Transient Nucleate Boiling as a Basis for Designing Austempering and Martempering New Technologies

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Abstract

As a rule, austempering and martempering processes are performed in melted salts and alkalis that is not environment friendly technology which has several restrictions due to slow cooling. The paper discusses unexpected and cardinally new technologies. Austempering and martempering processes are performed intensively in environment friendly water solutions or just in plain water under pressure. Due to intensive cooling, all restrictions are released and several opportunities are added such as combining austempering with the HTMT and LTMT processes. The new technologies are based on self – regulated thermal process (SRTP) meaning maintenance the surface temperature of steel parts at the level of boiling point of a cold liquid. Based on SRTP, the recipes calculations are considerably simplified, more accurate and understandable. The paper can be useful for engineers and scientists dealing with the improvement the quality of materials.

Keywords - *Nucleate boiling, Self – regulated thermal process, Intensive austempering and martempering, Simplified calculations, Accuracy, Benefits.*

I. DURATION OF TRANSIENT NUCLEATE BOILING PROCESS AND ITS MAIN CHARACTERISTICS

Very simple equations (1), (2), and (3) were received by author [1, 2, and 3] for calculating duration of transient nucleate boiling process:

$$\tau_{nb} = \left[0.24k + 3.21\ln\frac{\vartheta_I}{\vartheta_{II}} \right]\frac{K}{a} \qquad (1)$$

$$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R} \right]^{0.3} \qquad (2)$$

$$\vartheta_{II} = \frac{1}{\beta}\left[\alpha_{conv}\left(\vartheta_{II} + \vartheta_{uh} \right) \right]^{0.3} \qquad (3)$$

Here $\vartheta_0 = T_0 - T_s$; $\vartheta_I = T_1 - T_s$; $\vartheta_{II} = T_2 - T_s$; $\vartheta_{uh} = T_s - T_m$; T is temperature; T_o is initial temperature; T_m is bath temperature; T_s is saturation temperature; T_1 is start nucleate boiling temperature; T_2 is finish of nucleate boiling temperature; τ_{nb} is duration of transient nucleate boiling process in sec; R is radius in m; a is thermal diffusivity in m^2/s, λ is thermal conductivity of a material in $W/m\,K$; α_{conv} is convective heat transfer coefficient in W/m^2K; $\beta = 3.41$ for water at 20^oC; $m = 10/3$ is exponent; K is Kondrat'ev form factor in m^2; $k = 1,2,3$ for plate, cylinder and sphere correspondently; Pr is dimensionless Prandtl number.

Eqs. (1), (2), and (3) were reduced to more simple from (4) [4]:

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

The value Ω is a function of the convective Biot number when initial temperature T_o is fixed at 850^oC and bath temperature is fixed at room temperature (see Fig. 1).
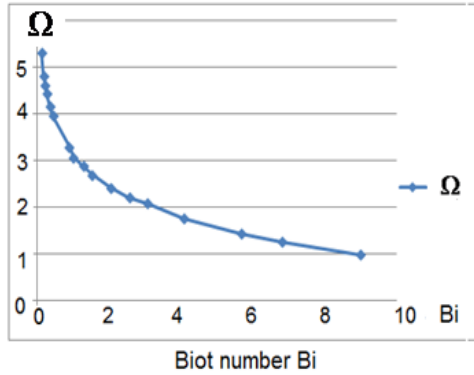
Fig. 1 Value Ω versus Biot number Bi depending on size of steel part and heat transfer coefficient during convection [4]

Table 1 provides form coefficients k_F and Kondrat'ev K coefficient for different shapes of steel parts which don't depend on initial temperature since they are soul characteristic of each specific form of steel part.

Table 1 Form coefficient k_F and Kondrat'ev K coefficient for different shapes of steel parts

Form	k_F	K, m^2
Plate	0.1013	$L^2/9.87$
Cylinder	0.0432	$R^2/5.783$
Sphere	0.0253	$R^2/9.87$
Cube	0.0338	$L^2/29.61$
Cylinder D = Z	0.0303	$Z^2/33$

Data in Table 1 are used for recipes development during performing austempering and martemperinh processes.

The duration of transient nucleate boiling along with steel surface temperature Tsf is a basis for developing the new intensive austempering and martempering technologies.

II. SELF – REGULATED THERMAL PROCESS

The duration of transient nucleate boiling process, when film boiling is completely absent and surface temperature of steel part maintains at the level of boiling point of a liquid, is called the self – regulated thermal process (SRTP). The notion "self – regulation" follows from the fact that overheat of the boundary layer during transient nucleate boiling process is controlled by cooling system itself. Existence of self – regulated thermal process (SRTP) during quenching probes and steel parts was proved by theoretical consideration and by many experimental data [3]. Its meaning consists in

following. The surface temperature of steel part during immersion into liquid quenchant drops immediately almost to saturation temperature of a liquid and maintains at this level relatively a long time until transient nucleate boiling is finished. This can be easily explained. The real heat transfer coefficient (HTC) at the beginning of boiling is very large and can reach more than 200,000 W/m^{2}K [5]. Convective HTC is rather small and for still water and water salt solutions is within 400 - 1200 W/m^{2}K. Convective HTC in average is 200 times smaller as compared with the nucleate boiling process [5]. It means that $\alpha_{conv} << \alpha_{nb}$ or

$$Bi_V^{conv} << Bi_V^{nb} \qquad (5)$$

Here Bi_V^{conv} is generalized Biot number during convection; Bi_V^{nb} is generalized Biot number during transient nucleate boiling process. To prove theoretically existence of SRTP let's consider a well-known universal correlation (6) [6]

$$\frac{\overline{T}_{sf} - T_m}{\overline{T}_V - T_m} = \frac{1}{\sqrt{Bi_V^2 + 1.437 Bi_V + 1}} \qquad (6)$$

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

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. (5), one can assume that $Bi_V \rightarrow 0$. In this case, according to Eq. (6), $\overline{T}_{sf} \rightarrow \overline{T}_V$. It means that surface temperature must increase immediately if it drops below T_s and occurs in convection area. Assume now that overheat of boundary layer is rather large. In this case generalized Biot number Bi_V is very large also which tends to infinity, *i.e.* $Bi_V \rightarrow \infty$. According to Eq. (6), in this case $\overline{T}_{sf} \rightarrow T_s$ and it means no temperatures overheat of a boundary layer at all and transient nucleate boiling process must stop. Only one way is left. The surface temperature must be very close to boiling point of a liquid from the very beginning of cooling. That is in good agreement with the experiments of French [7]. The cooling system regulates overheat $\Delta\overline{\zeta}$ by itself which depends on size and form of a steel part. The overheating is small as compared with the initial temperature T_0. For practical use, one can consider this behavior of the surface temperature as:

$$T_{sf} = T_S + \Delta\overline{\zeta} \approx const \qquad (7)$$

It means that equations (1), (2), and (3) can be used to predict approximately surface temperature during transient nucleate boiling process. Some results of calculations supporting this idea are provided below.

III. ACCURACY OF SIMPLIFIED CALCULATIONS

Accuracy of simplified calculations was checked based on accurate experimental data received in 2011 in Japan (see Fig. 2) [8]
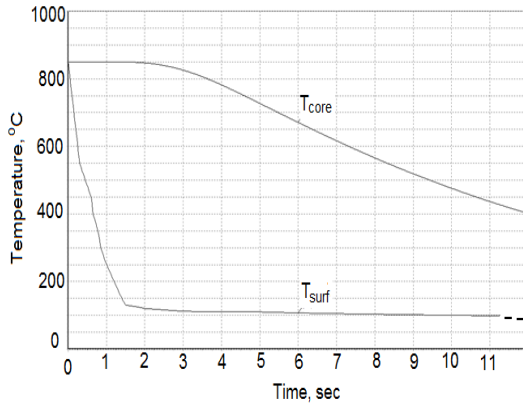

Fig. 2 Cooling curves obtained in Idemitsu Kosan Co., Ltd. lab for cylindrical specimen of 28 mm diameter and 112 mm length when quenching in water flow of 1.5 m/s at 20 ^{o}C [8]

Fig. 2 provides experimental cooling curves versus time received in 2011 in the Idemitsu Kosan Co., Ltd. Lab (Japan) for cylindrical specimen of 28 mm diameter and 112 mm length when quenching in directed flow of water salt solution at 20 ^{o}C moving with a speed 1.5 m/s. The results of joint investigations were published in Ref. [8]. Let's used this accurate experimental data to compare results of simplified calculations with the results of experiments. To construct simplified calculation, we'll explore the notion of the "self – regulated thermal process" and classical experiments of French [7]. According to French, cooling curves (surface temperature) versus time during quenching in 5% water NaOH solution at 20°C are always the same independently on size of the probe [7]. And the surface temperature of his probes drops from 875°C to 150°C within 1 s. To establish developed nucleate boiling process, it takes in average 1.5 sec when film boiling is completely absent. Experiment of authors [8] showed the same results (see Fig.2). Thus, we can assume that for majority of sizes and different forms of steel parts transient nucleate boiling process establishes within 1.5 sec. This is the first requirement for our simplified

calculations. The second requirement is averaging surface temperature during SRTP. As discussed above, the overheat $\Delta\overline{\zeta}$ is very small as compared with the initial temperature T_0. For practical use, one can level this behavior as $T_{sf} = T_S + \Delta\overline{\zeta} \approx const$. Here T_{sf} is surface temperature during transient nucleate boiling process; $\Delta\overline{\zeta}$ is average overheating responsible for transient nucleate boiling process.

According to Eq. (2), overheat at the beginning of nucleate boiling for cylindrical probe 28 mm in diameter is 23.7^{o}C and at the end of nucleate boiling (Eq. (3) overheat is 14.3 ^{o}C. Duration of nucleate boiling process, according to Eq. (1), is 12 sec. We calculated average surface temperature during transient nuclear boiling process as T = (123.7^{o}C + 114.3^{o}C)/2 = 119°C. The constructed by such a way the surface temperature of cylindrical probe of 28 mm in diameter was used for numerical calculations. Calculated cooling curve data coincide well with the experimental data at the center of cylindrical probe 28 mm in diameter (see Fig 2 and Fig. 3).
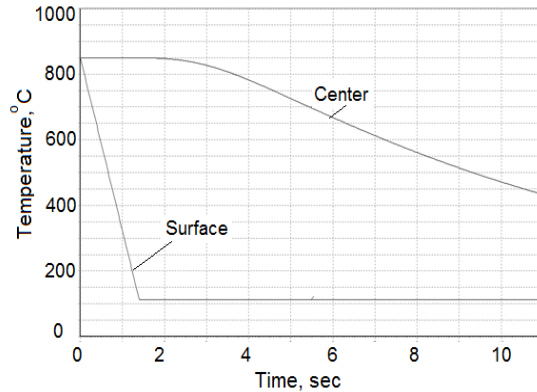

Fig. 3 Calculated cooling curves for cylindrical specimen of 28 mm diameter and 112 mm length when quenching in water flow of 1.5 m/s at 20 ^{o}C.

As seen from Fig. 2 and Fig. 3, simplified calculation coincides with the experimental data of authors [8].

The question is how averaging affects the accuracy of calculations. To find out the effect of averaging, the calculations were made with average surface temperature during self – regulated thermal process and with the real changing the overheating during SRTP. For calculations temperature fields in cylindrical specimen were used the next thermo-physical data: T_0 = 850°C, α_{conv} = 380 W/m^{2}K; λ = 22 W/mK;; a =

5.4 x 10^{-6} m^2/s; D = 30 mm, ϑ_I = 20; ϑ_{II} = 5°C; K = 38.91 x 10^{-6}m^2.

It was established that accuracy of core temperature calculation was less than 0.2%. Thus, the averaging of surface temperature during SRTP doesn't affect significantly calculated core temperature during quenching process.

In heat treating industry, effective heat transfer coefficients are often used for recipes calculation. As known [4], effective HTCs can be used only for core cooling curves calculations and cannot be used for temperature field calculation during transient nucleate boiling process. To support this idea, additional test calculations were fulfilled using IQLab software [9]. Computer simulation was performed for plate quenched in water salt solution of $CaCl_2$, Boiling point of solution was 130°C and bath temperature was 30°C. The convective heat transfer coefficient was 380 W/m^{2}K. . For calculations temperature fields in plate (slab) 30 mm in thickness the next thermo-physical data were used: T$_0$ = 850°C, α_{conv} = 380 W/m^{2}K; λ = 22 W/mK;; a = 5.4 x 10^{-6} m^2/s; L = 30 mm. Results of calculations are presented in Fig. 4 and Fig. 5.
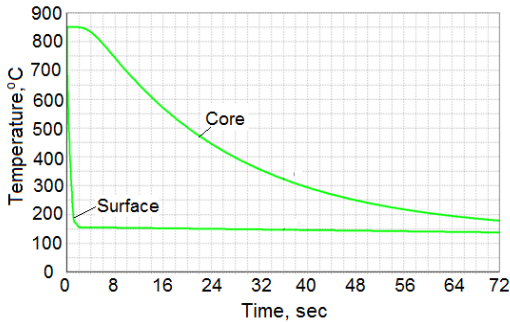

Fig. 4 Surface and core cooling curves vs time during quenching the slab sample 30 mm in thickness in water solution of CaCl₂ at 30°C.

Fig. 4 provides cooling curves on the surface and at the center of 30 mm thickness plate during quenching in water solution of $CaCl_2$ at 30°C. As seen from Fig. 4, the surface temperature during transient nucleate boiling process maintains a long time at the level of 150°C. This fact can be used for performing austempering and martempering processes via underheated water salt solutions of $CaCl_2$ if martensite start temperature M$_S$ is 130°C.
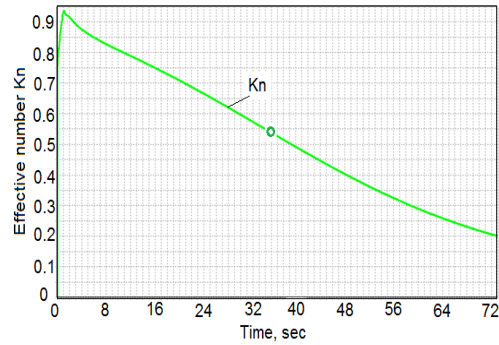

Fig. 5 Effective number Kn vs time during quenching the slab 30 mm in thickness in water solution of CaCl₂ at 30°C. Average Kn = 0.57

Fig. 5 presents effective number Kn versus time observed during quenching of 30 mm thickness plate in water solution of $CaCl_2$. Its average value is Kn = 0.57. This average value of Kn can be used to predict core temperature using generalized equation (8).

Numerical calculations shown in Fig 4 and analytical calculations performed by equation (8) are compared in Table 2.

$$\tau = \left[\frac{kBi_V}{2.095 + 3.867 Bi_V} + \ln \frac{T_0 - T_S}{T - T_S} \right] \frac{K}{aKn} \qquad (8)$$

Table 2 Comparison results of numerical calculations with the simplified analytical calculationa for plate (slab) 30 mm of thickness.

Core , °C	Numerical calculation, s	Analytical calculation, s	Error, %
300	37.35	38	+1.7
350	32.5	32.5	0
400	28	28.3	+1.1
450	23	24.6	+6.9
500	20	21.38	+6.9

Table 2 shows that effective HTCs can be used for austempering and martempering recipes development providing accuracy of calculation 0 – 7%..

Similar calculations were fulfilled for cylindrical and spherical specimens which are presented in Fig. 6 and Fig. 7.
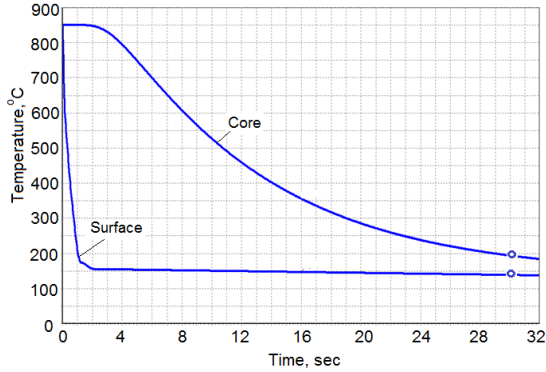
Fig 6 Surface and core cooling curves vs time during quenching the cylindrical sample 30 mm in diameter in water solution of CaCl₂ at 30°C

Note that average effective number Kn for plate is 0.57, for cylinder Kn is 0.56 and for spherical sample Kn is 0,53.

Using this fact, one can assume that other forms of steel parts will show the same result. Comparison of numerical calculation with the analytical calculation for cylinder is shown in Table 3.

Table 3 Comparison results of numerical calculations with the simplified analytical calculation when quenching cylindrical specimen 30 mm in diameter in water solution of CaCl₂ at 30°C

Core temperature, °C	Numerical calculation, s	Analytical calculation, s	Error, %
300	19	18.9	+0.5
350	16	16.6	+3.7
400	14	14.7	+ 5
450	12.3	13.1	+6.5
500	10.5	11.1	+6

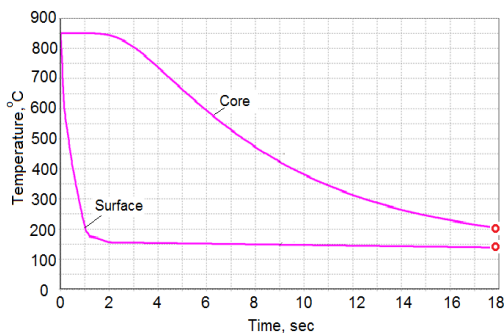The same is true for spherical specimens (see Fig. 7 and Table 4)

Fig. 7 Surface and core cooling curves vs time during quenching the spherical sample 30 mm in diameter in water solution of CaCl₂ at 30°C

Table 4 Comparison resultsss of numerical calculations with the simplified analytical calculationa when quenching spherical specimen 30 mm in diameter in water solution of CaCl₂ at 30°C

Core temperature, °C	Numerical calculation, s	Analytical calculation, s	Error, %
300	12.4	12.6	+1.6
350	10.7	10.8	+0.9
400	9.5	9.75	+2.6
450	8.45	8.8	+4
500	7.5	7.97	+6.2

Thus, the smoothing of the surface temperature during SETP results in 0.2% error during core cooling curve calculation while effective HTC results almost 7% error.

IV. AUSTEMPERING AND MARTEMPERING PROCESSES VIA UNDERHEATED WATER SALT SOLUTIONS

For the first time, the martempering process via cold water salt solutions of elevated concentration was used .in Ukraine in 1990 for strengthening of tools for needs of the AutoKrAZ company [10, 11]. The patented coolant consists of one or two valence chlorides (6 – 77% wt) and additive of Ca(OH)₂ (0.01 – 0.15% wt) to keep pH at the level of 7.5 – 12.5 [10]. In the heat treating shop of AutoKrAZ was used water solution of CaCl₂ of elevated concentration (1375 kg/m³) with additive providing pH 8. The boiling point of water solution was approximately 130°C. Convective heat transfer coefficient was within 380 -400 W/m²K. Tools made of plain high carbon and alloy high carbon steels were quenched first in underheated water salt solution and then, after finishing the nucleate boiling process, cooling was interrupted and tools were immersed immediately into mineral oil to complete cooling to bath temperature. Service life of martempered tools increased in 1.5 – 2 times as compared with conventional oil quenching in oil. To be more specific, below the process of stamp hardening is considered (see Fig. 8). The square stamp, shown in Fig. 8, has a thickness of working area 32 mm and its width is 140 mm. Diameter of working area is 90 mm. Martensite start temperature of high carbon steel used is 130°C. Bath temperature is 50°C and boiling point of CaCl₂ solution is 130°C. With the provided initial data, one should perform martempering process to increase service life of stamp shown in Fig. 8.
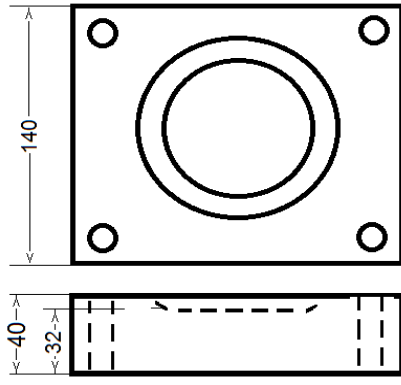
Fig. 8 Stamp made of high carbon steel to be martempered via cold water salt solutions with boiling point 130°C

First of all, one should calculate overheating of a boundary layer at the beginning and at the end of nucleate boiling and its duration using equations . (1), (2), and (3). Austenitizing temperature for high carbon steel is 800°C. Average thermal conductivity of steel is 22.65 W/mK and average thermal diffusivity of steel is 5.37 x 10^{-6} m^2/s.

According to Eq. (2),

$$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3} = \frac{1}{3.41}\left[\frac{2\times22.65(700 - \vartheta_I)}{0.016}\right]^{0.3} = 22.52^o\,C$$

Accrding to Eq. (3), overheating of a boundary layer at the end of nucleate boiling process is:

$$\vartheta_{II} = \frac{1}{3.41}\left[380(80 + \vartheta_{II})\right]^{0.3} = 6.64^o\,C$$

Duration of transient nucleate boiling process, according to Eq. (1), is:

$$\tau_{nb} = \left[0.24 + 3.21\ln\frac{22.52}{6.64}\right]\frac{103.7\times10^{-6}}{5.37\times10^{-6}} = 80.3\,\text{sec}$$

Now, one can design the first kind of boundary condition for quenching of stamp, taking into account that surface temperature of stamp, according to French, drops from 800°C to 152.52°C in 1.5 sec. At the end of transient nucleate boiling process surface temperature of stamp is 136.64°C. Using any available software that provides FEM numerical calculation, it is possible to receive cooling curve at the center of stamp (see Fig. 9).
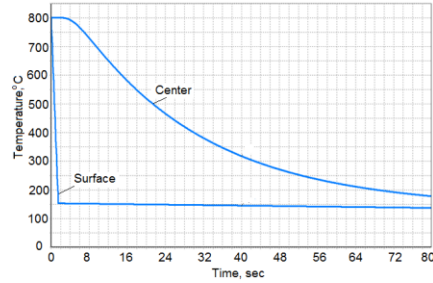

Fig. 9 Cooling curves within the nucleate boiling process during stamp quenching in water solution of CaCl$_2$ at 50°C that has a boiling point 130°C

As one can see from Fig. 9, the core temperature of stamp at the end of transient nucleate boiling process is close to the surface temperature which is above the martensite start temperature M_S . At the moment of time 80 seconds there are two options. The first option is austempering process via cold liquid. In this case one should put the stamp after 80 seconds of accelerated cooling for immediate tempering at a temperature which exceeds M_S. The second option is martempering. In this particular case one should put stamp into oil for cooling to bath temperature. The option depends on working condition of stamp. The proposed new technology is environment clean that increases significantly service life of tools.

V. AUSTEMPERING PROCESS PERFORMED IN COLD WATER UNDER PRESSURE

Fig. 10 presents the basic scheme of an automated process for performing austempering process in liquid quenchant under controlled pressure. The quenching process is conducted such a way. When the mobile cover 3 is at starting position I, the sample (5), which is austenitized, is delivered to the tray (1). At this time, the driving mechanism is turned on, and the movable cover occupies work position II hermetically closing the top of the quench tank. Simultaneously, through an aperture (2), compressed air is introduced, creating the necessary pressure between the quenchant and the movable cover. When pressure is delivered, the quenchant saturation temperature become equal to martensite staert temperature Ms. When quenching in water under pressure, a delay of the transformation of austenite into martensite takes place until nucleate boiling is finished. The formation of the ferromagnetic martensitic phase is fixed by the solenoid (6). The signal from the solenoid is amplified by (A) and triggers the relay (R) to actuate the driving mechanism (G), which moves the movable cover (3) to top starting position I. The part (5) is ejected from the tray (1) and delivered for immediate tempering at a temperature T > M$_s$. The cycle is repeated again [1]. This cooling process under pressure

may be used for continuous automated industrial lines to perform austempering process vial cold liquids under pressure. The described quenching method [12] expands the potential of low-temperature thermomechanical treatment (LTMT). At the end of the nucleate boiling process, the steel part consists wholly of supercooled austenite. The temperature in the core of the part at the end of nucleate boiling is still high and material is supercooled austenite. Therefore, after nucleate boiling is finished, the part consists completely of supercooled austenite which can be subjected to the plastic deformation that is called low – temperature thermomechanical treatment (LTMT). In this case, the mechanical and plastic properties of steel are improved [13 - 17]. The method of steel quenching in water and aqueous solutions under controlled pressure can be effectively applied for those steel grades that have a martensite start temperature M_s equal to or less than 200^oC. Below, an examples of performing austempering process via cold liquid under pressure illustrates the main idea.

Example 1. A cylindrical steel part 20 mm in diameter, made of AISI 1080 steel, is batch quenched under pressure 0.7 MPa in the system shown in Fig. 10. Previously experiments showed that martensite transformation can be delayed for 10 seconds (see Fig. 11) [1]. Note that the surface temperature of steel parts during self – regulated thermal process maintains at the level of saturation temperature plus overheat of a boundary layer.
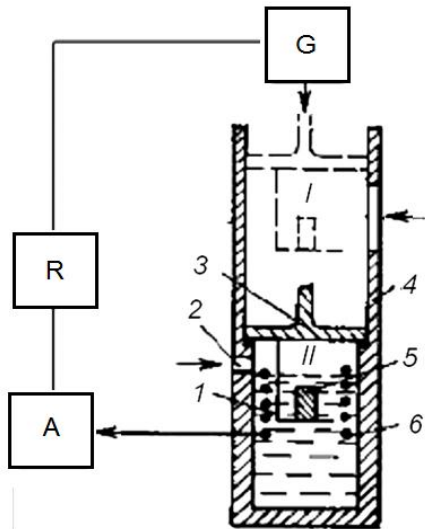

Fig. 10 Basic scheme of the automated austempering process under pressure [1]: 1, tray; 2, compressed air; 3, mobile cover; 4, tank; 5, workpiece; 6, solenoid; A, amplifier; R, relay; G, driving mechanism; I, starting position; II, work position

As seen from Fig. 11, martensite transformation in high carbon steel with Ms = 200^oC is completely delayed and immediate tempering at a temperature higher than 200^oC will provide bainitic transformation during tempering. More information on bainitic transformation, mechanical properties and other benefits one can find in the literature [14].
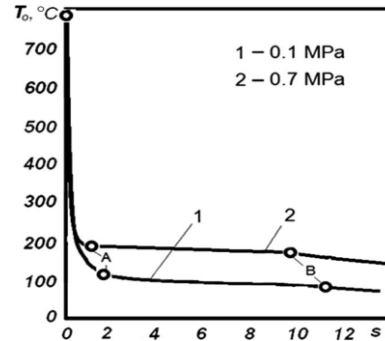

Fig. 11 Effect of redundant pressure on the elevating surface temperature of 20 mm steel probe during SRTP: 1, normal pressure (0.1 MPa); 2, Redundant pressure 0.7 MPa [15, 16]

Example 2 A cylindrical sample 50 mm in diameter and 75 mm height, made of high carbon steel, is prepared for quenching in cold liquid under pressure 0.7 MPa to perform low temperature thermomechanical treatment combined with the austempering process. Calculate cooling time to be used for quenching specimen in quenching system 10. Kondrat'ev form factor K = 90.8×10^{-6} m^2; thermal diffusivity a = 5.4×10^{-6} m^2/s; thermal conductivity λ = 23 W/mK; convective HTC = 790 W/m^2K.
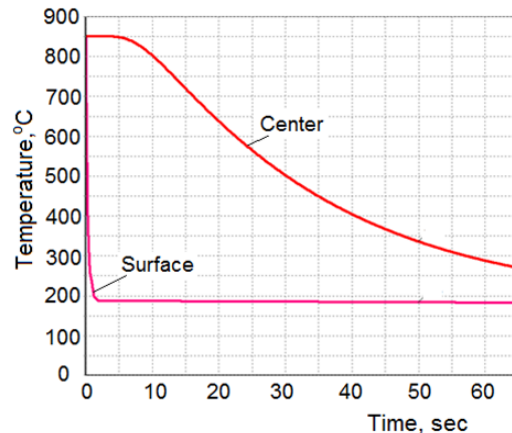

Fig. 12 Cooling curves vs time during quenching of cylindrical sample 50 mm dia 75 mm height in cold water under pressure 0.7 MPa

Results of numerical calculations are shown in Fig. 12. Surface temperature of specimen during quenching

under pressure 0.7 MPa maintains at the level almost 200°C It means that martensite transformation is delayed up to 65 seconds. At the moment of time 65 seconds the intensive cooling should be interrupted to perform low temperature themomechanical treatment.. As seen from Fig. 12, average temperature after interruption of cooling process is (560°C + 190°C)/2 = 375°C. Temperature 375°C is suitable for performing LTMT process. After performing LTMT the specimen should go for tempering at a temperature 200°C to obtain bainitic microstructure after austempering process . Such technology can provide superior mechanical properties of material which significantly exceed mechanical properties after conventional hardening process.

Fig. 13 shows how effective number Kn changes versus time during quenching of cylindrical specimen. Its average value is 0.57 that can be used for LTMT recipes development. For example, if we need interrupt cooling process at 500°C , then interruption time is calculated using Eq. (8).

Calculations showed that this time is approximately 30 sec. Accuracy of calculations are provided by Table 5.
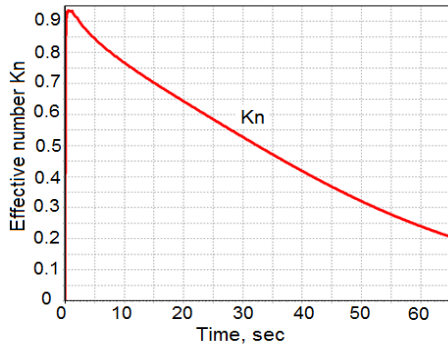

Fig. 13 Effective number Kn vs time during quenching the cylindrical sample 50 mm in diameter and 75 mm height in water at a pressure 0.7 MPa at 20°C. Average Kn = 0.57

Table 5 Comparison results of numerical calculations (see Fig. 12) with the simplified analytical calculations, Eq. (8)

Core temperature, ^{o}C	Numerical calculation, s	Analytical calculation, s	Error, %
300	57	57	0
350	47	49.6	- 5
400	40	38	- 5
450	35	35.7	+2
500	30	31.5	+5

VI. AUSTEMPERING PROCESS VIA WATER SOLUTIONS OF INVERSE SOLUBILITY POLYMERS

During quenching steel parts in water polymer solutions of inverse solubility thin surface polymeric layer is formed which increases essentially a shoulder of self – regulated thermal process up to 450°C. This can be explained as follows. After formation of surface polymeric layer, on its surface self – regulated thermal process is established and surface temperature is fixed at

a level $T_{sf} = T_S + \Delta\bar{\zeta} \approx const$ (see Eq. (7)).

Due to this fact, the temperature gradient in the insulating layer is much larger as compared with the temperature gradient in steel part or probe [15, 16]. That is a main reason for increasing the surface temperature of steel part during transient nucleate boiling process. To see such behavior, let's consider heat flux densities on the border of insulating layer – steel which should be equal, *i.e.*

$$\lambda_{in} grad_{in} = \lambda_{sl} grad_{sl} \qquad (9)$$

or

$$\frac{grad_{in}}{grad_{sl}} = \frac{\lambda_{sl}}{\lambda_{in}} \qquad (10)$$

Here $grad_{in}$ is a temperature gradient in the insulating layer; $grad_{sl}$ is a temperature gradient in cylinder; λ_{in} is thermal conductivity of insulating layer; λ_{sl} is thermal conductivity of steel.

Since the surface temperature of insulated probe during transient nucleate boiling is fixed and maintains at the level of boiling point of a liquid, surface temperature of steel must increase to satisfy the ratio (10). As known, thermal conductivity of insulating polymeric layer is very low and is equal approximately to 0.2 W/mK as the same time the thermal conductivity of steel in average is 22 W/mK . It means that surface of steel, according to Eq. (7) and Eq. (10) must increase to the level of 400°C – 450°C creating a "shoulder" during self – regulated thermal process. This fact is very important and can be used for performing austempering processes via cold water solution of inverse solubility polymers. Moreover, it was noticed by authors [17, 18] that temperature in the surface layer of the probe was varying with passing of time. It can be easily explained by varying the thickness of the insulating layer [15, 18]. More information on contemporary quenching processes one can find in Ref. [15 - 18]. The above consideration is supported by experiments of authors [17 -18]. Fig. 14

shows cooling curves versus time during quenching of cylindrical probe 20 mm in diameter and 80 mm long in water solution of polyoxyethylene (0.2 %) at a temperature 23 ºC [18]. Here 1 is surface temperature; 2 is core temperature of cylindrical probe.

Austempering process can be easily performed if cooling process in water solution of polyoxyethylene (0.2 %) is interrupted at a time 25 seconds of cooling and specimen is put for immediate tempering at a temperature 400°C. In this case the austenite in surface layers of cylindrical probe transforms into lower bainite while in the core of cylindrical specimen austenite transforms into mixture containing upper bainite and pearlite (see Fig. 14).
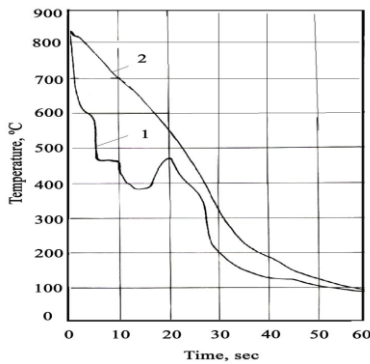

Fig. 14 Surface (1) and core (2) temperature vs time during quenching cylindrical probe 20 mm in diameter and 80 mm length in water solution of 0.2% polyoxyethylene at 23 ^{o}C [18]

Our experiments showed the possibility of performing austempering and martempering processes via cold liquids which can be conbined with HTMT and LTMT [19].

VII. CONCLUSIONS

Austempering and martempering processes can be performed via cold liquids due to existing of SRTP. Three different possibilities exist for performing austempering and martempering processes in cold liquids: interrupted intensive cooling in high concentration of water salt solutions; interrupted cooling in cold water under pressure; interrupted cooling in water solutions of inverse solubility polymers with immediate tempering at a temperature T > M$_s$.

Combining austempering and martempering processes with the high temperature and low temperature thermo – mechanical treatment, one can anticipate essential improvement of the mechanical properties of materials [19].

It is shown that complicated analytical calculations can be simplified if self – regulated thermal process is taken into account

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