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Contemporary Methods of Super Strong Materials Design via Intense Quench Process

Nikolai I. Kobasko

Intensive Technologies Ltd, Kyiv, Ukraine

Abstract:-*In last decades intensive quenching processes were used to improve essentially strength and ductility of materials. The new technology was used in the USA and results of investigations were widely discussed by leading journals. The author of current paper suggests further essential improvement strength and ductility of materials combining high and low temperature thermomechanical treatment(HTTMT and LTTMT)with intensive quenching that results in obtaining fine bainitic microstructure after forgings and intense cooling. The trick of suggested technology is delaying during intense quench martensite transformation for bainite transformation. For this purpose, discovered new characteristics of transient nucleate boiling process were used. Since suggested technology is rather promising that could save alloy elements, energy, increase essentially strength of materials and improve environment, it makes sense to start testing of new idea in forging shops of many companies which are interested in proposed innovations.*

Keywords: *Super strengthening, Delay martensitic transformation, Alloy elements savings.*

1. Introduction

The low and high temperature thermomechanical treatment is well known technology which was discussed in 1968 in two books [1]. Benefits of intensive quenching processes were discussed by authors [2, 3, and 4].It was shown that after accelerated high temperature thermomechanical treatment mechanical properties of AISI 1040 steel are essentially improved as compared with conventional quenching (see Table 1) [3].

Table 1: Mechanical properties of AISI 1040 steel after conventional quenching and HTTMT when tempered at 200°C [1, 3].

R_m(MPa)	$R_{p0.2}$(MPa)	A(%)	Z(%)	a_k(J/cm²)
1422	1246	2	16	30
1972	1570	7	40	35

As seen from Table 1, strength of AISI 1040 steel increases for 38% while elongation increases for 250%.

Further investigations in this field were performed by authors [4] who reported on many benefits concerning of strength and ductility of materials after HTTMT and accelerated cooling. It should be noted here that direct intensive quenching after forging (DFIQ), performed by authors [4], provided martensite microstructure. Due to DFIQ, it was possible to eliminate additional heating and quenching in oil that saved time and energy along with the improvement of strength [4]. As known, further improvement of material can be provided by obtaining fine bainitic microstructure after intensive quenching (IQ) process. Strength and plastic properties of bainite are essentially better as compared with martensite. It has been shown by author [5] that strength of bainite is evaluated as (see Eq. (1))

$$\sigma = \sigma_{Fe} + \sum_i \sigma_{SS}{}^i + \sigma_C + k_c\left(\bar{L}_3\right)^{-1} + k_p\Delta^{-1} + C_{10}\rho_d{}^{0.5} \quad (1)$$

Here σ_{Fe} is strength of pure annealed iron in MPa; σ_{SS} is substitution solid strengthening contributions; σ_C is strengthening due to carbon in solid solution; $k_c = 115 MPa.m$; $\left(\bar{L}_3\right)^{-1} \propto N_V{}^p$, where $N_V{}^p$ is number density of nucleating sites [5]; $k_p = 0.52 V_o MPa.m$, where V_o is the volume fraction of cementite; Δ is distance between a cementite and pearlite; $C_{10} \approx 7.34 Pa.m$; ρ_d is dislocation density.

However, there are some problems in the way of obtaining bainitic microstructure during intense quenching (IQ). During IQ process surface temperature of quenched material drops immediately to bath temperature that results in martensite microstructure formation. Such problems were avoided by high alloying of material and using melted salts as a quenchant [6] that makes process unprofitable. This problem was not solved until very important for the heat-treating practice new characteristics of transient nucleate boiling processes were discovered by author [7, 8, and 9]. It was shown that heat transfer coefficient (HTC)during transient nucleate boiling process tends to infinity and surface temperature of material in such condition of cooling is controllable [7].

2. Transient Nucleate Boiling Process Characteristics

Author of recently published paper [10] used three characteristics of transient nucleate boiling process to restore surface temperature of material during quenching. The first characteristic of transient nucleate boiling process was formulated due to painstaking experiments of French [11]. It says that time of developed transient nucleate boiling establishment doesn't depend on size and form of tested material, for example from875°C in slowly agitated 5% NaOH water solution at 20°C [11]. And its time is equal approximately to 1- 1.5 s when film boiling is completely absent. Such behaviour of quench process is explained by extreme surface cooling rate during nucleate boiling. In 1968 a notion of self – regulated thermal process was introduced and it was explained why surface temperature during transient nucleate boiling process maintains at the level of boiling point of a liquid [7, 10 and 12] and its average value can be considered as (see Eq. (2)):

$$\overline{T}_{sf} = T_s + \Delta\overline{\xi} \approx const \qquad (2)$$

Here T_{sf} is surface temperature; T_s is saturation temperature; $\Delta\overline{\xi}$ is overheat of a boundary layer responsible for nucleate boiling process. The second characteristics of transient nucleate boiling process states that duration of transient nucleate boiling process is directly proportional to squared thickness of tested sample, inversely proportional to thermal diffusivity of material, depends on form of sample, cooling intensity of liquid quenchant. It's true if initial temperatures are fixed (see Eq. (2)) [9, 13, and 14].

$$\tau_{nb} = \overline{\Omega} k_F \frac{D^2}{a} \qquad (3)$$

Here τ_{nb} is duration of transient nuclear boiling process; $\overline{\Omega}$ is parameter depending only on convective Biot number (see Table 2); k_F is form coefficient; D is thickness of sample in m; a is thermal discursivity of sample' material in m^2/s.

Table 2 provides correlation between parameter $\overline{\Omega}$ and dimensionless number Bi

Table 2: Correlation between parameter $\overline{\Omega}$ and convective Biot number Bi [7] for normal pressure.

Bi	$\overline{\Omega}$	*Bi*	$\overline{\Omega}$
0.1	5.40	2	2.41
0.2	4.72	3	1.98
0.3	4.32	4	1.69
0.4	4.02	5	1.46
0.5	3.79	6	1.27
0.6	3.63	7	1.12
0.7	3.47	8	0.98
0.8	3.33	9	0.86
0.9	3.21	10	0.75
1.0	3.11	12	0.56

When quenching in water under pressure, parameter $\overline{\Omega}$ is calculated using equation (4) [10]:

$$\overline{\Omega} = 0.48 + 3.21 \cdot \ln \frac{\vartheta_I}{\vartheta_{II}} \qquad (4)$$

Form coefficients k_F are recalculated via use Kondrat'ev coefficients K [15, 16].

Form coefficient for finite cylinder of diameter D and height Z($Z = nD$) is:

$$k_F = \frac{n^2}{23.132n^2 + 9.87} \qquad (5)$$

Form coefficient for squared plate of thickness L, width nL and length mL is calculated by Eq. (6):

$$k_F = \frac{n^2 m^2}{9.87\left(n^2 m^2 + n^2 + m^2\right)} \qquad (6)$$

The main characteristics of transient nucleate boiling process can be used for restoring temperature fields during quenching forged materials in liquid media.Film boiling should be completely absent. To restore the surface temperature of quench samples, the French law of cooling is used. According to his investigations, cooling curves within interval of temperatures 875°C – 150°C, when quenching in 5% electrolyte at 20°C,are identical for different forms and sizes of probes [11, 14]. In this case the initial temperature of self - regulated thermal process T_I is evaluated as $T_I = T_s + \vartheta_I$:

Here

$$\vartheta_i = 0.293 \cdot \left[\frac{2\lambda(\vartheta_O - \vartheta_i)}{R}\right]^{0.3} \qquad (7)$$

The temperature at the end of transient nucleate boiling process is evaluated as $T_{II} = T_s + \vartheta_{II}$ [6, 14].

Here

$$\vartheta_{iI} = 0.293 \cdot \left[\alpha_{conv}\left(\vartheta_{II} + \vartheta_{uh}\right)\right]^{0.3} \qquad (8)$$

3. Design of High and low Temperature Thermomechanical Treatment

For designing of low temperature thermomechanical treatment high carbon steel is used. Its chemical composition is 1.4 C; 0.50 Mn; 0.30Si; 0.8 Cr; 0.3 Ni. According to Grossmann [17], critical diameter DI for given chemical composition is equal to 68 mm. We'll design HTTMT – LTTMT for cylindrical probe 60 mm diameter and 180 mm long. Martensite start temperature Ms for given steel is 150°C. To delay martensite transformation, the sample is quenched in water under pressure 0.5 MPa that provides saturation temperature T_s = 151.84°C.Initial temperature of cooling is 900°C and bath temperature is 20°C. Average convective HTC for water at 20°C is 756 W/m²K. Average thermal conductivity and diffusivity of high carbon steel is 23.4 W/mK and 5.55 x 10^{-6}m²/s [6]. Convective Biot number is equal to 0.99. For provided initial data, the restoring of surface temperature was fulfilled(see surface temperature on Fig. 1), FEM calculations were performed (see core temperature on Fig. 1), real and effective Kondrat' ev numbers Kn were obtained (see Fig. 2). According to Fig. 1, core temperature 600°C is reached at a time 30 s. According to simplified calculations (see Eq. (9)) [18] core temperature 600°C is reached at a time 28 s that considers rather well.

More information on universal equation (9) for heating and cooling time calculations one can find in [18, 19] where dimensionless value $E_{eq}$is found from detail tables.

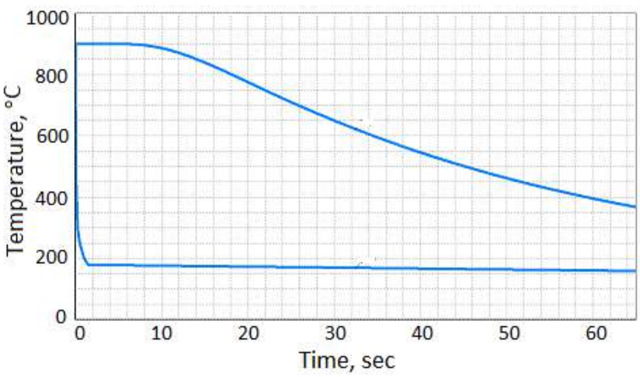

Fig.1: Surface and core cooling curves vs time for cylindrical specimen 60 mm quenched in water under pressure 0.5 MPa.

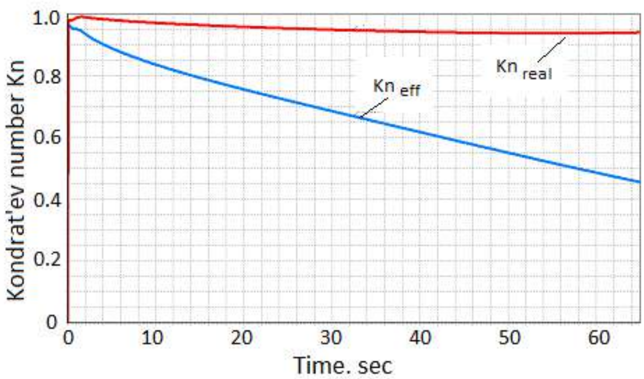

Fig. 2: Real and effective Kondrta'ev numbers Kn vs q. (time for cylindrical specimen 60 mm quenched in water under pressure 0.5 MPa.

$$\tau_{eq} = E_{eq} \cdot \frac{K}{aKn} \quad (9)$$

For simplified calculations dimensionless was used N equal approximately 1.5 (see Eq. (10)):

$$N = \frac{T_o - T_m}{T - T_m} \quad (10)$$

N = (900°C-20°C}/(600°C-20°C) = 1.52

To perform LTTMT process, intense cooling after forging, according to performed calculations, one should interrupt at a time 30 s when core temperature reaches 600°C and surface temperature 170°C degrees(see Fig.). After equalizing, the second forging starts at a temperature 385°C and is finished at a temperature 200°C. The sample is immediately delivered to tempering (200°C) for bainitic transformation.

According to numerical calculation (see Fig. 1), core cooling time for tested sample is 30 seconds, Core cooling time, when using universal Eq. (9), is 28 seconds that coincides rather well with experiment.

4. Discussion

To create a specific software for controlling quenching processes during hardening materials and correctly manage recipes development, there is a need to study physics of boiling processes during cooling in liquid media. The wide implementation the new technology into practice can be done via thoroughly calculation and computation. Currently, the problem of strength and ductility improvement is solved by increase costly alloying elements in material. However, alloying requires slow cooling in mineral oils negatively resulting on environment condition. The proposed alternative way of strength and ductility improvement looks promising and reliable if technological process is thoroughly controlled.

5. Conclusions

1. Super strengthening of material is achieved by combining high temperature HTTMT, low temperature LTTMT, and providing bainitic transformation during intensive quenching.

2. Delaying of martensite transformation in the course of extremely fast cooling is possible due to self – regulated thermal process that allows controlling surface temperature during IQ process.

3. Since technology provides many benefits including materials savings, strength and ductility improvement, environment shielding, it makes sense to start testing the new technology in forging shops of interested companies.

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Authors' Biography

N.I. Kobasko received his Ph.D. from Ukrainian National Academy of Sciences. He is an ASM Int. Fellow. His scientific activity focuses on materials strengthening and reducing their cost.