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RESEARCH ARTICLE

RESEARCH ON NEW WAYS OF DECREASING DISTORTION OF STEEL PARTS DURING HARDENING IN LIQUID MEDIA

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ABSTRACT

In the paper a new direction in decreasing distortion of steel parts during quenching in liquid media is considered. Its essence consists in creation of thin insulating surface layer during quenching in low concentration of inverse solubility polymers. Simplified calculations of initial heat flux densities, to be compared with the first critical heat flux densities, are provided. Condition for absence of local film boiling is discussed. Accelerated cooling process during hardening should be interrupted prior local insulating layer during batch quenching is dissolved. Such technological process decreases significantly distortion of steel parts during hardening.

INTRODUCTION

It was noticed by investigators that film boiling is absent during quenching in vegetable oils even in still condition (see Fig. 1, curve 1). During quenching in mineral oils film boiling is clearly seen (see Fig. 1, curve 2). However, after severe agitation of mineral oil film boiling was not observed during quenching (Grabov, 2012; Kobasko, 2010). Many hypotheses were proposed to explain such behavior. After numerous of experimental investigations, only one hypothesis was left which explains absence of film boiling by creation of thin insulating layer on the surface of steel parts that reduces initial heat flux density and drops it below the critical one (Kobasko, 2012; Lohvynenko, 2016). As known, inverse solubility polymers dissolved in cold water are excellent solution to create surface polymeric layers. Until now, inverse solubility polymers are used in heat treating industry as the quenchants which contain 10%, 20%, and 35% polymer in water. Author of this paper suggests using low concentration of water polymer solution of inverse solubility to create surface polymeric layers on the surface of steel parts and by this way govern effectively hardening processes. The regular thermal condition theory is used for investigation effect of insulating layers on initial heat flux densities and cooling rate of steel parts during quenching (Lykov, 1967; Kondratjev, 1957 and Kobasko, 2010). It is shown that quenching processes can be governed by comparing initial heat flux densities with the critical heat flux densities and correction of thickness of insulating layer. Detail consideration of such technological processes is provided below.

Critical heat flux densities

As known, frequency of vapor bubble departing and their diameters don't depend on heat flux density. According to Tolubinsky, average departing diameter of bubble for water is 2.5 mm and frequency is 120 departs per second. The higher the heat flux density, the higher number of active bubbles on a unit of heated surface is. At high heat flux density the situation appear, when no more room on the heated surface for bubbles is left. At this point bubbles start to stick to each other creating vapor film which separates from metallic surface. This heat flux is called the first critical heat flux density q_{cr1} (Kutateladze, 1963; Tolubinsky, 1980). During cooling heat flux decreases and film vapor destroys and transient nucleate boiling starts again. The last heat flux is called the second critical heat flux density, q_{cr2}. A ratio $q_{cr2}/q_{cr1} = 0.2$ is the same for all liquid media. Critical heat flux densities are specific characteristic of a liquid which depend on its thermal

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and physical properties. The first critical heat flux densities for oils and water are provided in Table 1.

Table 1. The first critical heat flux densities in MW/m^2 versus temperature (°C) of oils and water.

Liquid	T-re, °C				
	20	40	60	80	100
Oils NZM-120	1.3	1.5	1.75	1.9	2
MS	1.75	1.9	2.2	2.35	2.40
MZM-16	2.5	2.8	3.0	3.3	3.4
Water	5.90	4.72	3.57	2.40	1.27
Water	5.50	4.40	3.3	2.25	1.185

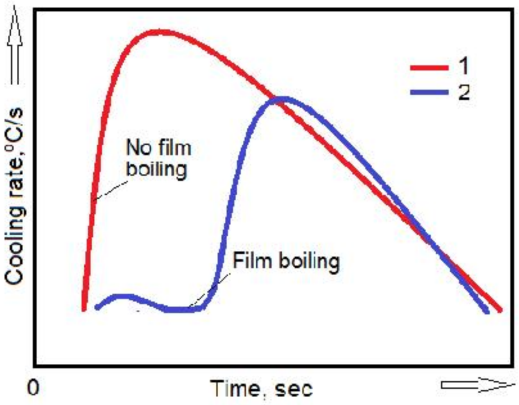


Fig. 1. Cooling rate curves without presence of film boiling process (1) and with the developed film boiling (2) versus time

Critical heat flux densities are used to see whether film boiling during quenching in liquid medium exists or not exists. To be more specific, let's see what is happening during quenching of standard Inconel 600 probe 12.5 mm in diameter and Liscic/Petrofer probe 50 mm in diameter during quenching in mineral oil and water polymer solutions of UCON A (www.astm.org; www.astm.org and Liscic, 2016).

Table 2. Thermal properties (diffusivity and conductivity) of Inconel 600 and stainless steel depending on temperature, °C.

Temperature, °C	Inconel 600		Stainless steel AISI 304	
	$a\times10^{-6}, m^2/s$	$\lambda, W/mK$	$a\times10^{-6}, m^2/s$	$\lambda, W/mK$
100	3.7	14.2	4.55	17.5
200	4.1	16	4.63	18
250	4.3	16.9	4.66	18.8
300	4.5	17.8	4.7	19.6
400	4.8	19.7	4.95	21
500	5.1	21.7	5.34	23
600	5.4	23.7	5.65	24.8
700	5.6	25.9	5.83	26.3
800	5.8	26.3	6.19	27.8
900	6.0	28	6.55	29.3

Table 3. Kondratjev numbers Kn for Amolite 22 mineral oil at 90°C with agitation 0.5 m/s versus diameter of cylindrical specimens made of AISI 4140 steel

Probe diameter, mm	Kn			$\bar{Kn}$
	700 °C	340 °C	205 °C	
12.5	0.167	0.185	0.151	0.17
	0.071	0.037	0.025	
25.4	0.216	0.245	0.211	0.23
	0.210	0.268	0.211	
38.1	0.370	0.310	0.273	0.31
	0.373	0.290	0.267	
50.8	0.392	0.305	0.278	0.32
	0.378	0.305	0.266	

Table 4. Kondratjev numbers Kn for 20% water solution of UCON A at 43°C with agitation 0.5 m/s versus diameter of cylindrical specimens made of AISI 4140 steel

Probe diameter, mm	Kn			$\bar{Kn}$
	700 °C	340 °C	205 °C	
12.5	0.301	0.347	0.265	0.32
	0.326	0.361	0.201	
25.4	0.452	0.463	0.351	0.42
	0.443	0.449	0.378	
38.1	0.497	0.474	0.419	0.46
	0.490	0.471	0.215	
50.8	0.509	0.480	0.470	0.48
	0.509	0.462	0.441	

Initial heat flux density can be approximately evaluated by Eq. (1) (Kobasko *et al.*, 2012) when no insulating surface layer:

$$q=\frac{k_1\lambda Kn}{R}\left(\bar{T}-T_m\right). \qquad \text{…………………}(1)$$

And Eq. (2) when insulating surface layer exists [3]:

$$q=\frac{k_1\lambda Kn}{\left(1+2\frac{\delta}{R}\frac{\lambda}{\lambda_{coat}}\right)R}\left(\bar{T}-T_m\right). \qquad \text{…………………}(2)$$

For a plate, a cylinder, and a sphere, the coefficient k_1 is equal to 2.47, 2.89, and 3.23 respectively. Let's assume that standard Inconel 600 probe is quenched from 850°C in mineral oil at 20°C and 60°C. According to Eq. (1), initial heat flux densities are:

$$q=\frac{2.89\times23W/mK\times0.17}{0.00625m}\left(850^oC-20^oC\right)=1.50W/m^2,$$

$$q=\frac{2.89\times23W/mK\times0.17}{0.00625m}\left(850^oC-60^oC\right)=1.428MW/m^2.$$

Comparing obtained data with Table 1, one can say that film boiling is observed during quenching of standard Inconel 600 probe in MZM -120 oil at 20°C and no film boiling during quenching in hot mineral oils. Initial heat flux density for Liscic/Petrofer probe is almost four times less and it means that probability of film boiling formation during quenching in oils decreases to zero.

$$q=\frac{2.89\times23W/mK\times0.32}{0.050m}\left(850^oC-20^oC\right)=0.353MW/m^2,$$

$$q=\frac{2.89\times23W/mK\times0.17}{0.00625m}\left(850^oC-60^oC\right)=0.335MW/m^2.$$

Similar analysis can be performed for plain water. Inconel 600 probe creates minimum heat flux:

$$q=\frac{2.89\times23W/mK\times1}{0.00625m}\left(850^oC-100^oC\right)=7.97MW/m^2$$

And Liscic/Petrofer probe creates minimum heat flux

$$q = \frac{2.89 \times 23W/mK \times 1}{0.025m}\left(850^{o}C - 100^{o}C\right) = 2MW/m^{2}.$$

During quenching in cold water, standard Inconel 600 probe always produces developed film boiling because initial heat flux density significantly exceeds the first critical heat flux density (see Table 1). During quenching in cold water, Liscic/Petrofer probe can produce developed film boiling too because water around the probe is heated almost to 100^{o}C due to large mass of probe. So, initial heat flux density taking place during quenching in water Liscic/Petrofer probe Liscic , (2016), Should be compared with the -data which are true for 100^{o}C or little bit less (see Table 1). In this condition local film boiling can be formed on the surface of probe which is a reason for big distortion after quenching.

A role of insulating layer in film boiling elimination

During quenching in water polymer solutions of inverse solubility, a polymer layer on the surface of steel parts is formed. The thermal conductivity of this layer is more than 100 times less as compared with thermal conductivity of steel. As known, thermal conductivity of polymeric insulating layer is 0.22 W/mK. Assume that thickness of insulating layer is 25micron or $25 \times 10^{-6} m$. Due to presence of insulating layer, the initial heat flux density decreases. When quenching standard probe in oil, initial heat flux density is

$$q = \frac{2.89 \times 23W/mK \times 0.17}{\left(1 + 2\frac{25 \times 10^{-6}m}{6.25 \times 10^{-3}m} \times \frac{23W/mK}{0.22W/mK}\right) \times 6.25 \times 10^{-6}m}\left(850^{o}C - 20^{o}C\right) = 0.816MW/m^{2}$$

When quenching standard probe in cold water polymer solution of inverse solubility (approximately 1%), initial heat flux density is

$$q = \frac{2.89 \times 23W/mK \times 1}{\left(1 + 2\frac{25 \times 10^{-6}m}{6.25 \times 10^{-3}m} \times \frac{23W/mK}{0.22W/mK}\right) \times 0.00625m}\left(850^{o}C - 100^{o}C\right) = 4.34MW/m^{2}$$

that is less than 5.50 MW/m^{2} for water at 20^{o}C.

Cooling intensity of PAG polymers was evaluated using generalized equation for cooling rate calculation [6, 7]:

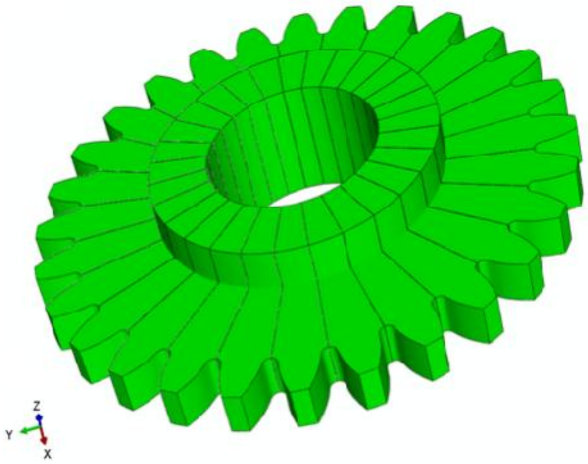


Fig. 2. A spur gear made of AISI 8620 steel which should be carburized and quenched

Peculiarities of hardening steel parts of complex configuration

During hardening steel parts of complex configuration, like gears (see Fig. 2), probability of film boiling, especially local film boiling, is the most higher. Impact of local film boiling on distortion and residual stresses after batch quenching was investigated by DANTE software, which allows receiving also metallurgical data like amount of martensite, bainite, etc. For computer FEM modeling a gear, shown in Fig. 2, was used. The maximum outer diameter of the spur gear shown in Fig. 2 is 63.5 mm. The gear has 28 teeth and has a common configuration that is often used in machine building. The local film boiling appears between teeth of a gear creating a big distortion. Authors (2012) reported on dubble distortrion caused by non – uniform martensitic transformation. Liquid between teeth of gear is rapidly heated almost to boiling point that decreases the first critical heatv flux density of water and as a result local film boiling takes place. As a result, duble distortion takes place. It means that the left tooth 1 (see Fig. 3) bends during quenching to the right side and the right tooth 2 bends to the left side because of delayed martensitic transformation between two teeth due to local film boiling. When quenching gear in oil, overheating a liquid between teeth increases the first critical heat flux density (see Table 1). Probability of local film boiling during quenching in oil is very low. However, gears can be quenched in water solutions of inverse solubility polymers which create surface insutating layer that decreases initial heat flux preventing presence of film boiling.

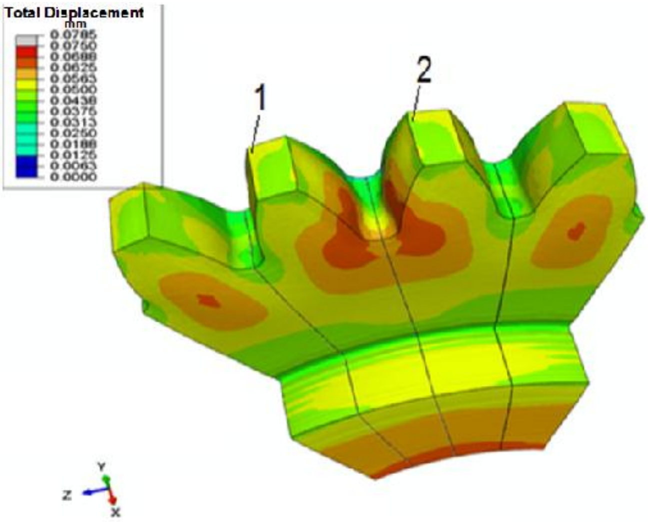


Fig. 3. Total displacement between tooth 1 and tooth 2 where film boiling took place (Source: Kobasko, N.I., Aronov, M.A., Ferguson, B.L., Li, Z., MPC, Vol. 1, No. 1, 2012, page 336)

When performing intensive quenching, three methods should be taken into account:

- Use small amounts of additives, which create insulating surface layer and destroy completely local film boiling.
- Use an optimal concentration of water-salt solution, which provides maximal critical heat flux density.
- Increase the boiling point of a liquid to delay martensite transformation during nucleate boiling process.

Note that insulating layer increases temperature of metallic surface during quenching due to establishing large temperature gradient in insulating layer and small temperature gradient through section of metal. This means that transformation from austenite to martensite during nucleate boiling process can be delayed, especially when quenching high carbon steels. Their cooling rate is calculated as:

$$v=\frac{aKn}{K}\left(T-T_m\right) \qquad (3)$$

$$v=\frac{aKn}{\left(1+2\frac{\text{¢}}{R}\frac{\text{a}}{\text{a}_{coat}}\right)K}\left(T-T_m\right) \qquad (4)$$

Here V is cooling rate in ^{o}C/s; a is average thermal diffusivity of a material in m^2/s; Kn is dimensionless Kondratjev number; K is Konratjev form factor in m^2 (Kobasko, *et. al*., 2012). T is current temperature in ^{o}C; T_m is temperature of quenchant in ^{o}C.. Dimensionless number Kn changes within 0 and 1 when heat transfer coefficient or generalized Biot number changes from 0 to infinity (Kondratjev, 1957).

Table 5. Core cooling rate at different temperatures of cylindrical specimen 12.5 mm in diameter made of AISI 4140 steel when quenching in Amolite 22 oil at 90^{o}C, 20% UCON A water polymer solution and low concentration ($\approx 1\%$) of UCON A at 40^{o}C

Liquid		Cooling ^{o}C/s	Rate,	
	700^{o}C	500^{o}C	400^{o}C	300^{o}C
Amolite 22 oil at 90^{o}C	125	53	38	24
20% UCON A at 43^{o}C	152	93	66	43
1% UCON A at 43^{o}C	270	165	116	73

Small concentration of inverse solubility polymer creates very thin surface layer that cannot radically decrease cooling rate of steel parts, however can change radically situation by decreasing initial heat flux density and such a way can drop it below the first critical heat flux density. In this case, instead of film boiling (300–500 W/m^{2}K) will be nucleate boiling process with real HTC 200,000 W/m^{2}K that provides uniform and intensive cooling. As known, intensification of cooling doesn't affect distortion (Kobasko, *et. al.* 2010) if quenching is uniform. Investigation of effect of insulating layers on intensity of cooling is a new direction in heat treating industry since it makes processes cheaper, more effective and very simple for implementation. However, prior to be widely used in the practice, additional investigations should be performed concerning kinetics of creation and dissolving polymeric surface layers during quenching. Also, thermal properties of polymeric surface layers should be carefully investigated versus temperature and variation of thickness of insulating layers on the surface of steel parts during quenching should be known.

Interrupted intensive quenching process

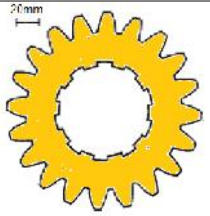
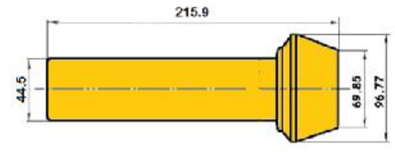
During immersion of heated to 850^{o}C steel part into cold liquid, overheated layer is formed first and surface temperature of part drops almost to the temperature of overheated layer. Assume that during this short time regular thermal condition is already established and average volume temperature is equal to initial temperature T_0. In this case the initial heat flux is calculated approximately by Eq. (1). Table 6 shows initial heat flux density versus diameter of cylinders.

Table 6. Initial heat flux density vs. diameter of cylinder when quenching in cold water

Diameter, mm	12.5	20	30	40	50
Heat flux, MW/m^2	7.96	4.98	3.32	2.49	2

As seen from Table 6, during quenching cylinders of 12.5 mm in diameter in cold water, developed film boiling takes place because initial heat flux density prevails critical heat flux density (see Table 1). During quenching cylindrical specimens 50 mm in diameter, high probability of film boiling or local film boiling exists because bath temperature is overheated due to large mass of 50 mm cylinder. Overheating of water can reduce critical heat flux density to 1.2 MW/m^2 that is less than 2 MW/m^2 (see Table 1 and Table 6).

Table 7. Kondratjev form factors K in m^2 for gear and shaft

Steel part	K, m^2
	$73\times10^{-6}m^2$
	$171\times10^{-6}m^2$

This situation results in big distortion of steel parts. To prevent any film boiling, appropriate agitation of bath should be organized and insulating surface layer should be provided. Along with the effect of local film boiling on increasing distortion, interruption of cooling has a big effect too. The reason is local dissolving of polymeric layer below temperature 74^{o}C during convection. To prevent local dissolving of polymeric layer, one should interrupt cooling when core temperature is 400^{o}C – 500^{o}C. Time interruption is calculated by Eq. (5):

$$\tau=\left[\frac{kBi_V}{2.095+3.867Bi_V}+\ln\left(\frac{T_0-T_m}{T-T_m}\right)\right]\frac{K}{aKn} \qquad (5)$$

For example, gear shown in Table 7, should be cooled in 20% water polymer solution of UCON A at 43^{o}C no more than

$$\text{²}=\left[0.36+\ln\left(\frac{850^{o}C-43^{o}C}{500^{o}C-43^{o}C}\right)\right]\frac{73\times10^{-6}m^2}{5.4m^2/s\times0.37}=34\sec$$

Shaft (see Table 7) should be cooled in 20% water polymer solution of UCON A at 43^{o}C no more than

$$\text{²}=\left[0.48+\ln\left(\frac{850^{o}C-43^{o}C}{400^{o}C-43^{o}C}\right)\right]\frac{171\times10^{-6}m^2}{5.4m^2/s\times0.47}=87\sec$$

All initial data for calculations were taken from Table 1, Table 2, Table 7 and Fig. 4.

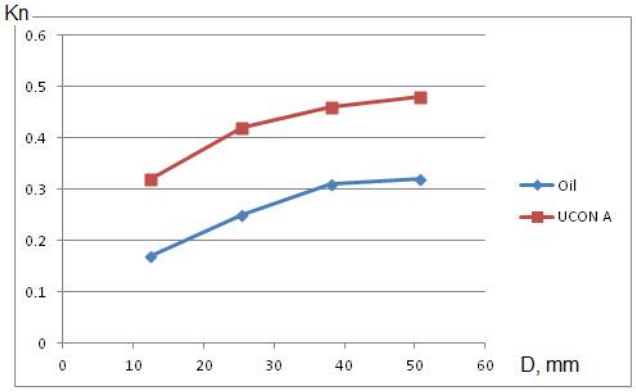


Fig. 4. Effective Kondrtajev numbers Kn for oil Amolite 22 at 90°C and UCON A at 43° versus diameter of cylinders

Similar calculations can be fulfilled for oil and low water polymer concentration.

DISCUSSION

Inverse solubility polymers are excellent solutions used as the quenchants in heat treating industry. However, industry doesn't use 100% of their possibilities. The proposed approach on governing thickness of insulating layer opens several new ways in strengthening materials by heat treating processes. However, to make success, further investigations on mechanism formation of insulating layer, its thermal and physical properties are needed. It can be done by use thermal, video and sonar systems technique. Also, initial heat flux densities should be evaluated using solutions of hyperbolic heat conductivity equation (Buikis, 2009; Bobinska, 2010). Since quenching in water solution of low concentration polymers provides accelerated cooling process, surface residual stresses should be measured to be sure that they are compressive (Rath, 2009; Rath, 2010; Zoch, 2014). Interrupted cooling, along with decreasing distortion, can provide very fine bainitic microstructure at the core of steel parts that significantly increases their service life (Bhadeshia, 2015). There are many achievements in the field of heat treatment and there is experience accumulated during practical use of inverse solubility water polymers (Totten, 1993; Xie; 2004; Totten, 2007). However, low concentration of water polymer solutions of inverse solubility was not investigated in respect to forming surface insulating layers to increase quality of steel parts after quenching. The paper discusses such original approach. Optimizing thickness of surface insulating layer is a new way for decreasing distortion of steel parts after quenching, increasing significantly their service life and reduce cost of technological processes.

Conclusions

- A method for elimination any film boiling during quenching in liquid media is proposed. It consists in creation a micro insulating layer on the surface of steel parts which reduces initial heat flux density and drops it below the first critical heat flux density that prevents any film boiling. Procedure is based on use inverse solubility polymers of optimal concentration in water or special additives which create insulating surface micro layer.
- A simplified method of calculation initial heat flux densities depending on thickness and thermal conductivity of insulating layer is considered.
- During batch quenching in liquid media, for example gears, coolant can be heated locally to its boiling point and create local film boiling. To prevent it, initial heat flux density should be less than the first critical density at boiling point of liquid.
- A local film boiling is a main reason for a big distortion taking place during quenching that is why elimination of the local film boiling minimizes distortion of steel parts after hardening.
- During batch quenching, insulating polymeric surface layer can be locally dissolved in convection zone and result in big distortion too. To reduce significantly distortion during quenching, cooling should be interrupted before insulating layer is dissolved.
- Thermal and physical properties of insulating layer, thickness variation during quenching should be carefully investigated in the nearest future.
- Insulating polymeric layer increases surface temperature of steel parts and can maintain it at the level of martensite start temperature that creates a basis for performing austempering processes in cold liquids.
- Absence of film boiling during quenching the standard Inconel 600 probe in still vegetable oils, in still mineral oil being previously vigorously agitated or processed by DPIE method, is explained by creation insulating layer which drops initial heat flux density below the first critical heat flux density that prevents any film boiling.

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