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Methods of Choosing High-Strengthened and Wear-Resistant Steels on a Complex of Mechanical Characteristics

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1. Introduction

Tribology, as the science, has passed a long and complicated path of development, but still has not received that stage of completeness which guesses the decision of engineering tasks connected with increase of wear resistance of machines and instruments' parts in factory practice. In a large array of works on different aspects of tribology published for the last half century there are not enough investigations about the role of metal science in a nature of wear. It is characteristic specially for knots of machines working under abrasive affect conditions that cause an intensive mechanical wear and loss of life by executive links (Kragelsky, 1965; Beckman & Kleis, 1983).

A role of mechanical characteristics and aspects of metal science began to study in tribology much later (Rabinowicz, 1965; Tribology handbook, 1973). For this reason, the providing wear resistance of machines parts was reached, primarily, by possibilities of the experienced designers' specialists trying to exclude their breaking and deformation in conditions of small-cycled and a long-lived loading of working links based on known methods of toughness computation.

In accordance with designer's ideas of development and machines creation with higher operational characteristics, there was an apparent necessity for more detailed study of outwearing nature, especially in conditions of abrasive affect, as one of the basic reasons of equipments refusal. Specially, it concerns the work of oil-industry machines and drilling equipment, ore-mining, coal-extracting, ore- grinding, agricultural, building and other equipments (Richardson, 1967; Wellinger, 1963). Thus, the independent direction was discovered in tribology - the investigation of mechanical wear nature at the different acts variants of external forces and abrasives: at the sliding friction, at the rolling friction, at the blow over an abrasive, in the stream of abrasive particles, in the not fastened abrasive mass, etc.

The final goal of these investigations was the search of criteria tie of wear for steels and alloys with their standard mechanical characteristics, with regimes of heat treatment and structure, with the purpose of technological possibilities revealing in industrial conditions to control the processes capable to influence positively on the wear resistance increase of machines' parts under mechanical wear conditions.

In the chapter given, the basic dependences describing this complex process are reviewed and the recommendations connected to the methodology of its study and the definitions of criteria for an estimation of wear resistance of materials in similar conditions are marked.

2. Materials and methods of investigations

Mechanical characteristics of steels defined by standard methods on which basis are carried out calculations of machine details, are not connected with their design features and practically do not change within time of equipment exploitation. Unlike these characteristics the wear resistance is being defined not only by initial properties of tested material in interaction with which occurs the outwearing at exploitation, and also by character of uploading, especially by temperature in a friction zone. Dependence of one material's wear resistance from conditions of wear and properties of another material contacting with him complicates an estimation of actual wear and a choice of methods for its definition.

The development of materials trial methods on outwearing is caused by necessity of reliable choice of wear-resistant materials for the purpose of resource increase of machines and mechanisms.

The basic investigations of mechanical wear nature were conducted by sliding friction over monolithic abrasive as one of the wide-spread kinds of wear rendering the most negative influence on work resource of equipment in numerous branches of machine industry. For this purpose, the original laboratory machine (Fig. 1) for conducting the wear trials of any materials by sliding friction over monolithic abrasive wheel was manufactured.

The methodical feature and difference of this machine from those that were used earlier is that the cylindrical sample is moving radially by its lower face on rotary abrasive wheel plain and is rotating in addition around of own axle. This is stipulated to eliminate the passage of sample on the friction surface "track in track" and thus to avoid the "blocking" of working surface of abrasive wheel.

Technical characteristics of laboratory machine are as follows:

Diameter of a sample (mm) 10
Length of a sample (mm) 25-30
Load on a sample (N) . . . . up to 1000
Abrasive . . . . Grinding wheel 350 x 70 x 40
a green silicon carbide SiC, graininess ≤0.070 mm, HV = 32 GPa
Rotating speed of a wheel (rad/s) 3.2
Radial submission of a sample on one turn-over of a wheel (mm) 4.3

Symbols

|	
WR wear resistance (g^{-1})	HRC Rockwell hardness
Δm mass wear (g)	KCV impact strength (MJ/m^2)
σ_b ultimate strength (MPa)	σ_{-1} endurance limit (MPa)
$\sigma_{0.2}$ conventional yield limit (MPa)	ρ resistivity (Ω m)
ψ relative reduction of area (%)	K_1 coefficient of heat resistance at the furnace heat
δ relative elongation (%)	K_2 coefficient of heat resistance at the heat-up from
τ_{sh} shear strength (MPa)	friction
	a_H coefficient of impact strength (kg m/cm^2)
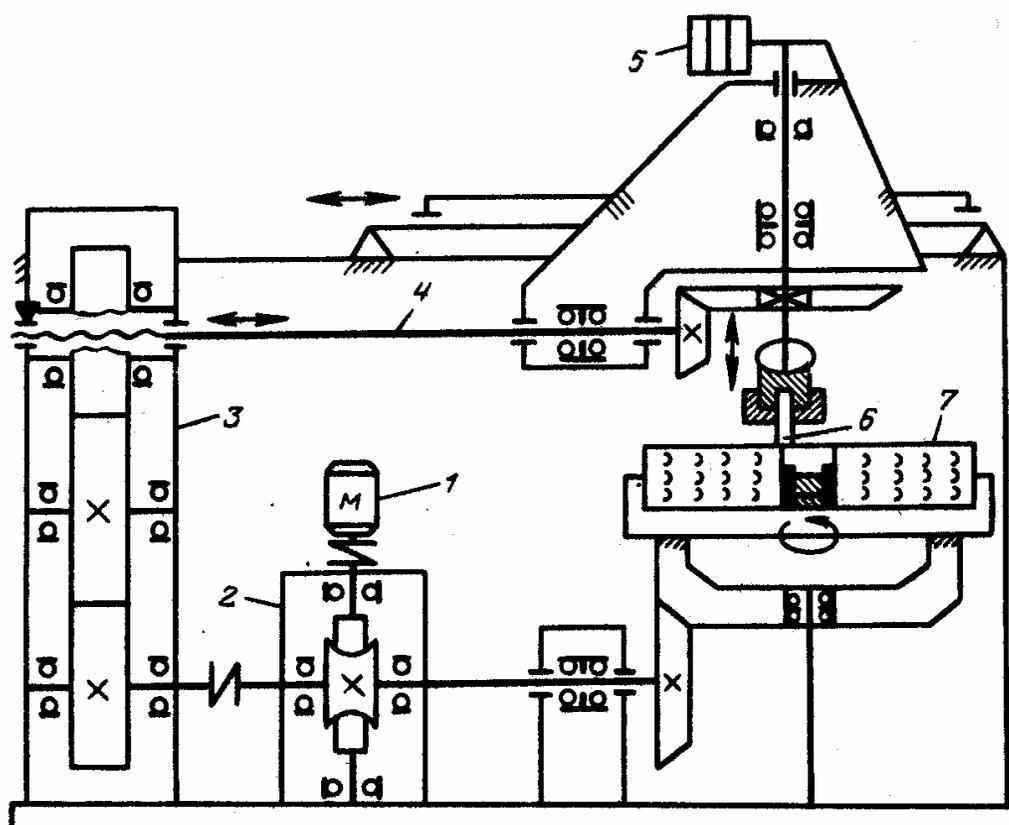
Fig. 1. A kinematics schema of original laboratory machine for materials trials on abrasive wear at the sliding friction: 1-electric motor; 2-worm reducer; 3-reducer; 4-feed screw; 5-weights; 6-sample; 7-abrasive wheel.

Such scheme of a trial ensures the higher convergence of tests data from experience to experience. The loading of sample was carried out by a lever with a weight. The outwearing path of sample on the abrasive wheel is 2.53 m for one-time pass. The velocity of samples slide over the abrasive wheel per tour of test was being changed from 0.1 up to 0.28 m/s. The unit load was selected 1.27 MPa experimentally that allowed to avoid a heat-up of friction surface at the trial. The wear was defined on a loss of samples mass Δm per tour of trial, i.e. for friction path 2.53 m. For comparative estimation of wear resistance of various steels the absolute parameter - the value return to mass wear - «$WR = 1/\Delta m$, g^{-1}» was chosen (Sorokin, 1991). Such indicator of wear resistance is most universal at comparison of this characteristic of steels tested in various conditions. The plots of dependences were built out of tests results as mean of minimum 5-6 experiences. The supplementary rotating of sample around own axle not only eliminates the directional roughness of samples friction surface, but also restores the cutting ability of the abrasive wheel as a result of gradual breaking down of its friction surface.

The advantage of this laboratory machine is the capability of trials conduction with chilling by any liquid environments, at the dry friction also and at the outwearing of the metal over the metal. In this case, the abrasive wheel is being substituted by the metal disk.

The abrasive outwearing is mechanical and represents the removing of metal from friction surface at the complex uploading. The removal of metallic particles at the outwearing is a destruction version by its nature, therefore it is quite lawful the using for it a classical

concepts about toughness. In this connection it is methodically expedient to consider the role of all standard mechanical characteristics of steels, because other criteria of an estimation of steels' wear resistance are not present.

Regular investigations of wear resistance interrelation of hardened steels with all standard mechanical characteristics have been carried out. The steels of different structural classes with various levels of mechanical characteristics were selected for this goal: pearlitic class of average and high toughness, carbidic, austenitic and maraging classes. The trials have been complicated by using some other laboratory installations (for example Fig.2): along with tests at the sliding friction some trials were conducted at the blow over an abrasive and at the friction of metal surfaces without abrasive.

The basis of test method on this installation (Fig. 2) consists in outwearing of cylindrical samples by consecutive repeated blows on a layer of not fastened abrasive of the certain thickness located on a flat anvil. Installation is supplied by the adaptation allowing the regulation of abrasive layer thickness on the anvil and by the device for anvil moving after each cycle of trial. Energy of individual blow was being defined as product of weights placed on flat die on height of free fall (50 mm). Change of blow energy was possible in limits from 2.5 to 30 J. Frequency of blows were being changed from 60 to 120 min-1.

Use of various installations at trials has allowed comparing influence of various schemes and conditions of mechanical outwearing on criteria of steels' wear resistance estimation.
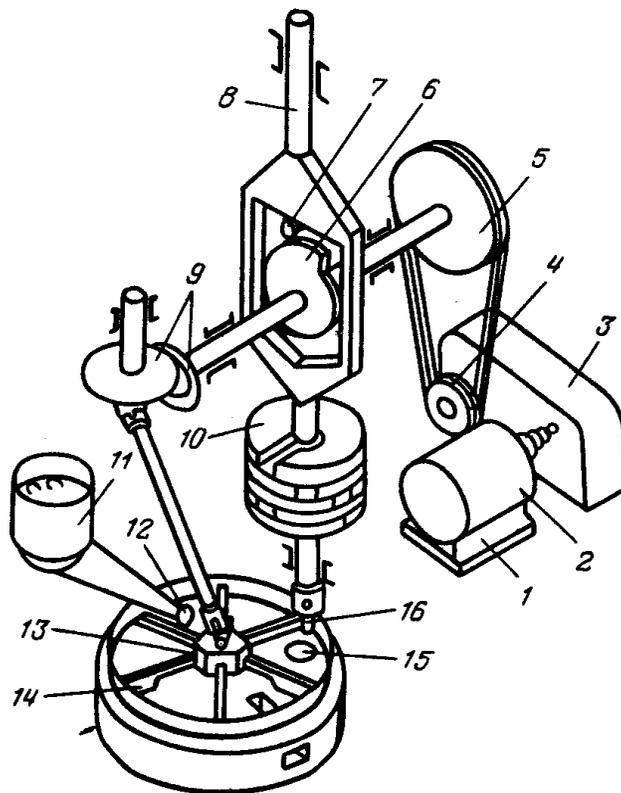

Fig. 2. Laboratory installation for wear trials at the blow on a not fastened abrasive: 1 – welding frame; 2- electric motor; 3 – reducer; 4,5 – pulleys of belt drive; 6 - cam; 7 – roller; 8 – spindle-flat die; 9 –bevel gearing; 10 – weights; 11 – hopper; 12 – batcher; 13 –rotated disk; 14 – brushes; 15 – anvil with abrasive; 16 – sample.

Apart from steels of different structural classes for which the chemical composition and mechanical characteristics are instituted by national standards (GOST) (Machine building Materials, 1980), the mechanical characteristics and wear resistance of experimental steels conditionally marked as D4, D5, D6 and D7 and created in different time under orders of petroleum industry were studied (Vinogradov, 1989). The elemental chemical composition of steels of different structural classes used in trials is given in Table 1.

Grade of steel	Content of chemical elements, %										
	C	Si	Mn	Cr	Ni	Mo	V	S u P	Co	W	Ti
95X18	1.0	≤0.8	≤0.7	18	-	-	-	≤0.03	-	-	-
110Г13Л	1.1	-	13	1	1	-	-	-	-	-	-
Н18К9М5Т	-	-	-	-	18	5	-	-	9	-	1
P18	0.8	≤0.4	≤0.4	4.2	≤0.4	0.3	1.2	≤0.03	-	18	-
X12M	1.55	0.25	0.35	12	-	0.5	0.25	≤0.03	-	-	-
40X13	0.4	0.30	0.65	1.3	≤0.4	-	-	≤0.04	-	-	-
40X	0.4	0.28	0.55	0.9	≤0.4	-	-	≤0.04	-	-	-
У8	0.8	0.25	0.45	0.20	0.15	-	-	≤0.03	-	-	-
У10	1.0	0.20	0.25	0.20	0.15	-	-	≤0.02	-	-	-
45	0.45	0.28	0.70	0.25	0.25	-	-	≤0.04	-	-	-
40	0.40	0.30	0.70	0.25	0.25	-	-	≤0.04	-	-	-
20	0.20	0.30	0.50	0.25	0.25	-	-	≤0.04	-	-	-
D4	0.39	0.28	0.54	0.4	1.1	-	-	-	-	-	-
D6	0.58	0.26	0.55	0.8	1.2	-	-	-	-	-	-
D7	0.7	0.25	0.42	0.6	1.5	-	0.22	-	-	-	-
D5	0.47	0.27	0.69	1	1.4	0.18	0.25	≤0.02	0.25	0.25	0.25

Note: *Fe* – the rest

Table 1. Chemical composition of tested steels

3. Results of investigations

The purpose of investigations on the first stage was the definition of functional bond of steels' wear resistance at the mechanical (abrasive) outwearing with their standard mechanical characteristics: ultimate strength σ_b, conventional yield limit $\sigma_{0.2}$, endurance limit σ_{-1}, Rockwell hardness *HRC*, relative elongation δ, relative reduction of area ψ and impact strength *KCV*.

3.1 Interrelation of wear resistance with indexes of steels' mechanical properties

At the analyses of correlation of each mechanical characteristics separately, "wear resistance-property", the enough defined tendencies are discovered: with increasing of strength characteristics (σ_b, $\sigma_{0.2}$, *HRC*) the wear resistance of steels grows, and the characteristics of plasticity and viscosity (δ, ψ, *KCV*) reduce the wear resistance with their increasing. The similar dependence is characteristic for all mechanical properties (Sorokin, 2000).

Mechanical characteristics depend, first of all, from class of steel and its structural features: it means here the type of steels' structure, the ability of structure to hardening at the heat treatment and its propensity to unhardening under thermal influence. If to combine

graphics changes of mechanical characteristics of hardened steels of different structural classes depending on tempering temperature, it is possible to reveal characteristic tendencies in change of properties and their numerical values. There have been compared, first of all, the characteristics of toughness group - hardness, ultimate strength and conventional yield limit, and also the characteristics of plasticity - relative reduction of area.

3.1.1 Steels hardness change of various structural classes from tempering temperature

The hardness of hardened steels of various structural classes changes in a wide interval of numerical values at the rise of tempering temperature (Fig. 3). The law of hardness change is ambiguous: at the rise of tempering temperature the hardness can be constant - for steels of austenitic class, sharply decrease - for steels of pearlitic class and increase - for steels of carbidic class. Hardness of austenitic steel 110Г13Л is low - 18 HRC, but in the range of tempering temperatures 0-600 ^{0}C it is constant. It can be explained by absence of structural transformations in this steel at tempering, and consequently, unhardening. Steels hardness of pearlitic class (20, 45, 40X, У10, D7) after hardening is various: the minimal hardness (35 HRC) has the steel 20 and the maximal hardness (65 HRC) has an experimental steel D7. At the rise of tempering temperature the hardness of these steels is decreasing: at tempering temperature 600 ^{0}C the hardness for D7 is equal 38 HRC, and for steel 20 is equal 15 HRC. Steel hardness of carbidic class P18 directly after hardening is approximately 62 HRC; at the rise of tempering temperature the hardness of this steel not only does not decrease, but increases at tempering temperature 600 ^{0}C until 65 HRC. The law of hardness change at the tempering of hardened steels of martensitic class 95X18, maraging class H18K9M5T and ledeburitic class X12M essentially differs from the law of steels hardness change of pearlitic and carbidic classes.
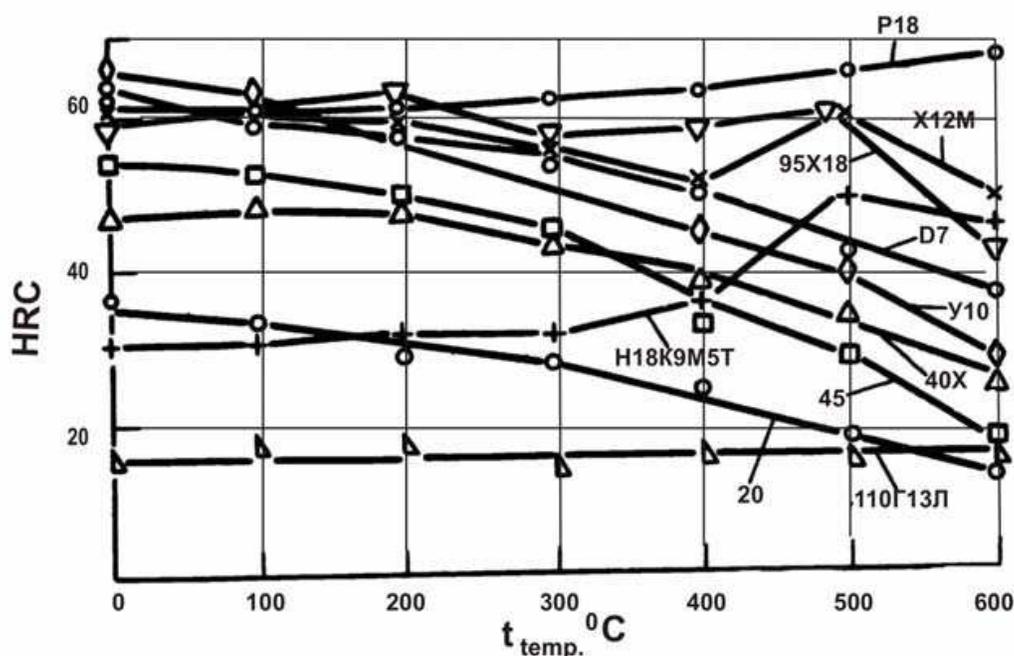

Fig. 3. Dependence of steels hardness change of various structural classes from tempering temperature

Steel's initial hardness of maraging class H18K9M5T (30 HRC) remains until tempering temperature 300 °C; after this it starts to increase until 44 HRC at 500 °C and is stabilizing at this level up to 600 °C. Hardness of steel 95X18 decreases a little at the rise of tempering temperature until 400 °C, then increases at 500 °C, and decreases again (to 48 HRC) at 600 °C. Hardness of steel X12M at tempering temperature until 500 °C is constant and high enough, its heating up to 600°C reduces this value to 50 HRC.

Thus, the area of hardness change is in a range from 18 up to 62 HRC at tempering of hardened steels of basic structural classes in the range of temperatures from 0 to 600 °C. The lower level of this area is limited by hardness of austenitic steel 110Г13Л and upper level - by hardness of carbidic steel P18. By comparison of steels hardness of various classes in the conditions of tempering becomes obvious, that for the hardened steels of pearlitic class it is characteristic a strong unstrengthen at heating; by this index they cannot be attributed to group of wear-resistant steels. For work in the conditions of heats when force uploading is accompanied by mechanical outwearing, the best steel with structural stability and hardness is the steel of carbidic class P18.

3.1.2 Change of ultimate strength for steels of various structural classes from tempering temperature

The ultimate strength was compared for the same hardened steels in the same interval of tempering temperatures. Polarization of this mechanical characteristic depending on tempering temperature (Fig. 4) is even more, than for hardness.
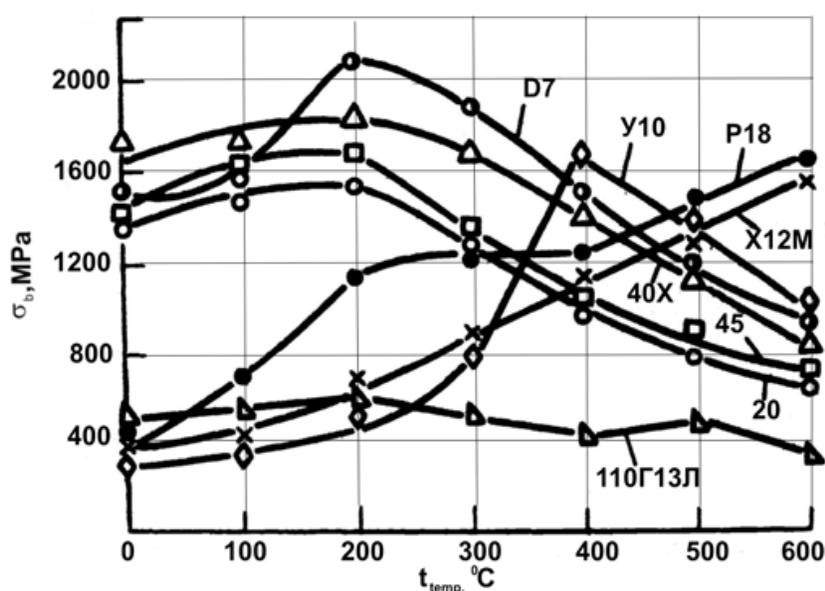

Fig. 4. Change of ultimate strength for steels of various structural classes from tempering temperature

The value of ultimate strength is stable in a wide interval of tempering temperatures for austenitic steel 110Г13Л and is minimal in relation to other steels - nearby 400 MPa. The ultimate strength of steels pearlitic class 20, 45, D7 changes under one law: it is increasing a little at tempering temperature 200 °C and then decreasing monotonous. The maximum of ultimate strength is fixed for steel D7 at tempering temperature 200 °C - 2200 MPa; after high

tempering this value decreases approximately in 2 times (up to 1000 MPa). The ultimate strength of steel X12M almost linearly increases from 400 to 1860 MPa at rising of tempering temperature. The ultimate strength of steel P18 increases stably in process of rising tempering temperature and has a maximum at 600 ^{0}C. The analysis of these dependences shows that for conditions of static uploading the steels of pearlitic class have appreciable advantages before steels of other classes on level of ultimate strength, but stability of its maximum values is limited by an interval of tempering temperatures 100-300 ^{0}C.

3.1.3 Change of relative reduction of area for steels of various classes from tempering temperature

Relative reduction of area ψ for steels 20, 45, 40X, У10 is increasing at rising of tempering temperature, but for steels 110 Г13Л and X12M this characteristic does not change practically (Fig. 5).
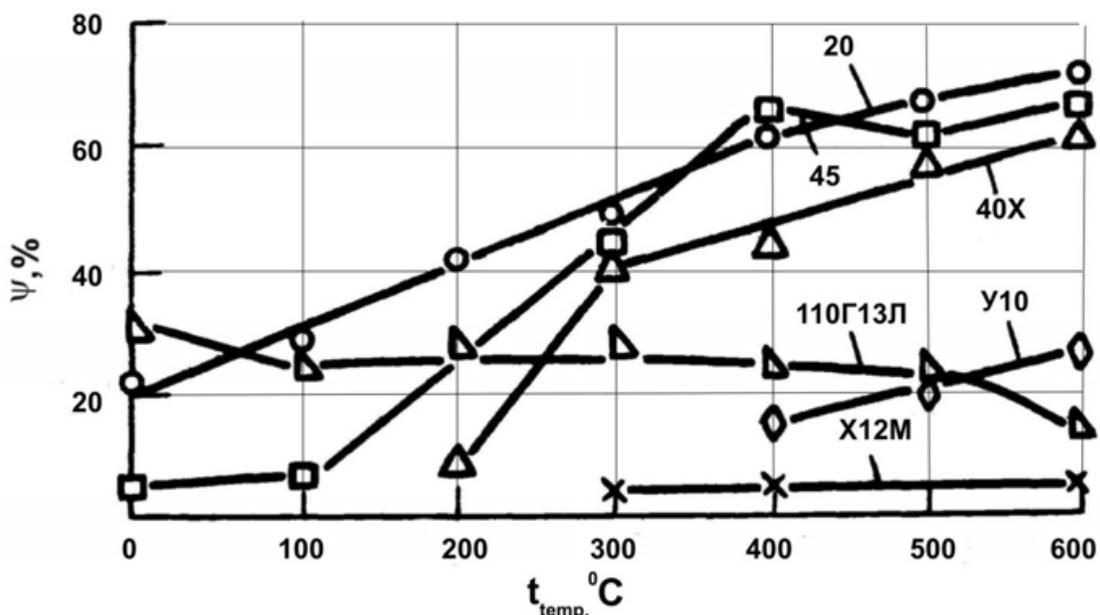
Fig. 5. Change of relative reduction of area for steels of various structural classes from tempering temperature

Relative reduction of area ψ and relative elongation δ vary practically under one law. Thus, relative reduction of area of the steels majority is maximum at high tempering (600 ^{0}C).

3.1.4 Dependence of steels' wear resistance from one parameter of mechanical properties

The steels' wear resistance may be defined for some external uploading conditions on one of the parameters (Fig.6) (Sorokin, 2000), for example,
-    at a blow over a not fastened abrasive - the shear strength (τ_{sh}),
-    at an erosive outwearing when the angle of attack is equal 90^0 - the relative elongation (δ),
-    at a blow over a metal without abrasive - the endurance limit (σ_{-1}),
-    at an abrasive outwearing of surface hardening alloys - the resistivity (ρ).

Thus, there are some external forces conditions of abrasive affecting or of blow of metal over metal, when one of mechanical properties can be selected as criterion of wear-resistant steels

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for defined work conditions. However, for more other cases of work conditions it is very difficult to find reliable criteria of steels wear resistance. The subsequent separated investigations of interrelation of steels wear resistance with all standard mechanical characteristics has allowed concluding that neither of them cannot serve as criterion for estimation of wear resistance, because they are not connected with wear resistance by univocal dependence. For revealing of more generalized dependence of steels wear resistance and their mechanical characteristics it was necessary to conduct the whole cycle of investigations.

(a)   (b)
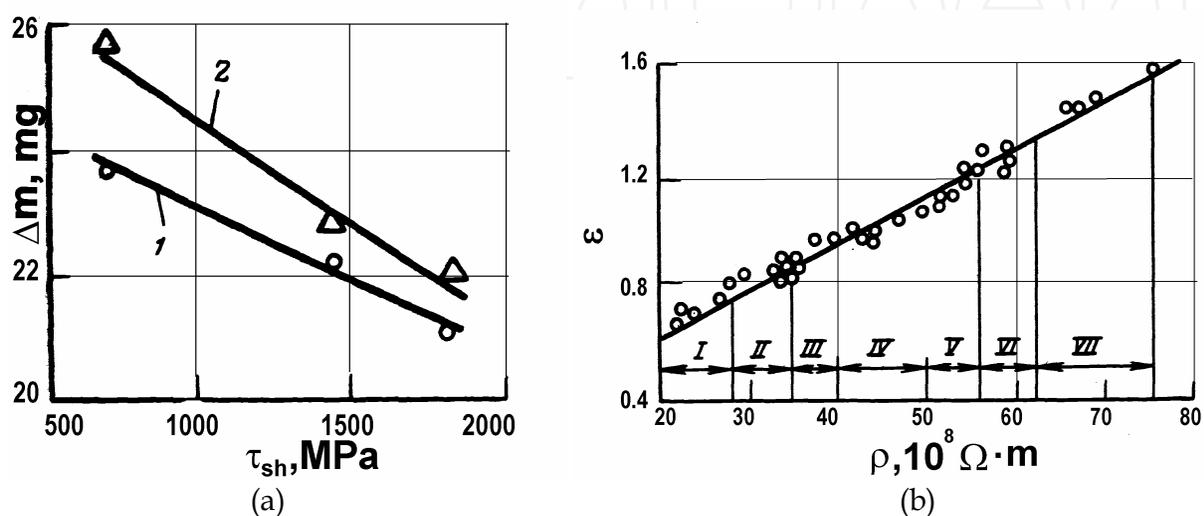
a - dependence of mass wear Δm of austenitic and martensitic structure from shear strength τ_{sh} at blow-abrasive wear and energy of blow accordingly, J: 1 - 5; 2 - 10;

b - dependence of relative wear resistance ε of surface hardening layer of system Fe-C-Mn from their resistivity ρ : I - ferrite + pearlit; II - pearlit + cementit; III - martensit; IV - austenit + disintegration products; V - martensit + carbides; VI - austenit + carbides; VII - austenit+martensit.

Fig. 6. Examples of unequivocal dependence of wear resistance parameters and one of physical and mechanical characteristics of steels:

3.1.5 The law of change conformity of toughness characteristics and wear resistance of steels from tempering temperature

The analysis of pairs ties of type "wear resistance - one of steels characteristics" gives the basis for assuming that the resistance to abrasive outwearing is more complicated by the character of forces interaction into friction surfaces, than resistance to introduction of indentor at hardness definition or resistance to tension at toughness characteristics definition - ultimate strength, conventional yield limit, relative elongation etc.

For more detailed analyses of cause of this dependence the correlations of wear resistance with steels mechanical characteristics of all structural classes were studied.

If abrasive wear is considered as mechanical destruction it is necessary to recognize its toughness basis. So, the interrelation between wear resistance and other mechanical characteristics for steels of different classes (Fig. 7) is received.

Character of toughness parameters change and wear resistance is identical: the decreasing at the rising of tempering temperature. As the standard for comparison the steel 45 is accepted; its relative wear resistance is accepted for unit. In each class of steels the tendency of change of toughness and plasticity characteristics are not identical at the tempering in the conditions of heating:
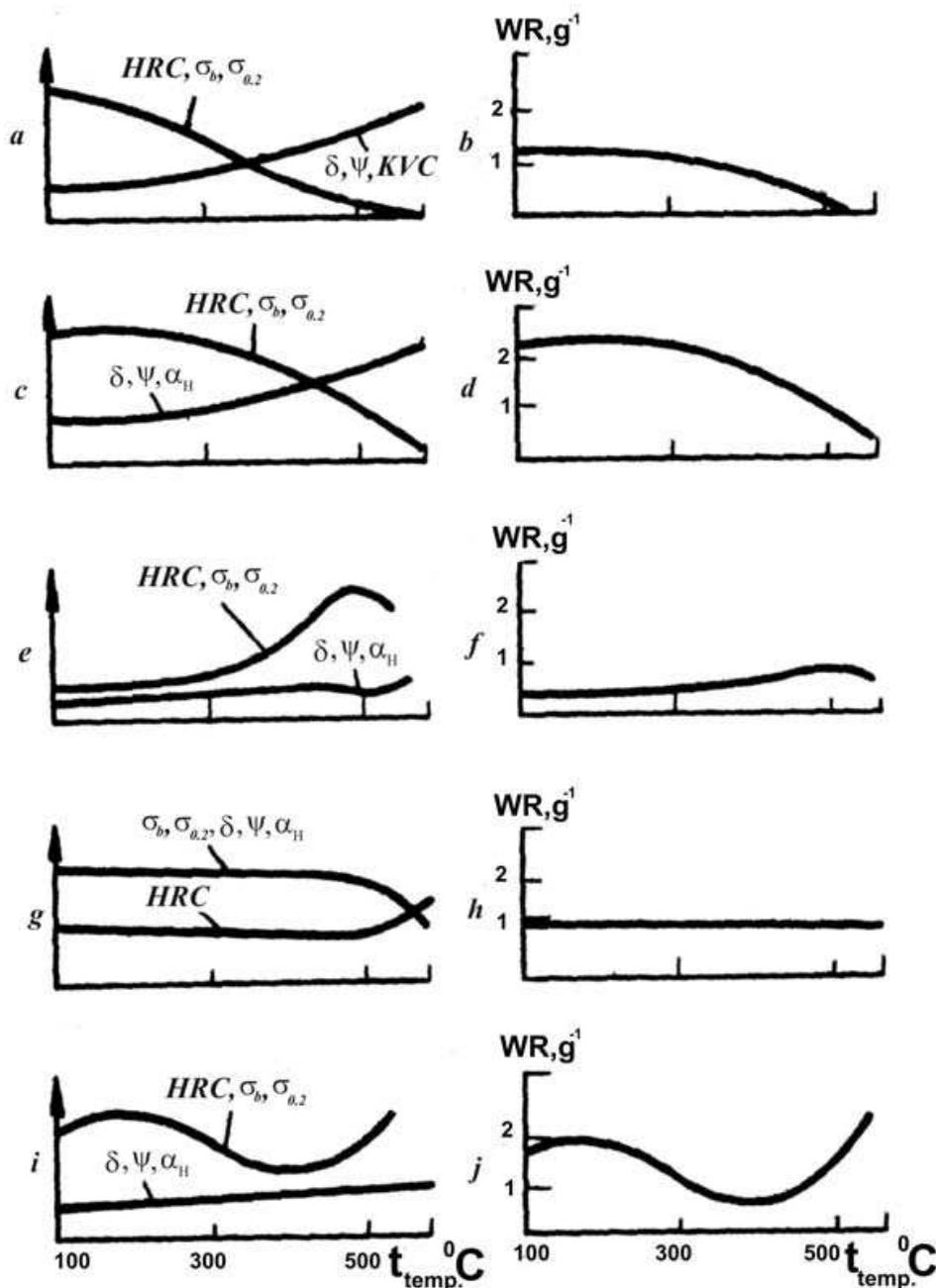
Fig. 7. Curves changes of toughness characteristics *(a,c,e,g,i)* and wear resistance (*b,d,f,h,j*) for steels of various structural classes from tempering temperature: *a,b* –steel 45 of pearlitic class; *c,d* – 95X18 of martensitic class; *e,f* –H18K9M5T of maraging class; *g,h* – 110Г13Л of austenitic class; *i,j* – P18 of carbidic class

For steels of pearlitic class at the rising of tempering temperature the toughness parameters are decreasing, and the plasticity characteristics are increasing;
For martensitic class steels is the same tendency, like for pearlitic class steels, but decrease of toughness characteristics and increase of plasticity characteristics are displaced into area for higher tempering temperature;
For maraging steels in process of rise of tempering temperature until 500 ^{0}C the toughness parameters increase at preservation of high plasticity;

For austenitic class steels at the rising of tempering temperature until 400 °C the toughness
and plasticity characteristics do not change; the further rising of tempering temperature
leads to decreasing of ultimate strength and plasticity characteristics; the hardness of steels
is being raised a little.

For steels of carbidic class in rise process of tempering temperature the toughness
characteristics are decreasing at first, and at the tempering temperature above than 400 °C
start to increase; the plasticity characteristics do not change almost.

For the first time was established the conformity between changes of toughness characteristics
and wear resistance depending on tempering temperature for steels of each class.

The results of tribological investigations have allowed to determine the law of conformity
between variations of toughness characteristics (σ_b, $\sigma_{0.2}$, HRC) and wear resistance at
different temperatures of tempering for hardened steels of all structural classes (Sorokin et
al., 1991). These data have allowed concluding that in a nature of mechanical wear, the
toughness ground lays, but the mechanism of these processes is more complicated.

The wear resistance estimation of several steels grades of different structural classes by the
one characteristic of mechanical properties reveals the complicated dependence (Fig. 8). Its
feature is that the different wear resistance corresponds to one value of any mechanical
steels characteristics of different structural classes.
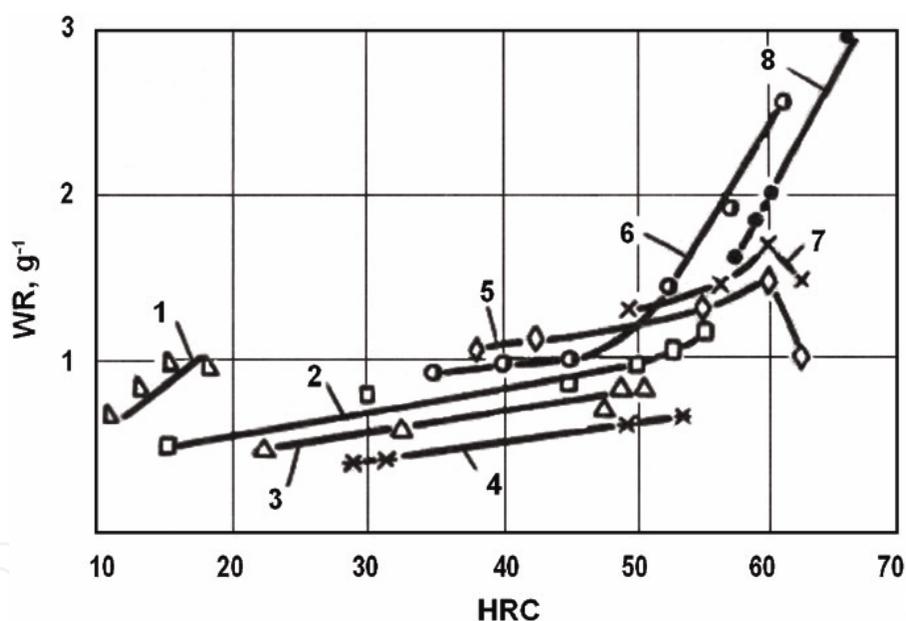
Fig. 8. Dependence of steels wear resistance WR from hardness HRC: 1—110Г13Л, 2—45 (BS
En8), 3—40 (BS En8), 4-Н18К9М5Т, 5—У10 (tool steel), 6—D7, 7—Х12М, 8—Р18.

There was a basis to consider that at the mechanical outwearing only one of toughness
characteristics (σ_b, $\sigma_{0.2}$, HRC) cannot be the full criterion of steels' wear resistance, because on
the final process of forming and separating the corpuscles of wear from a friction surface,
apart from strength properties, other mechanical characteristics exercise influence also.

This supposition was confirmed by analyses of steels plasticity characteristics correlations (δ,
ψ, KCV) with their toughness characteristics.

It became apparent that the advantage of steels' wear resistance at the equal toughness is
connected to a higher plasticity. There was a necessity to demonstrate these reasons
experimentally.

3.2 The elaboration of wear resistance definition method

Such a problem was decided with applying a new wear resistance definition method which is taking into account simultaneously two properties "the toughness and the plasticity" (Fig. 9).
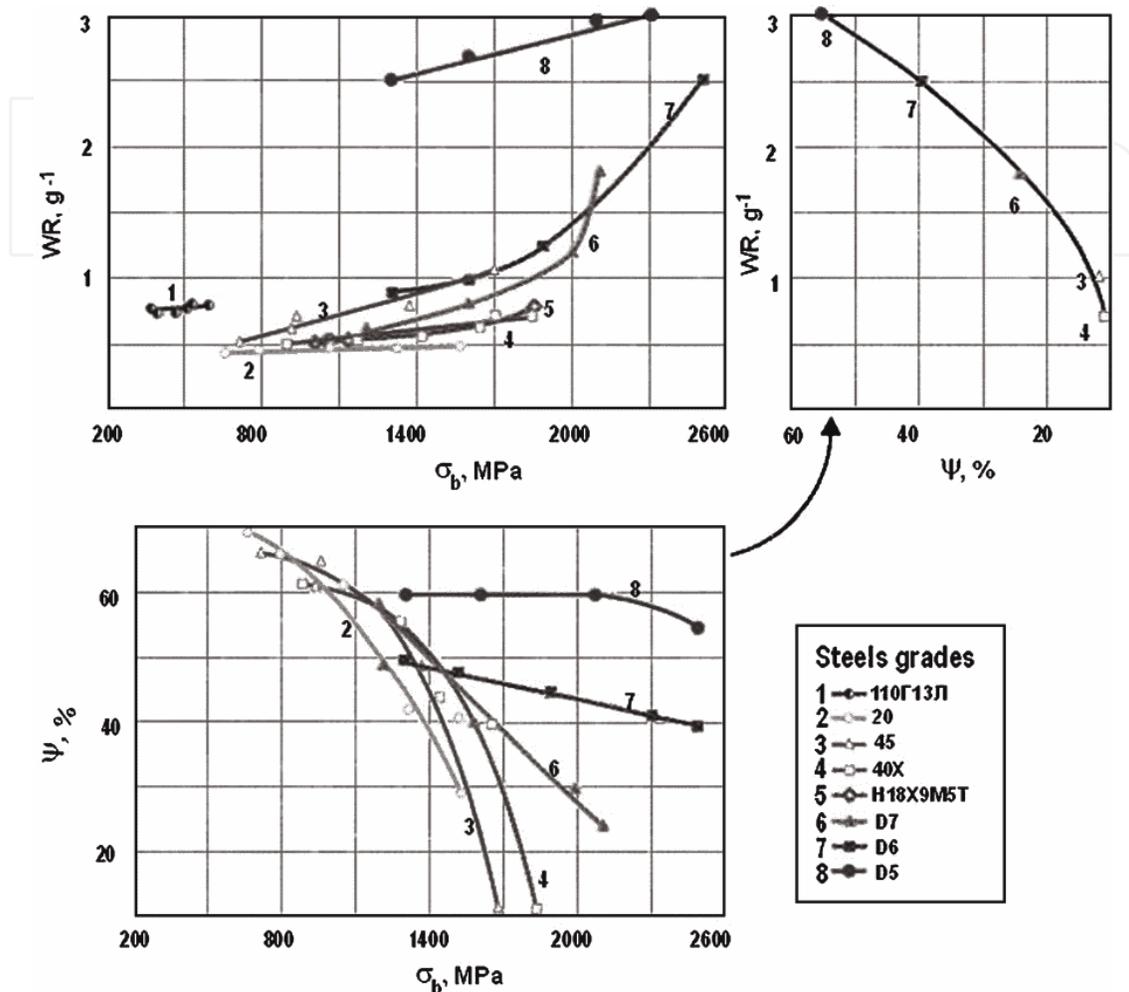

Fig. 9. Dependence of steels' wear resistance *WR* from ultimate strength σ_b and relative reduction of area ψ: 1 – 110Г13Л, 2 - 20, 3 - 45, 4 - 40X, 5 - H18K9M5T, 6 - D7, 7 - D6, 8 - D5.

The essence of this method consists in combination of two functional dependences: "wear resistance – toughness" and "toughness-relative reduction of area". Then, out of these dependences data, the final parameter in coordinates "wear resistance-relative reduction of area" is being defined. This method convincingly has confirmed that in a nature of mechanical wear at sliding friction over an abrasive the leading role belongs to steels' toughness, but the level of strength properties is more significant with higher plasticity.

All standard mechanical characteristics such as σ_b, $\sigma_{0.2}$, *HRC* enter into group of toughness. It is a dignity of this method because the selection of wear-resistant steels in factories conditions is being simplified. For this purpose it is enough to have one of three known characteristics.

The relative reduction of area is enough to have as an index of plasticity. The shape of handling and constructing the graphic dependences can be simplified, without representing a tie of relative reduction of area with toughness characteristic, and can be restricted by the dependence "wear resistance-plasticity" only (Fig. 10).
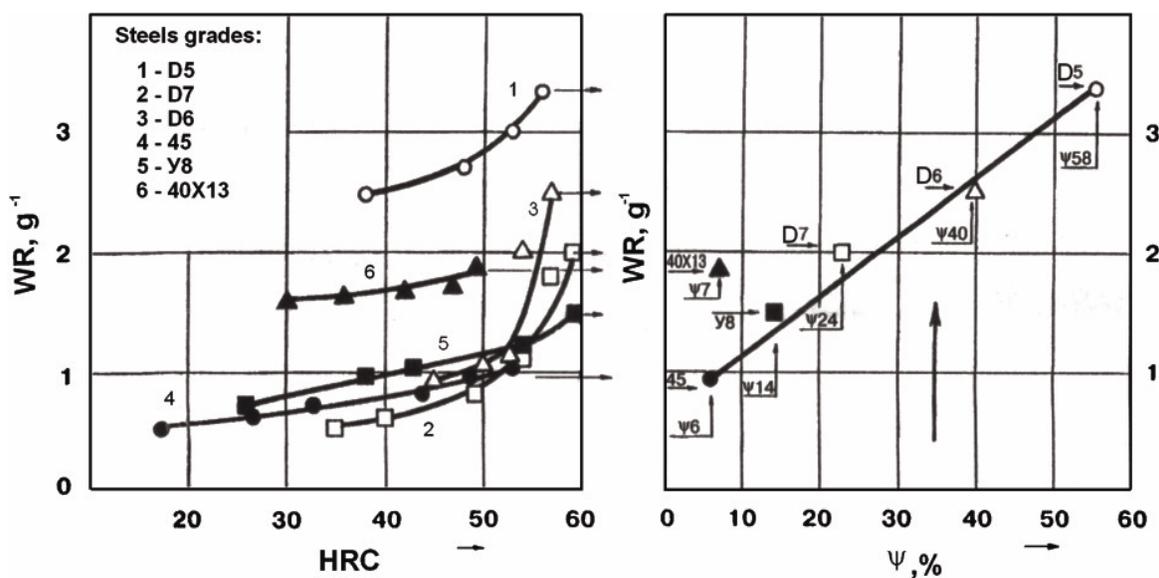
Fig. 10. Dependence of steels' wear resistance *WR* from hardness *HRC* and relative reduction of area ψ: 1 - D5, 2 - D7, 3 - D6, 4 - 40, 5 - У8 (tool steel);6 - 40X13.

3.3 Methods of steels' wear resistance ranking

We also used other methods for ranking of steels' wear resistance. In this case, the combinations of two characteristics were applied: product of hardness on relative reduction of area (*HRC* ψ) versus ultimate strength (Fig.11) and product of ultimate strength on relative reduction of area ($\sigma_b \cdot \psi$) versus hardness (Fig.12).
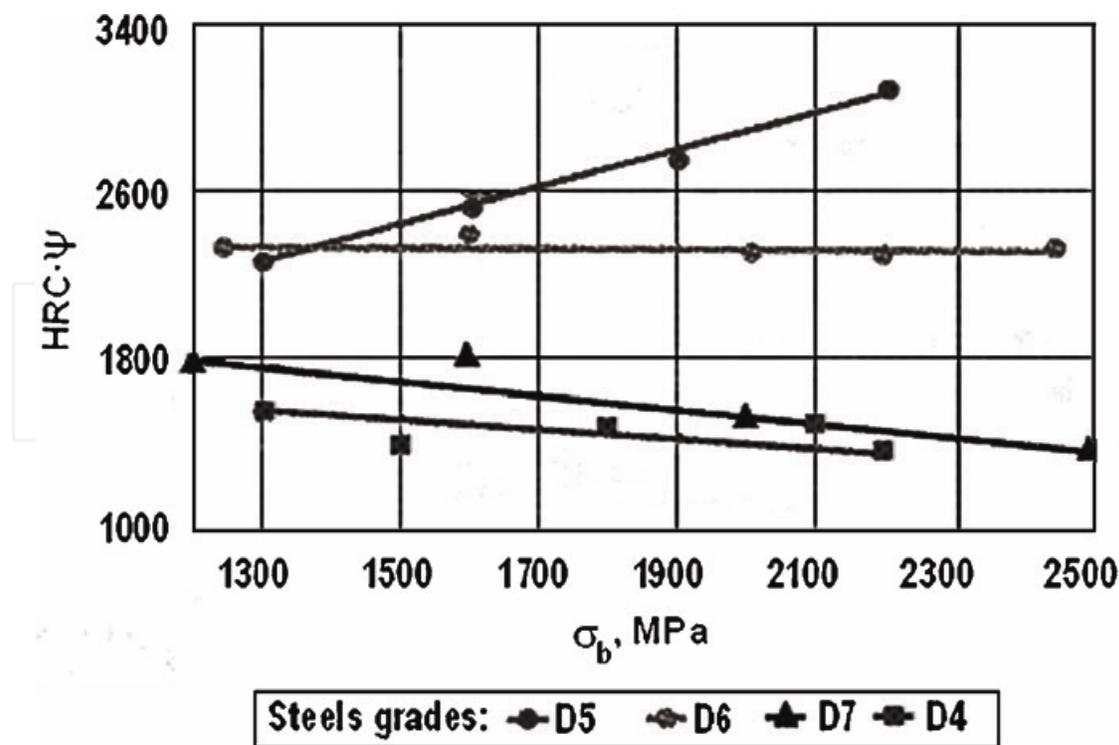
Fig. 11. Correlation of product of hardness on relative reduction of area (*HRC* $\cdot \psi$) from ultimate strength σ_b.
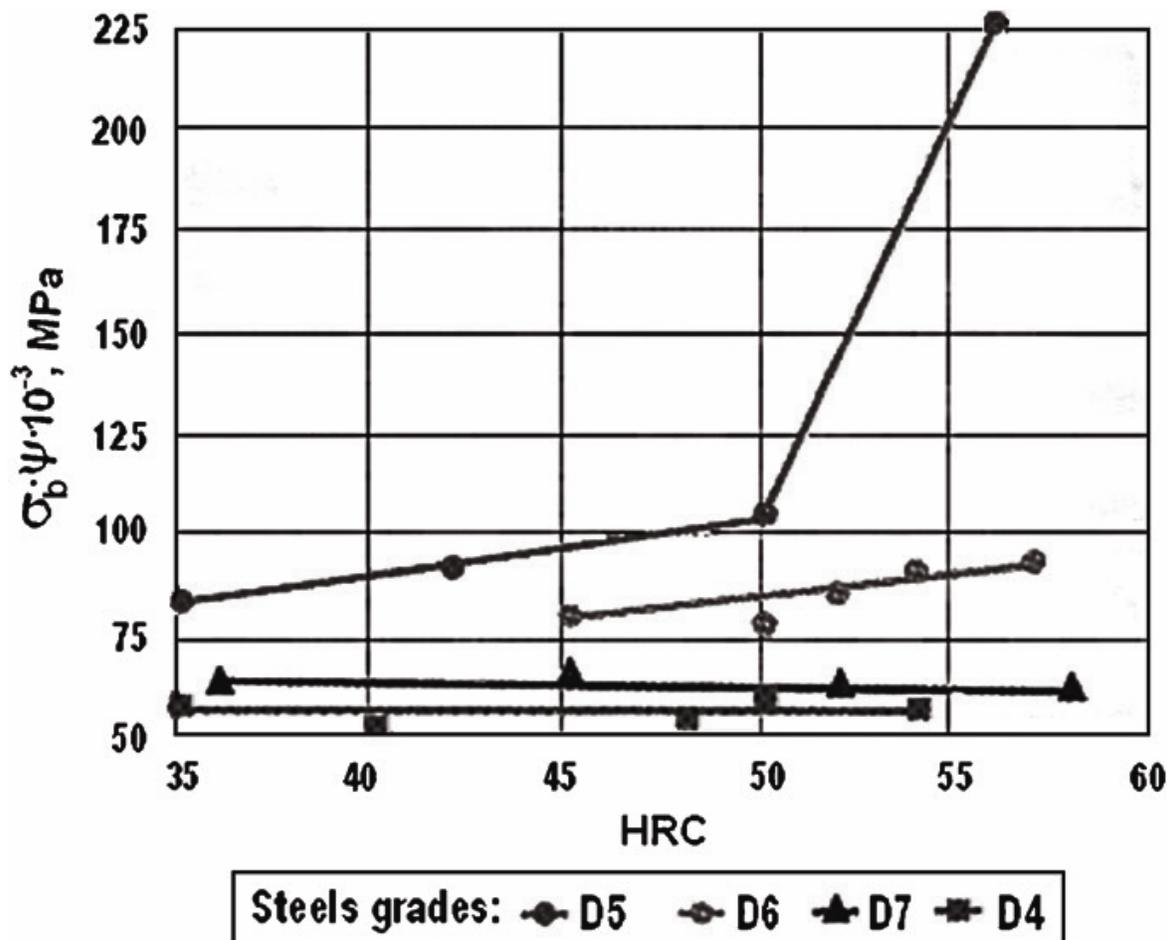
Fig. 12. Correlation of product of ultimate strength on relative reduction of area ($\sigma_b \cdot \psi$) from hardness HRC.

The points recieved on these plots represent the outcomes of experiments for five to six samples of each tested steels. All steels on these dependences can be divided in three groups: steels for which with growth of ultimate strength or hardness the parameters of wear resistance ($\sigma_b \cdot \psi$) or ($HRC \cdot \psi$) were being diminished, remained constant or increased. Thus, the principle of selection of wear-resistant steels out of these dependences is as follows: it is necessary to recommend for industrial production such steels for which the parameters of wear resistance ($\sigma_b \cdot \psi$) or ($HRC \cdot \psi$) are maximal and tends of growth with increase of second (pair) characteristic.

3.4 The influence of carbon content in steels on their wear resistance

With a purpose of studying the influence of carbon content in steels on their wear resistance, several steels with miscellaneous carbon content (from 0.2% up to 1.2%) at the equal hardness, 30, 40, 50, 55, 60 *HRC*, were selected for experiments. The dependences of steels' wear resistance from carbon content at different levels of hardness are shown on Fig. 13. The carbon content renders the direct influence on structure of steel forming and consequently, its mechanical characteristics and, first of all, the hardness. Our investigation's outcomes of structural stability influence on wear resistance of steels have allowed more widely considering this problem. The selected steels were tested after hardening and tempering at different temperatures to receive all possible structural statuses. At the low level of hardness

(up to 30 *HRC*), changing of carbon content in a wide interval (0.2-1.0%) practically does not influence wear resistance. At the hardness 40 - 50 *HRC* the wear resistance of steels is being increased proportionally carbon content in them. At *HRC* 60 the carbon content in steels from 0.6% up to 1.2% cause a sharp falling of wear resistance.
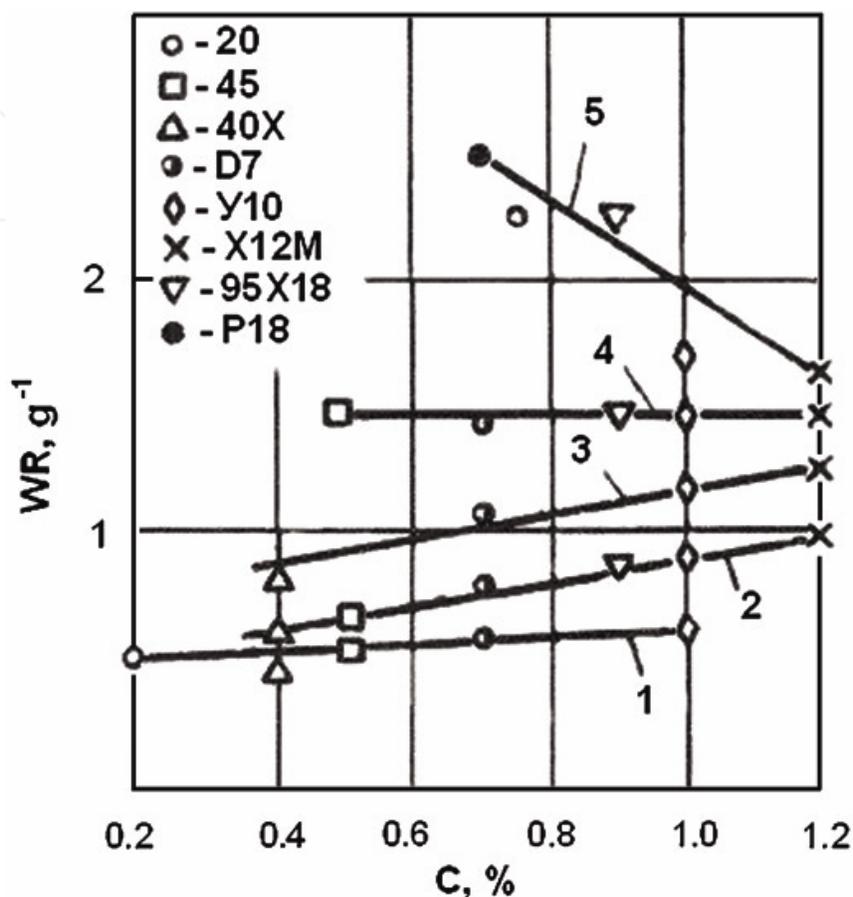
Fig. 13. Dependence of steels wear resistance *WR* from carbon content *C* at the different levels of hardness (*HRC*): 1 - 30, 2 - 40, 3 - 50, 4 - 55, 5 - 60.

4. Discussion

The investigations of last years have set more complicated task to which all tribologists are aspired. This task consisted in the elaboration of methods for ranking steels wear resistance without their trials on wear.

The logic of reasoning has specified the methodical necessity to use as criterion of outwearing simultaneously two characteristics of mechanical properties - the toughness (σ_b) and the plasticity (ψ). So, it was proposed that the product of ultimate strength on relative reduction of area ($\sigma_b \cdot \psi$) can be used as the complex criterion for an estimation of steels wear resistance at the mechanical outwearing.

The advantage of this method is in the kept dimensionality of toughness (MPa) which is "strengthened" by the influence of plasticity. This criterion takes into consideration the nature of dependences shown on Figs. 9 and 10. Besides, the criterion ($\sigma_b \cdot \psi$) in a certain measure reflects the power consumption of steel, because it considers actually two indexes: static toughness and plasticity.

The possibility of using this criterion was exhibited under different conditions of external forces influence. It was enough reliable at an estimation of steels wear resistance in conditions of sliding and rolling friction over an abrasive, of erosive wear with angles of attack less than 90^0 (Sorokin et al., 1991). The product of ultimate strength on relative reduction of area ($\sigma_b \cdot \psi$) has appeared universal, allowing to explain not only distinction of steels wear resistance at an equal value of one toughness characteristics, but the difference of endurance strength at an equal value of ultimate strength, also (Fig. 14) (Sorokin & Malyshev, 2008).
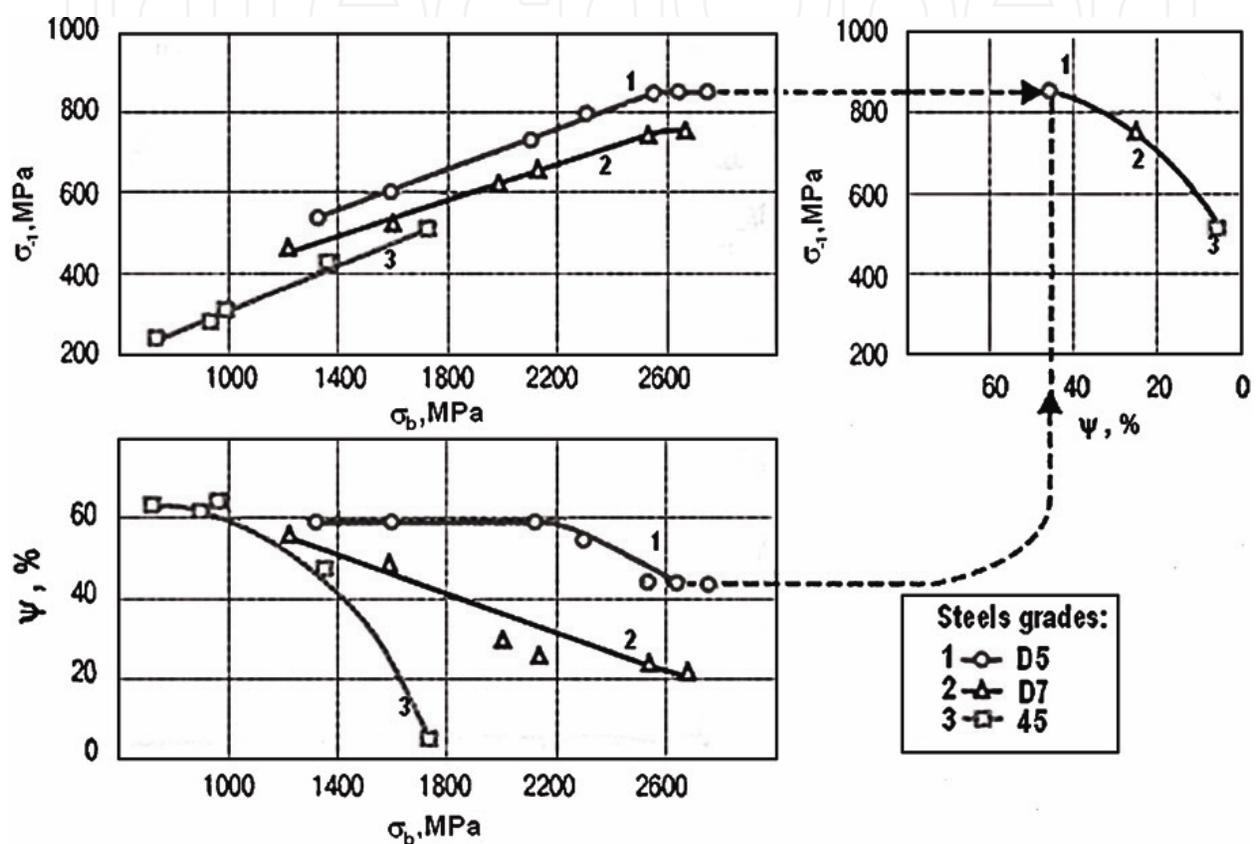
Fig. 14. Dependence of endurance strength σ_{-1} from ultimate strength σ_b and relative reduction of area ψ.

The ranking of steels wear resistance of miscellaneous structural classes was held using obtained criteria and taking into account their structural stability under thermal affect conditions.

There were used the coefficients of structural stability (thermo stability) which were taking into account the destruction of original structure at the heating in furnace K_1 and as a result of heating by friction K_2. The coefficient K_1 was being defined as hardness ratio of steels after their hardening and tempering at defined temperature (100 ^{0}C) to steels hardness after hardening, but without tempering. The coefficient K_2 was being defined as a ratio of steels wear resistance during defined time to its initial wear resistance after a trial within 3 min.

All steels on their thermo stability at the outwearing may be subdivided to as self-hardening, self-softening and stable steels. Coefficient of thermo stability (K_1) may change from 0.5 up to 1.5 (Sorokin, 2000). The maximal steels wear resistance of different structural classes was distributed as follows:

Structural class of steel	Criterion, $(\sigma_b \cdot \psi)$ (MPa)	Wear resistance, WR (g^{-1})
Pearlitic experimental steel	140250	2.5
Martensitic steel 95Х18	14400	2.0
Austenitic steel 110Г13Л	9156	0.89
Maraging steel Н18К9М5Т	-	0.57
Carbidic high-speed steel Р18	-	3.2

It is necessary to mark that the warmly-resistant steels unconditionally have advantage before other steels in their capacity to keep an initial wear resistance under high thermal conditions. But their large shortcoming consists in a low magnitude of complex criterion $(\sigma_b \cdot \psi)$ that characterizes a capability to perceive the high external forces of uploading on the executive links of mechanisms. In particular, the value of complex criterion $(\sigma_b \cdot \psi)$ for the warmly-resistant austenitic steel 110Г13Л has 10 times less magnitude, than for steel of the pearlitic class D5. The carbidic steel (Р18) has a high wear resistance under thermal conditions, but as steel for machine building it can't be applied because has a low value of plasticity. This feature should be taken in consideration by designers at the creation of machines. The complex criterion $\sigma_b \cdot \psi$ is suitable for an estimation of steels wear resistance not only in the conditions of sliding friction over an abrasive, but also in the conditions of rolling friction that Fig. 15 is visually illustrates.
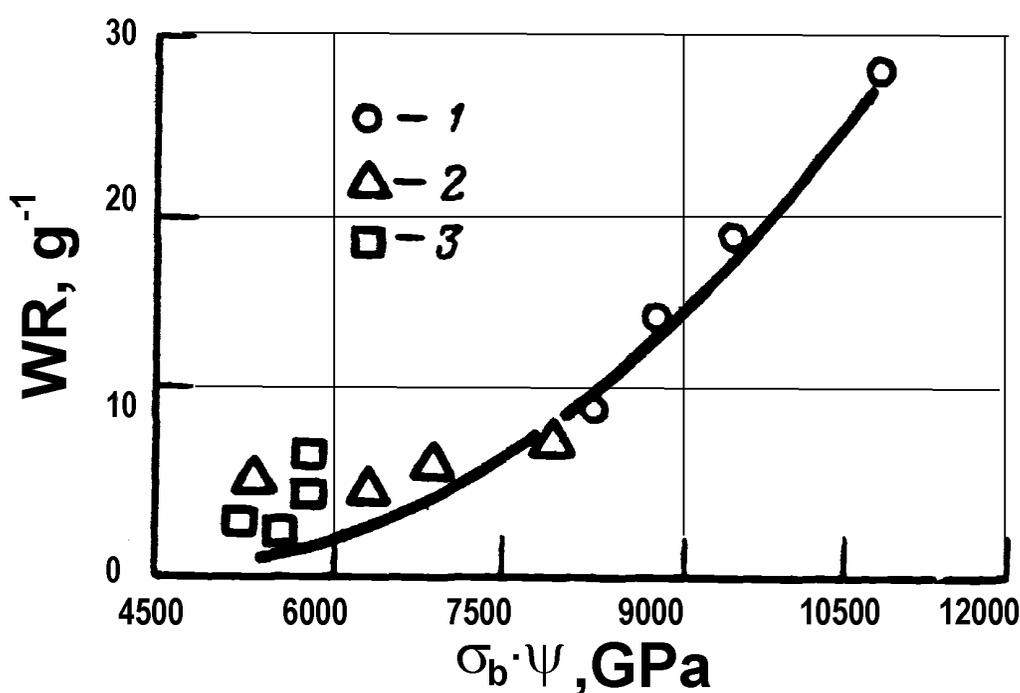

Fig. 15. Dependence of wear resistance WR of steels at rolling friction on an abrasive from criterion $\sigma_b \cdot \psi$: 1 - D5; 2 - D7; 3 - steel 55СМ5ФА

The carbon content in steels influences their wear resistance in that measure in which are increasing the toughness characteristics under condition of providing the indispensable reserve of structure plasticity.

When this condition is not being observed - the wear resistance diminishes because of rising fragility of structure causing a crumbling in micro volumes of a friction surface. The analysis of obtained data shows that for the steels wear resistance estimation it is necessary to take into consideration their chemical composition.

The obtained new information has allowed to discover the law of abrasive outwearing and to show the influence of mechanical characteristics and their combinations on steels wear resistance of miscellaneous structural classes, to formulate the mechanism and criteria of this kind of outwearing from positions of metal science and toughness of metals. At the analysis of detected dependences became apparent that in a nature of mechanical (abrasive) outwearing lies a strengthened ground which allows simplifying the criteria connected to an estimation of steels wear resistance using only a well-known in industrial conditions the standard characteristics of mechanical properties and their combinations.

Out of obtained results data of investigations became indisputable the significance of plasticity reserve in steels with an obligatory high value of all characteristics of toughness (σ_b, $\sigma_{0.2}$, HRC) (Sorokin,2000; Gokhfeld, 1996; Kimura, 1975).

Thus, a toughness "reinforced" of indispensable plasticity, is a basic component in understanding mechanical wear nature under complicated external forces affect conditions, where simultaneously with one-time contact of a single abrasive particle can take place the low-cycle fatigue from the repetitive multiple acts of such affect.

This feature can be explained by the mechanism of interplay of single abrasive particle with wear surface: at the friction of solid particle on the steel surface is occur simultaneously its intrusion with defined effort and consequent migration. This, at the result, shapes the "products" of wear and leaves on the contact surface the risks or crushing oriented in direction of particles' moving. The intrusion of a corpuscle in metal and its migration meets a complex resistance in which ones participate the characteristics of toughness and plasticity. The combination of these characteristics can be various, but the positive effect will be in the events when the selected combination of mechanical characteristics ensures indispensable resistance:

-    to an intrusion - this function executes the hardness *HRC*;
-    to a tension, shear, crushing - this is ensured with high values of ultimate strength, yield limit in combination with relative elongation, relative reduction of area or difference (σ_b - $\sigma_{0.2}$).

Namely, such purpose was pursued by the selection of reviewed above mechanical characteristics and their combinations.

Definition of estimation criteria of materials wear resistance and, first of all, steels are one of the major problems of tribology development in the near future. The successful decision of this problem will open wide prospect of a choice and creation of wear-resistant materials.

There is necessary to notice that tribological toughness of materials is a complicated concept and completely is not discovered; it will be gradually specified in process of accumulation of new experimental data. This new characteristic will be connected with studying of new aspects, and first of all, metal science and classical laws of strength. It means the behavior of steels of different structural classes in difficult conditions of force uploading and temperature influence. New data, certainly, will allow expanding representations about the mechanism of mechanical outwearing. But already today it is possible to assert that

hardness of materials, especially steels, will be the base characteristic of wear resistance at mechanical wear. Hardness as the measure of resistance of material to introduction in its surface of a solid body defines a possibility of development of the basic stage of mechanical outwearing - the introductions of a solid particle into another surface. If particle introduction occurs, there is possible the following stage of wear process consisting in micro cutting or plastic deformation at moving in the conditions of sliding. If initial introduction is absent, the second stage, i.e. actually the outwearing or damage of a contact surface, becomes impossible. In this case the particle is not capable to damage a surface. It means that a wear is absent and the wear resistance as an inversely value of wear aspires to infinity, i.e. it is become unwear situation that at the mechanical outwearing happens extremely seldom.

Thus, there are possible two ways of wear resistance increase at mechanical outwearing: the creation of structures with high initial hardness and thermo-resistance in all volume of detail or in superficial layer only. These structures shielding the surface from introduction of abrasive particles are capable, if not in whole, but significant reducing a wear. However, on the modern stage of metal science development such structures are practically not present - all steels are exposed to mechanical outwearing.

Quite probably that the creation of new steels structures considerably surpassing in hardness the existing steels (60-62 *HRC*) can cardinally decide the problem of wear resistance rising. But, the difficulty consists in that that at the rise of toughness characteristics and hardness the plasticity characteristics reduce very sharply and it lead to undesirable fragile destruction. Analysis of works on the creation of high-strengthened steels for the last quarter of the century confirms all complexity of realization this direction in metal science. The repeated increase of limits of ultimate strength, fluidity, endurance, shear strength resistance and hardness was not possible to reach as at us in Russia and abroad.

The second way of wear resistance increase of machine details supposes the creation in superficial layer the structure of high hardness on small depth from friction or blow zone. This way has more perspectives from tribology positions because it does not demand high strength of steel structure in whole volume of detail. Increase of superficial hardness in some cases influences significant positively on the wear resistance because the relation hardness law of abrasive and metal at the high hardness of metal provides sharply increase of wear resistance.

Results of the analysis of an extensive experimental data show that for providing the best indexes of wear resistance at mechanical outwearing it is necessary to combine three components: high static toughness, hardness and plasticity. Only the combination of such characteristics provides the best results regarding the wear resistance increase.

The problem of steels wear resistance rise is a major task of technical progress in machine industry. The path to successful decision of this task is the creation of high strengthened steels that not only have the separate high characteristics of mechanical properties, but also the exceeding from other steels by high values of combinations of these separate characteristics, such as ($\sigma_b \cdot \psi$), ($HRC \cdot \psi$), ($\sigma_b - \sigma_{0.2}$) and high thermo stability. The difference of ultimate strength and yield limit ($\sigma_b - \sigma_{0.2}$), the so-called - "barrier effect" (Alekhin,1983), is almost linearly connected to ultimate strength and positively influences on wear resistance of steels. Out of our data (Sorokin et al., 1991), the maximal ultimate strength is fixed, when ($\sigma_b - \sigma_{0.2}$) is in a spacing 500 - 700 MPa. The steel D5 has the best indexes of the wear resistance and endurance strength from among experienced steels that is being provided by their higher combination of all mechanical characteristics (see Table 2).

Grade of steel	σ_b, MPa	$\sigma_{0.2}$, MPa	HRC	δ, %	ψ, %	KCV, MJ/м²	$\sigma_b \cdot \psi$, MPa	HRC·ψ	σ_b-$\sigma_{0.2}$, MPa	WR, g⁻¹
D4	2000	1900	53	8	35	0.34	70000	1855	100	1.55
D5	2550	1850	56	12	55	0.55	140250	3080	700	1.94
D6	2500	2000	57	8	40	0.30	100000	2280	500	1.82
D7	2100	2100	57	7.5	33	0.32	69300	1881	0	1.75
H18K9M5T	1070	900	31	7	-	-	-	-	170	0.54
95X18	1800	1700	61	8	8	0.15	14400	488	100	2.4
110Г13Л	327	327	16	37	28	1.53	9156	448	0	0.79
X12M	730	730*	59	-	-	0.016	-	-	0	1.69
40X13	1850	1520	48	7	8	0.18	14800	384	330	0.73
P18	1150	1150*	58	-	-	0.015	-	-	0	1.51
45	1700	1700*	49	8	8	0.39	13600	392	0	0.98

Note: *The yield limit of samples that were being destroyed at the test fragile is accepted equal to ultimate strength.

Table 2. Steels' mechanical properties at the tempering temperature 200 ⁰C and wear resistance *WR*

Thus, the long-term problem connected to a searching of reliable criteria of an estimation of steels wear resistance, without the necessity of labor-intensive and not always realized wear trials in industrial conditions has received its further development. This task in defined aspects is finished up to an engineering decision and can be used in designer's practice for choosing the wear-resistant steels and alloys. The tendered methods allow not only to produce an estimation of suitable steels for different conditions of wear and external forces of uploading, but also to orient metallurgists to melting new steels with quite defined mechanical properties and their combinations.

The perspectives of wear resistance rise of steels and alloys is necessary to bind not only with toughness increase of materials matrix structure, but also with searching of methods for strengthening surface parts of machines, as one of the possible ways to increase the work resource of machines. In this event, the different methods of forming wear-resistant surface layers are of interest. There are different coatings obtained by laser strengthening (Gnanamuthu D.S.,1979), by spark doping and also ceramic coatings formed by microarc oxidation method (Malyshev & Sorokin, 1996).

It is necessary to recognize that tribology as an effective facility for increase of work resource of machines by means of protecting them from wear could give for factory practice much more for machinery production of different assignment if it have been founded, first of all, on the basis of metal science investigations, especially under mechanical wear conditions.

5. Conclusion

1. The mechanical outwearing of steels under abrasive affect conditions is a variety of breaking down of metals in their nature . Its basic difference is conditioned by the

    scaling factor by means of formation and removing of wear corpuscles in micro volumes of friction surfaces.

2. The functional tie of steels wear resistance with toughness characteristics at the indispensable reserve of plasticity is the confirmation of this hypothesis. The toughness characteristic intensified of necessary plasticity is the main component in understanding of mechanical outwearing nature under complex external forces affects conditions.

3. The method reviewed in this chapter allows in the practice of designing machinery to select the more wear-resistant steels without necessity of much labor-intensive and not always accessible in industrial conditions the wear trials using only standard mechanical characteristics - the indexes of toughness and plasticity.

4. It is possible to assert definitely that in the general problem of wear resistance increase of machines the metal science role is exclusively great: in any specific target of resource increase of machines details two third of volume of possible measures will always make aspects of metal science or if to speak more widely - materials of different structural systems.

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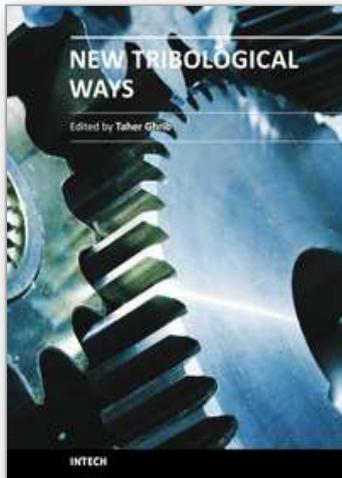
New Tribological Ways

Edited by Dr. Taher Ghrib

This book aims to recapitulate old information's available and brings new information's that are with the fashion research on an atomic and nanometric scale in various fields by introducing several mathematical models to measure some parameters characterizing metals like the hydrodynamic elasticity coefficient, hardness, lubricant viscosity, viscosity coefficient, tensile strength .... It uses new measurement techniques very developed and nondestructive. Its principal distinctions of the other books, that it brings practical manners to model and to optimize the cutting process using various parameters and different techniques, namely, using water of high-velocity stream, tool with different form and radius, the cutting temperature effect, that can be measured with sufficient accuracy not only at a research lab and also with a theoretical forecast. This book aspire to minimize and eliminate the losses resulting from surfaces friction and wear which leads to a greater machining efficiency and to a better execution, fewer breakdowns and a significant saving. A great part is devoted to lubrication, of which the goal is to find the famous techniques using solid and liquid lubricant films applied for giving super low friction coefficients and improving the lubricant properties on surfaces.

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