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Contemporary Methods of Steel Hardening in Liquid Media Based on Laws of Modern Physics

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Review Article

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ABSTRACT

In the paper an overview of early published by author papers are provided and additional data are discussed to support the fundamental ideas forwarded in the last two decades. These main ideas include duration of transient nucleate boiling process, composing of optimal hardenability steel depending on form and size of machine components, cooling time calculation to provide proper time interruption that results in high compressive residual stresses formation and super strengthening of material. Accurate experimental data of different authors are used to double check correctness of forwarded by author ideas. The praiseworthiness of current overview consists in considering all early published material together and showing relationship between ideas. The physical meaning of obtained equations is provided and examples of calculations are considered. Such composing of the paper allows understanding of material and physics of quenching processes to usefully utilize the new ideas in the practice.

INTRODUCTION

As known, the bell-shaped curve was discovered in 1964 **(Figure 1)** [1,2]. It states that distortion and quench crack formation of steel parts are minimal when performing very slow cooling or extremely high cooling during quenching. Cooling rate of any steel part is a linear function of dimensionless Kondrat'ev number Kn which varies within 0 and 1, i.e., 0<Kn<1 [3]. As a rule, alloy and high alloy steels are quenched slowly in oils or air flow to receive minimal distortion and avoid crack formation. However, slow cooling in zone I (0<Kn<0.2) requires more alloy elements in steel to provide required hardened depth and in many cases results in creation of surface tensile residual stresses. Temperature gradient through section of steel part in zone I during its quenching is small that decreases probability of quench crack formation. The zone III **(Figure 1)** is intensive quenching (IQ) process where temperature gradients and cooling rate are maximal [4]. When Kondrat'ev number Kn=1, surface temperature during quenching of steel parts drops immediately to bath temperature creating maximal temperature gradient. The zone III is called direct convection since there are no nucleate boiling at all. Convection starts from the very beginning of cooling. In zone III distortion is minimal, high surface compressive stresses are formed during intensive quenching preventing quench crack formation. Additional strengthening (superstrengthening) of material is observed here that all together increases significantly service life of hardened steel parts. A long time this principle was not adopted by industry because customers didn't believe in it. It cannot be-was the answer. After painstaking experiments and many computer simulations made in the USA, Germany and Japan this principle was finally accepted by engineers and is currently successfully used in heat treating industry[5-7]. Authors believe that reason for eliminating quench crack formation during intensive quenching of splined semi-axles in water flow up to 8 m/s is uniform cooling [8].

As known, Kondrat'ev number Kn is used to evaluate cooling rate at the core of any configuaration of steel parts, exploring equation 1 [3,4]:

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

What is the difference between quenching alloy steel in oil and intensively quenched optimal hardenability steel in water? When steel is hrough hardened in oil, it has tensile surface residual stresses while intensively quenched, optimal hardenability steel has very high compressive residual stresses at the surface of steel part [9]. The difference is very large because the difference between tensile stresses and compressive residual stresses at the surface is really very large. As is well known, compressive residual stresses at the surface of steel parts increases their service life due to increased fatigue limit to fracture. Moreover, during intensive quenching additional strengthening (superstrengthening) is observed that additionally improves service life of steel parts. Therefore, compressive residual stresses at the surface of steel parts and superstrengthening of material make possible the replacement of alloy steels with less expensive steel of optimal chemical composition which ensures an optimal quenched layer (shell hardening) in steel. In many cases, it is also possible to eliminate the carburising process and decrease significantly the manufacturing cost of machine components. **Figure 2** shows tensile stresses at the core (1) and compressive stresses (2) at the surface of cylinder versus Biot number when the quenched layer is optimal. Such a function exists at the moment when martensitic layer is at optimal value or chemical composition of steel is optimal which provides optimal quenched layer after quenching. The first can be achieved by the interruption of intensive quenching at the moment when compressive current stresses at the surface are maximal. The second can be achieved by optimising the chemical composition of steel which ensures an optimal quenched layer after cooling giving high compressive residual stresses at the surface and superstrengthening of material. These new technologies are discussed below which are modified based on discovered new phenomenon.

Compression surface residual stresses and super strengthening phenomenon

It was established in 1983 that there is an optimal depth of hardened layer which provides formation of surface compression residual stresses in quenched steel parts [10-12]. Later was established a correlation between chemical composition of steel and size of steel part that provides maximal compression residual stresses after quenching (equation 3) [13-15]:

$$\frac{DI \cdot Kn^{0.5}}{D_{opt}} = 0.35 \pm 0.095 \qquad (2)$$

$$D = 2\ .4 \times f_E \times f_M \times f_S \times f_C \times f_N \times ..... \qquad (3)$$

Hardenability factors f_{Fe} and fx are provided [16,17].

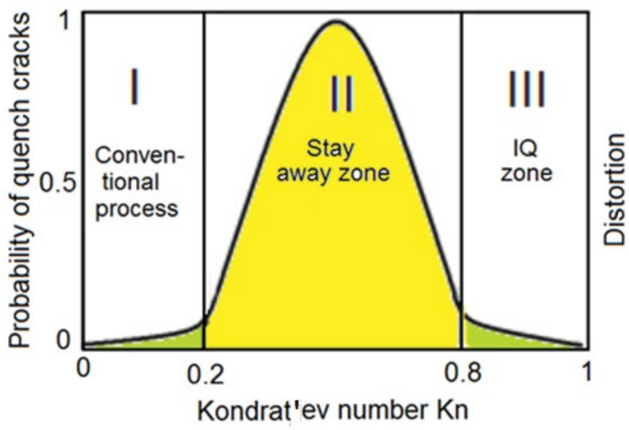

Figure 1: The bell-shaped courve showing probability of quench crack formation and distortion varying versus Kondrat'ev number Kn [1,2].

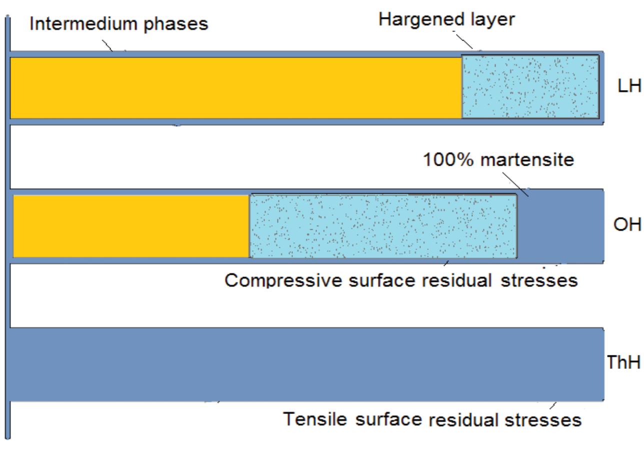

Figure 2: Optimal depth of hardened layer corresponding to the maximum surface compressive residual stresses: LH, low hardenability steel; OH, optimal hardenability; ThH, through hardening [13].

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The designed technology was patented in Ukraine in 2013 [14].

Here DI is critical diameter in m which depends on chemical composition of steel and is calculated using well known Grossmann's equation [16]; D_{opt} is thickness of steel part in which optimal hardened layer is formed. More information is available in Ukrainian patent [14]. A procedure of its use is shown below:

- A steel grade with certain chemical composition is chosen.
- An ideal critical size for steel is determined.
- A ratio DI/D_{opt} for specific steel is evaluated which must be within the range of 0.2-0.5.
- The part is quenched in condition $0.8 \le Kn \le 1$.
- Intensive quenching is interrupted to provide self-tempering.
- The part is tempered at the temperature Ms or higher.

If a ratio (2) is satisfied, residual hoop stress distribution in steel component is optimal. More information related to optimal hardenability steel is available in the book issued by Lambert Academic Publishing in 2018 [13].

Patented technology allows decrease alloy elements in steel, increase service life of machine components and tools make environment green and significantly reduce cost of technological process. Optimal hardenability steel (OH) differs from Low Hardenability (LH) steel by its application to any size and form of steel part [18]. Conventional plain carbon steel can be used as optimal hardenability steels if correlation (2) is satisfied. Some differences between LH, OH, and high alloy steel are shown schematically in **Figure 2** [13].

The higher the cooling rate is within the martensite range, the greater is the extent to which the austenite is deformed, and the higher the dislocation density. Moreover, during rapid cooling, there is not enough time for the dislocations to accumulate in the grain boundaries to form nuclei of future microcracks; they are frozen in the material. It means that the superficial layer acts like a blacksmith: under conditions of high stress, the plates of martensite arise explosively, deforming the austenite and creating extremely high dislocation densities which are frozen during rapid cooling. This process is analogous to low-temperature thermomechanical treatment **(Figure 3)**.

When the density ρ_D of dislocation in a material increases, the strength σ_τ of material increases according to correlation (3) [19]:

$$\sigma_\tau = \sigma_o + k_1 bG\sqrt{\rho_D} \qquad (4)$$

Where σ_o is transverse stress before deformation; k_1 is strengthening factor depending on the kind of lattice and alloy composition; b is Burger's vector; G is the shear modulus; ρ_D is density of dislocation.

The idea discussed above is supported by experimental data provided in **Table 1**.

Due to super strengthening effect and high surface compressive residual stresses, it was possible to start commercialization and build equipment for intensive quenching processes which were successfully applied into the practice [9].

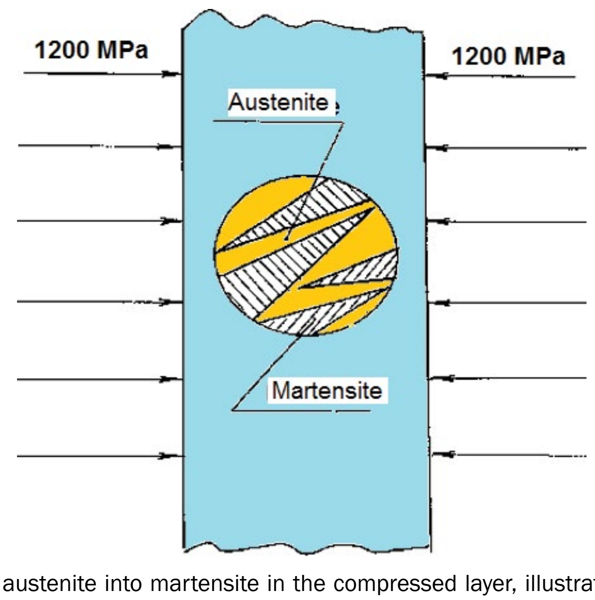

Figure 3: The transformation scheme of austenite into martensite in the compressed layer, illustrating the effect of additional strengthening (super-strengthening) of the material [13].

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The above investigations' main conclusion is that the IQ process can be fulfilled even in still water if any film boiling is completely absent. In this case a saturation temperature of the liquid is below the martensite start temperature Ms that allows forming thick enough surface martensitic layers **(Figure 4)**.

As seen from **Table 2**, martensite starts temperature Ms for steel containing 0.8%C is 250°C. During transient nucleate boiling process surface temperature of steel maintains at the level of 100°C. Within the interval of temperatures 100°C-250°C more than 50% martensite appear that has larger specific volume resulting in compressive surface residual stresses formation and micro-hammering effect. The idea is supported by industrial experiments which were fulfilled with the high-speed steel AISI M2 [20]. Chemical composition of steel and martensite start temperature Ms are shown in **Figure 5**. According to **Figure 5**, 50% martensite transforms at the temperature 200°F or 93°C. So, there is enough percentage of martensite to develop compressive residual stresses and improve wear resistance of material due to super strengthening phenomenon. It was shown by author that during intensive quenching of molybdenum high speeds steel the packet-morphology martensite emerges that is a reason for wear resistance increase [21].

For testing, punches were made of the molybdenum high-speed steel M2. Intensive quenching of punches in aqueous chloride solutions increased the tool life by 2.5 times **(Table 3)**. The punch is 126 mm long, and its maximum diameter is 15.3 mm. Thus, the intensification of cooling within the martensite range results in an increase in strength and service life for machine components and tools.

Seven punches were intensively quenched and seven others (made from the same steel heat) were quenched in accordance with the current technology. Both sets of punches were heated up prior to quenching in a high-temperature salt bath furnace. **Table 2** presents the field test data. As the data show, the IQ process improved the average service life by about 2.5 times. This improved performance is attributed to increased material toughness and residual surface compressive stresses from the IQ process [4,20].

The self-regulated thermal process and its duration

It was established that during the transient nucleate boiling process so called self-regulated thermal process takes place where surface temperature during nucleate boiling maintains relatively a long time at the level of saturation temperature T_s of a liquid **(Figure 6)** temperature is self-regulated thermal process; A is start temperature of developed nucleate boiling process; B is end of nucleate boiling process [4,22].

Table 1: Comparison of the mechanical properties of different steels quenched in oil and two steps quenched with accelerated cooling rate within the martensite range when cooling in liquid nitrogen [20].

Method	Cooling Rate, ℃/s	Steel	Ultimate strength, MPa	Yield strength, MPa	A (%)	Z (%)
Oil	3 – 6	U7A	1400	1250	4	-
		60C2A	1476	1355	8.5	-
IQ	30	U7A	1610	1570	7.9	31
		60C2A	1920	1740	5	22

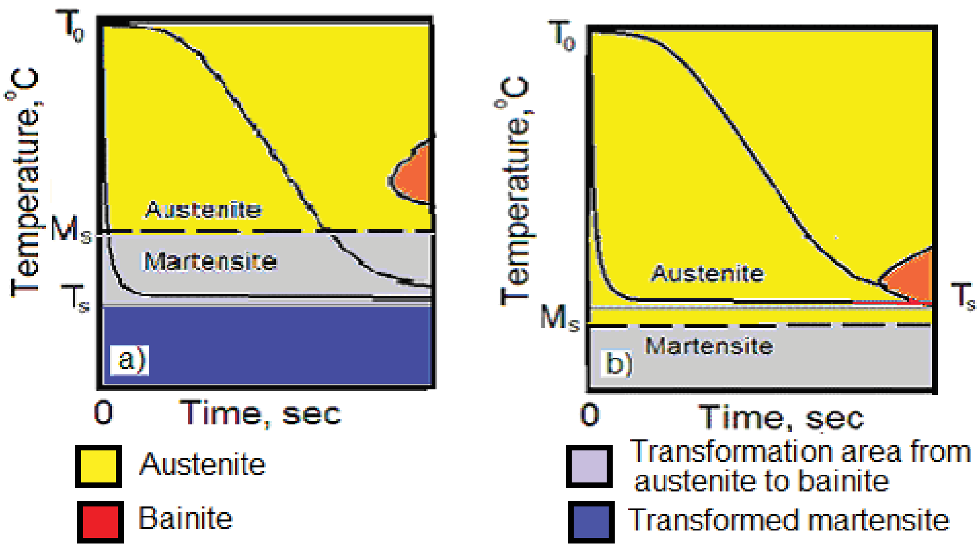

Figure 4: Relationship between martensite start temperature Ms and self-regulated thermal process: a) self-regulated thermal process is below martensite start temperature Ms; b) self-regulated thermal process is above Ms that delays completely martensite transformation during nucleate boiling; T_s is saturation temperature; M_s is martensite start temperature; B is bainite.

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Table 2: Residual surface compressive stresses after intensive quenching and tempering [4,13].

Steel part	Residual hoop surface compressive stresses, MPa
52100 Roller Æ3” (76 mm)	-840
52100 Roller Æ1.8” (46 mm)	-900
4140 Kingpin Æ1.8” (46 mm)	-563
S5 Punch Æ1.5” (38 mm)	-750

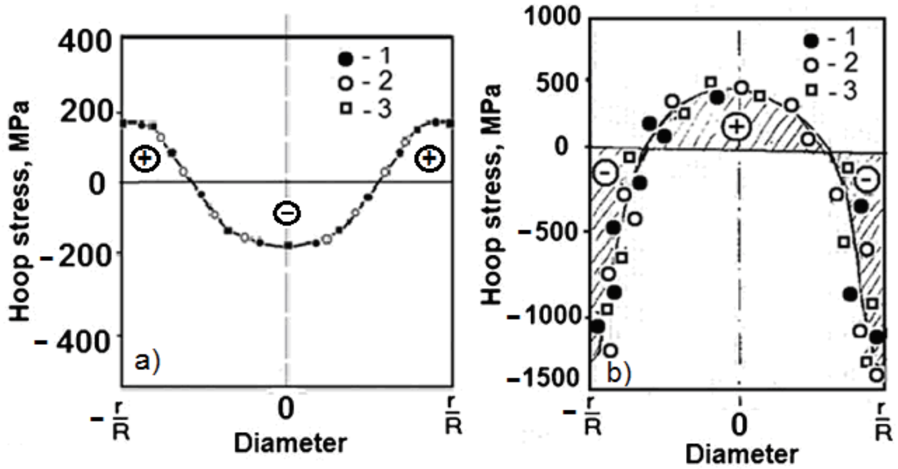

Figure 5: Residual stress distribution in cylindrical spcimen sfter quenching in oil and after intensive quenching [9].

Table 3: Martensite start temperature Ms and martensite finish temperature M_F versus content of carbon in steel.

Carbon, %wt	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
M_S,°C	450	350	300	250	210	180	140	100
M_F,°C	380	110	Below 0	Below 0	-100	-105	-110	-115

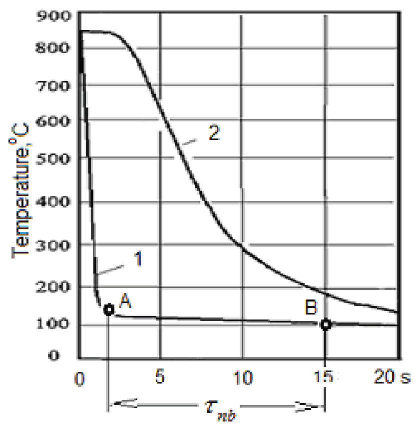

Figure 6: Typical surface and core cooling curves when film boiling is absent [22]: 1 is surface temperature; 2 is core.

Duration of transient nucleate boiling process τ_{nb} is evaluated by equation 5. According to French time between 0 and A **(Figure 6)** is the same for different forms and sizes of steel parts. If any film boiling is completely absent [23]. This time is rather short and is varying within 0.6 sec-1.5 sec.

$$\tau_{nb} = \overline{\Omega} k_F \frac{D^2}{a} \quad (5)$$

Here Ω is a function of the convective Biot number (initial temperature is fixed here at 850°C and bath temperature is fixed at 20°C); k_F is dimensionless form coefficient; D is thickness in m; ∞ is thermal diffusivity of steel in m²/s. Note that the value $\infty \to 0$ when Bi $\to \infty$ **(Figure 7)**.

Proceeding from equation 5, one can state that duration of the transient nucleate boiling process is directly proportional to the square of the thickness D of an arbitrary body and is inversely proportional to thermal diffusivity of the material *a*, and depends on a form k_F of a body, its initial temperature, and properties of the cooling system. Furthermore, it was established that

Table 4: Results of testing punches on automatic line "National-164" with performance of 175 strikes per minute [20].

Number of strikes until the destruction of punches		Increase in service life (multiplier)
Normal quenching	Intensive quenching	
6400	15600	2.4
6670	16500	2.9
3200	5300	1.65
4000	12075	3
6620	8110	1.2
2890	10500	3.6
2340	7300	3.1

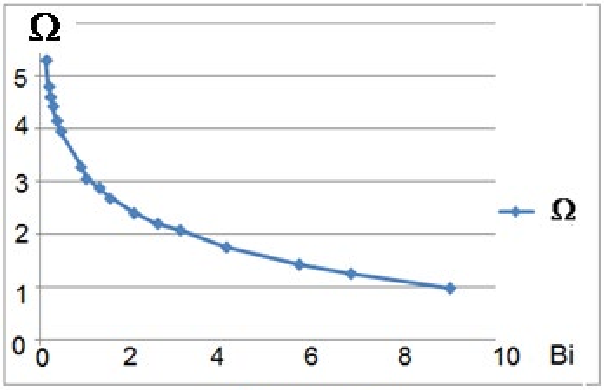

Figure 7: The value Ω versus Biot number Bi depending on size of steel part and heat transfer coefficient during convection [13].

during quenching, a so-called self-regulated thermal process occurs, where the part surface temperature during nucleate boiling maintains for a relatively long time at the level of the liquid saturation temperature Ts [4]. Mathematically it can be formulated as:

$$T_{sf} = T_s + \Delta\overline{\xi} \approx const \qquad (6)$$

These new characteristics of transient nucleate boiling process were used:

- For developing original IQ-2 technology which increases service life of machine components and tools after hardening.
- For evaluating thermal diffusivity of different materials.
- To explain secrets of Damascus steel.
- For developing a new technology called austempering and martempering processes taking place in cold liquids to eliminate hazard melted salts and alkalis.
- For developing new method of controlling quench process taking place in liquids.
- Can be also used in Astrophysics and Geology.

Real Heat Transfer Coefficient (HTC) during transient nucleate boiling process is very large **(Figure 8)**. It means that intensive quenching can be performed in still water salt solutions of optimal concentration when any film boiling process is completely absent. To create conditions for intensive quenching steel parts in liquid media, first of all, it is required to eliminate film boiling processes.

Since equation 5 is a basis for designing new quenching technologies, it is very important to compare it with the many experimental data to be sure that it works correctly. To follow this goal, **Table 4** presents results of calculations which are compared with the results of experiments which were performed by different authors in last decade.

Duration of transient nucleate boiling process was measured by authors using sonar system which provides rather accurate data on transition from nucleate boiling to convection [24]. Authors measured transition visually in the area where self-regulated thermal process finishes [2,25]. For calculating transient nucleate boiling process, the equation 5 was used and results of calculations are presented in **Table 5**.

As one can see from **Table 5**, results of calculations the duration of transient nucleate boiling process for long cylindrical probes coincide very well the performed experiments performed by different authors **(Table 5)**. Similar comparison can be made for different forms of probes using **Table 6** where dimensionless form coefficients k_F are provided.

Data in tables 6-9 are used for recipes development during performing austempering.

According to author, convective heat transfer coefficient during cooling in water flow 1.3 m/s-1.5 m/s is equal to 5000 W/m^{2}K [4]. Konvective Biot number for cylindrical specimen 28 mm diameter is calculated as $Bi = \frac{5000W/m^2K}{23W/mK} \times 0.014m = 3{,}04$.

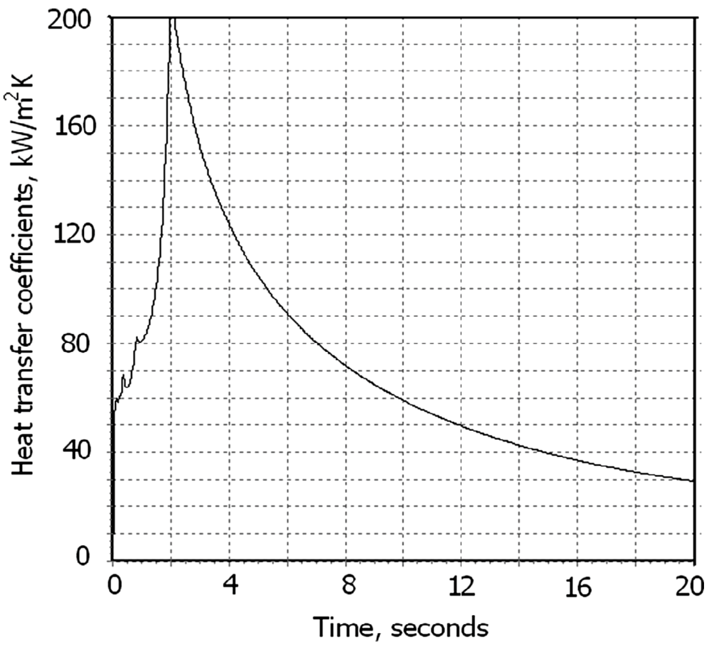

Figure 8: Shock and nucleate boiling heat transfer coefficients versus time for a sphere of 38.1 mm in diameter quenched from 875°C in a 5 % aqueous NaOH solution at 20°C [4].

Table 5. Duration of transient nucleate boiling process τ_{nb} for cylinders of different diameters and cube when quenching in still water salt solutions of optimal concentration and water flow when heat transfer coefficients are equal to 776 W/m^{2}K and 5000 W/m^{2}K.

Diameter or thickness, mm	Bi_{conv}	Ω	K·10^{-6}, m^2	Calculation τ_{nb}, sec	Experiment τ_{nb}, sec
Cylinder, 10	0.18	4.83	4.32	3.87	3.8
12	0.2	4.72	6.23	5.4	5.3
12.5	0.22	4.62	6.75	5.78	5.7
15	0.265	4.44	9.8	?.8	-
20	0.353	4.18	17.2	13.3	15
25	0.441	3.96	27	19.8	-
28	3.04	2	33.9	11.68	11.5
50	0.882	3.3	108.1	66.1	67
50 x 100	0.88	3.3	97.64	59	50
Cube 100x100x100	2	2.3	337.7	142	140

Table 6: Form coefficient k_F and Kondrt'ev K coefficient for different shapes of steel parts.

Form	k_F	K, m^2
Plate, infinite	0.1013	$L^2/9.87$
$0.1 \cdot L_1 = L_2 = L_3$	0.0993	$L^2/10.07$
Cylinder, infinite	0.0432	$R^2/5.783$
Cylinder 2D=Z	0.03906	$D^2/25.6$
Cylinder 3D=Z	0.04127	$D^2/24.2$
Cylinder 4D=Z	0.04211	$D^2/23.75$
Cylinder 5D=Z	0.0425	$D^2/23.53$
Sphere	0.0253	$R^2/9.87$
Cube, $L_1 = L_2 = L_3$	0.0338	$L^2/29.61$
Cylinder, D=Z	0.0301	$D^2/33$

Figure shows that for convective Bio 3 the value Ω =2. According to main equation 6, cooling of transient nucleate boiling process τ_{nb} is equal to 11.68s:

$$\tau_{nb} = 2 \times 0.0432 \times \frac{0.028^2 m^2}{5.4 \times 10^{-6} m^2 / s} = 11.68s$$

Here Ω = 2; $k_F = 0.0432$; $D = 0.028m$; $a = 5.4 \times 10^{-6} m^2 / s$

According to very accurate experiment, which was achieved in Idemitsu Kosan Co., Ltd. Lab (Japan) [25], time of transient nucleate boiling process is equal to 11.48 s. Difference between experimental and calculated data is 1.7%.

For cylindrical specimen shown in **Figure 9** which was quenched in still water solution. The Biot number Bi is:

$$Bi = \frac{600W / m^2 K}{23W / mK} \times 0.01m = 0.26 .$$

For convective Bio 0.26 the value Ω is equal to 4.44.

According to main equation (6), cooling of transient nucleate boiling process τ_{nb} is equal to 11.68s:

$$\tau_{nb} = 4.44 \times 0.0432 \times \frac{0.02^2 m^2}{5.4 \times 10^{-6} m^2 / s} = 14.2s$$

According to our experiment, the duration of transient nucleate boiling process is equal to 15 s that is very close to each other. The above discussed self-regulated thermal process is successfully used for designing austempering and martempering processes via cold liquids [26,27].

Forced heat exchange phenomenon taking place during quenching in electrolytes

According to the classical statistical thermodynamic, the pressure created by free electrons in metal is directly proportional to the absolute temperature T and is considered as [28]:

$$P = nkT \qquad (7)$$

Where n is a number of electrons in one sm^3 of metal; k is the Boltzmann constant which is equal to $k = 1.3806488(13) \times 10^{-23} \left[JK^{-1} \right]$.

For the high electrical conductivity metals like silver and copper the number of free electrons n_{ml} in one sm^3 is several times larger as compared with steel, i.e., $n_{ml} >> n_{steel}$. As a result, in a double electrical layer a high electrical force appears when quenching metal in electrolyte of optimal concentration **(Figure 10)** [29].

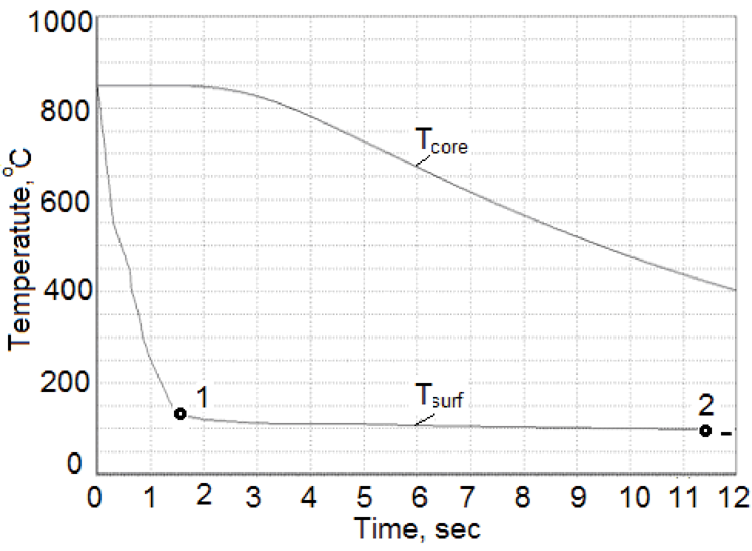

Figure 9: Cooling curves obtained in Idemitsu Kosan Co., Ltd. lab for cylindrical specimen of 28 mm diameter and 112 mm length when quenching in water flow of 1.5 m/s at 20°C [25].

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As a rule, during quenching in electolytes HTC decreases versus time. Author observerd cardinal increase HTCs during quenching in electrolytes silver and copper probes that contrudicts the existing theory of nucleate boiling process **(Table 7-9)** [30-32]. To solve the contrudiction, it was proposed an idea consisting in periodical replacenment of film boiling process by shock boiling process. Such phenomenon can be also generated if steel during quenching in electrolytes is charged negatively.

Table 6 shows increasing HTCs vs decrease of core temperature of silver 20 mm probe. Practical use of some innovations was discussed in publications [31,32].

Discovered phenomenon can be used for designing new quenching technology governed by external electrical forces **(Figure 11)**. The quench system includes quench tank filled with an electrolyte of optimal concentration; an elevating system to move steel parts down into quench tank and up when quench process is finished. An electrical accumulator, a resistor and a relay are used to create high density of electrons in steel parts at the beginning of quenching in the electrolyte of optimal concentration.

Cooling time interruption, when quenching charged steel parts, can be calculated using universal correlation 8. The proposed correlation occurs very simple if explore the next rations.

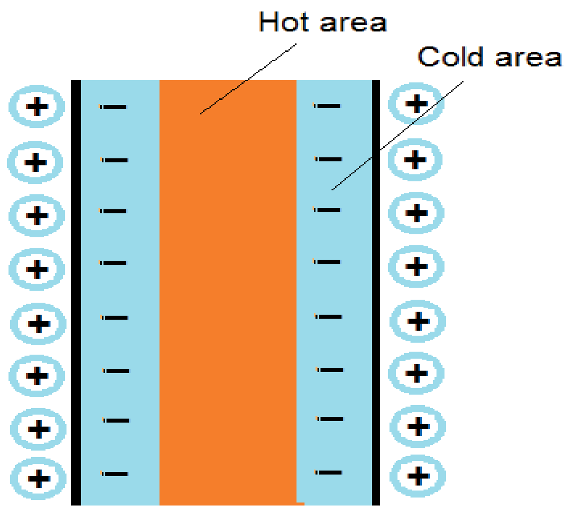

Figure 10: A double electrical layer taking place suring quenching metal in electrolytes.

Table 7: Effect of NaCl concentration and core temperature of silver spherical probe 20 mm diameter on heat transfer coefficients (W/m^{2}K) during quenching in solutions at a temperature 20°C.

Concentration (%)	HTCs (W/m^{2}K)				
	700°C	600°C	500°C	400°C	300°C
5	8750	27138	42140	64300	90500
10	15170	40710	60800	88120	92880
15	30470	42310	67420	98000	117050
20	18500	20230	22270	30600	47990

Table 8: Effect of NaOH concentration and core temperature of silver spherical probe 20 mm diameter on heat transfer coefficients (W/m^{2}K) during quenching in solutions at a temperature 20°C.

Concentration %	HTCs (W/m^{2}K)				
	700°C	600°C	500°C	400°C	300°C
5	18500	40580	48640	62160	74190
15	27880	43670	69830	97880	116815
30	24670	28370	24800	38105	36080

Table 9: Effect of temperature water NaCl solution (15%) and core temperature of silver spherical probe 20 mm diameter on HTC (w/m^{2}k) during quenching in liquid bath at a temperature 20°C.

Bath temperature, °C	HTC (NaCl)				
	700°C	600°C	500°C	400°C	300°C
20	27880	43670	69830	97880	116815
40	18760	29615	34560	50030	71470
60	13270	18880	27700	30970	42880

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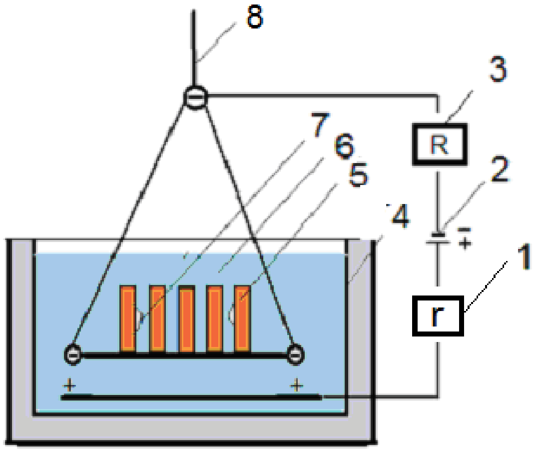

Figure 11: Schematic installation to provide intensive and uniform cooling by exploring short lasting external electrical forces: 1 is resistor; 2 is electrical accumulator; 3 is relay to interrupt electrical force in 2 seconds; 4 is insulation; 5 is steel part; 6 is electrolyte; 7 is local film boiling; 8 is moving system.

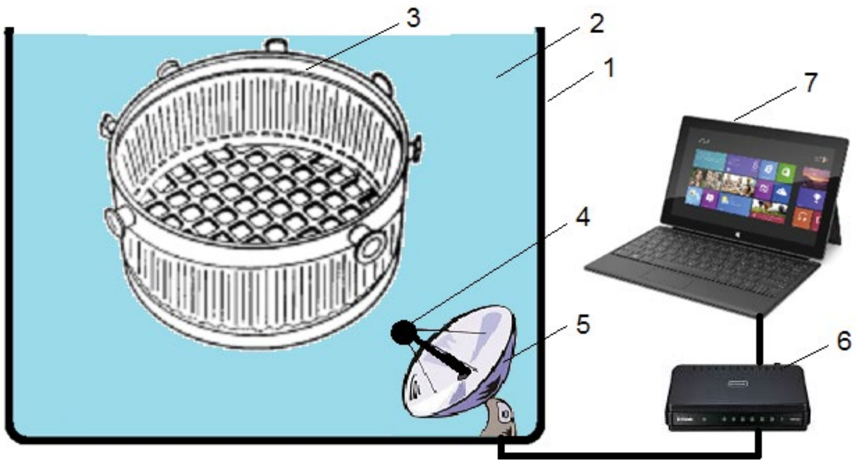

Figure 12: Set-up for controlling a quality of hardening process taking place in liquids [33]: 1-quench tank; 2-quenchant; 3-container; 4-sensor for recording acoustic effects; 5-fixture for catching acoustical waves; 6-multiplier and analyser; 7-computer.

The ratio $\theta = \frac{T - T_m}{T_o - T_m}$ which is called dimensionless temperature and the ratio $N = \frac{T_o - T_m}{T - T_m}$ which is called dimensionless number N. The last shows how many times interval between two thermal equilibriums has been changed [13,33]:

$$\tau_{eq} = E_{eq} \frac{K}{aKn} \qquad (8)$$

For example, maximal surface compressive residual stresses are developed in the intensively quenched cylindrical sample in agitated water at 20°C if cooling is interrupted at the core temperature 450°C. One should remember the dimensionless number N for this specific case which is equal to $N = \frac{850^o C - 20^o C}{450^o C - 20^o C} = 1.93$. The number N can be 2 because there is a window 400°C-450°C where maximal compressive stresses appear. For number N=2 and intensive quenching ($Bi_V \rightarrow \infty$) parameter E_{eq} is equal to 1.16. Kondrat'ev form coefficient K is calculated as $K = R^2 / 5.783$ and Kondrat'ev number Kn for condition $Bi_V \rightarrow \infty$ is equal 1. The average thermal diffusivity of steel for the given interval of temperatures is equal to $a = 5.4 \times 10^{-6} m^2$. If thickness of cylinder is 40 mm (0.04m), then Kondrat'ev form coefficient is $K = 69.2 \times 10^{-6} m^2$. Thus, cooling time interruption is $\tau_{eq} = 1.16 \times \frac{69.2 \times 10^{-6} m^2}{5.4 \times 10^{-6} m^2 / s \times 1} = 12.8 s \approx 13 s$.

The proposed new technology can be controlled and governed by patented system shown in **Figure 12**.

The proposed technology is less costly and can save energy, materials and is environmentally green.

CONCLUSIONS

- The duration of the transient nucleate boiling process is directly proportional to the square of the thickness D of an arbitrary body and is inversely proportional to a thermal diffusivity of the material *a*, depends on a form k_F of a body, its initial temperature, and properties of the cooling system. During the self-regulated thermal process, the part surface temperature maintains for a relatively long time at the level of the liquid saturation temperature Ts. The discovered characteristics of the transient nucleate boiling process are used for developing original IQ-2 technology which increases service life of machine components and tools after hardening; for evaluating thermal diffusivity of different materials; for explanation the secrets of Damascus steel; for developing a new technology called austempering and martempering processes taking place in cold liquids to eliminate hazard melted salts and alkalis; for developing new method of controlling quench process taking place in liquids and can be used in Astrophysics and Geology
- A correlation for optimizing chemical composition of steel depending on size and form of steel part is proposed by author. There is an optimal depth of hardened layer which provides formation of extremely high surface compression residual stresses in quenched steel parts. The optimal hardened layer can be achieved by chemical composition of steel correction or by proper cooling time intrerruption if steel is through hardened
- A universal correlation for cooling time calculation, which is valid for any form and size of steel part, is proposed to provide optimal hardened layer and high compressive residual surface tresses formation
- A new forced heat transfer phenomenon is discovered by author. Its essence consists in periodical replacement of film boiling by shock boiling that considerably increases heat exchange process during quenching of metal components in water salt solutions of optimal concentration making cooling process very intensive. The discovered new phenomenon can be governed by external electrical forces that competes with powerful pumps, noisy rotating propellers which require a lot of energy and are expensive
- A new method and apparatus were proposed for controlling quench process taking place in liquid media based on use a sonar system which was patented in Ukraine

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