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Improved Intensive Quenching Processes for Global Mass Production

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Abstract: The three principles of transient nucleate boiling are used for transition from IQ- 3 technology to IQ -2 technology to obtain the same or even better final results in hardening of machine components. That provides compressive surface residual stresses and super strengthening of materials. It is shown that cooling process in this case is extremely intensive. To provide optimal hardened layer during intensive quenching, it was developed a method for optimizing chemical composition of steel. The proposed method, patented in Ukraine, can be used to sort already existing steels in order to find suitable chemical composition that creates optimal hardened layer in hardened machine components. Cooling time should be interrupted to choose right time for bainitic transformations. Very simple and understandable for wide audience cooling time method of calculation is also proposed for recipes development. These innovations allow refusing from powerful pumps and expensive technology since similar condition of cooling, equal to IQ – 3 technologies, can be performed in already existing IQ-2 and conventional quenching tanks. It makes sense to distribute proposed innovations in the international market.

INTRODUCTION

The IQ – 3 technology is intensive quenching process where film boiling and transient nucleate boiling are absent and main mode is convection. In US Patent [1] this technology was called as direct convection. In 1999 and 2000, the two companies were established for wide investigations of intensive quenching processes. The first company IQ Technologies Inc (IQT) was established in Akron, USA (1999) while Intensive Technologies Ltd (ITL) was established in Kyiv, Ukraine (2000). The two companies have collaborated fruitfully during the long period of time. The first company focused mainly on developing intensive hardening equipment, while ITL focused on refining new intensive hardening technologies. The progress in this area runs slowly because equipment is rather expensive and customers do not believe in quick results. To organize the mass production of intensive hardening methods in the heat-treating industry, it is necessary that the new technology be:

- Attractive and promising
- Simple and comprehensively understandable to the wide audience of customers
- Inexpensive and competitive in the international market

For this purpose, the author of current article, based on recently discovered three principles of transient nucleate boiling process, has proposed the innovations for the IQ - 3 technology. The proposed innovations are listed below:

- According to the first principle of transient nucleate boiling, the cooling process is extremely intensive since surface temperature of quenched steel parts drops from initial T_0 = 850°C to 125°C within 1 – 2 seconds [2]. This initial boiling temperature T_I

in many cases is below martensite start temperature M_f . It is true if steel contains carbon up to 0.45 C (see Fig. 1). This means that there is no need to use powerful pumps for direct convection because extremely intensive quenching is produced by vapor bubbles.

- According to the second principle of transient nucleate boiling, the surface temperature of steel parts maintains at the level of boiling point of fluid creating ideal intensive quenching [2, 3]. It is true when any film boiling is absent. In this case heat transfer coefficient is extremely large and Kondratiev number Kn tends to 1 (see Fig. 2).
- The third principle is a function of a size, form, thermal diffusivity of material and intensity of cooling and evaluates duration of transient nucleate boiling process which allows easily calculate core temperature at the end of nucleate boiling. The last makes possible the evaluation an average number Kn which is used for prediction the maximal compressive residual stresses at the surface (see Fig. 3).

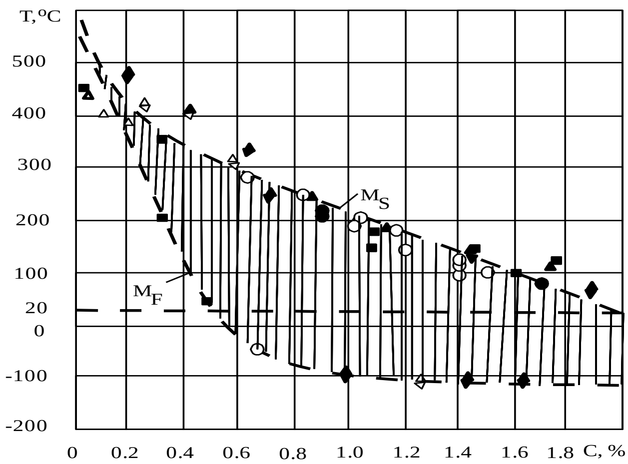

Fig 1: Martensite start temperature M_S and martensite finish temperature M_F versus content of carbon in steel [4, 5].

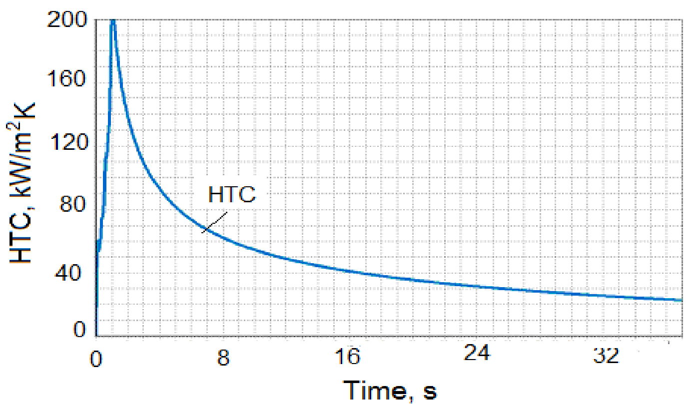

Fig. 2: Heat transfer coefficients versus time when quenching cylindrical probe 60 mm in diameter in water solution at 20°C with agitation generating convective heat transfer coefficient 5000 $Wm^{-2}K^{-1}$. Core temperature at the end of transient nucleate boiling process is 530°C (Bi =.6.51).

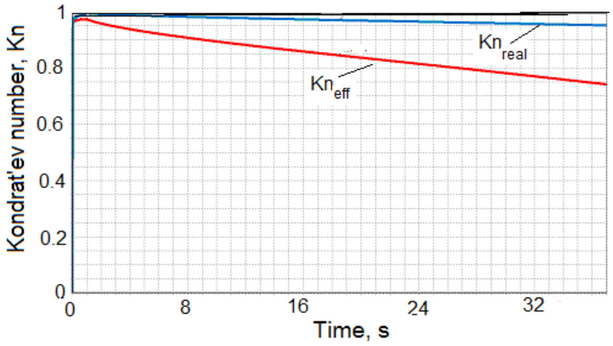

Fig. 3: Kondratiev numbers versus time when quenching cylindrical probe 60 mm in diameter in water solution at 20°C with agitation generating convective heat transfer coefficient 5000 $Wm^{-2}K^{-1}$. Core temperature at the end of transient nucleate boiling process is 530°C (Bi =.6.51).

Intensive quenching should be interrupted at proper time of cooling to fit of bainitic transformation as is shown in Fig. 4.

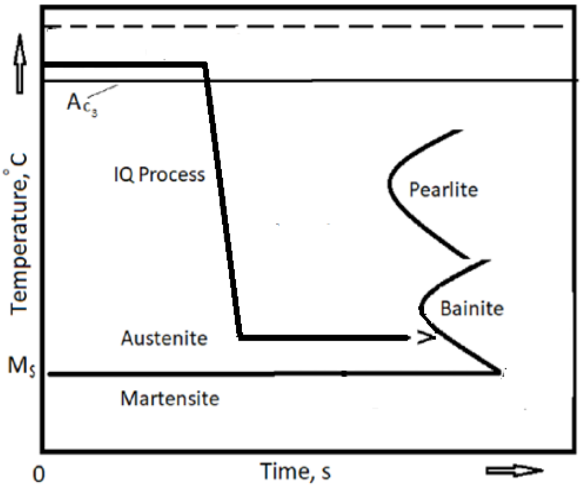

Fig. 4: Typical intensive quenching to receive bainitic microstructure throughout all section of steel part.

In this case surface the hardened martensitic layer of optimal depth with high compressive residual tresses and bainitic core of fine microstructure are formed in machine component (see Fig. 5).

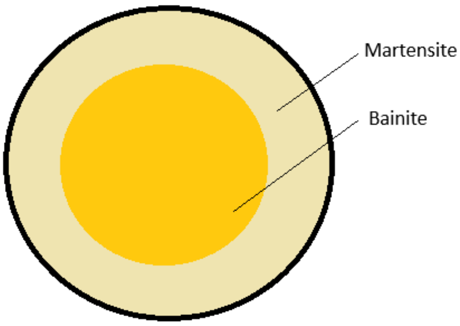

Fig. 5: Martensitic surface layer of optimal thickness and bainitic fine or nano- bainitic microstructure in cylindrical specimen after intensive quenching according first method of bainitic transformation.

When steel contains high concentration of carbon and martensite start temperature is below 100°C (see Fig. 1), direct intensive quenching is needed to provide high surface compressive residual stresses and get the super strengthened material. This issue is discussed below.

DIRECT CONVECTION

The parabolic heat conductivity equation with the third type of a boundary condition can approximately provide data for convective cooling time calculations [6]. Based on this approach, regular thermal condition theory makes possible to perform needed calculations for bodies of arbitrary form and shape [7]. According to regular condition theory, in a short time core cooling curve of any steel part is simple exponent [7, 8]. The generalized equation for cooling time calculations of arbitrary forms was developed by author [9]:

$$\tau = \left[\frac{kBi_V}{2.095 + 3.783Bi_V} + \ln \frac{T_0 - T_m}{T - T_m} \right] \frac{K}{aKn} \tag{1}$$

$$Bi_V = \frac{\alpha}{\lambda} K \frac{S}{V} \tag{2}$$

$$Kn = \frac{Bi_V}{\left(Bi_V^{\ 2} + 1.437Bi_V + 1\right)^{0.5}} \tag{3}$$

Here τ is time in s; Bi_V is generalized Biot number; $k = 1,2,3$ for plate -shaped, cylindrical – shaped and spherical shaped forms; K is Kondratiev form factor in m^2; Kn is Kondratiev dimensionless number; a is thermal diffusivity of steel in m^2s^{-1}; h is heat transfer coefficient in $Wm^{-2}K^{-1}$; k is thermal conductivity of steel in $Wm^{-1}K^{-1}$; S is surface in m^2; V is volume in m^3; the complex $kBi_V/(2.095 + 3.783Bi_V)$ is presented graphically in Fig. 6 versus generalized Biot number Bi_V.

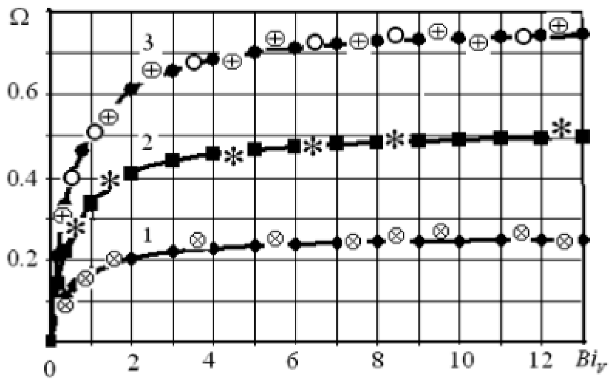

Fig. 6: Theta value versus generalized Biot number for: 1, plate-shaped forms; 2, cylindrical- shaped forms; 3, spherical -shaped forms [6].

These generalized equations (1), (2) and (3) were used by IQ Technologies Inc in Ohio (USA) for designing simple computer code to help engineers perform cooling recipes developments.

It should be noted that direct convection can take place during batch quenching as well, if criterions (4) is satisfied [1, 6]:

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

Here

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

Where $Bi = \frac{\alpha_{conv}}{\lambda}R$ is conventional Biot number; α_{conv} is convective heat transfer coefficient (HTC); $\vartheta_0 = T_0 - T_S$; T_0 is initial austenitizing temperature; $\vartheta_I = T_I - T_S$; T_I is nucleate boiling start temperature; T_S is saturation temperature; $\vartheta_{uh} = T_S - T_m$; T_m is bath temperature; $\beta = 3.41$; λ is thermal conductivity of steel in W/m·K; R is radius in m.

The heat conductivity theory states that thermal equilibrium is established when time tends to infinity [8] while zeroth law of thermodynamics says that thermal equilibrium is established in the final period of time [10, 11 and 12]. To solve this contradiction, let's analyze the exact solution (5) for cooling process of a long cylinder [8]:

$$\theta = \frac{T(r,\tau) - T_m}{T_0 - T_m} = \sum_{n=1}^{\infty} A_n J_0\left(\mu \frac{r}{R}\right)\exp\left(-\mu^2 Fo\right) \tag{5}$$

$$A_n = \frac{2J_1(\mu_n)}{\mu_n\left[J_o^{\,2}(\mu_n) + J_1^{\,2}(\mu_n)\right]}$$

Here A_n are temperature amplitudes; $J_o(\mu r/R)$, $J_1(\mu_n)$ and $J_o(\mu_n)$ are Bessel functions [8].

Assume that direct connection is performed in water at 0°C from 1000°C and 800°C. Calculate cooling time from 1000°C to 1°C and from 800°C to 0.8°C. Dimensionless temperature in the first experiment is 0.001 and for the second experiment dimension temperature is also 0.001.

According to analytical exact solution (5), the cooling time for both experiments is the same, if thermal properties of material and cooling intensity remain constant. Note that 0.8°C and 1°C from practical point of view for given interval temperatures 0°C - 1000°C is the same value.

Some real experiments were performed a long ago with the spherical samples 60 mm diameter made of an iron. Very sensitive semi – conductor was instrumented at the center of the probe. To keep thermal properties of material unchanged, cooling was arranged within 0°C and 100°C. Convective cooling was performed in ice water at 0°C. Results of experiments are available in Table 1.

Table 1: Cooling time of the spherical probe 60 mm diameter from initial temperature T_0 to bath temperature with ice water at a temperature 0°C. Samples were cast from an iron.

Initial temperature T_o of probe in °C	Cooling time in s
100	127
80	128
60	130
50	130
30	129
20	129

The performed natural experiments showed the same cooling time equal to 129 s in average (see Table 1).

Physicists have noticed a very interesting property of a simple exponent. One can find that the exponential distribution of temperature over time is directly proportional to its initial (see Fig . 7 and Table 2).

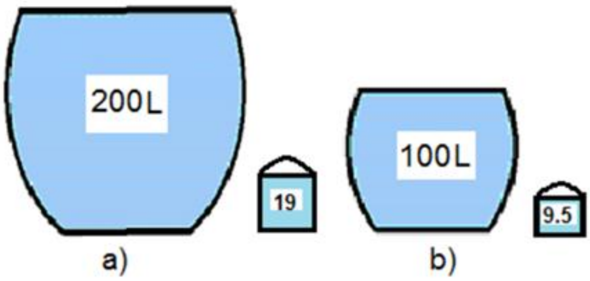

Fig. 7: An example with two volumes of liquid and two buckets to explain meaning of exponential law of cooling: volume a) every single second loses two times more water as compared with the volume b).

Table 2: Changing of volumes of buckets vs. time according to exponential law: index I is bucket a) and index II is bucket b) [7].

Time, s	1	2	3	4	5	N	
200 L	19	17	16	14	13	…….	2 molecules
100 L	9.5	8.5	8	7	6.5	…….	1 molecule

According to Table 2, process is final because at the end only two molecules and one molecule will be left exactly suitable for both micro buckets. The time for both processes is the same.

Heat exchange processes occur similarly. At the end of cooling, the temperature difference is comparable to temperature fluctuations (see Fig . 8) [13], which contribute to the establishment of temperature equilibrium in a finite time. Thus, temperature equilibrium is established in a finite period of time, regardless of the initial temperature of a heated body, if all parameters of the system are strictly constant. Author [14] suggests that temperature equilibrium is established if the dimensionless temperature decreases by a thousand times (see Table 3).

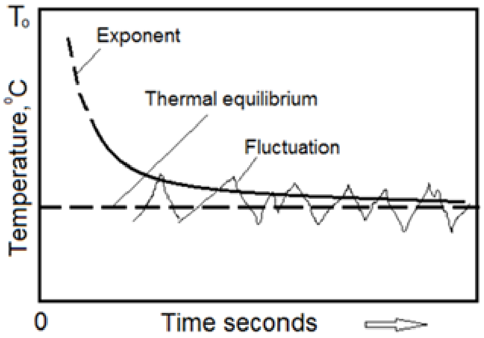

Fig. 8: Physics of thermal equilibrium establishment

Furthermore, it is known that modified thermal conductivity law of Fourier generates hyperbolic heat conductivity equation which represents simultaneously exponential and wave properties in heating and cooling processes [8].

Assume that two cylindrical specimens were cooled in refrigerates and their initial temperature differ two times. Then both samples are "heated" in ice water at 0°C. The heat penetrates into cylinders like it is shown in Fig. 9. Both samples are experiencing wave and exponential character of heating and thermal equilibrium is established in final period of time independently of their initial temperature.

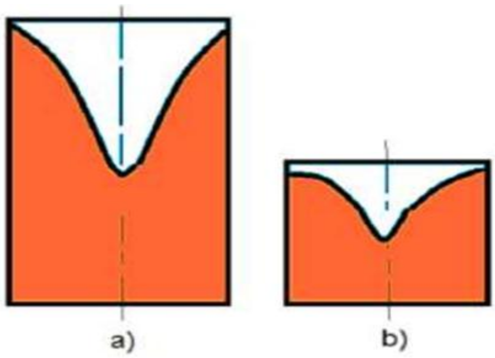

Fig. 9: Illustration to wave character of heat distribution: a) is sample with temperature two times larger as compared with the sample b) [14].

Based on modified principle of thermal equilibrium establishment the generalized correlation (6) was developed which can be used for heating and cooling time calculation steel parts of any form and configuration [14]:

$$\tau_{eq} = E_{eq} \frac{K}{aKn} \tag{6}$$

These simplify calculations can help engineers perform easily recipes developments. More accurate calculations can be performed using contemporary computer codes focused on computer modeling of heat-treating processes [15, 16 and 17]. Below are presented two examples of simple calculation to see how our equation (6) works.

Example 1. Calculate full cooling time for cylindrical probe 50 mm in diameter in a quench tank with the temperature 25°C where average Kn = 0.7. Kondratiev form coefficient $K = R^2/5{,}783 = 108.07 \times 10^{-6} m^2$. The average value of thermal diffusivity of material is equal to $5.4 \times 10^{-6} m^2 s^{-1}$. The value $N = (T_o - T_m)/ (T - T_m) = (875^{\circ}C - 25^{\circ}C)/ (25.85^{\circ}C - 25^{\circ}C) = 1000$. We agreed that full cooling is established when N = 1000. In this case (see Table 3) E_{eq} =

7.31. Taken these data into account, we get t = 7.31 x (108.07 x $10^{-6}m^2$)/(5.4 x $10^{-6}m^2s^{-1}$ x 0.7) = 209 s or approximately 3.5 minutes.

Example 2. Calculate cooling time from 875°C to 450°C for cylindrical probe 50 mm in diameter in a quench tank with the temperature 25°C where average Kn = 0.7 and maximal compressive surface stresses occur. Kondratiev form coefficient K = R^2/5,783 = 108.07 x $10^{-6}m^2$. The average value of thermal diffusivity of material is equal to 5.5 x $10^{-6}m^2s^{-1}$. The value N = (T_o – T_m)/ (T – T_m) = (875°C – 25°C)/ (450°C – 25°C) = 2. When N = 2, E_{eq} = 1.095 (see Table 3). In this case t = 1.095 x (108.07 x $10^{-6}m^2$)/(5.5 x $10^{-6}m^2s^{-1}$ x 0.7) = 31s.

Thus, the important recipes developments are so simple that they can be performed in every kitchen of our Globe. It should be because our plan is to organize implementation of intensive quenching processes for Global mass production. Table 3 below will be helpful for recipes development during quenching machine components in cold fluids.

Table 3: Parameter E_{eq} for the fundamental equation (11) as a function N = (T_o-T_m)/(T-T_m) and dimensionless Kondratiev number Kn.

N	$Kn = 0.7$			$Kn = 0.8$			$Kn = 0.9$		
	E_{pl}	E_{cl}	E_{sph}	E_{pl}	E_{cl}	E_{sph}	E_{pl}	E_{cl}	E_{sph}
1.40	0.537	0.738	0.939	0.556	0.776	0.996	0.575	0.814	1.053
1.45	0.573	0.774	0.975	0.592	0.812	1.032	0.611	0.850	1.089
1.50	0.606	0.807	1.008	0.625	0.845	1.065	0.644	0.883	1.122
1.55	0.639	0.840	1.041	0.658	0.878	1;098	0.677	0.916	1.155
1.60	0.671	0.872	1.092	0.690	0.910	1.130	0.709	0.948	1.187
1.65	0.702	0.903	1.104	0.721	0.941	1.161	0.740	0.979	1.218
1,70	0.732	0.933	1.134	0.751	0.971	1.191	0.770	1.009	1.248
1.75	0.761	0.962	1.163	0.780	1.000	1.220	0.799	1.038	1.277
1.80	0.789	0.990	1.191	0.808	1.028	1.248	0.827	1.066	1.305
1.90	0.842	1.044	1.245	0.862	1.082	1.302	0.881	1.120	1.359
2.00	0.894	1.095	1,296	0.913	1,133	1.353	0.932	1.171	1.410
2.10	0.943	1.144	1,364	0.962	1.182	1.421	0.981	1.220	1.459
2.20	0.989	1.190	1.391	1.008	1.228	1.448	1.027	1.266	1.505
2.30	1.034	1.235	1.436	1.053	1,273	1.493	1.072	1.311	1.550
2.40	1.076	1.277	1.479	1.095	1;315	1.535	1.114	1.353	1.592
2.50	1.117	1.318	1.519	1.136	1.356	1.576	1.155	1.394	1.633
2.60	1.157	1.358	1.559	1.176	1.396	1.616	1.195	1.434	1.673
2.70	1.194	1.395	1.596	1.213	1.433	1.653	1.232	1.471	1.710
2.80	1.231	1.432	1.633	1.250	1.470	1.690	1.269	1.508	1.747
2.90	1.266	1,467	1.668	1.285	1.501	1.725	1.304	1.543	1.782
3.00	1.300	1.500	1.702	1.319	1.539	1.759	1.338	1.577	1.816
4.0	1.587	1.788	1.989	1.606	1.826	2.046	1.625	1.864	2.103
5.0	1.810	2.011	2.212	1.829	2.049	2.269	1.848	2.087	2.326
10	2.504	2.705	2.906	2.523	2.743	2.964	2.542	2.781	3.020
100	4.806	5.001	5.202	4.825	5.045	5.265	4.844	5.083	5.322
1000	7.109	7.310	7.511	7,128	7.348	7.568	7.147	7.386	7.625

OPTIMAL SURFACE HARDENED LAYER

Per Grossmann [18], the critical diameter DI is a diameter of a bar that can be quenched to 50% martensite in the center when the bar surface is cooled at an infinitive rate (the heat transfer coefficient tends to infinity ∞). A value of the critical diameter DI depends on the steel chemistry and grain size. Grossmann proposed the following correlation for calculating of the critical diameter for a given steel [18, 19]:

$$DI = 25.4 \cdot f_c \cdot f_{Mn} \cdot f_{Ni} \cdot f_{Cr} \cdot f_{Mo} \ldots \cdot f_x \quad (7)$$

The Grossmann's equation (12) was designed based on many accurate and costly experiments performed in US [18]. It was tested by many authors within a long period of time and was accepted by heat treating community [4, 5].

Using the potentialities of computing complex HART and taking into account the theory of similarity, authors [15] noticed that maximal surface compressive residual stresses occur when the ratio (8) is fulfilled:

$$\frac{DI}{D_{opt}} Kn^{0.5} = 0.35 \pm 0.095 \quad (8)$$

This ratio later was used for steel chemical composition optimization.

The fundamental correlation (9) below, developed in 2013 by Kobasko, summarizes a huge amount of numerical and experimental data collected between 1975 and 1980 concerning current and residual stress distribution in quenched steel parts. It includes the experimental data from Grossmann on valuable multiplying factors f_x. All of this provides accuracy in predicting the optimal hardened layer depth. Thus, equation (9) is responsible for maximum surface residual stress prediction [20, 21]. In equation (9), the multiplying factor f_{fe}_ depends on the carbon content and grain size of the steel, while the other 'alloy' factors depend on the content of alloying elements.

$$D_{opt} = 73 f_{Fe} \cdot \begin{pmatrix} 1+3.33Mn \\ 1+3.00Mo \\ 1+2.16Cr \\ 1+1.80Cu \\ 1+0.70Si \\ 1+0.364Ni \\ 1-0.715S \\ 1+2.50P \end{pmatrix} \cdot \left(\frac{K_{DI}}{K_{opt}}\right)^{0.5} \cdot Kn^{0.5} \quad (9)$$

The generalized equation (9) represents the method on steel chemical composition optimization and was patented in Ukraine by author [21]. It allows the production of a highly strengthened surface martensite layer and a bainitic fine microstructure in the core of hardened products. The latter has significant advantages over other intermediate structures [22]. Helpful data for use in the practice the fundamental equation (9) are provided in Fig. 10.

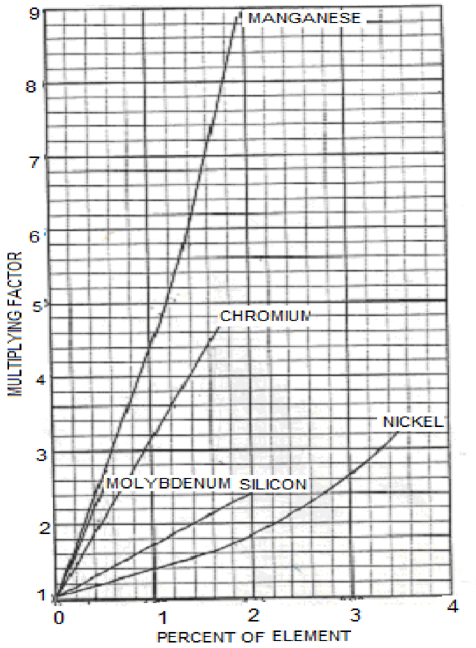

Fig. 10: Multiplying factors for alloying elements [18]

Multiplying factors presented by Fig. 10 were included into generalized equation (9). They can be used also by other authors who need to check their own correlations concerning ideal diameter DI evaluation. There are many methods for ideal diameter DI evaluation, however some data in [23] don't coincide well with the Grossmann's data.

It should be underlined that many costly empirical investigations of authors [24, 25 and 26] brought very useful knowledges to understanding intensive quenching phenomena. Particularly valuable is the possibility of replacing carburized steel parts with steel parts made of low hardenability (LH) steels [24] which leads to significant savings in materials and increasing the durability of intensively hardened machine components.

CONCLUSIONS

1. It is proposed IQ – 3 processes perform in IQ – 2 tanks if steel parts have a complicated form. In this case optimal hardenability steel should be used for manufacturing machine components.
2. Intensive quenching should be interrupted at a time that provides fine bainitic or nano – bainitic microstructure at the core of quenched steel parts.
3. To calculate appropriate cooling time interruption, the universal correlation is proposed which takes into account the zeroth law of thermodynamics [10].
4. For complicated machine components preferable is intensive batch quenching in IQ – 2 tanks. It makes sense to perform direct convection during intensive quenching mainly for simple steel parts like semi – axles.
5. When quenching includes transient nucleate boiling and convection, optimal cooling time is calculated by modified equation that considers both processes separately [2].

SUMMARY

When direct convection, the thermal equilibrium is established within the final period of time independently on initial temperature T_0 if thermal properties of material and quenchant are strongly constant. That creates a basis for obtaining the fundamental equation for heating and cooling time evaluation of machine components no matter what is size and configuration.

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