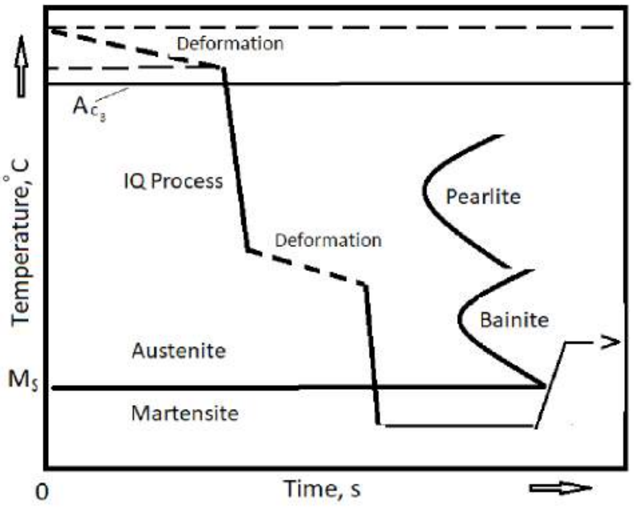


Fig. 16: High and low temperature mechanical treatment (Scheme).

Some experimental results on strength material improvement are collected in Table 4.

Table 4: Mechanical properties of steel 30KhN2MA after normal, high temperature (HTMT) and low temperature (LTMT) mechanical treatment [1, 24, and 25].

Technology	In Water			In Oil		
	R_m	Z,%	A.%	R_m	Z,%	A.%
Normal	1864	8.3	5.3	1777	10	7
HTMT	2007	9.8	5.7	919	9.9	6.3
LTMT	2600	9.2	5.7	1716	10.4	7.4

One can expect that combining thermomechanical treatment with the accelerated quenching in PAG water solutions will result in essential strength improvement of materials. That belief is based on comparison cooling rates of standard probes (see Table 5).

Table 5: Cooling rate at the core of standard cylindrical probes vs temperature and condition of cooling

Quenchant	Cooling rate in °C/s		
	300°C	500°C	700°C
Oil	30	56	85
PAG, 5%	95	187	205

As seen from Table 5, water solutions of polymers cool center of probes almost three times faster and uniformly when film boiling is completely absent. More information on cooling intensity of PAG quenchants is available in published papers [34, 35].

V. DISCUSSION

The main target of current paper is mechanism of formation and dissolving the surface polymeric layer which makes possible to understand how one can effectively eliminate film boiling process during quenching. A shoulder formation on the surface cooling curve also is a goal. These two issues are very important for introducing new technologies into practice. If any film boiling during quenching in liquid media is completely absent, cooling process is uniform and, in many cases, intensive. Mechanism of shoulder formation and understanding its physics makes more believers. A possibility to perform austempering process via cold water polymer solutions can bring big benefits for heat treating industry.. Currently, for this purpose melted salts and alkalis are used that harm environment. However, further painstaking experiments in this pass are needed which include:

- More detail investigation the mechanism of surface polymeric layer formation.
- Evaluation thermal properties of insulating layer and its thickness variation.
- Elaboration of special additives to increase the first critical heat flux density.
- Establishing correlation between thickness of insulating layer and the thickness of quenched steel parts to guarantee absence film boiling process during quenching.
- Studies on stability of shoulder formation and evaluating temperatures at which phenomenon takes place.
- Optimization the cooling processes taking place during quenching steel covered by insulating layer.
- Mathematical description of quenching processes to make automation possible.

Such investigations will make environment green, improve strength of material and decrease their cost.

VI. CONCLUSIONS

An insulating polymeric layer formed during quenching in inverse solubility polymers is used to shift initial heat flux density below its critical value. This shifting eliminates any film boiling process that provides uniform cooling, decreases distortion, increases strength of material and improves environment condition.

Optimized cooling process during hardening materials in inverse solubility polymers in the interval of transient nucleate boiling temperatures is intensive since dimensionless Kondrat'ev number Kn is within 0.8 < Kn < 1 and slow cooling during convection.

Basics of performing hardening materials in optimal concentration of inverse solubility polymers is proposed to make appropriate calculations and design software and automate technological processes.

It is expected that, due to surface insulating surface layer, low and high temperature mechanical treatment will result in increasing service life of machine components and tools.

Two the most promising directions: study of critical heat flux densities and behavior and mechanism of surface insulating layer formation should be carefully further investigated since they'll bring essential benefits for heat treating industry.

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