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QUANTITATIVE ASSESSMENT OF YIELD STRENGTH OF CARBON AND LOW-ALLOY STEELS BY STRUCTURE PARAMETERS

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ABSTRACT

Based on the analysis of literature data and our own experimental studies, the contribution of various strengthening mechanisms to the yield strength of carbon, wheel and low-alloy steels has been quantified. It is established that for normalized steel (St5ps) the greatest contribution to the yield strength is made by hard-solution and grain boundary hardening (37.0 % and 28.0 %), and for low-alloy steel 16G2AF, along with these hardening components, the role of dispersion hardening (21.4 %) is noticeable. It is shown that thermomechanical treatment of St.5ps steel leads to the growth of dislocation hardening up to 27.6 % due to the growth of dislocation density and preservation of most dislocations in the rolled products at accelerated cooling of hot-deformed austenite. In wheel steels heat-treated using conventional technology (intermittent hardening and tempering), grain boundary hardening and dislocation hardening (31.5; 23.4%, respectively) make a major contribution to the yield strength. In the same steel, which is treated with surface plasma hardening, the share of grain boundary hardening in the total yield strength increases significantly (54.7%) due to strong structure refinement.

Keywords: hardening mechanisms, yield strength, thermomechanical treatment, accelerated cooling, plasma hardening, phase components, grain size.

INTRODUCTION

It is commonly known that the establishment of a quantitative relationship between the structure and properties of metal materials is one of the main problems of applied material science, as it is the basis for the development and creation of new effective ways to improve the operating characteristics of the items. Thus, nowadays, in the production of long products thermomechanical treatment (TMT) is increasingly used, which is a set of two effective methods of hardening: deformation from plastic deformation and thermal from phase transformations. Another thing that attracts the attention of researchers is the fact that the application of TMT on the regime of intermittent hardening in the surface layers of rolled products formed a layered structure, which can be classified as structural composites with their undeniable advantages.

The formation of the gradient-layer structure and the surface layer properties is of particular interest, which is explained by the essential difference between the processes of wear and destruction of the surface layer and the processes of wear and volume destruction. As it is known, the processes of wear, occurrence and growth of cracks at static, dynamic and alternating loads begin from the surface. Therefore, they are defined by physical and mechanical properties of relatively thin surface layer, which plays an important role in ensuring the reliability and durability of machines and mechanisms.

The identification of features of structure formation and properties in the yield strength of steels exposed to various heat treatments allows us to approach the solution of this problem. The purpose of this work is a quantitative assessment of the yield strength of structural steels in terms of chemical composition and structure parameters, comparing the calculated values with the data of relevant State Standards to obtain information on the existing mechanisms of hardening after a particular treatment and alloying [1, 2].

MATERIALS AND METHODS

The input data for calculation (evaluation) of structural strength are the chemical composition data, distribution of constant and alloying impurities between the phases and quantitative parameters of the structure: grain size, ratio of phase and structural components, their distribution, distance between reinforcing particles, density of dislocations, etc. It should be noted that such assessments of yield strength are semi-quantitative rather than quantitative in nature, since a number of simplifications and assumptions in the theory of hardening mechanisms are accepted in the calculation, which do not allow a strict quantitative assessment of the yield strength of steel.

Thus, in the theory of dislocation hardening, the precise determination of the density of dislocations plays an important role. However, the decrease of dislocation density in the foil thinning process under transmission electron microscopy is ignored in calculations, or the distribution of dislocations over the material volume is considered homogeneous and isotropic, but in fact it does not always correspond to reality. Nevertheless, the density of dislocations was determined using transmission electron microscopy of thin foils by the number of dislocations on the surface. For the image area F and the number of dislocations output to the N surface the dislocation density is determined by the expression $\rho = N / 2F$. Or, the reliability of the calculated dispersion hardening is largely determined by the reliability of the inter-particle distance determination - λ, since it is included in the calculated Oren equation:

ARPN Journal of Engineering and Applied Sciences

$\Delta\sigma_{д.у} = (9, 8*10^3/\lambda) \ln 2\lambda$

The difficulty is that the inter-particle distance - λ is practically impossible to measure directly on the images, so it can be calculated through other measured parameters: volume fraction - f and diameter of strengthening particles:

$\lambda = D(\pi / 6 f)^{1/2}$ [3,4].

The determination of the volumetric fraction of the phases by the dot analysis method is based on the statement that the fraction of the points randomly applied to the microphotograph, falling on the image of the phase under study, is equal to the volumetric fraction of this phase. Fα = nα / n0, where nα is the number of points falling on the phase sections α; n0 is the total number of points applied to the microstructure image.

The comparative analysis of the role and contribution of different strengthening mechanisms to the total yield strength of carbon, wheel and low-alloy steels used in construction and railway transport was carried out using the methodology proposed in [4]. The studied steels differ not only in chemical composition, but also in the applied hardening heat treatment. High-temperature thermomechanical treatment (HTMO) of steel St.5ps was carried out according to the scheme of interrupted hardening: the temperature of the end of rolling 1050 °C, a pause between the end of rolling and the beginning of intensive cooling 2 s., the temperature of self-pumping ~ 500 °C.

Surface plasma hardening of wheel steel was performed in the following mode:

Arc current, A	275.
Arc voltage, V	120.
Rated arc power, kW	35
Nozzle diameter, mm	3.5
Distance from cut to hardened surface, mm	10- 15
Protective gas flow rate, l/min	3-6
Wheelset speed, rpm	0.14-0.25
(5.0-7.0 revolutions per minute)	

The value of the individual hardening components and their contribution to the total yield strength of these steels were determined by the known empirical formulas given below. The coefficients required for calculation were taken from the literature data indicated. The calculated values of yield strength of the studied steels were compared with the data of GOST 5781, GOST 10884, GOST 19281 and GOST 10791 to obtain reliable information about the applicability of the method of yield strength assessment.

Determination of structure parameters (perlite content in steel, 2755nterpolate distance measurement, ferrite grain diameter, carbonitride phase size and volume fraction, etc.) for quantitative assessment of yield strength was performed by methods of quantitative metallography using research horizontal microscope NeoPhot 21 and electronic microscope UEMV-100.

The calculation is based on the principle of additivity of the hardening mechanisms, which to date has been confirmed in many structural steels by many researchers. The essence of this principle is that the contribution of individual hardening mechanisms to the total yield strength of polycrystalline material is summarized.

The yield strength of the steel is determined by the known Hall-Petch equation, which for tensile conditions has a form:

$\sigma_т = \sigma_i + k_y * d^{-1/2}$.

where σ_i- the friction stress of the crystal lattice during the movement of dislocations inside grains, i.e. intra-grain hardening without taking into account the contribution of grain boundaries (monocrystal type) to the yield strength;

$k_y d^{-1/2}$ - grain boundary strengthening,

where, k_y - coefficient characterizing the contribution of grain boundaries, which are barriers to the advancement of dislocations from one grain to another; d - grain diameter.

This formula is applied with sufficient accuracy to ferritic steels for grains of 0.3 to 400 microns [4], from which it follows that the yield strength of the material increases with decreasing grain size.

Equation (1) assumes linear additivity between intra-grain (σ_i) and grain boundary strengthening $\sigma_з = k_y d^{-1/2}$.

In turn, intra-grain strengthening can be presented in a form:

$\sigma_I = \sigma_0 + \Delta\sigma_{тв} + \Delta\sigma_P + \Delta\sigma_д + \Delta\sigma_{д.у.}$

whereσ_I is the sum:

(A) σ_0 - lattice friction stresses to the motion of free dislocations, considering the defects of the crystal structure and taking into account a certain amount of impurities (C+ N) in the solid solution, for iron-based steels with a cubic volume-centered lattice σ_0 ~ 30 MPa;

Calculated strengthening formula. $\sigma_0 = 2 *10^{-4}$ G, for iron G = 84000 Mpa

(B) $\Delta\sigma_{тр}$- strengthening of solid solution with alloying impurities, $\Delta\sigma_{тр} = \sum K_i * C_i$ where K_i - the strengthening coefficient determined in special studies on the effect of alloying elements on ferrite strengthening, C_i - concentration of the alloying element found in a solid solution (ferrite). In this paper the following (literary) K_i values are taken for calculation $\Delta\sigma_{тр}$:

Element	C+ N	P	Si	Mn	V
Ki Mpa / %,	4670	690	86	33	3

As can be seen, the embedding atoms (C+ N) strengthen ferrite very strongly than the substitution atoms.

(C) $\Delta\sigma_P$ - strengthening due to formation of perlite component in steel with ferritic base, $\Delta\sigma_P$=2,4P, where 2, 4 empirical coefficient Mpa/P %,

P - perlite component share in the structure, %; it depends on steel composition, cooling rate during heat treatment. The degree of dispersion of perlite is determined by the interpolate distance - Δ. We should note that Δ represents the sum of thicknesses of two adjacent ferrite and cement plates in perlite structures. Depending on the cooling rate Δ changes. Thus, measured values of Δ for normalized St.5ps Δ = 0.6 μm, after WCS it decreases to 0.11 μm.

(D) $\Delta\sigma_D$ - strengthening due to the resistance of a sliding dislocation to other dislocations (strain hardening), $\Delta\sigma_D = \alpha$ M G$b\rho^{1|2}$,

whereα is a coefficient depending on the nature of the distribution and interaction of dislocations in the range 0.1-0.3. For the considered steels (with a ferrite base) the parameters included in the above equation, according to the literature, are: M=2.75; G=84000 Mpa; b = 0.25 nm.

Due to the fact that the density of dislocations by the transmission electron microscopy of thin foils gives more reliable results than the X-ray structure, the density of dislocations for normalized steels is determined by the electron microscopy of thin foils.

(E) $\Delta\sigma_{ду}$ - strengthening caused by the formation of disperse particles of the second phase (dispersion strengthening) Calculation formulas.

$\Delta\sigma_{ду} = (9{,}8 * 10^3 /\lambda) \ln 2\lambda, \lambda = D * (\pi / 6 f)^{1/2}$

RESULTS AND DISCUSSIONS

As can be seen from the presented data (tables I and II) the yield strength of structural steels which include all investigated steels (St 5ps, wheel and low-alloyed 16G2AF) can be considered as the sum of the constituents in Equation $\sigma_m = \sigma_i + k_y * d^{-1/2}$.

The contribution of individual hardening factors to the total yield strength of steel is not the same and depends on the type of alloying elements and the degree of alloying, the presence and dispersibility of the hardening phases, the applied thermal, thermomechanical, plasma treatment and other factors.

In St.5ps carbon steel (hot-rolled condition) the main components of hardening are hard-solution and grain boundary hardening, the fraction of which is ~ 65 %. In absolute terms, the sum of these components are equal to 125.3 Mpa and 95 Mpa. Straining (dislocation) hardening makes a significant contribution to the overall hardening of St.5pc steel exposed to high-temperature thermomechanical treatment. If the share of strain-hardening in ST.5pc steel cooled in calm air from the end of rolling temperature 1050°C (hot-rolled condition) is ~ 1,5 %, in the same steel thermomechanically processed according to the scheme of interrupted hardening with the subsequent high self-pumping (heat-strengthened condition) the share of strain-hardening increases to 27,6 %.

ARPN Journal of Engineering and Applied Sciences

Table-1. Initial data for quantitative assessment of yield strength of the studied steels.

Characteristics of Steel	Steel grade and its heat treatment				
	St.5ps, normalization	**St.5ps, HTMO**	**Wheel Steel, Hardeners with medium vacation.**	**Wheel Steel, Plasma Hardening**	**16G2AF Normalization**
Content of alloying elements in α-Fe, %:					
Mn	0.55	0.58	0.63	0.63	1.5
Si	0.11	0.15	0.41	0.41	0.3
P	0.04	0.04	0.033	0.033	0.035
V	-	-	-	-	0.11
(C+ N)	0.015	0.015	0.015	0.015	0.015
Strength phase (disperse particle)	-	-	-	-	V(C,N)
Share of perlite structures with different interplate spacing -Δ, %	35	42	secondary sorbite	self-temperingsorbite	17
Grain size:					
GOST 5639-82	6	9	8	11	9
d, mm	0,051	0,012	0,021	0,007	0,014
Volumetric fraction of disperse particles, f, %	-	-	-	-	0,096
Dispersed particle size, D, nm	-	-	-	-	30
Interpartial distance, λ, nm	-	-	-	-	765
The nature of the dislocation structure, ρ, cm^{-2}.	10^8	10^9	10^9	10^9	10^8

Note. 1. Based on the experimental data, it is accepted that in ferrite dissolved ~ 0.015 (C + N), the rest of carbon and nitrogen are bound in carbonitrides.
2. For hardened steels the character of the dislocation structure is estimated for homogeneous distribution of dislocations), ρ, cm^{-2}.

Table-2. Quantitative assessment of yield strength of steels with different structural-phase states.

Indicator	Steel grade				
	St.5ps	**St.5ps**	**Wheel Steel**	**Wheel Steel**	**16G2AF**
Hardening Components:					
Lattice friction tensions	30/8.8	30/5.9	30/4.8	30/4.3	30/6.1
Hard core hardening	125.3/37	129.6/25.6	148.9/24.0	148.9/21.1	115/23.5
Hardening introduced by perlite structures	84/24.7	102.3/20.2	101.1/16.3	-	40/8.2
Dislocation hardening	5/1.5	140/27.6	145/23.4	140/19.9	5/1.0
Dispersion hardening	-	-	-	-	105/21.4
Grain boundary hardening	95/28	105/20.7	195/31.5	385/54.7	195/39.8
Calculated yield strength	340	507	620	703.9	490
Yield stress value as per GOST	285	440	540	590	440
Difference of data from GOST and calculated value of yield stress	19.4	15.2	14.8	19.3	11.4

This is apparently explained by the increased density of dislocations when combining hot-rolling with subsequent immediate hardening and tempering. Recrystallization processes are suppressed by rapid cooling and a significant portion of dislocations that occurred during hot rolling of austenite is recorded. The dislocation structure of hot-deformed austenite is inherited by the martensite formed during the austenite-martensite phase transformation. In addition, grinding of the austenitic grain at thermomechanical treatment leads to grinding of martensite crystals [5-7].

While specifying the effectiveness of the hardening mechanism and its applicability, it should be emphasized that there is probably some optimal degree of ∟-Fe alloying, for saturation of ⌟-Fe with impurity atoms of substitution and introduction leads only to dangerous elastic deformation of the lattice and reduction of the toughness of the alloy fracture.

Taking into account that solid-solution hardening is caused by the difference in atomic diameters of ferrite and alloying element and their modulus of elasticity, the high proportion of this hardening can be explained by the resistance to dislocations from the side of dissolved atoms [8].

The strong structure crushing during surface plasma hardening attracts attention: the average grain size of plasma hardened wheel steel is 0.007 mm against 0.012 mm during traditional heat treatment (intermittent hardening + average tempering) [9, 10]. Such a significant reduction in grain size and a significant increase in the volume fraction of their boundaries, probably, leads to an increase in grain boundary hardening of wheel steel (∟ ⌟3 = 385MPa).

In 16G2AF low-alloy steel the dispersion hardening effect is noticeable - 21.5%, du=105.0 MPa. As can be seen from Table-1, in this steel the disperse carbonitride phase V(C, N) is formed, which hardens ferrite by the Ovan principle. It is assumed that the carbonitride phase V(C, N) is incoherent with the matrix (-Fe) and therefore the dislocations surround the secretions of V(C, N), thus causing dispersion strengthening.

The impact of dispersion phases on the grain size also indicates the effectiveness and prospects of dispersion hardening. From Table-1 it follows that in 16G2AF steel, which has a disperse carbonitride phase V (C, N), a finer grain d = 0.014 mm is formed. This is explained by the germinal influence of particles V(C, N) at crossing the critical points As1 and As3. In addition, the carbonitride phase inhibits the growth of austenite grains when further heated up to the dissolution temperature of these phases in austenite. These two factors lead to a significant grinding of ferritic grains in 16G2AF steel. Thus, the disperse particles of the carbonitride phase V(C, N) in the steel cause additional grain boundary hardening. [11-12].

In mild and low-alloy steels, the main phase and structural component is ferrite, as is known. Its proportion in these steels reaches 70-75%. Under load application, deformation starts to develop in ferrite, and perlite colonies are "barriers" to the movement of dislocations causing deformation. Therefore, hardening from the pearlite component also contributes to the overall hardened state.

The tables above show that the share of hardening from perlite content ranges widely from 8.8% for 16G2AF steel to 24.7% for heat-strengthened steel St.5ps. It should also be noted that non-metallic inclusions can influence the mechanical properties of these steels. However, their volumetric share in the steels under consideration does not exceed 0.1%, they have no strengthening effect and therefore the behavior of non-metallic inclusions was not considered in this paper.

Thus, depending on the structural state, solid-solution, dislocation, dispersion and grain boundary hardening contribute mainly to the yield strength of the studied steels [13-15].

CONCLUSIONS

a) Analysis of the quantitative yield strength data of carbon and low-alloy steels by structure shows that the main mechanisms of their hardening are hard-solution hardening by alloying with comparatively cheap alloying elements (Mn, Si), as well as dislocation and dispersion hardening using hardening heat treatment and microalloying of steel with carbide and nitride forming elements V(C,N).

b) Formation of gradient-layer structure in the surface layer of the product at the combination of hot deformation with subsequent hardening in the technological flow of rolling (HTMO) and high-speed heating and cooling during plasma hardening leads to a significant increase in the yield stress (strength) of steel, thus the wear resistance of the surface layer. The gradient-layer structure excludes the formation of a sharp transition boundary from marten site structures to mixed perlite type plate structures, which is one of the main factors that increase the contact-fatigue strength of wheel steel and contribute to its crack resistance.

c) Comparison of calculated values of yield strength with its value in corresponding State Standards shows satisfactory difference of values: after normalization - 11, 4 % for 16G2AF steel and 19, 4 % for St.5ps. After hardening heat treatment, the difference between the calculated value of yield strength and the value in accordance with State Standard varies from 14.8% to 19.3%. These data indicate the applicability of a quantitative assessment of the yield strength of steel based on the analysis of the parameters of the formed structure.

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