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Three Principles of Transient Nucleate Boiling to be Used for Designing Super Strong Bainite

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ABSTRACT

The three principles of transient nucleate boiling are considered which are successfully used for recipes development and software designing. These principles were formulated based on accurate experiments of French, modified law of Fourier and many accurate experiments of the author of the current paper. Based on modified law of Fourier and existence of a double electrical boundary layer, it is stated that film boiling during quenching in cold electrolytes is completely absent and the main modes are transient nucleate boiling and convection. In many cases engineers use average heat transfer coefficient (HTC) for both nucleate boiling and convection that works perfectly when convective HTC is comparable with HTC of nucleate boiling process. But such approach generates big errors in cooling rate and time calculations when HTCs during boiling and convection differ many times between each other. The problem is solved easily when using the third principle to calculate core temperature at the end of nucleate boiling. In this case, core temperature at the end of transient nucleate boiling is initial temperature for convection and the problem is solved. This approach is discussed in the paper to be used for recipes development and appropriate software design.

Keywords: principles, cooling time, recipes, error, nucleate boiling, convection, joined process.

INTRODUCTION

It has been discussed by author [1] the three principles of transient nucleate boiling related to quench process in cold fluids**.** The first principle says that for a given condition of cooling in cold fluid, the duration of establishing developed nucleate boiling is the same, independently of the form and size of the steel part. It can be explained by an extremely high heat exchange during shock boiling which lasts for a very short time, thereby creating a huge temperature gradient in a very thin surface layer. Core temperature during this time is not affected by shock boiling at all and cooling process at the very beginning is considered as a cooling of semi-infinity domain. It is happening because the speed of heat distribution is a finite value and during this short time of cooling, the heat does not reach layers located at the core of steel parts. The second principle says that the surface temperature of a steel part, beginning from the start of full nucleate boiling establishing, maintains at the level of boiling point of the fluid insignificantly differing from it. The so-called self-regulated thermal process (SRTP) is established. The initial temperature of self-regulated thermal process T_I and its end temperature T_{II} are evaluated by known and simple equations. The third principle says that duration of transient nucleate boiling is directly proportional to the squared thickness of steel part, inversely proportional to the thermal diffusivity of material, depends on the form of steel part, and convective Biot number Bi. The generalized fundamental equation for such statement is mathematically formulated and successfully used in practice. If film boiling during quenching is absent, it is possible to calculate temperature field in quenched steel part using the first type of a boundary condition without performing experiments. Thus, the first type of boundary condition appears from the three principles of transient nucleate boiling process. It allows temperature field calculation and evaluates core temperature at the end of transient nucleate boiling process. This simple approach is discussed below.

BOUNDARY CONDITION DESIGN DURING TRANSIENT NUCLEATE BOILING

The boundary condition design is a three-step approach. The first step is designing the surface temperature within initial heating temperature T_0 and initial temperature of transient nucleate boiling process T_I. According to the first principle, surface curve between T_0 and T_I is similar to already existing experimental curves recorded by French (see Table 1) [2].

Table 1: Time required for the surface of steel samples to cool to different temperatures when quenched from 875°C in 5 % NaOH-water solution at 20°C and moving at 3 feet per second (0.914 m/s), according to French [2]

D, mm	Time, Sec								
	700°C	600°C	500°C	400°C	300°C	250°C	200	150°C	125°C
12.7	0.028	0.042	0.058	0.071	0.11	0.15	0.26	0.60	1.0
25.4	0.028	0.04	0.048	0.064	0.14	0.21	0.34	0.71	1.2
50	0.025	0.04	0.06	0.065	0.08	0.10	0.29	0.65	1.4
120	0.043	0.066	0.09	0.12	0.17	0.21	0.29	0.95	1.5

The initial temperature of transient nucleate boiling is evaluated by equation (1) [3]:

$$T_I = T_S + \vartheta_I, {}^{o}C \tag{1}$$

Where

$$\vartheta_I = 0.293 \cdot \left[\frac{2\lambda\left(\vartheta_o - \vartheta_I\right)}{R} \right]^{0.3}$$

The temperature T_{II} at the end of transient nucleate boiling is evaluated by equation (2):

$$T_{II} = T_S + \vartheta_{II}, {}^{o}C \tag{2}$$

Where

$$\vartheta_{II} = 0.293 \cdot \left[\alpha_{conv}\left(\vartheta_{II} + \vartheta_{uh} \right) \right]^{0.3}$$

The third type of boundary condition for transient nucleate boiling process is written as [3, 4]):

$$\left[\frac{\partial T}{\partial r} + \frac{\beta^m}{\lambda}\left(T - T_s\right)^m \right]_{r=R} = 0 \tag{3}$$

Here $3 \le m \le \frac{10}{3}$; $-\lambda \frac{\partial T}{\partial r} = \beta^m (T - T_s)^m$; $q = \beta^m (T - T_s)^m$.

It means that heat flux density is very strong dependance from the temperature difference ($T - T_S$) and is written as:

$$q \propto 120(T - T_s)^{10/3} \tag{4'}$$

The value $\frac{1}{\beta} = 0.293$ is true at normal (atmospheric) pressure and is evaluated from the dimensionless equation of Tolubinsky [4], where $\beta^m = 120$.

The duration of transient nucleate boiling process is calculated using generalized equation (5):

$$\tau_{nb} = \Omega k_F \frac{D^2}{a} \tag{5}$$

Here τ_{nb} is duration of transient nucleate boiling measured in seconds; Ω is dimensionless parameter depending on convective HTC; k_F is dimensionless form coefficient; D is thickness of steel part in m; a is thermal diffusivity of material in m^2s^{-1}. Parameter $\overline{\Omega}$ as a function of convective Biot number is discussed in [1].

Thus, based on three principles of transient nucleate boiling, the surface temperature was design as shown in Fig. 1. The core temperature is a results of numerical calculation using surface curve as the first type of the boundary condition.

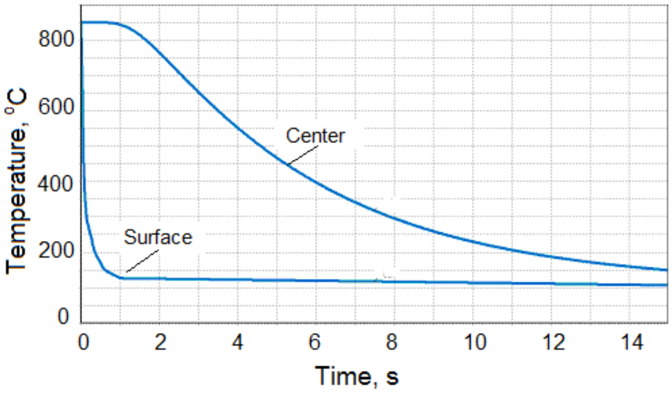

Fig 1: Cooling curves versus time when quenching cylindrical probe 20 mm in diameter in water solution at 20°C with agitation generating 500 W/m²K. Core temperature at the end of transient nucleate boiling process is 150°C (see Table 2).

Calculations show that Kondratiev number Kn [5, 6] is linear function versus time (see Fig, 2).

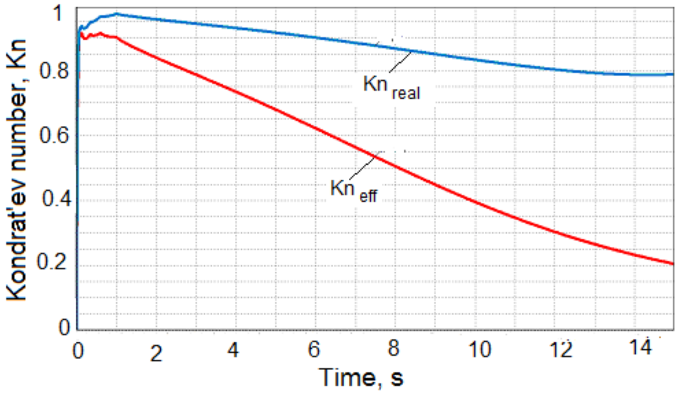

Fig 2: Kondratiev numbers Kn versus time when quenching cylindrical probe 20 mm in diameter in water solution at 20°C withщге agitation.

Similar surface curve designing for cylindrical specimen was used when convective HTC was 15000 W/m²K. In this case cooling curves and Kondratiev numbers Kn are presented by Fig.3 and Fig. 4.

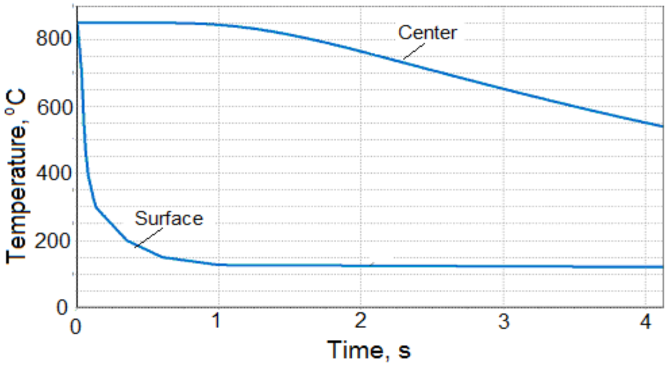

Fig 3: Cooling curves versus time when quenching cylindrical probe 20 mm in diameter in water solution at 20°C with agitation generating convective heat transfer coefficient 15000 W/m²K. Core temperature at the end of transient nucleate boiling process is 545°C (see Table 2).

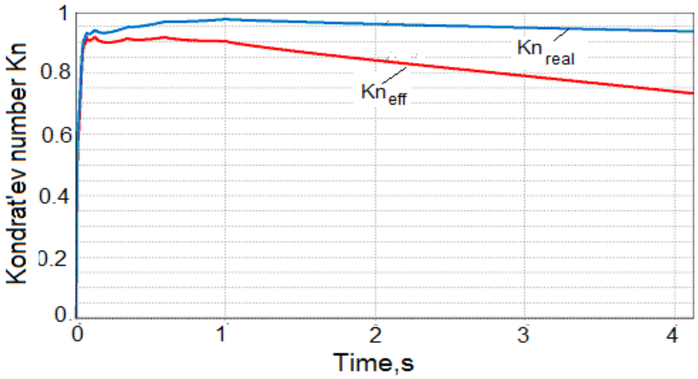

Fig 4: Kondratiev number Kn versus time when quenching cylindrical probe 20 mm in diameter in water solution at 20°C with agitation generating сщтмусешму руфеииекфтіаук сщуаашсшуте 15000 W/m²K.

As seen from Fig. 1 and Fig. 3, agitation decreases essentially duration of transient nucleate boiling process that is a shortcoming for the possibility of optimizing bainitic transformations. Strong agitation with convective heat transfer coefficient 15000 W/m^{2}K decreases transient nucleate boiling (so called self- regulated thermal process} from 15 sends to 4.2 s, almost 3.6 times. This is a shortcoming for obtaining pure bainite to create advantages from bainitic transformations. The self- regulated thermal process is used to prevent martensitic transformations in order to get fine or even nano- bainitic microstructure. For this purpose, duration of transient nucleate boiling (self-regulated thermal process) should be as long as possible. Table 2 provides information needed for calculating the duration transient nucleate boiling versus convective HTCs.

Table 2: Parameters used for designing the first type of a boundary condition for cylindrical specimen 20 mm diameter versus convective heat transfer coefficient.

$\alpha, W/m^2K$	$\vartheta_I, ^oC$	$\vartheta_{II}, ^oC$	τ_{nb}, s	Ω	$T_c, ^oC$	Fo
500	27	7.22	15	4.71	150	0.81
1000	27	9	12.8	4	174	0.69
2000	27	11,1	10.7	3.33	212	0.58
3000	27	12,6	9.38	2.93	249	0.51
4000	27	13.8	8,42	2.63	280	0.45
5000	27	14.8	7.72	2.41	308	0.42
10000	27	18.4	5,68	1.71	414	0.31
15000	27	21	4.13	1.29	543	0.22

COUPLING NUCLEATE BOILING WITH CONVECTION

Exploring three principles of transient nucleate boiling, it is possible to evaluate core temperature at the end of self-regulated thermal process. For this purpose, first two principles are used to design surface cooling curve and the third principle is used to evaluate duration of transient nucleate boiling. Next, the temperature field is calculated using analytical or numerical calculation. There are many simple and fundamental well-known codes for this purpose [7]. The coupled equation (6) is written as:

$$\tau = \tau_{nb} + \frac{K}{aKn} \ln \frac{T_c - T_m}{T - T_m} \tag{6}$$

Equation (7) is used for convection where irregular stage is absent because at the end of nucleate boiling it is already in regular condition;

$$\tau = \left[\frac{kBi_V}{2.095 + 3.783 Bi_V} + \ln \frac{T_0 - T_m}{T - T_m} \right] \frac{K}{aKn} \tag{7}$$

Where k = 0 when irregular thermal process is absent k = 1 for plate forms, k = 2 for cylindrical forms and k = 3 for spherical forms. According to Ref. [5, 6]:

$$Bi_V = \frac{\alpha}{\lambda} K \frac{S}{V} \tag{8}$$

For plate forms Kn is evaluated by Eq, 9 (see Table 3)):

$$Kn = \frac{Bi_V}{\left(Bi_V^{\,2} + 1.437 Bi_V + 1\right)^{0.5}} \tag{9}$$

Equation (5) contains duration of self – regulated thermal process τ_{nb} which is a basis for monitoring bainitic transformations to obtain super strengthened fine or nano – bainite [8, 9, and 10]. It should be noted here that due to self – regulated thermal it is possible to perform high temperature and low temperature thermomechanical treatment resulting in super strengthened bainite. Such possibilities are investigated deeply enough for martensitic transformations [11, 12, and 13], but not yet for bainitic transformations. The values $\frac{Bi_V}{2.095 + 3.873 Bi_V}$ and Kn as a function of generalized Biot number Biv are presented in Table 3;

Table 3: Correlation between Kn and Biv [7].

Bi_V	$\frac{Bi_V}{2.095 + 3.873 Bi_V}$	Kn
0	0.000	0.00
0.1	0.040	0.09
0.6	0.136	0.40
1.0	0.167	0.54
2.0	0.203	0.71
3.0	0.219	0.79
4.0	0.227	0.84
5.0	0.233	0.87
6.0	0.237	0.89
8.0	0.240	0.91
10	0.240	0.93
∞	0.240	1.0

Here k = 1, 2, 3 for plate, cylinder and spherical like form correspondently; τ is cooling time in seconds; Bi_V is generalized Biot number; T_0 is initial austenitizing temperature; T_m is bath temperature; T is current temperature; a is thermal diffusivity of material in m^2/s; K is Kondratiev form factor in m^2..

Creation of the first type of the boundary condition allows investigate properly temperature fields and current, and residual stress distribution during quenching steel parts focusing on martensitic and bainitic transformations [14, 15, and 16]. The self- regulated thermal process is related to monitoring bainitic transformations while direct thermal convection is related to extremely intensive cooling used for quenching semi-axles made of optimal hardenability steels

[17,18]. Intensive quenching results in creation surface compression residual stresses and super strengthening of steel in the surface layers of quenched product. This effect is observed even during through hardened probes [19]. The maximal surface compressive residual stresses occur when intensive cooling is interrupted at proper time forming optimal hardened surface layer. In the core can be formed fine bainite if after interruption product goes for tempering and bainitic transformations. Cooling time is calculated using generalized equation (7). Table 4 provides necessary values for such calculations.

Table 4: Kondratiev coefficient K, S/V, K(S/V) depending on different shapes and sizes of solid bodies [3]

Shape	**Kondratiev coefficient K, m^2**	$\frac{S}{V}$, **m^{-1}**	$K\frac{S}{V}$, **m**
Infinite plate of thickness L	$\frac{L^2}{\pi^2}$	$\frac{2}{L}$	$\frac{2L}{\pi^2}$
Infinite cylinder of radius R	$\frac{R^2}{5.784}$	$\frac{2}{R}$	0.346 R
Infinite square bar with sides of L	$\frac{L^2}{2\pi^2}$	$\frac{4}{L}$	$\frac{2L}{\pi^2}$
Cylinder of radius R and height Z	$\frac{1}{\frac{5.784}{R^2}+\frac{\pi^2}{Z^2}}$	$\left(\frac{2}{R}+\frac{2}{Z}\right)$	$\frac{2RZ(R+Z)}{5.784Z^2+\pi^2R^2}$
Plate with sides L$_1$, L$_2$, L$_3$	$\frac{1}{\pi^2\left(\frac{1}{L_1^2}+\frac{1}{L_2^2}+\frac{1}{L_3^2}\right)}$	$\frac{2(L_1L_2+L_1L_3+L_2L_3)}{L_1L_2L_3}$	$\frac{2(L_1L_2+L_1L_3+L_2L_3)L_1L_2L_3}{\pi^2(L_1^2L_2^2+L_1^2L_3^2+L_2^2L_3^2)}$
Sphere	$\frac{R^2}{\pi^2}$	$\frac{3}{R}$	$0.304R$

To evaluate the duration of transient nucleate process, convective HTC$_s$ are required which are presented in Table 5 depending on temperature of water and pressure in quench tank.

Table 5: Convective HTCS versus pressure (MPa) and temperature of water

P, Mpa	**Water 10^{o}C** $\alpha_{conv}, W/m^2K$	**Water 20^{o}C** $\alpha_{conv}, W/m^2K$	**Water 30^{o}C** $\alpha_{conv}, W/m^2K$
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

Using all of these available data, the duration of transient nucleate boiling, the core temperature at the end of nucleate boiling process and the value of $\overline{\Omega}$ were calculated (see Table 6).

Table 6: Core temperature at the end of transient nucleate boiling process vs diameter of cylindrical specimen during quenching in electrolytes (is true for HTC equal to 640 W/m²K).

$Dia., mm$	K, $\times 10^{-6} m^2$	$\overline{\Omega}$	τ_{nb} ,s	T_{core} at the end of NB, °C
12.5	6.755	4.90	6	147
20	17.3	4.45	14.3	157
30	38.91	4.07	29.3	163
50	108.07	3.56	71.2	198
80	276.67	3.11	159.4	207
100	432.3	2.91	233	238
125	675.74	2.70	338	264

As one can see from Table 6, core temperature at the end of transient nucleate boiling process is below the martensite start temperature M_s. if medium carbon steel in liquid medium is quenched. It means that there are possibilities to govern quenching processes by adjusting saturation temperature T_s of coolant, for example, by adjusting the pressure. Now, having such useful information, let's consider several specific examples of quenching process to see behavior of initial heat flux densities and Kondratiev numbers Kn since they are every time used for recipes development and quench equipment design. Number one priority here is initial heat flux density which is compared with the first critical heat flux density to predict absence or presence of film boiling process. When film boiling is absent, the duration of transient nucleate boiling and core temperature at the end of boiling vs pressure, are presented in Table 7.

Table 7: Core temperature at the end of nucleate boiling versus pressure when quenching cylindrical specimen 20 mm diameter in cold water

P, MPa	**T_s,°C**	$\alpha, W/m^2K$	**T_I,°C**	**T_{II},°C**	**τ_{nb} ,s**	**T_c, °C**
0.1	100	640	126.5	108	14	158
0.5	151.8	756	178	162	12.5	212
0.7	165	780	191	175	12.3	240
1.0	180	806	206	190	12	252

Table 7 show possibility for performing low temperature thermomechanical treatment to obtain super strengthened bainite (see Fig. 5).

TOOL FOR BAINITIC TRANSFORMATION MONITORING

A long time, it was impossible to produce in mass production the ultra-strong bainitic microstructures and distribute them globally across large enterprises. This is because bainite is hidden between pearlite and martensitic transformations, and to access it, quenching must be performed very slowly in hot oils, molten salts, and even molten metals. It's clear that such slow cooling technology, which requires use of high alloy steel, can't find widespread application. Bainite is a curiosity that amazes scientists and engineers with its extraordinary strength and ductility. I was fortunate to attend a wonderful lecture delivered by Professor Bhadeshia [9, 10], who amazed the audience with bainite's unusual properties. I approached him and expressed my admiration for bainite's potential. He told me that problem is slow cooling which should be overtaken. Since then, I've pondered for a long time how to overcome these obstacles and open up a new avenue for bainitic transformations. Consider, for example, the results presented in Table 7. From this Table 7, it's clear that under conditions of intensive cooling, the surface temperature of the hardened sample can be maintained within 100 ˚C and 200 ˚C. This coincides with the onset of martensitic transformations M_S , thereby completely preventing martensitic transformations in favor of bainite. Moreover, quenching in liquid media under pressure allows for high-temperature thermomechanical processing and low-temperature processing to produce high strengthened bainite. Thermomechanical treatment enhances additional advantages of bainite over martensite. Based on these facts, it is advisable to establish research centers on different continents for a more thorough study of bainitic transformations and the creation of equipment for the mass use of this new approach in industry. This will lead to savings of materials and make the technological process popular due to mass-production. Instead of powerful pumps and electromotors with rotating propellers for agitation quenchants in quench tanks, it will be used special additives to water solutions in order to eliminate any film boiling during quenching caused by essential increase the first critical heat flux densities [21, 22]. Also, hydrodynamics emitters creating resonance effect will be widely used [23]. Theory on different kinds of resonance effects one can find in Ref. [24, 25]. Transient nucleate boiling provides intensive and uniform cooling if any film boiling is absent.

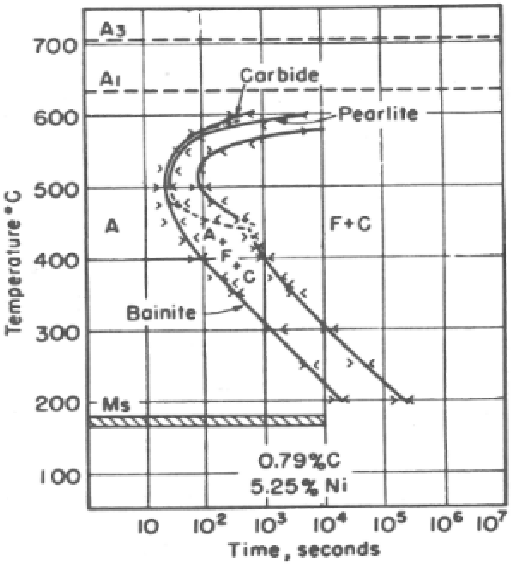

Fig 5: Nickel steels isothermal diagrams depending on content carbon in steel containing 0.79 C, 0.23 Mn, 0.22 Si, 5.25 Ni, 0.04 Cr, 0.01 Mo, 0.006 P, 0.015S [20].

As can be seen from Fig. 5, bainitic transformations begin at a temperature of 350 ˚ C. Current technology involves slow cooling of the hardened part from the initial temperature T_0 to 350˚C without visible temperature gradient inside to avoid martensitic transformations. With intensive cooling, the surface temperature of the part instantly drops to the boiling point of the quenching medium, resulting in the formation of martensite on the surface of the steel part, nullifying the possibility of bainitic microstructure formation. These significant disadvantages are easily eliminated by using three principles of quench cooling, formulated and tested by the author. According to the first principle, the surface temperature of the steel part drops very quickly to the boiling point of the fluid and the cooling curves are approximately the same for different shapes and sizes, if there is no film boiling. This means that quenching in a liquid medium under pressure 0.7 MPa prevents the formation of martensite (see Fig. 5 above). According to second and third principles of transient boiling, the surface temperature of quenched steel part maintains at the level of martensite start temperature Ms and its duration directly proportional to squared thickness of part and inversely proportional to thermal diffusivity of material.

CONCLUSIONS

1. Based on two generalized equations, developed by author, an algorithm for calculating the coupled cooling time is proposed. It is used for developing hardening recipes and new technologies including bainitic transformations.
2. The development utilizes the theory of regular thermal conditions, which considers hardening steel parts of arbitrary shape.
3. A new approach has been proposed that couples transient nucleate boiling with convective cooling, where end temperature of nucleate boiling is an initial temperature for convective heat transfer mode. This provides much more accurate calculations.
4. The end core temperature of transient nucleate boiling is calculated using three principles of quench process when film boiling is absent.
5. The increased calculation accuracy is essential for developing correct quench cooling recipes focused on production of high-strength and more ductile bainite instead of brittle martensite.
6. The first version of the quench cooling method uses an average heat transfer coefficient for full quenching, is satisfactory for intensive cooling, where the heat transfer coefficients for both transient nucleate boiling and single-phase convection that works perfectly for intensive quenching (direct convection [3]). When convective heat transfer coefficient is an order of magnitude lower than for nucleate boiling, averaging is unacceptable.
7. Based on three principles of steel parts quenching, where film boiling is absent, a more accurate calculation method has been developed for creating recipes and strengthening steels, including the production of bainitic super-strong structures. The results were used by Intensive Technologies Ltd (Kyiv, Ukraine) for less costly software design.

SUMMARY

This work shows how transient nucleate boiling and convection should be coupled to provide accurate results of calculations to be used for recipes development and optimization of bainitic transformations. Its aim is to make bainitic transformation a mass production and less costly.

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