New Ways of Obtaining Super - Strengthened Large Components Based on Use of Optimal Hardenability Steel

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***Abstract* -** In the paper new patented in Ukraine optimal hardenability steel and method of its designing is discussed to eliminate completely costly carburization process during thermal strengthening of large gears and improvement quality of hardening of big rotors, rollers by implementation intensive quenching processes. Usually, metallurgists are trying to improve mechanical properties of steel components by increasing alloy elements in steel that require slow cooling in oils or high concentration of water polymers solutions. It is proposed opposite way in increasing service life of machine components by cardinal decrease alloy elements in steel and providing intensive cooling during hardening in water, water solutions combined with moving in quenching baths sprayers connected with the pumps. The proposed new approach is based on two fundamental phenomena which include creation of high surface compressive residual stresses after intensive quenching and obtaining super – strengthened material in surface layers after complete cooling. These two factors compensate decrease alloy elements in steel. The paper provides methodology of calculation for achieving maximal effect in residual surface compressive stress formation and super- strengthening of material depending on martensite finish temperature of steel. Effectiveness and benefits are considerable due to saving alloy elements, energy and increasing service life of products. A team of Ukrainian leading specialists is organized to design appropriate software for governing and optimizing hardening processes with the aim of achieving above benefits and make environment clean. New steel and technology of hardening is based on UA Patents No. 109577 and No. 114174.
Keywords: compressive residual stress, super-strengthening, alloy elements decrease, service life increase, local cooling, sprayers

I. INTRODUCTION

Intensively quenched low hardenability steels for elimination carburizing processes were used in practice a long ago [1, 2,and 3]. There is a well known patented low hardenability steel containing 0.40 - 0.85C; $\le$ 0.20Mn; $\le$ 0.20Si; $\le$ 0.10Cr; $\le$ 0.1 Ni; $\le$ 0.1 Cu; 0.03 – 0.10 Al; 0.06 – 0.12 Ti; $\le$ 0.40 V; and Fe [3]. It can be used only for manufacturing small and medium gears, shafts and so on and cannot be used for manufacturing large gears, rollers, rotors, *etc.*Moreover, large steel parts cannot be individually quenched in fixtures to provide intensive quenching needed for super strengthening effect. That is why, there is a problem with intensive hardening of large steel components.

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The problem was solved in Ukraine by proposing new optimal hardenability steel, method of its designing, developing special apparatus for intensive quenching of large steel components and elaboration software for controlling and governing quenching processes [4]. If intensive quenching method for large steel parts is properly designed, all benefits of intensive quenching are achievable. New optimal hardenaby steel, contains 0.4 – 1.2 C; $\le 0.20Mn$; $\le 0.20Si$; $\le 0.50Cr$; $\le 1.6Ni$; $\le 0.25Mo$; $\le 0.20Cu$; 0.03 – 0.10Al; 0.05 – 0.12Ti; $\le 0.40V$; $\le 0.035S$; $\le 0.035P$ and creates optimal hardened layer after intensive quenching process (see Fig. 1) [4].

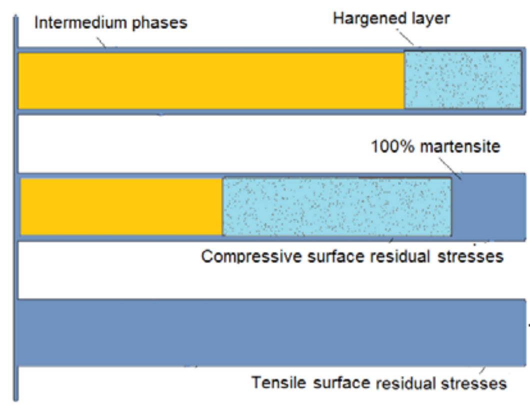

Fig. 1 Optimal depth of hardened layer corresponding to the maximum surface compressive residual stresses: LH, low hardenability steel; OH, optimal hardenability; ThH, through hardening

Since low hardenability steel (LH) contains very small amount of alloy elements, it creates shell hardening shown in Fig. 1. Optimal hardenability steel containing alloy elements creates deeper hardened layer and provides maximal surface compressive residual stresses after intensive quenching (IQ) process (see Fig. 2). Conventional alloy and high alloy steels, as rule, are hardened through when quenching in oils and result in creation low tensile or neutral surface residual stresses. It should be noted here that low hardenability steels work perfectly when intensively quenched due to creation of high surface compressive residual stresses and super strengthening effect [5, 6, 7]. However, low hardenability steels cannot be used for manufacturing large steel components like large rollers, rotors, large shafts used in marine industry, *etc.* Also, large steel components cannot be quenched in special fixtures providing very intensive cooling. The paper discusses intensive quenching of large steel parts manufactured from optimal hardenabily steels recently patented in Ukraine [4].

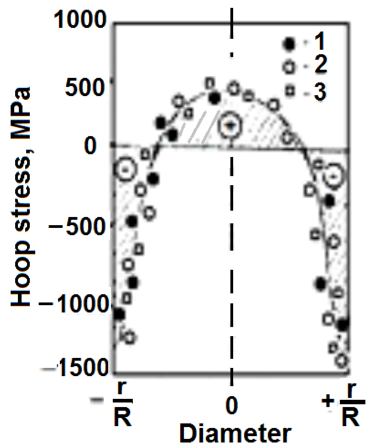

Fig. 2 Residual hoop stress distribution in cylindrical specimens when quenching intensively in water flow or by moving sprayers

Optimal hardenabily steels (OH) provide optimal hardened layer and maximal surface compressive residual stresses as shown in Fig. 1 and Fig. 2.

II SUPER – STRENGTHENING EFFECT

To understand the nature of super-strengthening, imagine a superficial layer compressed to the limit (1,200–1,500 MPa) in which martensitic plates are formed with greater specific volume than the initial phase structure of supercooled austenite (see Fig. 3). A period of appearance of such plates is very short and is less than 10^{-6} s. The plates of martensite deform the supercooled austenite that is allocated between them. The higher the cooling rate is within the martensite range, the greater will be the extent to which the austenite is deformed, and the higher is the dislocation density. Consequently, during rapid cooling, there is not enough time for the dislocations to accumulate in the grain boundaries and to form nuclei of future micro cracks; they are frozen in the material. Thus, the superficial layer acts like a blacksmith: under conditions of high stress, the plates of martensite arise explosively, deforming the austenite and creating extremely high dislocation densities, which are frozen during rapid cooling. This process is analogous to low-temperature thermo-mechanical treatment (LTMT) [8, 9]. Strength and plastic properties improvement is shown in Table 1.

Table 1 Comparison of the mechanical properties of different steels quenched in oil and two step quenched with accelerated cooling rate within the martensite range when cooling in liquid nitrogen [10].

Method	Cooling Rate, °C/s	Steel	Ultimate strength, MPa	Yield strength. MPa	A (%)	Z (%)
Oil	3 – 6	U7A	1400	1250	4	-
		60C2A	1476	1355	8.5	-
IQ	30	U7A	1610	1570	7.9	31
		60C2A	1920	1740	5	22

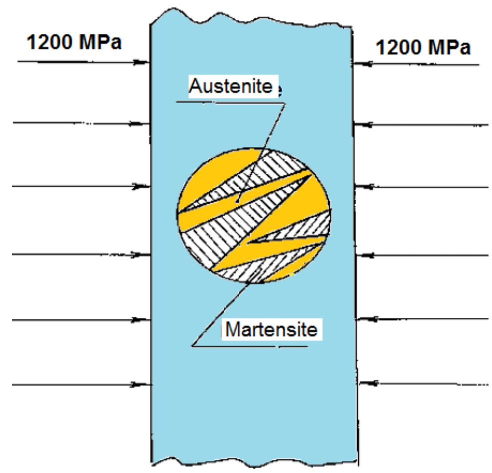

Fig. 3 The transformation scheme of austenite into martensite in the compressed layer, illustrating the effect of additional strengthening (super-strengthening) of the material

Due to super strengthening effect and high surface compressive residual stresses, it was possible to start commercialization and build equipment for intensive quenching processes which were successfully applied into the practice [11 – 16].

III METHOD FOR OBTAINING OPTIMAL HARDENED LAYER

Alloyed low hardenability steels which provide 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 established by author [4, 5] the similarity ratio (1):

$$\frac{DI}{D_{opt}} = 0.35 \pm 0.095 \qquad (1)$$

here DI is critical diameter in m; D_{opt} is diameter of steel part to be quenched in m (see UA Patent No. 114174 [4]). According to painstaking investigations of Grossmann [17], critical diameter DI depends on size of grains and chemical composition of steel and is written as:

$$DI = DI_{base}(carbon - grain) f_{Mn} f_{Si} f_{Cr} f_{Ni} f_{Mo} \dots \qquad (2)$$

where f_x is multiplying factor for the particular alloying element evaluated from the painstaking experiments of Grossmann [17, 18].

A procedure of its use is as follows:

- A steel grade with certain chemical composition is chosen.
- The ideal critical size for this steel is determined.
- The ratio DI/D_{opt} for specific steel part is evaluated and alloy elements are reduced two or three times to satisfy the ratio (1) which must be in a range of 0.2 – 0.5.
- The part is quenched in condition $0.8 \le Kn \le 1$ by locally moving sprayers [7].
- Intensive quenching is interrupted to provide self – tempering].
- The part is tempered at the temperature ≥ Ms.

Eq. (1) is based on similarity stress distribution which was for the first time discussed in the publications [6 - 19] and used for software development. If a ratio (1) is satisfied, residual hoop stress distribution in steel component is optimal which is shown in Fig. 2.

IV APPARATUS FOR INTENSIVE QUENCHING OF LARGE STEEL PARTS

Apparatus for quenching large steel parts is shown in Fig. 4. It consists of two sectioned sprayer which creates round coil when put together [20]. To provide intensive quenching of large steel part, there is no need to agitate a huge amount of water in quench tank. It is enough to provide intensive cooling below sprayer which is moving along the axis of stepped cylinder (roller or rotor) and by this way completely eliminates film boiling and decreases immediately surface temperature of steel part below martensite finish temperature M_F. Method of quenching shows several benefits:

- It creates very high compressive residual stresses on the surface of quenched steel parts.
- Surface layers of steel component are properly super strengthened
- Service life of steel parts increases due to high compressive residual stresses and super strengthening effect.
- Alloying of material decreases from 1.5 to 3 times.
- Instead of environment non – friendly oils the plain water or water solutions are used.
- The hardening process can be used for direct quenching from forging temperature in forging shops.

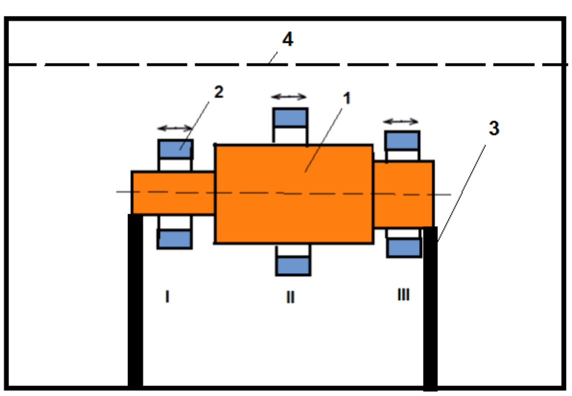

Fig. 4 Apparatus for hardening of large steel parts consisting of two sectioned sprayers moving periodically along the axis in areas I, II, and III:1 is rotor; 2 is sprayer, 3 is fixture; 4 is water level [20].

V. HEAT TRANSFER COEFFICIENT PROVIDED BY SPREYERS AND SLOTS

A. Sprayers

In most cases sprayer cooling represents rather simple device consisting of two hollow finite cylinders, one of them being inserted into the other in a parallel way, and both being sealed at end faces. Here the inner hollow cylinder has nozzles, which can be of different diameters D and located at generatrix of the cylinder in many different ways (see Fig.7 a), b), c)), square or hexagonal [21].

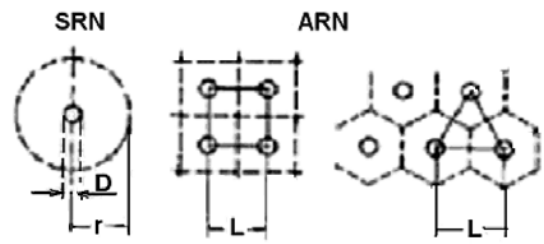

Fig. 5 Possible ways of hollows arrangement in sprayers [21].

The average heat and mass transfer coefficients for impinging flow from regular (square or hexagonal) arrays of round nozzles (ARNs) may be calculated from [21] with accuracy of ± 15 %.

The generalized dimensionless dependence has the following form [21]

$$\overline{Nu} = K_1 \cdot K_2 \cdot \mathrm{Re}^{\frac{2}{3}} \cdot \mathrm{Pr}^{0.42} \qquad (3)$$

where

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

$$f = \frac{\left(\pi/4\right)D^2}{A_{square(hexagon)}};$$

D is a diameter of a nozzle in sprayer ;

H is a distance from a nozzle (aperture) to a surface to be quenched;

A is the area of the square, hexagon.

Dimensionless numbers K_1 also K_2 are connected with geometry and arrangement of nozzles with respect to the surface to be quenched. Reynolds number Re is connected with the speed of the quenchant in the beginning of the outlet from a nozzle, and the number Pr characterizes physical properties of the quenchant. The dimensionless equation of similarity (9) is fair within the boundaries of the following values and given parameters: $2000 \le \mathrm{Re} \le 100000$; $0.004 \le f \le 0.04$; $2 \le \frac{H}{D} \le 12$.

B. Slots

As a rule, gears are quenched in special fixtures creating slots openings directed toads teeth of gear shown in Fig. 6 and Fig. 7.

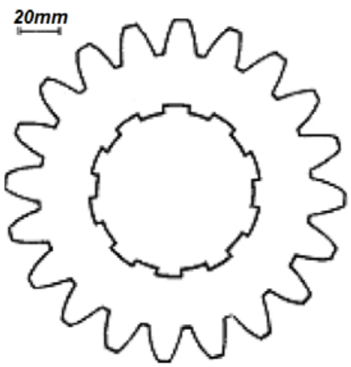

Fig. 6 The dimensionless equation of similarity for slot nozzles, according to Ref.[9], has the form:

Such approach was used by authors [22] to quench helicopter gears made of Pyrowear – 53 steel. It was noticed that intensively quenched helicopter test gears made of carburized Pyrowear-53 steel withstand 14% greater load for the same fatigue life as standard gears quenched in oil. Also, investigators came to conclusion that uniform intensive quencxhing of steel parts decreases considerably distortion. .

Table 2 Form factor coefficients for gear shown in Fig. 6 size of which proportionally increases from thickness 30 mm to thickness 90 mm.

Thickness, mm	Kondratjev coefficient K in m^2	K_{DI} in m^2	K_{DI} / K
30	73×10^{-6}	38.91×0^{-6}	0.533
40	129.78×10^{-6}	69.17×10^{-6}	0.533
50	203×10^{-6}	108.1×10^{-6}	0.533
60	292×10^{-6}	155.64×10^{-6}	0.533
80	519.1×10^{-6}	$276.26. \times 10^{-6}$	0.533
90	657×10^{-6}	350.2×10^{-6}	0.533

The main ratio (1) for designing optimal hardenability steels and providing high surface compressive residual stresses is true for cylindrical forms. For complicated forms, like gears, additional parameter should be taken into account. The idea on such parameter is shown in Table 2. Along with the ratio (1), software for developing or choosing optimal hardenability steel, depending on size and form of steel component, contains also a ratio K_{DI} / K which allows transition from cylindrical forms to complicated forms like gears. Here K_{DI} is Kondratjev coefficient [23] of cylinder which is equal to thickness of real steel part and is taken as a critical diameter depending on chemical composition of steel; K is Kondratjev coefficient of complicated form like gear.

It should be noted also that large gears made of alloy steels are carburized in furnaces for 60 – 80 hours and more and then are slowly quenched in oils that is long and very costly procedure. If large gears are made of optimal patented steel and intensively quenched by plain water with application slots, carburizing process can be completely eliminated.

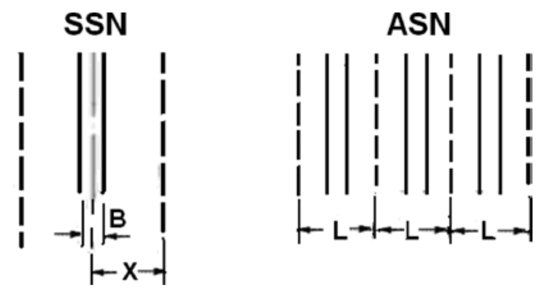

Fig. 7 Character of the positions of slots in the sprayer.

$$\overline{N}u = \frac{2}{3} f_0^{\frac{3}{4}} \left(\frac{2\,\mathrm{Re}}{f / f_0 + f_0 / f} \right)^{\frac{2}{3}} \cdot \mathrm{Pr}^{0.42} \qquad (4)$$

where $f_0 = [60 + 4(H / S - 2)^2]^{-0.5}$;

$S = 2B$ for slot nozzles; B is the width of a slot nozzle.

$f = \frac{S}{2L}$; $L = \frac{2\pi R}{n}$;

R is inner radius of a slot round sprayer;

n is the number of slots located at the generatrix.

quenching in the case of jet cooling.

C. Tightly loaded batch quenching

Tightly loaded gears or other steel parts subjected to batch quenching can create inside a load local film boiling area as shown in Fig. 8. The film boiling process can be fully eliminated in IQ water tanks due to the following measures: providing a vigorous (intensive) agitation of the quench bath, maintaining the water at close to ambient temperature, and using a small amount of water additives (usually mineral salts) that affect electrostatic conditions of the thin quenchant layer bearing against the part surface, resulting in an increase of quenchant surface tension. All these factors increase the value of the first critical heat flux density, qcr1, in the quench water. In other words, a greater heat flux from the part surface is required to bring the IQ-2 quench water to the saturated temperature needed to initiate the film boiling process at the part surface. However, from time to time local film boiling can take place between steel parts in batch load (see Fig. 8) due to water flow resistance if steel parts are tightly loaded. In this case, emitters providing resonance effect with existing local films, can radically help [24, 25].

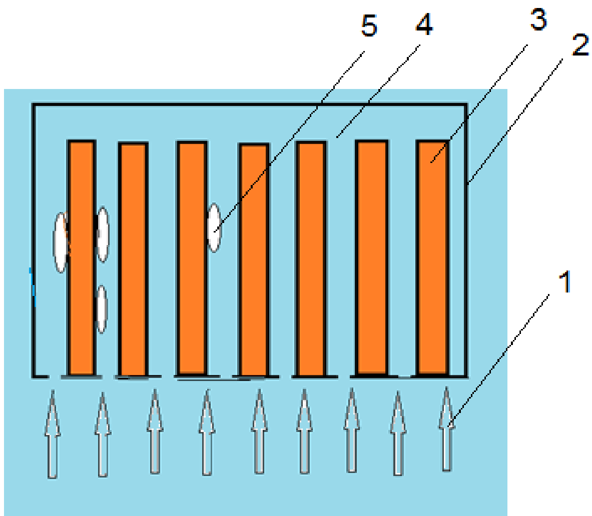

Fig. 8 A load of cylindrical steel parts prepared for batch quenching in the integral quench 36”x36”x72” atmosphere furnace: 1 is water flow; 2 is container; 3 is cylindrical steel part; 4 is quenchant; 5 is local film boiling.[24, 25].

To eliminate local film boiling processes, a new method of destroying effectively vapor films during quenching was proposed by author [24]. Its essence consists in providing resonance effect between frequency of a local film boiling or full film boiling and frequency of oscillation generated by emitters [24, 25] located in a bath with a quenchant. Resonance effect destroys vapor blankets more effectively as compared with directed flow of liquid since it doesn’t face resistance created by load.

VI COUPLING THE TRANSIENT NUCLEATE BOILING PROCESS WITH THE CONVECTION MODE

If film boiling is absent and transient nucleate boiling takes place immediately, the mathematical model for cooling process is written as

$$c\rho\frac{\partial T}{\partial\tau}=div(\lambda gradT)+Q \qquad (5)$$

$$\left[\frac{\partial T}{\partial r}+\frac{\beta^m}{\lambda}(T-T_S)^m\right]_{r=R}=0 \qquad (6)$$

$$T(r,0)=T_0. \qquad (7)$$

After the transient boiling process is finished, convection starts and the third kind of boundary condition (8) is used instead of boundary condition (6):

$$\left[\frac{\partial T}{\partial r}+\frac{\alpha_{conv}}{\lambda}(T-T_m)\right]_{r=R}=0 \qquad (8)$$

$$T(r,0)=T\left(r,\tau_{conv}^{\ start}\right) \qquad (9)$$

Initial

It means that $T\left(r,\tau_{nb}^{\ end}\right)=T\left(r,\tau_{conv}^{\ start}\right)$ and is chosen as an initial condition for convection mode. Where T is temperature; T_s is saturation temperature; T_m is bath temperature; T_o is initial temperature; Q describes phase transformation in solid material during quenching; R is radius; τ is time; c is specific heat capacity; ρ is density; β is parameter depending on physical properties of liquid; m = 10/3; λ is thermal conductivity of material; α_{conv} is heat transfer coefficient during convection.

VII OPTIMAL QUECHED LAYER IN THE ROLLER DESIGNED BY COMPUTER SIMULATION

As an example, for computer simulation was chosen a roller shown in Fig. 9.

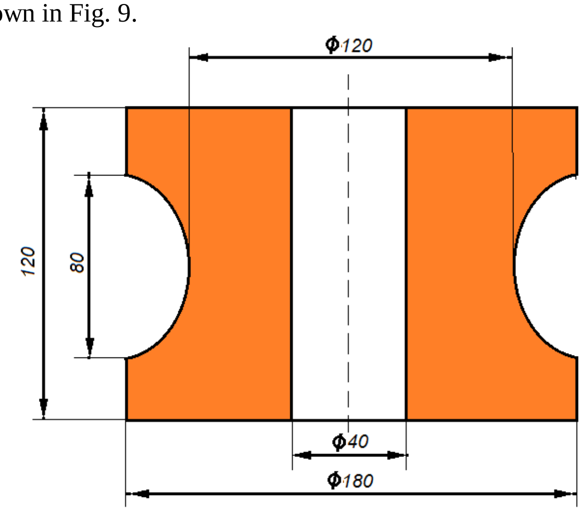

Fig. 9 Drawing of a roller used for FEM calculations

Heat transfer coefficient of 10,000 W/m^{2}K provides direct convection during quenching of the roller with 180 mm OD and 40 mm ID diameters (see Fig. 9). It was assumed that optimized chemical composition of steel has continues cooling transformation (CCT) diagram shown in Fig. 10. When taken this CCT diagram into account, the microstructure in the roller has very favorable distribution. Surface layer is formed by 100% martensite 5, further goes a large area of bainite 3 and only small area the core is occupied by pearlite (see Fig, 11). Note that at present time there are very powerful computer program for residual stress calculation such as DANTE, HEARTS and others [26 – 29]. However, due to lack of data connected with the boundary condition, sometimes it is difficult to get good results of calculations. This problem is discussed in recently published paper [30].

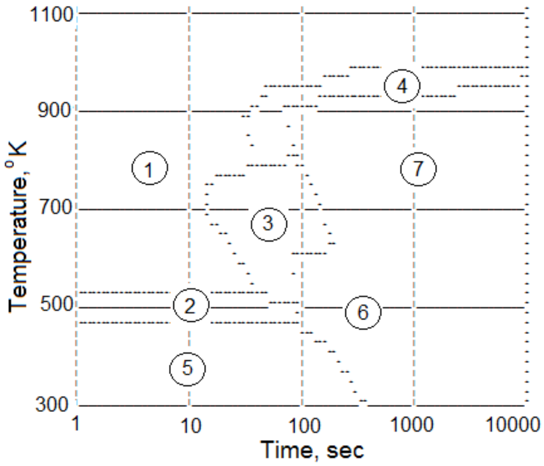

Fig. 10 CCT diagram used for FEM calculations: 1 is austenite; 2 is martensite; 3 is bainite; 4 is pearlite; 5 is martensite after full transformation; 6 is bainite after full process transformation; 7 is pearlite after full process transformation

Fig. 11 Micro- structure distribution in the section of the

This work was possible due to cooperation between two companies: IQ Technologies Inc. and Intensive Technologies Ltd. IQ Technologies Inc is an engineering consulting firm founded in 1999 in Akron, Ohio, USA. IQ Technologies Inc is dedicated to enhancing the performance, environmental soundness, cost effectiveness, and safety of heat-treating processes. The prime its mission is to commercialize intensive quenching processes for steel parts in US and abroad and to provide intelligent solution of wide range of heat-treating problems. It is committed to IntensiQuench® process and equipment engineering excellence, and it is working as a team consisting of DANTE Solution Inc., Air Flow Science Corporation, AFC-Holcroft, Ajax TOCCO Magnethermic, etc. The consulting company Intensive Technologies Ltd (ITL) was founded in 2000 in Kyiv, Ukraine and its prime mission is development of new intensive quenching processes, designing appropriate software for governing of developed new technologies. It is cooperating with leading experts from National Academy of Sciences of Ukraine and National Metallurgical Academy of Ukraine. Author of the paper participated in foundation of both companies and is a fellow of ASM International. He has been working on designing super strong materials since 1983..

roller when HTC is equal to 10,000 W/m^{2}K. and optimal hardenability steel is used.

Optimized micro – structure distribution, shown in Fig. 11, provides very high compressive residual stresses at the surface of the roller (see Fig. 12). As seen from Fig. 12, on the surface of the roller hoop compressive residual stresses reach – 900 MPa as the same time at the core tensile residual stresses rerach only 180 MPa. Due to high compressive surface stresses and accelerated cooling, surface layers of the roller are subjected to super strengthening effect (see Fig. 3). Due to high compressive residual stresses and super strengthening effect, service life of machine components increases. Instead of alloy and high alloy steels less costly materials can be used for manufacturing elements of cars and trucks [31, 32 , 33].

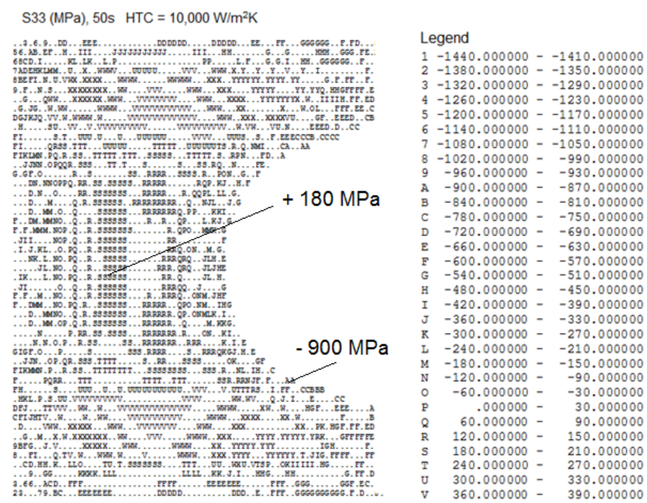

Fig. 12 Hoop stresses distribution in MPa in the roller (see Fig. 9).

It should be noted that results of calculations coincide well with the experimental data shown in Table 3.

Table 3 Residual surface compressive stresses after intensive quenching and tempering [32].

Steel part	Residual hoop surface compressive stresses, MPa
52100 Roller ∅3” (76 mm)	-840
52100 Roller ∅1.8” (46 mm)	-900
4140 Kingpin ∅1.8” (46 mm)	-563
S5 Punch ∅1.5” (38 mm)	-750

As seen from Table 2, experimental results of measuring residual stresses are close to calculated. Very important investigations in this field were fulfilled in Germany [35, 36]. Authors measured residual stresses which shoved a good agreement with the FEM computer calculations [35, 36].

VIII CONCLUSIONS

A method for designing optimal hardenability steel is proposed which can also easily find among already existing steel grades tolerant chemical composition to given size and form of component to maximize surface compressive residual stresses and provide super- strengthening effect.

A method is proposed to destroy local film boiling processes, based on resonance effect, which in the nearest future will compete with expensive powerful propellers agitating huge amount of liquid during batch quenching or hardening of large steel components. .

An apparatus is proposed to quench intensively large components, like rotors and big rollers, just in plain water which consists of moving sprayers immersed in a liquid and governed by microprocessor.

Further painstaking investigations should be planned in this field to accelerate applications of new ideas for the needs of the global community with the aim of improving environment condition and savings materials and energy.

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