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RESEARCH ARTICLE

CONTEMPORARY METHODS FOR COOLING TIME CALCULATION AND HARDENING PROCESSES ANALYZING

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ABSTRACT

The paper discusses contemporary methods of quenching processes analyzing and cooling time evaluation to provide engineers with the correct data needed for hardening process interruption. It is shown that intensive interrupted cooling combined with the optimized chemical composition of steel allows reduce distortion and increase service life of steel parts due to creation of high compressive residual stresses at the surface of quenched products. Examples of calculations are supported by analytical equations and computer code HART- TANDEM developed and used in Ukraine within 1978 – 1998. The paper is illustrated with many images: phase and stress distribution, distortion and quench cracks prediction. It is underlined that contemporary powerful software such as DANTE (Dowling *et al*., 1996; Ferguson *et al*., 2002), HEARTS (Inoue *et al*., 1992; Inoue, 2002) and many others can investigate all aspects of hardening processes including carburization and quenching under pressure if correct data on boundary condition are available. The DATABASE on cooling characteristics of liquid quenchants is not developed yet and in spite of existing powerful software no quick progress can be made without careful investigation of liquid quenchants. Authors of the paper hope that big companies interested in making benefits and quick progress connected with hardening processes will do investments to investigate carefully liquid quenchants and create for them DATABASE suitable for computer simulation on the basis of testing Liscic/Petrofer probes of different sizes and forms.

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INTRODUCTION

At present time a tendency exists to switch from oils and high concentration of polymers as the quenchants to plain water or low concentration of water salt solutions due to environment problems. Oil as quenchant was used to eliminate quench cracks and reduce distortion after quenching. In last decades was shown that accelerated cooling reduces distortion if film boiling is completely absent and uniform martensitic shell is formed around the surface of steel parts during hardening process (Kobasko, Aronov *et al*., 2010). Along with decreasing distortion intensive quenching (IQ) increases significantly service life of steel parts due to creation of high compressive residual stresses and super – strengthening effect. A long ago, two intensive water quenching methods IQ-2 and IQ-3 were developed and discussed in published within 1980 – 1992 papers and books (Kobasko, 1980; Kobasko, 1992). The IQ-3 technique, also known as "direct convection cooling," and the IQ-2 technique, a three-step quenching process that initially cools under the nucleate boiling mode and then the convection heat transfer mode. Within 1983 – 1999 experiments were conducted in Ukraine for a variety of steel products quenched in agitated water salt solutions. Later, IQ-2 and IQ-3 technologies were tested in US (Aronov, Kobasko, *et al.,* 1999 – 2002), including automotive parts (coil springs, kingpins, torsion bars, bearing products, ball studs, etc.), fasteners of different types, and tool products: punches, dies, die components, etc., (Kobasko, Aronov *et al.,* 2010). For the above referenced technologies computer software package HART-TANDEM was developed in early 1980 (Morhuniuk, 1982; Kobasko and Morhuniuk, 1981, 1983, 1985) to determine optimal IQ conditions for each of the subject parts. Along with computer package, analytical equations were achieved for cooling time calculations. Simplified methods for cooling time calculations during quenching steel parts of any configuiration in liquid media were developed in 1969 – 1992 (Kobasko, 1969; Kobasko, 1992). These methods manipulate with two main equations. The first deals with the duration of transient nucleate boiling process and its final version was published by Springer-Verlag in 1992 (Kobasko, 1992). The second deals with the generalized equation for cooling time calculation during direct convection. Its final version was published in a book in 1980 (Kobasko, 1980). Full time of

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cooling during quenching consists of three periods of heat transfer modes (film boiling, nucleate boiling and convection). Film boiling, especially local film boiling, should be and can be eliminated completely using special additives and other possibilities. This problem is discussed below.

Cooling time calculation during hardening of steel parts

Cooling time calculations during quenching of steel parts is the first approach in recipes development. It is enough to calculate duration of transient nucleate boiling process τ_{nb} and duration of convection τ_{conv} at the area of maximal thermal inertia of any steel part to provide engineers with full time of cooling written as, Eq. (1):

$$\tau_c = \tau_{nb} + \tau_{conv} \tag{1}$$

It has been made thousands of calculations since 1980 using Eq. (2) and Eq. (3) and published hundreds papers in different scientific and technical journals and books discussing benefits and shortcomings of mentioned equations. At present they are public domain and are widely used in heat treating industry. Generalized Eq. (2) was constructed to calculate duration of transient nucleate boiling mode known as self – regulated thermal process (Kobasko, 1992).

$$\tau_{nb} = \left[0.24k + 3.21\ln\frac{\vartheta_I}{\vartheta_{II}}\right]\frac{K}{a} \tag{2}$$

$$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3}; \qquad \vartheta_{II} = \frac{1}{\beta}\left[\alpha_{conv}\left(\vartheta_{II} + \vartheta_{uh}\right)\right]^{0.3}.$$

Based on regular thermal condition theory of Kondratjev (Kondrajev, 1957), it has been proposed a generalized equation (3) for calculating cooling (heating) time of the objects of any configuration in condition of $0 \le Bi_V \le \infty$ (Kobasko, 1980):

$$\tau = \left[\frac{kBi_V}{2.095 + 3.867Bi_V} + \ln\left(\frac{T_0 - T_m}{T - T_m}\right)\right]\frac{K}{aKn} \tag{3}$$

The value $\Omega_{ir} = \dfrac{kBi_V}{2.095 + 3.867\,Bi_V}$ is responsible for irregular thermal process and is true for plate like forms when k = 1, for cylindrical different forms when k = 2 , and for spherical forms when k – 3. Note that

Bi_V is generalized Biot number and is determined as, Eq. (4):

$$Bi_V = \frac{\alpha}{\lambda}K\frac{S}{V} \tag{4}$$

Kn is Kondratjev number; K is Kondratjev form factor in m^2; T_0 is initial temperature in ^oC or in ^oK; T_m is bath temperature; α is heat transfer coefficient (HTC) in W/m^2K; λ is thermal conductivity of steel in $W/m\ K$; S is surface in m^2; V is volume in m^3.

There is an universal interconnection between Kn and Bi_V numbers (Kondrajev, 1957) and can be approximated by one curve which has analytical presentation:

$$Kn = \frac{Bi_V}{\left(Bi_V{}^2 + 1.437Bi_V + 1\right)^{0.5}} \tag{5}$$

Eq. (5) is an universal correlation of regular thermal condition theory of Kondratjev and is often presented as

$$Kn = \psi Bi_V \tag{6}$$

where the non- smoothness criterion of temperature distribution ψ along with Eq. (7)

$$\psi = \frac{1}{\left(Bi_V{}^2 + 1.437\,Bi_V + 1\right)^{0.5}} \tag{7}$$

has also a meaning

$$\frac{\overline{T}_{sf} - T_m}{\overline{T}_V - T_m} = \frac{1}{\left(Bi_V{}^2 + 1.437Bi_V + 1\right)^{0.5}}. \tag{8}$$

Here $\overline{T}_{sf}$ is average surface temperature; $\overline{T}_V$ is average volume temperature.

Direct convection

Direct convection during quenching means immediate decrease surface temperature of steel parts below boiling point of liquid. It means that transient nucleate boiling process is eliminated and convection starts after immersion steel parts into liquid. That cardinally simplifies cooling time calculations (Kobasko, 2002). Direct convection is provided when criterion (9) is satisfied:

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

where

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

$\vartheta_o = T_0 - T_S$; $\vartheta_{uh} = T_S - T_m$; Bi is conventional dimensionless Biot number; T_S .is saturation temperature; $\beta = 3.41$; R is radius in m. Criterion (see Eq. (9)) is used when nucleate boiling process should be eliminated. For water, it occurs approximately at 100^{o}C. However, finish temperature of martensitic transformations for many steels is below 100^{o}C. In this case, universal correlation (10) can be used as a criterion for elimination transient nucleate boiling process (Kondratjev, 1957):

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

$\overline{T}_{sf}$ is average surface temperature; $\overline{T}_V$ is average volume temperature.

Heat transfer coefficients of water flow and jets evaluation

The processes of heat transfer at the forced convection are described by equations of similarity:

$$Nu = f(\text{Re}, \text{Pr}) \qquad (11)$$

Here Nu is Nusselt number; $\text{Re} = \frac{wD}{v}$ is Reynolds number;

$\text{Pr} = \frac{v}{a}$ is Prandtl number.

The similarity equation for water flow is written as (Mikheev and Mikheeva, 1977; Kobasko*, et al.,* 2010):

$$\overline{N}u = 0.021\,\text{Re}^{0.8} \cdot \text{Pr}^{0.43} (\text{Pr}_m / \text{Pr}_{sf})^{0.25} \cdot \varepsilon_e \qquad (12)$$

where equivalent diameter d_{eq}, is evaluated from Eq. (13):

$$d_{eq} = \frac{4S}{u} \qquad (13)$$

Some data related to explore Eq. (12) are provided in Table 1.

Table 1. Correction $\left(\frac{\text{Pr}_m}{\text{Pr}_{sf}}\right)^{0.25}$ versus pressure and temperatures of water at the time of transition from nucleate boiling to a single-phase convection

Water temperature, °C	Pressure, MPa	$\left(\frac{\text{Pr}_m}{\text{Pr}_{sf}}\right)^{0.25}$	Average
20	0.10	1.42	1.54
	0.20	1.48	
	0.27	1.51	
	0.36	1.54	
	0.48	1.57	
	0.62	1.59	
	0.79	1.61	
	1	1.62	
40	0.10	1.23	1.36
	0.20	1.31	
	0.27	1.34	
	0.36	1.36	
	0.48	1.39	
	0.62	1.41	
	0.79	1.43	
	1	1.43	

where S is the area of cross-section of the channel; u is the full perimeter of the channel; Pr_m is Prandtl number for a quenchant far from the surface; Pr_{sf} is Prandtl number for a quenchant near a surface to be quenched. For fixtures of round section the equivalent diameter d_{eq} is equal to geometrical diameter d. If $\ell/d > 50$, then ε_e=1. At $\ell/d < 50$ the value ε_e is taken from Table 2.

Table 2. Values of dependence $\varepsilon_\ell = f(\ell/d, \text{Re})$ at the turbulent mode

Re	ℓ/d								
	1	2	5	10	15	20	30	40	50
$1\cdot10^4$	1.65	1.50	1.34	1.23	1.17	1.13	1.07	1.03	1
$2\cdot10^4$	1.51	1.40	1.27	1.18	1.13	1.10	1.05	1.02	1
$5\cdot10^4$	1.34	1.27	1.18	1.13	1.10	1.08	1.04	1.02	1
$1\cdot10^5$	1.28	1.22	1.15	1.10	1.08	1.06	1.03	1.02	1
$1\cdot10^6$	1.14	1.11	1.08	1.05	1.04	1.03	1.02	1.01	1

Methodology for evaluating heat transfer coefficients (HTCs) during quenching with sprayers is well known and is widely used in practice (Martin, 1990). HTC depends on many factors shown in **Fig. 1.**

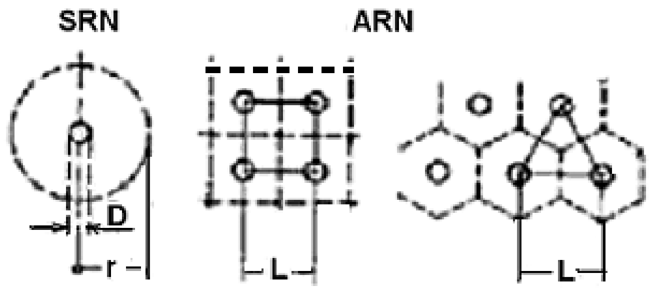

Fig. 1. Positions of round holes in the sprayer used for intensive quenching of large steel part

The average heat and mass transfer coefficients for impinging flow from regular (square or hexagonal) arrays of round nozzles (ARN) may be calculated as described in (Martin, 1990) with an accuracy of ±15 %. The generalized dimensionless equation has the following form, Eq. (14):

$$\overline{N}u = K_1 K_2\, \text{Re}^{2/3}\, \text{Pr}^{0.42}, \qquad (14)$$

$$K_1 = \left[1 + \left(\frac{H/D}{0.6}\sqrt{f}\right)^6\right]^{-0.05}; \quad K_2 = \frac{\sqrt{f}\left(1 - 2.2\sqrt{f}\right)}{1 + 0.2(\text{H/D} - 6)\sqrt{f}};$$

$$f = \frac{(\pi/4)D^2}{A_{sq/hex}}.$$

D is diameter of a nozzle in sprayer; H is a distance from a nozzle (aperture) to the surface to be quenched; and A is the area of the square, hexagon. Dimensionless numbers K_1 and K_2 are connected to the geometry and arrangement of nozzles with respect to the surface to be quenched. The Reynolds number Re is related to the speed of the quenchant at the beginning of the outlet from a nozzle, and the Prandtl number Pr characterizes physical properties of the quenchant. The dimensionless equation of similarity (Eq. (14)) is valid within the boundaries of the following values and given parameters (Martin, 1990):

$$2000 \le \text{Re} \le 100000$$
$$0.004 \le f \le 0.04$$

$$2 \le \frac{H}{D} \le 12 \quad .$$

Software HART-TANDEM for analyzing hardening processes

Despite of existing powerful computer codes like DANTE (Dowling *et al.,* 1996; Ferguson *et al*., 2002), HEARTS (Inoue *et al*., 1992; Inoue, 2002) and many others, the old software HART-TANDEM (Morhuniuk, 1982; Kobasko and Morhuniuk, 1983, 1985), developed in early 1980, can work successfully if combined with the accurate experimental data concerning cooling characteristics of different kinds of liquid quenchants. Some results of computer simulation connected with the hardening of roller (Fig. 2) are discussed below.

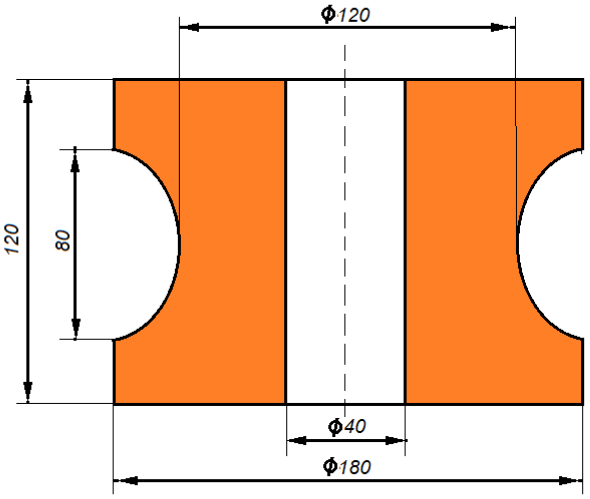

Fig. 2. Drawing of a roller used for FEM calculations

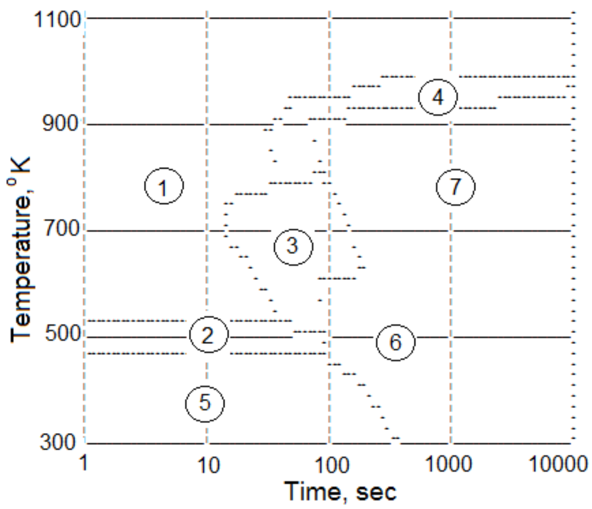

Fig. 3. CCT diagram used for FEM calculations: 1 is austenite; 2 is martensite; 3 is bainite; 4 is pearlite; 5 is martensite after full transformation; 6 is bainite after full process transformation; 7 is pearlite after full process transformation

A roller shown in Fig. 2 was made of low hardenability alloy steel similar to AISI 52100 steel which has reduced content of Mn and Cr. To simulate hardening of low alloy hardenability steel, the CCT diagram (Fig. 3) was shifted to the left side for 10 seconds. Such shifting cannot provide through hardening of the roller and will create uniform martensitic shell around the roller to see creation of high compressive residual stresses and observe distortion after intensive quenching. Along with mowing CCT diagram left and right, one can move martensite start temperature Ms up and down to simulate hardening of low carbon steels and high carbon steels. This opportunity were developed when designing software HART-TANDEM (Kobasko and Morhuniuk. 1981; Morhuniuk, 1982; Kobasko and Morhuniuk, 1983 - 1985). More information on simulation quenching processes and investigation of residual stress distribution in quenched steel parts one can find in the published papers and proceedings (Arimoto *et al.,* 1998 – 2002; Inoue, 2002; Freborg, *et al*., 2003, 2004; Ferguson *et al.,* 2005; Sugianto, *et al.,* 2009).

It was assumed that in Fig. 3 all phases 1 – 7 have the same thermal and physical properties and they are: thermal conductivity is equal to 20 W/mK; density is equal to 7600 kg/m^3; specific heat capacity is equal to 570 J/kgK, and thermal diffusivity is equal to $4.61 \times 10^{-6} m^2/s$. Mechanical properties of all phases are provided in Table 3. It should be noted that not a long ago scientists came to conclusion that bainitic structure can provide better mechanical and plastic properties of steel as compared with martensite (Bhadeshia, 2001). It means that intensive quenching of steel parts should be interrupted at proper time to provide the best condition for bainitic transformations at the core of steel partds.

Table 3. Physical and mechanical properties of materials (see Fig. 3) taken into account during current and residual stress calculations

T-re, °K	E	ν	α_t	$R_{p0.2,}$ MPa	E_1	$R_{m,}$ MPa
			Phase 1			
293	208000	0.30	0.0000120	420	4428	730
423	200000	0.30	0.0000139	400	5000	640
873	160000	0.30	0.0000152	200	7800	550
973	120000	0.31	0.0000150	100	1170	300
1073	115000	0.35	0.0000180	70	240	130
1173	115000	0.40	0.0000300	60	110	90
			Phase 2			
293	208000	0.30	0.0000064	1200	10000	1700
423	200000	0.35	- 0.0000170	130	1000	230
873	200000	0.37	- 0.0000230	100	100	150
973	200000	0.40	- 0.0000450	90	100	150
1073	200000	0.40	- 0.0001540	100	100	190
1173	200000	0.30	0.0000140	380	5280	700
			Phase 3			
293	208000	0.30	0.0000120	420	4428	730
423	200000	0.30	0.0000139	400	5000	640
873	160000	0.30	0.0000152	200	7800	550
973	120000	0.31	0.0000150	100	1170	300
1073	115000	0.35	0.0000180	70	240	130
1173	115000	0.40	0.0000300	60	110	90
			Phase 4			
3	208000	0.30	0.0000120	420	4428	730
423	200000	0.30	0.0000139	400	5000	640
873	160000	0.30	0.0000152	200	7800	550
973	120000	0.31	0.0000150	100	1170	300
1073	115000	0.35	0.0000180	70	240	130
1173	115000	0.40	0.0000300	60	110	90

Notes: Yong's modulus (E) describes tensile elasticity. It is defined as the ratio of tensile stress to tensile strain. Poisson's coefficient ν is a ratio of transverse strain to axial strain named after Simeon Poisson. Thermal expansion coefficient α_t is defined as a change in length or volume of a material for a unite change in temperature; $R_{p0.2}$ is yield strength in MPA; . R_m is ultimate strength in MPa.

Table 3 provides physical and mechanical properties of austenite, bainite, pearlite and martensite versus temperature which were used during simulation of hardening processes (see Fig. 3). It should be noted that at present time there are many very powerful codes developed for simulation carburizing and quenching processes (Dowling, Pattok, Ferguson *et al.,* 1996, USA). Inoue and Arimoto discussed development and implementation of CAE system "Hearts" for heat treatment simulation based on metallo-thermo-mechanics (Inoue and Arimoto, 1997, Japan). Using these powerful codes, hundreds of very important investigations were fulfilled which were successfully used in heat treating industry in the USA (Ferguson*, et al.,* 2002; Freborg *et al.,* 2003; Freborg, *et al,* 2004; Ferguson *et al.,* 2005 – 2007) and many others. Japanese scientists predicted successfully crack formation and distortion during quenching in liquid media using code "HEARTS" (Arimoto, Lambert *et al.,* 1999; Arimoto, Ikuta *et al.,* 2004; Arimoto, Horino *et al*., 2006; Arimoto, Yamanaka *et al*., 2006) and many others. Contemporary codes for temperature fields and stress- strain state calculations are developed in EC and used for needs of heat treating industry.

Here 0.24k =0.24x1.5 = 0.36; Kondratjev form factor K is taken for prism 0.055m x 0.12m x 0.3m and is equal to $246.4\times10^{-6}m^2$. Thermal diffusivity of material is $4.61\times10^{-6}m^2/s$. Calculations show correctness of both methods in recipes development for hardening processes.

Fig. 5 presents phase distribution in the section of the roller (see Fig. 2) after 50 seconds of intensive quenching with the heat transfer coefficient (HTC) equal to 10,000 W/m^{2}K. As follows from Fig. 5, martensite phase (2 and 5) creates a shell at the surface of the roller average thickness of which is 7.5 mm in ID and 6 mm in OD areas. Ratio of martensitic layer to minimal thickness of the roller is 0.1 and 0.125. It is a little bit less than optimal thickness of hardened layer, but it is close to it. It means that one should expect compressive residual stresses at the surface of the roller after its complete cooling.

Prediction of crack formation

Fig. 6 shows the area, marked by red, where quench crack formation starts first. A generalized Pisarenko – Lebedev

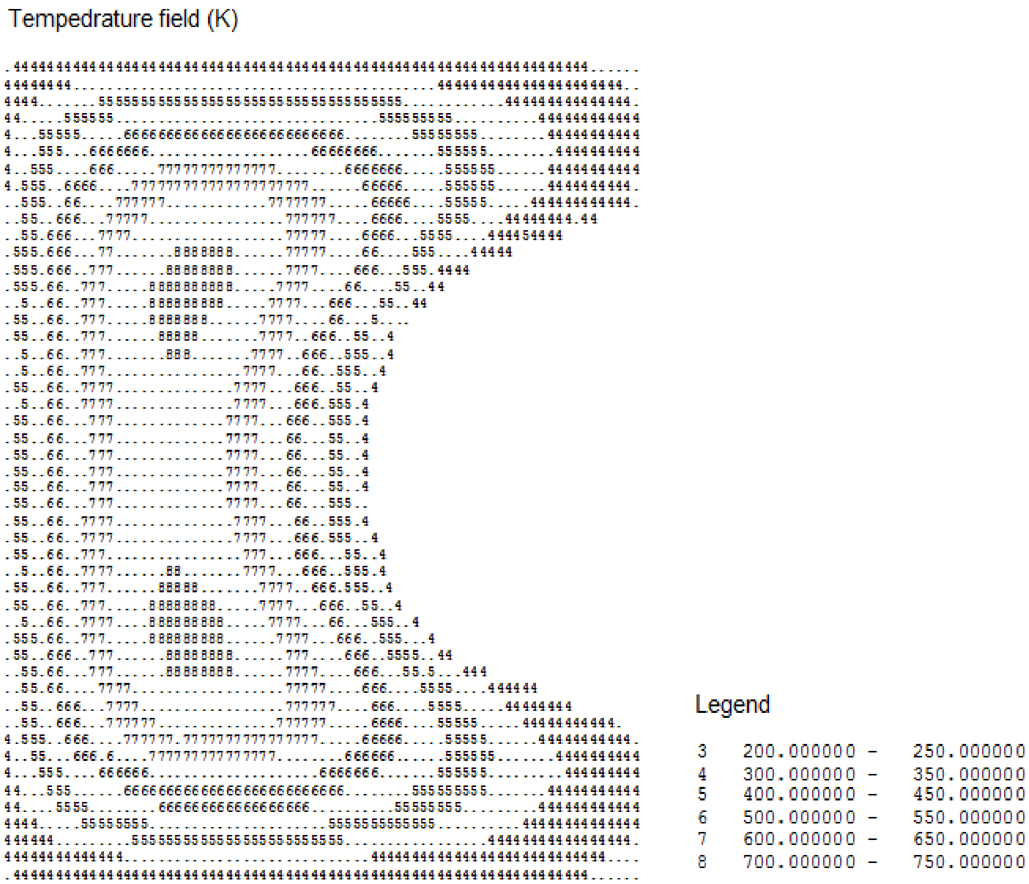

Fig. 4. Temperature field in ^{o}K in the roller (see Fig. 2) at the moment 50 sec when dir x ect convection quenching with heat transfer coefficient equal 10,000 W/m^{2}K

Fig. 4 shows temperature field in the section of the roller at the moment 50 sec. As seen from the Fig. 4, there are two thermal inertia areas where cooling rate is minimal as compared with other locations. Temperature in these two areas is 750^{o}K or 477^{o}C. According to simplified calculations (see Eq. (3)), cooling time from 830^{o}C to 477^{o}C is:

$$\tau=\left[0.36+\ln\left(\frac{830^oC-20^oC}{477^oC-20^oC}\right)\right]\frac{246.4\times10^{-6}m^2}{4.61\times10^{-6}m^2/s}=49.8\sec\cdot$$

criterion (Pisarenko and Lebedev, 1976) was selected as a failure criterion during hardening of steel components, Eq. (13):

$$\chi`\sigma_i+(1-\chi)\sigma_1\le\sigma_t \qquad (15)$$

Where; $\chi=\frac{\sigma_t}{\sigma_c}$ σ_t is ultimate tensile strength; σ_c is ultimate compressive stress; σ_1 is greatest principal strength.

Formed

Fig. 5 Micro- structure distribution in the section of the roller at the moment 50 sec when direct convection quenching with a heat transfer coefficient equal to 10,000 W/m^{2}K: 3 is bainite; 4 is pearlite; 5 is martensite

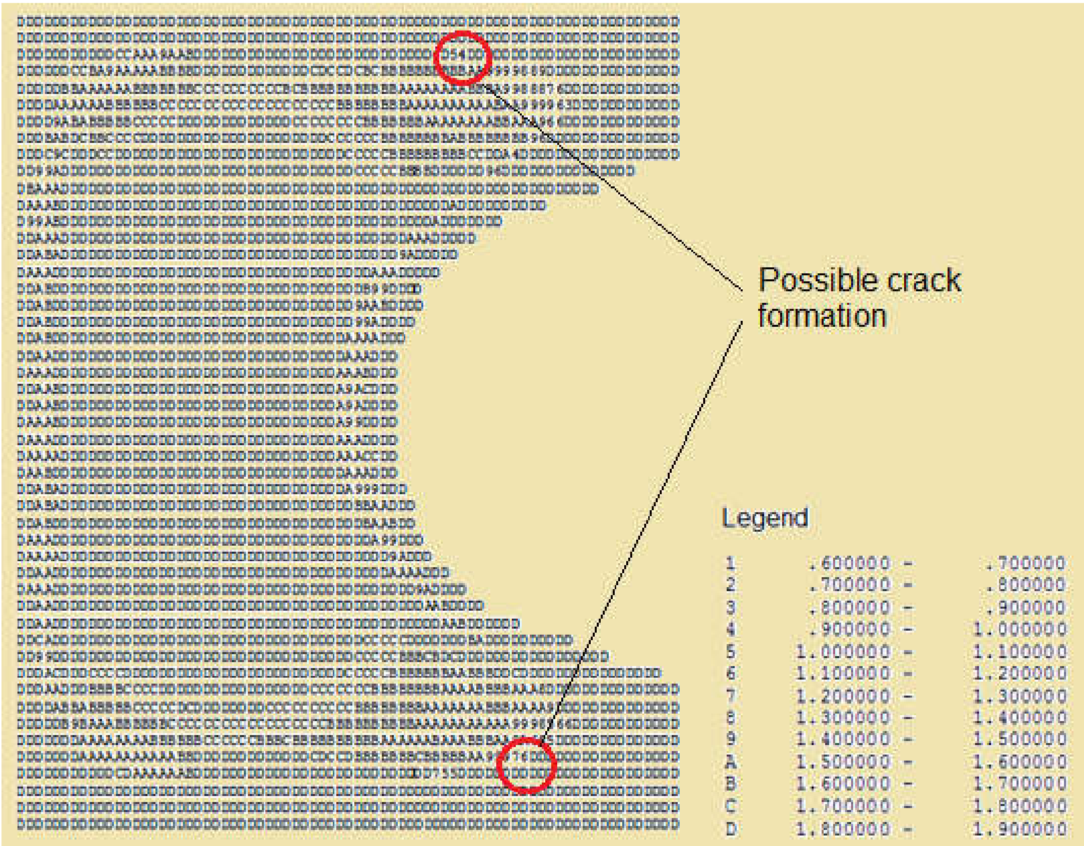

Fig. 6. Area in the roller where micro- cracks can appear at the moment 50 sec when direct convection quenching with a heat transfer coefficient equal to 10,000 W/m^{2}K

Distortion in steel parts after quenching is generated by main three reasons: stress distribution, specific volume density of formed phases and local film boiling on the surface. Intensive quenching decreases distortion due to martensitic shell and absence of any film boiling during quenching. Fig. 7 supported these ideas. Fig. 8 shows that the most intensive plastic deformations take place within the martensitic shell and at the boundary of martensite – bainite. As known, during phase transformation the phenomenon super-plasticity takes place which can effect intensity of plastic deformation, distortion and stress distribution. Unfortunately, there are not enough information on it to take into account during computer simulation. Such information can be received experimentally that needs special technique and is very costly. As expected, at the surface of the roller high compressive residual stresses are formed (see Fig. 9 and Fig. 10). On the working surface of the roller compressive axial stresses reach 780 MPa (see Fig. 9) and hoop compressive residual stresses reach 900 MPa (see Fig. 10). At the core of the roller tensile axial and hoop stresses are rather low and are within 180 – 300 MPa

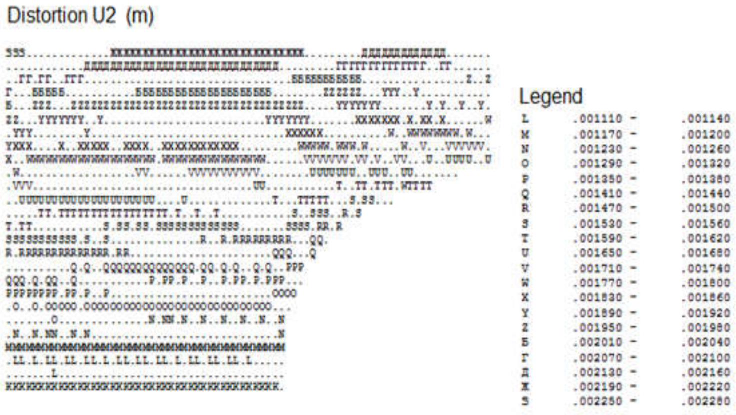

Fig. 7. Distortion U(2) distribution in m in the section of the roller at the moment 50 sec when direct convection quenching with a heat transfer coefficient equal to 10,000 W/m^{2}K.

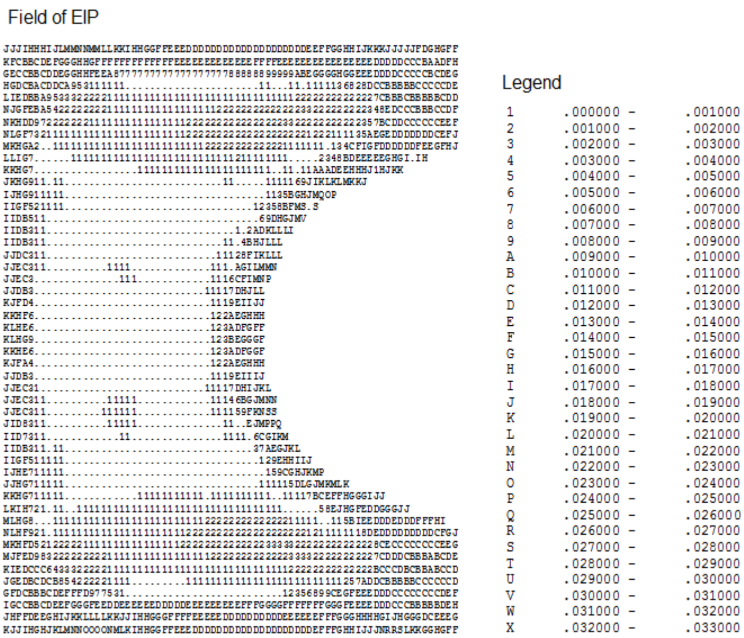

Fig. 8. Intensity of plastic deformation distribution in m in the section of the roller at the moment 50 sec when direct convection quenching with a heat transfer coefficient equal to 10,000 W/m^{2}K

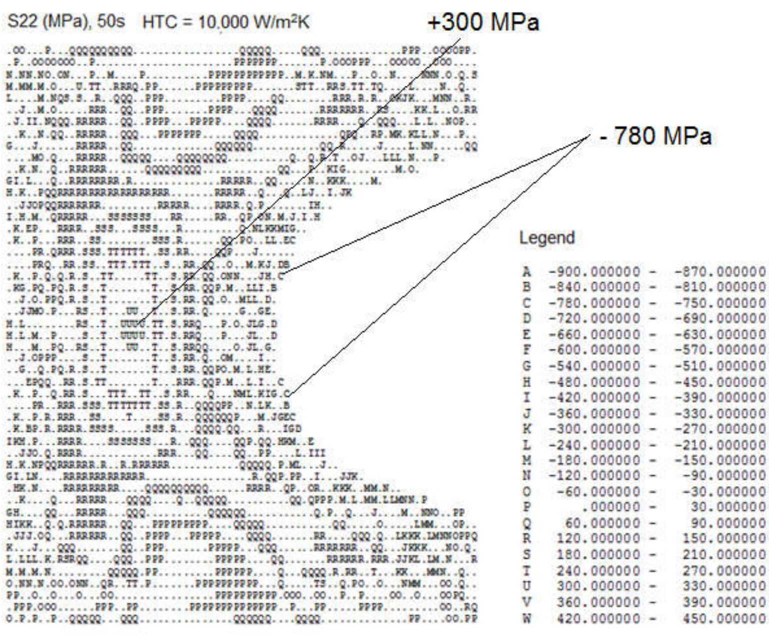

Fig. 9. Axial stresses distribution in MPa in the roller (see Fig. 2) at the moment 50 sec when direct convection quenching with heat transfer coefficient equal 10,000 W/m^{2}K

(see Fig. 9 and Fig. 10). As known, compressive residual stresses increase fatigue and wear resistance and are reason for decrease distortion of steel parts when martensitic shell is formed around the surface uniformly.

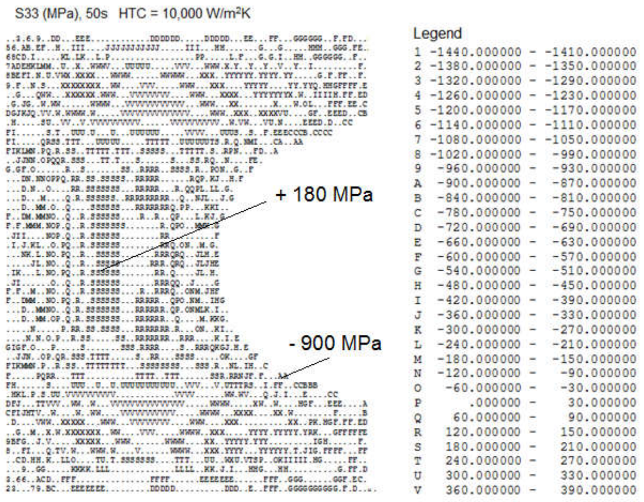

Fig. 10. Hoop stresses distribution in MPa in the roller (see Fig. 2) at the moment 50 sec when direct convection quenching with heat transfer coefficient equal 10,000 W/m^{2}K

Alloy low hardenability steel

Compressive residual stresses and super-strengthening phenomenon allow cardinal decrease of alloy elements in steels. In Ukraine alloy low hardenability steel was patented (Kobasko, 2017). Optimal hardenability steel which provides optimal hardened martensitic surface layer with maximal compressive residual stresses in it and bainitic or pearlitic microstructure at the core after intensive quenching can be designed using similarity ratio:

$$\frac{DI}{D_{opt}} = 0.35 \pm 0.095 \qquad (16)$$

here DI is critical diameter in m; Dopt is diameter of steel part in m to be quenched in agitated liquids.

A procedure of its use is as follows:

1. A steel grade with certain chemical composition is chosen.
2. The ideal critical size for this steel is determined.
3. The ratio DI/Dopt for specific steel part is evaluated which must be in the range of 0.2–0.5.
4. The part is quenched in condition of $0.8 < Kn < 1$ (Kobasko, 2002).
5. Intensive quenching is interrupted when optimal quenched layer is achieved with maximal compressive stresses at the surface.
6. The part is tempered at the temperature Ms or higher.

The history of such development started when it was noticed that not through hardened but intensively quenched steel parts has much better service life as compared with through hardened steel parts (Kobasko *et al.,* 2010). As a result, steels with reduced content of Mn, Cr and Ni were recommended to use to increase service life of machine components. Thus, a method for optimizing chemical composition of steel is proposed and a correlation is established to reduce cardinally alloy elements in existing steel grades that results in high compressive residual stresses at the surface of intensively quenched steel parts and increasing strength and ductility of material due to super-strengthening phenomenon. The algorithm of optimization consists in reducing alloy elements in existing alloy steel in 1.5–2 times and then lowering step-by-step content of steel, beginning from the most costly alloy element and ending the most cheaper one, until established correlation is satisfied. The range of reduction is minimal and during computer calculations can be chosen as 0,001 wt %. The proposed approach can save alloy elements, energy, increase service life of machine components and improve environmental condition. The method is a basis for development of the new low hardenability (LH) and optimal hardenability steels.

DISCUSSION

As follows from the overview, there are many codes for calculating temperature fields and stress – strain states during quenching of steel parts. The most famous are DANTE (USA) and HEART (Japan) which are widely used for quenching processes simulation. Within the period of time 1978- 1998 authors successfully used software HART-TANDEM (Morhuniuk, 1982, Kobasko and Morhuniuk, 1985) for investigations hardening processes. Along with FEM calculations, analytical equations were provided for cooling time calculation (Kobasko, 1980) and calculation duration of transient nucleate boiling process (Kobasko, 1992). Despite of excellent software availability in many countries, a a rather big problem in computer simulation of quenching processes still exists. The matter is that boundary condition during quenching in liquid media are unknown or provided incorrectly. That is why in many cases results of computer simulations can be wrong. To make correctly calculations and computer simulations, one needs the DATABASE on liquid quenchants used as the boundary condition during computer simulations. As for analytical calculations, ITL (Kyiv, Ukraine) developed software for calculating form factors values and optimal chemical composition of steel to provide maximal surface compressive residual stresses in quenched steel parts. Also, IQCalc software is available for recipes development when quenching in liquid media. Especially, such approach is very important when quenching in liquid media under pressure to perform austempering processes in cold liquids (Kobasko, 2016). Also, a great future have the hydrodynamics emitters for elimination any film boiling during batch quenching by proving resonance effects (Kobasko, 2016). It this case batch quenching can be successfully used for quenching alloy low hardenability steels, for example large gears, to eliminate completely carburizing processes and receive huge benefits (Kobasko, 2017).

Conclusion

1. Combining analytical methods of cooling time calculation with the computer mode HART-TANDEM and experimental data on cooling characteristics of liquid quenchants provides engineers with the accurate data on steel parts hardening process including all aspects of phase transformation, stress distribution and distortion to be used for recipes development.

2. Developed later powerful computer codes DANTE (USA), HEARTS (Japan) and many others can be successfully used for investigation of any aspect of hardening process, including carburization, quenching in liquid media under pressure, and so on, if accurate experimental initial data are available.
3. It is impossible to design universal software for cooling time calculation based only on pure analytical equations concerning duration of transient nucleate boiling process and convection. Some accurate experimental initial data are needed for this purpose.
4. Despite of existing highly developed methods of inverse problem (IP) solving, the cooling characteristics of liquid quenchants are not investigated yet correctly in terms of using them for computer simulation. This problem needs serious attention.
5. To make further progress in contemporary methods of hardening based on computer simulations, a team of leading specialists should be organized and investments on the global level should be made for wide investigations of liquid media as the quenchants.

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