

DESIGNING OF ADVANCED AND ORIGINAL AUSTEMPERING PROCESSES BASED ON THERMAL SCIENCE AND ENGINEERING PHYSICS APPROACHES

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Abstract

In the paper, a small concentration of inverse solubility polymers in water and other liquid media is recommended to eliminate film boiling by means of reducing initial heat flux density. Quenching steel parts and tools in a small concentration of water solutions under pressure allows performing austempering process just using cold liquids. Its essence consists in coinciding martensite start temperature M_s with the average temperature of self-regulated thermal process during nucleate boiling mode and further immediate transferring steel parts for tempering at the temperature which exceeds value M_s . The new technology increases the service life of austempered workpieces by more than two times, saves alloy elements, is suitable for larger metallic components, improves environmental conditions, since instead of melted salts and alkali, plain water and water salt solutions can be used. The new austempering process can be used in forging shops to obtain super-strengthened materials in order to switch from alloy steel to plain carbon steels. And it can be also widely used for obtaining nano-bainitic structure in plain carbon steels resulting in saving alloy elements and improving mechanical characteristics of materials.

Keywords: film boiling, nucleate boiling, duration, distortion, austempering, pressure, ductility, strength, service life.

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1. Introduction

When quenching steel parts in water or water solutions, local film boiling often can take place resulting in a big distortion and crack formation during hardening. Local film boiling is observed when initial heat flux density q_{in} is comparable with the first critical heat flux density q_{cr1} . When the initial heat flux density exceeds the critical heat flux density q_{cr1} , full film boiling takes place. When the initial heat flux density is less than the critical heat flux density q_{cr1} , there is no film boiling. To optimize quenching processes correctly, one should always compare the initial heat flux density with the first critical heat flux density q_{cr1} . There is a big problem when calculating the initial heat flux density. The matter is that according to the classical parabolic heat conductivity equation initial heat flux density, as known, is infinity. It means that the full film boiling always should be present during immersion of heated to high temperature steel parts into cold liquid. In reality, initial heat flux density is a finite value which can be calculated solving the hyperbolic heat conductivity equation. Initial heat flux density can be significantly reduced if steel part is quenched in cold polymeric water solutions of inverse solubility. In the paper, a new austempering process is proposed which is performed by quenching steel parts in low concentration polymeric water solutions of inverse solubility under pressure until nucleate boiling is finished. In this case, film boiling is completely prevented. After that, steel parts go to immediate tempering. This core technology of the paper is discussed step by step below.

2. Initial heat flux densities evaluation

To make possible initial heat flux density calculation, let's start calculating initial heat flux when the developed transient nucleate boiling process begins. Before it, cold liquid layer around the steel part is heated to boiling point and during that time a surface of steel parts cools drastically since the heat capacity of liquid, for example water, is significantly larger as compared with a steel. Assume that regular thermal process of Kondratjev [1, 2] establishes at the moment of establishing developed transient nucleate boiling process. To be more specific, let's consider an arbitrary shape of a body, for example, very long parallelepiped with a section shown on **Fig. 1** covered by a polymeric layer of thickness δ (**Fig. 1**).

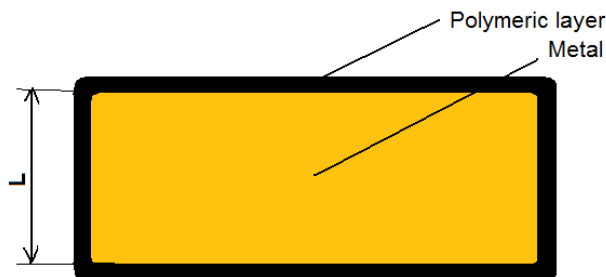


Fig. 1. Section of steel part of height $L = 2l$ covered with the polymeric layer of thickness δ

Taking into account existence of polymeric layer, the author [3] proposed an equation for calculating initial heat flux density for any forms of steel parts which is covered with a thin layer of thickness δ . It can be written as:

$$q_{in} = \frac{\lambda Kn V}{\left(1 + 2 \frac{\delta}{l} \frac{\lambda}{\lambda_{coat}}\right) KS} (\bar{T}_{rg} - T_s), \quad (1)$$

or

$$q_{in} = \frac{k_1 \lambda Kn}{\left(1 + 2 \frac{\delta}{l} \frac{\lambda}{\lambda_{coat}}\right) l} (\bar{T}_{rg} - T_s), \quad (2)$$

$$\frac{V}{KS} = \frac{k_1}{l}; \quad 1 - \frac{L}{2}, \quad (3)$$

where q_{in} is the initial heat flux density in W/m^2 ; k_1 is the coefficient depending on the form of a steel part; λ is the thermal conductivity of steel in W/mK ; λ_{coat} is the thermal conductivity of the coating (polymeric layer); Kn is the dimensionless Kondratjev number; δ is the thickness of the polymeric layer in m; l is the radius or half of the thickness of the plate in m; \bar{T}_{rg} is the average temperature at the moment of establishing a regular thermal process; T_s is the saturation temperature; S is the surface in m^2 ; V is the volume in m^3 ; K is the Kondratjev form factor coefficient in m^2 (**Table 1**).

Using equations (1) and (2), engineers can predict local and full film boiling which are not desirable. Some suitable data for calculating initial heat flux densities are provided in **Table 1**, **Table 2** and **Table 3**.

Table 1

Coefficient k_1 , surface S , volume V and Kondratjev form factor K for different shapes of steel parts

Configuration	k_1	S	V	K
Plate of thickness L	2.47	$2S$	SL	$L^2/9.87$
Cylinder	2.89	$2\pi RZ$	$\pi R^2 Z$	$R^2/5.783$
Cylinder with height $Z=2R$	2.75	$6\pi R^2$	$2\pi R^3$	$R^2/8.25$
Long parallelepiped with sides L_1, L_2 and L_3	2.70	$2L_1 L_2 + 2L_1 L_3 + 2L_2 L_3$	$L_1 L_2 L_3$	$\frac{1}{\frac{\pi^2}{L_1^2} + \frac{\pi^2}{L_2^2} + \frac{\pi^2}{L_3^2}}$
Sphere	3.23	$4\pi R^2$	$4/3\pi R^3$	$R^2/9.87$
Cube	3.29	$6L^2$	L^3	$L^2/29.61$

Table 2

Critical heat flux density q_{cr1} versus water temperature according to Kutateladze and Tolubinsky [4, 5]

$T, ^\circ\text{C}$	$q_{cr1}, \text{MW/m}^2$
5	6.60–7.06
20	5.50–5.90
40	3.33–3.57
80	2.25–2.40
100	1.27–1.185

Table 3

Critical heat flux densities q_{cr1} of salt and alkali water solutions at their optimal concentration in MW/m^2

Quenchant	$q_{cr1}, \text{MW/m}^2$	Authors
12 % water solution of NaCl at 20 °C	11	[6, 7]
5–12 % water solution of NaOH at 20 °C	10–13	[7]
12 % water solution of CaCl ₂ at 20 °C	12	[6]

Table 4

Initial heat flux densities q_{in} in MW/m^2 for cylinders at the moment of establishment of developed transient nucleate boiling process during quenching in water at 20 °C

Diameter, mm	$q_{in}, \text{MW/m}^2$
6	11,9
10	7,11
20	3,56
40	1,78
50	1,42

As seen from **Table 4**, initial heat flux density for cylinders of 20 mm is equal to 3.56 MW/m^2 . Critical heat flux density for water at 20 °C is 5.5 MW/m^2 , i. e. $q_{in} < q_{cr1}$. It means that any kind of film boiling is absent. However, for cylindrical specimen 6 mm in diameter, film boiling takes place since $q_{in} > q_{cr1}$. Film boiling can be eliminated for small specimens if water contains a small amount of inverse solubility polymer which creates a thin insulating layer that reduces initial heat flux. It is known that thermal conductivity of polymers is very low. For example, the thermal conductivity of polystyrene is 0.14 W/mK and thermal conductivity of polytetrafluoroethylene is 0.34 W/mK. Assume that the thermal conductivity of inverse solubility polymer is 0.22 W/mK. Then taking into account that data and using equation (1), one can calculate the initial heat flux density for a small cylinder if the thickness of the layer is known. Assume that it is 0.1 mm. Then using Eq. (2), we have

$$q_{in} = \frac{k_i \lambda K n}{\left(1 + 2 \frac{\delta}{R} \frac{\lambda}{\lambda_{coat}}\right) R} (\bar{T} - T_s) = \frac{2.89 \times 22 \text{ W/mK} \times 0.8}{\left(1 + 2 \frac{0.0001 \text{ m}}{0.003 \text{ m}} \times \frac{22 \text{ W/mK}}{0.22 \text{ W/mK}}\right) \times 0.003 \text{ m}} (800^\circ\text{C} - 100^\circ\text{C}) = 1.54 \frac{\text{MW}}{\text{m}^2}.$$

In this case, the initial heat flux density $q_{in} \ll q_{cr1}$ (**Table 2**, **Table 4**). It means that there is no possibility for the film boiling. Note that during quenching of steel probe in vegetable oils in many cases film boiling is absent completely. It is due to creation insulating layer at the surface of tested probe caused by oxidation of the vegetable oil.

It turned out that inverse solubility polymers can be used to eliminate completely film boiling and by that way intensify quenching processes which decrease significantly distortion and increase the strength of materials. It is a new approach based on engineering physics and thermal science achievements.

3. Quenching under pressure

Pressure increases the first critical heat flux density and the average temperature of self-regulated thermal process (Fig. 2, Fig. 3) [6, 8, 9].

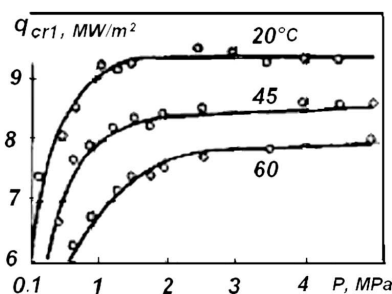


Fig. 2. First critical heat flux density q_{cr1} versus pressure and temperature of water [6, 7]

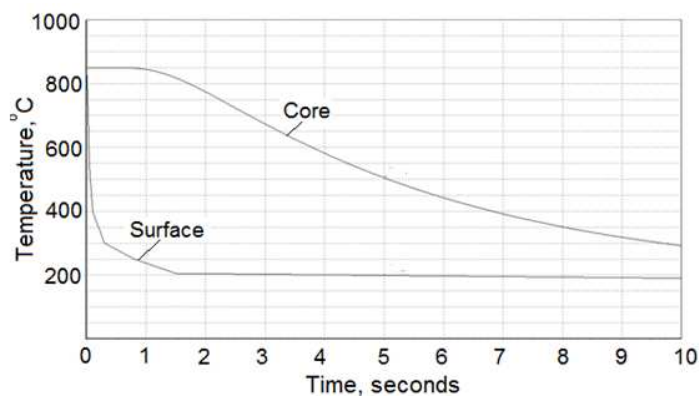


Fig. 3. Surface and core temperature versus time for cylindrical specimen 20 mm in diameter made of AISI 304 steel and quenched from 850 °C in cold water under pressure 1 MPa

Table 5

Water saturation temperature versus pressure

P, MPa	T_s , °C
0,1	99,6
0,2	120,2
0,3	133,5
0,4	143,6
0,5	151,8
0,6	158,8
0,7	165
0,8	170,4
0,9	175,4
1	180
2	212,4

Table 6

Convective HTC_s versus pressure (MPa) and temperature of water

P, MPa	Water 10 °C	Water 20 °C	Water 30 °C
	α_{conv} , W / m ² K	α_{conv} , W / m ² K	α_{conv} , W / m ² K
0,1	548	640	1015
0,2	586	690	1105
0,3	609	719	1156
0,4	625	740	1196
0,5	638	756	1223
0,6	648	769	1246
0,7	657	780	1265
0,8	664	790	1280
0,9	670	798	1295
1,0	677	806	1310

As one can see from **Fig. 3**, the surface temperature of cylindrical specimen drops within 1.5 sec almost to boiling point of water (**Table 5**) and then maintains at that level 9 seconds until convection starts. The higher the convective heat transfer coefficient (HTC) is, the shorter of self- regulated thermal process is and quicker convection starts. Convective HTC's are provided in **Table 6**. However, during nucleate boiling process surface temperature reduces very slowly (**Table 7**). Instead of that, the intensity of the transient nucleate boiling process is very high. HTC's during nucleate boiling reach values 200 KW/m²K and more (**Fig. 4**).

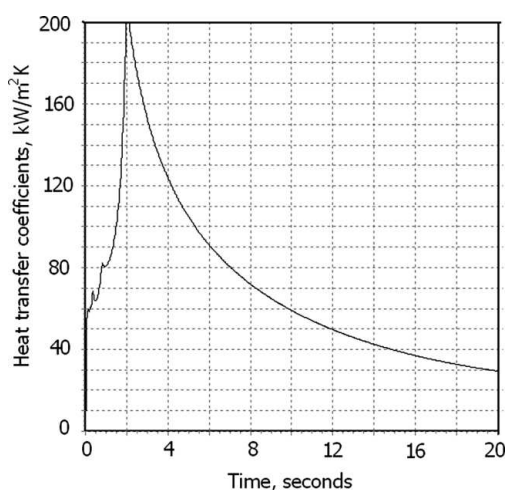


Fig. 4. The real heat transfer coefficients versus time for a sphere of 38.1 mm in diameter quenched from 875 °C in a 5 % aqueous NaOH solution at 20 °C [7]

Table 7

Initial and ending temperature of the full transient nucleate boiling process and its duration versus pressure (MPa) for an infinite cylinder of 20 mm in diameter when quenching in water at 20 °C

Pressure, MPa	Initial temperature, °C	Ending temperature, °C	Duration of transient nucleate boiling process, seconds
0.1	126	108	14
0.4	169	155	12
0.7	190	175	11
1.0	205	190	10.5

Duration of transient nucleate boiling can be calculated using equation (4) [10–12]

$$\tau_{nb} = \bar{\Omega} k_F \frac{D^2}{a}. \quad (4)$$

Here τ_{nb} is the duration of the transient nucleate boiling process in seconds; $\bar{\Omega}$ is characteristic of a quenchant when the austenitizing temperature is fixed at 850 °C; k_F is coefficient responsible for a geometrical form of a steel part; D is the size (thickness or diameter) in m; a is the thermal diffusivity of a material in m²/s [13].

It should be underlined that real heat transfer coefficients (HTCs) provided in **Fig. 4** are calculated as a ratio $\alpha = \frac{q}{T_{sf} - T_s}$. Often engineers use effective HTCs for calculating nucleate boiling processes which is a ratio $\alpha = \frac{q}{T_{sf} - T_m}$. Here α is HTC; q is the heat flux density; T_{sf} is the surface temperature; T_s is the saturation temperature; T_m is the medium temperature. Boiling process is a function of overheat $T_{sf} - T_s$ and doesn't depend significantly on underheat $T_s - T_m$. That is why, temperature fields during nucleate boiling processes should be calculated using real HTCs.

4. Austempering process performed in low concentration of polymers under pressure

Taking into account the absence of film boiling in cold water polymeric solutions of low concentration and possibility of increasing the average temperature of the self – regulated thermal process by adjusting pressure, one can perform the austempering process using cold liquids. The procedure is as follows:

1. A water polymeric solution of low concentration (up to 2 %) is prepared which is used as a quenchant in the apparatus where cooling from high temperature (850 °C) takes place.
2. A sample made of AISI steel W1 with martensite start temperature 200 °C, for example cylinder of 20 mm in diameter, is immersed into 2 % water polymeric solution (2 %) of inverse solubility under pressure 1 MPa and is kept in solution for 10 seconds (**Fig. 3** and use Eq. (4)).
3. The sample is quickly taken out of solution and put immediately into furnace for tempering at 200 °C. Duration of tempering is 2 hours.

The technology requires special installation similar to vacuum furnaces. However, for high carbon steels and irons with the martensite start temperature of 100 °C, conventional technological lines can be used for performing austempering at normal atmospheric pressure.

5. Discussion

Self – regulated thermal process, discovered by the author, was used for developing intensive technologies called IQ-2 and intensive austempering processes [14–20]. The new technologies were developed and patented in Ukraine and are used in US [7, 21]. Especially, excellent results are obtained in the heat treating industry for rolls made of Ductile Irons [16, 21, 22]. The proposed technologies are improved by creating an insulating layer on the surface of quenched steel parts that decreases initial heat flux density. It eliminates local and full film boiling completely during hardening.

Mathematicians Prof. Buikis, Prof. Guseynov and their colleagues paid serious attention to solving hyperbolic heat conductivity equations with the appropriate boundary conditions responsible for transient nucleate boiling processes [23–27]. Now, engineers and metallurgists are looking forward to obtaining practical data, based on the hyperbolic equation, to be easily used for recipes development for different configuration of steel parts during quenching. Especially, initial heat flux densities are important since they allow to predict possible local film boiling. Local film boiling is the main reason for big distortion. Bearing industry spends a lot of money (millions) to reduce distortion of bearing rings. Proposed engineering physics approach, discussed in the paper, can help minimize distortion of different steel parts after quenching. Developed new austempering processes can reduce radically distortion of steel parts after hardening and increase significantly strength of materials [28].

6. Conclusions

1. For the first time, it is recommended to use small concentrations of inverse solubility polymers in water and other liquid media to eliminate any kind of film boiling by means of reducing initial heat flux density.

2. It is proposed to quench steel parts in small-concentration water solutions under pressure where the advanced austempering process can be performed. The new technology increases the service life of austempered steel parts, saves alloy elements, is suitable for larger steel parts, improves environmental conditions since instead of melted salts and alkali plain water and water salt solutions can be used.

3. The new austempering process can be used in forging shops to obtain super-strengthened materials in order to switch from alloy steel to plain carbon steels. And it can be also widely used for obtaining nano - bainitic structure in plain carbon steels resulting in saving alloy elements and improvement of mechanical characteristics [28].

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