Optimized Steel Quenching Processes and Their New Modifications

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Abstract

The paper discusses quenching steel parts in water flow when transient nucleate boiling process is completely absent. This process was called intensive quenching (IQ-3) technology or direct convection which was patented in Ukraine and US. According to patented technology, IQ process should satisfy the direct convection criterion and should be interrupted at proper time to create optimal hardened layer resulting in maximal surface compressive residual stresses. Equipment for performing this technology is complicated and expensive. Author proposes a new modified IQ-3M technology that provides optimized hardened layer during conventional accelerated quenching via optimizing chemical composition of steel. In contrast to existing IQ-3 process, optimized hardened layer can be achieved in any size of steel part and technology is less costly which should be widely used in heat treating industry. It is shown that cooling process should be interrupted at a time where nano – bainitic microstructure at the core of quenched steel parts is formed and high surface compressive residual stresses after quenching are appeared. For this purpose, an optimal hardenabily steel is used which is patented in Ukraine. The new IQ-3M technology saves alloy elements, increases service life of steel components and reduces cost of new technology. For governing quenching process, the software was developed by Intensive Technologies Ltd (ITL), Kyiv, Ukraine. The main attention is paid to physics of the quenching process that significantly simplifies recipes development. The new idea, discussed in this paper, will be useful for engineers and scientists who are working on materials savings and environment improvement.

Keywords - *Nucleate boiling absence, direct convection, IQ-3M technology, service life, material savings, environment improvement, cost reduce.*

I. INTRODUCTION

In last decades serious attention is paid to bainitic and nano – bainitic microstrutures which provide very high mechanical properties of steel, especially its plastic properties [1]. As a rule, bainitic appropriate transformation is performed using austempering processes. In previous publications [2, 3], it has been discussed the possibility of performing austempering processes via cold liquids that significantly increases cooling rate during quenching. In this paper is shown that bainitic microstructure can be easily obtained at the core of steel parts combined with high compressive residual stresses on the surface of steel parts. Such procedure is possible due to use of optimal hardenabily steel which provides optimal hardened layer and high surface compressive residual stresses even after intensive cooling to room temperature [2]. This new technology is discussed below.

II. CRITERION TO BE USED FOR PROVIDING DIRECT CONVECTION

As is already known, the duration of transient nucleate boiling process is calculated using equation (1) [4 - 6]:

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

Here τ_{nb} is duration of transient nucleate boiling in sec; k = 1, 2, 3 for plate, cylindrical and spherical like forms correspondently;

$$\vartheta_I = \frac{1}{3.41}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3} \qquad (2)$$

$$\vartheta_{II} = \frac{1}{3.41}\left[\alpha_{conv}\,(\vartheta_{II} + \vartheta_{uh})\right]^{0.3} \qquad (3)$$

$\vartheta_I = T_I - T_s$; $\vartheta_{II} = T_{II} - T_s$; T_I is start temperature of transient nucleate boiling process; T_{II} is finish temperature of transient nucleate boiling process; T_s is saturation temperature; α_{conv} is convective heat transfer coefficient in W/m^2K; $\vartheta_{uh} = T_s - T_m$ is underheat; T_m is bath temperature; R is radius in m; K is Kondrat'ev form coefficient in m^2; a is thermal diffusivity of steel in m^2/s; λ is thermal conductivity of steel in W/mK. To avoid nucleate boiling process, it is necessary for econd part of Eq. (1) to be zero, *i.e.*, $\ln\frac{\vartheta_I}{\vartheta_{II}} = 0$ or $\vartheta_I = \vartheta_{II}$.

Equating Eqs. (2) and (3), one can get a criterion of direct convection (4):

$$Bi = \frac{2\left(\vartheta_0 - \vartheta_I\right)}{\vartheta_I + \vartheta_{uh}} \qquad (4)$$

Equation (4) is the basic criterion that determines absence of transient nucleate boiling process during steel part quenching. As a rule, steel parts are quenched in water flow or powerful shower to avoid transient nucleate boiling process and provide direct convection [4, 6]. Basic scheme of cooling cylindrical steel parts in water flow is shown in Figure 1 [4].

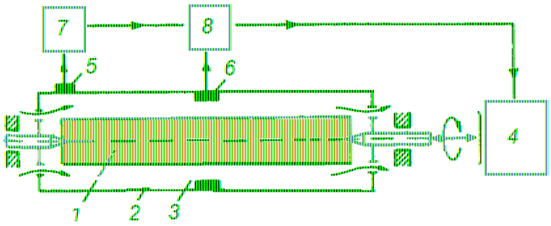


Figure 1. .Detailed scheme of quench chamber with automatic control [4, 8]: 1 – semi-axle; 2 – quench chamber; 3 – pressurized water flow; 4 – mechanical drive for semi-axles; 5 – sensor for analyzing the process of nucleate and film boiling; 6 – sensor for analyzing the portion of transformed structures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

In the generalized form the equation of similarity for evaluating heat transfer coefficients during quenching in channels is provided in Ref. [7]. During quenching the long enough cylindrical steel parts in round chamber the equation for calculating speed of water flow is [7, 8]:

$$W = \frac{\nu}{D}\left(\frac{Nu}{0.03\,\mathrm{Pr}^{0.43}}\right)^{1.25} \qquad (5)$$

Here W is water flow speed in m/s; ν is kinematic viscosity of liquid in m^2/s; D is inner diameter of chamber in m; Nu is Nusselt number; Pr is Prandtl number.

Accelerated cooling should be interoperated at proper time. As known, cooling time versus core temperature of any steel part during direct convection is calculated as:

$$\tau = \left[\frac{kBi_V}{2.095 + 3.867\,Bi_V} + \ln\frac{T_0 - T_m}{T - T_m}\right]\frac{K}{aKn} \qquad (6)$$

Here τ is cooling time in sec; k = 1, 2, 3 for plate cylinder and sphere correspondently;

Bi_V is generalized Biot number; T_0 is initial austenitizing temperature; T_m is bath temperature; Kn is dimensionless Kondrat’ev number, $0 \le Kn \le 1$. $\vartheta_I = T_I - T_s$; $\vartheta_{uh} = T_s - T_m$; T_s is saturation temperature.

III. THERMAL EQUILIBRIUM ESTABLISHMENT

In 1926 well known mathematician Boussinesq proposed the general solution for parabolic heat conductivity equation with the third type of boundary condition for objects of any configuration which was presented in form (7) and used by Kondrat’ev to develop regular thermal condition theory [9 - 10].

$$\frac{T - T_m}{T_0 - T_m} = \sum_{n=1}^{\infty} A_n U_n \exp\left(-m_n \tau\right) \qquad (7)$$

$$m_1 < m_2 < m_3 \ldots.. m_n < m_{n+1} \qquad (8)$$

A_n are temperature amplitudes;

U_n are eigenfunctions dependent on coordinates which are known only for simple configurations.

In a very short time, due to inequities (8), the process of cooling of a body of any shape is described just by a simple exponent (9):

$$\frac{T - T_m}{T_0 - T_m} = A_1 U_1 \exp\left(-m_1 \tau\right) \qquad (9)$$

What does mean the simple exponent from the point of view of physics? Ref. [11] provides the next explanation. Assume that there are two barrels: 200 liters and 100 liters in volume and two cups which differ two times from each other (see Figure 2).

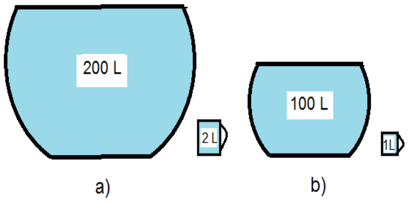


Figure 2. Explanation of physical meaning of the exponential law by reducing water in barrels: a, barrel 200 L; b, barrel 100 L.

According to simple exponent (9), for two barrels are true the two simple exponents (10) and (11):

$$V_I = 200\,L\exp\left(-0.1\tau\right) \qquad (10)$$

$$V_{II} = 100\,L\exp\left(-0.1\tau\right) \qquad (11)$$

The first barrel every single second looses twice more water as compared with the second barrel (see Eqs. (12), (13), and Table 1).

$$\Delta V_I = 200L\left[\exp(-0.1\tau_n) - \exp(-0.1\tau_{n+1})\right] \qquad (12)$$

$$\Delta V_{II} = 100L\left[\exp(-0.1\tau_n) - \exp(-0.1\tau_{n+1})\right] \qquad (13)$$

Table I

Decrease water in barrels according to exponents (12) and (13).

Time, sec	**0**	**1**	**2**	**3**	**4**	**5**	$\tau \to \infty$
ΔV_I	0	19	17	16	14	13	2 molecules
ΔV_{II}	0	9.5	8.5	8	7	6.5	1 molecule

At the end of exponential process in the first barrel will be two molecules of water and in the second barrel will be only one molecule of water. The first micro-cup will take two molecules of water and the second one will take one molecule of water. At this point, the process is finished simultaneously since there is no more water in both barrels.

Let's consider one more example, concerning cooling time measurement, when cooling the same spherical probe 60 mm in diameter from 200°C and 100°C in water at 0°C to temperatures 0.2°C and 0.1°C. According to simple exponent, cooling time from 200°C to 0.2°C is equal to cooling time from 100°C to 0.1°C because ln (200°C – 0°C)/(0.2°C – 0°C) = ln (100°C – 0°C)/(0.1°C – 0°C). In reality, at the end of cooling temperature difference can be reduced up to fluctuation temperature which according to Ref. [12] is:

$$\Delta T = 10^{-10}T \qquad (14)$$

Taking into account temperature difference equal to temperature fluctuation (14), cooling time from 200°C and 100°C to 0°C is 353 sec and 347 sec correspondently [11]. Difference between both duration of cooling is only 1.7% that is within the frame of experimental accuracy measurement. It means that thermal equilibrium is established in final period of time and initial temperature doesn't effect significantly its time establishment that is in good agreement with the zeroth law of thermodynamics [11].

Based on above analysis, author [11] proposed to consider the thermal equilibrium establishment when dimensionless temperature θ decreases 1000 times (see Table II). Table II provides cooling time of arbitrary body in point C. The volume V and surface S of a body is shown in Fig. 3. This arbitrary body is cooled in condition where generalized Biot nunber Bi_V is known (see Eq. (15) [8, 9].

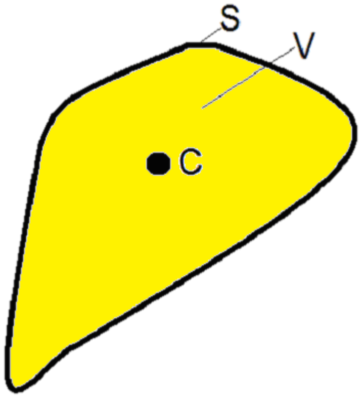


Figure 3. Example of arbitrary steel part shape for calculating cooling time during its quenching: S is surface in m²; V is volume in m³; C is center where cooling curve is calculated.

$$Bi_V = \frac{\alpha}{\lambda} K \frac{S}{V} \qquad (15)$$

Here α is heat transfer coefficient in W/m^2K ; λ is thermal conductivity in W/mK; K is Kondrat'ev form coefficient in m^2.

There is a universal correlation between generalized Biot number and dimensionless Kondrat'ev number Kn (see Figure 4 and Eq. (16)) [9, 10].

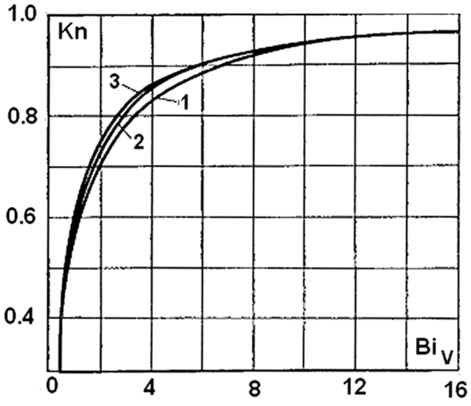


Figure 4. Universal relationship between Kn and Bi$_V$, [9, 10]: 1, plate; 2, cylinder; 2, cylinder; 3, sphere.

$$Kn = \frac{Bi_V}{\left(Bi_V^{\,2} + 1.437\,Bi_V + 1\right)^{0.5}} \qquad (16)$$

Obtained curves in Fig. 4 are so close to each other that creators of the regular condition theory [9, 10] recommended to use it for any shape and size of steel part because inverse radius for classical shapes changes from 0 to infinity. Since 1954 the regular condition theory of Kondrat’ev has been supported by thousands of accurate experiments. At present time it is successfully used for recipes development during quenching steel parts of complex configurations [13 - 15]. And finally, the regular condition theory creates the opportunity for obtaining universal equation for heating and cooling time calculation of steel parts which is presented below (see Eq. (17)).

TABLE II

Coefficients E_{eq} depending on dimensionless value θ which decreases from 1.5 to 1000 times for different generalized Biot numbers Bi_V.

E_{eq}											
$Bi_V = 0.1$											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.44	0.73	0.96	1.14	1.29	1.43	1.54	1.65	2.38	4.64	6.95
Cylinder	0.49	0.77	1.00	1.18	1.33	1.47	1.58	1.69	2.42	4.68	6.99
Sphere	0.55	0.81	1.04	1.22	1.37	1.51	1.62	1.73	2.46	4.72	7.02
$Bi_V = 0.5$											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.50	0.78	1.01	1.19	1.34	1.48	1.60	1.70	2.39	4.70	7.00
Cylinder	0.59	0.88	1.10	1.28	1.44	1.57	1.69	1.79	2.49	4.79	7.09
Sphere	0.68	0.97	1.19	1.37	1.53	1.66	1.78	1.88	2.58	4.88	7.18
$Bi_V = 1$											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.53	0.817	1.04	1.22	1.38	1.51	1.63	1.73	2.43	4.73	7.03
Cylinder	0.65	0.94	1.16	1.35	1.50	1.63	1.75	1.86	2.55	4.85	7.16
Sphere	0.78	1.07	1.29	1.47	1.62	1.76	1.88	1.98	2.67	4.98	7.28
$Bi_V = 2$											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.57	0.86	1.08	1.27	1.42	1.55	1.67	1.78	2.47	4.77	7.07
Cylinder	0.74	1.03	1.25	1.44	1.59	1.72	1.84	1.94	2.64	4.94	7.25
Sphere	0.91	1.20	1.42	1.60	1.76	1.89	2.01	2.11	2.80	5.11	7.41
$Bi_V = 3$											
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	1.1	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
$Bi_V = 5$											
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	1.73	1.83	2.53	4.83	7.13
Cylinder	0.86	1.15	1.37	1.55	1.71	1.84	1.96	2.07	2.76	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
$Bi_V = \infty$											
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	1.74	1.84	2.54	4.84	7.15
Cylinder	0.87	1.16	1.38	1.56	1.72	1.85	1.97	2.08	2.77	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

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

For condition, when generalized Biot number is larger 2 and Kondrat'ev number is within 0.7 and 1 , $0.7 \le Kn \le 1$, thermal equilibrium establishment can be calculated by Eq. (17 a):

$$\tau_{eq} = 7.36\frac{K}{aKn} \tag{17 a}$$

. Its physical meaning is explained by Figure 5.

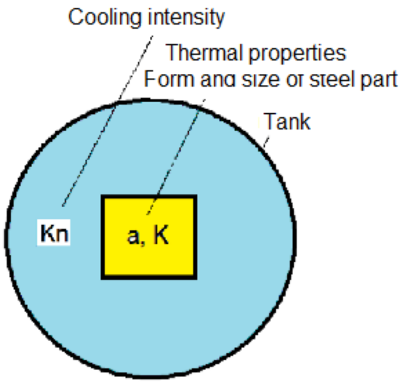


Figure 5. A scheme which shows which parameter of quench system should be taken into account to calculate correctly cooling time during direct convection: Kn is Kondrat'evdimensionless number; a is thermal diffusivity of steel in m^2/s; K is Kondrat'ev coefficient in m^2

Here Kn is responsible for cooling intensity of quenchants; a and K are responsible for thermal properties, form and size of steel part. These three main parameters allow calculating heating and cooling time during hardening of steel components.

IV. IDEAL CRITICAL DIAMETER TO BE USED FOR OPTIMIZING CHEMICAL COMPOSITION OF STEEL

From available in literature CCT diagrams [8, 14 - 16] is known that $\tau_M \approx 10$ sec. If so, then the ideal critical diameter, according to equation (19), is:

$$DI = \left(\frac{23.13 \times 5.4 \times 10^{-6} m^2/s \times 10s.}{2.54}\right)^{0.5} = 0.02217m$$

.or DI = 22.17 mm. The ideal critical diameter (DI) refers to the largest bar diameter that contains 50% martensite at the center after being quenched in the condition $Bi \to \infty$. The ideal critical diameter can be estimated from Jominity standard curves, well known Grossmann equation or from the cooling continuous transformation (CCT) diagram (see Figure 6) when $Bi \to \infty$ [17] resulting in new technologies with the many benefits (see Table III). The last is easily calculated using obtained equation (17) which can be rewritten as:

$$DI = \left(\frac{23.13 a\tau_M Kn}{E_{eq}}\right)^{0.5} \tag{18}$$

Here $\tau_{eq} = \tau_M$. When $Bi \to \infty$., ideal critical diameter DI is calculated as:

$$DI = \left(\frac{23.13 a\tau_M Kn}{E_{eq}}\right)^{0.5} \tag{19}$$

For AISI 1045 steel the value E_{eq} is:

$$E_{eq} = \frac{860^{\circ}C - 20^{\circ}C}{350^{\circ}C - 20^{\circ}C} = 2.54 \cdot$$

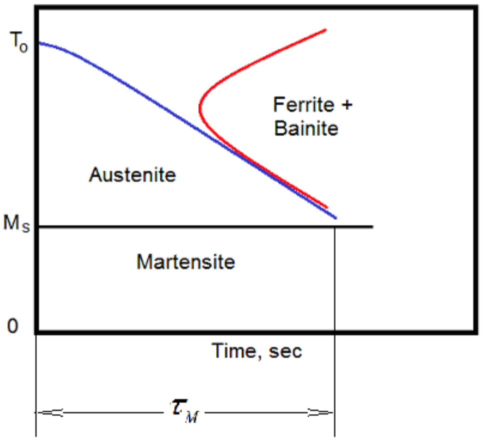


Figure 6. CCT diagram for calculation the ideal critical diameter DI.

According to Grossmann equation, the ideal critical diameter for AISI 1045 steel containing 0,45 C, 0.25 Si, and 0.80 Mn is calculated as [17]:

$$DI = 25.4 \times f_{Fe} \times f_{Si} \times f_{Mn} =$$
$$= 25.4 \times 0.21 \times 1.175 \times 3.667 = 22.98mm$$

Table III
The main differences between old and new patented technologies

Old technology	New technology	Comments
Intensive cooling is interrupted at proper time to provide maximal surface compressive residual stresses.	Maximal surface compressive residual stresses are achieved by optimizing chemical composition of steel..	New technology allows reducing alloy elements in steel from 2 to 3 times as compared with old technology
Old technology requires performing intensive quenching in costly and complicated cooling systems to provide direct convection .	New technology allows performing conventional cooling in water polymer or water salt solutions of low concentration that drastically reduces its cost.	New technology can be easily and widely implemented into practice.
Sizes of steel pars are restricted by sizes of special fixtures.	Any size of steel part, including large rotors and rollers, are suitable. ,	New technology allows cooling in open quench tanks with moderate agitation of quenchant.
There is no possible to combine maximal surface compressive residual stresses with nano- bainitic microstructure at the core of steel parts since interruption of cooling occurs at a more higher temperature.	There is possible to combine maximal surface compressive residual stresses with nano- bainitic microstructure at the core of steel parts since compressive stresses are provided by optimizing chemical composition of steel	High surface compressive residual stresses and bainitic microstructure at the core of steel parts provide increased service life of hardened components.
There is no software for optimizing chemical composition of steel. Alloy steels are used for intensive quenching.	There is software for optimizing chemical composition of steel. Plain carbon or low alloy steels are used for intensive quenching	New technology significantly saves alloy elements in steel.

Both results of calculations coincides very well with each other. Approximately the same result of calculation of ideal critical diameter one can achieve from Jominy standard curve. It means that equation (15) can be used to optimize chemical composition of steel when quenching machine components in water salt solutions or water polymer solutions of optimal concentration. In this case, according to Ukrainian Patent UA No. 114174, C2, the base equation for optimizing chemical composition of steel can be wreritten as [16, 17]:

$$\frac{DI \cdot Kn^{0.5}}{D_{opt}} = 0.35 \pm 0.095 \qquad (20)$$

When quenching steel parts in water salt solutions or polymer water solutions, the effective Kondrat’ev numbers Kn should be known from accurate experiments. As an exaple, Figure 7 provides Kondrt’ev numbers Kn for PAG water polymer solution of different concentration [16]. For the first time this approach was used in 1980 for optimizing chemical composition of steel for AutoKrAZ semi –axles [5, 8]. Later it was used for other cylindrical steel parts. The novelty of chemical composition optimizing, patented in Ukraine [14], consists in its extension for any form of steel part. It was possible due to achievements of regular thermal condition theory [9, 10]. Proposed method of chemical composition optimizing allows switching from quenching intensively in water flow to quenching in water salt solution of optimal concentration or water solutions of low concentration polymers [15, 16] that is less costly. Other benefits are discussed in Table III. .

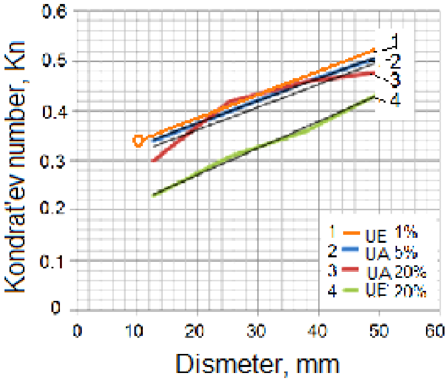


Figure 7. Effective Kondrat’ev numbers Kn for inverse solubility water solutions of polymers depending on their concentrations and size of product [16]: 1 is 1 % of UCON E in water; 2 is 5 % of UCON A in water; 3 is 20 % of UCON A in water; 4 is 20 % of UCON E in water at 20oC

Example 1. Semi- axle of truck 62 mm in diameter should be made from medium carbon low alloy steel to provide optimal hardened layer after quenching in 1% water solution of PAG. The solution can be made by following the next steps:

1. Calculate ideal critical diameter using Grossmann method [17].
2. Provide for calculation effective Kondrat'ev number Kn [16].

0.40 C;; 0.20 Si; 0.50 Mn. ; 0.25 Cr. Its critical diameter DI

$$DI = 25.4 \times f_{Fe} \times f_{Si} \times f_{Mn} \times f_{Cr} = .$$

$$= 25.4 \times 0.20 \times 1.14 \times 2.67 \times 1.54 = 23.81 mm$$

According to Fig. 7, effective Kondrat'ev number Kn for thickness 62 mm of semi-axles is 0.56.

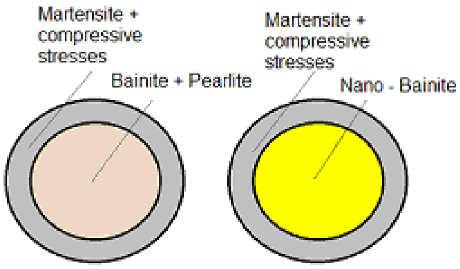
To satisfy chemical composition of steel to given thickness of semi - axles, the ratio (20) should be equal to 0.35. It is:

$$\frac{23.81 mm \times (0.56)^{0.5}}{62 mm} = 0.287$$

that satisfies the ratio (20) **.**

V. HIGH SURFACE COMPRESSIVE RESIDUAL STRESSES COMBINED WITH NANO-BAINITIC MICROSTRUCTURE

When optimal hardenability steel is chosen, maximal surface compressive residual stresses are formed even during complete cooling. In this case cooling should be interrupted to get nano - bainitic or very fine bainitic microstructure at the core of steel parts. Old technology doesn't allow intensive cooling interruption at reduced core temperature because surface compressive residual stresses will be significantly reduced. Figure 8 provides difference between old and new technologies.



a) b)

Figure 8 Difference between IQ-3 and IQ-3M technologies: a), optimal martensitic layer with high surface compressive residual stresses and bainite- pearlite microstructure at the core; b), optimal martensitic layer with high surface compressive residual stresses and bainite or nano - bainite microstructure at the core

Intensive cooling during direct convection should be interrupted at a time which provides bainitic or nano –

3. Satisfy the ratio (20) by adjusting chemical composition of steel .

One can start with use the medium carbon steel containing

banitic microstructure at the core of quenched steel part and high compressive residual stresses in surface layers where superstrengthening of material takes place. Combining intensively quenched optimal hardenability steel that provides optimal martensitic surface layer and high surface compressive residual stresses (see Figure 9).

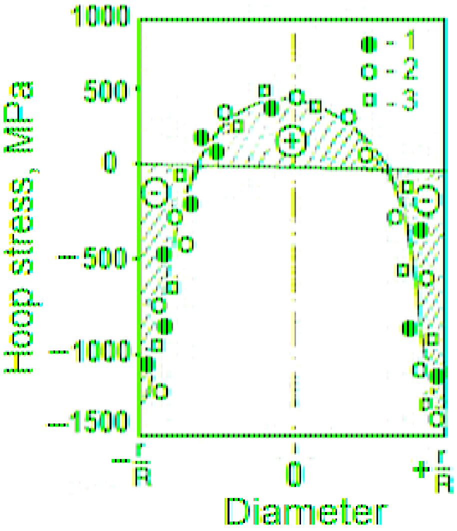


Figure 9. Residual hoop stress distribution in cylindrical *specimens* ***when quenching intensively in water flow [13, 14, 15]***.

Table IV shows increased mechanical properties of steel at the core of cylindrical specimens for AISI 4135 steel .

TABLE IV

Mechanical properties at the core of cylindrical specimen 50 mm dia made of ASTM 4135 steel after oil and intensive quenching [8].

Me-thod	R_m MPa	$R_{p0.2}$ MPa	**A (%)**	**Z (%)**	a_k J/cm^2	**HB**
Oil	950 955	775 770	14 16	53 57	54 54.5	285 293
IQ	970 970	820 820	17 17	63 59	150 140	285 285

New technology can provide elevated mechanical and plastic properties of materials due to presence nano - bainitic microstructure at the core of steel parts [1, 8, 14].

VI. CONCLUSIONS

1. Modified direct convection technology IQ-3M differs from already known technology IQ – 3 by use optimal hardenability steel to provide optimal hardened layer with the maximal surface compressive residual stresses and proving cooling time interruption at a moment when bainitic and nano – bainitic transformation takes place at the core of steel parts.
2. Simplified method of cooling time interruption is proposed based on established correlation between cooling time and thermal properties of material, Kondra'ev form factor , amd dimensionless number Kn.
3. The proposed method of simplified calculation can be used for optimizing chemical composition of steel

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