

FSBEO HE
“UFA STATE AVIATION TECHNICAL UNIVERSITY”

Department of Material Science and Physics of Metals

LABORATORY WORKSHOP
“TECHNOLOGY OF HEAT TREATMENT”

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DEFINITION OF MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS

Introduction

Ability of details of machines and various constructions to preserve working capacity and non-failure operation depends on properties of materials of which they are fabricated. The knowledge of properties of materials taking into account conditions of a stressing and maintenance of details allows designers to select a material correctly, for the processmen knowing mechanical and technological properties of materials - to assign an optimum condition of their processing, and for the economists having of sufficient knowledge in the field of technique and costs of materials - to calculate economic efficiency of manufacturing techniques of details of machines correctly.

For definition of mechanical properties of materials there are carried out special tests. In this paper the methods of metals tests on a tension, hardness and bending are considered.

Before execution of operation students should independently examine this reference, prepare answers for tests and control questions for self-examination.

At execution of laboratory work students are formed such professional competence as ability to use methods of standard tests for definition of mechanical properties and technological indexes of constructional materials.

Having performed laboratory work, the student should:

- **know:**

- Methods of standard tests of materials for definition of mechanical properties;

- The equipment for standard tests;

- **be able** to apply methods and the equipment of standard tests of materials for definition of mechanical properties;

- **have skills:**

- Operations on test equipment for standard tests;

- Analysis of the received results according to technical requirements.

Before each lesson the student should be prepared for forthcoming operations and should made the preliminary record according to requirements. Records are made on each laboratory work accurately and

competently, in the text it is necessary not to suppose abbreviations of records. Sketches and graphs must be followed with necessary explains. Applied terms and designations should correspond to standard requirements. Before execution of laboratory work the preliminary individual record on operation, and also theoretical readiness of students is checked. The students who do not made the individual record, and not ready to the answer the control questions are not supposed to execution of operations. Upon finishing of laboratory woks students are obliged to return the record for checking and to speak in support of paper, answering questions of the teacher about the contents of laboratory work and results of its practical part.

LABORATORY WORK №1
**DEFINITION OF MECHANICAL PROPERTIES OF
STRUCTURAL MATERIALS**

1. The operation purpose – acquisition by students of skills and the abilities necessary for definition of the basic mechanical properties of metal materials.

2. Operation problems:

- 1) to study methods of definition of mechanical properties of materials from test on a tension;
- 2) to master techniques of mechanical properties control via materials hardness gauging;
- 3) to learn impact strength definition.

3. A theoretical part

Strength, elasticity, plasticity, hardness, viscosity are treated to mechanical properties of metals and alloys. These properties are the basic indexes on which suitability of metal to various working conditions is judged. First three properties are defined by tests of materials on a tension.

3.1. Tensile test [GOST 1497 - 84]

For tensile test use special specimens (fig. 1.1) with length of a working part l in the form of the barrel or with a rectangular cross section (flat samples).

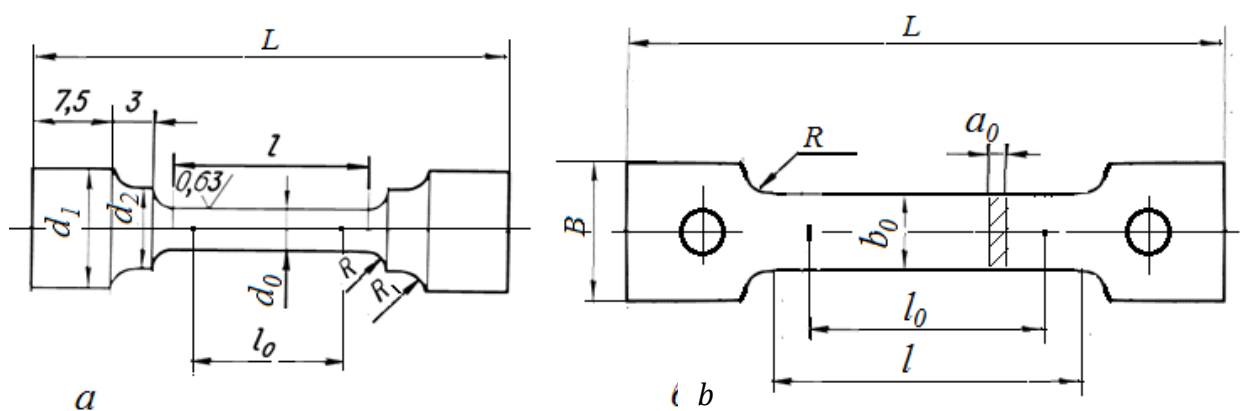


Fig. 1.1. Standard specimens for tensile test: *a* - cylindrical; *b* – flat

On a working part of the sample the initial settlement length of the

sample l_0 (mm) is selected by matchmarks. Elongation is defined due to this length. Samples of a circular cross-section with a diameter $d_0 = 5$ mm and $l_0 = 25$ mm are applied most often (fig. 1.1). Flat samples apply at tests of sheet materials. They have following sizes: initial depth a_0 and width b_0 , settlement length of a working part l_0 (fig. 1.1). Tests are carried out on universal tensile test machines (look fig. below).



Universal tensile test machine INSTRON

During test tensometric device of the tensile machine records in the form of the chart dependence between axial load P and an increment of length of the sample Δl . On fig. 1.2 typical tension charts recorded by tensile machine during testing of metal materials are presented. The chart with gradual transition from elastic in a plastic deforming region (fig. 1.2.a) is peculiar to the majority of metals in a plastic condition (steel alloys, colored alloys). For low-carbon annealed steels and some bronzes after their annealing the chart with a plasticity stage (fig. 1.2.b) is characteristic. Fragile metals (tempered and not drawn steels, cast iron, etc.) fail at small plastic deformations (fig. 1.2.c).

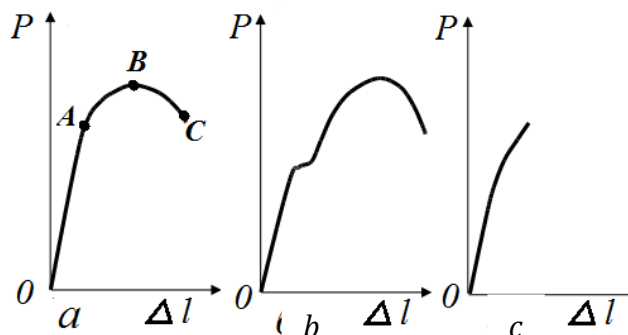


Fig. 1.2. Chart of a tension of various metals: OA - area of an elastic strain; AB - a site of viscoelastic strains; BC - a collapse stage

For practical evaluations of engineering stresses there are used the charts of a tension with characteristic points (fig. 1.3). The tension chart $P - \Delta l$ characterizes behavior of the sample made of tested material with certain geometrical parameters. To eliminate influence of the sizes, the chart $P - \Delta l$ is re-counted in the diagram $\sigma - \varepsilon$, where σ - stresses, ε - a relative strain which is defined as: $\varepsilon = (l - l_0)/l_0$, where l - current length of the sample during test. The chart $\sigma - \varepsilon$ - the same diagram $P - \Delta l$, drawn on the scale of P/F_0 on a axis of ordinates and in scale l/l_0 - on a axis of abscissas. At a tension the sample is lengthened, and its cross-section is continuously diminished. But as the area of cross section of the sample into each moment of a strain is difficult to define so strength properties (limit of plasticity and tensile ultimate strength) use conditional stresses. They are evaluated by division of a corresponding load onto an initial cross-section of sample F_0 .

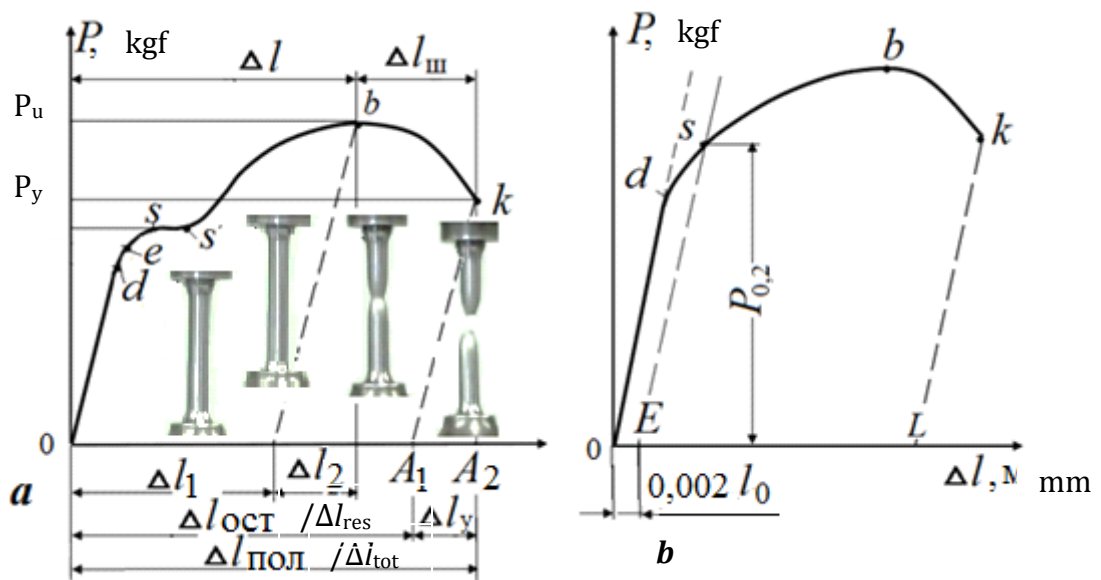


Fig. 1.3. Characteristic sites and points of the chart of a tension: *a* - the chart of a tension of a low-carbon steel with a plasticity stage; *b* - the circuit of definition of a conventional yield point $\sigma_{0,2}$ (location of point *S*)

At small loads on a chart site Od the residual strain does not arise also the sample after load intakes initial length - its behavior is elastic. This site of an elastic strain has a rectilinear appearance and characterizes rigidity of a material. The smaller elastic strain displays a material under the influence of a load, the higher its rigidity which is evaluated via coefficient of elasticity (Young modulus): $E = \sigma / \delta$, МПа.

At the further increase in a load the rectilinear dependence is

disturbed. Behind a point «e» there is an appreciable residual deformation and in a point «s» (fig. 1. 3,) the plasticity stage s-s' is formed. The least stress at which the sample is deformed without appreciable increase in a load ("flows"), is called *as real yield point*. It is defined by the formula

$$\sigma_y = \frac{P_y}{F_0}, \text{MPa} \quad (1.1)$$

For the materials which do not have on the tension chart a horizontal stage (fig. 1.2,a or 1.3,b), load $P_{0,2}$ which calls a residual strain equal of 0,2 % from settlement length of the sample is defined. At big enough scale of the primary chart of a tension a value of load $P_{0,2}$ define graphically directly on this chart. For this purpose there postpone a cut equal of 0,2 % ($0,002 \cdot l_0$, mm) settlement length of the sample and from this point spend a line parallel to an elastic site of the chart. The cross-point of this line with the chart corresponds to magnitude of load $P_{0,2}$ (fig. 1.3,b). When value $P_{0,2}$ is fixed then conventional yield point is evaluated by the formula

$$\sigma_{0,2} = \frac{P_{0,2}}{F_0}, \text{MPa} \quad (1.2)$$

The yield point characterizes stress at which there is a transition from an elastic strain to the plastic.

The stress induced by the greatest load P_e (a point «b») is called *as ultimate resistance or tensile strength*:

$$\sigma_u = \frac{P_u}{F_0}, \text{MPa} \quad (1.3)$$

During testing before a point «b» the sample has the cylindrical shape. After a point «b» there is an appreciable local contraction of the sample with necking where the further strain of the sample concentrates. Therefore on a site **b-k** the section of the sample (fig. 1.3,a) is quickly diminished, owing to what the stretching load is diminished too. In some point «k» the sample is broken off on the least section of neck F_k . In a fragile material necking is not expressed almost, and when tensile

strength reaching σ_B at once there is a collapse (fig. 1.2,c). After test fragments of the sample combine and measure its final settlement length after a break l_K and final diameter d_K (fig. 1.4). Due to it there are defined indexes of plasticity of a material.



Fig. 1.4. The sample before test (a) and after the test, combined for gauging (b)

Two parameters of plasticity are distinguished: an elongation δ and a contraction ratio ψ .

They are defined via formulas

$$\delta = \frac{l_K - l_0}{l_0} 100 \% = \frac{\Delta l_{\text{res}}}{l_0} 100 \%, \quad (1.4)$$

Where l_K - length of the sample after a break; l_0 - initial settlement length of the sample.

The contraction ratio is evaluated under via formula

$$\psi = \frac{F_0 - F_K}{F_0} 100 \% = \frac{\Delta F_K}{F_0} 100 \%, \quad (1.5)$$

Where F_K - the area of sample section after a break;
 F_0 - initial section of the sample.

It is conditionally considered that metal is reliable if $\delta \geq 15 \%$ and $\psi \geq 45 \%$.

Tensile test treats to destroying methods of definition of materials mechanical properties. For current quality inspection of the thermotreated metals usually use not destroying methods the main one from which is hardness gauging.

3.2. Test of metals on hardness

The most simple mode of definition of mechanical properties is hardness gauging. *Hardness* is an ability material to resist to introduction in its surface of solid body – the indenter. As a indenter

there is use the tempered steel ball or a diamond tip in the form of a cone or a pyramid. Methods of impression hardness gauging of Brinell and Rockwell are most widely used.

3.2.1. Hardness gauging via a method of Brinell. For hardness gauging via a method of Brinell the hardness meter type TIII is applied. Under load P (from 62,5 to 3000 kg) the steel tempered ball (fig. 1. 5,a) with diameter D (1,0; 2,0; 2,5; 5,0 and 10 mm) presses into a surface of a tested material. After load removal on a surface of the sample there is a print (fig. 1.5,c), which diameter d is measured by means of a microscope (magnifier) of Brinell МПБ-2 with accuracy $\pm 0,05$ mm (fig. 1.5,). Hardness number define as a ratio of load P to a spherical surface of indentation print F (a spherical segment) - diameter d , left due to the spherical indenter with diameter D :

$$HB = \frac{P}{F} = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}. \quad (1.6)$$

In practice hardness do not evaluate via the formula (1.6), and define due to the table of GOST 9012-59, based on the obtained value of print diameter d , and also on known ball diameter D and a value of attached load P .

Conditions of gauging of hardness (diameter of a ball, a load, stressing time) are selected depending on width of the sample and hardness of the examined material. Thus it is necessary to consider that for deriving of identical hardness numbers at test of the same material with balls of different diameters it is necessary to observe the similarity law between obtained diameters of prints. For sufficing of such law hardness gauging spend at a fixed ratio between magnitude of load P and quadrate of diameter of ball D^2 : $K=P/D^2$. This ratio is different for materials with various hardness and it is reached by selection of diameter of ball D , effort P so that diameter of a print was within $0,24 D \leq d \leq 0,6 D$.

Brinell hardness is designated by symbol HB (*Hardness Brinell*). At gauging of hardness with use of the tempered steel ball (in order to avoid its collapse) hardness of being gauging material should not exceed 450 units. Then at hardness gauging in the considered conditions ($D=10$ mm; $P=3000$ kg; $\tau = 10$ s) hardness is designated, for example, 300 HB. At use of a ball from a firm alloy it is possible to measure the firmer materials (> 450 HB). In this case hardness is designated, for example, 500 HW. If tests were carried out in the conditions different from considered the record will look like the following: 250 HB 5/750/20 or 500 HB 5/750/20. In these designations of hardness the first digit displays a hardness value (250 and 500); then digits: 5 - diameter of a ball, mm; 750 - loading on indenter, kgf; 20 - time under a load, sec. The method is unsuitable for gauging of hardness of thin sheet materials, details with a firm surface.

3.2.2. A method of hardness gauging via Rockwell. At hardness gauging via a method of Rockwell as a indenter in a device **TK-2** use a steel ball in diameter of 1,59 mm or a diamond cone with an apex angle 120° . In accordance with GOST **9013-59** depending on a combination «indenter/load» there is distinguished 11 scales of hardness in a method of Rockwell (A, B, C, D, E, F, G, H, K, N, T). But most often use scales A, C (with a diamond cone) and B, F (with a steel ball). Rockwell hardness is meant by digits and letters HR with the indicating of a scale A, B, C or F (for example, 60 HRC, 80 HRA and etc.).

At hardness gauging the indenter is pressed into metal by two consecutive stressings (fig. 1.6). In the beginning the indenter is preloaded with $P_0=98$ N (10 kgf) which apply to an exception of influence on gauging result of an elastic strain, a surface finish and local surface damages. The indenter under load P_0 intrudes on distance h_0

from a material surface. On such depth the initial measuring surface is. Then is affixed the basic load P_1 so that the total load makes $P=P_0+P_1$. Under the influence of a total load the indenter will take root into a material on depth h_1 from an initial measuring surface of the sample. Then load P_1 after some soaking is took off and thus indenter **because of** elasticity of the examined material will be displaced up and will stop on distance « e » from an initial measuring surface that corresponds to residual depth of indenter permeation.

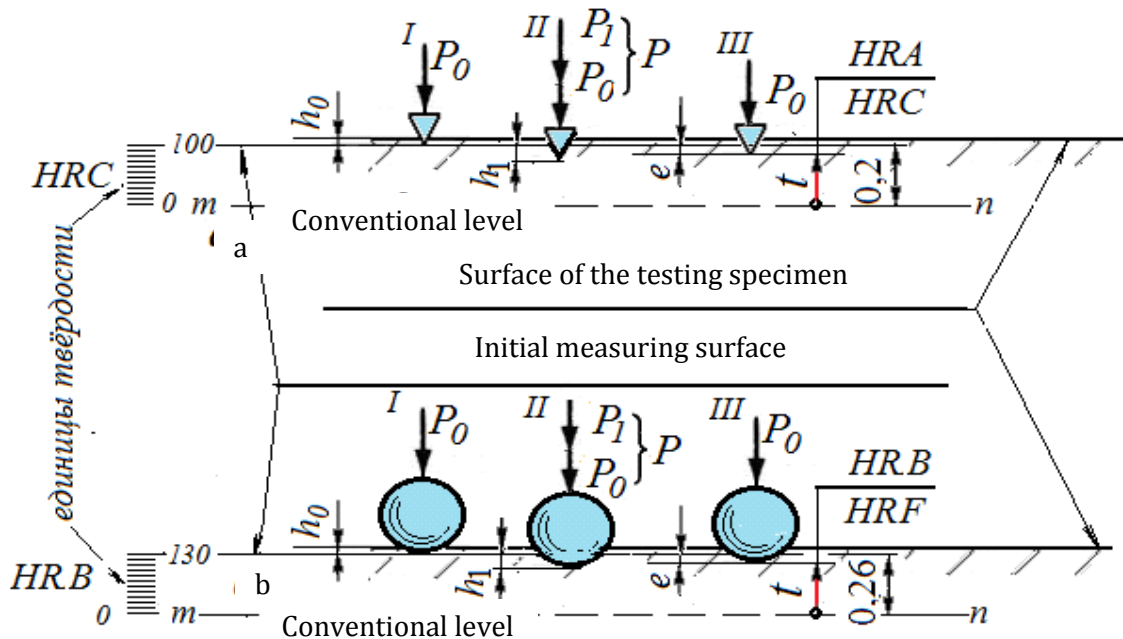
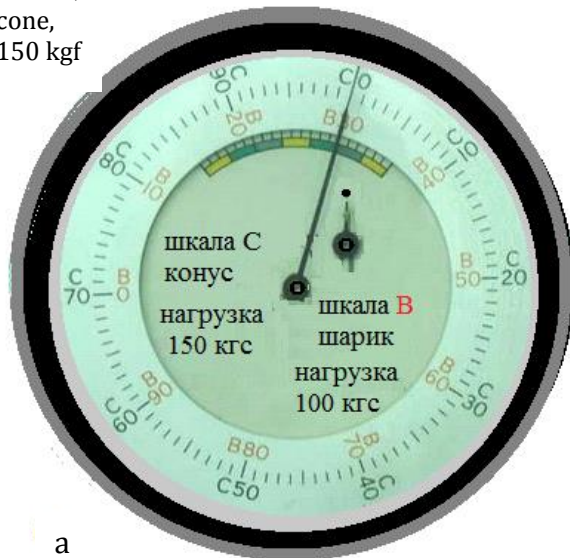


Fig. 1.6. Circuits of introduction of diamond (a) and spherical (b) indenters during Rockwell hardness gauging: I - a preliminary stressing; II - a final stressing; III - gauging

It is considered that Rockwell hardness is the distance t in standard units on which indenter at gauging has not reached conventional level. Conventional level mn is located, depending on the indenter shape, on distance equal 0,2 or 0,26 mm from an initial measuring surface (fig. 1.6).

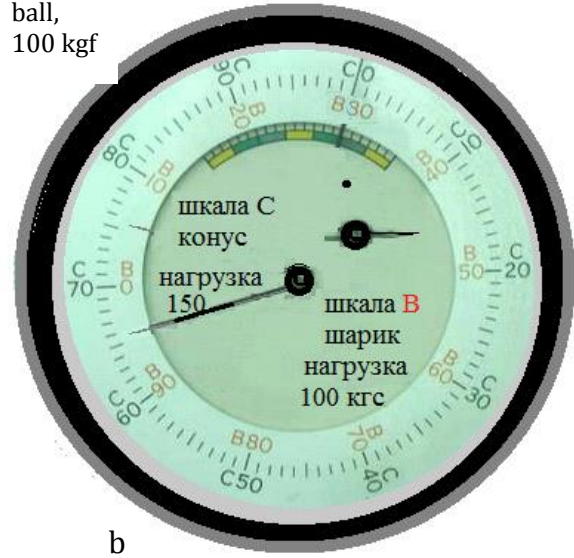
All displacements of indenter at hardness gauging are fixed by the hour type indicator on which circular scale define a hardness value (fig. 1.7). The indicator has two scales - black and red. On a black scale there is measured hardness of firm materials in HRA and HRC units, and on red – hardness of soft materials is measured in HRB and HRF units.

Scale C,
cone,
150 kgf



a

Scale B,
ball,
100 kgf



b

Fig. 1.7. The indicator of a Rockwell press **TK-2** with clock-face hardness scale: *a* - position of arrows after a preliminary stressing when the small arrow coincides with a point, and big - with scale zero; *b* – position of the arrows after material testing

The scales graduating marks is identical and correspond to a hundredth part of a scale circle and is equal 0,002 mm of depth of indenter impression. Thus the black scale will have at testing with a conic tip $0,2/0,002=100$ divisions, and at testing by a spherical tip (a red scale) - $0,26/0,002 = 130$ divisions.

Hardness number is defined under formulas:

- on black scale HRC (HRA) = $t = 100 - e/0,002$;
- on red scale HRB (HRF) = $t = 130 - e/0,002$.

Rockwell hardness unit is dimensionless magnitude counting in standard units and also corresponds to indenter axial displacement at 0,002 mm. On a scale C there is usually measured hardness of tempered steels at load $P = 150$ kgf. On a scale A spend gauging of thin parts or layers. This scale completely coincides with a scale C, but gaugings are carried out at smaller load $P = 60$ kgf and smaller depth of permeation. At gauging by a steel ball on a scale B (a load of 100 kgf) hardness gauging is carried out at its moderate values (for example, steels after annealing), and on scale F (a load of 60 kgf) hardness of nonferrous metals and alloys is defined. A choice of a load and indenter type for a material hardness test via Rockwell is made according to actual standards. The distance between two prints centers should be not less

than 3 mm.

Virtues of a method of hardness gauging via Rockwell are: 1) possibility of hardness gauging in a wide range both very firm and rather soft materials; 2) prints from a cone and a ball are so small that it is possible to carry out testing on already finished details; 3) testing occupies not enough time, and hardness number is read immediately on a device scale.

Rockwell hardness values can be counted on re-counted to Brinell by means of empirical conversion tables.

3.3. Impact resistance definition [GOST 9454 - 84]

Important characteristic of material reliability is the ductility. *The ductility* is ability of a material to collapse resistance at dynamic loads. The materials demanding the big amount of energy to a breaking (collapse) are called *ductile*. Ductility of a material can be fixed via test data of impact bending or by the form of a breaking.

The test method on impact bending is grounded on collapse of notched test specimens which serves as the concentrator of stresses. Samples can have concentrators of three aspects: an incision in the form of U character with radius of concentrator $R=1$ mm; an acute incision in the form of the V character with $R=0,25$ mm and with fracture T (fig. 1.8). Samples with U-shaped concentrators (samples of Sharpi) apply at an acceptance inspection of metals. At testing of metals of responsible assignment it is recommended to apply specimens of Mesnager with a V-shape incision (details of flying machines, vehicles, capacities of a high pressure and etc.). Samples with T flaw are intended for especially responsible constructions and details where resistance to flaw development has a primary value. For testing the ends of the sample fix horizontally on supports of pendulum impact testing machine with incision side directed opposite to pendulum blade impact. Before testing the pendulum of the impact machine is lifted up to the home position to height H (fig. 1.9) and keep it in this position by a trigger. The floating lever liberated from a trigger, drops down, destroys the sample and due to inertia rises to height h . On a scale of pendulum impact machine the total work of impact K , spent for specimen destruction, is defined or is calculated under the formula

$$K = P (H - h) = mgl (\cos \beta - \cos \alpha), \text{ J (kgf}\cdot\text{m)}. \quad (1.8)$$

Then this work is divided onto a cross-section of the sample in a place of incision F_0 (use standard bars with $F_0=0,8 \text{ cm}^2$ is more often).

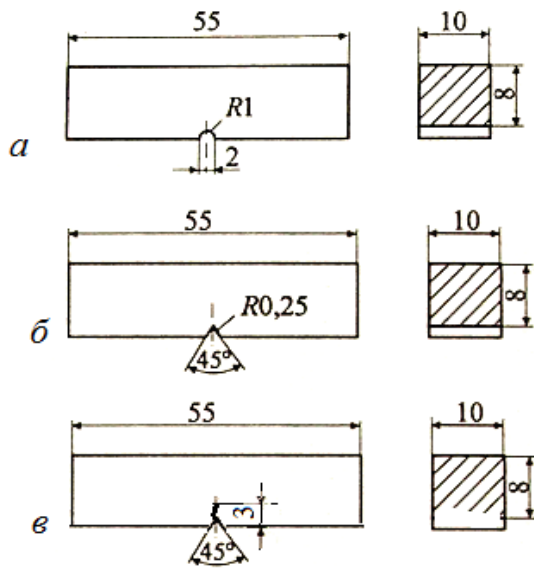


Fig. 1.8. The basic types of ductility test specimens with a various aspect of incisions:
 a - U-shaped; b - V-shaped;
 c - T-shaped with the initiated flaw

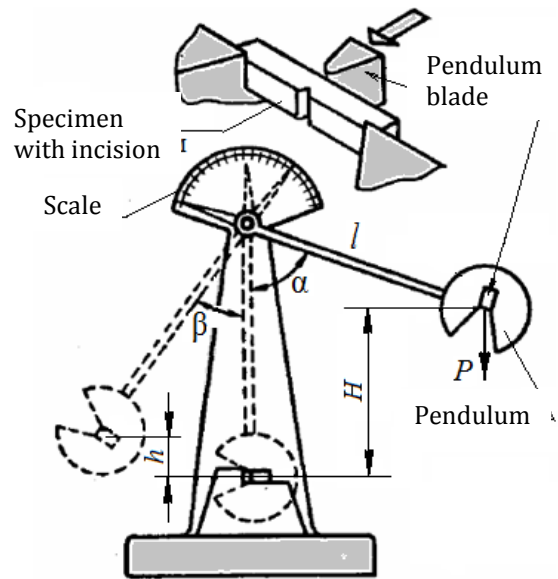


Fig. 1.9. The impact test circuit on pendulum testing machine MK-30:
 α - a lead angle; β - a flight angle; H and h - lead height and flight height of floating lever accordingly; l - length of a floating lever

Obtained value $KC = K/F_0, \text{ J/cm}^2$ ($\text{kgf} \times \text{m/cm}^2$) is called as specific work of collapse or *impact resistance*. The impact strength of a material is more, the ability to collapse resist under the influence of impact loads is better. Total magnitude of work of collapse develops of two components: work for flaw origin A_o and work for flaw spreading A_s , i.e. $K=A_o+A_s$.

Reliability of a material is defined by flaw spreading work. The more A_s , the is less possibility of sudden fragile collapse. For definition of A_s the samples with a fatigue flaw (concentrator) which create on the special vibrator is used. At collapse of such sample the work is expended only on flaw spreading. After a impact test and definition of A_s it is necessary to analyze a fracture aspect. At good material with high enough value of A_s the fracture should be ductile with filamentary or dimple aspect.

Depending on the shape of an incision the impact strength is meant

KCU, KCV or KCT. If first two KC characters mean an impact strength symbol, the third character - a concentrator aspect. Then after characters the following first digit displays the maximum energy of floating lever impact (J), the second - depth of the concentrator and the third - width of the sample (for example, *KCT 150/3/7,5*).

Digits in an impact strength designation are not presented, if at definition of impact work were used the impactor with the maximum energy of floating lever blow 30 J, and samples with the sizes 10x10 mm, with depth of the concentrator of 2 mm for samples with both U and V concentrators and 3 mm - for samples with the T-shaped concentrator.

Deficiency of impact strength as strength characteristic, that it is not used in calculations of details strength. However the practical value of this characteristic is great enough, because it allows evaluating ability of a material to collapse resist.

Having obtained numerical values of mechanical properties as a result of mechanical trials, it is possible to state the technical estimation of strength of metal. As structurally strength material it is possible to consider only such material which in exploitation conditions possesses an optimum combination of strength, plasticity and ductility.

4. A practical part

4.1. Security measures at operation execution

Before to start execution of laboratory work, it is necessary:

- 1) to pass instructing of safety engineering (SE) and fire safety (FS) and to undersign the control sheet;
- 2) only those students who have taken place examination on FS and have putted their signature in control sheet of student instructing registration are supposed to execution of laboratory operation;
- 3) laboratory operation is executed in educational laboratory where electrogears and office equipment corresponding to requirements of SE are placed.

4.2. The equipment and materials

- slide gauge;
- samples from a steel 10, steel 45 and steel Y8 for hardness test;
- samples for tensile test (samples for tension of various aspects

before and after a break);

- hardness meter of Brinell TIII-2M;
- hardness meter Rockwell TK-2;
- educational movies about test methods of materials on tensile and impact strength.

4.3. Sequence of execution of operation

1. To familiarize with standard samples on a tension and impact strength. To look at videoclips, paying attention to the construction, mode of functioning of testing machines, a technique of carrying out of trials, definitions of strength and plastic characteristics, impact strength of materials.

2. To define relative elongation δ and a contraction ratio ψ (at $l_0 = 25$ mm) via the samples exposed a tension.

3. To study by means of the educational master (teacher) the construction of used hardness meters.

4. To carry out hardness gaugings via three samples of annealed and tempered steel with a various carbon content by means of Brinell and Rockwell methods, having selected test specifications. Diameter of a print for a method of Brinell is measured in two orthogonally related directions and define as an arithmetical average.

5. To measure hardness of duralumin via scale HRF of a Rockwell hardness meter. At gauging via a method of Rockwell iterate trials on one sample 4 times, accepting an average from three last. For comparison of results it is necessary to translate all obtained data a scale of Brinell HB.

6. To calculate tensile strength based on a hardness value, using the empirical formula for a material being measured.

7. Experimental and calculated data should be putted in tab. 1.1 to make the conclusion about influence of carbon on strength and hardness of a steel.

Table 1.1

Results of hardness tests

| Material | Hardness measuring method | Brinell hardness HB | σ_B , MPa |
|--------------------------|---------------------------|---------------------|------------------|
| Low-carbon steel (10) | | | |
| Medium-carbon steel (45) | | | |
| High-carbon steel (Y8) | | | |
| Tempered steel (45) | | | |
| Duralumin | | | |

8. By results of trials to draw graphs of dependence of hardness and strength of a steel in annealed condition from carbon contents in percents.

9. To make the written record of lab.

Criteria of productivity of operation

Laboratory operation is considered as being executed in the event that the student:

- 1) has learnt to analyze correctly experimental data of definition of the basic mechanical properties of materials;
- 2) results of the performed operation are presented accordingly with requirements to record drawing up;
- 3) has correctly answered all control questions.

Requirements to the record contents and drawing up

The record is made with use of an electronic variant of the description of this laboratory work by carrying over of fragments of the text and necessary drawings to the text of the record and the further editing. This part of the record is made out before occupations at preparation for laboratory researches. On laboratory work the record is made out definitively by importation of calculations and by writing of summaries. The record should have volume no more than 3 ... 4 pages. After definitive drawing up of the record the student protects lab to the teacher by the answer of control questions.

Control questions

1. What mechanical characteristics can be defined by trial of materials on a tension?
2. What samples are applied to tensile test?
3. What dependence is figured by the primary tension chart, recorded by a testing machine on a tension?
4. What typical charts meet in practice when tension of metals is?
5. How due to the tension chart to define σ_B and σ_T ?
6. What is the variance between a physical and conditional yield point?
7. How to define plasticity characteristics δ and ψ ?
8. What is called as hardness?
9. What is the essence of hardness gauging via Brinell?
10. What values of diameters are used for spherical indenters at hardness test via Brinell and what conditions they are selected from?
11. What gear is used for gauging of print diameter at hardness test via Brinell and how to realize the gauging?
12. How Brinell hardness is designated?
13. What are dependences between hardness and strength of a material on a tension exist?
14. What is Rockwell hardness gauging consists of?
15. What types of tips and loads are applied at trial of materials onto hardness via method of Rockwell?
16. In what cases scales *A*, *C* at hardness test via Rockwell are used? In what cases scales *B*, *F*? How to adjust a gear on these scales?
17. How the Rockwell hardness measured on scales *A*, *B*, *C* and *F* is designated?
18. Why smaller depth of permeation of a tip corresponds to higher hardness of a material at hardness gauging via Rockwell?
19. What conditions can be observed at Rockwell hardness gauging (minimum distances between prints centers and from edge of samples, minimum width of samples)?
20. On what scales (red or black) hardness reference at impression of a diamond tip and a steel ball accordingly is performed?
21. What is the method of definition of impact strength consists of?
22. What property of structural materials is called as ductility and what materials are named ductile?
23. What are methods due to it is possible to fix ductility of a

material?

24. What aspects of incisions are used in test specimens on impact strength and what is its role?

25. How the total work expended on collapse of the sample is defined and what two parts it consists of?

26. What is variance between the total work expended on collapse and specific work?

27. Whether is there a variance between specific work of collapse and impact strength?

28. How impact strength of materials is designated?

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ALLOYED STEELS AND ITS HARDNESS PENETRATION

Introduction

Alloyed steel widely are used as constructional materials in mechanical engineering. Their application as an exchange of less strong carbon steels allows reducing metal consumption of designs considerably. Properties of alloyed steels are defined by type of solid solution, its structure, the grain size, distribution in volume of the second phase and dislocation structure. However it is necessary to know that properties of alloyed steels fully are shown only after heat treatment when the necessary structure providing the required properties is formed. Besides the alloyed steels are more expensive than usual structural carbon steels. Therefore its choice has to be comprehensively reasonable.

In this work the alloyed structural steels of perlitic, martensitic and austenitic classes and also the influence of the alloying elements on their hardness penetration are considered.

When performing laboratory work the student professional competences are formed – ability to distinguish the alloyed steels by structure, to distinguish they by application and properties.

Having performed laboratory work, the student has to:

- **to know:**

- marking and classification of alloyed steels;
- gradess and appointment of the main groups of constructional alloyed steels;

- **to be able:**

- began to distinguish alloyed steels belonging to various structural classes by structure;
- to define influence of the alloying elements on a hardness penetration;

- **to have skills** of carrying out the microstructural analysis of alloyed steels.

LABORATORY WORK №2

ALLOYED STEELS AND ITS HARDNESS PENETRATION

1. The work purpose – increasing student knowledge about alloyed steels and their hardness penetration.

2. Work tasks:

- to study marking, classification and structure of alloyed steels;
- to acquire regularities of influence of the alloying elements on structure and properties of steels; to illustrate action of these regularities on the most widespread grades of heat treatable and carburizing alloyed steels; to consider types of the microstructures which are formed when alloying.
- to establish the influence of the alloying elements on a steels hardness penetration.

3. Theoretical part

In process of technology progress the requirements to steels continuously raise and plain carbonaceous structural steels not always provide a necessary complex of properties. Therefore in the industry alloyed steel are widely applied to production of details of responsible appointment.

Steel is called *alloyed* if its structure contains specially added elements or the increased amounts of constantly present manganese or silicon (on 0,9 ... 1,0% and above).

The most widespread alloying elements are: chrome (Cr), manganese (Mn), nickel (Ni), silicon (Si), molybdenum (Mo), tungsten (W), vanadium (V), titanium (Ti), zirconium (Zr), niobium (Nb), boron (B), copper (Cu), aluminum (Al), nitrogen (N), rare-earth elements (Sc scandium, Ce cerium, Y yttrium, Nd neodymium, etc.).

3.1. Marking of alloyed steels

For designation of the standard grades of alloyed steels the alphanumeric system of marking is accepted. For this purpose each alloying element is designated by a letter of the Russian alphabet: А–N (in the middle of grade), Б –Nb, В –W, Г – Mn, Д – Cu, Е– Se (selenium), К – Co, М – Mo, Н – Ni, П – P, Р – B, С – Si, Т –Ti, Ф –

V, X – Cr, Ц – Zr, Ю – Al, etc.

The first digits in designations of steel show the average content of carbon:

1) in structural steels and steels with special properties – in the 100-th shares of %;

2) in tool steels – in the tenth shares of %. At the content of carbon ~ 1% the digit is not put.

The first digit is followed by the letters designating the alloying element (AE). Digits behind letters specify the content of AE in %.

At the end of grades designation of quality structural steels with the small content of harmful impurity (sulfurs <0,03% and phosphorus <0,03%) the letter "A" is put, and at the end of grades designation of especially high-quality alloyed steels – a letter "III".

For example, steel 30XГCA – high-quality steel, has the following structure: C = 0,3%, Cr ≈ 1,0%, Mn ≈ 1,0%, Si ≈ 1,0%; steel 9XC – tool steel, qualitative, has the following structure: C = 0,9%; Cr = 0,95 ... 1,25%; Si = 1,2 ... 1,6%. Thus, the lack of digits after a letter designating AE shows its approximate contents near or less than 1%.

However it should be noted that there are elements which are a part of alloyed steels in a small amount – in the tenth and 100-th shares of %: for example, B up to 0,005%; Ti and Nb up to 0,1%. The content of these elements is also not specified in steel grade.

3.2. Classification of alloyed steels

Alloyed steel classify by the following features: 1) by application; 2) by the chemical composition; 3) by quantity of the alloying elements; 4) by structure.

By application alloyed steels, as well as carbonaceous, share on constructional, tool and steels with special characteristics. Low-carbon (up to 0,3% C) and medium-carbon steels (0,3 ... 0,5% C) applied to production of machine details is treated *to group of structural* (GOST 4543-71) Structural steels in turn can be carburizing, heat-treatable, spring and bow-spring, etc.

High carbon steels belong *to group of tool* (GOST 5950-2000). They are applied to production of the cutting, stamping, measuring tools. wear-proof steels, heat resisting, corrosion-resistant steels and etc. belong *to steels with special characteristics group*.

Classification by composition. According to the name of the contained alloying elements the steel is called: *chromic* (15X, 15XA, 30XPA, 40X, etc.), *manganic* (15Г, 20U, 40ГР, etc.), *chrome-nickel* (12XH, 12XH3A, 20XH, 20XHP and etc.), *chrome-silicium-manganese* (20XГC, 30XГC, 30XГCH, etc.), etc.

By quantity of the alloying elements (AE) distinguish *low - alloyed* steels, the containing no more than 2,5% of AE, *medium-alloyed steels* – from 2,5 to 10% of AE and *high-alloyed* steels, containing more than 10% of AE.

Classification of alloyed steels by structure. At classification by structure structure features in the annealed and normalized states are considered. **By structure in the annealed (equilibrium) state** alloyed steel are subdivided on: 1) *hypo-eutectoid steels* with structure of perlite and the excess alloyed ferrite; 2) *eutectoid* with perlitic structure; 3) *hyper-eutectoid* with structure of perlite and excess (secondary) carbides; 4) *ledeburitic* (carbide) steels, having in structure the excess carbides emitted at crystallization from a liquid phase. In these steels in a cast state carbides together with austenite form an eutectic – ledeburite which at further processing by deformation (forging, rolling, etc.) breaks into the isolated particles of carbides and austenite. Except listed there are distinguished also ferritic and mixed classes of alloyed steels.

By structure in the normalized state alloyed steel are divided onto three main classes: *a – perlitic*, *b – martensitic* and *c – austenitic*. The class of steel can be determined by charts of isothermal disintegration of austenite in dependence on the content of carbon and the alloying elements (fig. 4.1). Charts show that in process of increase in content of the alloying elements stability of the overcooled austenite increases in perlitic area (curves are displaced to the right), and the temperature area of martensitic transformation goes down. In fig. 4.1 lines which inclination characterizes the speed of cooling ($V_{\text{oxл}}$) of samples of steel on quiet air (normalization) are also drawn.

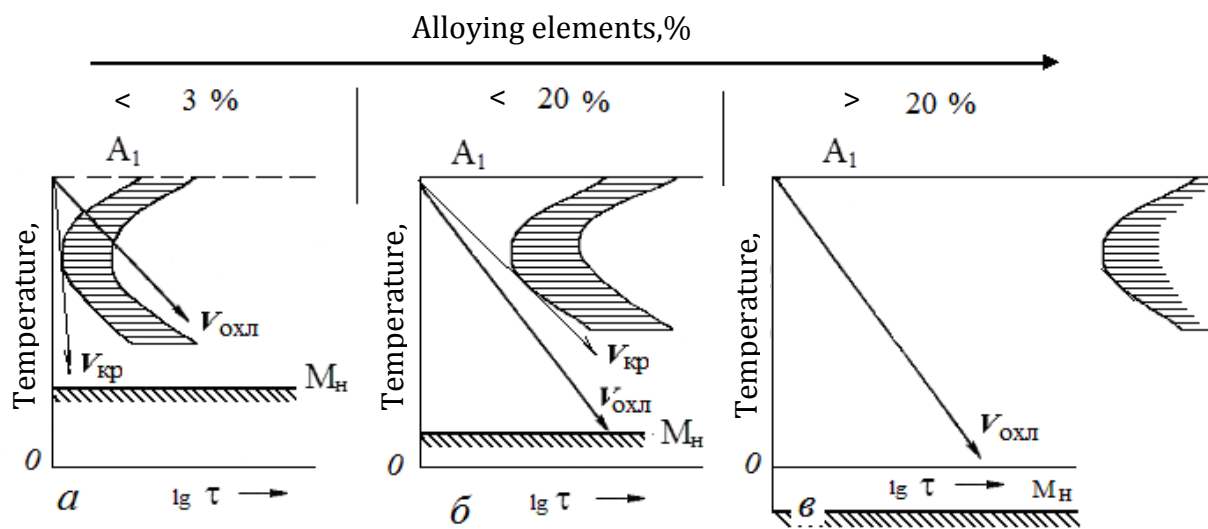


Fig. 4.1. The chart of isothermal transformation of the overcooled austenite for steels of perlitic, martensitic and austenitic classes; ($V_{\text{oxл}}$ – the characteristic speed of cooling in air)

Steels of a perlitic class. The majority of alloyed steels belong to the perlitic class, generally it is low-alloyed steels (up to 3% of AE) with any amount of carbon. For them the line of speed of cooling in air crosses area of perlitic disintegration (fig. 4.1, a) that means disintegration of austenite with formation of ferrite-cementite mixes – perlite, sorbite or the troostit. Steels of grades 40X, 30XГCA, 18XГT, etc. belong to this class (GOST 4543-71) and also tool steel of grades X, 9XC, XБГ, 15XM, etc. (GOST 5950-2000). In a microstructure of a perlitic class steels depending on the content of carbon and the alloying elements the excess phases – ferrite in hypoeutectoid steels (fig. 4.2) or cementite in hypereutectoid steels – can be.

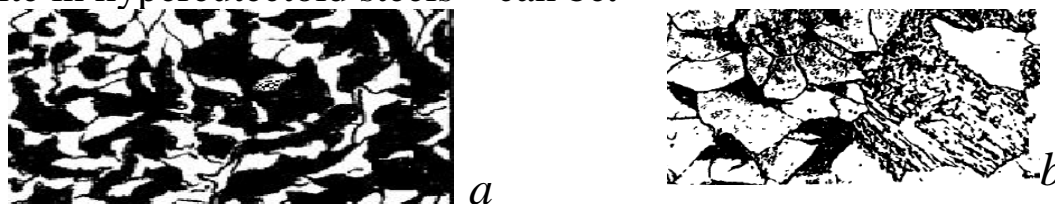


Fig. 4.2. A microstructure of hypoeutectoid steels of a perlitic class after annealing: a – steel 40X; b – steel 15XM; ferrite (light grains) and perlite (rest grains)

Via structure of steel it is possible to establish its properties. For example, the steel having perlitic structure has the small hardness and high plasticity, and the steel having martensitic structure after tempering is firm and fragile.

Steel of a martensitic class contain the considerable bigger quantity of the alloying elements (3 ... 20%). Treat to this class there are steels 15X5M, 12X8, 12X18BΦ, 20X13, 30X13, 40X13, 20X8BJI, 10X9MΦБ, 18XH4BA, etc. They differ in high mechanical properties and are applied to production of details of responsible appointment. Their area of perlitic disintegration is considerably shifted to the right (see fig. 4.1, *b*) and the line characterizing the speed of cooling does not cross a curve of the beginning of austenite disintegration. Austenite overcools without disintegration up to the temperatures of martensitic transformation of M_H here, and at further cooling there is a formation of martensite.

In fig. 4.3 the microstructure of martensitic class structural steel 18XH4BA after normalization is shown. This steel is applied to production of bent shafts, shafts of reducers, gear wheels. After tempering in air and a high drawing steel has quite high mechanical properties: $\sigma_B = 1000$ MPa, $\delta = 10\%$ and $KCU = 1,2$ of MJ/m^2 . Its structure after normalization is martensite.



Fig. 4.3. A steel 18XH4BA microstructure after normalization: martensite (dark plates) and residual austenite

Among the steels a martensitic class broad application is found for steel with containing about 13% of chrome and to 0,4% of carbon. At the content of chrome more than 12,5% steel becomes corrosion-resistant because of education on a surface of a protective oxidic film of Cr_2O_3 , reliably protecting metal from oxidation in sea water, in nitric and sulfuric acids and in some other mediums. Steel of this group well resist to atmospheric corrosion and corrosion in the environment of water vapor, i.e. they are corrosion-proof steels. Various details of machines demanding the increased durability and corrosion resistance and also some types of the tool are made of them. Hardening is reached by tempering in oil or in air till structure of martensite is. The drawing depending on appointment can be high (for details of machines) or low

(for the tool). Steel of a martensitic class differ in the high hardness, low plasticity at the room temperature and are badly processed by cutting.

Steels of an austenitic class - high-alloyed steel, containing a large amount of nickel or manganese (not less than 10% of each element) in the structure and the chromium which lead to a bigger shift of area of perlitic transformation also at the same time reduce a martensitic point of M_H , transferring it to the area of negative temperatures (see fig. 4.1, c).

Steels of an austenitic class - corrosion-resistant chrome-nickel steel of grades 04X18H10, 08X18H10T, 12X18H10T in accordance with GOST 5949-75, chrome-manganese-nickel (10H14G14N4T), chrome-nickel-molybdenum (10X17H13M2T), heat resisting steel of grades 40X14H14B2M, 12X14H16B in accordance with GOST 5632-72, etc.

At these steels with structure of uniform austenite the largest resistance is shown to corrosion. They also have the best technological properties in comparison with chromic stainless steels, welding better, keep durability to more high temperatures, are less inclined to growth of grain when heating and do not lose plasticity at low temperatures. Austenitic steels are strengthening with cold plastic deformation that causes effect of a peening. For reduction of scarce nickel a part of it is replaced with manganese (steel 40X14Г14Т) or nitrogen (steel 10X14АГ15).

Mechanical properties of all steels in this class are close: $\sigma_B = 500 \dots 550$ MPa; $\sigma_{0,2} = 150 \dots 240$ MPa; $\delta = 40 \dots 45\%$; KCU = 2 ... 3 MJ/m²; hardness 200 ... 250 HB.

In fig. 4.4 the microstructure of austenitic steel 12X18H9T is shown. This steel is corrosion-proof as the content of chrome in it about 18%. It is applied to production of various equipment in the chemical, oil and food industry.

Steel 12X18H9T is applied more often in cast state (a letter Л designation at the end - 12X18H9ТЛ), and more rare – in a hot-rolled state. The structure of steel after casting consists of austenite and excess carbides which are emitted on borders of grains (fig. 4.4, a) that reduces durability and ductility of steel. For improvement of properties cast products subject to the tempering consisting in heating till 1050 ... 1100°C with the subsequent cooling in water. At such high-temperature heating carbides are dissolved, and steel after tempering acquires steadier austenitic structure (fig. 4.4, b) that provides the highest

mechanical ($\sigma_B = 600$ MPa, $\delta=35 \dots 55\%$.) and corrosion-resistant properties.

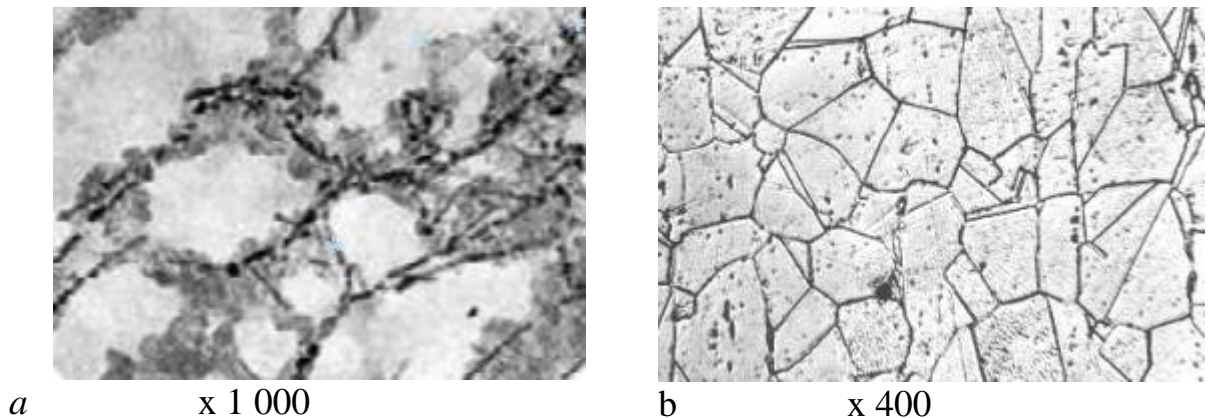


Fig. 4.4. A steel 12X18H9Tl microstructure after: *a* – casting; *b* – tempering of cast steel from 1100 °C (austenite grains with doubles)

Steels of an austenitic class – not magnetic, therefore they are used in electrical equipment and other fields of the industry for production of not magnetic details with the increased durability. In aircraft-engine manufacturing it is applied to production of collectors and exhaust branch pipes.

Steels with the small content of carbon (up to 0,15%) and with chrome in number of not less than 12% or a large number of other ferrite-forming AE (Al, V, Mo, Si, Ti, W, Nb, Zr) are belong to *the ferritic class*. Steel acquires purely ferritic structure. These steels capable to keep the structure at very high temperatures, they are cheap enough, but have tendency to integration of grain and intercrystalline corrosion because of chrome presence. Some ferritic chromic steels: 08X13, 12X17, 08X25T, 15X28, 10X13H3, 12X17H2, etc.

Treating a **ledeburite** or **carbide class** there are highly - alloyed steels with high content of carbon (more than 0,8%) and carbide-forming elements (Fe, Mn, Cr, Mo, W, Nb, Ti). Steel of a ledeburite class apply at tools. The most typical steel of this class is high-speed steel.

Distinguish also austenitic-ferritic steels, an austenitic-martensitic steels.

Austenitic-ferritic steels have an optimum complex of properties at approximately equal ratio between austenite and ferrite. They contain less than 8% of nickel and after tempering since 1000 ... 1100 °C the optimum structure and properties turn out. For example, steel 08X22H6T, 08X21H6M2T, 08X18Г8M2T.

Austenitic-martensitic steels, in comparison with austenitic steels, have higher durability which is defined by their structural state. When the structure steels contains 70 ... 90% of martensite and 30 ... 10% of austenite, steel have $\sigma_{0,2} = 700 \dots 1000$ MPa, $\sigma_B = 1100 \dots 1400$ MPa. Steel of this class contain less than 0,1% of carbon and Al, Ti, Be, Mo (having these alloying elements the solubility in martensite is much less than their solubility in austenite) and are in addition alloyed. Examples of grades of austenitic-martensitic steels and their heat treatment: 07X16H6, 09X15H8Ю (tempering 975 ... 1000 °C in water or air, processing by cold at -70 °C, 2 h, aging 350 ... 450 °C, 12 h), 08X17H5M3 (normalization 950 °C, processing by cold at -70 °C, 2 h, aging 350 ... 450 °C, 4 h).

3.3. Constructional machine-building alloyed steels

Depending on the content of carbon constructional machine-building alloyed steels subdivide on cemented, toughened, spring and bow-spring, bearing, high-strength steels, etc. Here is considered cemented and toughened steels.

3.3.1. The alloyed cemented structural steels. They are low-carbon, containing less than 0,2% C and are poorly strengthened by tempering. They get the high hardness and wear resistance of a blanket after cementation, tempering and a low drawing and at the same time keep ductile and rather strong core. They are applied to production of details like piston pins, cam-shafts, gear wheels, etc., working under the influence of bending and torques, dynamic and sign-variable loadings in the conditions of friction and wear. The core of such details is not treated to action of big loadings and therefore the through hardness penetration is not always necessary, moreover, the ductile, not tempered for martensite core is required. At such loadings it is important to provide high contact endurance. Thanks to cementation the blanket is saturated with carbon to concentration 0,8 ... 1,2% and also have structure of hypereutectoid steel with the perlitnic grains surrounded with a grid of the cementite (fig. 4.5).

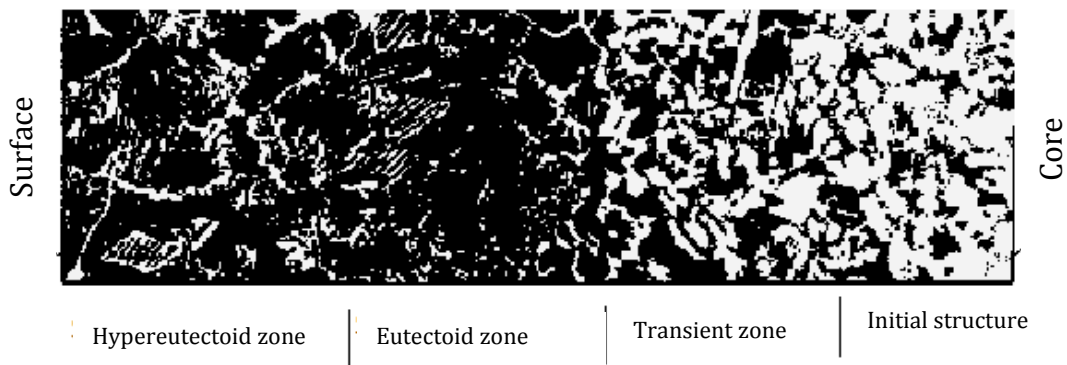


Fig. 4.5. A microstructure of a blanket of the cemented steel, $\times 200$

Towards a core concentration of carbon decreases and the hypereutectoid zone gradually passes into eutectoid and transitional zones. The eutectoid zone contains $\approx 0,8\%$ C, it has structure of perlite. In a transitional zone the amount of ferrite gradually increases as approaching to a core.

Thickness of the cemented layer is total thickness of hypereutectoid, eutectoid and half of a transitional zone (see fig. 4.5). High content of carbon of a blanket allows to subject these steels tempering and after the low drawing to receive the high hardness and contact endurance of a surface. The core is not tempered and remains soft. As the alloying elements in cemented steel Cr (1 ... 7%), Ni (1 ... 4%), Mn (to 1,5%) and it is a little Mo (0,2 ... 0,4%), W (0,8 ... 1,2%), etc. are used. Let's consider several grades cemented steels.

The chromic low-alloyed steels 12X, 15X, 20X with contents to 1% of Cr. Chrome increases depth of the tempered layer. Additional alloying of these steels with small additives of vanadium (0,1 ... 0,2%) (steel 15X) promotes receiving a fine grain and increases plasticity and ductility. These steels are applied to products of small section, simple in a form, working at the raised loadings (plugs, rollers, axes, cams, piston pins, etc.).

For details of the average sizes working at high specific loadings chromic steels are added with nickel into structure (**chrome-nickel steel 20XH, 12XH3A, 12X2H4A**). In view of deficiency of nickel sometimes it is replaced with manganese, besides a small amount of the titan (0,006 ... 0,12%) is added for grain crushing (**chrome and manganese steels 18XGT, 30XGT**).

Chrome-nickel steel can be alloyed with Mo (up to 0,4%) or W ($\sim 1\%$) also in addition. In this case high-alloyed cemented steel of grades 18X2H4MA or 18X2H4BA turn out. They have stable austenitic structure, a good hardness penetration and are the most high-strength of

all cemented steels. They are applied to large heavy-duty details like the cogwheels, axes, shafts working in the conditions of dynamic loading.

After heat treatment (tempering + a low drawing) the structure of a blanket of the cemented steel consists of martensite of a drawing (fig. 4.6) and has hardness 50 ... 53 HRC.

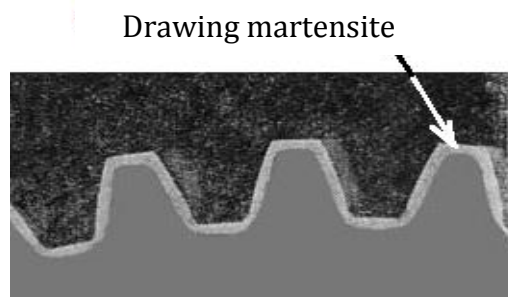


Fig. 4.6. A cogwheel after cementation, tempering and a drawing

3.3.2. The toughened alloyed structural steels. *Toughened* (medium-carbon) steel contain (0,3 ... 0,5% C) and up to 5% of various AE. Steel of this group are exposed to heat treatment – toughening, consisting in tempering in oil with the subsequent high drawing at 550 ... 650 °C for structure of granular sorbite. As a result of such processing these steels possess a combination of high durability and plasticity, providing high reliability of products in work at influence of sign-variable and dynamic loadings. Therefore toughened steels are the most widespread and are applied, depending on structure and properties, to production of connecting rods, gear wheels, axes, shaft, disks, rotors of turbines and other heavy-duty details.

The main AE in toughened steels, as well as in a case with cemented steels, is chrome with contents within 0,8 ... 1,1%. Content of chrome in steel lowers the critical speed of tempering and raises their hardness penetration. Besides, thanks to the smaller critical speed of tempering alloyed steel are calcinated in less sharp coolers, than water (oil, air) that reduces deformation of products and danger of cracks formation. The steel hardness penetration increases at increase in quantity of the alloying elements.

Besides, the toughened structural steels is alloyed with Ni, Mo, Mn, Si, W in such quantities that the total amount of AE did not exceed 3 ... 5%. All listed elements, except Ni, increase steel durability, but at the same time reduce plasticity and impact strength. Nickel the only element that with increase in durability does not reduce plasticity of steel. For crushing of grain also steel can be alloyed by V, Ti, Nb, Zr (totally about 1%).

Let's consider the most widespread grades of toughened (GOST

4543-71) alloyed steels.

Chromic steel 40X, 38XA, 40XC. Thanks to the high durability and rather good hardness penetration these steels is applied to production of bent shafts, cogwheels, axes of rollers, levers, plugs, bolts, nuts. Details from these steels temper in oil from temperature 820 ... 850 °C. Depending on specified requirements the drawing of details is carried out at various temperatures.

Chrome-silicium-manganese steels 30XГCA, 35XГCA. Do not contain the scarce alloying elements. Have high mechanical properties. Well weld and replace chrome-nickel and chrome-molybdenum steels.

Chrome-nickel steels (40XH, 45 XH). They have the high durability and plasticity after heat treatment and well resist shock loadings. Durability of steel is provided by chrome, and plasticity – by nickel. Chrome-nickel steels are calcinated on very depth in comparison not only with carbonaceous, but also another alloyed steels. Specified steels are applied to production of strongly loaded details of responsible appointment – for gear wheels, shafts, etc.

Chrome-nickel-molybdenum steels 38XH3MA, 40XHMA, 40XH2MA, etc. These steels in the toughened state has high durability at good viscosity, high fatigue durability, are deeply calcinated, are applied to production of strongly loaded details working in the conditions of big sign-variable loadings. Toughening is carried out on the mode: tempering with 850 °C in oil, a drawing at 620 °C.

Introduction of the alloying elements allows to increase durability as a result of hardening of ferrite or austenite and also due to formation in a core of more high-strength structures of sorbite, troostite or bainite. Tempering of alloyed steels is made in oil in view of lower critical speed of tempering. It reduces danger of formation of cracks and deformation of products of irregular shape.

3. 4. Definition of steel hardness penetration

Hardness penetration is ability of steel to be tempered on a certain depth. When tempering details their surface and a core are cooled with a different speed. The blanket is cooled quicker as it directly adjoins to the cooling environment; the core is cooled more slowly. Not through hardness penetration of details is explained by it.

Depth of the tempered layer is defined by a point of intersection of lines of critical speed of tempering V_{kp} (the horizontal line) and speeds of

cooling of V_{oxn} and will correspond to thickness of the shaded layer (fig. 4.8).

In practice the hardness penetration is determined by depth of the tempered zone for which conditionally take distance from a surface to a semi-martensitic zone (50% of martensite and 50% of a troostite). It is connected with the fact that experimentally it is simpler to determine border of a semi-martensitic zone by measurement of hardness of steel, than border of purely martensitic and troostitic zones. In layers where the speed of cooling is higher than critical (V_{kp}), the structure of martensite is formed and where it is less critical – the structure of the troostite and sorbite is formed or even the initial structure remains. If in a core the speed of cooling is higher than critical, on all section the structure of martensite is formed and the detail receives a through hardness penetration. At a through hardness penetration all section of a detail gains uniform structure and properties. At small hardness penetration a core of details is not tempered and will have the lowered durability and hardness (fig. 4. 9). For practical assessment of a hardness penetration use a concept of critical diameter. *Critical diameter* D_{kp} is depth of a layer of specimen in which center the semi-martensitic structure is formed when tempering. Such method allows to estimate a hardness penetration not depending on the sizes of details and a way of their cooling.

Hardness of steels with semi-martensitic structure depends generally on the content of carbon and in much smaller degree – on the alloying elements (fig. 4.10). Speed of cooling depends on properties of the hardening environment and strongly influences a hardness penetration. At increase in speed of cooling the size of critical diameter increases. That not to put a hardness penetration into dependence on a way of cooling, the concept of ideal critical diameter is proposed. *Ideal critical diameter* of " D_k " is the such diameter with which the semi-martensitic structure in the center turns out when tempering in ideal hardening liquid, i.e. in liquid which takes away heat with infinitely high speed.

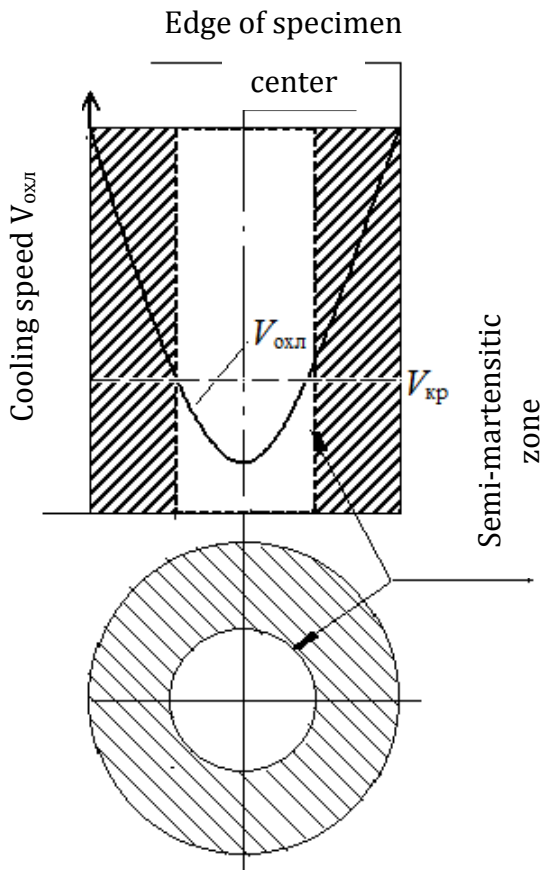
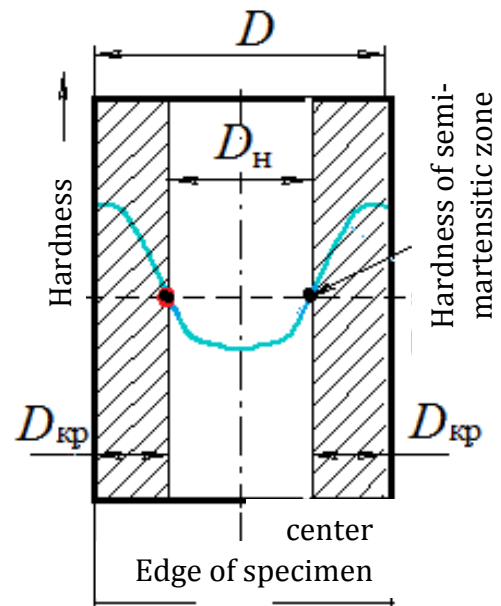


Fig. 4.8. Distribution of speed of cooling (V_{oxl}) on sample section when tempering: the tempered zone with martensitic structure is shaded



D_{kp} – depth of the tempered zone;
 D_n – diameter of not tempered zone

Fig. 4.9. Distribution of hardness on sample section.

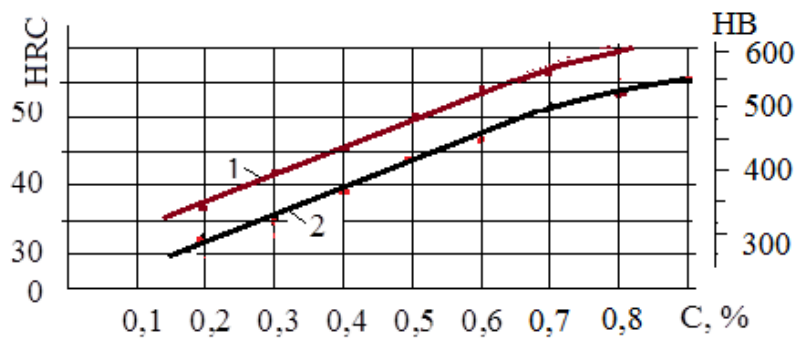


Fig. 4.10. Influence of content of carbon on the hardness of semi-martensitic alloyed (1) and carbonaceous (2) steels

The product sizes also have significant effect on a hardness penetration. At increase in section of a product, since the moment of manifestation of the tempered zone, thickness of the tempered zone

decreases. The hardness penetration can be defined experimentally. For this purpose use the method of face tempering is more often. According to GOST 5657-79 the cylindrical sample with a diameter of 25 mm and 100 mm long is heated to tempering temperature, and then cooled from an end face with a water stream at special installation. After that one side of a sample is ground and measured the hardness (HRC) from an end face through each 2 mm (fig. 4.11, *a*). As in process of distance from an end face the speed of cooling decreases, also hardness with gradual transition from martensitic to perlitic structures will decrease. On the obtained values the schedule of change of hardness on length of a sample L is drawn (fig. 4.11, *b*). For determination of hardness penetration via the obtained schedule it is necessary to carry out the horizontal corresponding to the hardness of a semi-martensitic zone (is determined by fig. 4.10 on the content of carbon specified in steel grade). Projections of points of intersection of a horizontal with schedules of hardness characterize a hardness penetration in mm (L_{kp1} and L_{kp2}). At steels with a bigger hardness penetration (see fig. 4.11, – a curve 2) hardness goes down gradually, and at steels with a small hardness penetration (a curve 1) decrease in hardness happens sharply.

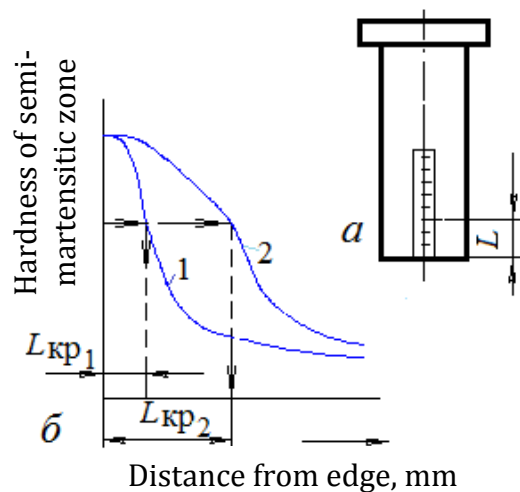


Fig. 4.11. The scheme of measurement of hardness on length of a sample (*a*) and the schedule of change of hardness on it: a curve 1 – for steel with a smaller hardness penetration; a curve 2 – for steel with a bigger hardness penetration

The size L_{kp} characterizes a hardness penetration of steel of this grade. However the objective characteristic of a hardness penetration is **the critical diameter D_{kp}** which allows to determine the extreme section

of the product which is calcinated through in this cooler. Transition from results of face tempering (size L_{kp}) to the size of critical diameter D_{kp} is made according to the nomograph of Blanter.

The shaped line with arrows on the nomograph shows a technique of definition of D_{kp} in size L_{kp} when tempering in various environments.

4. Practical part

Practical part includes: 1) definition of a structural class of alloyed steels; 2) definition of a hardness penetration.

4.1. Security measures when performing work

Before to start execution of laboratory work, it is necessary:

1) to pass instructing of safety engineering (SE) and fire safety (FS) and to undersign the control sheet;

2) only those students who have taken place examination on FS and have putted their signature in control sheet of student instructing registration are supposed to execution of laboratory operation;

3) laboratory operation is executed in educational laboratory where electrogears and office equipment corresponding to requirements of SE are placed.

4.2. Materials and equipment

Collection of the polished sections of alloyed steels:

- steels of a perlitic class: steel 40X, 30XГСА (или 18 ХГТ, X, 9XC, ХГ, etc.);

- steels of a martensitic class: 18XH4BA, 18X2H4BA (or 20X2H4, 20X13, 30X13, 40X9C2);

- steels of an austenitic class: 12X18H10T (or 08X18H10T, 10X14Г14H4T, 12X14H16Б and etc.)

- a set of standard samples for a hardness penetration from carbonaceous steel 40 and alloyed steel 40X.

Equipment:

- installation for end quenching;

- Rockwell's device;

- chamber electric furnace of ЧОЛ type;

- nippers, mittens for providing safety conditions at work with heat treatment samples;

- tool grinding machine for preparation of a surface for

determination of hardness on sample length;

- a metal ruler for a sample length marking for measurement of hardness;
- visual aids.

4.3. Sequence of performance of work

Part 1. To study structural classes of alloyed steels

To establish belonging to a structural class of several steel grades (not less than four).

There can be following set of steel grades:

40X or 30XГCA – template No. 1, 8X2H4BA or 8XH4BA - template No. 2 and 12X18H10T - template No. 3. To establish belonging of these steels to this or that structural class after normalization by an indirect method in such sequence:

1) to heat two samples from the offered steel grades to temperature of normalization and to soak them at this temperature;

2) to take from the furnace by one sample of each steel grade and to put on an asbestos (heat-insulating) sheet for cooling on quiet air (normalization);

3) to temper in water the second samples of each steel grade;

4) to smooth out flat surfaces of all samples via an emery cloth or grinding machine with small intensity of grinding and to measure hardness on Rockwell's device. To enter the corresponding indications of hardness in tab. 4.1.

Table 4.1

Results of measurement of hardness

| No. of sample. | Quenching way | Hardness, HRC | Structural class of steel |
|----------------|---------------|---------------|---------------------------|
| 1 | 2 | 3 | 4 |
| 1 | air | | |
| 1' | water | | |
| 2 | air | | |
| 2' | water | | |
| 3 | air | | |
| 3' | water | | |

5. To use an indirect way to define belonging of each steel grade to this or that class on structure after normalization. The essence of a way consists in the following.

If steel did not become tempered when cooling on air, and became tempered in water (it is corresponded via the hardness of the semi-martensitic tempered layer depending on the content of carbon in the steel presented on fig. 4.10), then, obviously, on air there was a disintegration of austenite in the field of perlitic transformation and the structure of perlitic type was formed (perlite, sorbite or troostite). Means, this steel belongs to a perlitic class.

If steel became tempered both in water and on air (i.e. hardness in both cases corresponds to the hardness of martensite for this content of carbon in it and is approximately identical), i.e. in steel at normalization the martensite was formed, then steel belongs to a martensitic class.

If when cooling both in water and on air steel did not become tempered and has very low hardness, then it is steel of an austenitic class.

Part 2. Definition of a hardness penetration

To experimentally determine a hardness penetration of the carbonaceous and alloyed steel (it is recommended to use for an experiment a combination of steels 40 and 40X or 30 and 30XГСА) by method of end tempering on special installation (fig. 4.12).

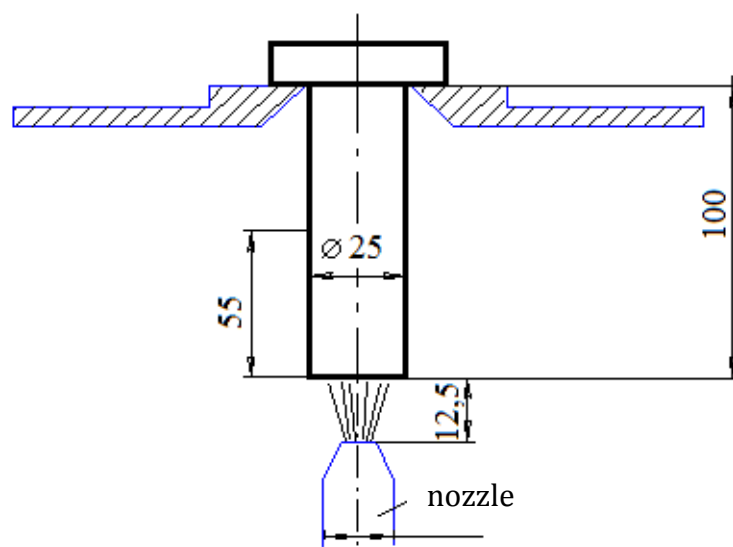


Fig. 4.12. Installation for cooling of samples

The hardness penetration is defined in such sequence:

1) Samples of the standard sizes with a diameter of 25 mm and 100 mm of height on which one end there is a flange; samples are made of carbonaceous steel 40 and of the alloyed steel 40X, and are heated up in the electric furnace at a temperature at 30 ... 50 °C higher than A3 point, are maintained at this temperature about 30 minutes and quickly serially transferred and inserted into a special cell of hardening installation they are cooled with a water stream from an end face. Speed of cooling of samples in different points will be various. At the tempered end face it corresponds to cooling in water, and on the other end – cooling speed on air. Also the structure will change respectively: from martensitic to sorbitic and ferritic-perlitic.

2) after tempering samples are subjected to test for hardness. For this purpose on length of samples a strip 2.3 mm wide is smoothed out and, beginning from an end face, hardness is measured through everyone 1,5 ... 2 mm and is written down it in tab. 4.2

Table 4.2

| Steel grade | Hardness at distance L mm from an end face | | | | | | | | | | Hardness penetration | | |
|-------------|--|---|---|---|----|----|----|----|----|----|----------------------|----------------|--------------|
| | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | D | D_K in water | D_K in oil |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |

Processing of results of observation

1. According to data of tab. 4.3 curve in coordinates hardness – distance from an end face of the tempered sample (see fig. 4.11, *b*) is drawn. Thus, knowing the content of carbon in steel and having measured hardness on a side surface, it's possible to find distance from the tempered end face to a layer with semi-martensitic structure L_{kp} .

2. Due to found L_{kp} distance, using the nomograph of a hardness penetration cooling speed in the center of a sample and actual critical diameter depending on a form of a sample and the environment of cooling are determined. For this purpose on the top scale characterizing distance from the tempered end face to a semi-martensitic zone L the distance "x" which was defined by practical consideration on a standard sample of the studied steel is found. From the found point a perpendicular to a scale "Ideal cooling" is lowered. From a point of

intersection a horizontal line to the left until crossing with the line respective to the set cooling environment (for example, waters) is drawn where find cooling speed in the center of a detail. From a point of intersection the perpendicular falls by a horizontal axis. In a point of intersection there is obtained the critical diameter (the side of a cube) of the body of the set form (in mm) having semi-martensitic structure in the center.

3. Comparison of a hardness penetration of the carbonaceous and alloyed steel is made. To explain the received results.

Criteria of effectiveness of work

Laboratory work is considered as executed if the student:

- 1) correctly answered control questions and questions of test tasks;
- 2) learned to distinguish alloyed steel by their marking, composition and structure;
- 3) gained practical skills of hardness penetration definition and knowledge of influence of the alloying elements on hardness penetration.

Requirements for drawing up and contents of the report

1. Title, purpose and tasks of work.
2. Classification of alloyed steels and their marking
3. The chart of isothermal transformation of the overcooled austenite for various structural class alloyed steels
4. Some basic concepts (definitions of hardness penetration, distribution of structures on the section of the tempered detail – martensitic and semi-martensitic zones, influence of various factors on a hardness penetration, etc.).
5. Results of measurements (the table of measurements of hardness from distance from an end face of the tempered sample; determination of diameter having semi-martensitic structure in the center).
6. Conclusions about steel hardness penetration.

Control questions

1. What steel is called alloyed?
2. At what content of Mn and Si do they become the alloying elements, but not constant impurity in steels?
3. What letters of the Russian alphabet designate the alloying elements?

4. How grades of alloyed steels are designated? To describe steel 12X18H10T grade.
5. How are classified steel by equilibrium structure?
6. Into what structural classes are divided alloyed steel in the normalized state? Explain, using C – shaped curves.
7. What steels belong to the martensitic class?
8. What structure is formed after heating with the subsequent cooling on air in steels of a martensitic class?
9. What steels belong to the austenitic class?
10. What steel of a structural class found bigger application and why?
11. What groups alloyed steel are divided into by purpose?
12. What alloyed steels belong to cemented and to toughened?
13. What is feature of a steel microstructure after cementation in an equilibrium state?
14. What is purpose of steels subjecting to cementations?
15. What structure is formed on the section of the cemented steel after tempering?
16. What steel are called toughened?
17. List the titles of steels according to classification by the chemical composition.
18. What is called as hardness penetration of steels?
19. What is structural sign to define hardness penetration?
20. What is difference between a through and not through hardness penetration?
21. What diameter of a sample is called critical and what is its sense?
22. What factors does the hardness penetration of steel details depend from?
23. When the through hardness penetration and when not through is reached? Explain proceeding from the scheme of distribution of cooling speed on sample section when tempering.
24. What ways it is possible to raise a hardness penetration?
25. How experimentally to define a hardness penetration?
26. How to use the Blanter nomograph when determining critical diameter?
27. What is called the ideal critical diameter?
28. Whether cooling speed influences the size of critical diameter (hardness penetration)?

29. How do AE influence on the location of C - curves?

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LABORATORY WORK №3

STRUCTURE OF STEELS AFTER CEMENTATION AND TEMPERING BY HIGH FREQUENCY CURRENTS

Work purpose

- Study structure of the cemented steels.
- Study structure of steels after tempering via currents of high frequency.

Theoretical part

Cementation (carburizing) - the chemical heat treatment (CHT) consists in diffusion saturation of a surface layer of metal (product) by carbon. The **cementation purpose** - obtaining high hardness and wear resistance of a surface layer of products with maintaining high viscosity of their core that is reached by heat treatment after cementation.

Usually cementations is subjected to products from constructional carbonaceous and alloy steels with the low-carbon content (to 0,25%) and it is carried out at temperatures of 900-950 °C and above, i.e. heating of steel is carried out to an austenitic state (above a critical point of A_{c3}) in connection with the increased solubility of carbon in austenite in comparison with ferrite. With temperature increase of cementation and increase in soaking time the depth of the cemented layer increases. However at increase of temperature over 950 °C, together with acceleration of process of steel carbon saturation, there is also a strong growth of grain of austenite that is undesirable. Therefore high-temperature cementation at 980-1050 °C is recommended to be applied for hereditarily fine-grained steels that are not afraid of austenite grain growth when heating.

Depending on aggregate state of the external environment in which workpiece is placed there is distinguished cementation in firm, liquid and gas environments. In the industry generally apply two types of

cementation: cementation by the firm carburizer and more progressive - gas carburizing.

At cementation in the solid carburizing agent, products stack in metal boxes what are filled up with wood coal mixed from 20...25% of BaCO_3 (for process acceleration) and 3,5...5% of CaCO_3 (for prevention of agglomeration of particles of the carburizer). When heating in the furnace of boxes with products and the carburizer the atomic carbon which diffuses in steel is formed. Duration of such cementation is 5... 24 hours.

For gas carburizing as the carburizer use the natural gas (consisting generally of methane CH_4); the controlled atmospheres is obtained in special generators; and also liquid hydrocarbons (kerosene, benzene, etc.) that drops to the furnaces hermetic working space where they form the active gas phase what is rich with atomic carbon.

Gas carburizing is the main process at mass production, and cementation in the solid carburizing agent is used in small-scale production. Gas carburizing, in comparison with cementation in the solid carburizing agent, has a number of advantages: cementation time is reduced to 3.... 12 hours since there is no low-heat-conducting solid carburizing agent; it is easy to regulate process of gas carburizing (changing composition of gas and a gas rate) and to mechanize it; working conditions are improved; the working area of workshop is reduced; further heat treatment becomes simpler.

At cementation, as well as at other versions CHT, several processes at the same time proceed:

1. Formation in a circumambient (or in separate reactionary volume) of diffusing element in the atomic (ionized) state (*thermal dissociation*);
2. *Adsorption* ("sticking") of atoms (ions) on the surface of metal with formation of chemical bonds between ions of the saturating element and base metal;
3. *Diffusion* of the adsorbed atoms from a surface in depth of processed metal (or product).

Thermodynamic driving force of diffusion is the difference in

concentration of diffusing element.

As a result of course of these processes the chemical composition of a surface layer is changed, formed a gradient of concentration of the saturating element in surface and underlying layers. Concentration of diffusing element decreases from a surface in depth of metal (fig. 1). As a result of it the structure and properties of steel change. After slow cooling in structure of the cemented layer it is possible to distinguish (from a surface to a core) the following zones:

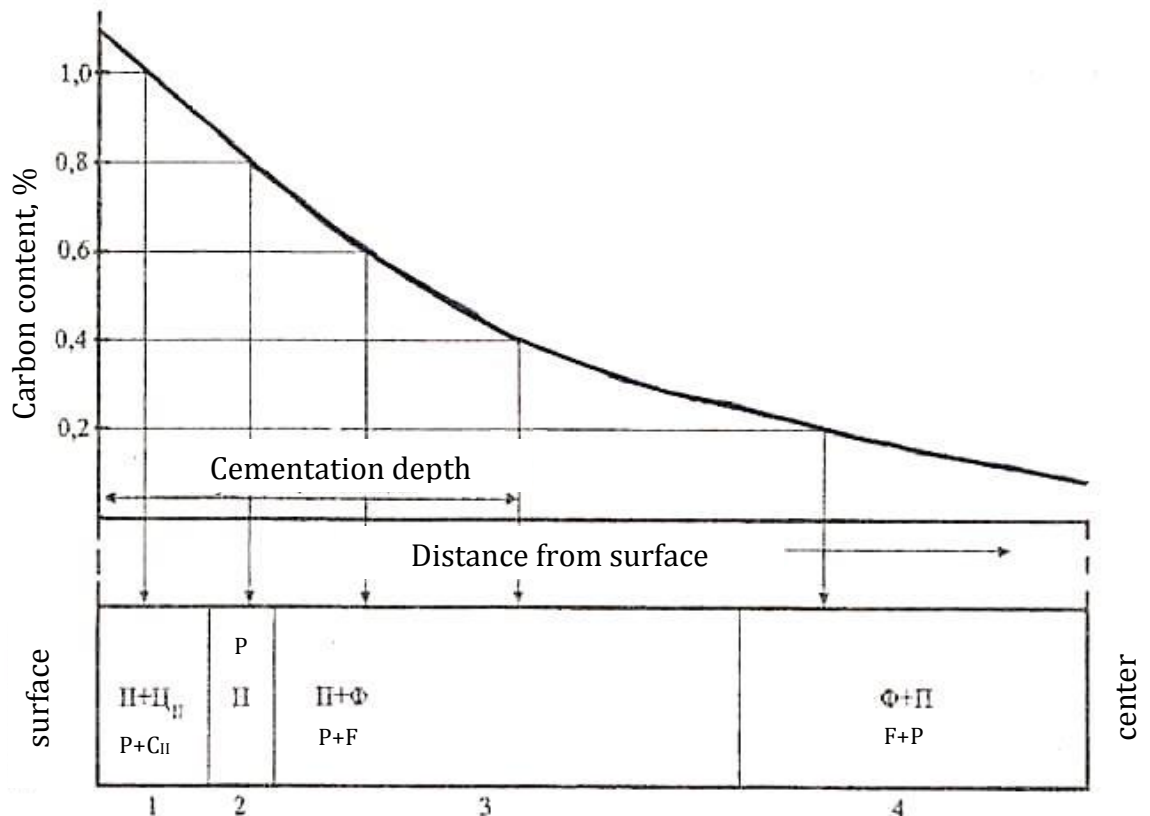


Fig. 1. The nature of distribution of carbon concentration and change of a microstructure on zones in a sample of a low-carbon steel after cementation: 1 - the zone is hypereutectoid, 2 - a zone is eutectoid, 3 - a pro-eutectoid zone, 4 - a pro-eutectoid zone, corresponding to structure of initial steel before cementation.

- 1) *the hypereutectoid*, consisting of perlite and secondary cement carbide of the austenite forming a grid on the former grain;
 - 2) *the eutectoid*, consisting of one lamellar pearlite, and
 - 3,4) *the pro-eutectoid zone* consisting of perlite and ferrite.
- The amount of ferrite continuously increases in this zone as

approaching a core. The core will have structure of initial (before cementation) steel.

Thus, studying structure of cemented steel after slow cooling, it is possible to determine cementation depth. The technical depth of cementation is often defined as distance from a surface to a zone where concentration of carbon is equal to 0,4%, i.e. the structure consists of 50% of perlite and 50% of ferrite. Depth of cementation is determined by metallography (on annealed samples) at magnification 100...500 X. Cementation depth depending on assignment of a product and on composition of steel is usually in limits of 0,5...2,0 mm. Concentration of carbon in a surface layer of a product at the same time is 0,8... 1,0%.

Enrichment of a surface layer with carbon at cementation is intermediate operation because it does not give necessary hardening of a surface. Required hardening of a surface layer of a product is reached by tempering after cementation. Tempering should not only strengthen a surface layer, but also correct the structure of overheating (to crush structure of a core and the cemented layer) arising because of hours-long soaking of steel at a cementation temperature and also to eliminate a cementite grid in the cemented layer.

After tempering of the cemented steel from temperature of 750-780 °C the surface layer acquires structure of martensite with fine particles of globular carbides (secondary cement carbide), and a few quantity of residual austenite. The transition layer containing carbon from 0,8 to 0,6% is also tempered on martensite. The zone with a smaller total carbon (0,6-0,35%) perceives incomplete hardening, i.e. in its structure, except martensite, a few quantity of ferrite as at such total carbon the temperature 750-780 °C are above A_{c1} but below A_{c3} remains. The low-carbon core does not accept tempering and keeps ferritic-perlitic structure with a small amount of perlite ($\approx 15\div 30\%$).

Final operation of heat treatment after cementation and tempering is the low drawing at a temperature 160 - 180 °C which is reducing residual stresses and not reducing the hardness of surface layers of a product (HRC 58-63)

Chemical heat treatment of steel products, and including

cementation, is rather labor-intensive and long process. For obtaining high hardness and durability in a surface layer of a part in combination with a viscous core in the industry use also surface hardening of medium carbon steel consisting in heating of a surface layer of hardening steel above A_{c3} with the subsequent rapid cooling.

In this case heating for hardening is made by the currents of high frequency (HFC) - the most widespread way, in molten metals or salts, by flame of gas or oxygen acetylene burners, an electric-contact method and also by laser radiation.

Surface hardening with use of induction heating in comparison with CHT, is less labor-consuming, highly productive and in many cases of parts is not of a lower quality than cementation. When tempering by HFC the magnetic field induced in a product leads to emergence of eddy currents and allocation of Joule heat in the heated body. After heating in the inductor (the inductor represents copper tubes with the water circulating inside for cooling of the inductor) the part is cooled by means of the special spray device.

Use of induction heating by currents of high frequency allows to heat a surface of a steel part very quickly. Maximum temperature of a surface is defined by time of transmission of current by the inductor, and depth of heat penetration - current frequency: the frequency is higher, the depth of heat penetration is less (frequency of current can be ranged from 50 Hz to $10^5 \dots 10^6$ Hz).

Schematically the schedule of change of temperature on depth of a part is shown in fig. 2.

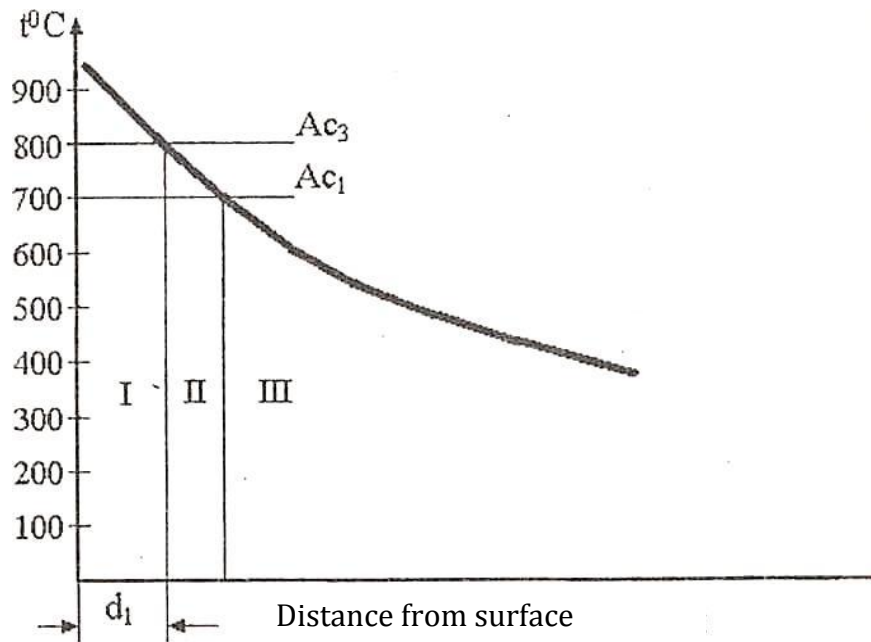


Fig. 2. The scheme of change of temperature on part depth when heating by HFC

If we heat, for example, steel 45, then at a depth d_1 the temperature will exceed A_{c3} ; under a surface layer I there is a second layer heated up to one temperature above A_{c1} , but below A_{c3} . At last, under the second layer, there is a layer III - a core in which reheat temperature has not reached A_{c1} .

At the subsequent rapid cooling the first layer will receive full hardening on martensite. The second layer - incomplete hardening. In structure of this layer except martensite there will be a ferrite which amount is more than the zone is farther from a surface. The third zone - will not apprehend tempering and will keep structure of initial annealed steel, i.e. F+P.

Thus, after tempering the part surface with martensitic structure will have the highest hardness. In process of distance from a surface the hardness decreases.

High hardness of martensite is caused by the distortions of a crystal lattice connected with big internal stresses; high density of dislocations, different borders and subborders complicating the movement of dislocations and also emergence of a phase peening due to increase in

volume at austenite transformation in martensite.

1. Necessary equipment and materials

1. Metallographical microscopes.
2. Collections of microsections
 - a) polished section №1 - steel 20 after cementation and slow cooling
 - b) polished section №2 - steel 20 after cementation and water hardening from temperature of 760...780 °C.
 - c) polished section №3 - steel 45 after tempering of HFC.

2. Order of laboratory work carrying out and record of experiment results

In this work it is necessary to investigate change of a microstructure of samples of steel 20 after cementation, cementation and tempering and steel 45 after tempering of HFC.

For this purpose should place the studied sample on an objective table of a microscope so that under a lens there was an edge of a sample. Slowly moving a microscope table, to study change of a microstructure on sample depth. To put results of observations in a workbook, consistently representing schemes of structures, from a surface to the center zones with taking into account change of chemical composition of samples No. 1 and 2 during cementation and taking into account a gradient of temperatures in a sample No. 3 before tempering. To sketch schemes of structures with pencil in rectangles of 30 x 120 mm in size with allocation of 4 characteristic zones in samples No. 1 and 2 in each of 3 zones in a sample No. 3.

3. Requirements to the report

The report on laboratory work should contain:

1. Subject and purpose of work.
2. Basic theoretical provisions.
3. Drawings.
4. Schemes of structures by samples and zones.
5. Conclusions with an explanation of experimental results according to the work purpose.

6. Answers to control questions.

6. Control questions

1. What kind of chemical heat treatment is called cementation?
2. What is the purpose of cementation?
3. What steels are subjected to cementation?
4. What temperatures the cementation is carried out at and why?
5. To call kinds of cementation depending on aggregate state of the external environment for cementation.
6. List the advantage of gas carburizing.
7. What is the main processes proceeding at cementation?
8. What is taken for the technical depth of cementation?
9. Why after cementation the heat treatment is necessary?
10. What is the tempering of HFC?
11. How the frequency of current and time of current transmission influence on results of HFC tempering?
12. What steel can be subjected to HFC tempering?
13. Whether structures in the center of samples No. 1, 2 and 3 will be different from each other?

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