Transient Nucleate Boiling and Its Use for Thermomechanical Technologies Development

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Abstract: - In the paper high temperature and low temperature intensive thermomechanical treatment is discussed. It is based on recently discovered new three physical principles that belong to the transient nucleate boiling process taking place in cold fluids. Such processes are considered in conditions when any film boiling during quenching in cold fluids is completely absent. That makes nucleate boiling very intensive, *i.e.* $Bi_V \to \infty$. The discoveries are used for direct quenching articles after forgings. The first is intensive high-temperature thermo-mechanical treatment (HTTMT). It is used for low and middle-carbon alloy steels. Forged steel parts are intensively quenched with a cooling interruption at the proper time to form surface compression residual stresses and fine bainitic microstructure at the core that increases radically surface life of forgings. The second method includes high-temperature and low temperature intensive thermo - mechanical treatment (LTTMT) of high carbon alloy steels with delaying martensitic transformation to make low-temperature thermo - mechanical treatment (LTTMT) possible. Then, after high temperature and low-temperature thermomechanical treatment, the steel goes to immediate tempering to create highly strengthened fine bainitic microstructure throughout the section of the steel part. A modified method of cooling time calculation, suitable for any size and form of steel part, is widely discussed in this paper.

Key-Words: - Thermo- mechanical treatment, Forging, New intense technology, Surface compression stresses, Fine bainitic microstructure, Service life, Environment improvement.

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1 Introduction

High and low temperature thermomechanical treatment is known from literature and its practical use in forging shops [1], [2] and [3]. As a rule, thermomechanical treatment was performed in slowly cooling oils to prevent crack formation. Authors [4], used intensive cooling for direct quenching of forging designated by them as DFIQ process. As reported, [4], the intensive quenching of forging immediately after hot forging operations (DFIQ) improves the mechanical properties of parts, allowing in many cases, a substitution of lower alloy and less expensive steel for higher alloy steel. Also, the use of the DFIQ process allows the manufacturer to eliminate post-forging heat treatment resulting in a significant reduction in the heat treatment costs. In addition, the DFIQ forgings have very little surface scale, since the parts are not reheated two times. It was noticed by the author, [2], that the mechanical properties of AISI 1040 steel after high-temperature accelerated thermomechanical treatment are significantly improved as compared with the conventional hardening process (Table 1). The quenching after forging was performed in cold water. One can expect that forging combined with intensive quenching to obtain fine bainite at the core of forged steel parts will provide more benefits. After intensive high-temperature thermomechanical treatment at the surface of forgings the compression stresses are formed while at the core intermediate phases are present. In contrast to existing technology, this paper considers situations when at the surface of forgings high compression stresses are formed simultaneously with forming fine or nano-bainitic microstructure at the core of forgings. It can be achieved by interrupting the quenching process at the proper time and delivering forging to tempering at the temperature that provides fine or nano–bainitic microstructures. The second possible approach consists of delaying martensite transformation during intensive quenching that allows performing effective high and low thermo-mechanical treatment while obtaining fine bainitic microstructure throughout the forged articles. The fine bainitic microstructure possesses high mechanical properties of steel, [5], [6]. As known, alloy and high alloy steels were quenched in slowly cooled liquid media (oils, water solutions of polymers of high concentration) to prevent crack formation during forging and quenching.

Table 1. Mechanical properties of AISI 1040 steel for heavy rolling with 19 mm diameter in the case of high–temperature thermo-mechanical treatment and conventional heat treatment, [2]

Tempering	$R_m\,(MPa)$	$R_{p0.2}\,(MPa)$	A(%)	Z(%)	R_m (J/cm^2)
200°C	$\frac{1{,}972}{1{,}422}$	$\frac{1{,}570}{1{,}240}$	$\frac{7.0}{2.0}$	$\frac{40.0}{16.0}$	$\frac{35}{30}$
300°C	$\frac{1{,}766}{1{,}628}$	$\frac{1{,}472}{1{,}511}$	$\frac{7.5}{7.0}$	$\frac{39}{35}$	$\frac{30}{40}$
400°C	$\frac{1{,}373}{1{,}177}$	$\frac{1{,}226}{1{,}099}$	$\frac{8.5}{8{,}5}$	$\frac{53}{50}$	$\frac{80}{85}$

Low-temperature thermomechanical treatment is performed in hot oils to delay the transformation of austenite into martensite to to perform forging at 400°C – 500°C. Since oil cools slowly, the low-temperature thermomechanical treatment is possible when alloy or high alloy steels are used. The current paper discusses high and low temperature thermomechanical treatment in conditions when cooling is intensive and is always suitable for plain carbon steels and alloy steels of any chemical composition. The technology is based on new physical principles published in [7], [8] which sound as:

- During quenching from high temperature in cold fluid any film boiling can be absent completely if initial heat flux density $q_{in} < q_{cr1}$.
- If any film boiling during quenching is completely absent, the cooling process is intensive and uniform.
- The time of full transient nucleate boiling establishment is the same for different sizes and forms of steel parts due to the very fast cooling process.
- Duration of transient nucleate boiling is directly proportional to the squared size of the steel part and inversely proportional thermal diffusivity of the material and is evaluated by a fundamental generalized equation, [6].
- Transition from nucleate boiling to convection is evaluated by equalizing heat fluxes at the end of nucleate boiling and the beginning of convection.

Based on these formulated principles, [6], the new intensive thermomechanical technologies were developed and used for direct quenching. From the point of view of thermal science these processes are discussed below. Such technology was not tested yet because it was a big problem to delay the transformation austenite to martensite to perform successfully low-temperature thermomechanical treatment.

2 Absence of Film Boiling during Quenching Steel in Cold Fluids

The most significant achievement in developing intensive quenching technologies is the theoretical explanation why during quenching in cold fluids the film boiling can be completely absent and cooling in this case is intensive. Since the fluid is cold during steel part immersion. first starts incredibly short convection (Figure 1). After overheating of a boundary layer shock boiling begins which continues in two possible ways, [7].

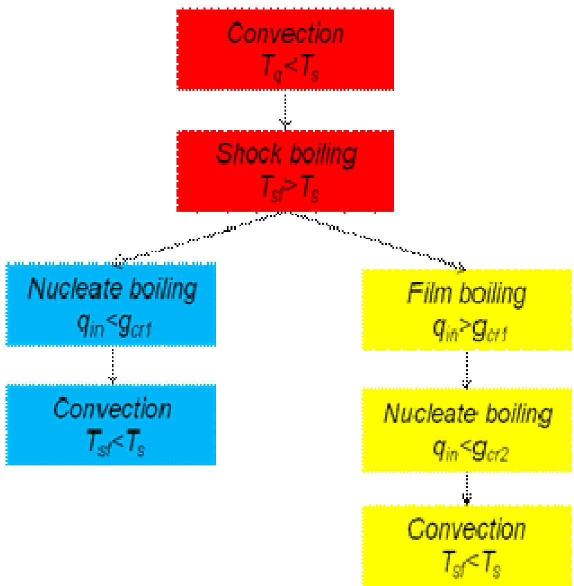


Fig. 1: Two possible ways of the quenching process taking place when steel part heated to high-temperature immersions into the cold fluid

If the initial heat flux density q_{in} is below the first critical heat flux density q_{cr1} ($q_{in} < q_{cr1}$). no film boiling will occur.

Due to the huge overheat of the boundary layer, small bubbles appear known as the shock boiling process (Figure 2a).

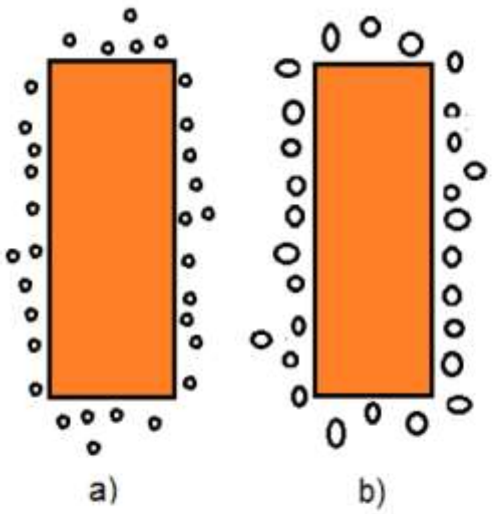


Fig. 2: Shock (a) and nucleate boiling (b) processes during quenching in liquid media

These small bubbles became larger passing to the developed nucleate boiling process if $q_{in} < q_{cr1}$ (Table 2, film boiling is absent). The process of cooling in cold fluid is uniform since any film boiling is completely absent which decreases distortion of hardened steel parts, [7], [8]. Note, shock boiling is present also at the beginning and at the end of film boiling oscillating with high frequency 13.6 kHz (Figure 3).

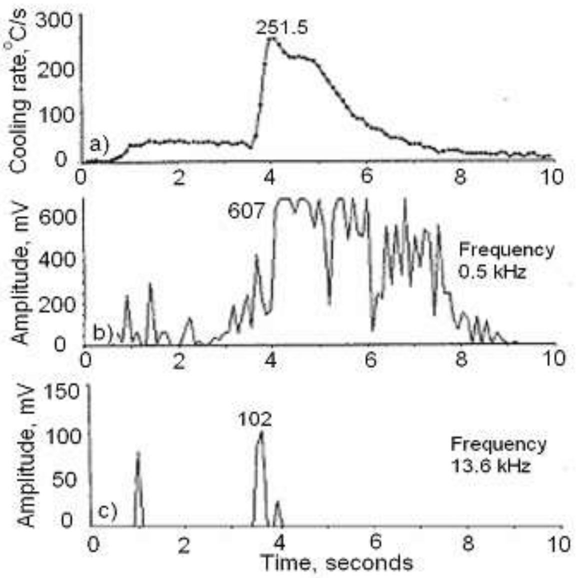


Fig. 3: Temperature–time, broadband, and narrowband quenching data [7]: a) is cooling rate vs time; b) are frequencies of film and nucleate boiling modes; c) is the frequency of shock boiling.

Table 2. Time required for the surface of steel spheres of different sizes to cool to different temperatures when quenched from 875 °C in 5 % water solution of NaOH at 20 °C agitated with 0.9 m/s, [9]

Size in Mm and Temperature	Time, sec							
	700°C	600°C	500°C	400°C	300°C	250°C	200°C	150°C
6.35	0.027	0.037	0.043	0.051	0.09	0.15	0.29	0.69
12.7	0.028	0.042	0.058	0.071	0.11	0.15	0.26	0.60
120.6	0.043	0.066	0.09	0.12	0.17	0.21	0.29	0.95
180	0.043	0.070	0.10	0.14	0.24	0.31	0.42	1.15
286	0.043	0.12	0.19	0.33	0.57	0.96	1.28	2.18

If $q_{in} > q_{cr1}$ film boiling starts which decreases the cooling process during quenching of steel parts [6].

3 Fundamentals of the Transient Nucleate Boiling Process

To be sure that the absence of film boiling process is intensive and can compete with powerful propellers and pumps, let's see a decrease of Kondra'ev numbers Kn versus time. Such data can be received by solving inverse problems, [10], [11] using accurate experimental data of author, [9], presented in Table 2. The initial temperature of the transient nucleate boiling process and the initial temperature of convection are evaluated using equations (1) and (2).

$$\vartheta_I = \frac{1}{\beta}\cdot\left[\frac{2\lambda\left(\vartheta_o - \vartheta_I\right)}{R}\right]^{0.3} \tag{1}$$

$$\vartheta_{II} = \frac{1}{\beta}\cdot\left[\alpha_{conv}\left(\vartheta_{II} + \vartheta_{uh}\right)\right]^{0.3} \tag{2}$$

$$\beta = \frac{75\lambda'\left(\rho' - \rho''\right)^{0.5} g^{0.5}}{\sigma^{0.5}\left(\rho'' r^{*} W''\right)^{0.7} \Pr^{0.2}}; \quad \frac{1}{\beta} = 0.293; \quad \Pr = \frac{\nu}{a}.$$

Duration of transient nucleate boiling process is evaluated as:

$$\tau_{nb} = \overline{\Omega} k_F \frac{D^2}{a} \tag{3}$$

where

Pr is Prandtl number; $\dfrac{W''}{W''_{0.1}} = \left(\dfrac{\rho_{0.1}}{\rho''}\right)^{2.3+0.5\lg\frac{P}{P_{cr}}}$;

$W''_{0.1}$ is bubble growth rate at normal pressure P; P_{cr} is critical pressure in Pa; α is heat transfer coefficient at nucleate boiling (W/m^2K); λ is thermal conductivity of fluid ($\frac{W}{mK}$); σ is surface tension (N/m); g is gravity acceleration factor (m/s^2); ρ' is liquid density (kg/m^3); ρ'' is vapor density (kg/m^3); q is heat flux density (W/m^2); r^* is heat of vapor formation (J/kg); W'' is steam bubble growth rate (m/s); T_o is initial temperature; ν is kinematic viscosity (m^2/s); a is thermal diffusivity of liquid (m^2/s).

Tabe 3 presents values of $\overline{\Omega}$ when initial temperature of heated steel part is fixed at 850°C and the temperature of quenchant is fixed at 20°C.

Table 3. Parameter $\overline{\Omega}$ as a function of convective Biot number when initial temperatures T_m and To are fixed at 20°C and 850°C

Bi	$\overline{\Omega}$	*Bi*	$\overline{\Omega}$
0.1	5.40	2	2.41
0.2	4.72	3	1.98
0.3	4.32	4	1.69
0.4	4.02	5	1.46
0.5	3.79	6	1.27
0.6	3.63	7	1.12
0.7	3.47	8	0.98
0.8	3.33	9	0.86
0.9	3.21	10	0.75
1.0	3.11	12	0.56

Table 4 provides coefficients k_F depending on the forms of different steel parts.

Table 4. Coefficients k_F depemnding on forms of steel parts.

Shape of a body	k_F
Plate	0.1013
Cylinder	0.0432
Sphere	0.0253
Round plate D = nZ: n = 1	0.0303
n = 2	0.0639
n = 5	0.0926

Using experimental data of author, [9] (see Table 1) and equations (1), (2), and (3), it was possible to restore surface temperature for different sizes of probes during the transient nucleate boiling process to solve the inverse problem discussed in [7], [10]. Simultaneously. a system with hyperbolic heat conductivity equations (4) and (5) – (8) was solved by authors [12], [13] to investigate properly quenching processes when during cooling any film boiling is completely absent.

$$\frac{\lambda}{a}\frac{\partial T}{\partial \tau} + \tau_r \frac{\partial^2 T}{\partial \tau^2} = div\left(\lambda gradT\right) + \dot{q} \tag{4}$$

$$\left[\frac{\partial T}{\partial r} + \frac{\beta^m}{\lambda}\left(T - T_s\right)^m\right]_{r=R} = 0 \tag{5}$$

$$T(r,0) = T_0 \tag{6}$$

$$q_{cn} = q_{nb} \tag{7}$$

$$\left[\frac{\partial T}{\partial r}+\frac{\alpha}{\lambda}\left(T-T_{conv}\right)\right]_{r=R}=0 \qquad (8)$$

$$m = 10/3$$

The problem is rather complicated and requires additional investigations to simplify methods of calculations.

4 Self-regulated Thermal Process to be used for HTTMT and LTTMT

Its essence is as follows. The surface temperature of the steel part during immersion into liquid quenchant drops immediately almost to the saturation temperature of a liquid and maintains at this level relatively a long time until transient nucleate boiling is finished. The real heat transfer coefficient (HTC) at the beginning of boiling is very large and can reach 200,000 W/m^{2}K. Convective HTC is rather small and for still water and water salt solutions reaches 400 - 1200 W/m^{2}K. Convective HTC on average is 200 times smaller as compared with the nucleate boiling process. It means that $\alpha_{conv} << \alpha_{nb}$ or

$$Bi_V^{\,conv} << Bi_V^{\,nb} \qquad (9)$$

Here $Bi_V^{\,conv}$ is the generalized Biot number during convection; $Bi_V^{\,nb}$ is the generalized Biot number during the transient nucleate boiling process. To prove the theoretical existence of SRTP let's consider a well-known universal correlation (10), [14], [15], [16]:

$$\frac{\bar{T}_{sf}-T_m}{\bar{T}_V-T_m}=\frac{1}{\sqrt{Bi_V^{\,2}+1.437Bi_V+1}} \qquad (10)$$

Here $\bar{T}_{sf}$ is average surface temperature; $\bar{T}_V$ is average volume temperature, T_m is bath temperature, Bi_V is generalized Biot number.

Note that during transient nucleate boiling process $T_m = T_s$.

Assume that the surface temperature of steel part at the beginning of cooling is below the saturation temperature T_S and is in the convection area. Taking into account Eq. (10), one can assume that $Bi_V \to 0$. In this case, according to Eq. (10), $\bar{T}_{sf} \to \bar{T}_V$. It means that surface temperature must increase immediately if it drops below T_s and occurs in the convection area. Assume now that the overheat of the boundary layer is rather large. In this case generalized Biot number Bi_V is very large also which tends to infinity, *i.e.* $Bi_V \to \infty$. According to Eq. (10), $\bar{T}_{sf} \to T_s$ and it means that overheating is zero and transient nucleate boiling process must stop. Only one way is left. The surface temperature must be very close to the boiling point of a liquid from the very beginning of cooling. The cooling system controls overheating $\Delta\bar{\zeta}$ by itself which depends on the size and form of a steel part. The overheating $\Delta\bar{\zeta}$ is small as compared with the initial temperature T_0. For practical use, one can consider this behavior of the surface temperature as:

$$T_{sf} = T_S + \Delta\bar{\zeta} \approx const \qquad (11)$$

4.1 Main Characteristics of SRTP

Below (Figure 4 and Figure 5) are surface and core cooling curves for cylindrical probes quenched from 850°C in water salt solution and water under pressure 0.7 MPa.

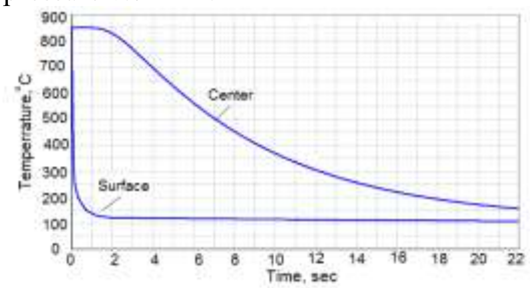


Fig. 4: Cooling curves vs time during quenching of cylindrical sample 25 mm dia 120 mm height in cold water salt solution of optimal concentration

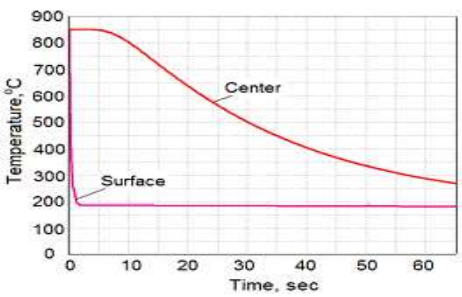


Fig. 5: Surface and core cooling curves vs time during quenching of cylindrical sample 50 mm dia 75 mm height in cold water under pressure 0.7 MPa

As seen from Figure 4 and Figure 5 the surface temperature of cylindrical probes is maintained at the level of boiling point of a liquid. The surface temperature during nucleate boiling can be replaced by average temperature when calculating the temperature field in the probe (Figure 6).

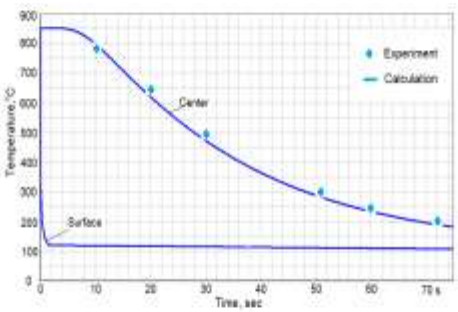


Fig. 6: Cooling curves vs time during quenching cylindrical sample 50 mm dia 200 mm long in cold water solution (14%) of NaCl at room temperature. Lines are numerical calculations; dots are experiments

To see how intense is cooling process is during quenching in water and water solution of low agitation, the real and effective Kondrat'ev numbers were evaluated using the IQLab program, [8] (Figure 7). Real Kn_{nb} and effective Kn_{conv} Kondrat'ev numbers versus time. when cooling the cylindrical sample 25 mm dia 120 mm height in cold water salt solution of optimal concentration. are within 0.2 – 1 for effective data and 0.8 - 1 for real Kondrat'ev numbers, [8]. Their average values are: $Kn_{eff} = 0.6$ and $Kn_{real} = 0.9$.

Quenching in water under pressure 0.7 MPa increases dimensionless numbers Kn and they are: $Kn_{eff} = 0.65$ and $Kn_{real} = 0.95$. All calculated data show that the transient nucleate boiling process provides intensive quenching because $Kn_{real} > 0.8$.

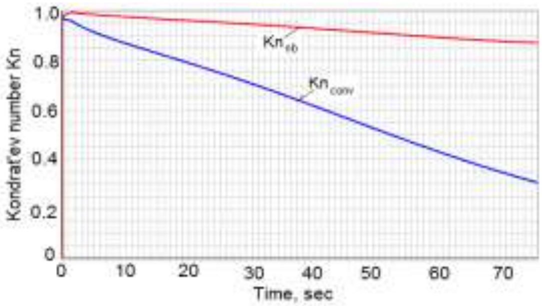
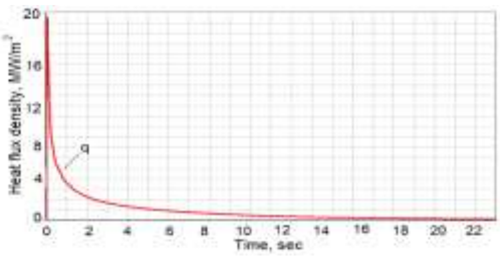


Fig. 7: Real Kn_{nb} and effective Kn_{conv} Kondrat'ev numbers versus time when cooling cylindrical sample 50 mm dia 75 mm height in cold water under pressure 0.7 MPa

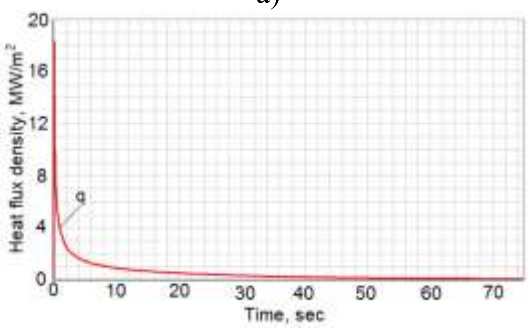
Based on the above investigations, it is possible to propose different types of thermomechanical treatment:

- HTTMT with the delay of martensite transformation to achieve bainitic fine or nano microstructures.
- LTTMT with the delay of martensite transformation to perform plastic deformation mediate temperatures.
- To combine HTTMT and LTTMT to improve significantly mechanical properties of materials.
- To combine HTTMT and LTTMT to delay martensite transformation and achieve fine bainitic microstructure.

The listed above technologies are possible if film boiling is completely absent and SRTP lasts relatively a long time. The film boiling is absent if the initial heat flux density q_{in} is below the first critical heat flux density q_{cr1}, *i.e.*, $q_{in} < q_{cr1}$. Initial heat flux densities are evaluated by solving inverse problems, [10], 12]. The critical heat flux densities were considered by authors, [17], [18], [19]. It was possible to evaluate initial heat flux densities for , different sizes of cylindrical probes (Figure 9a,b).
For both sizes, 25 mm and 50 mm initial heat flux densities were almost the same and were equal approximately to 20 MW/m^2. Such behavior is due to very fast cooling where heat transfer can be considered in the semi - infinity domain. For this situation both initial heat flux densities are below the first critical heat flux generated by the shock boiling process (Figure 8) which is why the film boiling was completely absent (Figure 4 and Figure 5).



a)



b)

Fig. 8: Heat flux density versus time taking place during quenching cylindrical probes in water salt solutions of optimal concentration: a) 25 mm diameter; b) 50 mm diameter

To explore the transient nucleate boiling process for new technologies development, convective HTC should be reduced as much as possible, it increases the duration of transient nucleate boiling.

Cooling time τ and cooling rate v at the core of steel parts during quenching are approximately evaluated using equations (12) and (13), [7], [8]:

$$\tau = \left[\frac{kBi_V}{2.095 + 3.867Bi_V} + \ln\frac{T_o - T_m}{T - T_m} \right] \cdot \frac{K}{aKn} \quad (12)$$

$$v = \frac{aKn}{K}\left(T - T_m\right) \quad (13)$$

Equations (12) and (13) are widely used for recipes development when hardening steel parts of different configurations.

5 Chemical Composition of Steel Optimization

The chemical composition of steel optimization was developed to provide optimal hardened layer (see Figure 9) that results in high surface compression residual stresses and a fine bainitic microstructure at the core of steel parts. Both of these factors increase the service life of quenched steel parts, [16].

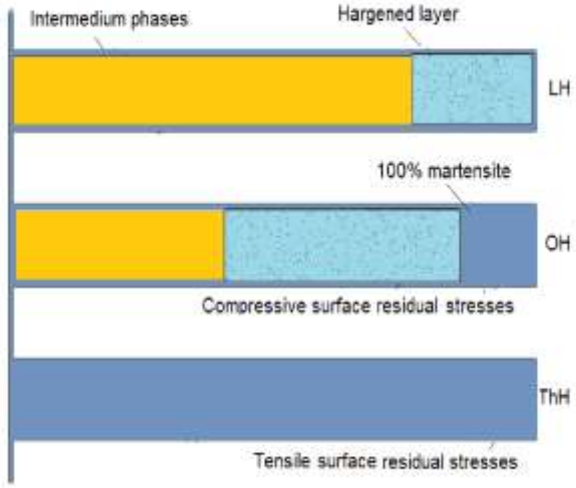


Fig. 9: Optimal depth of hardened layer corresponding to the maximum surface compressive residual stresses, [20], [21]: LH, low hardenability steel; OH, optimal hardenability; ThH, through hardening

The heat-treating industry can generate great benefits performing HTTMT and LTTMT using low hardenability steels (Figure 9). In this case, along with the increased mechanical properties of the material, hardened components will attain high compressive residual stresses and viscose core resulting in a higher degree of super- strengthening effect.

The generalized correlation for optimizing the chemical composition of steel, depending on the size and form of the steel part, is evaluated by equation (14), [20], [21]:

$$\frac{DI_a}{D_{opt}} Kn^{0.5} = 0.35 \pm 0.095 \quad (14)$$

The critical thickness of a small model DI_a, which is equal to the form of a real steel part, D_{opt} is the thickness of steel part to be quenched. Here Kn is Kondrat'ev number. For cylindrical forms like semi-axle, that is quenched in condition $Bi \to \infty$, the correlation (14) became more simple and is written as, [20]:

$$\frac{DI}{D_{opt}} = 0.35 \pm 0.095 \quad (15)$$

According to author, [22], critical diameter DI for a cylinder depends on the chemical composition of steel and is evaluated as:

$$DI = 25.4 \times f_{Fe} \times f_{Mn} \times f_{Si} \times f_{Cr} \times f_{Ni} \times ..... \quad (16)$$

where f_x is the multiplicative factor for the particular alloying element. The available set of alloy factors is presented in the book by author, [23]. These multiplicative factors are used for optimizing the chemical composition of steel depending on the size and form of the steel part. More information on an optimal hardenability steels and chemical composition optimization can be found in the book, [21].

It was shown by authors that intensive quenching (IQ) provides compressive residual stresses, [23], [24], [25]. The optimal hardenability steel provides optimal stress distribution through the section of hardened steel parts creating very high compression residual stresses and hardness at the surface. Core hardness is reduced with the high viscosity of material that increases the service life of hardened components.

6 Technique of Film Boiling Elimination

6.1 Optimal Concentration of Water Salt Solutions

The HTTMT and LTTMT, as a rule, in many cases are performed in water solutions under pressure to eliminate the developed film boiling process.

Quenching is performed in water solutions of neutral salts. The optimization of aqueous salt solutions is achieved by controlling the ionic charge that is present at the interface of the quenchant and the metal surface. A phenomenon was described by author, [26], [27] and further developed by authors, [28]. It should be noted here that quenching processes, [29], [30], are investigated by scientists thoroughly while intensive HTTMT and LTTMT are not investigated enough. The current paper asks scientists put together their efforts to investigate properly the intensive HTTMT and LTTMT technologies.

As known, for all electrolytes there are optimal concentrations where the first critical heatflux densities are maximum (Figure 10).

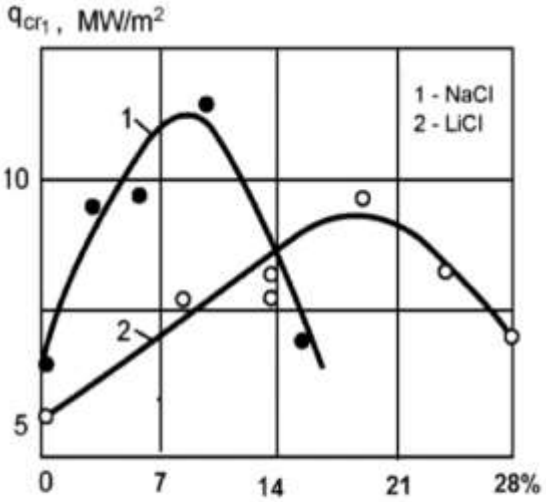


Fig. 10: Maximal critical heat flux densities qcr1 versus concentration for NaCl and LiCl [7]: 1 is NaCl; 2 is LiCl

Some water salt solutions are used in the heat treating industry as quenchants to eliminate film boiling processes that provide uniform cooling and decrease distortion of steel parts after quenching.

Any water salt solution provides the maximum value of the first critical heat flux density if the concentration is optimal (Figure 10).

6.2 Intensive Quenching in Pressurized Fluid Flow

Figure 11 shows the schematic installation to provide intensive and uniform cooling by exploring pressurized fluid flow. Critical heat flux density in this case can be increased by short-lasting external negative electrical force directed to semi – the axle.

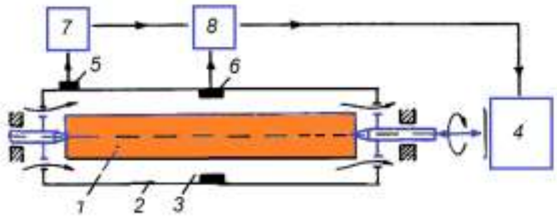


Fig. 11: Detailed scheme of quench chamber with automatic control, [7], [31], [32]: 1 – semi-axle; 2 – quench chamber; 3 – pressurized water flow; 4 – mechanical drive for semi-axles; 5 – sensor for analyzing the process. of nucleate and film boiling; 6 – sensor for analyzing the portion of transformed structures by the changing ferromagnetic state; 7 – electronic device (amplifier and microprocessor); 8 – amplifier

Currently, the technology is used for intensive quenching of trucks [7], [30], [31]. The technology provides high surface compression residual stresses and viscose core of semi-axles if low hardenability steel is used for their manufacturing. It can be incorporated easily in line with HTTMT and LTTMT technologies.

6.3 Surface Insulating Polymeric Layer that Reduces Initial Heat Flux Density

Low concentration (1%) of inverse solubility polymers is used as a quenchant for intensive quenching of steel parts. The technology explores thin surface polymeric insulating layer to reduce initial heat flux density according to equation (17):

$$q_{in} = \frac{q_o}{1 + 2\dfrac{\delta}{R} \cdot \dfrac{\lambda}{\lambda_{coat}}} \qquad (17)$$

It can be used also for performing HTTMT and LTTMT processes. Figure 12 shows a thin surface polymeric layer that covers metal to reduce initial heat flux density during quenching, [8]. The proposed technology saves polymers and increases the mechanical properties of steel due to the reduced concentration of polymers and intensive quenching (IQ) process. It decreases also distortion due to uniform and intensive cooling.

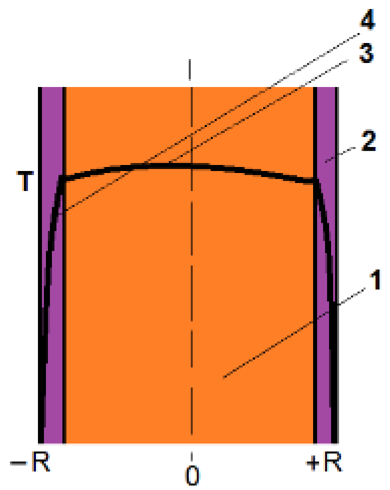


Fig. 12: Section of a coated cylindrical probe and typical temperature distribution during quenching in polymer water solution of inverse solubility

6.4 Resonance Effect to Eliminate Local and Developed Film Boiling Processes

To eliminate film boiling processes one can use special emitters that produce waves with frequencies equal to the frequencies of film boiling processes. The arrangement of emitters in the quench tank are shown in Figure 13, [8].

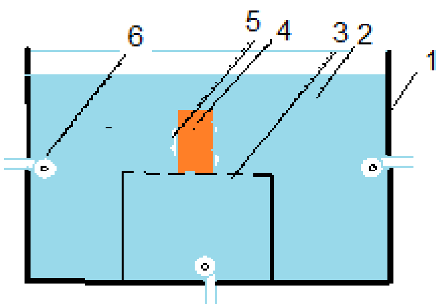


Fig. 13**:** Emitters arrangement in quench tank: *a* is emitter, where 1 is liquid flow, 2 is tube, 3 is circulated liquid stream, 4 is generator waves in liquid, 5 is regulator of wave frequency, 6 is liquid flow combined with generated waves; *b* is quench tank with located in it emitters, where 1 is quench tank; 2 is water salt solution of optimal concentration; 3 is fixture; 4 is steel part; 5 is local film boiling; 6 is emitter

6.5 Effect of Intensive Quenching for Providing High Surface Compression Stresses

The effect of intensive quenching on surface compression residual stress formation was for the first time discussed by authors, [7]. Further accurate numerical investigations in this field were fulfilled in the USA, Germany, and Japan [33], [34] and [35]. An overview, of concerning results of experiments and calculations, is provided in the handbook [30]. Now is clear that compression residual stresses can be formed by interrupting intense cooling at the proper time, [8], or reducing alloying of steel to provide an optimal hardened layer in quenched component, [21]. Cooling time interruption is discussed below.

7 Universal Correlation for Cooling Time Calculation

The universal correlation was proposed for calculating the heating and cooling times of any steel part during its hardening, [7], [8]. The same technique can be used when performing HTTMT and LTTMT processes. The equation contains Kondratjev form factor K, Kondratjev number Kn, the average thermal diffusivity of a material, and a function depending on how N times the core temperature of a steel part differs from its initial temperature. It is shown that these parameters are enough to calculate recipes when heating and cooling the steel parts of any configuration. A tendency of thermal equilibrium establishment is considered, which depends on the size and configuration of objects, thermal diffusivity of material, and the condition of cooling (heating) characterized by Kondratjev number Kn. The proposed generalized equation provides engineers with extremely simple and understandable parameters for calculating the heating (cooling) soak time of any object. According to the proposed equation, the time of thermal equilibrium establishment is directly proportional to Kondrat’ev form factor K, inversely proportional to the thermal diffusivity of material and Kondratjev number Kn, and depends on the accuracy of the thermal equilibrium measurement, see Eq. (17) and Table 5:

$$\tau_{eq} = E_{eq} \frac{K}{aKn} \tag{17}$$

Table 5. Coefficients E_{eq}, depending on dimensionless value $N = (T_0 - T_S)/(T - T_S)$ which was decreased from 1.5 to 1,000 times

$Bi_V = 2$ E_{eq}										
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.61	0.90	1.12	1.30	1.46	1.59	1.71	1.81	2.51	4.81	7.11
Cylinder	0.81	1.10	1.32	1.50	1.66	1.79	1.91	2.02	2.71	5.01	7.33
Sphere	1.01	1.30	1.52	1.71	1.86	1.99	2.11	2.22	2.91	5.21	7.51
$Bi_V = 3$ E_{eq}											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.625	0.912	1.135	1.318	1.472	1.605	1.723	1.828	2.522	4.824	7.127
Cylinder	0.843	1.131	1.354	1.537	1.691	1.824	1.942	2.047	2.741	5.043	7.346
Sphere	1.062	1.350	1.573	1.757	1.910	2.043	2.161	2.266	2.960	5.262	7.565
$Bi_V = 5$ E_{eq}											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.63	0.92	1.14	1.32	1.48	1.61	1.74	1.83	2.54	4.83	7.13
Cylinder	0.86	1.15	1.37	1.50	1.71	1.84	1.97	2.07	2.77	5.06	7.36
Sphere	1.10	1.38	1.61	1.80	1.94	2.08	2.20	2.30	3.00	5.29	7.58
$Bi_V = \infty$ E_{eq}											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.64	0.93	1.15	1.33	1.49	1.62	1.73	1.84	2.53	4.84	7.15
Cylinder	0.87	1.16	1.38	1.51	1.72	1.85	1.96	2.08	2.76	5.07	7.38
Sphere	1.11	1.39	1.62	1.80	1.95	2.09	2.20	2.31	3.00	5.30	7.60

Approximately thermal equilibrium is established when $E_{eq} = 7.136$ for plate; $E_{eq} = 7.362$ for cylinder and $E_{eq} = 7.582$ for sphere.

8 High and Low-Temperature Thermo-Mechanical Treatment

The HTTMT of forgings, made of optimal hardenability steels, requires complete intensive cooling to room temperature. Figure 14 shows combined high and low thermomechanical treatment with the possibility of obtaining the fine or nano-bainitic microstructure at the core of forgings

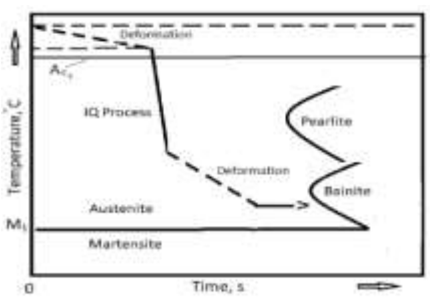


Fig. 14: HTTMT and LTTMT to obtain fine bainitic microstructure

In this case, after forging, the component is intensively cooled to low thermomechanical treatment temperature, forged again, and cooled a second time and tempers at the specific temperature that provides nano bainitic microstructure. Such technology can provide super-strengthened material and increase significantly the service life of forged machine components, [6], [7], [8]

9 Discussion

It has been shown by the author of well-known investigations, [5], [6] that fine bainitic microstructure has better mechanical properties (strength and viscosity) as compared with the martensitic microstructure. After a short discussion of some problems with the author, [5], it was clear that there is a big problem in delaying martensite transformation when steels are quenched intensively. As a rule, for obtaining bainitic microstructure steel components are quenched slowly in hot oils or melted salts to delay the start of martensitic transformation. After reducing of steel core temperature in melted salts, steel components go to tempering to obtain fine bainitic microstructure. Since the cooling rate in melted salts is rather low, engineers use high alloy steels to delay any transformation during slow cooling, and then undercooled steel goes for long tempering to obtain bainitic microstructure. It is impossible to obtain fine bainitic microstructure for low alloy steels using slow cooling. Our investigations allow delaying martensite transformation during the IQ process quenching steel in fluid under pressure (Figure 5 and Figure 10). It means that fine bainitic transformation can easily be obtained using plain carbon steels and any alloy steels. The problem is very important for the practice which is why it makes sense to further discuss the problem at the conferences. There are highly developed tools and devices for infestation cooling processes in fluids to predict hardness distribution during the hardening of materials, [35], [36]. There are computer codes for the fluid dynamics investigations, [37] and highly developed codes for temperature fields and stress distribution investigations, [38] and fracture phenomena when the material is brittle [39]. If these opportunities together, it will be possible to properly investigate HTTMT and LTTMT processes.

10 Conclusions

1. A new high-temperature thermo - mechanical strengthening of low-carbon or middle carbon alloy steel is proposed. After forging steel part is intensively quenched with an interruption cooling process at a moment when the optimal surface hardened layer is formed to create surface compression residual stresses. After the interruption of the cooling process, steel goes to immediate tempering to create fine bainitic microstructure at the core and a martensite surface strengthened layer at its surface.
2. A new high-temperature and low temperature thermo-mechanical strengthening of high-carbon alloy steel is proposed. After forging the steel part is intensively quenched delaying martensitic transformation and interrupting the cooling process at the moment when low-temperature thermo-mechanical treatment is possible. Then high temperature and low temperature thermo-mechanical treatment is performed followed by immediate tempering to create highly strengthened material (fine bainitic microstructure throughout all sections of forged steel part).
3. A modified method of cooling time calculation suitable for any size and form of steel part quenched intensively in cold water or special water solution is proposed to perform correctly high temperature and low-temperature thermo-mechanical treatment.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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