Hardening of Low and Optimal Hardenability Steels and their Physical Processes Explanation

Nikolai I. Kobasko

PhD, Fellow of ASM International
Intensive Technologies Ltd., Kyiv, Ukraine and IQ Technologies Inc., Ohio, USA

Abstract - *The main idea of this paper is the possibility of cardinal improving quenching technologies, reduce their cost, increase service life of machine components and tools and make technology green based on accurate investigations of the behavior a liquid coolant during hardening in it heated to high temperature metal. It is shown in the paper that recently discovered new features of transient nucleate boiling process allow designing new technologies for optimal hardenability steels comprising mentioned above characteristics. It is underlined in the paper that many already existing grades of steels can serve as low hardenability (LH) steel for large steel parts to provide similar stress distribution after quenching (high surface compression residual stresses and low tensile stresses at the core). Moreover, it is proposed by author a new criterion for designing quenching processes for low hardenability and optimal hardenability steels that always provide surface compression residual stresses. Along with mentioned above, the paper continues discussion the possibility of performing intensive quenching (IQ) processes in slow agitated water and water solutions. This fact cardinally reduces the cost of technological process and makes it as a mass production technology to be used worldwidly. It is shown in the paper that without investigation of physics of quench process, it is impossible to design appropriate software for governing and controlling of quenching processes. All provided information can be useful for investigators, scientists and engineers .* .

Keywords: *Physics of quench process; LH and OH steels; Hardenability criterion; Mass production; Power density; Low cost.*

I. INTRODUCTION

As known, low hardenability (LH) steel contains minimum alloy elements to provide shell hardening of small machine components during very intensive cooling [1,.2]. It cannot be used for large steel parts. Engineers in heat treating industry tried to use the high velocity quench systems to maximize cooling rate during quenching as much as possible. For this purpose were used quench systems proving water flow speed in channels up to 20 m/s [3 - 7]. Also, very powerful systems equipped with sprayers were used [6]. In 1967 authors [3] came to conclusion that intensive and uniform cooling prevents quench crack formation during quenching of splined truck semi- axles in water. Later author [6] showed that uniformity and intensity of cooling during quenching cannot prevent completely quench crack formation if different steel grades are used for intensive and uniform quenching. It means that chemical composition of steel affects quench crack formation which should be taken into account. In 2013 was invented optimal hardenability steel and method for its composing depending on size and form of tested sample [8 - 11]. Moreover, it is possible to perform uniform and intensive quenching in water polymer solutions of low concentration without their powerful agitation [12, 13]. That results in cardinal simplifying intensive quench process that uses optimal hardenability steel to prevent completely quench crack formation during intensive quenching. The main attention is paid to the physics of quench process to show engineers the great possibilities and benefits when all aspects of cooling in liquid media are taken into account.

II. CONTEMPORARY MATHEMATICAL MODEL FOR INTENSIVE QUENCHING PROCESS

The modern mathematical model for computation of temperature fields in steel parts during quenching in liquid media, when film boiling is absent, can be written as [14, 15]:

$$c\rho \frac{\partial T}{\partial \tau} + \frac{1}{w_r^2}\frac{\partial^2 T}{\partial \tau^2} = \lambda div\left(gradT\right) + \rho L \frac{\partial P}{\partial T}\frac{\partial T}{\partial \tau} \qquad (1)$$

$$\left[\frac{\partial T}{\partial r} + \frac{\beta^m}{\lambda}\left(T - T\right)^m\right]_{r=R} = 0 \qquad (2)$$

$$T\left(r,0\right) = T_o \qquad (3)$$

At the end of transient nucleate boiling process and establishing pure convection, the boundary conditions (2) transforms into normal form (4):

$$\left[\frac{\partial T}{\partial r} + \frac{\alpha}{\lambda}\left(T - T\right)\right]_{r=R} = 0 \qquad (4)$$

And temperature field in steel part at the end of nucleate boiling process become an initial condition for convection mode:

$$T(r, \tau_{nb}) = \varphi(r) \qquad (5)$$

The time of transition from transient nucleate boiling to pure convection is determined from equating heat flux densities q_{nb} and q_{conv}:

$$q_{nb} \cong q_{conv} \;, \qquad (6)$$

Here $w_r = \sqrt{\frac{a}{\tau_r}}$ is speed of thermal wave distribution in m/s [6]; $Q(T) = \rho L \frac{\partial P}{\partial T}\frac{\partial T}{\partial \tau}$ is a heat source connected with phase transformations inside of steel part to be quenched [16].

When speed of thermal wave distribution is infinity $(w_r \to \infty)$, the hyperbolic heat conductivity Eq. (1) become a classical parabolic heat conductivity equation (7):

$$C_{ef}\frac{\partial T}{\partial \tau} = \overline{\lambda}\, div(gradT) \qquad (7)$$

Where $C_{ef} = \rho\left(c \pm L\frac{\partial P}{\partial T}\right)$

Duration of transient nucleate boiling process is calculated using Eq. (8) [17]:

$$\tau_{nb} = \overline{\Omega}\, k_F \frac{D^2}{a} \qquad (8)$$

When $\overline{\Omega} = 0$, nucleate boiling is absent and its absence can be evaluated by Eq. (9) including Eq. (10):

$$Bi = \frac{2(\vartheta_o - \vartheta_I)}{\vartheta_I + \vartheta_{uh}} \qquad (9)$$

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

Plasticity theory equations are presented in detail in Ref 4 and 5 and have the following form:

$$\varepsilon_{ij} = \varepsilon_{ij}^{p} + \varepsilon_{ij}^{e} + \varepsilon_{ij}^{T} + \varepsilon_{ij}^{m} + \varepsilon_{ij}^{tp} \qquad (10)$$

with relevant initial and boundary conditions, where σ_{ij} is stress, ε_{ij} is total strain rate, ε_{ij}^{e} is elastic strain rate, ε_{ij}^{p} is plastic strain rate, ε_{ij}^{T} is thermal strain rate, ε_{ij}^{m} is strain rate for structural dilation due to phase transformations, ε_{ij}^{tp} is strain rate for structural dilation due to transformation plasticity, λ is thermal conductivity, and c is specific heat. Here $\vartheta_o = T_o - T_s$; $\vartheta_I = T_I - T_s$; $\vartheta_{uh} = T_s - T_m$.

α_{conv} is a heat transfer coefficient at convection;

r is the current radius of a cylinder, a sphere, or half of thickness of a plate;

τ_{nb} is the time of stationary nucleate boiling;

$\varphi(r)$ is the temperature field on cross section of a part at the time of the finish of the process of nucleate boiling;

T_m is a temperature of a bath far from a surface of a boiling layer. And $T_m < T_s$, where T_s is a saturation temperature of the quenchant in a boundary liquid layer. where q_{nb} is heat flux density at the end of nucleate boiling; q_{conv} is heat flux density at the beginning of convection.

III. CHEMICAL COMPOSITION OF LH AND OH STEELS AND THEIR DIFFERENCES

Chemical composition of Low hardenability (LH) steel was patented in 1999 in Russia (Russian Patent RU № 2158320) [2]:

C:	0.40 - 0.85
Mn:	≤ 0.20
Si:	≤ 0.20
Cr:	≤ 0.10
Cu:	≤ 0.10
Al:	0.03 - 0.10
Ti:	0.06 - 0.12
V:	≤ 0.40
Fe:	Bal

Optimal hardenability (OH) steel and method for its composing was filed in 2013 in Ukraine (Ukrainian Patent UA № 114174) [8, 9]:

C:	0.30 - 1.20
Mn:	≤ 0.20
Si:	≤ 0.20
Cr:	≤ 0.25
Ni:	0.06 – 1.6
Mo:	≤ 0.25
Cu:	≤ 0.10
Al:	0.03 - 0.10
Ti:	0.06 - 0.12
Fe:	Bal

Composition of optimal hardenability steel is supported by calculation of residual stress distribution and calculating depth of hardened layer.

Within 1979 – 1990 for calculating temperature fields and stress distribution in steel parts during quenching in Ukraine was widely used software HART which generated many interesting papers during that period of time [18 - 21].
Currently, in the USA for calculating residual stress distribution in steel parts during quenching well known software DANTE is used [22, 23].

A FEM method of current and residual stress calculations is described in Ref. [19, 20]. At each time and space step the calculated results were compared with the cooling continues temperature (CCT) diagram shown on Fig. 1 and thermal and mechanical characteristics for the nest step were chosen depending on structural components of hardened steel [20, 21]. It has been shown by such calculations that very high surface compression residual stresses appear after intensive quenching when steel parts is not quenched through. Mechanism of this phenomenon is explained in the book [16]. This fact was taken into account when developing chemical composition of optimal hardenability steel and method for its design [8, 9].

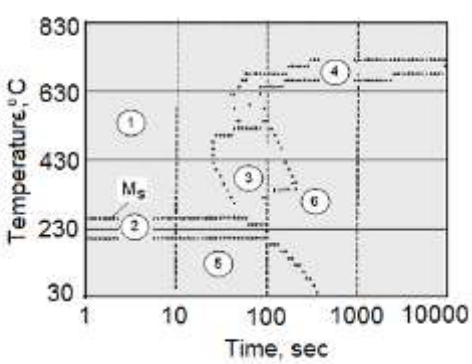


Fig. 1: CCT diagram for AISI 52100 steel: 1, austenite; 2, martensite (< 50 %); 3, bainite; 4, pearlite; 5, martensite
(> 50 %); 6, mixed structure [16].

As a result, the similarity in stress distribution and formation of hardened layer was established [18] which is shown on Fig. 2 and Fig. 3.

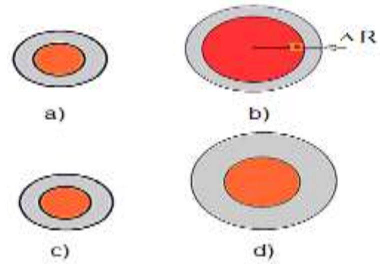


Fig. 2: Differences between LH and OH steels in hardened layer formation: a) and b) are shown hardened layers created by LH steel; c) and d) are shown hardened layers created by OH steel.

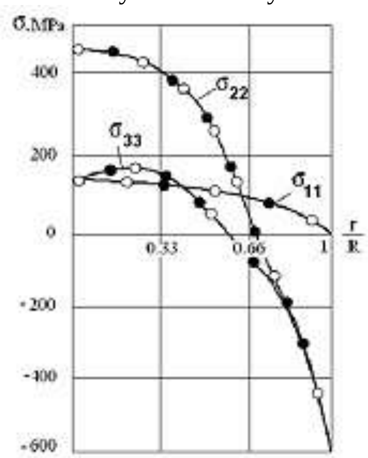


Fig. 3: Stress distribution through the section of two cylindrical specimens, one of diameter 6 mm (black data points) and the other of 60 mm (white points) at the time of the achievement of maximum compressive stresses at the surface of cylinders when Bi = 7; Fo = 0.7 [16].

Particularly, it has been established in 1983 that $\frac{\Delta R}{R} = const$ if Fourier number Fo and Biot number Bi are the same : $Fo = const$; $Bi = const$. Automatically it results in the similarity of the ratio:

$$\frac{DI}{D_{opt}} = const \quad (11)$$

According to Grossmann [24], critical diameter DI is function of chemical composition of steel and is written as:

$$DI = 25.4 f_C \cdot f_{Mn} \cdot f_{Si} \cdot f_{Cr} \cdot f_{Ni} \cdot f_{Mo} f_{Ti} \cdot \ldots \quad (12)$$

where all f_n components were evaluated by Grossmann experimentally (see Table 1) [25]. It should bre noted here that experiments of Grossmann are very important today becausee this data created a basis for designing software for chemical composition designing depending on form and size of machine components and tools to be hardened. To collect such experimental data it took a lond time and they were very costly. The experimental data obtained by Grossmann were compared with the data based on Jominy curves and they both fit each other very well. The program for optimazing chemical composition of steel depending on geometry of steel parts allows to find the most suitable steel among already existing grades to fit given geometry of steel part.

Table 1: Multiplier f_x depending on percentage of alloy element in steel and its grain size [2].

Content in %	f_C vs size of grain			f_x vs alloy elements in %				
	No. 6	No.7	No.8	Mn	Si	Ni	Cr	Mo
0.05	0.0814	0.0750	0.0697	1.167	1.035	1.018	1.1080	1.15
0.10	0.1153	0.1065	0.0995	1.333	1.070	1.036	1.2160	1.30
0.15	0.1413	0.1315	0.1212	1.500	1.105	1.055	1.3240	1.45
0.20	0.1623	0.1509	0.1400	1.667	1.140	1.073	1.4320	1.60
0.25	0.1820	0.1678	0.1560	1.833	1.175	1.091	1.54	1.75
0.30	0.1991	0.1849	0.1700	2.000	1.210	1.109	1.6480	1.90
0.35	0.2154	0.2000	0.1842	2.167	1.245	1.128	1.7560	2.05
0.40	0.2300	0.2130	0.1976	2.333	1.280	1.146	1.8640	2.20
0.45	0.2440	0.2259	0.2090	2.500	1.315	1.164	1.9720	2.35
0.50	0.2580	0.2380	0.2200	2.667	1.350	1.182	2.0800	2.50

The computer numerical modeling performed in 1983 – 1985 [18, 19] was a basis for establishing the criterion of optimal hardenability (13) used on the similarity theory and regular thermal condition theory of Kondrat'ev [26] . It can be used even for complicated steel parts. One of them is shown in Fig. 4. Fig. 5 shows stress distribution in a cylinder in condition when $Bi \to \infty$ [20].

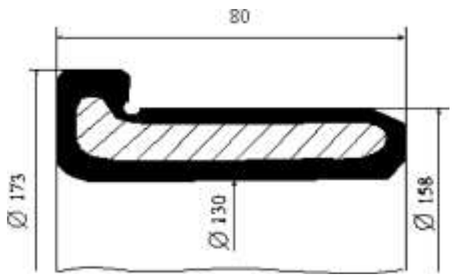


Fig. 4: Optimal hardened layer created during intensive quenching of bearing ring [20].

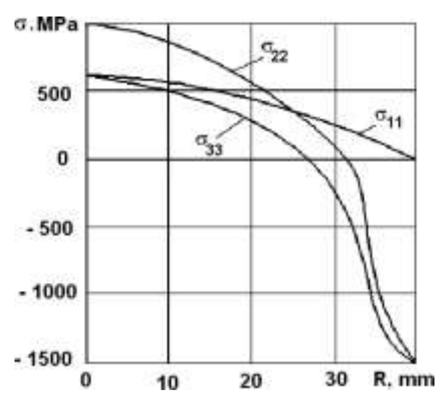


Fig. 5: Stress distribution through the cross-section of a cylindrical specimen (dia 80 mm) made of steel 45 (AISI 1045) after intensive hardening when cooling is completed in condition of Bi = 50 [18, 19].

Such behavior of stress distribution in cylinders was explained from the point of physics in Ref. [16].
Criterion of an optimal hardenability steel provides every time thickness of harnened layer which depends on thickness of a sample and is governed by the law of samilarity theory $\Delta r / R = const$. If sample prepared for quenching increases two times, the hardened layer Δr increases two times too (see Fig. 2 c),d)).

$$\frac{DI \cdot Kn^{0.5}}{D_{opt}} = \frac{25.4 \cdot Kn^{0.5}}{D_{opt}} \cdot f_c \cdot f_{Mn} \cdot f_{Si} \cdot \cdot f_{Ti} = 0.35 \pm 0.095$$
(13)

where DI is calculated using Grossmann's equation (12).

IV. EFFECT OF MARTENSITE START TEMPERATURE ON IQ PROCESS BEHAVIOR

Along with Eq. (12), critical diameter DI can be evaluated from CCT diagrams (see Fig. 6) using equation (14) [6].

$$\tau = \left[\frac{kBi_V}{2.095 + 3.867 Bi_V} + \ln \frac{T_0 - T_m}{T - T_m} \right] \frac{K}{aKn} \qquad (14)$$

which can be rewritten as:

$$DI_{Kn} = \left(\frac{23.1 aKn \tau_M}{E_{eq}} \right)^{0.5} = DI \cdot Kn^{0.5} \qquad (15)$$

Here $E_{eq} = \frac{kBi_V}{2.095 + 3.867 Bi_V} + \ln \frac{T_0 - T_m}{M_S - T_m}$

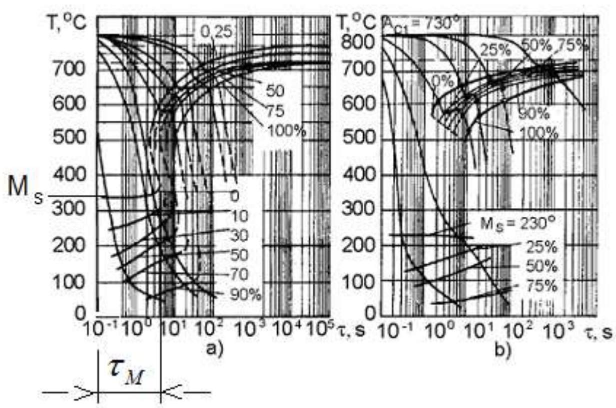


Fig. 6: CCT diagrams: a), AISI 1045 steel; b), AISI 1080 steel [6].

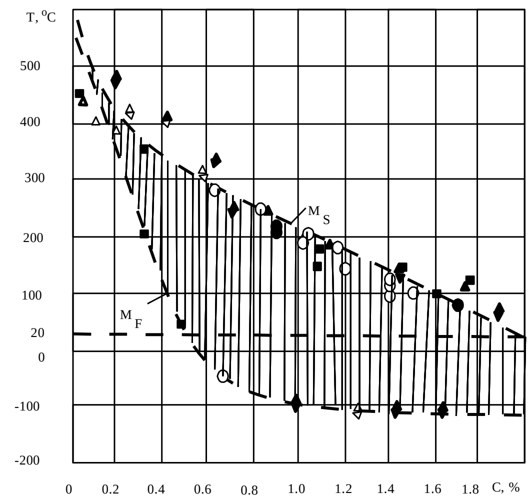
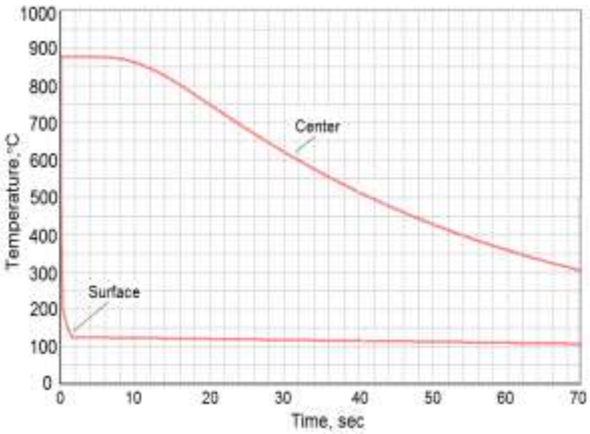


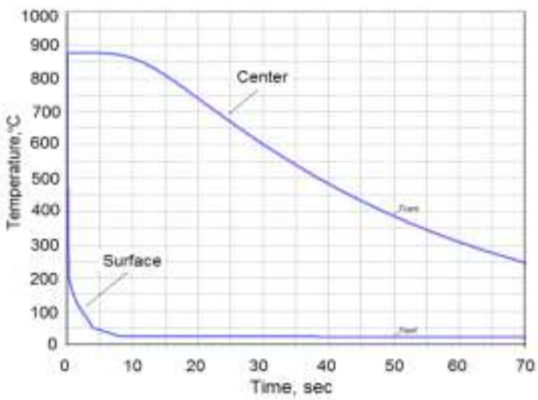
Fig. 7: Martensite start temperature M_S and martensite finish temperature M_F vs carbon content in steel.

As one can see from Fig. 6 and Fig. 7, martensite start temperature M_S depends on carbon content in steel and can be $\leq T_S$. Since during transient nucleate boiling process surface temperature maintains relatively a long time at the level of saturation temperature T_S, transformation austenite into martensite will be delayed during nucleate boiling (see Fig. 8 a)) that affects essentially and negatively residual stress distribution in hardened steel parts. To create high surface compression residual stresses in high carbon steels, intensive quenching is used in water flow which is called direct convection [16]. When martensite start temperature is 300°C or higher, boiling process itself provides high surface residual stress formation and makes material super strengthened without powerful water agitation [13, 16]. That is true if film boiling is absent. To eliminate film boiling formation during quenching, a low concentration of water polymer solutions of inverse solubility are used as a quenchant [13].

To see what is difference between pure transient nucleate boiling process and convection, computer calculation were performed which are presented in Fig. 8.



a)



b)

Fig. 8: Cooling curves at the surface and at the core of cylindrical probe 50 mm in diameter when pure transient nucleate boiling takes place (a) and during direct convection (b).

As seen from Fig. 8, during transient nucleate boiling process surface temperature quickly drops close to saturation temperature T_S while during direct convection it quickly drops to bath temperature T_m. There is no big difference between them (see Table 2 and Table 3).

Table 2: *Comparison of cooling time measurement within different temperature intervals during quenching cylindrical probe 50 mm in diameter in water salt solution and low concentration of UCON E in water [27].*

Temperature interval	750°C – 300°C	750°C – 400°C	750°C – 500°C
Cooling time in sec when quenching in 14% water NaCl solution at 23oC (Experiment)	36	24	16.3
Cooling time in sec when quenching in 14% water NaCl solution at 23oC (Simplified calculation)	37	25.3	16.6
Cooling time in sec when quenching in 1% water solution of inverse solubility polymer	35	23	17

Table 3: *Cooling time and cooling rate at the core of cylindrical specimen 60 mm when direct (ideal) convection and transient nucleate boiling process in still liquid without any film boiling*

Cooling condition	Cooling time from T_o to 700°C., s	Cooling time from T_o to 500°C, s	Cooling rate at 700°C, °C/s	Cooling rate at 500°C, °C/s
Direct convection	24	41	20	13
Nucleate boiling in still liquid	23	38	18	11

Direct convection during quenching was used for intense
hardening of semi –axles to increase their fatigue life [16].

Results of fatigue testing are provided by Table 4 [6]. Chemical compositions of steel used for testing see in Table 5. Table 4 provides unbelievable results of truck AutoKrAZ semi –axles field testing. Nobody could believe that intensively quenched AISI 1049 steel can compete with the high quality alloy steel AISI/SAE 4340 steel quenched in oil. The matter is that in semi – axles made of plain carbon steel very high surface compression residual stresses are formed during intensive quenching and phenomenon of super strengthening takes place that compensates alloy elements.

Table 4: *Fatigue testing of KrAZ tracks semi-axles through quenched in oil (4340H steel) and intensively quenched for obtaining optimal quenched layer (1040 steel) [6, 16]*

Quenching method	**Steel grade**	**Numbers of cycles to fracture**	**Notes**
Oil	AISI/SAE 4340	$(3{,}8–4.6)\times10^5$	Semi-axles were destroyed
Intensive water spray cooling	AISI 1040	$(3{,}0–3.5)\times10^6$	No fracture observed

Table 5: Chemical composition of intensively quenched steels

Alloy elements and DI	C	Mn	Si	Cr	Ni	Mo	Ti	DI, mm
1040	0.35-0.45	0.5 – 0.8	0.17- 0.37	< 0.30	< 0.30	-	-	15- 21
50G	0.48 – 0.56	0.70 – 1.00	0.17- 0.37	< 0.30	< 0.30			-
4340	0.38-0.43	0.60-0.80	0.15-0.35	0.70-0.80	1.65-2.0	0.20-0.30	-	112 – 397
47GT	0.44-0.51	0.10-0.25	0.95-1.25	< 0.25	< 0.25	< 0.30	0.06 – 0.12	-
52100	0.98 - 1.1	0.25 - 0.45	0.20 – 0.35	1.3 – 1.6	-	-	-	61 - 177

V. EXPERIMENTAL VALIDATION OF THE MAIN IDEA

For experimental study of effect very uniform and intense cooling on quench crack formation during quenching, the powerful spray system was built which is shown on Fig. 6 [6].

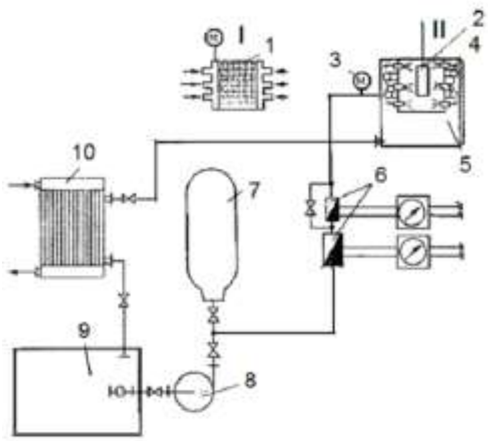


Fig. 9: Installation for quenching steel parts and cylindrical specimens in water jets [6]: I, sprayer with round holes; II, a different kind of sprayer; 2, pump; 3, water tank; 4, chiller; 5, receiver; 6, manometer; 7, cylindrical specimens with the splines; 8, spray system; 9, water tank and spray system; 10, equipment for measuring the amount of water used.

During quenching of steel samples, pressure in sprayer was developed up to 9 atmospheres [6]. Fig 7 shows effect of pressure P in sprayer on convective heat transfer coefficient (HTC) depending on water temperature used for experiments.

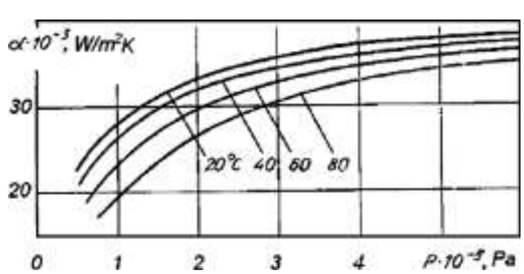


Fig. 10: Convective heat transfer coefficient versus pressure in the sprayer with water at 20^{o}C, 40^{o}C, 60^{o}C, and 80^{o}C [28].

The cylindrical specimens were machined for the tests. The sketch of specimen is shown in Fig. 11.

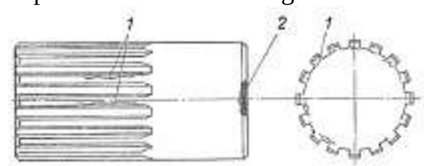


Fig. 11: Cylindrical specimen with splines: 1, quench cracks in splines; 2, cracked edge of specimen [6, 16].

Accurate experiments showed presence of quench cracks along the splines (see Fig. 11) during very uniform and intensive quenching. The cracks disappear when optimal hardened layer was formed due to correct time interruption see Table 7.

For splined cylindrical specimens the stress distribution during quenching was calculated by authors [21]. Computer calculations predicted tensile residual stresses on the top of the spline during quenching in condition $Bi \to \infty$ [21].

Early [6] this predicted result was supported by accurate experiments which are shown in Table 6.

Table 6: Surface hardness vs cooling time interruption for different grades if steel that affect crack formation [6].

Grade of steel	Cooling time in seconds	Percentage of cracked splines , %	Hardness HRC on the top of spline	Hardness HRC on cylindrical surface
47GT	10	5	49	42
47GT	15	6	50	47
47GT	20	10	57	50
4140	10	0	49	47

4140	15	0	52	49
4140	20	0	57	57
4140	40	0	61	65

To be sure that cooling process was enough intensive, for cylinder of 62 mm was evaluated needed convective HTC using Eq. (9) and Eq. (10).

$$\vartheta_I = \frac{1}{3.41}\left[\frac{2\times 23(760-\vartheta_I)}{0.031}\right]^{0.3} = 19^{o}C;$$

$$Bi = \frac{2(\vartheta_o - \vartheta_I)}{\vartheta_I + \vartheta_{uh}} = \frac{2\times(760-19)}{(19+80)} = 15;$$

$$\alpha = \frac{\lambda Bi}{R} = \frac{23\times 15}{0.031} = 11130\ W/m^2K.$$

To achieve such convective HTC, the pressure in the sprayer should be less that one atmosphere (see Fig. 10). It was used 9 atmosphere that was more than enough for developing condition $Bi \to \infty$. Conclusion here is that ideal uniformity and intensity of surface splined probe cooling cannot eliminate completely quench crack formation. The problem should be supported by correction of chemical composition of steel and proper cooling time interruption.

Table 7 provides core temperature in the splined specimen versus time interruption.

Table 7: *Core cooling time needed to drop initial temperature 860°C to transient temperature T when quenching cylindrical specimen 62 mm in diameter and 120 mm long in water jets at 20°C.*

Transient temperature, °C	700	600	500	400	300	200
Time. Sec	21	25	31	38	47	60

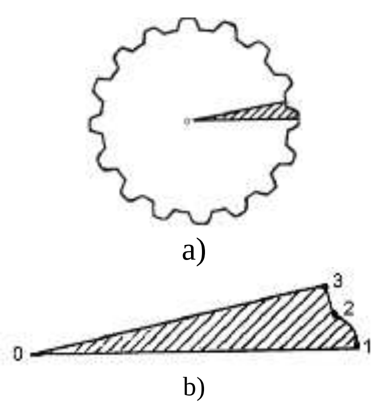


Fig. 12: Sketch of cross-section of splined semi-axle (a) and area for finite-element method meshing (b): 1, spline top; 2, spline side surface; 3, spline bottom [21].

For calculating current and residual stress distribution in splined specimen finite element method (FEM) was used [16, 21]. FEM calculations showed tensile stresses formation on the top of spline (admitted by number 1 on Fig. 12 b)). Cooling curves in points 1, 2, and 3 of spline during intense quenching look like is shown in Fig. 13.

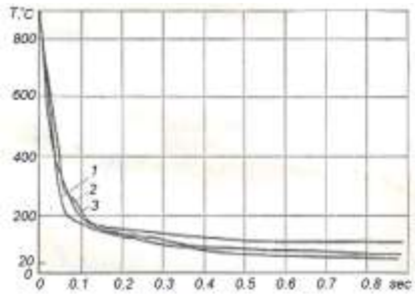


Fig. 13: Surface cooling curves during intense cooling of spined cylindrical probe [3]: 1, spline top; 2, spline side surface; 3, spline bottom.

Thus, uniform and intensive cooling prevents crack formation and decreases distortion during hardening steel parts of simple forms like plates, cylinders and spheres. During hardening more complicated steel parts like splined cylinders, crankshafts and other complicated forms uniform and intensive cooling cannot help. In this case cooling time interruption, chemical composition of steel and intensity of cooling should be corrected.

Table 8 provides cooling rates at the core of cylindrical specimens at temperature 700°C vs their diameters which are used to predict mechanical properties and microstructure depending on steel grade [29].

Table 8: *Cooling rate versus diameter of cylindrical specimen and Kondrat'ev number Kn.*

Diameter, m	Kn	K., m²	v, $^oC/s$
0.006	0.330	1.56×10^{-6}	736
0.012	0.350	6.27×10^{-6}	194
0.020	0.385	17.29×10^{-6}	77.3
0.030	0;435	38.90×10^{-6}	39
0.040	0.485	68.61×10^{-6}	24.6
0.050	0.535	108.1×10^{-6}	17.2
0.060	0.590	155.6×10^{-6}	13.2

Examples of use LH steel and steel with reduced alloy elements (optimal hardenability) is shown in Table 9 [6, 16].

Table 9; Examples of use LH steel and steel with reduced alloy elements show a great benefit after IQ procee [6].

Applications	Former steel and process	New steel and process	Advantages
Gears, modulus 5 – 8 mm	18KhGT carburized	58 (55PP)	No carburizing, cost decreases and service life increases.
Large – modulus gears, m = 10 = 14 mm	12KhN3A	ShKh4	No carburizing, cost decreases 1.5 times, service life increases 2 times.
Truck leaf springs	60C2KhG	45S	Weight decreases 15 – 20%, service life increases 3 times.

Further developments of IQ technologies were made by authors [16] who build equipment for IQ – 2 and IQ – 3 processes and commercialized new technologies in the USA. Currently, an important investigation is carried out to make intensive quenching process less costly and easy to perform [13]. Useful information one can find in Ref. [30 - 33].

The goal of the mentioned investigation is switching from complicated and costly IQ process to the simplest one to make it as a mass production around the world [13]. All developments are based on the knowledge of physics of complicated and very interesting quenching processes. An example below demonstrates of such possibilities.

Fig. 14 shows intensive quenching process of small rollers located in a tube which was heated to autenitizing temperature together with rollers. Then heated tube with the rollers was inserting into round fixture, locked and quenched by the water steam. It is rather complicated and costly experiment which provided not enough good results after quenching in water flow because inside the tube with the rollers film boiling was taken place. Such experiment can be performed by more simple way. Heated rollers with moving conveyor one by one are dropped into water polymer solution of low concentration (1%). Below the container the hydrodynamic emitter is located which produces resonance waves to destroy immediately film boiling process. There is here no pump, no film boiling at all, no special fixture and heated tube that results in possible film boiling process. Such simple technology provides better mechanical properties after quenching of free rollers as compared with the quenching in water flow of heated tube with the rollers. This example shows that heat treating process can be cardinally simplified if physics of the quench process is known in detail. Particularly, this simple technology uses inverse solubility polymer of 1% which creates surface insulating layer that decreases initial heat flux density below its critical value and by such way eliminates film boiling. The resonance effect helps to destroy film boiling if any during quenching. Slow agitation of water polymer solution increases of convective heat transfer coefficient that bin many cases is positive.

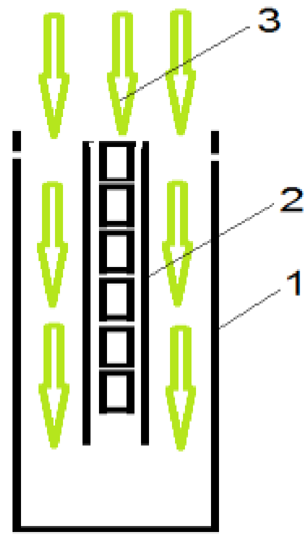


Fig. 14: Simplified scheme explaining intensive quenching process in water flow: 1 is fixture; 2 is tube with small rollers inside; 3 is water flow.

Fig. 15 explains what hydrodynamic emitters are and how they are fixed. Hydrodynamic emitter is a simple whistle that generates waves with the frequency equal to the frequency of film boiling oscillation to establish resonance.

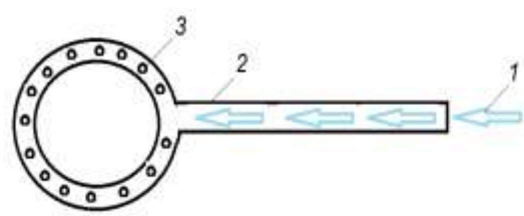


Fig. 15: A simple liquid secular platform to fix emitters: 1 is liquid flow; 2 is fixture made of round tube; 3 is hole to fix emitter.

The system shown in Fig. 15 is located in the simple quench tank to create resonance effect quenching of steel parts. It could be different versions of designed emitters.

VI. DISCUSSION

In contrast to widely distributed opinion that uniform and intensive quenching eliminates quench crack formation, in this paper is shown that to uniform and intensive quenching two more factors should be added dealing with the optimal hardenability steel and form of steel part. It can be formulated as follows. The uniform and intensive quenching prevents quench crack formation if chemical composition of steel is tolerant to size and form of steel component and the hardened layer is optimal that satisfies equation of similarity (13). It means that during quenching along with optimizing cooling intensity of liquid the chemical composition of steel should be optimized depending on size and form of steel component. The problem is quite complicated which requires sticking all technological processes together taking into account previous technological manipulations. For this purpose, based on optimal hardenability criterion similarity (13), Intensive Technologies Ltd (ITL), Kyiv, Ukraine, proposes software for optimizing chemical composition of steel. The software can find among existing steels suitable chemical composition which will be perfectly tolerant to geometrical sizes and sizes of micro grains of chosen steel that creates high surface compression residual stresses with fine bainitic microstructure at the core of intensively quenched steel parts [34, 35]. In 21st century the business makers should change their strategy in selling their products. They should collaborate with each other and sell the packages to customers. Author of this paper was informed that one small company sold low concentration of water polymer solution to customer. The customer could buy polymer concentrate and make water polymer solution by itself without paying extra money for water and its transportation for long distance. The customers should not be fooled by such small companies which not desire considering selling packages and trying to sell water with adding a little bit a small amount of polymer to it to get maximum income. The same is true regarding the LH steel. Some small companies are considering LH steel as the extraordinary material, not a material which can serve as an optimal hardenability steel for only small machine components. Due to minimum amount of alloy element in steel, one should design expensive high speed quenched systems to provide uniform hardened layer in steel. The required hardened layer can be formed at lesser cooling rate if alloy elements in steel are chosen according criterion (13). In this case the cost of technological process is cheaper and quench system is simpler that can result in its mass production.

In the paper (Powell, 2017) [36] author discussed the vision of heat treating technologies: his concept on lean, green technologies, and the emphasis to consider the chain of technological processes where every single element of the chain should be optimized by taking into account the effect of its neighbor. Every neighbor brings its own initial condition to a given element which should be taken into account when optimizing technology. From the perspective of math and physics it is a very serious, and complicated problem to be solved by intelligent mathematicians, physicians, and software programmers. The benefits presented can be very beneficial if optimization is a factor within the order. There is a lot of work to do in this field. A plan of such work could be:

- Use 1% well known PAG water polymer solution as a quenchant.
- Use hydrodynamic emitters instead of powerful pumps and motor-propellers
- Introduce into production several new software dealing with cooling in water polymer solutions.
- Carry out painstaking experiments with polymer solutions to evaluate thermal and physical properties of polymeric surface layer vs concentration and percentage of special additives and investigating cooling intensity of polymer quenchants.
- Introduce new method and apparatus for immediate control of quality of quenched steel parts

For this purpose it makes sense to plan establishing the branches of Ukrainian ITL in US and other countries to start essential saving of materials and energy globally and make environment green. To make developed technologies more popular, it makes sense also to open a couple of channels in “YouTube” to advertise new technologies and designed software. At present time, electronic and computer’s science is very far ahead of heat treating processes where there is a lack of knowledge on cooling intensity of liquid quenchants. Even such famous corporation like DOW provides only cooling curves and cooling rate of standard probe in each specific polymer quenchant which cannot be used for optimization cooling process. That results in loosing of great possibilities in obtaining many benefits from exploring polymers as the quenchants. Unfortunately, nobody knows how to switch from data obtained by testing standard Inconel 600 probe to data to be used for calculating temperature fields and stress distribution during quenching of real steel parts of different shapes and forms.

VII. CONCLUSIONS

1. Low hardenability (LH) steel provides optimal hardened layer only for small machine components like small gears and shafts and is not suitable for large steel components while optimal hardenability (OH) steel is suitable for any size and form of machine component and any condition of cooling.
2. In many cases, uniform and intensive cooling doesn’t eliminate quench crack formation if

chemical composition of steel is not tolerant to form and size of machine component.

3. It is proposed the criterion for composing chemical composition of steel depending on form and size of machine components and intensity of cooling during its hardening.
4. Based on study physics of transient nucleate boiling process, it is possible to perform intensive hardening of steel in slow agitated coolants if any film boiling is completely absent.
5. No further progress in hardening of steel and computer programs design can be done without careful investigation of quenching processes based on achievements of contemporary modern physics.
6. Due to inventing optimal hardenability (OH) steel and method of its composing, there is a possibility to switch from costly and complicated equipment to simple quench tanks filled with low concentration of water polymer solutions for intensive quenching OH steels.
7. It is shown that without painstaking study the physics of quenching processes in liquid media, automation and appropriate computerization, to optimize properly quench process, is impossible.

VIII. REFERENCES

[1] Kern Roy F., (1986). "*Intense quenching*", Heat Treating, No. 9, pp. 19 -23.

[2] Russian Patent No. 2158320, "*Construction Steel of Low Hardenability*", Application No. 99125102, Filed on Nov. 29, 1999.

[3] Bogatyrev, Yu.M., Shepelyakovskii, K. Z., Shklyarov, I.N., (1967). "*Cooling rate edffect on crack formation during steel quenching*", MiTOM, No. 4, pp. 15 – 22.

[4] Natanzon E.I., (1976). Temianko L.S., (1976). "*Simultaneous quenching of truck semi – axles*", Avtomobilnaya Promyshlennost, No. 10, pp. 33 – 35.

[5] Shepelyakovskii, K. Z. (1972). "*Strengthening of Machine Components by Induction Surface Hardening". Moscow:* Mashinostroenie, 288.

[6] Kobasko, N.I., (1980). "*Steel quenching in liquid media underf pressure*", Naukova Dumka, Kiev, 206 p.

[7] Shepelyakovskii, K. Z., Ushakov, B. K. (1990, December). *"Induction surface hardening-progressive technology of XX and XXI centuries*". In Proc. 7th Int. Congress on Heat treatment and technology of surface coatings, 33–40.

[8] Ukrainian Patent UA 114174, C2, "*Alloyed Low Hardenability Steel and Method of its Composing*", Filed on Sep.23, 2013, File number: a 2013 11311.

[9] Kobasko N., (2018). "*Optimal Hardenability Steel and Method for Its Composing*." Lambert Academic Publishing, Germany,122 p. IBSN-13: 978-613-9-82531-8.

[10] Kobasko N., (2019). "*High Quality Steel vs Surface Insulating Layer Formed during Quenching*". Lambert Academic Publishing, Germany, 108 p.

[11] Kobasko N., (2017). "*A method for optimizing chemical composition of steels to reduce radically their alloy elements and increase service life of machine components*". EUREKA: Physics and Engineering. Number 1, pp. 3 – 12. DOI: 10.21303/2461-4262.2016.00253

[12] Kobasko N.I., (2019). "*Uniform and Intense Cooling During Hardening Steel in Low Concentration of Water Polymer Solutions*", American Journal of Modern Physics, Vol. 8, Issue 6, pp. 76-85. DOI: 10.11648/j.ajmp.20190806.11.

[13] Kobasko N.I., (2020). "*Mechanism of film elimination when intensively quenching steel parts in water polymer solutions of low concentration*", Global Journal of Science Frontier Research – A: Physics and Space Science, Vol. 20, Issue 7, pp. 39 – 56.

[14] Kobasko N.I., (2019). "*Austempering Processes That are Performed via Cold Liquids*", Lambert Academic Publishing, Germany, 116 p., DOI: 10.1520/mnl64-eb, ISBN: 978-620-0-11330-6.

[15] Kobasko N.I., (2019). "*Transient Nucleate boiling as a Basis for Designing Austempering and Martempering New Technologies*", SSRG International Journal of Applied Physics (SSRG-IJAP), Vol. 6, Issue 2.

[16] Kobasko N.I., Aronov M.A., Powell J.A., Totten G.E., (2010). *"Intensive Quenching Systems: Engineering and Design*". ASTM International, USA, 234 p. doi: 10.1520/mnl64-eb.

[17] Kobasko, N. I. (2009). "*Transient Nucleate Boiling as a Law of Nature and a Basis for Designing of IQ Technologies*". Proceedings of the 7th IASME/WSEAS International Conference on Heat Transfer, Thermal Engineering and Environment (HTE '09), Moscow, 2009, August 20–22, 67–76.

[18] Kobasko, N. I., and Morhuniuk, W. S., (1983). Issledovanie teplovogo i napriazhenno-deformirovannogo sostoyaniya pri termicheskoy obrabotke izdeliy mashinostroeniya (Study of thermal and stress-strain state at heat treatment of machine parts), Znanie, Kyiv.

[19] Kobasko, N. I., and W. S. Morhuniuk, (1985). "*Numerical Study of Phase Changes, Current and Residual Stresses at Quenching Parts of Complex Configuration*", Proceedings of the 4th International Congress of Heat Treatment Materials, Berlin, Vol. 1, pp. 465–486.

[20] Kobasko, N.I., Morhuniuk, W.S., Ushakov, B.K., (2006). "*Design of Steel – Intensive Quench Processes".* Steel Heat Treatment Handbook (Second Edition), George E. Totten (Ed.), CRC Press, Boca Raton – London – New York, pp. 193 – 217. ISBN – 13: 978-0-8493-8454-7.

[21] Kobasko, N.I., Morganiuk, V.S., Morganiuk, A.P., (1990). "*Hardening of complex configuaration samples by intensive cooling*", Proc. of the 7th International Congress on Heat Treatment of Materials, Dec. 11 -14, Moscow, Vol. 2, pp. 232 – 239..

[22] Dowling, W., T. Pattok, B. L. Ferguson, D. Shick, Y. Gu, and M. Howes, "*Development of a Carburizing and Quenching Simulation Tool*," The 2nd International Conference on Quenching and Control of Distortion, ASM International, Cleveland, OH, 1996.

[23] Ferguson, B. L., A. M. Freborg, G. J. Petrus, and M. L. Collabresi, "*Predicting the Heat Treat Response of a Carburized Helical Gear*," Gear Technology, 2002, pp. 20–25.

[24] Grossmann, M. A. (1964). *"Principles of Heat Treatment."* Ohio: American Society for Metals, 302.

[25] Totten, G. E., Bates, C.E., and Clinton ,M.A., , (1993). "*Handbook of Quenchants and Quenching Technology*", ASM International, Materials Park, OH, USA.

[26] Kondrat'ev, G.M., (1957). Teplovye Izmereniya (Thermal Measurements). Moscow: Mashgiz, 1957.

[27] Kobasko, N.I., Moskalenko, A.A., Logvynenko, P.N, Dobryvechir, V.V., (2019). "*New direction in liquid quenching media development*", Teplofizyka ta Teploenerhetyka (in Ukr), Vol. 41, No.3, pp. 33 -40. https:doi.org/10.31472/ttpe.3.2019.5.

[28] Кадинова А.С., Хейфец Г.Н., Тайц Н.Ю., (1963).. О характере теплообмена при струйном охлаждении, ИФЖ., 6, № 4, сс. 46 – 50.

[29] Kobasko N., Guseynov Sh., Rimshans J., (2019). "*Core Hardness and Microstructure Prediction in Any Steel Part. Lambert Academic Publishing*", Germany, 104 p. IBSN-13: 978-613-9-94751-5

[30] Kobasko, N.I., (1992). "*Intensive Steel Quenching Methods, A Handbook "Theory and Technology of Quenching"*", B.Liscic, H.M. Tensi, W.Luty (Eds.), Springer- Verlag, Berlin, pp. 367 – 389.

[31] Ferguson, B.L., (2013). *"Applying DANTE Heat Treat Modeling to Intensive Quenching*," Presentation at the Intensive Quenching Workshop held on April 24 in Cleveland, Ohio, USA.

[32] Kobasko, N. I. (2005). "*Quench Process Optimization for Receiving Super Strong Materials*." Proceedings of the 5th WSEAS Int. Conference on simulation, modeling and optimization, 365–372.

[33] Kobasko Nikolai., (2017). "*A method for optimizing chemical composition of steels to reduce radically their alloy elements and increase service life of machine components*." EUREKA: Physics and Engineering. Number 1, pp. 3-12. DOI: 10.21303/2461-4262.2016.00253 .

[34] Bhadeshia, H.K.D.H., (2015). "*Bainite in Steels: Theory and Practice"* (3rd Edition), Money Publishing, 616 p.

[35] Kobasko, N. I. (2005). "*The main principles of intensive quenching of tools and dies*", Proc. of the 1th International Conference on Heat Treatment and Surface Engineering of Tools and Dies, 39–44.

[36] Powell J.A., (2017). "*Everything Matters to Reach ASM HTS's Vision 2020 Goals*" , ASM Heat Treating Society Conference Paper, Presented in Columbus, Ohio, October 24, 11 p.