

### Pryazovskyi State Technical University (PSTU)



## NEXT-GENERATION STRENGTHENING TECHNOLOGIES OF MATERIALS TREATMENT

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### **LEARNING OUTCOMES**

A student, having mastered this subject *must possess a good knowledge* of:

- □ basic perspective strengthening technologies and current tendencies of their modification;
- physical effects and phenomena, upon application of which technologies of strengthening are based;
- D phase, structural and other transformations, leading to increase in materials properties;
- □ rational spheres of practical application of various strengthening technologies;

#### A student is to acquire skills and ability of:

- choosing the appropriate methods of strengthening for parts and tools, with due regard to conditions of their application and technical specifications required, ensuring the highest possible improvement of their reliability and service lives;
- making evaluation of efficiency of various strengthening technologies, with regard to obtained mechanical, physical, chemical and exploitation properties and also their economy;
- analyzing by patent and literature data the tendencies of development of strengthening technologies and possibilities of their application in practice.

# This subject is connected with such previously mastered subjects like:

- □ "Physical metallurgy",
- □ "Physics of condensed state",
- □ "Physical and chemical fundamentals of the material science",
- □ "Theory and technology of heat and thermo-chemical treatment",
- □ "Alloys, possessing special physical properties",
- □ "Non-ferrous metals and alloys"
- □ "High-strength engineering materials".

#### **Duration of this course:**

18 weeks (4.5 ECTS). For full-time students it includes (hours):

- □ lectures: 36
- □ laboratory works: 18
- □ practical training: 18
- □ individual work: 30
- 6 hours of lectures are specified for extra-mural students, as well as 2 hours of laboratory works, 4 hours of practical training and one test paper.

### Chapter 1

### CRITERIA'S OF PROPERTIES AND MECHANISMS OF STRENGTHENING HIGH-STRENGTH MATERIALS. CLASSIFICATION OF STRENGTHENING TECHNOLOGIES

#### **1.1. Criteria's of properties of high-strength states**

These are materials, which possess the following complex of mechanical properties:

1. Ultimate tensile strength UTS  $\geq$  1300 MPa, yield strength YS  $\geq$ 1100 MPa;

2. Relative elongation  $\geq$  10 %, relative reduction  $\geq$  25 %;

3. Impact toughness  $KCU \ge 0.8 \text{ MJ/m}^2$ .

Other increased requirements for properties, depending upon expoitation conditions of high-strength materials:

1. High resistance to brittle destruction, i.e. reduced critical brittleness threshold ( $T_{c.b.t.} \leq$  - 60 °C);

- 2. Increased fatigue strength (FS);
- 3. Increased corrosion resistance in special (specified) media;
- 4. Increased characteristics of crack growth resistance ( $K_{1c}$ ,  $\delta_c$ ).
- 5. Increased fatigue strength (FS);
- 6. Increased corrosion resistance in special (specified) media;
- 7. Increased characteristics of crack growth resistance ( $K_{1c}$ ,  $\delta_c$ ).

#### **1.2 THE MAIN MECHANISMS OF STRENGTHENING**



Figure 1.1 – The scheme of formation solid solution substitutional and interstitial.



Figure 1.3 – Diagramme braking of sliding of dislocation by grain boundary.



Figure 1.2 – The diagramme of structure of grain boundary.



Figure 1.4 – Diagramme of formation of dislocation loops round of particles of hard phases under the action stresses.

### 1.3. MARTENSITE TRANSFORMATION UNDER QUENCHING AND DEFORMATION INDUCED



Figure 1.5 – Transformation of FCC lattice of austenite into BCT lattice of martensite.



Figure 1.6 - Critical speed of quenching eutectoid steel with 0.8 % C.

### THE MORPHOLOGICAL TYPES OF QUENCHED MARTENSITE





#### lath martensite

plate martensite

### DEFORMATION INDUCED MARTENSITE TRANSFORMATION





Figure 1.9 - The scheme of DIMT under rolling deformation.

Figure 1.10 – The passing of DIMT in specimen of metastable austenite steels under tensile testing which accompanied by "running neck" effect.



Figure 1.8 - Scheme of interrelation between the stress and temperature and martensite formation: a - the G.B. Olson and M. Cohen scheme:

1 – stress martensite; 2 – deformation induced martensite;  $\sigma_{\tau}^{A}$  – austenite yield strength;

b – extension to the scheme: 3 – deformation induced martensite,

appearing in the  $M_s...M_f$  range; 1'– stress martensite.



Figure 1.11 - Microstructure of steels: 30Cr4Mn6Si2V (a, b); 30Cr6Mn6Si2V (c, d); 30Cr8Mn6Si2V (e, f) after quenching at 1000 °C, tempering 200 °C, before (at left) and after tensile test (at right), x 500.

### **1.4 CLASSIFICATION OF STRENGTHENING TECHNOLOGIES**



# Table 1.1 - Classification of strengthening technologies according to theimpact on the material

Nº	Type of impact	Conditions	Treatment processes							
		Treatments in a bulk								
		Thermal, at above zero	<ul> <li>various methods of quenching;</li> </ul>							
		temperature range	- ageing, tempering;							
		At subzero temperatures	quenching + sub-zero treatment;							
			cryogenic treatment.							
		At temperature cycling	thermo-cyclic treatment (TCT).							
	Change of the	By applying electric	electric heat treatment							
	structure in the	current								
	bulk of metal	In vacuum	vacuum heat treatment							
		Heat +Deformation	<ul> <li>thermo-mechanical treatment (TMT);</li> </ul>							
			- hydro-extrusion;							
			- with application of the effect of super-plasticity							
		High speed	<ul> <li>explosion treatment;</li> </ul>							
		deformation	<ul> <li>by impulse magnetic field;</li> </ul>							
			-electric-hydraulic stamping.							
1	Change	Magnetic field	heat treatment in magnetic field							
	energy									
	balance									
ш	Change of	Directed crystallization of	directed crystallization of eutectics.							
	crystalline	eutectics								
	state	Mono-crystallization	growing of mono crystals.							
		High cooling rates	- methods of quenching from liquid state,							
		(Vcool. > 105 °C/c) from	electrolytic precipitation et al;							
		liquid state	- obtaining of nano-crystalline and amorphous							
			states of alloys.							

	Surfacing treatments									
N	Change of the	Physical-thermal (by the	- plasma treatment;							
	structure of the	sources of concentrated	- laser treatment;							
	surface layer	energy)	- electron beam treatment.							
		By eddy currents	- high frequency currents, industrial frequency							
			currents.							
		Gas flame	- gas flame quenching							
		Elementary particles	- radiation treatment with fast neutrons;							
			- α-, β-, γ- rays.							
		Mechanical impact	vibration, ultrasonic, frictional, (spinning,							
			knurling with rolls), shot-peening, reducing.							
V		Diffusion saturation of the	thermo-chemical treatment (TCT):							
		surface with chemical	carburizing, nitriding, nitro-carburizing,							
		elements	borating, chromium-plating, nickel-plating,							
	Change of the		aluminizing etc.							
	chemical	Saturation in vacuum	vacuum carburizing.							
	content of the	I glow discharge;	ionic carburizing, ionic nitriding, ionic							
	surface	bombardment with ions	implantation of chemical elements.							
N		By a chemical reaction	oxidation, sulphurizing, phosphatizing et al.							
		Electrolytic precipitation	chromium plating, nickel plating, copper							
			plating, borating, borating-chromium plating et							
			al.							
	Creation of	Precipitation from gas	- spark alloying;							
	coating	medium	- thermal evaporation;							
			- cathode-ionic bombardment, electron-ray							
			evaporation (PVP).							
		Metal coating	Plasma-sprade coating, laser, detonation,							
			electric-arc and other types of surface coating.							
		Surface hardfacing of	electric-arc, plasma, laser beam							
		alloyed metal	hardsurfacing, by means of a bunch of ions.							
		Mechanical	Mechanical alloying.							

### CHAPTER 2

### PERSPECTIVE TECHNOLOGICAL TECHNIQUES OF QUENCHING

### 2.1 METHODS OF QUENCHING IN A BULK



Figure 2.1 - The schemes of different methods of quenching: 1 - conventional cooling in one cooling media; 2 – consistent quenching in two cooling media; 3 - stepped quenching; 4 - isothermal quenching.







Figure 2.3 - Quenching combined with sub-zero treatment.

#### 2.2 Quenching from inter-critical ( $\alpha + \gamma$ ) area



Figure 2.4 – New methods of quenching:

6 – from  $(\alpha + \gamma)$  or  $(\alpha + \gamma + Carb.)$  area; 7 - with stepped heating and preliminary holding in inter-critical  $(\alpha + \gamma + Carb.)$  or sub-critical  $(\alpha + Carb.)$  areas and transitory austenitization (3...5 min.).



Figure 2.5 – Chart of quenching structural steels from ICA ( $\alpha$  +  $\gamma$ ) (a) and fragment of equilibrium diagram Fe-Fe3C (b).



Figure 2.6 - Chart of quenching steels Fe-Mn from ICA ( $\alpha + \gamma$ ) (a) and fragment of equilibrium diagram Fe-Mn (b).

### 2.3 Q-N-P-PROCESSING - A NEW WAY TO IMPROVE THE COMPLEX OF MECHANICAL PROPERTIES OF THE STEEL





Figure 2.8 - The schedule of the mode of Q-n-P-processing of low-alloyed steels.

Figure 2.7 - A schematic illustration of the relationship of the tensile strength and elongation of various steels grades: (F + M) double-phase steels (DPS), martensitic steels (M), Q-n-Pprocessed steels. Page 1

Figure 2.9 - Retained austenite (RA) as the films lying between martensite plates in Q-n-P-processed steel.

### **Chapter 3**

### NEW METHODS OF QUENCHING FROM HETEROGENEOUS STATES

### THE MODEL OF DISSOLUTION CARBIDES IN AUSTENITE AND DISTRIBUTION OF ELEMENTS CONCENTRATION



Figure 3.1 - The model of dissolution carbides in austenite and distribution of elements concentration (C, Cr etc.) for holding time:

 $\tau_2 > \tau_1 > \tau_0$ .

Concentration elements:

 $C_o$  – in austenite (at  $\tau_o$ );  $C_{carb}$  – in carbide;

 $C_{bound.}$  – on boundary austenite – carbide;  $r_o$ ,  $r_i$ 

- radius of carbide (elementary, various);  $h_o$ ,  $h_i$
- distance between carbide particles.



Figure 3.2 - Distribution of elements concentration in austenite caused by its heterogenization: 1 – instant distribution; 2 – at dissolution of carbides; 3 – at carbides precipitation.

#### MODEL OF FORMING HETEROGENEOUS AUSTENITE AT DISSOLUTION OF CARBIDES



Austenite:  $A_{s.s.}$  - super saturation a.;  $A_{dep}$  - depleted .a.;  $A_{ret}$  - retained a.; Martensite:  $M_q$  - m. quenching;  $M_d$  - m. deformation.

14.04.2016



Figure 3.4 - Process diagrams of quenching of high-strength steels from non-equilibrium states of heterogeneous austenite:

a – rapid high temperature quenching with electric contact or induction heating (a) and in salty bath (b) or metal liquid;

- $b low temperature quenching from (A_{het} + Carb.) state;$
- c quenching with stepped heating in intercrytitical ( $\alpha + \gamma + Carb$ .) or sub-critical ( $\alpha + Carb$ .) area;
- d by thermo-cyclic treatment (TCT);
- e quenching with stepped cooling;
- f low temperature thermo-mechanical treatment (LTMT);
- g heating of hardened steel in ( $\alpha + \gamma + Carb$ .) area with specified holding.



Figure 3.5 - Rapid high temperature quenching:

a - electric contact or induction heating;

b - gradient heating in electric-salty baths or metal liquid.



Figure 3.7 - Thermo-cyclic treatment, which realized multi  $\alpha \leftrightarrow \gamma$ transformations. 14.04.2016



Figure 3.6 - low temperature quenching from  $(A_{het.} + Carb.)$  area.



Figure 3.8 - Quenching with stepped cooling in  $(A_u + Carb.)$  area.



Figure 3.9 - Thermo-mechanical treatment (TMT).

Figure 3.10 - heating of hardened steel in ( $\alpha + \gamma + Carb.$ ) area with specified holding realized  $\alpha \rightarrow \gamma$  transformation.

## Table 3.1- Mechanical properties of steels after new heterogenious technologies

Steel grade	Heat treatment	UTS, MPa	YS, MPa	Percent elongatio n, %	Percent reduction, %	КСU, MJ/м²
	Standard quenching 1000 °C + tempering 200 °C	1,410	1,150	11	37	0.6
20Cr13	Quenching with stepped cooling 400 °C	1,760	1,320	14	46	1.0
	Rapid high temperature quenching 1250 °C + temper. 200 °C	1,650	1,220	15	55	1.1
200-12	Standard quenching 1000 °C + tempering 200 °C	1,370	1,050	8	20	0.45
300113	quenching with stepped heating 720 ºC + temper. 200 ºC	1,820	1,510	10	41	0.8

### **Chapter 4**

### THERMOCYCLIC TREATMENT

**Thermocyclic treatment (TCT)** – it is a treatment based on repeated alternation of heating and cooling cycles with the objective of gradual accumulation of positive changes in the structure that ensure improving the properties of the materials.



## 4.1 TCT in the area of full or partial structure change induced by phase transformation



Figure 4.2 – TCT of alloys with full (1) or partial (2) structure change induced by  $(\alpha \leftrightarrow \gamma)$  phase transformation.

# 4.2 TCT in the area of variable solubility of elements in solid solution



Figure 4.3

#### 4.3 TCT in the ageing area (age hardening)



Figure 4.2 – TCT of alloys with full (1) or partial (2) structure change induced by  $(\alpha \leftrightarrow \gamma)$  phase transformation

### 4.4 Peculiarities of phase and structural transformations at TCT

 Formation, shifting, annihilation, diffusion of point defects and redistribution of dislocations (fig. 4.5).



Fig. 4.5 – Redistribution of dislocations density at TCT.

Dislocations density will increase along with increase of cycle numbers.

- 2. Growth in the level of internal stresses at TCT. Additional stresses spring up due to the difference in coefficients of thermal linear expansion of separate phases.
- Growth of diffusion processes. It is connected with peculiarities No 1 and 2. Diffusion is stimulated by increase of stresses, formation of dislocations and their motion. This is confirmed by the addition, proposed by S.T. Konobeevsky to the well-known diffusion equation (Fick's second law):

$$\frac{dC}{d\tau} = D' \frac{\partial^2 c}{\partial x^2} + D'' \frac{\partial^2 \varepsilon}{\partial x^2}$$
(4.8)

- is alternation in concentration of C diffusing element in time  $\tau$ ;
- D' coefficient of diffusion, depending on temperature, time and concentration of the diffusing element
- D'' coefficient of diffusion, depending on the value of stresses;
- alternation of concentrations gradient;
- alternation of stresses gradient.

Diffusion at TCT is enhanced as the result of stresses action.

dC

 $d\tau$ 

 $\frac{\partial^2 c}{\partial x^2}$ 

 $\partial^2 \epsilon$ 

 $\partial x^2$ 

Diffusion at TCT is enhanced as the result of stresses action.

4. Refinement of grain size structure, following by repeated phase structure change (for instance, grain number in 08κπ, 45 steels after normalizing is № 4...5, while after TCT- № 11...12) (Fig. 4.6; 4.7).

5. Phase hardening i.e. phase hardening from the side of other phases, due to the difference of coefficients of linear and volume expansion of phases.

6. Size reduction (dispersion) of the structural components, for example, pearlite, martensite, bainite size reduction at TCT.

7. Fragmentation, spheroidizing and coagulation of the excessive phases.

8. In special high-strength steels and alloys stabilization and destabilization of austenite is possible





Figure 4.6 - Microstructure of the steel 08κπ (0,08 % C) after normalizing (a) and after thermo-cyclic treatment (STCT) during 5 cycle (b).



Figure 4.7 - Microstructure of steel 45 (0,45 % C) after normalizing (a) and after thermo cyclic treatment (STCT) during 5 cycle (b).

### 4.5 Classification of TCT types

Table 4.1 - Classification of thermo cyclic treatment types

Thermocyclic treatment												
With allotropicWithout allotropictransformationtransformation				С	Combined with other impacts							
Diffusion type	Shifting type	ined type	ined type TCT	тст	LTCT	тст	erature	Chemical		Deformation		
		Comb H	L.	5   I	S	Тет	СҺТСТ	MChTCT	MTCT	НТDTCT	LTDTCT	


Figure 4.8 - Sorbitizing thermo-cyclic treatment (STCT).

#### Table 4.2 - Mechanical properties of steels after normalizing and TCT

Steel grade	Heat treatment	UTS, MPa	YS, MPa	Elong., %	Reduc., %	KCU, J/sм²
<b>45</b> (0.45 %C)	Normalizing 880 ⁰C	660	375	22	47	62
(0.40 /00)	STCT	580	385	27	60	130
<b>30Cr1Mn1Si1</b> (0.3 %C; 1 % Mn; 1 % Si)	normalizing	alizing 845 450 13		29	120	
	STCT	815	550	21,5	62	320
<b>40Cr1</b> (0.4 %C; 1 %Cr)	Quenching 860 °C + tempering 200 °C	2020	1680	8	38	28
	STCT + tempering 200 °C	2120	1760	12	48	40

### **Chapter 5**

## THERMOMECHANICAL TREATMENT

#### TMT possesses the following technological parameters:

- method of deformation (rolling, stamping, drawing etc.);
- **u** temperature of deformation ( $t_{def.}$ , °C);
- **deformation rate**  $(V_{def.}, c^{-1});$
- duration of after-deformation pause(min.);
- $\Box$  temperature of heating before an after deformation (*t*, °C);
- $\Box$  time of holding at a given temperature ( $\tau$ , min.);
- cooling conditions after holding.

#### 5.1 Classification and the main process flow sheets of TMT





Figure 5.2 – Diagrams of controlled rolling with different temperatures of completion of deformation:  $a - above Ar_3 point$ ,  $b - within the interval of Ar_3 ... Ar_1 points; c - below Ar_1 point.$ 



Figure 5.3 – Diagrams of low temperature thermomechanical treatment: a) LTMT; b) LTMisT.

#### **CLASSIFICATION OF TYPE METHODS THERMOMECHANICAL TREATMENT:**





Figure 5.4 – Classification of type methods thermomechanical treatment:

a) high-temperature thermomechanical treatment (HTMT) with quenching and tempering;

b) high-temperature thermomechanical isothermal treatment (HTMisT) with decomposition in pearlite (1) and bainite (2) area;

c) controlled rolling with finished deformation in austenite, austenite-ferrite and pearlite conditions;

d) low-temperature thermomechanical treatment (LTMT) – "Ausforming"; e) low-temperature thermomechanical isothermal treatment (LTMisT) with deformation at the process austenite-pearlite transformation (1) – "Isoforming", or bainite transformation (2);

f) hereditary thermomechanical strengthening (HTMS-1) with preliminary HTMT and high-temperature tempering;

g) hereditary thermomechanical strengthening (HTMS-2) with preliminare HTMisT and decomposition in bainite area

h) hereditary thermomechanical strengthening (HTMS-3) with preliminare LTMisT;

i) preliminary thermomechanical treatment (PTMT);

k) thermomechanical treatment for deformation aging martensite - "Marforming";

I) thermomechanical treatment for deformation aging martensite after HTMT;

m) thermomechanical treatment for deformation aging bainite with warm or cold bainite deformation and tempering; n) patenting (usually for wire).



Figure 5.5 – The diagram of preliminary thermomechanical treatment (PTMT).

#### **5.2 Peculiarities of structure formation at TMT**

Simultaneous action of deformation and temperature on the material in the process of TMT brings about a series of specific peculiarities and advantages in structure formation in steels and alloys, which can be generalized as follows:

increased dislocations density ( $\rho = 10^9...10^{12} \text{ cm}^{-2}$ );

peculiar substructure – polygonal, recrystallized, cellular, mesh-like et al.

 $\Box$  grain is reduced to Nº8...12;

deformation of grains shape (they are elongated towards direction of deformation and formation of fiber-like structure);

□ fragmentation of phase and structural components;

□ inheritance of the austenite structure, obtained at deformation, by other phases, that originate from it, as a result of subsequent phase transformations;

□ increased level of stresses;

 acceleration of diffusion processes, stimulating development of diffusion phase transformations;

#### 5.3 Methods of strengthening by surface plastic deformation



Figure 5.6 – Character of contact interaction of tool with the treating surface at the different methods of PSD: a) smoothening; b) spinning and knurling by rolls; c) single reduction; d) impact influence.

#### 5.3.1 Spinning and knurling with rolls



Figure 5.7 – Spinning of cylindrical surfaces of parts with rolls: 1 - the part being spinning; 2 - the roll.

#### 5.3.2 Diamond burnishing (and super-finishing)



#### 5.3.3 Shot-peening treatment



Figure 5.9 – shot-peening treatment of parts' surfaces: 1 – a flow of shots peening; 2 – the part being treated; 3 – head of a shot-peening machine.



Figure 5.10. – distribution of nicro-hardness along depth of the surface layer of 12Cr2Ni4 carburized steel at different duration of treatment:

1. – original state ; 2 – 0.5 min; 3 – 1.0 min, 4

$$-1.5 \text{ min}; 5 - 2 \text{ min}; 6 - 4 \text{ min}.$$

#### **5.3.5 Vibration strengthening treatment (caulking)**



Figure 5.11 – Scheme SPD strengthening caulking part of machine.

**Chapter** 6

## STRENGTHENING OF MATERIALS BY HIGH VELOCITY DEFORMATION

#### Advantages of high velocity deformation:

1) possibility of manufacturing a wide range of parts;

2) possibility of treating parts of complicated configuration (up to 10 m in cross section);

3) small work cycle of part's manufacturing (only some seconds);

4) high level of mechanical properties, achieved simultaneously with the operation of deformation;

5) manufacturing of parts, made of high-strength, hard to deform materials, that hardly can be treated by other methods;

6) possibility of joining materials that are not likely to be joined by any traditional methods;

7) obtaining of parts made of ceramic, metal powder and shavings, by means of pressing.

## The essence and classification of the modern methods of high velocity deformation:

□ explosion treatment;

□ application of impulse magnetic field;

□ application of electro-hydraulic deformation;

□ application of laser or electron beam.

## 6.1 Deformation with application of explosives or explosion metal strengthening (EMS)

Deformation with application of energy of ES is subdivided according to the method of transfer of energy of explosion into the following:

- a) blasting of ES inside the carrying medium (liquid, air);
- b) contact explosion;
- c) application of energy of fast flying mass;

## 6.1a - HVD by means of explosive treatment in the carrying medium.



Figure 6.1 - The diagram of explosion stamping in liquid medium.

- 1 ES charge; 2 –water basin; 3 metal sheet fixture; 4 matrix ;
- 5 –sheet blank ; S original distance from the work piece to ES charge.

#### 6.1b – the contact explosion.

In this case ES are in contact with the blank under treatment. Possible technological diagrams are shown in Fig. 6.2.

The value of generated pressure depends mainly on mass and type of ES charge. These diagrams are successfully used for strengthening of parts, manufactured of Hadfield steel (110Mn13). Dependence of mechanical properties of this steel on applied explosive pressure at explosive strengthening is illustrated in Fig. 6.3.

The examples of practical application of explosive strengthening of parts, manufactured from Hadfield steel are: "DUPONT" company reduced wear of tracks of tractors and bulldozers and railway pointworks by 40 %; Taunbarton, a company from the USA increased wear-resistance and service lives of parts of cast railway tracks and parts of mining facilities by 30 %.

#### 6.1c. Application of energy of fast flying mass.

3



Figure 6.2 - The diagrams of metal strengthening at the contact explosion:

a) with flat (front) shock wave; b) with running (skew) shock wave;

c) strengthening with application of energy of fast flying mass;

1 – the part strengthened; 2 - ES; 3 - generator of flat wave; 4 - detonator;

5 - the plate thrown.



Figure 6.3 - Dependence of mechanical properties of Hadfield steel (110Mn13) on applied explosive pressure: 1 – yield strength (YS);

2 - ultimate tensile strength (UTS); 3 – HV (GPa); 4 – elongation .

#### 6.2 Application of impulse magnetic field



Figure 6.4 - The diagram of an impulse-magnetic unit for reduction of pipe blanks: 1 – workpiece; 2 – inducter; 3 – charger; 4 – condenser battery.

6.3 Application of electro-hydraulic deformation



Figure 6.5 – Principle diagram of a unit for electro-hydraulic stamping: 1 – workpiece; 2- electrodes; 3 – interrupter; 4 – condencer; 5 – matrix.

## 6.4 Application of laser or electron beam for high velocity deformation

The bulk of energy of laser or electron-beam radiation is accumulated in the surface layer of the treated metal within a very short period of time 10-6 sec. When a closed (it is to be opaque for radiation) screen is placed above the surface under treatment steam pressure of evaporated metal (up to 10 GPa) is generated. If time of propagation of the gradient of steam pressure on the surface is less than the time of energy extraction a shock wave is formed, that deforms the surface. Metal strengthening at laser treatment within close space is based on this principle.

# 6.5 Peculiarities of phase transformations at high velocity deformation

Under conditions of shock wave present:

- □ shift component of transformation increases;
- □ high transformation rate;
- □ diffusion rate increases by several orders;
- □ concentration of defects, initiating the origin of a new phase rises;
- □ the kinetics of phase transformation changes;
- new phase transformations are realized, that are impossible under normal conditions.



Figure 6.7 – Influence of alloying elements on pressure of phase  $\alpha \leftrightarrow \epsilon$  transformation



Figure 6.6 - Phase diagram of iron. p. 0 – equilibrium pressure of  $Fe_{\alpha} \leftrightarrow Fe_{\epsilon}$ ,  $Fe_{\alpha} \leftrightarrow Fe_{\gamma}$  and  $Fe_{\gamma} \leftrightarrow Fe_{\epsilon}$  transformations.

# 6.6 The reasons of strengthening at high pressure and high velocity deformation

The reasons of such strengthening are following:

- □ resistance of the lattice to dislocations motion raises;
- ❑ the number of obstacles to dislocations sliding is increase, due to initiating of the sources of dislocations formation;
- not only traditional Frank-Reid sources of dislocations formation are working in dislocation-free sections;
- □ atomic groups are shifted, forming defects in atomic packing;
- cellular dislocations substructure is formed at substantially smaller deformations (5...7 %) with much smaller size of mesh;
- dislocations sliding in one system (at small deformations) is replaced by multitude sliding (in several planes).

# 6.7 Examples of increase in properties at high pressure and high velocity deformation

Table 6.1 – Mechanical properties after high-temperature thermo-mechanical treatment and explosion.

				Relative	Relativ	KCU,
Mode of treatment	P,		UTS,	elongati	е	MJ/m <sup>2</sup>
	GPa	13, MFa	MPa	on, %	reductio	
					n, %	
HTTMT	0	1550	1760	12	55	0,85
HTTMT+explosion						
treatment (water, 1	15	1780	1830	11,5	62	0,95
mm)						
HTTMT+explosion						
treatment (water, 5	7,5	1820	1880	12	63	1,1
mm)						

## **Chapter 7**

## HEAT TREATMENT OF STEEL PARTS IN MAGNETIC FIELD

# 7.1 Thermodynamics, mechanisms and kinetics of phase transformations in magnetic field



Figure 7.1 – Dependence of free energy of a thermodynamic system on temperature: ----- without magnetic field; - - - - - - in magnetic field.

#### 7.2 Influence of magnetic field on martensite transformation



Figure 7.2 – Influence of magnetic field upon the kinetics of martensite transformation.

# 7.3 The influence of magnetic field on formation of austenite at heating



Figure 7.3 – Austenite growth according to the shear mechanism (relief) from low-angle (a) and high-angle boundary (b, darker field) in 30CrMnSi steel (vacuum heating), x 650.



Figure 7.4 – The diagram of thermo-cyclic treatment of 40Cr1 steel with application of magnetic field.

Table 7.1 – Mechanical properties of 40Cr steel after TCT with and without application of magnetic field

	UTS,	Relative	Relative	
Treatment mode	MPa	elongation (δ), %	reduction	
			(ψ), %	
Standard quenching	1850	0	0	
from 860 °C				
TCT 700↔760 °C				
(without magnetic	1050	0	0	
field), austenitization	1950	U	U	
860 °C, cooling in oil				
TCT 700↔760 ºC (in				
magnetic field $H = 0.8$	2050	o	22	
MA/m) austenitization	2030	0	22	
860 °C, cooling in oil				

#### 7.4 Influence of magnetic field upon pearlite transformation



Figure 7.5 – Microstructure of steels with 0,45 % C (a, b) and 1,2 % C (c, d) after isothermal decomposition o austenite at 680°C: a, c – treatment without the field; b, d – treatment in magnetic field with intensity 960 kA/m; a, b – ×100; c, d – ×500.

Table 7.3 – Influence of magnetic field on mechanical properties of carbon steels after isothermal treatment

Steel	T <sub>isoterm</sub> , ⁰C	YS, MPa	URS, MPa	Relative elongation (δ), %	Relative reduction (ψ), %
0.45 % C	670 °C (without magnetic field)	528	765	21	62,5
	670 °C (in the magnetic field )	365	600	27	55
1.0 % C	580 °C (without magnetic field )	1050	1315	9,4	15
	580 °C (in the magnetic field	1215	1500	9,2	12

#### 7.5 Influence of magnetic field upon the kinetics bainite transformation





Figure 7.7 – Steel microstructure after isothermal treatment on the lower bainite: a, b – steel 18Cr2Ni4W; c, d – steel 30CrMnSi; e, f – malleable ferrite cast iron; g, h – grey pearlite cast iron (a, c, e, g – without the magnetic field; b, d, f, h – in magnetic field with intensity H = 1,64 MA/m). Table 7.4 – Influence of magnetic field (H = 1,6 MA/m) upon mechanical properties of steels with the structure of lower bainite

Steel grade	YS MPa	UTS, MPa	Relative elongation (δ), %	Reduction (ψ), %	KCU, kJ/m²
30CrMnSi	<u>892</u>	<u>1070</u>	<u>17</u>	<u>63</u>	<u>980</u>
	880	1060	22	64	1090
65Mn	<u>1190</u>	<u>1280</u>	<u>10,5</u>	<u>45,2</u>	<u>230</u>
	<b>1220</b>	1325	<b>11,7</b>	<b>45,4</b>	<b>300</b>
14Cr2MnMoB	<u>670</u>	<u>920</u>	<u>19</u>	<u>63</u>	<u>640</u>
	730	1000	<b>23</b>	66	910

Note: in the numerator – the results of treatment without magnetic field application; in the denominator - the results of the treatment in magnetic field.

**Chapter 8** 

### **VACUUM HEAT TREATMENT**
# THE FOLLOWING PROCESSES OF VACUUM TREATMENT ARE USED MORE OFTEN:

#### 1. Vacuum heat treatment:

- vacuum quenching;
- vacuum tempering;
- vacuum ageing;
- vacuum annealing;
- vacuum degassing.

#### 2. Vacuum chemical-heat treatment:

- vacuum carburizing;
- vacuum carbonitriding;
- vacuum nitriding.

#### 3. Surface deposition in vacuum.





Figure 8.2 – The scheme of inert gas circulation in a vacuum chamber with convection heating and high-pressure cooling.



Figure 8.3 – The scheme of a vacuum quenching furnace: 1 - ventilator; 2 - first chamber; 3 - quenching tank; 4 - oil mixing mechanisms; 5 - heated setting; 6 - heating chamber.

### 8.1 Technology of vacuum heat treatment



Figure 8.4 – The schedule of heat treatment in vacuum of tools made of high-speed steel grade 85W6Mo5Cr4.

### 8.2 Vacuum carburizing



Figure 8.5 - Parts subjected to vacuum carburizing.



Figure 8.6 - Typical package of parts of gear boxes ready for carburizing.



Figure 8.7 - Schedule of vacuum carburizing process and the quenching by cooling gas.

#### 8.3 Vacuum carbonitriding

Vacuum carbonitriding is carried out similarly vacuum carburizing. It differs by operating temperatures (850 ... 880 ° C) and process gas type: for carbonitriding the mixture of acetylene and ammonia is applied.

The advantages of the process are similar to mentioned above for vacuum carburizing.

### 8.4 The vacuum nitriding

Vacuum nitriding is applied for the parts made of:

- structural steels;
- tool steels;
- heat resistant alloys;
- corrosion-resistant steels and alloys;
- refractory alloys;
- sintered powder materials.



Figure 8.8 – The diagram of the vacuum-arc appliance of "Bulat" model, designed by L.P. Sablev.



Figure 8.10 - Stamps coated with titanium nitride (TiN), obtained by vacuum-arc precipitation.

### 8.5 Vacuum-arc wear resistant coatings



Figure 8.9. – The structure of the lattice of cubic titanium nitride (TiN).



Figure 8.11 – The hob coated with nitride of aluminium, titanium, chromium (AICrTiN), obtained by vacuum-arc precipitation.



Fig.8.12. Titanium nitride (TiN) coating on the cathedral's domes.

### **Chapter 9**

## THE PROCESS OF STRENGTHENING BASED UPON THE EFFECT OF SUPERPLASTICITY

### 9.1 Types and mechanisms of superplasticity

Three types superplasticity :

- 1) structural superplasticity;
- 2) appearing in the area of diffusion phase (polymorphous) transformation in solid state;
- 3) appearing within the interval of temperatures of diffusionless (martensite) transformation.

### **Mechanisms of superplasticity**



Figure 9.1 – Mechanisms of inter-grain sliding, controlled by boundary (a) and volume (δ) diffusion (acc. to Ashby).



Figure 9.2 – The diagram of joint action of the mechanisms of sliding and vacancy creep at superplasticity.

# 9.2 Practical application of the effect of superplasticity for strengthening of alloys

The phenomenon of superplasticity is often employed in many processes of plastic working of metals, it allowing reducing power consumption of equipment, owing to drastic decrease in temperature and energy factors of the process of deformation. However, the effect of superplasticity can be rather efficiently applied for strengthening of various production alloys and parts, manufactured of them due to formation of a developed substructure with increased density of structural defects.

### **9.2.1 Superplasticity under diffusion transformations**

Table 9.1 - Mechanical properties of titanium alloy (BT-14) after pressing under conditions of superplasticity and subsequent heat treatment.

Mode of treatment	UTS, MPa	YS, MPa	Relative elongation (δ), %	Impact strength per crack propagation (a <sub>c.p.</sub> ), J/cm <sup>2</sup>
Pressing at 950 °C, 84 %, quenching, ageing at 480 °C, for 10 hours	1400	1300	7.0	8.0
Pressing at 950 °C, 84 %, quenching, cold rolling 26 %, ageing 310 °C, for 10 hours	1450	1400	7.5	-
Quenching at 870 °C in water, ageing at 480 °C for 10 hours	1200	970	5.5	1.1

#### 9.2.2. Superplasticity of steels under martensite transformations



Figure 9.3 – The comparison of characteristics of mechanical properties of 40Cr steel after different treatment modes: 1; 4 – quenching at 860 °C; 2; 5 – LTMO (degree of reduction 20 % at 400 °); 3; 6 – deformation in the process of martensite transformation (degree of reduction 20 % at 250...260 °C).

# Superplasticity of steels under deformation induced martensite transformations



Figure 9.4 – Influence of holding time in  $(\alpha + \gamma)$  area upon the kinetics of  $\gamma_{ret} \rightarrow \alpha'$ DIMT by torsion of 20Mn7SiTi steel:

1 – quenching from 900 °C, tempering 200 °C; Quenching from 900 °C, heating at 600 °C with holding : 2 - 7 min; 3 – 20 min.; 4 - 60 min.; 5 -120 min.



Figure 9.5 - Influence of holding temperature at quenching with step-by step cooling upon the kinetics of  $\gamma_{ret} \rightarrow \alpha'$  DIMT of 30Cr13 steel:

1 – standard quenching from 1,050 °C in oil, holding temperature : 2 - 200 °C; 3 - 400 °C;

4 - 500 °C; 5 - 600 °C.

### 9.2.3 Superplasticity of cast alloys

Table 9.2 – Mechanical properties of silumin (~11 % Si) after deformation under conditions of superplasticity

Mode of treatment	UTS, MPa	VS MDa	Relative	Relative r
		ro, ivira	elongation (δ), %	eduction (ψ), %
Superplastic				
deformation +	195	180	8.0	25
cold rolling				
Cast state	110	70	1.0	1.5

### 9.2.4. Superplasticity at manufacturing of composite materials

The advantages of their manufacturing include the following:

- reduction of the probability of fragmentation of brittle fibers and ensuring high single reduction up to 40...50 %;

- formation of FCM under conditions of superplasticity at optimal rate and deformation temperature ensures a drastic reduction of power parameters of rolling, by 5-6 times as well as the duration of the manufacturing process;

- a possibility of obtaining FCM matrix foil blank with a rather high share of strengthening fiber (up to 60 %).

## Chapter 10

## **IONIC TREATMENT**

The essence of ion treatment is in bombarding the part's surface with ions or a bunch of ions. As a result of ion treatment ions penetrate into certain depth, bringing it the specified properties. The types of ionic treatment can be divided into:

□ ionic carburizing;

- □ ionic nitrading;
- □ ionic implantation with chemical elements.

### **10.1 Ionic carburizing**



Figure 10.1 - The scheme of a unit for ionic carburizing: 1-vacuum chamber (furnace); 2 - treated part; 3 - heat insulation; 4 - electric heaters; 5 - peep hole; 6 - feed unit of glow discharge; 7 - heaters feed unit; 8 - temperature measuring unit; 9 - the system of supply and dosage of gaseous mixture; 10 - air discharge system.



Figure 10.2 – Distribution of carbon and hardness along thickness of the carburized layer at two-staged mode of ionic carburizing: 1 - active period; 2 - diffusion period; 3 – hardness.

### **10.2 Ionic nitriding**



Figure 10.3 - Ionic nitriding of machine parts.

### **10.3.3 Physical fundamentals of the method of ionic implantation**

Three ion energy diapasons can be distinguished as follows:

- □ low energy diapason,  $E \approx 100...1000 \text{ eV}$ ;
- □ mean energy diapason,  $10^4 < E < 10^6 \text{ eV}$ ;
- □ high energy diapason,  $E > 10^6 \text{ eV}$ .



Figure 10.4 – The scheme of interaction of ion with atoms of target.



Figure 10.5 – Principal scheme of installation for ionic implantation:

1 – ionization chamber, 2 – lenses for acceleration and focusing; 3 – system of separation of ions; 4 – target; 5 – system of target heating; 6 – ions' beam.

In depend of sort of impinged ions the following functional properties may be achieved:

- □ high or lower coefficient of friction;
- □ high-strength condition;
- □ high wear resistance;
- □ high resistivity to corrosion and high-temperature oxidation;
- □ high adhesive ability;
- □ catalytic ability;
- □ high reflective ability;
- □ decoration attraction.

Chapter 11

## TECHNOLOGIES OF SURFACE STRENGTHENING WITH APPLICATION OF SOURCES OF CONCENTRATED ENERGY

## 11.1 Peculiarities of phase and structural transformations under conditions of accelerated concentrate heating and cooling

Table 11.1 - Main technical characteristics of highly concentrated heating sources

Heating source	Power, W	Power density, W/cm <sup>2</sup>	Efficient heating coefficient			
Gas flame	10 <sup>2</sup> 10 <sup>4</sup>	2·10 <sup>2</sup> 6·10 <sup>2</sup>	0,55			
Electric arc	502·10 <sup>5</sup>	5·10 <sup>2</sup> 4·10 <sup>4</sup>	0,75			
Plasma jet	10 <sup>3</sup> 10 <sup>5</sup>	5.10 <sup>2</sup> 10 <sup>5</sup>	0,80			
Beam:						
- Ionic	1010 <sup>3</sup>	10 <sup>2</sup> 10 <sup>5</sup>	0,85			
- Electron	1010 <sup>5</sup>	5·10 <sup>2</sup> 10 <sup>7</sup>	0,85			
- Laser	102,5·10 <sup>4</sup>	10 <sup>2</sup> 10 <sup>7</sup>	0,05			
- Sun heaters	10 <sup>2</sup> 10 <sup>5</sup>	10 <sup>2</sup> 2·10 <sup>3</sup>	0,75			

### **11.2 Laser strengthening**



Figure 11.1 a general view of a laser technological complex:

1 - laser installation; 2 - laser control console; 3 - programmed numerical control console for coordinates table; 4 - an optical system; 5 - rigid stand; 6 - coordinate table; 7 - air funnel.





a)

b)

- Figure 11.2 Laser hardening the surface of the product:
- a the process of quenching;
- b a robotic system for laser heat treatment.

### **11.3 Plasma surface strengthening**



Figure 11.3 - The diagram of a technological plasma complex. (a) and plasmatron for surface treatment (b, c): 1 – plasmatron; 2 - power source; 3 - mechanism of plasmatron travel; 4 - a system of plasma forming gas supply; 5 - cooling system; 6 - a part being treated; 7 - a mechanism of part's travel; 8 - automatic control system.



Figure 11.4 – Steels microstructure following plasma strengthening: a) hypoeuctectoid steel 30CrMnSi (0.3 % C); b) eutectoid steel (0.76 % C); c) - hypereuctectoid steel (1.0 % C).

### **11.4 Electron beam surface treatment**



Figure 11.5 - Scheme electron beam installation for heat treatment: 1 - high-voltage insulator; 2 - the anode; 3 - magnetic lens; 4 - deflection coil; 5 - working chamber; 6 – colony's valve; 7 - the electron gun.

# 11.5 Application of concentrated heat sources for formation of meta-stable states and improvement of alloys properties





Figure 11.7 – Changes of micro-hardness along the depth of the strengthened zone after plasma treatment (with macro-melting of 140Cr12Mo steel (1) and electron-beam treatment of 140Cr12V1 steel (2).

Figure 11.6 – Microstructure of tool steel 140Cr12V1: original (a) and after application of electron-beam treatment with melting (b); x400.

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Figure 11.8 – Micro-structure of the strengthened zone of stainless steel 20Cr13 after plasma treatment in different modes a - 1; b - 3; c - 4; (see, also, Table 11.3); the upper layer – the surface area, the middle row - the transitional zone, the lower row –the core x200.


a)



Figure 11.9 – Influence of the mode of plasma treatment upon changes in micro-hardness along the depth of the strengthened layer (a) and relative wear resistance (b) of 20Cr13 stainless steel (figures mean the number of mode of treatment in: 11.3 Table).

Table 11.3 – Operation parameters of plasma treatment of chromium steels

Nº Mode number	Current <i>I</i> , A	Gas consumption Q, m <sup>3</sup> /sec	Rate of motion <i>V</i> , m/h	Degree of plasma action
1		1.01.2	1619	heating without melting
2	400	2.0	1820	micro-melting
3		2.0	1517	medium melting
4		2.0	1314	macro-melting

Chapter 12

### TECNOLOGIES OF OBTAINING AMORPHOUS, MONOCRYSTALLINE AND NANO-STRUCTURED ALLOYS

# 12.1 The structure, properties of amorphous alloys and conditions of their amorphization

# Amorphous metals and alloys are characterizing by the following properties:

- high strength (in some alloys tensile strength limit reaches 4000...5000 MPa and much higher, exceeding the level of the strongest up-to-date steel grades);\
- □ high hardness (HV 900...1400);
- **G** good stability at cyclic elastic bending;
- □ high electric resistance;
- □ low temperature coefficient of electric resistance;
- □ high magnetic permeability;
- □ small or high (depending on the composition) coercion force;
- □ insignificant losses at reversal magnetization;
- □ high corrosion resistance;
- □ increased resistance to radiation.



Figure 12.1 – The TTT-diagram of the process of formation of phases in overcooled melt: a – critical cooling rate with formation of amorphous state; b – isothermal annealing of the amorphous state, leading to crystallization within  $\tau_x$  period of time; c – slow heating of the amorphous state, leading to crystallization at  $T_x$  –temperature.

### **12.2 Structural models of amorphous alloys**



Figure 12.2 – Five types of Bernal's polyhedrons in structural models.



Figure 12.3 – A principal diagram of appliances of obtaining of MG by means of quenching from liquid state (QMS): a – the methods of melt's deposition on a rotating disc or cylinder; b – the method of drawing of wire or a band out of the melt by a rapidly rotating disc, where: 1 – the melt; 2 –heating unit (induction furnace); 3 - band or wire of metallic glass; 4 - quartz pipe.



Figure 12.4 – Methods of obtaining amorphous metallic materials. 114

# 12.4 Ways of obtaining monocrystalline alloys, their properties and application in engineering

Table 12.1 – The properties and spheres of application of some amorphous metallic materials.

Property	Area of application	Alloy's composition		
High strength, high ductility	Wire, reinforcing materials, springs, cutting tools	Fe <sub>75</sub> Si <sub>15</sub> B <sub>10</sub>		
High corrosion resistance	Electrode materials, filters for working in acid solutions, sea	$Fe_{45}Cr_{25}Mo_{10}P_{13}C_7$		
High magnetic induction of	Transformers' rods, converters,	FeadBacCo		
saturation, low losses	throttles			
High magnetic permeability,	Magnetic heads and screens,	Fe <sub>5</sub> Co <sub>70</sub> Sl <sub>10</sub> B <sub>15</sub>		
low coercion force	magnetometers, signaling units			
Stability of moduli of elasticity and temperature coefficients of linear expansion	Invar or elinvar materials	Fe <sub>83</sub> B <sub>17</sub>		
High elasticity and Young's	Springs, membranes	Vitrovac-0080		
modulus		(78 % Ni, В и Si)		
High specific electric	Resistors	Ni <sub>68</sub> Si <sub>15</sub> B <sub>17</sub>		
resistance		Cu <sub>79</sub> Ag <sub>6</sub> P <sub>15</sub> 115		



Figure 12.5 – Methods of growing of monocrystals

### 12.4.1 Growing of monocrystals from solid phase

## Examples of obtaining monocrystals by applying these methods are:

- molybdenum or Ti-Mo alloy crystals are obtained by the method of deformation annealing 1...3 cm in size (elongation 1...3 %, annealing at 1,300...2,300 K for several hours);
- Andrade's method can be used for obtaining crystals of Al in a form of sheets and rods up to 1 in length (treatment at 650...950 K, motion rate 10-2 mm/sec);
- Crystals of diamond and boron nitride are obtained by the method of polymorphous transformations 0.1...0.5 cm in size (temperature 1600...2000 K, pressure up to 8 GPa);
- The method of thermal cycling can be applied for obtaining a-Zr crystals of centimeters size (treatment at 1,110...1,500 K within 10 days).

### **12.4.2 Growing of monocrystals from liquid phase**

## Examples of application of the methods of growing monocrystals from liquid phase are the following:

- The methods of Strong-Schteber and Nacken's method are more often used for growing large crystals of easily melted organic substances (like naphthalene, 20...50 cm; potassium biphtalate, 1...20 cm in size);
- The methods of Bridgeman-Stockbarger and Kiropoulos are used for growing of crystals of inorganic salts (NaCl and KCl 20...90 cm in size);
- The methods of Chochralsky and zone melting for metal and semi-conductors crystals методы (Ge, Si, GdAs, ZnAs1...50 cm in size);
- Stepanov's method is used for obtaining metal crystals of complicate shape (Aluminium tubes and turbines blades up to 1m);
- Verneil's method is used for heat-resistant oxides and salts, alloyed with admixtures (corundum and ruby in the form of rods up to 3 m long).

### **12.6 Nanotechnologies in Metal Science**







Figure 12.6 –The structure of nano-structured steels: a – sub-grains in ferrite size 300...1,000 nм, x10,000; b – sub-grains in bainite size 200...500 nм, x56,000.



Figure - 12. 7 – The leading part of meso-structure (scale level of grain fragments and dislocation substructures 50: 100...3,000 nm) in formation of mechanical properties of steels.

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### Chapter 13

### DESIGN FUNCTIONAL META-STABLE MATERIALS SELF-STRENGTHENING AT OPERATION AND STRENGTHENING TECHNOLOGIES

# 13.1 Principles of design meta-stable materials and strengthening technologies

The principle of developing and systematic controlled using of phase meta-stable states and transitions, realized under the influence of exploitation media :

□ Phase-deformational meta-stable state;

□ Structural-deformational meta-stable state;

□ Atomic-crystallite meta-stable state;

## Classification of phase-morphological types of meta-stable austenite:

- $\Box$  the main phase-austenite (A);
- $\Box$  original austenite (A<sub>1</sub>) crystallized from liquid state;
- eutectic austenite (A<sub>e</sub>), containing within the structure of eutectic colonies;
- □ retained austenite (A<sub>ret</sub>), preserved after martensite transformation;
- □ retained austenite (A<sup>b</sup><sub>ret</sub>), preserved after bainite transformation;
- $\Box$  reversed austenite (A<sub>p</sub>), preserved after heating of ( $\alpha + \gamma$ ) zone;
- $\Box$  attendant  $\gamma$ -phase in dual-phase austenite-ferrite ( $\alpha + \gamma$ ) alloys;
- over-saturated austenite (A<sub>o.s.</sub>), crystallized from liquid state after: plasma, electron-beam or laser fusion;
- austenite, crystallized at heating of alloys from amorphous state (A<sub>a</sub>);
- $\Box$  main, residual or attendant, formed in powder alloys (A<sub>p</sub>);
- □ nitric austenite  $(A_N)$  solid solution of nitrogen introduction in  $\gamma$ -iron.

Physical-chemical mechanisms and factors of stabilization (or destabilization factors) of austenite:

□ chemical composition of austenite;

□ thermal, mechanical stabilization of austenite;

□ structural-phase factors;

□ kinetics factors;

□ high power and other factors.

#### The complexity principle is employed:

- $\Box$  for alloying;
- □ for developing of production and treatment technologies;
- □ for obtaining meta-stable states, owing to the use of physical and chemical mechanisms and stabilization factors;
- for combining in one alloy (if possible) all known strengthening mechanisms, plasticization and mechanisms obtaining some special properties alongside with the mechanisms of DIPT;
- □ for improvement of the entire complex of physical, mechanical and exploitation properties, which are often of alternative character and hard to combined in a single alloy.

The principle of interaction between the kinetics of formation of physical and mechanical properties and the kinetics of DIPT and DIMT realization:

 $\Box$  coefficient of deformational strengthening (K<sub>d</sub>);

□ the value of deformational strengthening by means of DIMT;

□ the limit of torsion strength;

plasticity is a relative shift during torsion;

□ impact strength (energy);

□ the fatigue limit;

□ relative impact-abrasive wear-resistance.

The principle of control over properties of meta-stable alloys by means of controlling phase composition, kinetics of DIPT and the structure forming. In case of necessity, meta-stability of the originally stable alloy may be created during the process of exploitation, owing to the impact of the media of exploitation.

The principle of raising energy intensity of meta-stable alloys, which possess improved energy intensity, unlike phase-stable materials. DIPT, developing inside them require absorption of external action power for the processes of phase transformations and are used as mechanisms of increasing and redistribution of the energy intensity, due to selfstrengthening, relaxation of stresses, increase in plasticity and slowing down of crack formation and development.

The principles of synergism and self organization, according to which meta-stable material is a self-organizing system owing to DIPT development and is better adapted to condition of exploitation media, the properties are increased due to optimum of DIPT kinetics.



Figure 13.1 - The general scheme of phase-structural evolution of a metastable alloy within its service life.



Figure 13.2 - The scheme of structural evolution of creation of metastability during the alloy's service life.

### 13.2 The examples of design a new functional lean-alloyed meta-stable alloys



Figure 13.3 - Multifunctional materials and strengthening technologies, which realized meta-stable state and effect of phase-structural self-organizing during operation. 14.04.2016 129

### **NEW HIGH-STRENGTH LEAN-ALLOYED STEELS.**

Table 13.1 - Mechanical properties of the known and developed high-strength steels

Steel grades	TS (σ <sub>в</sub> ), MPa	ΥS(σ <sub>0,2</sub> ), MPa	elongation, %	reduction, %	KCU, MJ/m²	
KNOWN CHROMIUM-NICKEL STEELS						
(QUENCHING 1000 ℃ IN OIL, SUB-ZERO –70 ℃, AGING 450 ℃)						
09CR15NI8AL	1300	1100	15	60	1.0	
07CR16NI6	1300	1150	20	69	1.0	
DEVELOPED CHROMIUM-MANGANESE STEELS						
(QUENCHING 1000 ℃ IN OIL, TEMPERING 200 ℃)						
13Cr13Mn7Si 1510		950	19	28	1.15	
10Cr14NMn6 1720		1170	14	28	1.2	
30Cr2Mn6Si2V	1910	1460	16	60	0.65	

### New corrosion-resistant lean-alloyed (nickel-free) steels.

Table 13.2 - Mechanical properties of corrosion-resistant steels after quenching with 1100 °C

Steel grades	TS,MPa	YS, MPa	Relative elongation, %	Relative reductin, %	KCU, MJ/m²	KCV, MJ/m²
Developed chromium-manganese steels						
08Cr18Mn 6SiV	1120	485	34	36	-	3.75
08Cr22Mn 6SiV	700	510	46	67	-	3.3
17Cr 16Mn12Cu2Si Ti	930	680	32	30	2.8	-
Known chromium-nickel steels						
08Cr22Ni6 Ti	680	410	40	45	2.5	-
10Cr18Ni 9	441	177	25	35	0.98	-



Figure 13.4 - Pump components from new lean-alloyed corrosion resistant steel 12Cr16Mn10CuSiTi for seawater and other liquids of medium aggressiveness: a) casting for the guiding device; b) working wheel; c) drain pipe.

### New heat-resistant lean-alloyed steels (nickel-free).



Figure 13.5 - Fasteners of thermal furnace from nickel-free heat resistant steel 35Cr23Mn3Si2V:

Advantages of new corrosion-resistant, high-strength and heat-resistant steels include:

□ saving of 70...100 kg of deficit and expensive nickel per ton of produced steels;

□ production cost reduction for steels by \$ 350...500 per ton;

□ improvement of mechanical properties (TS ( $\sigma_B$ ); YS ( $\sigma_{0,2}$ ); elongation, reduction, KCU, KCV) by 30...50 % as compared to more expensive standard steels, containing 7...10 % nickel.

### Wear resistance alloyed cast irons.



Figure 13.6 - Microstructure of the cast-iron 260Cr15Mn4Ti after quenching from the temperatures: 800 °C (a), 900 °C (b), 1050 °C (c), 1150 °C (d) and tempering at 250 °C, x 500.



Figure 13.7: The curves of wears (a) and the kinetics of DIMT (b) in a superficial layer in the process of wear of cast irons:

- 1-360Cr5Mn4Cu2;
- 2- 320Cr12Mn3Cu2;
- 3 290Cr20Mn3Cu



Figure 13.8 - Original appearance of blade of vehicle for throwing of shot (a) and scoop of vehicle for throwing of sand (b).



Figure 13.9 - Protective plates made of lean-alloyed cast iron 250Cr15Mn5TiAl before operation (a), after operation (b), breaking off knives after operation (c) during a one year.

## **THANK YOU FOR YOU ATTENTION**