New Era in Designing and Governing Cooling Intensity of Liquid Quenchants to Decrease Distortion During Hardening of Steel Parts

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RESEARCH ARTICLE

NEW ERA IN DESIGNING AND GOVERNING COOLING INTENSITY OF LIQUID QUENCHANTS TO DECREASE DISTORTION DURING HARDENING OF STEEL PARTS

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ABSTRACT

It was proved in last decade that very intensive and uniform cooling eliminates quench crack formation and significantly decreases distortion of quenched steel parts as compared with their slow cooling in mineral oils. That opened a new era in design ing and governing cooling intensity of liquid quenchants for strengthening steel parts and decrease their distortion after quenching. The new approaches were developed by authors to provide accelerated and uniform cooling steel parts during quenching by creation on their surface thin insulating layers. For this purpose low concentration of water polymer solutions of inverse solubility are used as a quenchant. More information on cooling intensity of Poly (Alkylene Glycol) polymers (PAG) solutions one can find in a well known book (Totten *et al.,* 1993). Along with decreasing distortion of steel parts, such approach decreases cost of bath's coolant which less affects environment. It is shown in presentation that accelerated cooling should be interrupted at proper time to provide self tempering, fix compressive residual stresses, decrease more distortion and prevent quench crack formation. To govern process of quenching and make cooling interruption, software IQCalc2 was developed

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INTRODUCTION

It was a well-known fact in a heat treating practice which stated that quench crack formation and distortion of products after quenching always increase with increasing their cooling rate during hardening (see Fig. 1, section I and II). Such correlation between a probability of part cracking and part cooling rate during quenching is represented by a parabolic curve: the higher the part cooling rate the greater the probability of part cracking and the greater the part distortion. The intensive quenching (IQ) process phenomenon proved that this is not always the case. Actually, the correlation between the probability of part cracking and the cooling rate is represented by a bell-shaped curve shown in Fig. 2 (Kobasko, 1980; 2016). Where Kondrat'ev numbers Kn is directly proportional to cooling rate of a given product.

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(Kobasko, Aronov *et al*. 2010). For the first time, the bell – shaped curve was established by experiment. To check correctness of such unusual statement, the special study was conducted by IQ Technologies Inc. of Akron, Ohio and DANTE Solutions, Inc., of Cleveland, Ohio using high velocity system for providing extremely high cooling rate and software DANTE (Distortion Analysis for Thermal Engineers). The IQ Technologies Inc. carried out experiments with a keyway shaft supported by mumerical calculations made by the DANTE Solutions Inc (Ferguson, 2013). Results of investigations were widely discussed by authors (Kobasko, Aronov, *et.al.,* 2010; Ferguson, 2013) and are presented in Fig. 2, Fig. 3, Fig. 4 and Table 1. It was shown (Kobasko, Aronov, *et.al.,* 2010) that distortion of keyway shaft during quenching in oil was greater than the distortion of the same keyway shaft intensively quenched by water. The reason for this was a uniform formation of the martensitic layer throughout the entire part surface area and development of high current and residual surface compressive stresses during the IQ process (see Fig. 2).

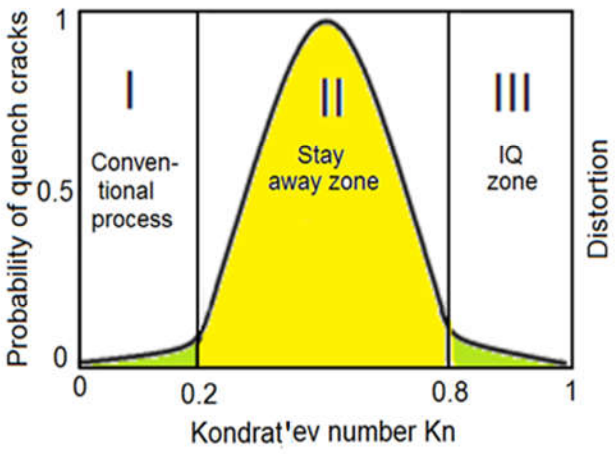

Fig. 1. Crack formation and distortion versus Kondrat'ev number Kn (Kobasko, 1980; 2016): I – conventional processes (quenching in oil, polymers of high concentration or vacuum gas quenching); II – stay away zone; III – intensive quenching zone

Both the uniform martensitic layer and high surface compressive stresses reduce the part distortion compared to conventional oil quenching, where the formation of the martensite is not as uniform and the surface compressive stresses are smaller or tensile. The keyway shafts were made of AISI 1045 steel bars of 25.4 mm (1 in.) in diameter and of 254 mm (10 in.) in length. A nominal chemical composition of AISI 1045 steel is 0.43– 0.50 % carbon and 0.6–0.9 % manganese. The shafts were ground and polished to within ±0.025 mm (0.001 in.). The intensively quenched shafts proved to have both greater surface hardness and core hardness (Kondrat'ev, 1957).

Table 2 presents the distortion data obtained during quenching in oil and high velocity system (Kobasko, Aronov, *et.al.,* 2010). As seen from Table 1, intensive quenching caused much less shaft distortion than that did conventional oil quenching. A finite-element heat-treating-process computer calculations showed the same results shown in Fig. 2 (Ferguson, 2013). Thus, the IQ-3 process provides three times less distortion as compared to oil quenching. Obtained results proof the idea that high cooling rates is not a reason for the high part distortion when a uniform cooling is provided (see Fig. 3, Fig. 4 , and Table 1). This important for the practice fact opens the new possibility in designing and governing cooling intensity of liquid quenchants. More info on new direction in heat treating industry is provided below. In contrary to existing opinions, very intensive quenching decreases distortion (see Table 1) due to formation a uniform shell that acts as a die preventing quench crack formation and minimizing distortion (Kobasko, Aronov, *et.al.,* 2012).

Designing of optimal concentration quenchants and governing of their cooling intensity by creation insulating layers on the surface of steel parts: An idea on decreasing initial heat flux density to eliminate film boiling processes using insulating surface layers was generated by authors in 1987 (Kovalenko, Kobasko, *et.al.,* 1987). In 1996 authors (Kobasko, Moskalenko, *et.al.* 1996; Moskalenko, Kobasko *et al*., 1996) discovered that low concentration of PAG in tap water (1%) increases cooling rate of spherical silver probe 20 mm in diameter more than two times as compared with its cooling in water solution of PAG of high concentration (see Table 2).

Experiments: In current paper the observed effect was investigted using large cylindrical stainless probe. To be closer to the Liscic/Petrofer probe (Liscic, 2016), experiments were carried out with cylindrical probe 50 mm in diameter and 200 mm length made of AISI 304 steel. Three thermocouples were instrumented in the probe: on the surface, 5 mm below surface and at the center of the probe. This probe was used for testing low concentration of PAG in tap water and NaCl water solution to compare results of experiments. Investigated polymer was similar to UCON E. As is known, PAG polymers dissolved in water are widely used as the quenchants for hardening machine components and tools. Currently, 10%, 20%, and even 30% water solutions of PAG polymers in water are used to substitute the costly oils. According to Fig. 5, maximal cooling rate for cylindrical probe 50 mm in diameter during quenching probe in 1% water PAG solution is 16.8 $^oC/s$ when core temperature is 600^{o}C. Taking into account thermal properties of AISI 304 steel from Tables 3 and 4, one can calculate effective heat transfer coefficient and effective Kn number using Eq. 1 and Eq. 2 (Kondrat'ev, 1957; Kobasko, *et.al.,* 2010):

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

or

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

Kondratjev (Kondrat'ev) form factor for 50 mm in diameter probe is 105.25 x 10^{-6} m^2 and average thermal diffusivity of steel AISI 304 at 600^{o}C, according to Table 3, is 5.1 x 10^{-6} m^2. That is why

$$Kn = \frac{16.8^o C/s \times 105.25 \times 10^{-6} m^2}{5.1 \times 10^{-6} m^2/s \times 565^o C} = 0.614$$

According to Fig. 6, cooling rate is 10^{o}C/s when core temperature is 465^{o}C. In this case

$$Kn = \frac{10^o C/s \times 105.25 \times 10^{-6} m^2}{4.85 m^2 \times 10^{-6} m^2/s \times 430^o C} = 0.505.$$

Author (Kobasko, 2017) calculated effective Kn numbers, when any film boiling was completely absent, for still and agitated water with different convective heat transfer coefficients (see Fig. 6) depending on size and form of probes. For cylindrical probe 50 mm in diameter and convective HTC = 750 W/m^2K, effective number Kn is equal to 0.66 that is close to 0.61. The difference is explained by decreasing convective HTC in 1% polymeric water solution due to increase its viscosity. It means that film boiling during quenching cylindrical probe 50 mm in diameter in 1% water solution of PAG polymer was completely absent. To be sure that this statement is true, let's compare identical cooling curves obtained during quenching the cylindrical probe 50 mm in diameter in 1% water solution of PAG and 14% water NaCl solution. During quenching in cold brine (14% water NaCl solution) film boiling was absent (see Fig. 7). According to Fig. 7, core temperature decreases from 650^{o}C to 300^{o}C for 31 sec.

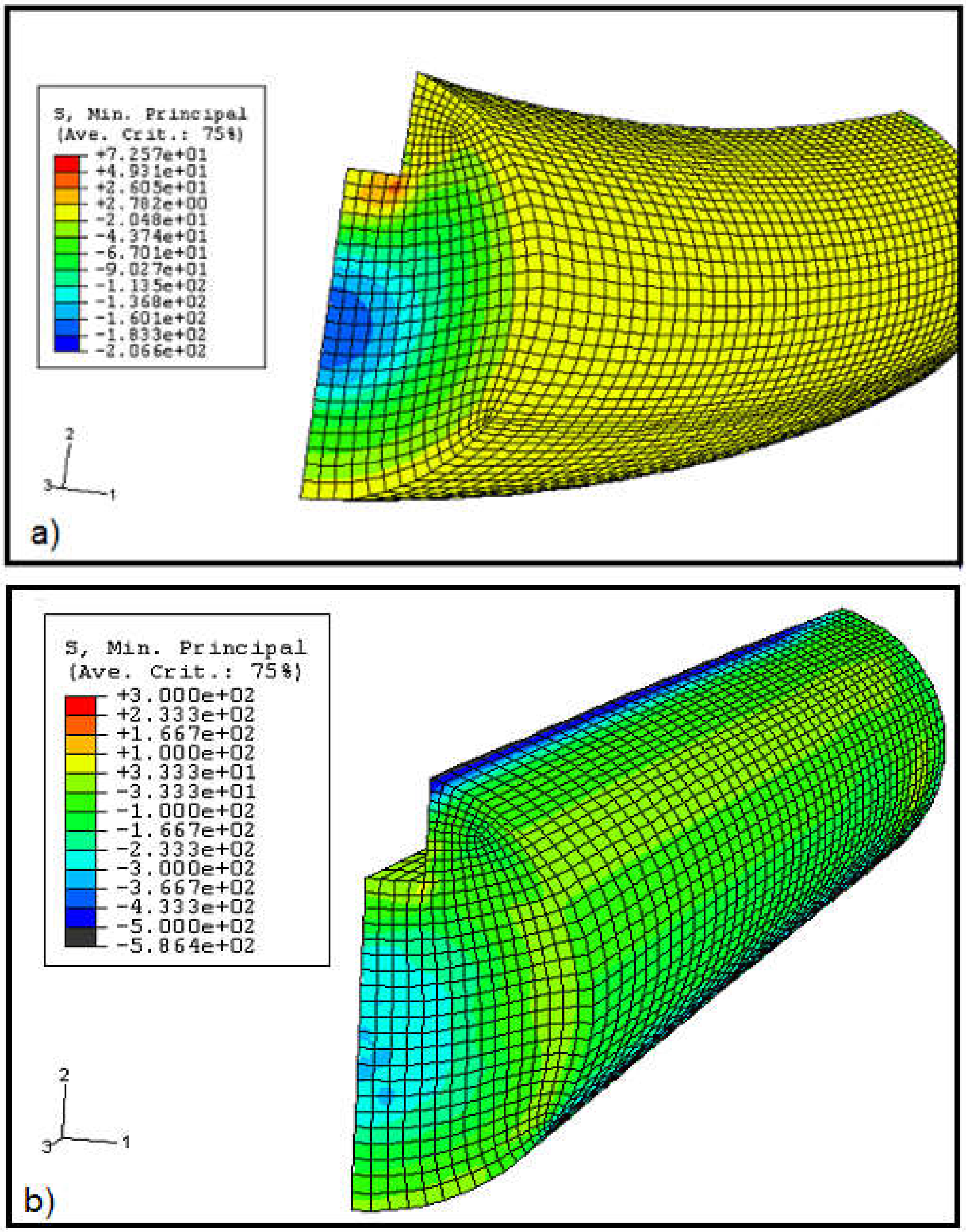

Fig. 2. Minimum principal residual stresses in keyway shaft after quenching in oil (a) and after IQ process (b) according to author (Ferguson, 2013)

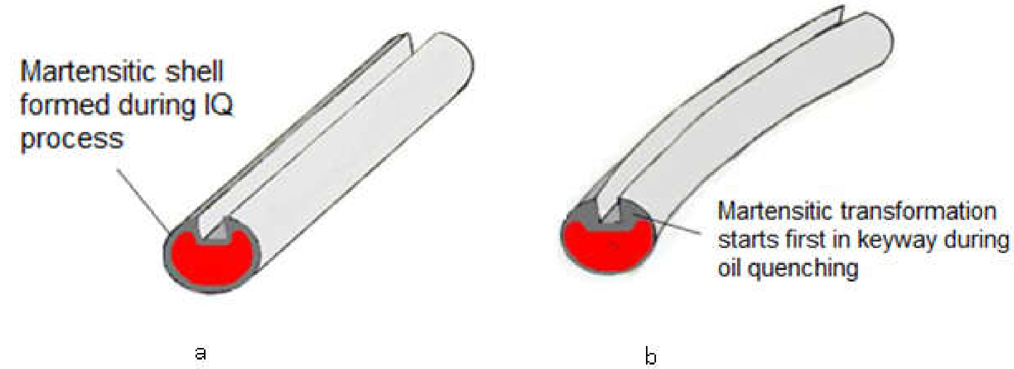

Fig. 3 Martensitic uniform shell formation in keyways during IQ process: *a* – providing minimum distortion due to uniform shell formation during IQ process; *b* – resulting in more distortion due to non-uniform shell formation during oil quenching (Table 1)

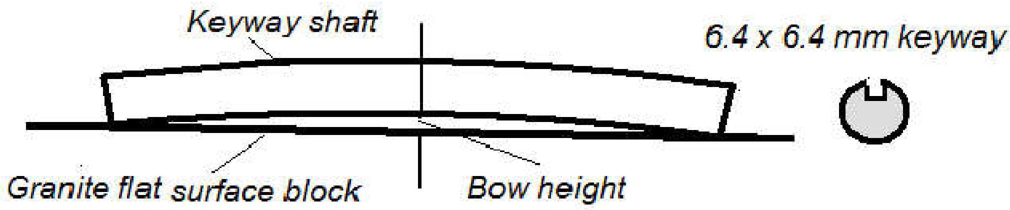

Fig. 4. Keyway shaft distortions (Kobasko, Aronov *et al.*, 2010)

Table 1. Keyway shaft distortion in mm (Kobasko, Aronov, *et.al.*, 2010; Ferguson, 2013)

Single part oil quenching	Batch oil quenching	Single part intensive quenching
0.20 – 0.36	0.25 – 0.51	0.08 – 0.12

Table 2. Influence of the PAG concentration on the duration of film- and nucleate boiling during quenching silver spherical probe 20 mm in diameter (20 oC) (Kobasko and Moskalenko, 1996)

Concentration, %	τ_{fb}, s	τ_{nb}, s	v_{max}, °C/s
Water	7	2	231
PAG, 1%	0.2	2.1	674
3	1.5	2.5	467
10	1.8	4	336
20	2.6	6	251

Table 3. Thermal conductivity of super cooled austenite versus temperature

T, °C	100	200	300	400	500	600	700	800	900
$\lambda, \frac{W}{mK}$	17.5	18	19.6	21	23	24.8	26.3	27.8	29.3
$\bar{\lambda}, \frac{W}{mK}$	17.5	17.75	18.55	19.25	20.25	21.15	21.90	22.65	23.4

Table 4. Thermal diffusivity a of super cooled austenite versus temperature

T, °C	100	200	300	400	500	600	700	800	900
$a \cdot 10^6, \frac{m^2}{S}$	4.55	4.63	4.70	4.95	5.34	5.65	5.83	6.19	6.55
$\bar{a} \cdot 10^6, \frac{m^2}{S}$	4.55	4.59	4.625	4.75	4.95	5.10	5.19	5.37	5.55

Note: $\bar{\lambda}$ and $\bar{a}$ at 500°C (analogously at other temperatures) mean average values for the range of 100°C - 500°C.

Table 5. Comparison of effective HTCs, generalized Biot numbers and effective numbers Kn obtained during quenching in brine, low and high concentration PAG in water and in mineral oils

Quenchant	Effective HTC in W/m²K	Bi_V	Kn
14% NaCl water solution at 20°C, no agitation	2750	1.12	0.57
1% PAG water solution at 25°C	3510	1.35	0.61
Houghton K oil at 43°C agitated with 0.5 m/s.	1215	0.50	0.35
Amolite 22 oil at 43°C agitated with 0.5 m/s.	972	0.40	0.30
Deacon 70 oil at 43°C agitated wit 0.5 m/s.	1070	0.44	0.33

It means (Lykov, 1967) that

$$m = \frac{\ln(650^oC - 35^oC) - \ln(300^oC - 35^oC)}{31s} = 0.027s^{-1}.$$

When

$$Bi_V = \infty, \quad m_\infty = \frac{a}{K} = \frac{5.1\times10^{-6}m^2/s}{105.25\times10^{-6}m^2} = 0.048s^{-1}$$

and $Kn = \frac{0.027s^{-1}}{0.048s^{-1}} = 0.56$.

Thus, intensity of cooling in brine (14% water solution of NaCl) is almost equal to intensity of cooling in 1% water polymer solution. It means that film boiling during quenching in low concentration of water polymer solution didn't take place.

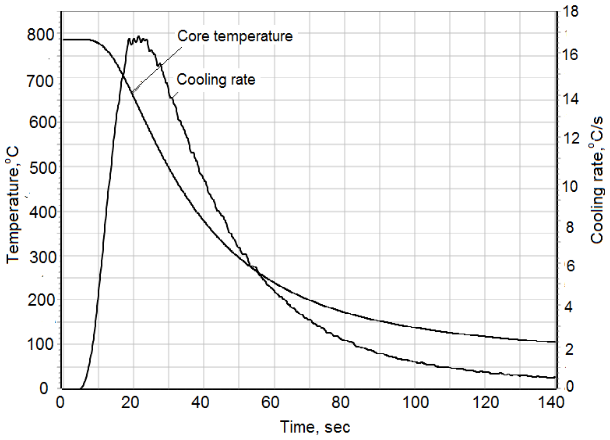

Fig. 5. Core cooling curve and cooling rate versus time during quenching probe 50 mm in diameter and 200 mm long in 1% water polymer (PAG) solution at 35°C

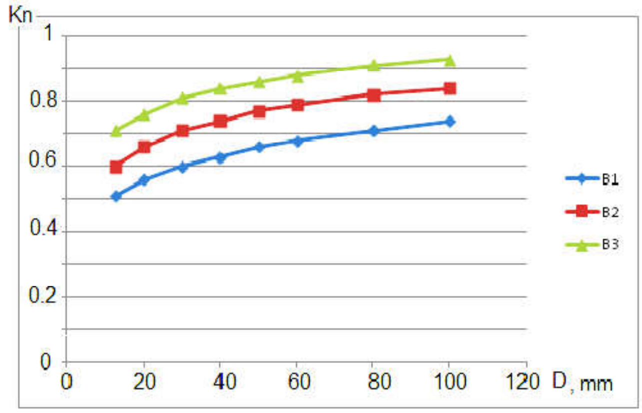

Fig. 6. Effective number Kn versus size of cylinders for different convective heat transfer coefficients: B1 is 750W/ m²K; B2 is 1500 W/ m²K; B3 is 4000 W/ m²K (Kobasko, 2017b)

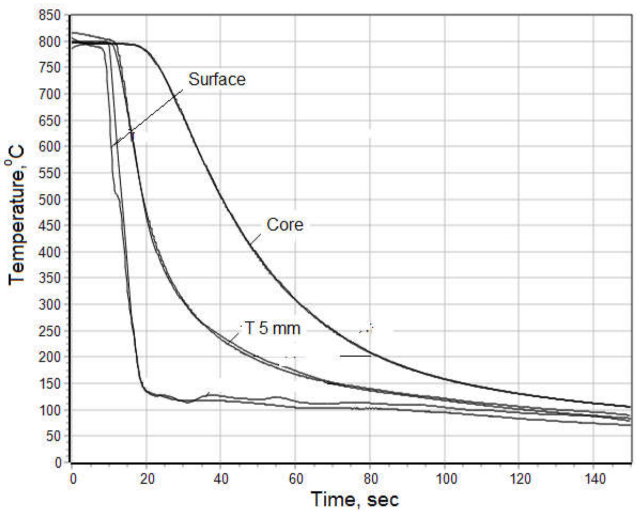

Fig. 7. Cooling curves obtained during quenching cylindrical probe 50x200 мм in 14% water solution of NaCl at 35⁰C: T5 мм is distance 5 mm below surface

Effective HTCs, generalized Biot numbers and effective numbers Kn are shown for comparison in Table 5. Along with water polymer solutions, an addition of small amount of poluisibutelene polymer to mineral oil also eliminates film boiling and decreases distortion (Logvynenko*, et.al*, 2016, Kobasko *et al.,* 2016).

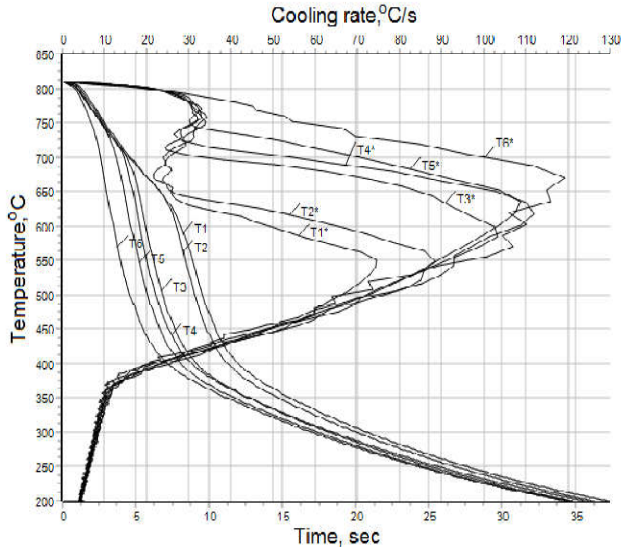

Fig. 8. Cooling curves and cooling rates for solutions of polyisobutylene polymer (PIB 2400) in I – 20A mineral oil at 50°C versus concentration, %wt: 1-0; 2–0.5; 3–1.0; 4-1.5; 5-2.0; 6–3.0 (Logvynenko *et al*. 2016; Kobasko *et al*., 2016)

Authors (Kobasko, 2012; Logvynenko *et al.,* 2017) explained such phenomenon by creating thin insulating layer with additive during quenching in oil. It was shown that the addition of PIB (polyisobutylene polymer) creates an insulating layer on the surface of steel parts during quenching in oils that eliminates film boiling without affecting physical properties of the oil. Insulating layer decreases initial heat flux density which becomes less than critical one of the oil. That is why film boiling during quenching with the PIB additive is absent (see Fig. 8). Authors believe that such approach will allow engineers to reduce effectively the steel parts distortion after quenching in oil too (Kobasko, 2012; Logvynenko *et al.,* 2017). Effect of insulating layer on decreasing initial heat flux density was considered in 2012 in detail by author (Kobasko, 2012). Further this effect was used to eliminate film boiling processes and govern cooling intensity of liquids during quenching in oils and inverse solubility polymers. Note that film boiling in mineral oil I – 20 was eliminated completely by adding to oil 3% PIB 2400 (see Fig. 8).

DISCUSSION

In this paper is shown that 1% water solution of PAG is perfect quenchant for uniform and intensive cooling of different steel parts and tools. Uniform cooling is caused by creation the thin insulating layer. Along, with decreasing initial heat flux density, insulating layer heals micro cracks on the surface of steel parts. All taken together decreases distortion during quenching and eliminates crack formation. The Ukrainian team of leading specialists is working currently on the problem of decreasing corrosion after intensive quenching of machine components and tools in 1% water cold solution of PAG by adding to water PAG solution of special nano- additives. To make technological process robust and cardinally cheaper as compared with conventional quenchants, a software was designed by Intensive Technologies Ltd, Kyiv, Ukraine to govern and interrupt intensive quenching processes. The software is based on DATABASE which includes effective Kondrat'ev numbers Kn for low concentration of PAG in water and PIB oils.

Also, Kondrat'ev form factors K for different forms of machine components and tools are available to to develop cooling recipes during hardening of different materials. Effective Kn number allows combining transient nucleate boiling process with convection mode that simplifies significantly recipes calculations and is used in software IQCalc2. Along with creation insulating surface layers in water PAG solution, this approach is already used in practice during quenching steel parts in mineral oils.. The oils with special additives are prepared and sold by Barkor – Oil Ltd, Kyiv, Ukraine . The JSC"SKF in Ukraine" uses such oils to increase quality of their bearing rings. Authors of the paper believe that designing and governing cooling intensity of liquid quenchants by creation of thin insulating layers on the surface of machine components and tools is currently a new era in heat treating industry. In opinion of authors, the developed approach combined with the hydrodynamics emitters (UA Patent, 2013) can compete with the costly and complicated systems widely used for heat treating processes exploring costly liquid quenchants for hardening machine components and tools. Cost of heat treating processes will be significantly reduced in the nearest future.

Conclusion

1.Instead of water PAG solutions 10%, 20% and 30% can be used 1% polymer PAG solution which creates surface insulating layer that prevents film boiling and makes cooling uniform and intensive. 3% solution of PIB 2400 in mineral oil I -20A eliminates film boiling and provides uniform cooling in that oil that decreases distortion of steel parts too. Effective numbers Kn are used, obtained by painstaking experiments, to simplify computer calculations. The value Kn also serves as an characteristic of a quenchant.

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