

**Ministry of Education and Science of Ukraine  
Ternopil Ivan Puluj National Technical University**

*Department of building mechanics*

**Notes and laboratory reports on  
“Technology of Structural materials and  
Material Science”  
Part 2**

***“Material Science”***

for students of “Engineering mechanics” *field of study 6.050502*

Student \_\_\_\_\_

Faculty \_\_\_\_\_

Course \_\_\_\_\_ Group \_\_\_\_\_

**Ternopil  
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**Authors:**                   **H.M. Kramar**  
                                     **L.H. Bodrova**

**Reviewer:**               **Ia.O.Kovalchuk**

The notes and laboratory reports have been approved at the meeting of building mechanics department (minutes № 4 from 6 February 2017)

The notes and laboratory reports have been approved by the Mechanical Engineering Faculty methodological committee (minutes № 4 from 10 February 2017)

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### Introduction

“Technology of Structural materials and Material Science” is one of the basic technical disciplines in the syllabus for “Engineering mechanics” field of study.

During the implementation of laboratory work considerable attention is given to the educational and experimental work for the study of materials that are used in different branches of an industry; alloy’s properties dependence on the chemical composition; structure, methods of treatment and external environments. The study of the theory and practice of different methods of materials strengthening is to provide a high reliability and longevity of the machine’s details, devices, tools etc.

After every practical class in the laboratory, students will fill the laboratory report. The content of the laboratory class corresponds with the syllabus of the course “Material Science” for students of the “Engineering mechanics” field of study.

The purpose of this manual is to provide guidelines for the students in preparation for independent laboratory work and to project its results in the laboratory reports.

## **Safety during lab activities**

The laboratory classes for “Material Science” will take place in the education-research laboratories of the department of building mechanics. The observation of the safety requirements is necessary during labs activities.

Students who are not taking part in the lab activities, must seat at their desks.

### **Students can't:**

- store any unnecessary things, which are not used during the lab on the work place;
- whirl adjustment knob of microscope, machine for tensile strength and hardness testing and other devices, if it is not used during labs activities.
- turn on machine-tools, weld transformer, presses etc.

### **Students can do labs only when they are supervised by a teacher.**

Labs equipment has high voltage (220 or 380 V).

To prevent danger by electrical current, **it is prohibited to:**

- turn on equipment that is not used during labs;
- open the doors of the electrical wardrobe and furnace;
- transfer equipment and devices.

Before turning on an equipment student must see that it is safe to do so. When a student observes that equipment has defects, it is prohibited to turn on voltage. The student must report such to the teacher immediately.

During some lab classes, students will use chemical substances. When chemical substance comes in contact with the student's skin or eyes, it is necessary to wash with water immediately.

During the lab classes that require equipment with heating, beware of catching fire with your clothes and skin burn.

Violation of these safety rules may lead to unhappy accidents.

**Follow these safety rules strictly!**

Laboratory work 1  
**MACROSCOPIC ANALYSIS OF STEEL GOODS**

**Objectives**

Studying the nature of the distribution of impurities in metals and alloys, the influence of the mode of production (welding, forging, casting) on the structure of individual zones macro metal methods analysis. Research kinks steel products and alloys based on non-ferrous metals.

**Scientific principles**

**Macroscopic analysis** is to examine the structure of metals and alloys without the use of any device and (or) through a magnifying glass at low magnification (30 times).

Macroscopic analysis allows to conclude that the structure of the metal or the sample as a whole. The structure of metals, which studied using macro analysis, called **macrostructure**.

Methods of studying the macrostructure are divided into three main groups: **deep and surface etching and prints**. Etching methods give information about material defects associated with its receipt and processing.

**Deep etching** reveals cracks, without carbon layers, saturated carbon layers and nitrided layers segregation of harmful impurities, dendritic structure. After deep etching macro grinding has a textured surface on which presents visible elements of the macrostructure and defects.

**Surface etching** reveals some details of the structure and conduct further microscopic study. It requires a thorough preparation surface grinding (fine grinding), especially for the evaluation of grain size and shape, determination variety of grain, grain growth direction.

**Print method** means that the image does not appear on the macrostructure but on photographic paper. Density contact of metal surface with photo paper must be complete; there shall be no air bubbles. Reagents react with certain structural elements, forming a characteristic color patterns. The most widely used method of print to identify the distribution of sulfur method (Bauman).

**The main objectives of macro study are:**

1. Identify hidden defects metal – cracks, porosity, films and zonal heterogeneity.
2. Identify the nature of the crystal structure of the metal.
3. Detection of impurities in the metal and the nature of their distribution.
4. Detection of metal structure after thermo mechanical processing.
5. Identify the structure of heat-treated or weld products (zone hardening, carburizing, thermal effects).

**Identifying hidden defects of metal.**

This problem is often solved by deep etching. Defects such as cracks (after hardening), separation of the metal are not visible on the surface even with a magnifying glass. Subjecting the products of such defects acids, we "uncover" them and as a result of vigorous erosion surface.

For this purpose a mixture of hydrochloric acid, sulfuric acid and distilled water use. To speed up the action reagent used it heated to 50°C. Etching time is depending on the composition of steel (from 20 minutes to 2 hours). The same reagent is used to identify dendritic structure. In this case, the duration is much shorter.

Also use a 20% solution of sulfuric acid heated to 60°C condition (time of up to 2 hours.).

#### ***Identifying the nature of the crystal structure.***

In the metal can be formed as granular and dendritic structure. Dendritic structure is the initial stage of crystallization of the metal, further development of which leads to the formation of homogeneous microstructure or granular structure.

Under certain etching methods can simultaneously detect both structures, showing their relationship. Fair active reagents such as reagent Heine (10% solution of aqueous solution of perchloric double salt of copper and ammonia), exhibit primarily grain boundaries. With more vigorous reagents (acid solution) can be found dendritic structure. To identify dendritic structure in carbon steels used reagents:

- 10% solution of ammonium persulfate  $(\text{NH}_4)_2\text{S}_2\text{O}_8$  heated at 80-90°C for 5-10 minutes;

- Reagent Keshiyena a mixture of concentrated hydrochloric and sulfuric acid and distilled water for 20 - 25 minutes at room temperature.

Macro grinding of steel, pre-wipe with alcohol, immerses the ground surface in one of the reagents. After holding samples were washed with water and analyzed.

#### ***Identification of impurities and the nature of their distribution.***

Chemical analysis gives the average content of metal elements in the sample, but not gives an idea of their distribution. Heterogeneity of chemical composition by volume castings, parts, grain, which occurs during the crystallization of metal, is called *liquation (phase separation)*. Most prone to liquation is sulfur, phosphorus, to a lesser extent – silicon, manganese, carbon occupies an intermediate position. Method of detection heterogeneity distribution of impurities is based on different locations with different color of their content.

Sulfur in steels is harmful element and its accumulation in certain areas of the structure causes increased fragility. To detect liquation of sulfur in steel specimen ***the method Bauman*** is using. Doing the following:

- Specimen wipe with cotton wool moistened with alcohol, and put on the table the ground surface up;

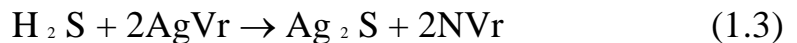
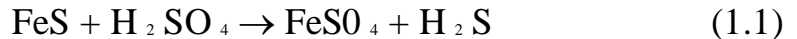
- Leaf glossy bromide silver photographic paper at light soak for 3 ... 5 min in 5 % aqueous solution of sulfuric acid, to dry between two sheets of filter paper to remove excess solution;

- Impose a photographic emulsion side on the work surface macro grinding, remove air bubbles;

- To withstand photographic macro grinding for 2 to 3 minutes, squeezing them together and carefully remove the photo paper;
- The resulting washes water mark, fixed in 25% aqueous solution of hyposulfite, rinse again with water and dried.

Getting on photo paper brown areas indicate the places enriched sulfur (sulfide clusters). If the photo paper has a uniform color, the sulfur is placed evenly.

In the boundary layers of metal, where are impurities of sulfur (as FeS, MnS) the interactions happen:



Gaseous hydrogen sulfide, which is released in areas where there is sulfur, acting on photo paper with the formation of  $\text{Ag}_2\text{S}$ . After this fix photo paper 10-15% hypo solution of sulfite. Sensitive layer of paper appear dark blotches that match the sulfur impurities in the metal. In addition, the relative density of inclusions can conclude the pollution with sulfur. Phosphorus in this way does not define.

**Method Heine** reveals liquation of phosphorus. Grinding sample, wipe with alcohol, immersed in a 10-12% solution of aqueous chloric double salt of copper and ammonium ground surface for 1-2 minutes. After washing grinding sample dried at filter paper. Places enriched with phosphorus, painted a dark color.

### **Study of breaks, their classification and characteristic features.**

At the macro analysis widely used method fractography. **Fractography** exploring structure breaks. Fracture is a kind of photo destruction process, structural condition and material properties in the local volume.

For the analysis using the newly formed fracture surfaces without mechanical damage, traces of oxidation, dirt etc. The presence of oxides, traces of oil paints may provide additional information on the conditions of formation of cracks. Macro analysis begin to break the surface destruction due to the naked eye or with a magnifying glass (increase 5 ... 10 times) and slowly moving to an increase of 20 ... 120 times.

When carrying out the macro analysis evaluated fracture and classified in the following **main features**: orientation fracture surfaces, macro geometry, the degree of plastic deformation, roughness, color.

Orientation of fracture associated with the nature of load and stress state, normal and tangential stresses, which determine the fracture.

**For orientation fracture surfaces** breaks are classified as straight, slanting and straight with slanting (cup).

**Direct** (Fig. 1.1) is called fracture which surface is oriented normal to the axis of the sample or product that is perpendicular to the direction of greatest tension efforts. This fracture orientation is a characteristic feature of brittle fracture.

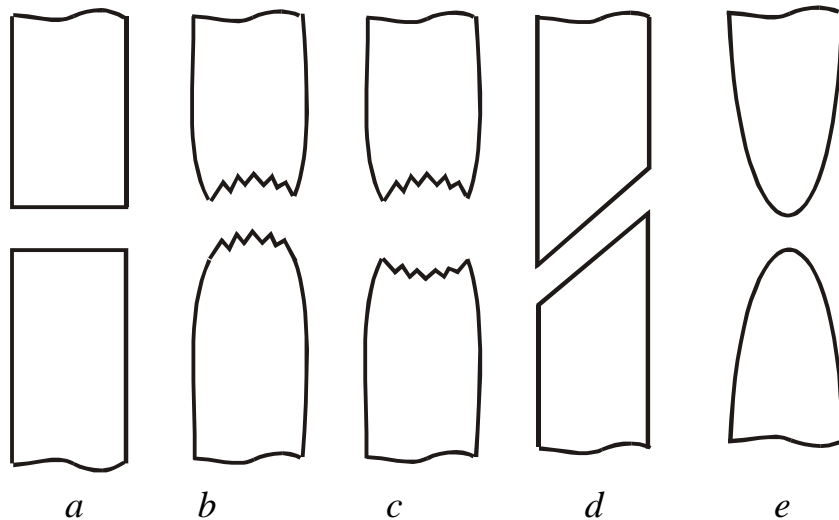


Fig.1.1. Specific types of fractures in tension  
 a) straight, b) straight and bevel type "cup - Cone"  
 c) straight from the bevel type "double cup", d) slanting, e) cone.

*Oblique* (slanting) fracture surface is inclined at an angle to the axis of the sample is formed by a cut in the plane of greatest stress. This fracture occurs in the destruction of anisotropic materials with limited ductility.

*Straight fracture with a slant* (cup) is formed of smooth cylindrical tensile specimens (usually alloyed steels).

Formation of the "cup" is associated with the formation of a neck in a deformed sample, leading to significant lateral and axial stresses in the center of the sample.

The presence of the side edges of cuts fracture is a sign macro viscous destruction. For maximum realization of plasticity of the material in the zone of fracture in tension may be formed entirely *conical* fractures, characteristic only for very ductile materials (plumbum, pure aluminum, electrolytic copper).

Type of fracture is the criterion of evaluation of quality material. There conditional division of breaks on **brittle** and **plastic**.

**For macro geometry** breaks divided into homogeneous and heterogeneous.

For **homogeneous** breaks characterized morphologically identical surface, this is rare, such as a fracture of brittle materials, carbon steel at low temperatures.

Most fractures **are heterogeneous**. This may be due to two reasons:

- Heterogeneity of the studied material chemical composition, structure, properties (anisotropy of material);
- Features of the destruction process associated with the original heterogeneity of the stress and strain state.

Heterogeneity of fracture surface visually visible with the change of roughness on different parts of fracture. At fatigue destruction roughness by the surface can be divided into areas: nucleation of cracks 2, development of fatigue destruction 3 (small roughness) and static fracture 4 (high roughness) (see Fig. 1.2). In addition, the sample shows a cut (stress concentrators).



For section 3 fatigue destruction characteristic by fine-grained structure, smooth matte surface.

Areas of fracture formed at the final stage of destruction as a result of fatigue fracture cross-sectional size decreases to a critical value and cyclic tension reaches the boundary strength. In the area of brittle materials fracture has large crystalline structure and for viscous materials are characteristic fibrous structure and plastic braces along the periphery of the sample (Fig. 1.2 b, pos. 4).

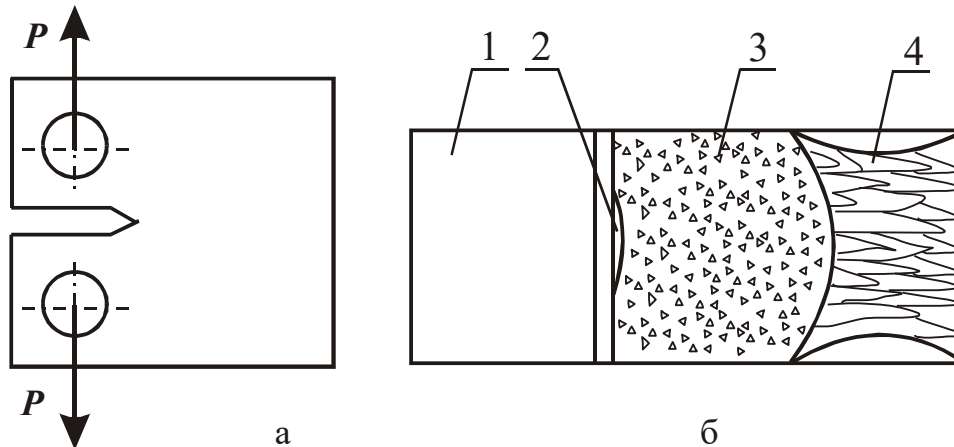


Figure. 1.2. The standard model for testing the strength of materials under cyclic loading (a) and scheme of fatigue destruction (b)

In real structures stress concentrators, which can begin fatigue, are:

- Design (grooves, ledges, etc.);
- Technological (low quality machining, cracks after forming by pressure and heat treatment);
- Metallurgical defects (structural heterogeneity of the material, liquation of sulfur and phosphorus in steel, etc.).

**Fractography** researches are mandatory peer review in surface damage in real structures. These results make it possible to identify the causes of destruction for them in the future.

Classification of fractures *with help of surface roughness*.

The presence of crystalline fracture is one of the characteristic features of brittle fracture, and the presence of fiber - viscous. Among the defects that cannot be eliminated and are caused by violation of the technology of heat and hot machining, shall break, that has large crystalline structure and forms on surface smooth, shiny areas of nonmetallic look like.

For *degree of plastic deformation* fracture divided into *brittle, quasi brittle and viscous*.

The difference *by color* is one of the characteristic signs of fractures related to structure, test conditions and the presence of alloying elements in steel. Carbon steel have silver color of breakdown, nickel - light gray. Manganese steel provides a breakdown characteristic dull gray color.

### **Materials and Equipment:**

1. Set of samples.
2. Sandpaper.
3. 5% solution of sulfuric acid.
4. Hypo solution sulfate.
5. Sheets of photo paper.
6. Filter paper.
7. Reactive Keshiyena.
8. Cups for reagent.
9. Foot 9 x 12, 11 x 19.
10. Magnifier.

### **Procedure:**

1. Get samples for macro research.
- 2 Draw and analyze defects, found in samples obtained by casting production or after rolling.
3. Clean up by sandpaper the surface of macro samples, clean with gasoline wool.
- 4 In the case of large sample set them horizontally on the stand.
- 5 Perform test by Bauman.
- 6 Rinse the surface with cotton wool and dry filter paper.
- 7 The print paste in the protocol.
- 8 Examine the collection of breaks, describe them and sketch the resulting structure.
- 9 Remove the workplace.
10. Fill report.

### **Questions:**

1. Define macroanalysis.
2. Explain the purpose (objectives) of macroanalysis.
3. Define macrostructure.
4. Explain macroanalysis methods.
5. Which of metal defects are called "hidden"?
6. Explain possible impurities in metals.
7. Explain types of crystal structure of the metal.
8. Explain types of metal fracture.
9. List the criteria for classifying metal fracture.
10. Explain effect of phosphorus and sulfur on the properties of steel.
11. Explain how impurities in the metal are located.
12. Define liquation.
13. Define anisotropy.
14. Define polymorphism.
15. Explain Bauman method.
16. Explain effect of alloyed metals on the color of fracture.

**MACROSCOPIC ANALYSIS OF STEEL GOODS**

**PURPOSE OF WORK:-**

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**DEVICES AND MATERIALS:**

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PROTOCOL № 1 (SAMPLE № 1)

Name of sample \_\_\_\_\_

Material \_\_\_\_\_

Description of macrostructure and identified defects: \_\_\_\_\_

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*Method of manufacturing sample*

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Figure

PROTOCOL № 2 (Bauman method)

Name of sample \_\_\_\_\_

Material \_\_\_\_\_

Description of macrostructure and identified defects: \_\_\_\_\_

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Conclusion:

\_\_\_\_\_  
(conclude the existence of sulphur liquation)

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PROTOCOL № 3

Name of sample \_\_\_\_\_

Material \_\_\_\_\_

Description of fracture by characteristic features: \_\_\_\_\_

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Mechanism of destruction \_\_\_\_\_

\_\_\_\_\_

Figure

PROTOCOL № 4

Name of sample \_\_\_\_\_

Material \_\_\_\_\_

Description of fracture by characteristic features: \_\_\_\_\_

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Figure

Conclusions: \_\_\_\_\_

(analyze the macrostructure of various metals and alloys, the reasons that led to the destruction)

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\_\_\_\_\_

Student's signature  
" \_\_\_\_\_ " \_\_\_\_\_ 20\_\_ y.

Teacher's signature  
" \_\_\_\_\_ " \_\_\_\_\_ 20\_\_ y.

LABORATORY WORK № 2  
**CRYSTALLIZATION PROCESS**

**Objectives**

1. To understand what the metallic bonding is and its effect on metal properties.
2. To learn about crystallization process of the water solution drop of various salts, which is a model of metal.

**Scientific principles**

There are three aggregate states of metals: crystalline, liquid and gaseous. In the gaseous state they do not differ from non-metals, and in liquid and crystalline the states are specific characteristics. Properties of the metals give **the metallic bonding** – bond between the metallic ions and the negative electron “cloud”.

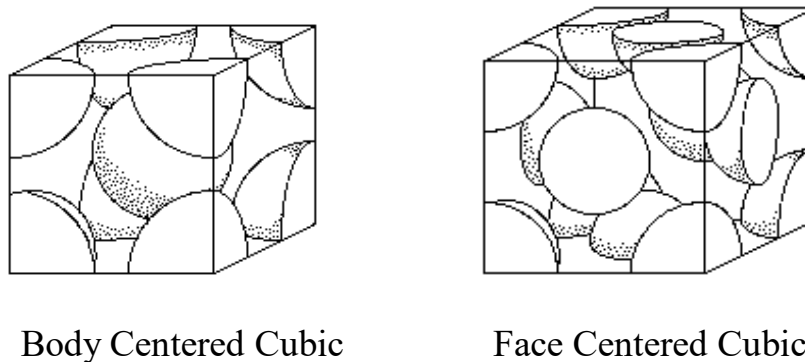
Above their melting point, metals are liquids, and their atoms are randomly arranged and relatively free to move. However, when cooled below their melting point, metals rearrange to form ordered, crystalline structures.

The smallest repeating array of atoms in a crystal is called a **unit cell**. The three dimensional array formed by the unit cells of a crystal is called **lattice**.

The majority of metals have one of **three well-packed crystal structures**:

- Face-centered cubic (F.C.C.): Aluminum,  $\gamma$ -Iron, Nickel, Copper, Lead, Gold, Platinum
- Body-centered cubic (B.C.C.) Chromium,  $\alpha$ -Iron, Niobium, Vanadium, Silver
- Hexagonal-close-packed (H.C.P.): Cadmium, Cobalt, Titanium, Zinc, Zirconium, Magnesium.

Unit cell structures determine some of the properties of metals. For example, FCC structures are more likely to be ductile than BCC, (body centered cubic) or HCP (hexagonal close packed). Figure 2.1 shows the FCC and BCC unit cells.



**Fig. 2.1.**    Unit cells for BCC and FCC.

**Basic descriptions** of unit cell are:

*Lattice parameter*, or period, – it is distance between neighboring atoms;  
*closeness of packing* – amount of atoms, that is on an elementary unit cell.

### **Crystal defects**

The most important crystal defects are:

- Vacancies
- Interstitials
- Dislocations

#### **Vacancies:**

Vacancies are simply empty atom. By successive jumps of atoms, it is possible for a vacancy to move in the lattice structure and therefore play an important part in diffusion of atoms through the lattice.

#### **Interstitials:**

It is possible that some atoms may fall into interstitial positions or in the spaces of the lattice structure which may not be used by the atoms of a specific unit cell. Interstitials tend to push the surrounding atoms farther apart and also produce distortion of the lattice planes.

Interstitial atoms may be produced by the severe local distortion during plastic deformation.

#### **Dislocations:**

A **dislocation may be defined** as a disturbed region between two substantially perfect parts of a crystal. A dislocation is a linear defect around which some of the atoms are misaligned. Two simple types of dislocation are :

- Edge dislocation
- Screw dislocation

Dislocations can be observed in crystalline materials using electron-microscopic techniques. Virtually all crystalline materials contain some dislocations that were introduced during solidification, during plastic deformation, and as consequence of thermal stresses that result from rapid cooling.

The importance of dislocations to the metal user is that dislocation interactions within a metal are a primary means by which metals are deformed and strengthened. When metals deform by dislocation motion, the more barriers the dislocations meet, the stronger the metal.

Deformation by dislocation motion is one of the characteristics of metals that make them the most useful engineering materials. The metallic bond is such that strains to the crystal lattice are accommodated by dislocation motion. Many metals can tolerate significant plastic deformation before failing.

The crystallization process is a basic part of the technological process of obtaining goods by **casting**.

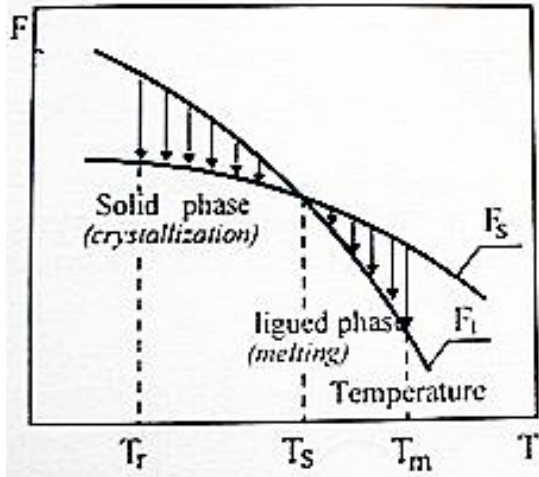
A **primary crystallization process** is the transition from the liquid to the solid state with forming of crystalline lattice.

Crystallization begins after some overcooling of liquid metal below the equilibrium **temperature of crystallization** (or theoretical temperature of crystallization)  $T_s$  (fig.2.3). At a temperature the  $T_s$  both phases (liquid and solid) are found in equilibrium and the process of crystallization or process of melting does not take place.

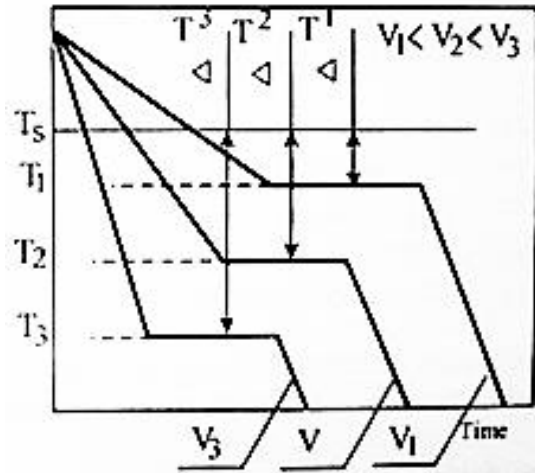
Thus, the process of crystallization can pass only at overcooling of metal below than equilibrium temperature  $T_s$ . Difference between theoretical temperature  $T_s$  and real temperatures of crystallization  $T_r$  is called **the overcooling degree**:

$$\Delta T = T_s - T_r \quad (2.1)$$

The degree of overcooling is not a permanent size (fig.2.4). It depends on speed of cooling, nature and cleanness of metal.



**Fig.2.3.** Change of free energy of the state liquid and crystalline depending on a temperature.



**Fig. 2.4.** Curve cooling during crystallization.

### **Stages of crystallization process**

The crystallization process occurs in two stages:

1. Nucleus formation.
2. Crystal growth.

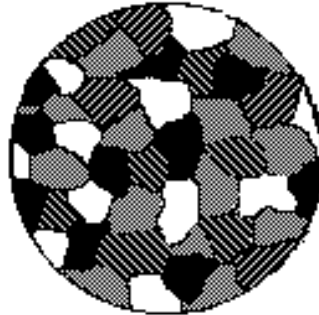
As the energy in the liquid system decreases, the movement of the atoms decreases and the probability increases for the arrangement of a number of atoms into a characteristic lattice for that material.

If crystal growth continues in three dimensions, the atoms attaching themselves in certain preferred directions, usually along the axes of a crystal. This gives rise to a characteristic treelike structure which is called **dendrite**.

As atoms of melted metal begin to pack together to form a crystal lattice, groups of these atoms form small crystals. These small crystals increase in size by the progressive addition of atoms. The resulting solid is not one crystal but actually many smaller crystals, called **grains**. The interface formed between them is called a **grain boundary**

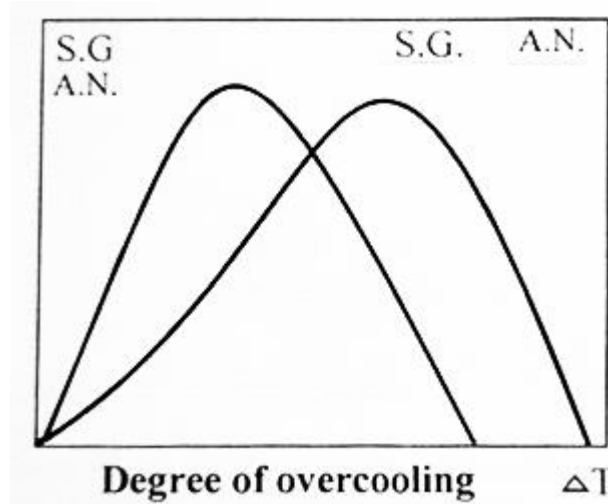
In a metal can show up both graininess and dendrite structure. The dendrite structure is the initial stage of consolidation of metal, further development of which results in formation of graininess structure.

Grains are sometimes large enough to be visible under an ordinary light microscope or even to the unaided eye. Fig.2.5 shows a typical view of a metal surface with many grains, or crystals.



**Fig.2.5. Grains and Grain Boundaries for a Metal.**

The amount of nucleus (A.N.) formed in a metal, and speed of crystals growth (S.G.) depends on the degree of system's overcooling which in the turn depends on cooling speed (fig.2.6).



**Fig.2.6. Speed of growth and amount of nucleus depending on the degree of overcooling.**

For metals and alloys cooled AN and SG does not achieve a maximum, so as metals in the liquid state a small weakness is fed to overcooling.

Crystallization at the large degrees of overcooling is instrumental in formation of shallow grainy structure. Consequently, changing speed of cooling it is possible to get the grains of a different size.

The size of grains is found in such dependence on the amount of nucleus and speed of growth:

$$d = 1,14 \sqrt{\left(\frac{s.g.}{a.n.}\right)^3} \quad (2.2).$$



### **Phenomenon of anisotropy and polymorphism**

**Anisotropy** is difference of crystalline bodies' properties in various directions. It is due to the different distances and, consequently, by different values of communication forces between ions in different directions in a crystal.

**Polymorphism** is a physical phenomenon where a material may have more than one unit cell. A material that shows polymorphism exists in more than one type of space lattice in the solid phase. If the change in structure is reversible, then the polymorphic change is known as **allotropy**. Different crystalline structures of the same element are called its polymorphic **modifications** and marked by the initial letters of the Greek alphabet, beginning from low temperatures ( $Fe_{\alpha}$ ,  $Fe_{\gamma}$ ;  $Co_{\alpha}$ ,  $Co_{\beta}$ ;  $Mn_{\alpha}$ ,  $Mn_{\beta}$ ,  $Mn_{\gamma}$ ,  $Mn_{\delta}$  and etc.)

**There are two mechanisms** of formation of centers of crystallization: **spontaneous and heterogeneous**.

A **spontaneous mechanism of formation passes** in a pure liquid metal only. For a liquid there is a characteristic fellow creature order in disposing of atoms, that is only in separate micro volume the well-organized disposing of atoms is saved, that answered the hard state. As a result of thermal motion a fellow creature order is unsteady, and to that with the decline of temperature an amount and size of such micro volume is multiplied. At the temperatures of crystallization they grow into the nucleus of solid phase. Formation of nucleus causes reduction of free energy due to transition of some volume from the liquid state in solid one.

**Heterogeneous** formation of nucleus passes on prepared bases which are solid particles in an alloy, walls of form, impurities. In the real terms of formation of nucleus passes by a heterogeneous mechanism.

### **Materials and Equipment:**

1. Kitchen-range.
2. Chemical cups for water solution of salts.
3. Water solution of salts ( $K_2Cr_2O_7$  and  $CuSO_4$ )
4. Glass stick.
5. Glass plate.
6. Biological microscope.

### **Procedure:**

1. Get equipment and water solution of salts.
2. Heat the water solution of salt to a temperature of 70-80 °C.
3. Set glass plate on a microscope, inflict a drop of  $K_2Cr_2O_7$  and watch the process of crystallization (stages and structure).
4. Set glass plate on a microscope, inflict a drop of  $CuSO_4$  and watch the process of crystallization (stages and structure).
5. In both cases, draw crystal structure on the first and second stage of crystallization.

*Questions:*

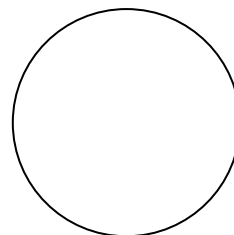
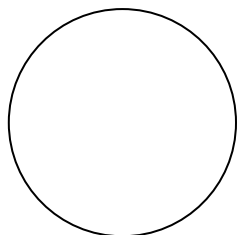
1. What is metallic bonding?
2. What are the structures of crystalline body?
3. What is a unit cell?
4. What are the types of lattice structure?
5. What is the different between F.C.C. and B.C.C.?
6. What are descriptions of a unit cell?
7. What are the defects of crystal structure?
8. What is a primary crystallization process?
9. What is the overcooling degree? Write formula.
10. Plot a graph showing the change of free energy of the liquid and crystalline phases on a temperature.
11. What are stages of crystallization process?
12. What kinds of crystalline structures do you know?
13. What are the mechanisms of crystallization process?
14. How do you determine grain size?
15. What is anisotropy?
16. What is polymorphism?
17. Which elements of Mendeleev's Periodic Table have polymorphic modifications and give an example how it marked?

LABORATORY REPORT №2  
**CRYSTALLIZATION PROCESS**

PROTOCOL №1

The name of the salt \_\_\_\_\_

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The crystalline structure  
at the beginning of crystallization

The crystalline structure  
at the end of crystallization

**Conclusion:**

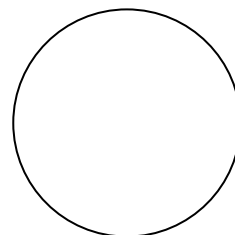
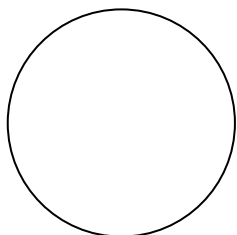
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PROTOCOL №2

The name of the salt \_\_\_\_\_



The crystalline structure  
at the beginning of crystallization

The crystalline structure  
at the end of crystallization

Conclusion: \_\_\_\_\_

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General conclusion: \_\_\_\_\_

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Student's signature

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Teacher's signature

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LABORATORY WORK № 3  
**PROCESS OF PLASTIC DEFORMATION**

**Objectives**

1. To learn the influence of plastic deformation and temperature on aluminum grain's size after recrystallization.
2. To learn the influence of plastic deformation and recrystallization on aluminum properties.
3. To learn how to determine the critical degree of deformation and recrystallization temperature.

**Scientific principles**

When small loads (stresses) are applied to metals they deform, and they return to their original shape when the load is released. This is called **elastic deformation** and involves temporary stretching or bending of bonds between atoms.

When higher stresses are applied plastic deformation take place. The **plastic deformation** involves the breaking of bonds, often by the motion of dislocations. Dislocations move easily in metals, due to the delocalized bonding (fig.3.1). This largely explains why metals are ductile, while ceramics are brittle.

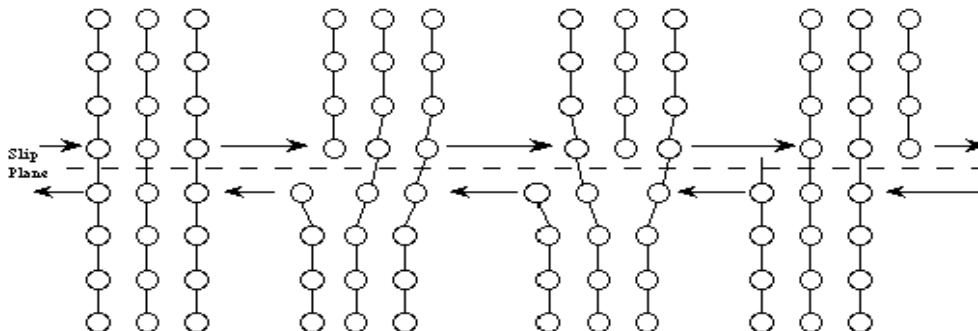


Fig.3.1. Dislocation movement in a crystal

If placed under large of a stress, metals will mechanically fracture. This can also result over time from many small stresses. The most common reason (about 80%) for metal failure is fatigue. Through the application and release of small stresses as the metal is used, small cracks in the metal are formed and grow slowly. Then the metal is permanently deformed or it breaks (fractures).

When a material is stressed below its elastic limit, the resulting deformation or strain is temporary. When a material is stressed beyond its elastic limit, plastic or permanent deformation takes place, and it will not return to its original shape by the application of force alone. The ability of a metal to undergo plastic deformation is most important outstanding characteristic in comparison with other materials.

All shaping operations such as stamping, pressing, spinning, rolling, forging, drawing, and extruding involve plastic deformation of metals. Various machining

operations such as milling, turning, sawing, and punching also involve plastic deformation.

**Plastic deformation** may take place by :

- Slip
- Twinning
- Combination of slip and twinning

**Deformation by Slip:**

If a single crystal of a metal is stressed in tension beyond its elastic limit, it elongates slightly, a step appears on the surface indicating relative displacement of one part of the crystal with respect to the rest, and the elongation stops. Increasing the load will cause another step. It is as if neighboring thin sections of the crystal had slipped past one another like a sliding cards on a deck. Each successive elongation requires a higher stress and results in the appearance of another step, which is actually the intersection of a slip plane with the surface of the crystal. Progressive increase of the load causes the material to fracture.

**Deformation by Twinning:**

When mechanical deformation is created by twinning, the lattice structure changes. The atoms move only a fraction of an interatomic space and this leads to a rearrangement of the lattice structure. Twinning is observed as wide bands under the microscope. These wide bands can not be removed by polishing.

### **Processes of cold working and annealing:**

Because plastic deformation results from the movement of dislocations, metals can be strengthened by preventing this motion. When a metal is bent or shaped, dislocations are generated and move. As the number of dislocations in the crystal increases, they will get tangled or pinned and will not be able to move. This will strengthen the metal, making it harder to deform. This process is known as **cold working**. At higher temperatures the dislocations can rearrange, so little strengthening occurs.

Heating removes the effects of cold-working. When cold worked metals are heated, recrystallization occurs. New grains form and grow to consume the cold worked portion. The new grains have fewer dislocations and the original properties are restored.

**Annealing** is a process in which metals are heated and then allowed to cool slowly.

As a result of cold working, the hardness, tensile strength, and electrical resistance increase, while ductility decreases. There is also a large increase in the number of dislocations, and certain planes in the crystal structure are severely distorted. Most of the energy used to cold work the metal is dissipated in heat, and a finite amount of energy is stored in the crystal structure as internal energy associated with the lattice defects created by the deformation.

**Full annealing** is the process by which the distorted cold worked lattice structure is changed back to one which is strain free through the application of heat. This process

is carried out entirely in the solid state and is usually followed by slow cooling in the furnace from the desired temperature.

The **annealing process** may be divided into three stages:

- Recovery
- Recrystallization
- Grain growth.

**Recovery:**

This is primarily a low temperature process, and the property changes produced do not cause appreciable change in microstructure or the properties, such as tensile strength, yield strength, hardness and ductility. The principal effect of recovery is the relief of internal stresses due to cold working.

When the load which causes plastic deformation is released, all the elastic deformation does not disappear. This is due to the different orientation of crystals, which will not allow some of them to move back when the load is released. As the temperature is increased, there is some spring back of these elastically displaced atoms which relieve most of the internal stresses. Electrical conductivity is also increased appreciably during the recovery stage.

Since the mechanical properties of the metal are essentially unchanged, the main purpose of heating in the recovery range is stress relieving cold worked alloys to prevent stress corrosion cracking or to minimize the distortion produced by residual stresses.

**Recrystallization:**

As the temperature of the recovery range is reached, minute new crystals appear in the microstructure. These new crystals have the same composition and lattice structure as the original undeformed grains and are not elongated but are uniform in dimensions. The new crystals generally appear at the most drastically deformed portions of the grain, usually the grain boundaries and slip planes. The cluster of atoms from which the new grains are formed **is called a nucleus**. Recrystallization takes place by a combination of nucleation of strain free grains and the growth of these nuclei to absorb the entire cold worked material.

The term recrystallization temperature does not refer to a definite temperature below which recrystallization will not occur, but refers to the approximate temperature at which a highly cold worked material completely recrystallizes in one hour.

**Recrystallization temperature** is determined by the Bochvar's rule:

$$T_{\text{recryst.}} = a \times T_{\text{melt.}}, \text{ K} \quad (3.1)$$

where a – coefficient of material purity ( it is equal to 0.1 – for pure metal; 0.4 - for technical pure metal; 0.8 – for alloy),

$T_{\text{melt}}$  – melting point.

**Cold working** takes place at the temperature below recrystallization temperature.

**Hot working** takes place at the temperature that is higher than recrystallization temperature.

Pure metals have low recrystallization temperatures as compared with alloys. Zinc, tin and lead have recrystallization temperatures below room temperature. This

means that these metals cannot be cold worked at room temperature since they crystallize spontaneously, reforming a strain free structure.

The greater the prior deformation, the lower the temperature for the start of recrystallization. Increasing the annealing time decreases the recrystallization temperature for the start of recrystallization.

Small degree of deformation (8-15%) is a reason for sharp grain growth after recrystallization (grain's size is maximum). It is called the critical degree of deformation. The appearance of large grains makes material to be brittle. During the cold work the critical degree of deformation must be avoided.

During the recrystallization stage, there is a significant drop in tensile strength, hardness and a large increase in the ductility of the material (See Fig.3.2).

**Grain Growth:**

In this stage the tensile strength and hardness continue to decrease but at a much less rate than the recrystallization stage. The major change observed during this stage is the growth of the grain boundaries and reaching the original grain size (See Fig.3.2)

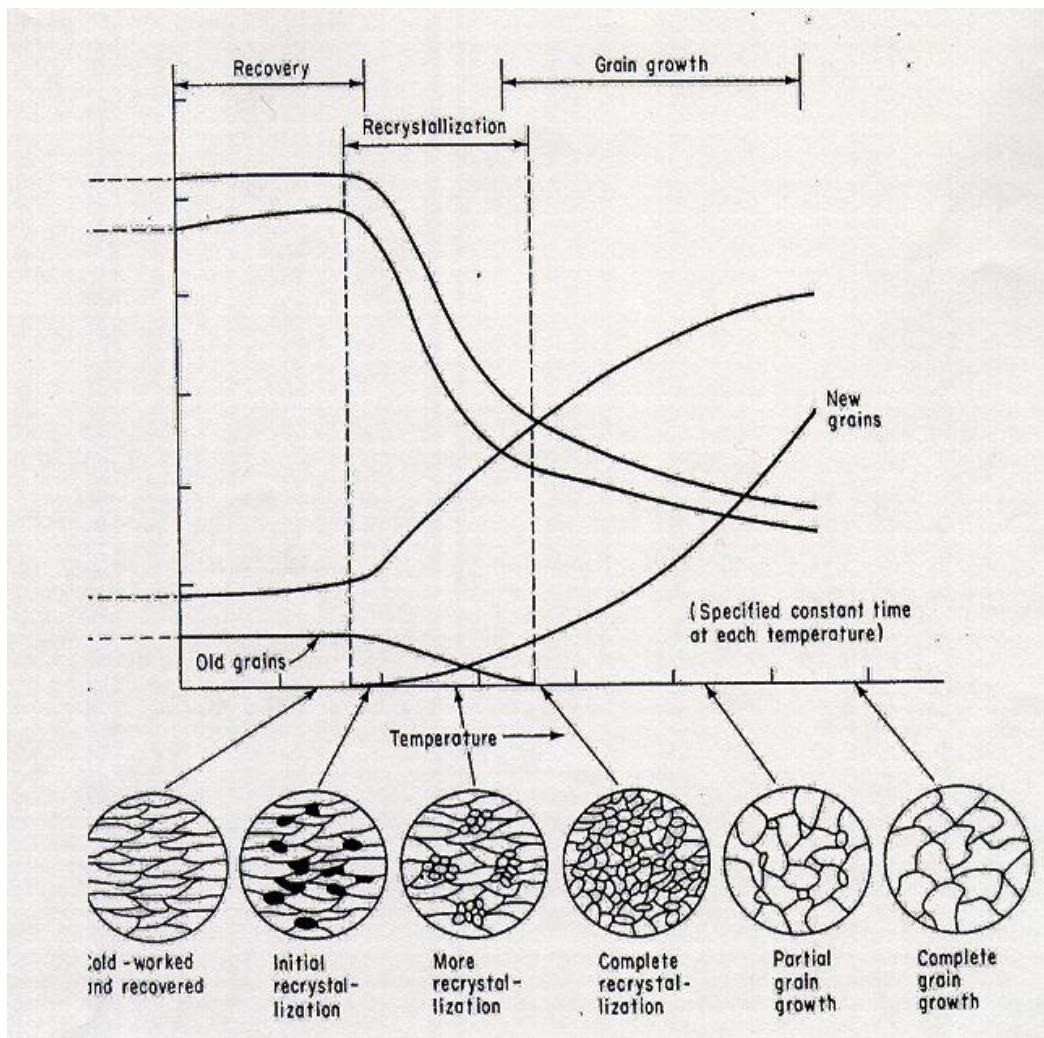


Fig.3.2. Effect of annealing on tensile strength, hardness, ductility and grain size

### **Materials and Equipment:**

1. 6 specimen of aluminum plate after recrystallization (without plastic deformation and with 3, 6, 9, 12, 15% degree of deformation).
2. Magnifying glass.

### **Procedure:**

1. To get equipment and specimens of aluminum plate after recrystallization.
2. To determine the critical degree of deformation.
3. To draw the microstructure of aluminum after recrystallization (without plastic deformation and with 3, 6, 9, 12, 15% degree of deformation).
4. To calculate the recrystallization temperature for tungsten, iron, aluminum, zinc, tin, cooper and titanium of different purity.
5. To determine at what temperatures the cold working of pure tungsten is possible.

### **Questions:**

1. What is elastic deformation?
2. What is plastic deformation?
3. What is the difference between elastic and plastic deformation?
4. Why do dislocations occur easily in metal?
5. What shaping operations do you now?
6. In what ways may plastic deformation take place?
7. Describe plastic deformation by slip.
7. Describe plastic deformation by twinning.
6. What is cold working?
7. What is annealing process?
8. How do the mechanical properties change after cold working?
9. What are the stages of annealing process?
10. Describe the recovery process.
11. Describe the recrystallization process.
12. How do the mechanical properties change during the stage of grain growth?
13. Show how to determine the recrystallization temperature? Write the formula.
14. What is the critical degree of deformation?
15. Why must critical degree of deformation be avoided?
16. At what temperatures does cold and hot working take place?
17. Why can zinc not be cold worked at room temperature?
18. Graph the effect of annealing on tensile strength, hardness and ductility.

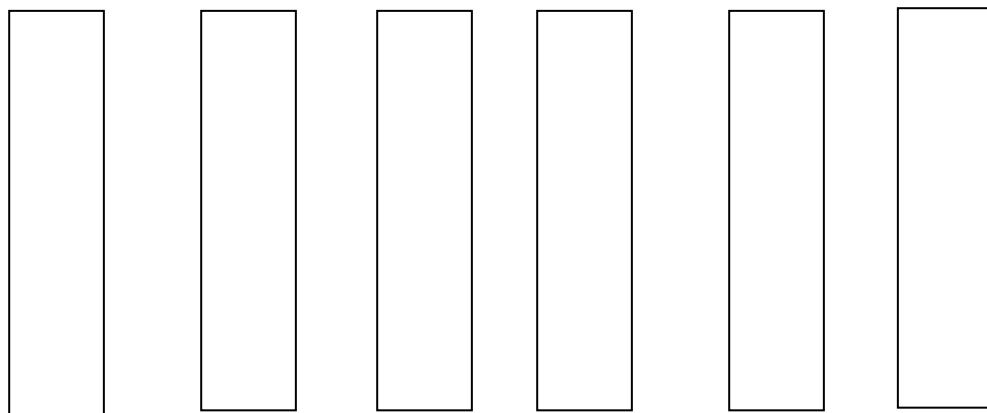


LABORATORY REPORT №3  
**PROCESS OF PLASTIC DEFORMATION**  
 PROTOCOL №1

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Material \_\_\_\_\_

The influence of plastic deformation on the grain's size and determination the critical degree of deformation



0%                      3%                      6%                      9%                      12%                      15%

**Conclusion:**

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PROTOCOL №2

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Determination of the recrystallization temperature

Metal	Purity of the metal	Coefficient of metal purity, a	T <sub>melt</sub> , °C	T <sub>melt</sub> , K	T <sub>recryst.</sub> , K	T <sub>recryst.</sub> , °C
Fe	Technical pure metal		1539			
Al	---		658			
Cu	---		1083			
Zn	---		419			
W	---		3410			
Sn	Pure metal		232			
Ti	---		1672			
W	---		3410			

**Conclusion:**

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Student's signature  
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Teacher's signature  
 " \_\_\_\_\_ " \_\_\_\_\_ 20\_\_ y.

## LABORATORY WORK 4

### THERMAL ANALYSE

#### Objectives

1. To learn the method of cooling curves construction.
2. Determination of critical points by the method of thermal analysis for alloy Pb-Sn.
3. To learn to determine the chemical composition and the percentage of each phase that is present at various temperatures by the inverse lever rule.

#### Scientific principles

The properties of a material depend on the type, number, amount, and form of the phases present, and can be changed by altering these quantities. In order to make these changes, it is essential to know the conditions under which these quantities exist and the conditions under which a change in phase will occur.

The best method to record the data of phase changes in many alloy systems is in the form of **phase diagrams**, also known as equilibrium diagrams.

In order to specify completely the state of a system in equilibrium, it is necessary to specify three independent variables: temperature, pressure and composition. When pressure is constant and equal at atmospheric value, the equilibrium diagram indicates the structural changes due to variation of temperature and composition.

**Phase diagrams show** the phase relationships under equilibrium conditions, that is, under conditions in which there will be no change with time. Equilibrium conditions may be approached by extremely slow heating and cooling, so that if a phase change is to occur, sufficient time is allowed.

Phase diagrams are usually plotted with temperature as the ordinate, and the alloy composition as the abscissa.

#### Experimental Methods:

The data for the construction of equilibrium diagrams are determined experimentally by a variety of methods, the most common methods are:

- Metallographic Methods
- X-ray Diffraction Technique
- Thermal Analysis

#### Thermal Analysis:

This is the most widely used experimental method. **It relies** on the information obtained from the cooling diagrams. In this method, alloys mixed at different compositions are melted and then the temperature of the mixture is measured at a certain time interval while cooling back to room temperature.

A cooling diagram for each mixture is constructed and the initial and final phase change temperatures are determined. Then these temperatures are used for the construction of the phase diagrams.

Every point of the diagram answers the certain state of the system at a certain temperature in the conditions of equilibrium. On fig.4.1 the chart of experimental plant for determination of metal's and alloy's critical points is shown. It includes heater 1, which melts the explored alloy 2 in crucible 3, covered by plate 4. For the control of the temperature changes, a thermo-electric pyrometer is used. It consists of the thermocouple 5, wires 6 and term voltmeter 7.

**Thermocouple** represents by itself two wires from different metals with the soldered ends from one side and which connects with term voltmeter from another side. This connection in thermocouple is named hot solder and intended for placing in the area of temperature determination.

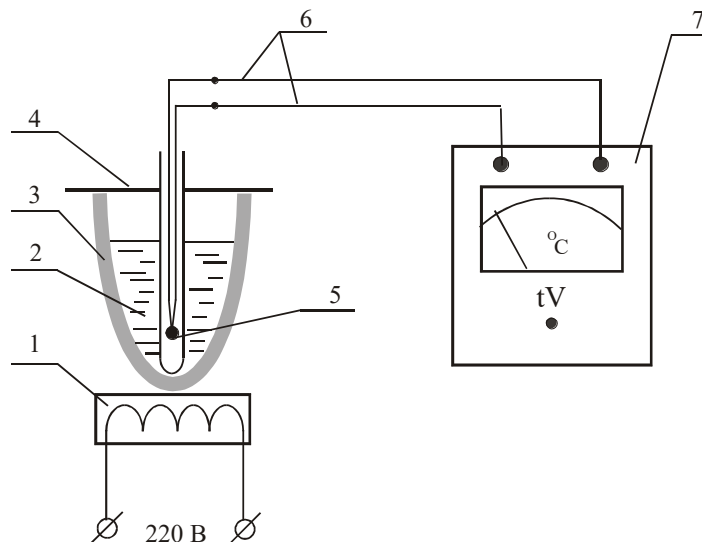


Fig.4.1. Chart of experimental plant for determination of metal's and alloy's critical points by the method of thermal analysis.

In a technique the widest application was found following thermocouple (on material of wires):

platinum - platinumrhodium, PP-1-1 (0...1300°C);

chromel - alyomel, ChA (0...100°C);

cooper-constantan, CC (0...400°C).

For measuring of Pb - Sn alloys temperature use cooper-constantan thermocouple (constantan - alloy 58.4% Cu, 1.6% Mn, 40% Ni).

**Cooling Curve of a Pure Metal:**

Under equilibrium conditions, all metals exhibit a definite melting or crystallization point. If a cooling curve is plotted for a pure metal. It will show a horizontal line at the melting or crystallization temperature.

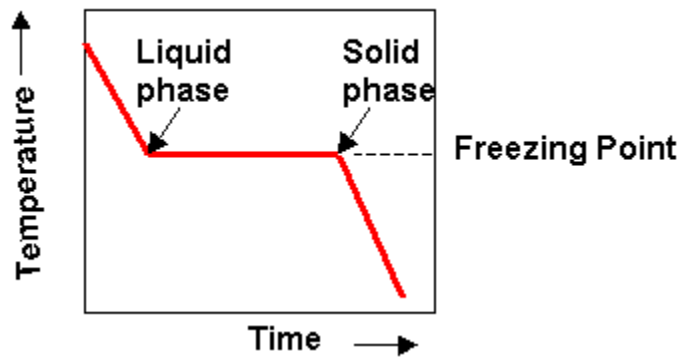


Fig.4.1. Cooling curve for the solidification of a pure metal.

There are three kinds of initial elements (or components) interaction:

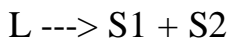
1. Solid solution (complete and limited). It marked as  $\alpha \Rightarrow A(B)$ ,  
 $\beta \Rightarrow B(A)$ .
2. Mechanically mixture. It marked as  $A + B$ .
3. Chemical composition. It marked as  $A_n B_m$ .

**Cooling Curve of a Solid Solution:**

A solid solution consists of two kinds of atoms combined in one type of space lattice. A solution is composed of two parts: a solute and a solvent. The solute is the minor part of the solution or the material which is dissolved, while the solvent constitutes the major portion of the solution. When solidification of the solution starts, the temperature may be higher or lower than the crystallization point of the pure solvent. Most solid solutions solidify over a range in temperature.

**Eutectic System:**

**Eutectic system** is a phase transformation that takes place when a single-phase liquid transforms directly to a two-phase solid.



(This is a reversible phase transformation).

Phase diagram of real alloys Pb-Sn (soft solders for soldering process) is shown in the fig. 4.2. This is typical phase diagram with eutectic transformation, which takes place at temperature equal 183 °C. There are two limited solid solutions at room temperature:  $\alpha \Rightarrow \text{Pb}(\text{Sn})$  and  $\beta \Rightarrow \text{Sn}(\text{Pb})$ .

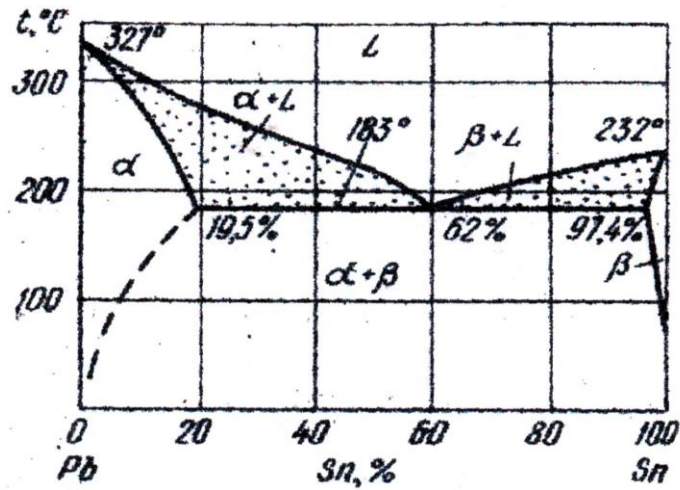


Fig.4.2. Phase Diagram of the alloys Pb-Sn.

**Inverse Lever Rule:**

Inverse lever rule is used to determine the percentage of each phase that is present at various temperatures.

The length of line XY represents the sum of the two phases as 100 percent. The inverse lever rule states that liquid phase can be calculated by taking the length of the line XZ and dividing this by XY.

The solid phase can be calculated by taking the length of the line ZY and dividing it by XY. To get the percentages, the values are multiplied by 100.

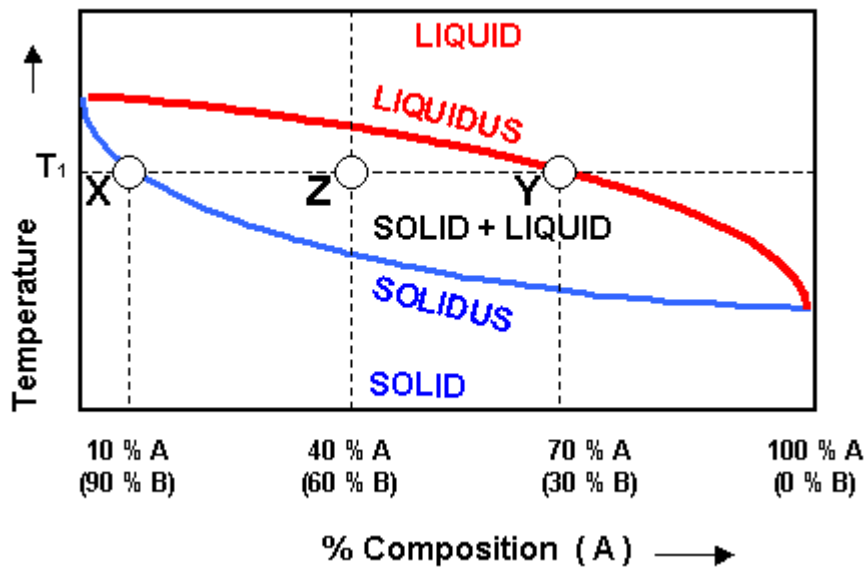


Fig.4.3. Phase diagram of a mixture with complete solubility in liquid and solid states

**Sample Calculation :**

Alloy with 40 % A and 60 %B at room temperature is heated to a temperature T1 . Calculate the liquid and solid phase and indicate the composition of each phase.

$$\text{Liquid Phase} = (XZ / XY) \times 100 = [(40-10) / (70-10)] \times 100 = 50\%$$

$$\text{Solid Phase} = (ZY / XY) \times 100 = [(70-40) / (70-10)] \times 100 = 50\%$$

At temperature T1, the solid composition is found by the intersection (point X) of isothermal (tie) line T1 and the solidus curve.

Solid composition: 10 % A and 90 % B

The liquid composition at temperature T1 is found by the intersection (point Y) of isothermal line T1 and the liquidus curve.

Liquid composition: 70% A and 30 % B

### **Materials and Equipment:**

1. Experimental plant for determination of metal's and alloy's critical points.
2. Pb-Sn alloy.
3. Watch with second hand.

### **Procedure:**

1. Put 100-150g Pb-Sn alloy of certain composition at the bottom of a crucible.
2. Set hot solder of thermocouple in crucible and put cold ends of thermocouple with the termvoltmeter together.
3. Cover crucible by plate.
4. Turn on the heater.
5. Turn off the heater, when the temperature is 250 °C.
5. Record the indicators of termvoltmeter every 30 second.
6. Stop recording the indicators of termvoltmeter when the temperature is 140°C.
7. Add 15 °C (room temperature) to each temperature.
8. From the data obtained, graph the cooling curve of alloy in coordinates "temperature – time".
9. Define the temperature of beginning and end of crystallization for explored alloy.
10. Plot a phase diagram of Pb-Sn alloys.
11. Through the cross point of the line of liquidus curve for hypoeutectic alloys and temperature of the explored alloy beginning of the crystallization take the vertical line.
12. Apply inverse lever rule at the temperature equal 200 °C for explored alloy.
13. Determine chemical composition of the explored alloy.

### **Questions:**

1. What does the phase diagram show?
2. Which experimental methods of phase diagram construction do you know?
3. Describe the thermal analysis process.
4. What does the experimental plant for determination of metal's and alloy's critical points by the method of thermal analysis consist of?
5. What is a thermocouple?
6. What types of thermocouple do you know?
7. Construct the general shape of a cooling curves for pure metal and alloys.
8. What kinds of initial elements interaction do you know?
9. Plot phase diagram with complete solubility in liquid and solid state forming.
10. Plot phase diagram with mechanical mixture of initial elements in solid state forming.
11. Plot phase diagram with eutectic transformation.
12. Plot phase diagram with eutectoid transformation.
13. Apply inverse lever rule for any alloy of phase diagram with complete solubility in liquid and solid state forming. Temperature must be chosen independently.

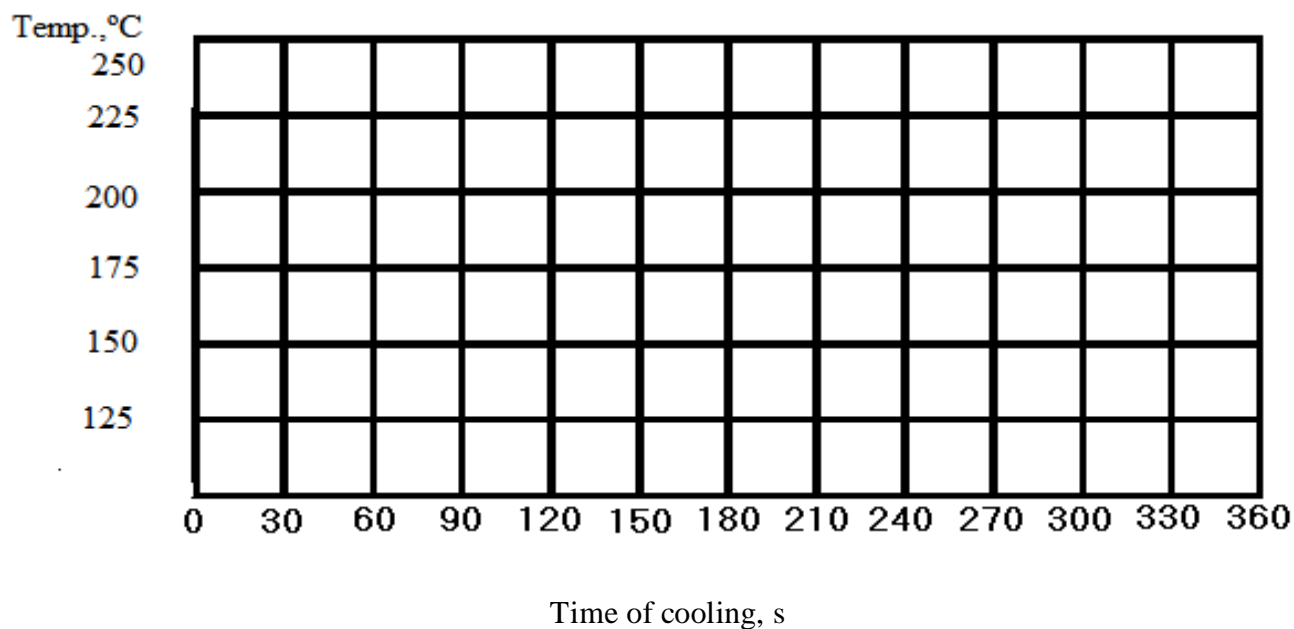
Laboratory work № 4  
**THERMAL ANALYSE**

PROTOCOL №1  
Determination of critical points at cooling of alloy  
Results of thermal analysis

Time, s	0	30	60	90	120	150	180	210	240	270	300	330	360
Temperature of the cooling, °C	250												
Temperature of the cooling +15°C	265												

Time, s	390	420	450	480	510	540	570	600	630	660	690	720	750
Temperature of the cooling, °C													
Temperature of the cooling +15°C													

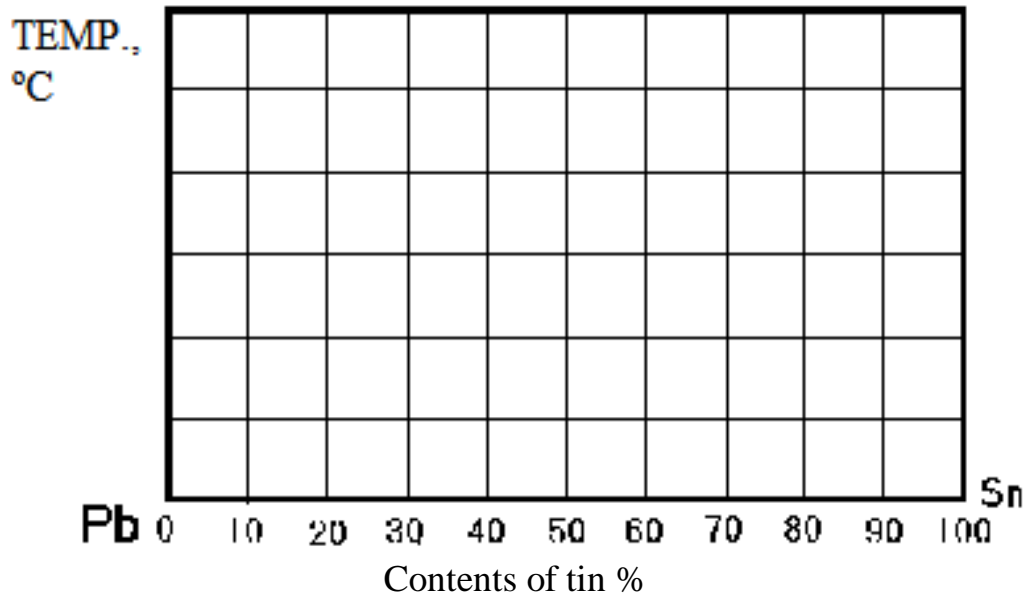
Cooling curve of the alloy



Temperature of critical points (°C)

Begining of the crystallization- \_\_\_\_\_ End of the crystallization- \_\_\_\_\_

### Phase Diagram of the alloys lead and tin



Application of the inverse lever rule for explored alloy at temperature 200 °C

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Conclusions:

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 Teacher's signature  
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# Practical 1. PHASE DIAGRAMS

## Objectives

1. To learn the process of phase diagrams analysis.
2. To learn the construction of cooling curves.
3. To learn how to apply the phase rule and inverse level rule.

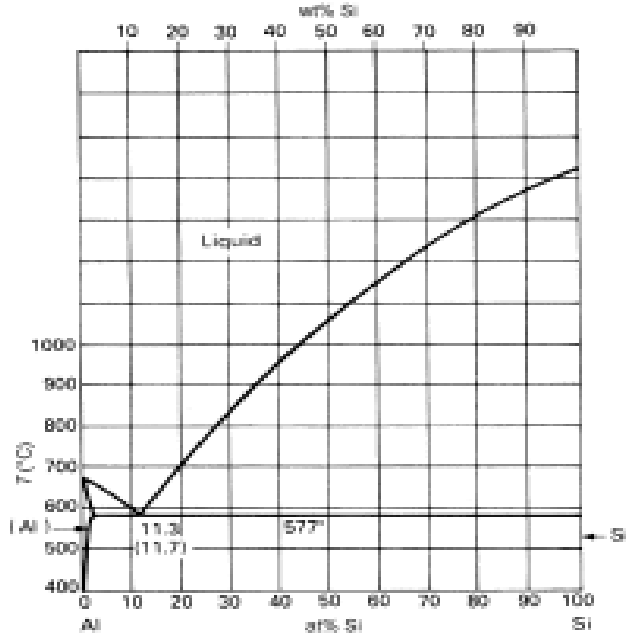
## Activity

1. To analyse the phase diagram choose it from Table according to your variant and plot it.

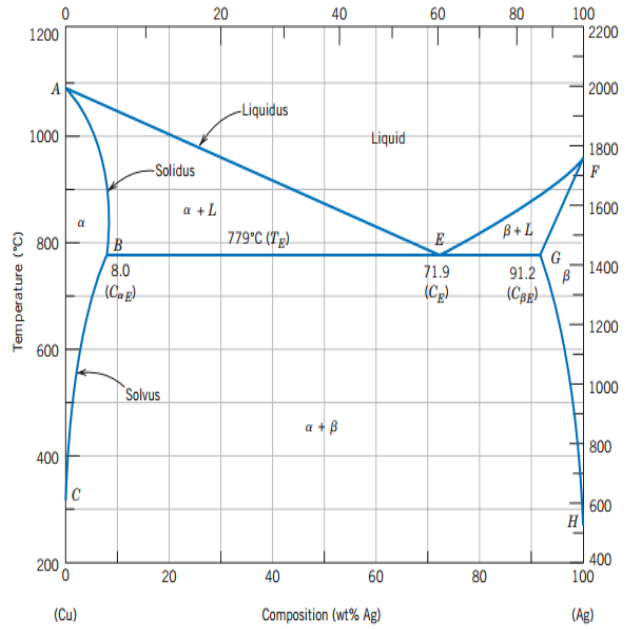
Note! Your variant is your number in the group list or your number in the group list minus 10 (20).

2. Mark all critical points with letters.
3. Describe the lines of phase diagram (liquidus, solidus, phase transformation, lines of the solubility (if they are present)).
4. Identify the components of the alloys. Are there allotropic forms in the components? List them.
5. What kinds of initial elements interaction take place? Identify all phases which occur in the alloys.
6. Describe the phase reactions (if they are present) and write down their formula.
7. To analyse the alloy, choose its chemical composition and temperature at any two-phase field. Draw alloy's vertical, mark the point of chosen temperature and all points of where alloy's vertical crosses the lines of phase diagram.
8. Construct the general shape of a cooling curve for chosen alloy.
9. Mark phases at every temperature period on the cooling curve.
10. Describe what happens if the alloy is cooled to room temperature. At which temperatures do changes in the number or type of phases occur?
11. Application of the phase rule. How many degrees of freedom are there at constant  $p$  in all fields.
12. How many phases can coexist in equilibrium at constant  $p$ ? Define them.
13. Describe what happens if the alloy is cooled to room temperature. At which temperatures do changes in the number or type of phases occur?
14. Application of the inverse level rule. Calculate the approximate composition and proportions by weight of each phase that is present at chosen temperature.

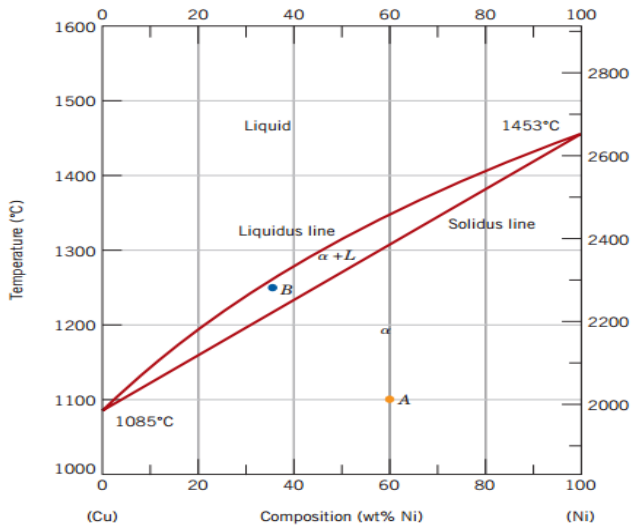
**Table. Variants of the phase diagrams**



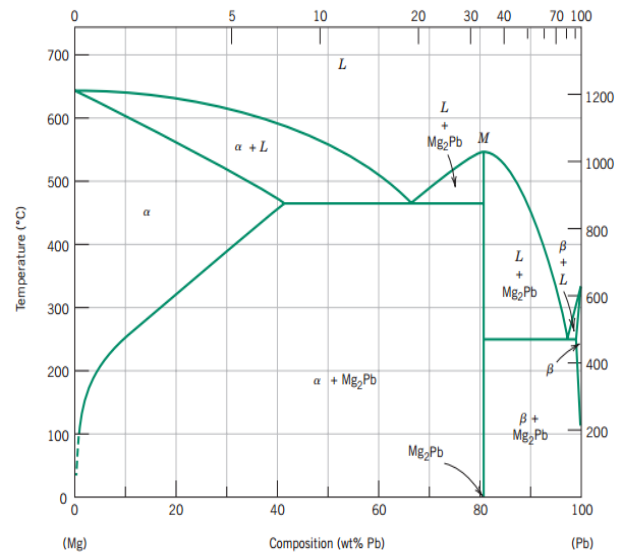
**V1**



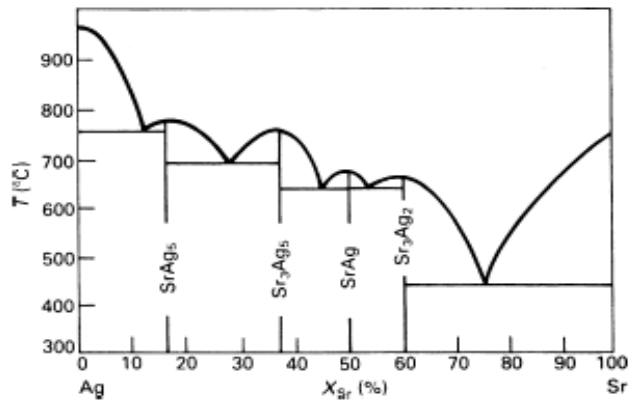
**V2**



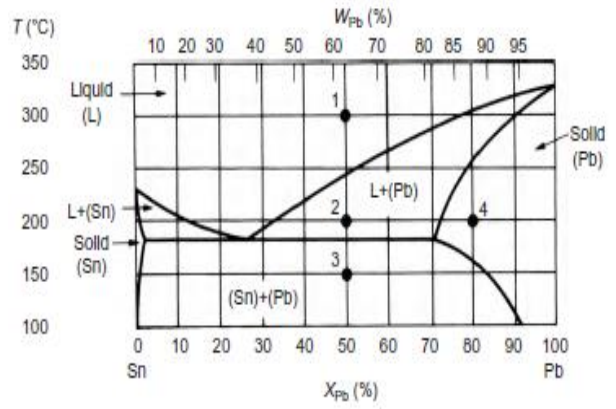
**V3**



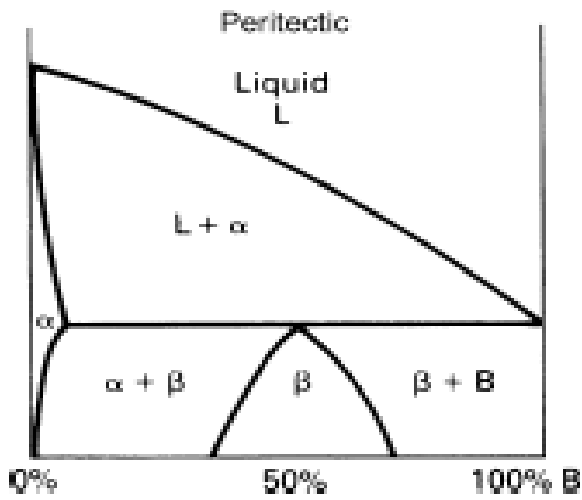
**V4**



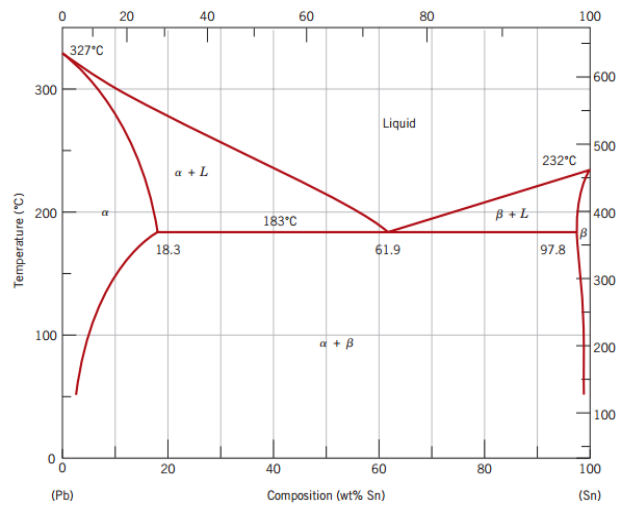
**V5**



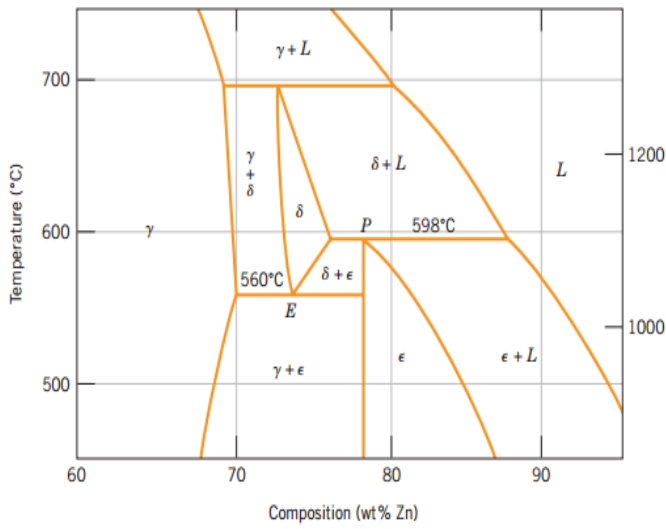
**V6**



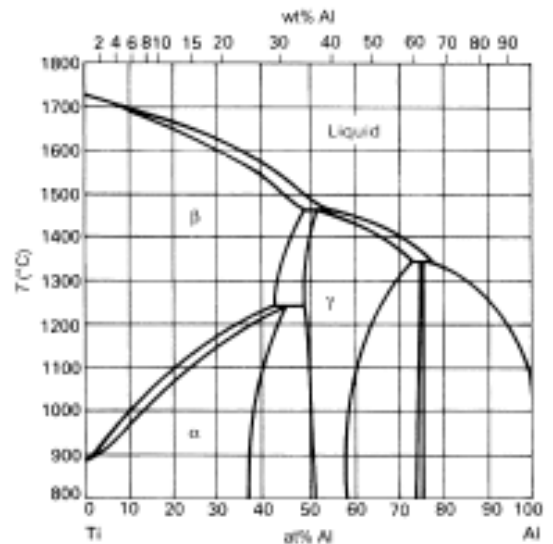
**V7**



**V8**



**V9**



**V10**

1.Phase diagram	2. Cooling curve

3. Lines of the phase diagram :

liquidus \_\_\_\_\_, solidus \_\_\_\_\_,  
 equilibrium phase transformation \_\_\_\_\_,  
 lines of the solubility

\_\_\_\_\_

\_\_\_\_\_

4. Components of the alloys. \_\_\_\_\_.

Allotropic forms in the components \_\_\_\_\_.

5. Kinds of initial elements interaction \_\_\_\_\_

6. Phases, which occur in the alloys

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_.

7. Phase reactions and their formula

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

8. Chemical composition chosen alloy \_\_\_\_\_

9. Application of the phase rule. Calculate the degrees of freedom in all fields at constant  $p$ .

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10. How many phases can coexist in equilibrium at constant  $p$ ? Define them.

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11. Describe what happens if the alloy is cooled to room temperature. At which temperatures do changes in the number or type of phases occur?

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12. Application of the inverse level rule. Calculate the approximate composition and the proportions by weight of each phase that is present at chosen temperature.

The composition of phase 1 is \_\_\_\_\_.

The composition of phase 2 is \_\_\_\_\_.

What (roughly) are the proportions by weight of each phase?

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**Conclusion** \_\_\_\_\_

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Teacher's signature  
" \_\_\_\_\_ " \_\_\_\_\_ 20 \_\_\_\_ y.

## Practical 2. IRON-CARBON EQUILIBRIUM DIAGRAM

### Objectives

1. To learn the process Fe – Fe<sub>3</sub>C diagram analysis.
2. To learn how to apply the phase rule and inverse level rule.

### Scientific principles

Fe and C are the main components of Fe – Fe<sub>3</sub>C diagram. Fe has polymorphic modification; it's marked by the initial letters of the Greek alphabet, beginning from low temperatures (Fe $\alpha$ , Fe $\gamma$ , Fe $\delta$ ).

When iron crystallizes at 1539 oC it is B.C.C. ( $\delta$  -iron), at 1392 oC its structure changes to F.C.C. ( $\gamma$ -iron or austenite), and at 911 oC it again becomes B.C.C. ( $\alpha$  -iron or ferrite) (Fig2.1).

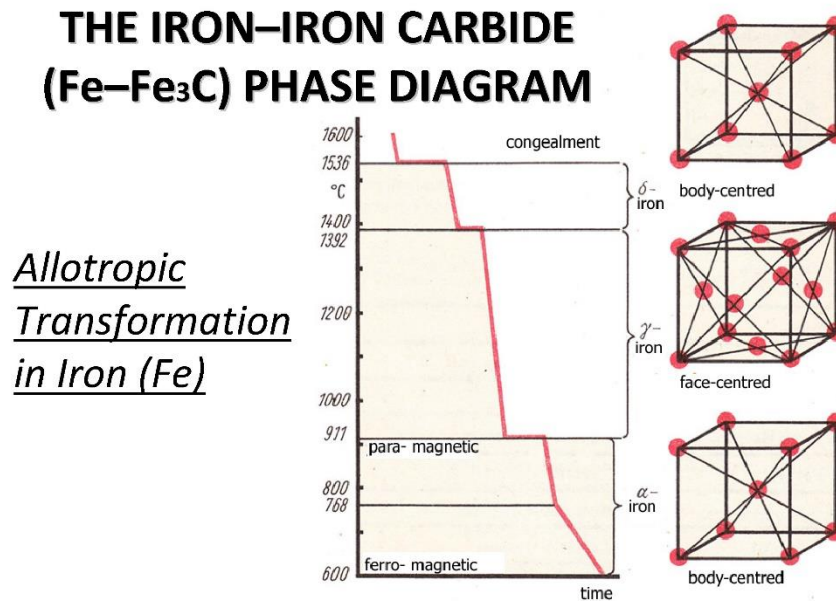


Fig.2.1. Allotropic Transformation in Iron.

Fig. 2.2. shows, the Fe-C equilibrium diagram in which various structure (obtained during heating and cooling), phases and microscopic constituents of various kinds of steel and cast iron are depicted.

# THE IRON-IRON CARBIDE (Fe-Fe<sub>3</sub>C) PHASE DIAGRAM

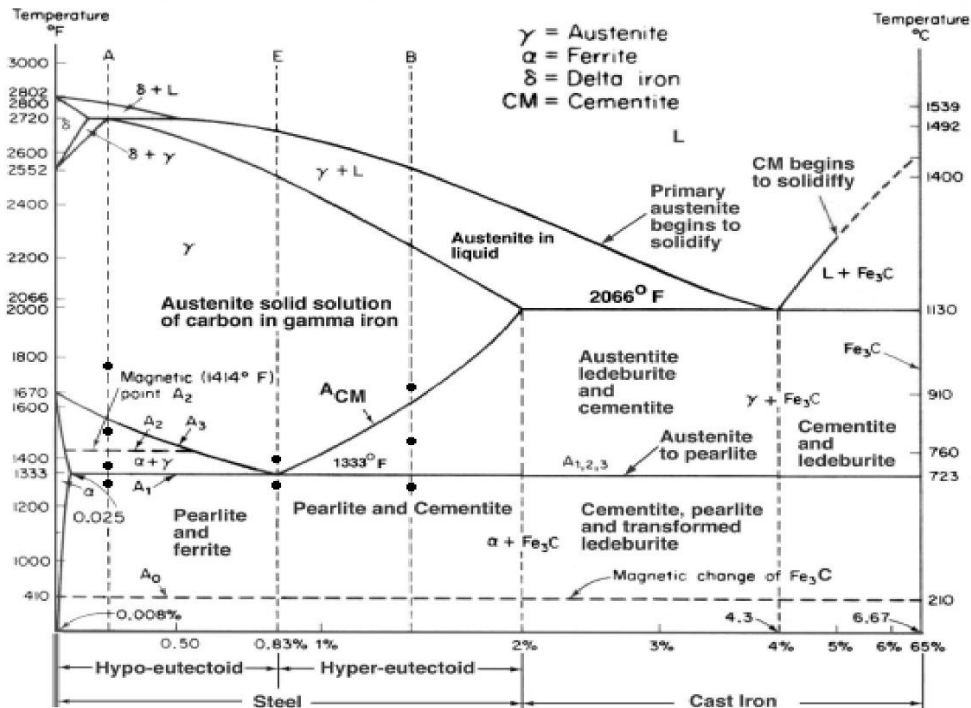


Fig. 2.2. Fe-C equilibrium diagram

The main structures, significance of various lines and critical points are discussed as under.

## Structures in Fe-C-diagram

There are following phases and structure of Fe – Fe<sub>3</sub>C diagram:

**CEMENTITE** is a chemical compound of carbon with iron and is known as iron carbide (Fe<sub>3</sub>C). It contains 6.67 % carbon by weight. It is a typical hard and brittle interstitial compound of low tensile strength but high compressive strength. Its crystal structure is orthorhombic.

Cementite is Cast iron having 6.67% carbon is possessing complete structure of cementite. Free cementite is found in all steel containing more than 0.83% carbon. It increases with increase in carbon % as reflected in Fe-C Equilibrium diagram. It is extremely hard. The hardness and brittleness of cast iron is believed to be due to the presence of the cementite. It decreases tensile strength. This is formed when the carbon forms definite combinations with iron in form of iron carbides which are extremely hard in nature. The brittleness and hardness of cast iron is mainly controlled by the presence of cementite in it. It is magnetic below 200°C.

### **AUSTENITE ( $\gamma$ - iron):**

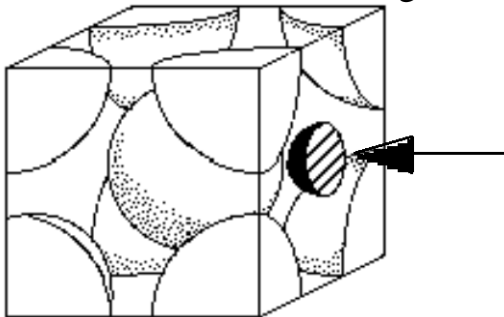
Austenite is a solid solution of free carbon and iron in gamma iron. It is also known as ( $\gamma$  -) gamma-iron, which is an interstitial solid solution of carbon dissolved in iron with a face centered cubic crystal (F.C.C) structure.

Austenite is normally unstable at room temperature. Under certain conditions it is possible to obtain austenite at room temperature.

On heating the steel, after upper critical temperature, the formation of structure completes into austenite which is hard, ductile and non-magnetic. It is able to dissolve large amount of carbon. It is in between the critical or transfer ranges during heating and cooling of steel. It is formed when steel contains carbon up to 1.8% at 1130°C. On cooling below 723°C, it starts transforming into pearlite and ferrite. Austenitic steels cannot be hardened by usual heat treatment methods and are non-magnetic.

### **FERRITE ( $\alpha$ - iron):**

It is ( $\alpha$  -) alpha -iron, which is an interstitial solid solution of a small amount of carbon dissolved in iron with a Body Centered Cubic (B.C.C.) crystal structure. It is the softest structure on the iron-iron carbide diagram.



#### **Interstitial Carbon in Iron**

**Since the interstitial sites are so small, the maximum solubility in BCC iron is only one carbon atom for 5000 iron atoms.**

Fig. 2.3. BCC iron showing the location of interstitial carbon atoms

Ferrite contains very little or no carbon in iron. It is the name given to pure iron crystals which are soft and ductile. The slow cooling of low carbon steel below the critical temperature produces ferrite structure. Ferrite does not harden when cooled rapidly. It is very soft and highly magnetic.

### **PEARLITE ( $\alpha$ - Fe + Fe<sub>3</sub>C)**

Pearlite is a eutectoid alloy of ferrite and cementite. It occurs particularly in medium and low carbon steels in the form of mechanical mixture of ferrite and cementite in the ratio of 87:13. It is the eutectoid mixture containing 0.8 % carbon and is formed at 723°C on very slow cooling. It is very fine platelike or lamellar mixture of ferrite and cementite. The structure of pearlite includes a white matrix (ferritic background) which includes thin plates of cementite.



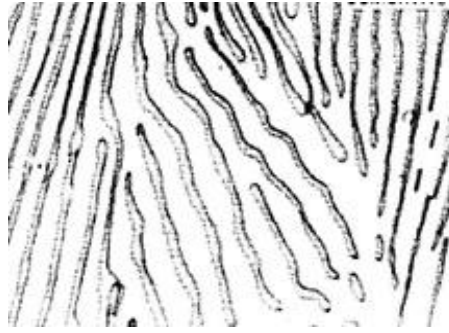


Fig. 2.4. Pearlite microstructure (Light background is the ferrite matrix, dark lines are the cementite network)

Its hardness increases with the proportional of pearlite in ferrous material. Pearlite is relatively strong, hard and ductile, whilst ferrite is weak, soft and ductile. It is built up of alternate light and dark plates. These layers are alternately ferrite and cementite. When seen with the help of a microscope, the surface has appearance like pearl, hence it is called pearlite. Hard steels are mixtures of pearlite and cementite while soft steels are mixtures of ferrite and pearlite.

As the carbon content increases beyond 0.2% in the temperature at which the ferrite is first rejected from austenite drop until, at or above 0.8% carbon, no free ferrite is rejected from the austenite. This steel is called eutectoid steel, and it is the pearlite structure in composition.

#### **LEDEBURITE ( $\gamma - Fe + Fe_3C$ )**

It is the eutectic mixture of austenite and cementite. It contains 4.3% carbon and represents the eutectic of cast iron. Ledeburite exists when the carbon content is greater than 2.14%, which represents the dividing line on the equilibrium diagram between steel and cast iron.

As iron having various % of carbon (up to 6%) is heated and cooled, the following phases representing the lines will tell the about the structure of iron, how it changes.

#### **Significance of Transformations Lines**

##### **Line ABCD – liquidus line**

The line ABCD tells that above this line melting has been completed during heating the iron. The molten metal is purely in the liquidus form. Below this line and above line AHJECF the metal is partially solid and partially liquid. The solid metal is known as austenite. Thus the line ABCD represents temperatures at which melting is considered as completed. Beyond this line metal is totally in molten state. It is not a horizontal line the melting temperature will vary with carbon content.

##### **Line AHJECF – solidus line**

This line tells us that metal starts melting at this temperature. This line is not horizontal and hence the melting temperatures will change with carbon content. Below this line and above line GSEC, the metal is in solid form and having austenite structure.

##### **Line PSK – eutectoid reaction**

This line occurs near 723°C and is a horizontal line and is known as **lower critical temperature** line because transformation of steels starts at, this line. Carbon % has not effect on it that means steel having different % of carbon will transforms at the same temperature.

The range above the line up to GSE is known as transformation range. This line tells us the steel having carbon up to 0.8% will start transforming from ferrite and pearlite to austenite during heating.

### **Line ECF – eutectic reaction**

It is a line at temperature 1130°C which tells that for cast iron having % of C from 2% to 4.3%. Below this line and above line SK, Cast iron will have austenite + ledeburite and cementite + ledeburite.

### **Critical Temperatures**

The temperatures at which changes in structure takes place is known as critical temperatures, these are as follows:

The temperature along GSE is known as **upper critical temperature**. The temperature along GS during heating as (upper critical temperature) where austenite + alpha iron changes into austenite and vice versa. The temperature along GS during cooling as A3 where austenite changes into austenite + alpha iron and vice versa during heating. The temperature along line SE during heating as Acm changes into austenite from austenite + cementite and vice versa.

The temperature along PSK is known as **lower critical temperature** when pearlite changes into austenite on heating as denoted, by A1.

When a steel specimen is heated, its temperature rises unless there is change of state or a change in structure. Fig. 2.5 shows heating and cooling curve of steel bearing different structures. Similarly, if heat is extracted, the temperature falls unless there is change in state or a change in structure. This change of structure does not occur at a constant temperature. It takes a sufficient time a range of temperature is required for the transformation. This range is known as transformation range. For example, the portion between the lower critical temperature line and the upper critical temperature line with hypo and hyper eutectoid steels, in iron carbon equilibrium diagram. This range is also known as critical range. Over heating for too long at a high temperature may lead to excessive oxidation or decarburization of the surface. Oxidation may manifest itself in the form of piece of scale which may be driven into the surface at the work piece if it is going to be forged. If steel is heated, well above the upper critical temperature, large austenite grains form. In other words steel develops undesirable coarse grains structure if cooled slowly to room temperature and it lacks both in ductility and resistance to shock

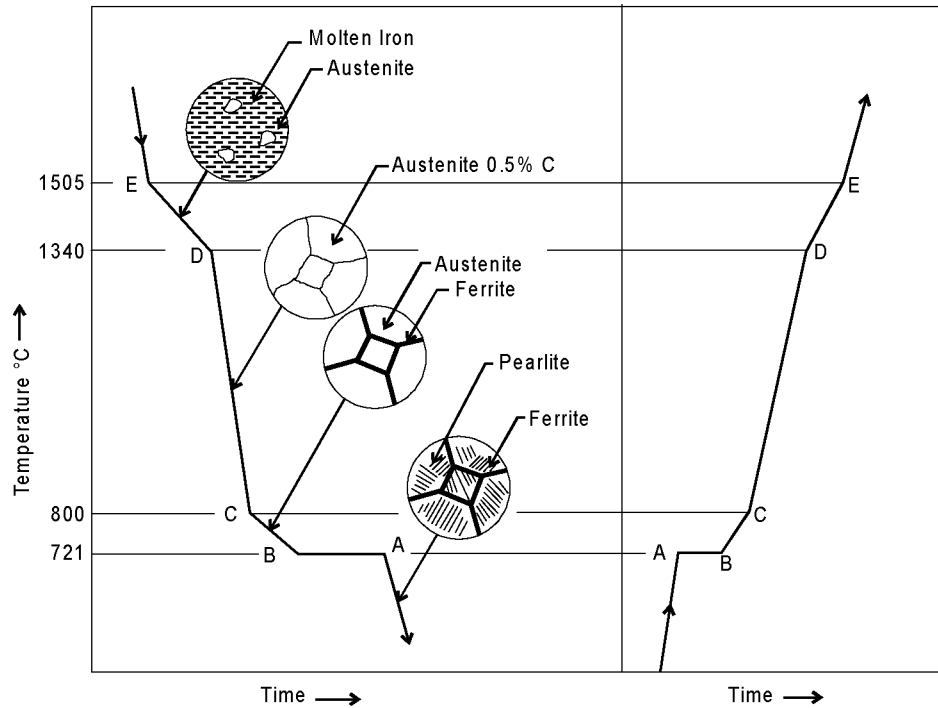


Fig. 2.5 Heating and cooling curve of steel

There are **three phase reaction** at different constant temperature:

At the eutectic point, the phase reaction, on cooling, is **eutectic**:

Liquid  $\Rightarrow$  austenite ( $\gamma$ -iron) + cementite

or

Liquid  $\Rightarrow$  ledeburite.

But the diagram shows another feature which looks like a eutectic: it is the at the bottom of the austenite field. The transformation which occurs there is very like the eutectic transformation, but this time it is a solid, austenite, which transforms on cooling to two other solids. The point is called a eutectoid point. The compositions of the two new phases are given by the ends of the tie line through the eutectoid point.

At the eutectoid point, the phase reaction, on cooling, is **eutectoid**:

Austenite  $\Rightarrow$  ferrite ( $\alpha$ -iron) + cementite

or

Austenite  $\Rightarrow$  pearlite.

At the peritectic point, the phase reaction, on cooling, is **peritectic**:

Liquid + ferrite ( $\delta$  -iron)  $\Rightarrow$  austenite .

### Activity

1. To analyse the Fe – Fe<sub>3</sub>C diagram mark at all critical points of the Fe – Fe<sub>3</sub>C diagram with letters.
2. Describe the lines of Fe – Fe<sub>3</sub>C diagram (liquidus, solidus, phase reactions, lines of the solubility).
3. Identify components of alloys. List allotropic forms of the components.

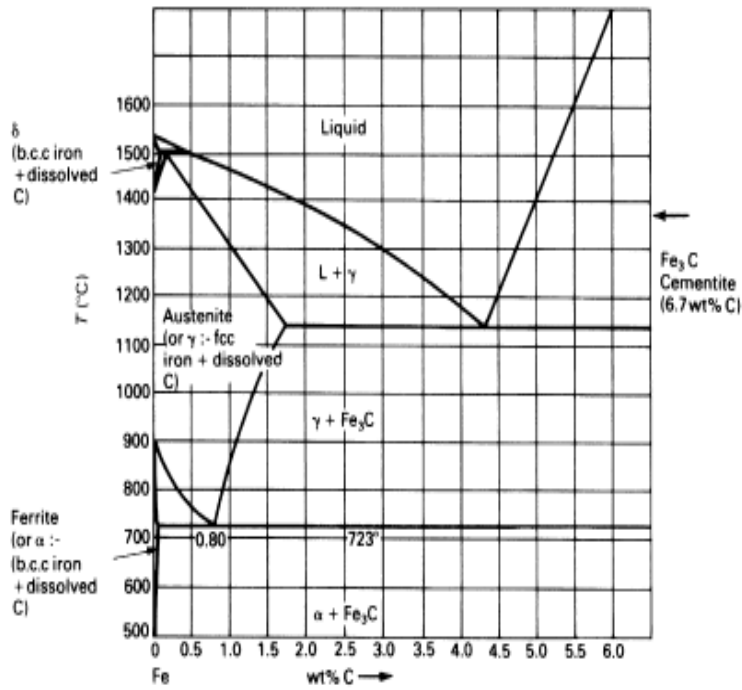
4. What kinds of initial elements interaction take place there? Identify all phases and structure which occur in the chosen alloy.
  5. Describe phase reactions and write down their formula.
  6. To analyse the alloy, choose its carbon content and temperature.
- Note! Your variant is your number in the group list or your number in the group list minus 10 (20).
7. Draw alloy's vertical, mark the point of chosen temperature and all points of where alloy's vertical crosses the lines of phase diagram.
  8. Construct the general shape of cooling curve for chosen alloy.
  9. Mark phases at every temperature period on the cooling curve.
  10. Application of the phase rule. How many degrees of freedom are there at constant  $p$  in all fields.
  11. How many phases can coexist in equilibrium at constant  $p$ ? Define them.
  12. Describe what happens if alloy is cooled to room temperature. At which temperatures do changes in the number or type of phases occur?
  13. Application of the inverse level rule. Calculate the approximate composition and proportions by weight of each phase that is present at chosen temperature.

Table. Carbon content in the alloy and temperature to Fe – Fe<sub>3</sub>C diagram analyse

	<b>V1</b>	<b>V2</b>	<b>V3</b>	<b>V4</b>	<b>V5</b>	<b>V6</b>	<b>V7</b>	<b>V8</b>	<b>V9</b>	<b>V10</b>
Carbon content % (wt.)	0.25	0.4	0.6	0.8	1.0	1.2	2.3	3.5	4.3	5.0
Temperature, °C	800	600	1450	1400	760	800	1000	1200	900	1200

1. Fe – Fe<sub>3</sub>C diagram

2. Cooling curve



3. Lines of the Fe – Fe<sub>3</sub>C diagram: liquidus \_\_\_\_\_, solidus \_\_\_\_\_, phase reactions \_\_\_\_\_

lines of the solubility \_\_\_\_\_

4. Components of the alloys. \_\_\_\_\_.

Allotropic forms in the components \_\_\_\_\_.

5. Kinds of initial elements interaction \_\_\_\_\_

6. Phases, which occur in the alloys \_\_\_\_\_ - \_\_\_\_\_.

7. Structure, which occur in the alloys \_\_\_\_\_.

8. Chemical composition of chosen alloy \_\_\_\_\_

9. Phase reactions in chosen alloy and their formulas \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

10. Application of the phase rule. Calculate degrees of freedom in all fields at constant  $p$ .

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11. How many phases can coexist in equilibrium at constant  $p$ ? Define them.

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12. Describe what happens if the alloy is cooled to room temperature. At which temperatures do changes in the number or type of phases occur?

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13. Application of the inverse level rule. Calculate the approximate composition and the proportions by weight of each phase that is present at chosen temperature.

The composition of phase 1 is \_\_\_\_\_.

The composition of phase 2 is \_\_\_\_\_.

What (roughly) are the proportions by weight of each phase?

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**Conclusion**

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\_\_\_\_\_  
Student's signature

“ \_\_\_\_\_ ” \_\_\_\_\_ 20\_\_ y.

\_\_\_\_\_  
Teacher's signature

“ \_\_\_\_\_ ” \_\_\_\_\_ 20\_\_ y.

## LABORATORY WORK 5 PLAIN CARBON STEELS

### Objectives

1. To learn the microstructures of the steels.
2. To learn the effect of carbon and impurities on the properties of steel.
3. To learn classification of Plain Carbon Steels.
4. To learn to determine of the steel chemical composition by its SAE-AISI number.

### Scientific principles

There are two types of iron-carbon alloys- steel and cast iron.

Plain carbon steel is an alloy of iron and carbon. It has good machineability and malleability. It is different from cast iron as regards the percentage of carbon. It contains carbon from 0.06 to 2% whereas cast iron possesses carbon from 2 to 4.2%.

Steels are an iron-carbon alloys, which contains less than 2 % carbon, impurities Mn, Si, Al, S, P, O, H, N and alloying elements, such as Cr, Ni, Ti, W and etc..

Cast irons are an iron-carbon alloys which contains more than 2 % carbon (carbon may be presented as carbide (connected) and as graphite (free)) and impurities S, P, Mn, Si. The microstructure of steels and cast irons are described by Fe – Fe<sub>3</sub>C diagram (Fig.5.1).

Plain Carbon Steels are an iron-carbon alloys, which contains less than 2.14% carbon and impurities Mn, Si, Al, S, P, O, H, N.

As the term “plain carbon steel” implies, these are alloys of iron and carbon. These steels were the first developed, are the least expensive, and have the widest range of applications. Steel is used for making camshafts, sheets and strips for fan blades, welded tubing, forgings, chains, stamping, rivets, nails, pipes, angle, channels, case hardening steel, rods, tubes, valves, gears, crankshafts, connecting rods, railway axles, fish plates, etc

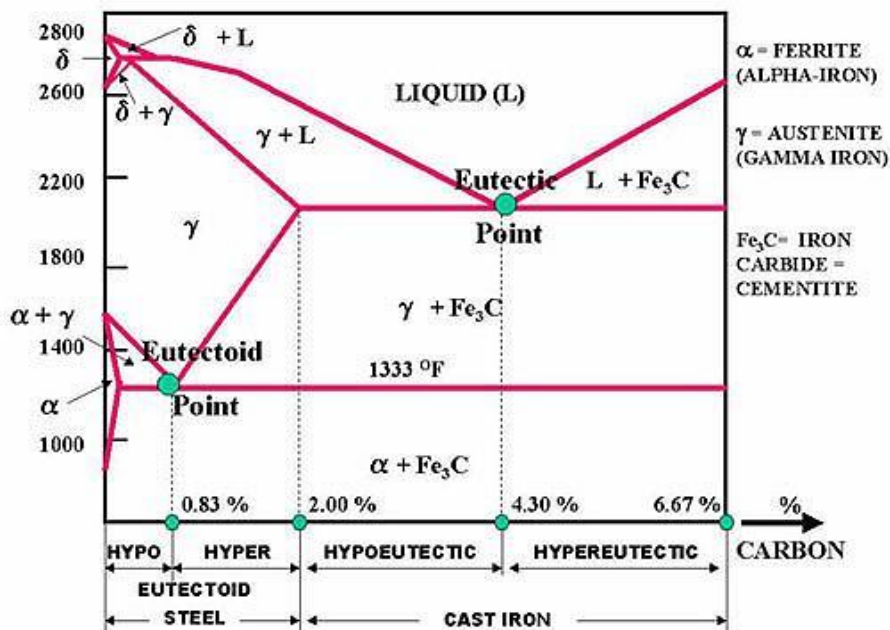


Fig.5.1. Fe – Fe<sub>3</sub>C diagram



### The effect of Carbon on the Properties of Steel

In general, as the carbon content increases the hardness of the steel also increases. The tensile strength and the yield strength also increase to about 0.8% carbon. Thereafter, they level out. This is shown in Figure 5.3.

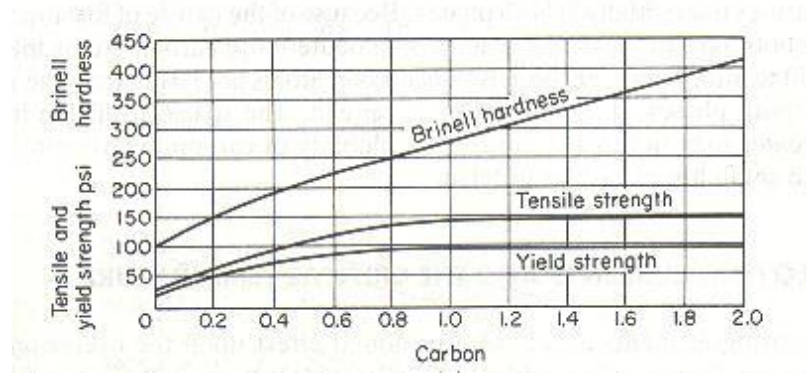


Fig. 5.3. The effect of carbon on the hardness, tensile strength and yield strength of steels.

The tensile strength and hardness are affected as the ratio of ferrite to cementite in the structure of steel changes. As the percentage of pearlite increases in the hypoeutectoid steels, the tensile strength increases. The hypereutectoid steels show only a slight increase in strength as the cementite-to-ferrite ratio increases.

The elongation and the reduction in area represent how ductile or brittle a material is. Fig.5.4. indicates the effect of carbon on the ductility and impact resistance (toughness) of steels. The elongation and the reduction in area drop sharply with increase in carbon content, going almost to zero at about 1.5 % carbon. This indicates that the carbon content of 1.5 % or more will cause high brittleness.

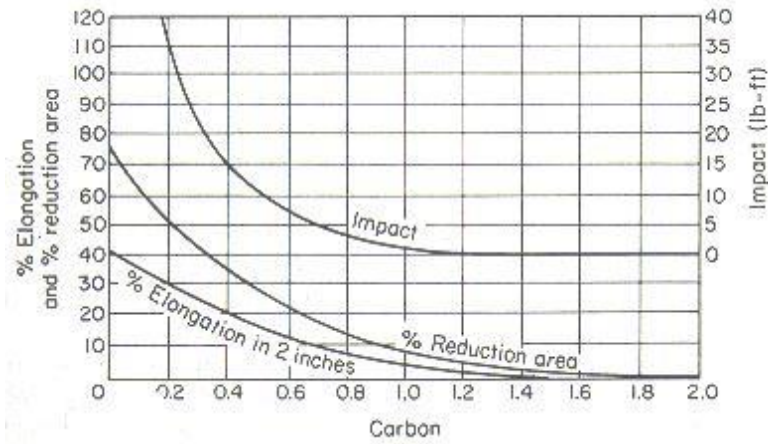


Fig. 5.4. The effect of carbon on the impact resistance and ductility of steels.

### The effect of impurities on steel

The effects of impurities like silicon, sulphur, manganese and phosphorus, on steel as discussed under.

**Silicon.** Silicon content in the finished steel usually ranges from 0.05 to 0.30%. It is added in low carbon steels for preventing them from becoming porous. It helps in removing the gases and oxides. It prevents blow holes there by making steel tougher and harder.

**Manganese.** It serves as a valuable deoxidizing and purifying agent, in steel. Manganese also combines with sulphur and thereby decreases the harmful effect of this element remaining in the steel. It increases wear resistance, hardness and strength and decreases machineability. When used in ordinary low carbon steels, manganese makes the metal ductile and of good bending quantities. In high speed steels, it is used to toughen the metal and to increase its critical temperature.

**Sulphur.** It renders free cutting properties in steel. It is found in steel either as iron sulphide or manganese sulphide. Iron sulphide due to its low melting point, produces brittleness whereas manganese sulphide does not affect so much. Therefore, manganese sulphide is less objectionable in steel than iron sulphide.

**Phosphorus.** It induces brittleness in steel. It also produces cold shortness in steel. In low carbon steels, it raises the yield point and improves the resistance to atmospheric corrosion. The sum of carbon and phosphorus usually does not exceed 0.25%.

**Hot-shortness:** Brittleness at high temperatures is called hot-shortness which is usually caused by sulfur. When sulfur is present, iron and sulfur form iron sulfide (FeS) that is usually concentrated at the grain boundaries and melts at temperatures below the melting point of steel. Due to the melting of iron sulfide, the cohesion between the grains is destroyed, allowing cracks to develop. This occurs when the steel is forged or rolled at elevated temperatures. In the presence of manganese, sulfur tends to form manganese sulfide (MnS) which prevents hot-shortness.

**Cold-shortness:** Large quantities of phosphorus (in excess of 0.12% P) reduces the ductility, thereby increasing the tendency of the steel to crack when cold worked. This brittle condition at temperatures below the recrystallization temperature is called cold-shortness.

### **Classification of Plain Carbon Steels**

The steel may be of various kinds and few important types are explained as under.

#### **Classification by structure**

There are three kinds of plain carbon steels: hypoeutectoid, eutectoid and hypereutectoid steels.

**Eutectoid steel.** In the abbreviated iron–iron carbide diagram of Fig. 5.1 the eutectoid point is the lowest temperature and composition at which the austenite phase can exist. It is that point corresponding to a composition of 99.2 wt% Fe 0.8 wt% C. This is the eutectoid point of the iron–iron carbide system.

Eutectoid deals with a solid-to-solid transformation, while the eutectic region begins with a liquid. At the eutectoid point, the eutectoid reaction takes place on cooling a 0.8 wt% C alloy composition slowly through the eutectoid temperature. At this temperature the reaction is



This is a reaction of a solid transforming to two different solids forming a parallel-plate microstructure of the two phases called **pearlite**.

A plain carbon steel of eutectoid composition is 1080 steel, which has a tensile strength of about 112,0 psi ( pound-force per square inch, lbf/in<sup>2</sup>) or about 772 MPa.

**\*Note 1psi = 6.89 MPa; 1 MPa = 0,145 psi**

If the austenite contains less than 0.80% carbon (**hypoeutectoid steel**), free ferrite will first be rejected on slow cooling through the critical temperature until the composition of the remaining austenite reaches 0.80% carbon, when the simultaneous rejection of both ferrite and carbide will again occur, producing pearlite. So a hypoeutectoid steel at room temperature will be composed of areas of free ferrite and areas of pearlite; the higher the carbon percentage, the more pearlite present in the steel. A 1040 steel is typical of a hypoeutectoid steel. It will be somewhat softer than a 1080 steel and have a tensile strength of about 75,0 psi (517 Mpa).

When austenite that contains more than 0.80% carbon (**hypereutectoid steel**) is slowly cooled, cementite is thrown out at the austenite grain boundaries, forming a cementite network, until the austenite again contains 0.80% carbon, at which time pearlite is again formed. Thus a hypereutectoid steel, when slowly cooled, will have areas of pearlite surrounded by a thin carbide network

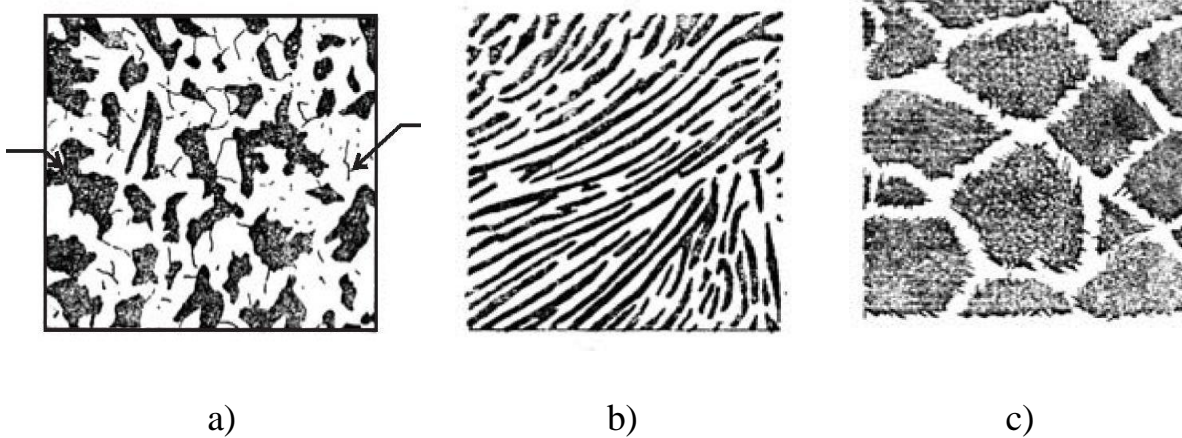


Fig.5.2. Microstructure of mild steel (a), pearlitic eutectoid steel (b), high carbon steel (c)

### Classification of steel by carbon content

Depending upon the carbon content, a plain carbon steels can divided to the following types:

**Table 5.1.** Classification of steel by carbon content

Dead carbon steel	Up to 0.05% carbon
Low carbon or mild steel	0.15% to 0.45% carbon
Medium carbon steel	0.45% to 0.8% carbon

High carbon steel	0.8% to 1.5% carbon
-------------------	---------------------

### **Dead Carbon Steel**

It possesses very low percentage of carbon varying from 0.05 to 0.15%. It has a tensile strength of 390 MPa and a hardness of about 115 BHN. Steel wire, sheets, rivets, screws, pipe, nail and chain are made from this steel. This steel is used for making camshafts, sheets and strips for fan blades, welded tubing, forgings, chains, stamping, rivets, nails, pipes, automobile body etc.

### **Low Carbon Or Mild Steel**

Low carbon steel is sometimes known as mild steel also. It contains 0.20 to 0.30% C which has tensile strength of 555 MPa and hardness of 140 BHN. It possesses bright fibrous structure. It is tough, malleable, ductile and more elastic than wrought iron. It can be easily forged and welded. It can absorb shocks. It rusts easily. Its melting point is about 1410°C. It is used for making angle, channels, case hardening steel, rods, tubes, valves, gears, crankshafts, connecting rods, railway axles, fish plates, small forgings, free cutting steel shaft and forged components etc.

#### **Applications**

Mild steel containing 0.15 to 0.20% carbon

It is used in structure steels, universal beams, screws, drop forgings, case hardening steel, bars, rods, tubes, angles and channels etc.

Mild steel containing 0.20-0.30% carbon

It is used in making machine structure, gears, free cutting steels, shafts and forged components etc.

### **Medium Carbon Steels**

Medium carbon steel contains carbon from 0.30 to 0.8%. It possesses having bright fibrous structure when fractured. It is tough and more elastic in comparison to wrought iron. It can be easily forged, welded, elongated due to ductility and beaten into sheets due to its good malleability. It can easily absorb sudden shocks. It is usually produced as killed or semi killed steels and is harden able by treatment. Hardenability is limited to thin sections or to the thin outer layer on thick parts. Its tensile strength is better than cast iron and wrought iron but compressive strength is better than wrought iron but lesser than cast iron. It rusts readily. Its melting point is 1400°C. It can be easily hardened and it possesses good balance of strength and ductility.

It is generally used for making railway coach axles, bolts, connecting rods, key stock, wires and rods, shift and break levers, spring clips, gear shafts, small and medium forgings, railway coach axles, crank pins on heavy machines, spline shafts, crankshafts, forging dies, set screws, die blocks, self tapping screws, clutch discs, valve springs, plate punches, thrust washers etc. The applications of different kinds of medium carbon steel are given as under.

#### **Applications**

Plain carbon steels having carbon % 0.30 to 0.45. Axles, special duty shafts, connecting rods, forgings, machinery steel, spring clips, turbine, rotors, gear shafts, key stock, forks and bolts.

Plain carbon steels having carbon % 0.45 to 0.60. Railway coach axles, crank pins, crankshafts, axles, spline shafts, loco tyres.

Plain carbon steels having carbon % 0.60 to 0.80. Drop forging dies, die blocks, bolt heading dies, self-tapping screws, valve spring, lock washers, hammers, cold chisels, hacksaws, jaws for vices etc.

### **High Carbon Steels**

High carbon steels (HCS) contain carbon from 0.8 to 1.5%. Because of their high hardness, these are suitable for wear resistant parts. Spring steel is also high carbon steel. It is available in annealed and pre-tempered strips and wires. High carbon steel loses their hardness at temperature from 200°C to 250°C. They may only be used in the manufacture of cutting tools operating at low cutting speeds. These steels are easy to forge and simple to harden. These steels are of various types which are identified by the carbon percentage, hardness and applications.

### **Classification by Applications**

#### **Free cutting steel**

The important features of free cutting steels are their high machinability and high quality surface finish after finishing. These properties are due to higher sulphur and phosphorus. Sulphur exists in the form of manganese sulphide (MnS) which forms inclusions in steel. These inclusions promote the formation of discontinuous chips and also reduce friction on the surface being machined so produces good surface finish easily. Phosphorus is dissolved in the ferrite and increases hardness and brittleness. Lead up to 0.35% can be added to improve the machinability of steel. These have high sulphur content present in form of manganese sulphide inclusions causing the chips to break short on machining. Mn and P make steel hardened and brittle. Lead (0.2% to 0.35%) is sometimes added to steel improving machinability properties of steel. This consists of three Bessemer grades B1111, B1112, B1113 which differ in sulphur content and the sulphurised steels from C1108 to C1151.

The tool life achieved in machining free cutting steels is from 2 to 2.5 times higher than when carbon steels of the same carbon content. However, it must be noted that free cutting steels have lower dynamic strength characteristics and are more susceptible to corrosion. Free cutting steels are frequently supplied in the cold drawn or work hardened form. These cold drawn steels have a high tensile strength and hardness but less ductile when compared to other kind of steels.

#### **Applications of free cutting steel**

These steels are used for manufacturing axles, bolts, screws, nuts, special duty shafts, connecting rods, small and medium forgings, cold upset wires and rods, solid turbine rotors,

rotor and gear shaft, armature, key stock, forks and anchor bolts screw stock, spring clips, tubing, pipes, light weight rails, concrete reinforcing etc.

### **Structural steels**

Structural steels possess high strength and toughness, resistance to softening at elevated temperatures and enough resistance to corrosion. In addition, they should possess weldability, workability and high hardenability. The principal alloying elements in structural steels are chromium, nickel and manganese.

These steels has various applications. They are used for structural members of bridges, buildings, rail road, cars etc. They are also used for manufacturing components subjected to static and dynamic loads. These components include valves, pins, studs, gears, clutches, bushes, shafts etc.

### **The Marking of Steel**

According to Indian standard ISO 1570-1961, plain carbon steels are designated by the alphabet 'C' followed by numerals which indicate the average percentage of carbon in it. For example C40 means a plain carbon steel containing 0.35% to 0.45% C (0.40% on average), although other elements like manganese may be present. In addition to the percentage of carbon, some other specification may include e.g. C55Mn75 means the carbon content lies between 0.50% to 0.60% and the manganese content lies between 0.60 to 0.90%. It may be noted that only average contents are specified in such designation of steelSteel, because of its strength, formability, abundance, and low cost, is the primary metal used for structural applications.

The Society of Automotive Engineers (SAE) has established standards for specific analysis of steels. In the 10XX series, the first digit indicates a plain carbon steel. The second digit indicates a modification in the alloys. 10XX means that it is a plain carbon steel where the second digit (zero) indicates that there is no modification in the alloys. The last two digits denote the carbon content in points. For example SAE 1040 is a carbon steel where 40 points represent 0.40 % Carbon content.

The American Iron and Steel Institute (AISI) numbering system for plain carbon steels also includes 11XX, 12XX, and 15XX. A brief description of each type of alloy is as follows:

10XX Plain carbon, Mn 1.00% max.

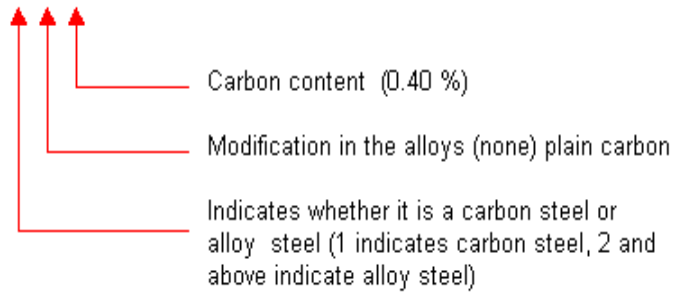
11XX Plain carbon, resulfurized

12XX Plain carbon, resulfurized and rephosphorized

15XX Plain carbon, Mn range 1.00–1.65% max.

General representation of steels:

## SAE 1040



Mechanical and Physical Properties several kinds of steel are in the tables 5.2 –5.4

**TABLE 5.2.** Average Mechanical Properties of Cold-Drawn Steel

AISI no.	Tensile strength (psi)	Yield strength (psi)	Elongation (%)	Brinell hardness	Reduction of area (%)
1010	67,000	55,000	25.0	137	57
1015	71,000	60,300	22.0	149	55
1020	75,000	63,700	20.0	156	52
1025	80,000	68,000	18.5	163	50
1030	87,000	73,900	17.5	179	48
1035	92,000	78,200	17.0	187	45
1040	97,000	82,400	16.0	197	40
1045	102,000	86,200	15.0	207	35
1120	78,000	66,300	19.5	159	49
1137	105,000	89,200	16.0	217	35

**TABLE 5.3.** Mechanical and Physical Properties of AISI 1020 Steel (Hot Worked)

Modulus of elasticity (psi)	29–30
Tensile strength (psi)	75
Yield strength (psi)	65.7
Elongation (%)	36
Brinell hardness	156
Density (g/cm <sup>3</sup> )	7.85
Thermal conductivity (Btu/hr ft <sup>2</sup> F)	27
Specific heat (Btu/lb F)	0.1
Thermal expansion 10 <sup>-6</sup> (in./in. F)	8.4

**TABLE 5.4.** Mechanical Properties of Selected Carbon Steels in Normalized and Annealed Condition

AISI no.	Treatment ( C/ F)	Yield strength (psi)	Elongation (%)	Hardness (RB)	
1020	N	870/1600	50,000	35.8	131
	A	870/1600	43,000	36.5	111
1040	N	900/1650	54,000	28.0	170
	A	790/1450	51,000	30.2	149
1060	N	900/1650	61,000	18.0	229
	A	790/1450	54,000	22.5	179
1080	N	900/1650	76,000	11.0	293
	A	790/1450	56,000	24.7	174
1095	N	900/1650	73,000	9.5	293
	A	790/1450	55,000	13.0	192
1137	N	900/1650	58,000	22.5	197
	A	790/1450	50,000	26.8	174

<sup>a</sup>N = normalized; A = annealed; temperature is that to which the piece was heated.

\*Notes  $F = (C \times 9/5) + 32$ ;  $C = (F - 32) \times 5/9$

### **Materials and Equipment:**

1. Specimen of the hypoeutectoid and hypereutectoid steels.
2. Microscope MM – 4.

### **Procedure**

1. For checking microstructure of steel, its specimen is prepared by preparing a flat mirror surface on small piece of metal through rubbing by sand papers, polishing and buffing etc. This surface is then followed by etching with a chemical solution. The chemical solution reacts with various constituents in varying degree to reveal crystal structure clearly. The revealed structure is then viewed through powerful microscope.
2. Set specimen of the hypoeutectoid and hypereutectoid steels on a microscope and look at their microstructure.
3. Draw the microstructure of the hypoeutectoid and hypereutectoid steels.
4. Determine the critical temperatures (UCT and LCT) for hypoeutectoid steel with 0.3 %C and hypereutectoid steel with 1.2%C.
5. Determine the chemical composition of the steels by its SAE-AISI number.

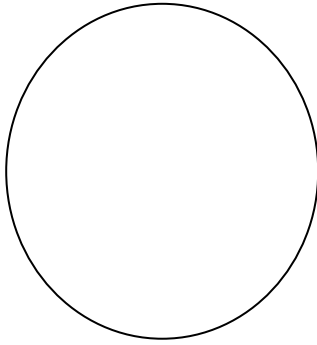
### **Questions:**

1. What are the types of iron- carbon alloys?
2. What is steel?
3. What is cast iron?
4. Which polymorphic modifications does the iron have and at what temperatures interval is it stable?
5. List phases and structure of the Fe-Fe<sub>3</sub>C diagram.

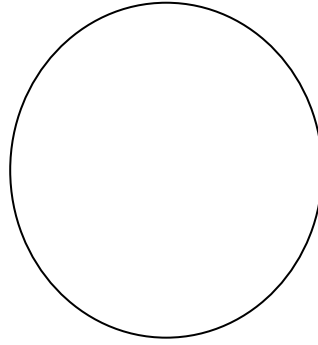


6. What is cementite and what properties does it have?
7. What is austenite and what properties does it have?
8. What is ferrite and what properties does it have?
9. What is perlite and what properties does it have?
10. What is ledeburite?
11. What carbon content does the hypoeutectoid steel have?
12. What carbon content does hyperutectoid steel have?
13. What carbon content does hypoeutectic cast iron have?
14. What carbon content does hypereutectic cast iron have?
15. Describe the effect of carbon on hardness and tensile strength of steels.
16. Describe the effect of carbon on toughness (impact resistance) and ductility of steels.
17. Describe the effect of impurities on steel.
18. What is hot-shortness and cold shortness?
19. Classification of Plain Carbon Steels by structure.
20. Classification of steel by carbon content.
21. Classification of steel by applications.
22. What does number SAE 1020 mean?

LABORATORY WORK № 5  
**PLAIN CARBON STEELS**  
PROTOCOL №1



Hypoeutectoid steel  
Carbon content \_\_\_\_\_%



Hypereutectoid steel  
Carbon contain \_\_\_\_\_%

Critical temperature, °C

UCT = \_\_\_\_\_

LCT = \_\_\_\_\_

UCT = \_\_\_\_\_

LCT = \_\_\_\_\_

PROTOCOL № 2

Steel	Carbon content, % C	Mechanical properties				
		Tensile strength (psi/MPa)	Yield strength (psi/MPa)	Elongation (%)	Brinell hardness	Reduction of area (%)
SAE 1010						
SAE 1025						
SAE 1030						
SAE 1045						

Conclusions:

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Teacher's signature

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## LABORATORY WORK 6

### CAST IRONS

#### Objectives

1. To learn the microstructures of the cast iron.
2. To learn the advantages and disadvantages of the cast iron.
3. To learn the applications of the cast iron.

#### Scientific principles

#### Types of cast iron

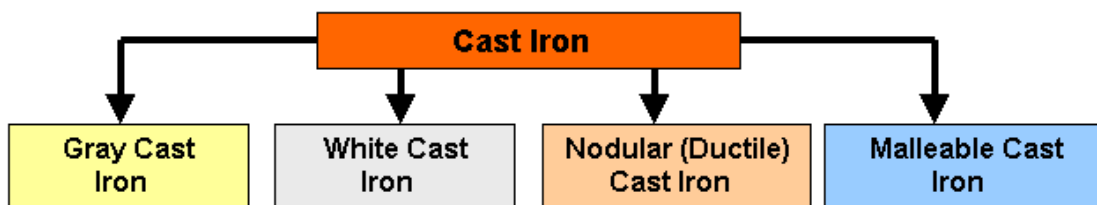
Cast irons may often be used in place of steel at considerable cost savings. The design and production advantages of cast iron include:

- Low tooling and production cost
- Good machinability without burring
- Ability to cast into complex shapes
- Excellent wear resistance and high hardness (particularly white cast irons)
- High inherent damping capabilities

The properties of the cast iron are affected by the following factors:

- Chemical composition of the iron
- Rate of cooling of the casting in the mold (which depends on the section thickness in the casting)
- Type of graphite formed (if any)

Major types of cast iron are shown in Figure 6.1.



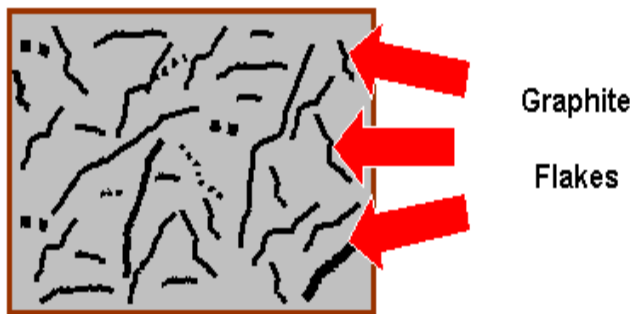
*Fig.6.1. Types of Cast Iron*

#### Gray cast iron

Gray iron, named so because of its fracture has a gray appearance. It contains carbon in the form of flake graphite in a matrix which consists of ferrite, pearlite or a

mixture of the two. The fluidity of liquid gray iron, and its expansion during solidification due to the formation of graphite, has made this metal ideal for the economical production of shrinkage-free, intricate castings such as motor blocks.

The flake-like shape of graphite in Gray iron, see Fig.6.2 and 6.3, exerts a dominant influence on its mechanical properties. The graphite flakes act as stress raisers which may prematurely cause localized plastic flow at low stresses, and initiate fracture in the matrix at higher stresses. As a result, Gray iron exhibits no elastic behavior but excellent damping characteristics, and fails in tension without significant plastic deformation. The presence of graphite flakes also gives Gray Iron excellent machinability and self-lubricating properties.



*Fig.6.2. Graphite Flakes in Gray Cast iron*



*Fig.6.3. Photomicrograph of Gray Cast iron*

**Advantages of Gray Cast Iron:**

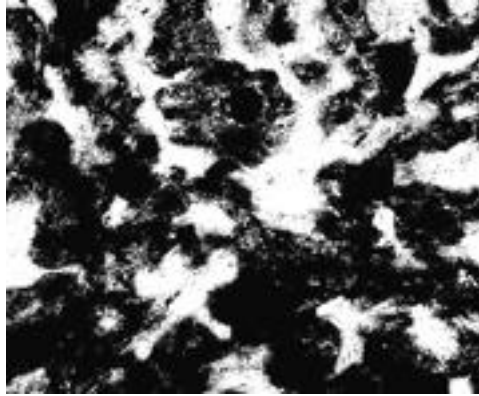
- Graphite acts as a chip breaker and a tool lubricant.
- Very high damping capacity.
- Good dry bearing qualities due to graphite.
- After formation of protective scales, it resists corrosion in many common engineering environments.

**Disadvantages:**

- Brittle (low impact strength) which severely limits use for critical applications.
- Graphite acts as a void and reduces strength.
- Changes in section size will cause variations in machining characteristics due to variation in microstructure.
- Higher strength gray cast irons are more expensive to produce.

**White cast iron**

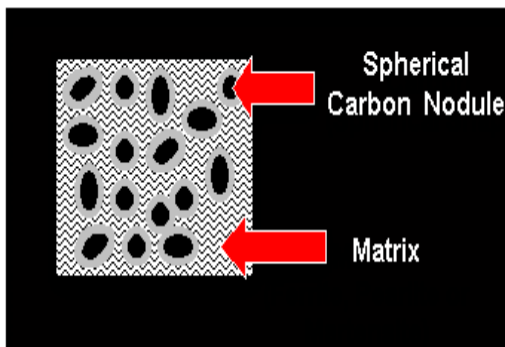
**White cast iron** is unique in that it is the only member of the cast iron family in which **carbon is present only as carbide**. Due to the absence of graphite, it has a light appearance. The presence of different carbides, depending on the alloy content, makes white cast irons extremely hard and abrasion resistant but very brittle. An improved form of white cast iron is the chilled cast iron.



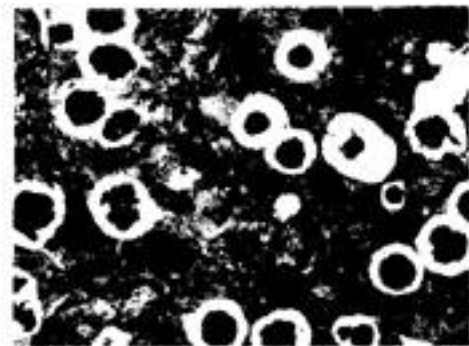
*Fig.6.4. Photomicrograph of White Cast Iron*

**Ductile Cast iron (nodular cast)**

This structure is developed from the melt. The carbon forms into spheres when cerium, magnesium, sodium, or other elements are added to a melt of iron with very low sulfur content that will inhibit carbon from forming. The control of the heat-treatment process can be pearlitic, ferritic, martensitic matrices into which the carbon spheres are embedded.



*Fig.6.5. Nodular (Ductile) Cast Iron and the spherical carbon embedded into the matrix.*



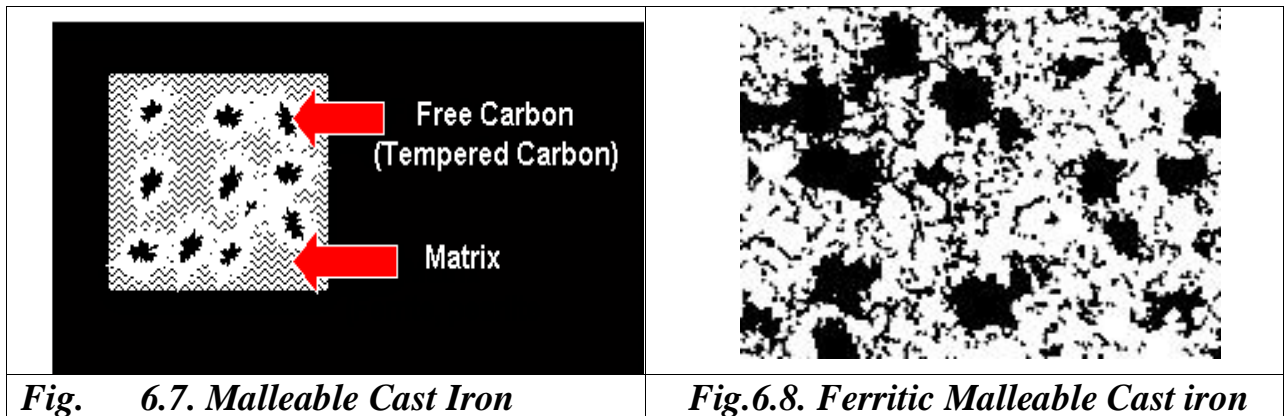
*Fig.6.6. Photomicrograph of Nodular Cast iron*

Ductile cast iron is used for many structural applications, particularly those requiring strength and toughness combined with good machinability and low cost. The automotive and agricultural industries are the major users of ductile iron castings. Because of economic advantage and high reliability, ductile iron is used for such critical automotive parts as crankshafts, engine connecting rods, idler arms, wheel hubs, truck axles, front wheel spindle supports, disk brake calipers, suspension system parts, power transmission yokes, high temperature applications for turbo housing and manifolds, and

high security valves for many applications. The cast iron pipe industry is another major user of ductile iron.

### Malleable Cast Iron

If cast iron is cooled rapidly, the graphite flakes needed for gray cast iron do not get a chance to form. Instead, white cast iron forms. This white cast iron is reheated to about 950°C for long periods of time and at the elevated temperatures cementite ( $Fe_3C$ ) decomposes into ferrite and free carbon. Upon cooling, the combined carbon further decomposes to small compact particles of graphite (instead of flake-like graphite seen in gray cast iron). If the cooling is very slow, more free carbon is released. This free carbon is referred to as temper carbon, and the process is called malleablizing.



Malleable cast iron is used for connecting rods and universal joint yokes, transmission gears, differential cases and certain gears, compressor crankshafts and hubs, flanges, pipe fittings and valve parts for railroad, marine and other heavy-duty applications.

#### Advantages:

- Excellent machinability
- Significant ductility
- Good shock resistance properties

#### Disadvantages:

The major disadvantage is shrinkage. Malleable cast iron decreases in volume during solidification, and as a result, requires attached reservoirs (feeders and risers) of liquid metal to offset the shrinkage and prevent the formation of internal or external shrinkage defect.

#### Materials and Equipment:

1. Specimens of the gray cast iron, nodular cast iron and malleable cast iron.
2. Microscope MM – 4.

**Procedure:**

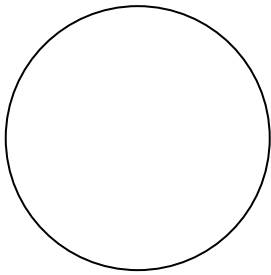
1. Set specimen of the gray cast iron, nodular cast iron and malleable cast iron on a microscope and look at their microstructure.
2. Draw the microstructure of the gray cast iron, nodular cast iron and malleable cast iron.

**Questions:**

1. What are the advantages of cast iron?
2. What are the major types of cast iron?
3. List forms of the graphite and write what types of cast iron have those forms of graphite.
4. What form of graphite does the gray cast iron have?
5. What are the advantages of gray cast iron?
6. Write an example of ductile cast iron applications.
7. Explain the malleable cast iron?
8. What are the advantages and disadvantages of malleable cast iron?

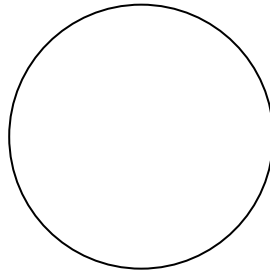


Laboratory work № 6  
**CAST IRONS**  
PROTOCOL №1



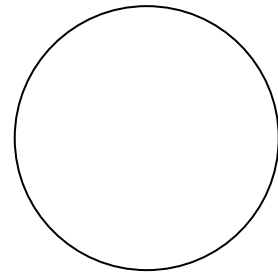
Gray cast iron

\_\_\_\_\_



nodular cast iron  
Graphite form

\_\_\_\_\_



malleable cast iron

\_\_\_\_\_

The type of the metallic matrix

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Conclusions:

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Teacher's signature

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## Glossary Metals

- alloy:** a substance that has metallic properties and is made up of two or more chemical elements, of which at least one is a metal.
- annealing:** a heat treatment of a metal designed to produce a soft, ductile condition. Typically the metal is heated and allowed to cool slowly.
- anode:** electrode at which electrons are released during corrosion. The half reaction at the anode is called oxidation and the metal is said to be oxidized. The anode is the electrode that disintegrates during corrosion.
- bronze:** An alloy composed of tin and copper.
- cathode:** electrode which accepts electrons during corrosion. The half reaction at the cathode is called reduction and the metal is said to be reduced. The cathode is not destroyed during corrosion.
- cathodic protection:** a more active metal is placed next to a less active metal. The more active metal will serve as an anode and will be corroded instead of the less active metal. The anode is then called a sacrificial anode.
- cold-working:** a permanent deformation of a metal below its crystallization temperature. Deforming the metal creates more dislocations which entangle, pinning them and thereby strengthening the metal.
- corrosion:** oxidation-reduction reaction where electrons are released at the anode and taken up at the cathode.
- dislocations:** linear defects in a crystal.
- ductile:** can be drawn or stretched into wire and other shapes.
- elastic deformation:** materials return to their original shape after a small load or stress is applied.
- face-centered cubic:** crystal arrangement of close-packed layers of particles where three layers of particles alternate positions. This layering is known as ABCABC.
- failure:** ultimate separation of metal parts due to applied loads. i.e. it breaks.
- fatigue:** the application and release of stresses as metal is used which cause small cracks to grow, during many cycles of application, until they fracture.
- grain:** a crystal (ordered arrangement of atoms).
- grain boundary:** the interface between the grains or crystals.
- Hall Process:** an electrolytic technique to refine aluminum from its ore.
- hardening:** heating and rapidly cooling steel.
- heat treating:** modification of properties and structure of alloys by specific heating and cooling cycles.
- hexagon closest packing (HCP):** crystal arrangement of layers of particles where two layers alternate positions. The layering is known as ABAB.
- malleable:** can be hammered into a sheet.
- martensite:** a super-saturated solid solution of carbon in ferrite. The carbon atoms distort the BCC ferrite into a BC-tetragonal structure.

**metallic bonding:** bond formed by positive ions surrounded by a cloud of valence electrons.

**ore:** a natural mineral deposit that contains enough valuable minerals to make it profitable to mine at the current technology.

**oxide:** a compound of oxygen with some other chemical element.

**oxidation:** the half of an electrochemical reaction where electrons are released. Oxidation occurs at the electrode called the anode.

**pinned:** the dislocations in a crystal get tangled or attached to atoms of an alloying agent.

**plastic deformation:** materials remain deformed after a load is added and then removed.

**quenched:** cooled rapidly.

**reduction:** the half of an electrochemical reaction where electrons are taken up. Reduction occurs at the cathode.

**reduction of metals:** changing a metal ion to a neutral atom by the addition of electrons.

**steel:** an iron-carbon alloy, malleable in some temperature range as initially cast. Steel usually contains some other alloying elements such as silicon, manganese, etc. as well as impurities such as sulfur and phosphorus.

**strength:** a measure of the ability of a material to support a load.

**stress:** the internal forces produced by application of an external load, tending to displace component parts of the stressed material. It is defined as the force (load) divided by the area on which it acts.

**toughness:** the ability to absorb energy of deformation without breaking. High toughness requires both high strength and high ductility.

**unit cell:** The smallest repeating array of atoms in a crystal.

### GLOSSARY Ceramic

**Abrasive:** A hard material used to grind, cut or wear.

**Absorption:** The inclusion of the energy of a photon within a substance.

**Amorphous:** A noncrystalline substance, atoms lack long range order.

**Annealing:** Heat treatment to alter properties.

**Annealing point (glass):** Temperature at which stresses are removed.

**Brittle fracture:** A break that occurs by rapid crack propagation.

**Capacitance (C):** Charge storing capability.

**Cement:** A material that binds particles together in a mixture.

**Ceramic:** A compound of metallic and nonmetallic elements.

**Color:** Wavelengths of light perceived by the eye.

**Component:** A part, or device.

**Conductivity:** The ability to carry an electric current (electricity) or thermal energy (heat).

**Covalent bond:** Bonding by sharing electrons.

**Crystalline:** A solid with a repeating three-dimensional unit cell.

**Crystal structure:** The orderly arrangement of the atoms or ions within a crystal.

**Diamagnetism:** Weakly repelled from a magnetic field.

**Dielectric:** An insulator.

**Dielectric constant:** Relative electrical permittivity of a material as compared to a perfect vacuum.

**Dielectric (breakdown) strength:** The amount of electricity needed to start an electric current flow in a dielectric material.

**Ductile fracture:** Break accompanied by large plastic deformation.

**Elastic deformation:** Change in shape that returns when a stress is removed.

**Elastic Modulus:** Ratio of stress to strain in elastic deformation, measure of elasticity.

**Electric field:** The gradient of voltage.

**Electronegativity:** The attraction of an atom for shared electrons.

**Electron volt (eV):** Unit of energy equivalent to the energy gained by an electron when it falls through an electric potential of one volt.

**Excited state:** An energy state to which an electron may move by the absorption of energy.

**Fiber Optics:** The technology of transferring information as light pulses through long thin fibers, usually made of glass.

**Firing:** High temperature processing to increase densification in a product.

**Fluorescence:** Light that is emitted a short period of time after an electron has been excited.

**Fracture toughness ( $K_{IC}$ ):** Measure of a material's resistance to crack propagation.

**Glass:** An amorphous solid showing characteristic specific volume behavior over a certain temperature range.

**Glass - ceramic:** Crystalline ceramic material that was formed by heat treating glass.

**Glass transition temperature ( $T_g$ ):** Temperature at which a glass changes from a supercooled liquid into a solid.

**Grain:** Individual crystal in a **polycrystalline** material.

**Grain boundary:** The boundary between grains (or crystals) that are misoriented with respect to one another.

**Green ceramic body:** Ceramic object that is dried but not fired.

**Ground state:** Lowest electron energy state.

**Hardness:** Resistance to deformation.

**Heat capacity:** Heat required to produce a unit increase in temperature per quantity of material.

**Imperfection:** Flaw, any deviation from perfection, as in a crystal.

**Index of refraction:** Ratio of the speed of light in a vacuum to the speed of light in a medium.

**Insulator:** Material that does not conduct electricity (electrical) or heat (thermal).

**Ionic bond:** Electrostatic force between oppositely charged ions.

**Laser:** Source of coherent light (Light Amplification by Stimulated Emission of Radiation).

**Lattice:** The regular arrangement of points in a crystal.

**Magnetic field strength:** Intensity of an applied magnetic field.

**Microstructure:** Structural features that can be observed with a microscope.

**Noncrystalline:** Amorphous, with no long-range atomic order.

**Piezoelectric:** Material that produces an electrical response to a mechanical force.

**Plastic deformation:** Permanent deformation, change of shape.

**Polycrystalline:** Composed of more than one crystal or grain.

**Porcelain:** A durable ceramic composite made by firing clay, feldspar and quartz together.

**Reflection:** Deflection of light at the interface between two materials.

**Refraction:** Bending of light as it passes from one medium into another.

**Refractory:** Material that can be exposed to high temperature without deterioration.

**Resistivity:** Measure of resistance to passage of electrical current (reciprocal of conductivity).

**Semiconductor:** Nonmetallic material that has a relatively narrow energy band gap.

**Sintering:** Coalescence of individual ceramic particles into a continuous solid phase at a high temperature.

**Slip:** Mixture of clay with water that can be poured into a mold.

**Slip casting:** Method of making ceramic objects by pouring slip into a mold.

**Softening point (glass):** Maximum temperature a glass can be heated before it permanently deforms.

**Smart materials:** Materials able to detect a change in the environment and react to it.

**Specific volume:** Volume per unit mass, reciprocal of density.

**Strain:** Change in length of a sample in the direction of an applied stress.

**Stress:** Force applied to a sample divided by its cross-sectional area.

**Structural clay products:** Ceramic objects made mainly of clay and used in structural applications.

**Structure:** Arrangement of internal components.

**Superconductivity:** Disappearance of electrical resistivity at low temperatures.

**Supercooling:** Cooling below the normal temperature for a phase change, without the change occurring.

**Tensile strength:** Maximum stress without fracture.

**Thermal expansion coefficient, linear:** Fractional change in length divided by change in temperature, a measure of a materials tendency to expand when heated.

**Thermal stress:** Residual stress caused by a change in temperature.

**Thermal tempering:** The introduction of residual compressive stresses to increase the strength of glass.

**Toughness:** Energy absorbed by a material as it fractures, a measure of its resistance to fracture.

**Transgranular fracture:** Fracture by crack propagation through the grains.

**Translucent:** Transmits light diffusely.

**Transparent:** Transmits light clearly.

**Unit cell:** The basic repeating unit in a crystal.

**Whiteware:** Clay-based ceramic that turns white after firing.

## **Glossary Polymers**

### **Abbreviations:**

HDPE: high density polyethylene

LDPE: low density polyethylene

PET: polyethylene terephthalate

PP: polypropylene

PS: polystyrene

PVA: polyvinyl alcohol

PVC: polyvinyl chloride

**addition polymerization:** a chemical reaction in which simple molecules are linked together to form long chain molecules.

**amorphous:** non-crystalline polymer or non-crystalline areas in a polymer.

**Bakelite:** a polymer produced by the condensation of phenol and formaldehyde.

**branched polymer:** polymer having smaller chains attached to the polymer backbone.

**cellulose:** a natural polymer found in wood and other plant material.

**composite polymer:** a filled or reinforced plastic.

**condensation polymer:** one in which two or more molecules combine resulting in elimination of water or other simple molecules, with the process being repeated to form a long chain molecule.

**configuration:** related chemical structure produced by the making and breaking of primary valence bonds.

**copolymer:** a macromolecule consisting of more than one type of building unit.

**creep:** cold flow of a polymer.

**cross-linking:** occurs when primary valence bonds are formed between separate polymer chain molecules.

**crystalline polymer:** polymer with a regular order or pattern of molecular arrangement and a sharp melting point.

**dimer:** a polymer containing two monomers.

**domains:** sequences or regions in block copolymers.

**elastomer:** a type of polymer that exhibits rubber-like qualities.

**Ekonol:** a moldable, high temperature polymer.

**end group:** functional group at the end of a chain in polymers, e.g. carboxylic group.

**extrusion:** a fabrication process in which a heat-softened polymer is forced continually by a screw through a die.

**filler:** a relatively inert material used as the discontinuous phase of a polymer composite.

**free radical:** A chemical component that contains a free electron which covalently bonds with a free electron on another molecule.

**homopolymer:** a macromolecule consisting of only one type of building unit.

**initiation:** the start of a chain reaction with a source such as free radicals, peroxides, etc.

**kevlar:** a high strength polymer which can withstand high temperatures.

**linear:** polymers made up of one long continuous chain, without any excess appendages or attachments.

**macromolecule:** a polymer.

**material:** a substance useful for structural purposes.

**monomer:** smallest repeating unit of a polymer.

**nylon:** a polymer used commonly in the textiles industry.

**oligomer:** a low molecular weight polymer in which the number of repeating units is approximately between two and ten.

**polyethylene:** the most extensively produced polymer.

**polyester:** a polymer with a COOR repeating unit.

**polymer:** a high molecular weight macromolecule made up of multiple repeating units.

**polymerization:** the chemical reaction in which high molecular mass molecules are formed from monomers.

**polystyrene:** a polymer commonly used in packaging.

**propagation:** the continuous successive chain extension in a polymer chain reaction.

**T<sub>g</sub>:** glass transition temperature below which a polymer is a hard glassy material.

**thermoplastic:** a polymer which may be softened by heat and hardened by cooling in a reversible physical process.

**thermoset:** a network polymer obtained by cross-linking a linear polymer to make it infusible or insoluble.

**T<sub>m</sub>:** melting temperature.

**Van der Waals forces:** intermolecular attractions.

**viscosity:** the resistance to flow as applied to a solution or a molten solid.

**vinyl chloride:** the monomer used in PVC production.

**vulcanization:** cross-linking with heat and sulfur to toughen a polymer.

### Composition and Applications of Few Typical Materials

No	Alloy	Composition	Uses
1	Duralmin,	95% Aluminium + 4% Copper+	Light structures, extruded sections and sheet
2	Gun metal	90% copper + 10% zinc	Small valves, fittings for water services
3	Monel	67% Ni + 28% Copper + remaining carbon, iron and Manganese	Valve parts for superheated steam turbine blades
4	Phosphor bronze	90% Copper + 9.7% Tin + 0.3% Phosphorus	Bearings, worm wheels, rods sheets
5	High carbon steel	0.8% to 1.5% Carbon + remaining iron	Files, dies for wire drawing, clutch disc
6	Spheroidal CI	3.2%-4.5% carbon 1-4% Si 0.1-8% Mn 0.1% P 0-3.5% Ni 0.05-0.1% Mn	For high wear resistance
7	Wrought iron	99% Pig Iron + 0.12% Carbon + 0.25% Phosphorus + 0.05 % Sulphur	Chains, crane hooks, railway couplings



**AISI/SAE and UNS Designation Systems and Composition Ranges for Plain Carbon Steel and Various Low-Alloy Steels**

<i>AISI/SAE Designation</i> <sup>a</sup>	<i>UNS Designation</i>	<i>Composition Ranges (wt% of Alloying Elements in Addition to C)<sup>b</sup></i>		
		<i>Ni</i>	<i>Cr</i>	<i>Mo</i>
10xx, Plain carbon	G10xx0			
11xx, Free machining	G11xx0			
12xx, Free machining	2xx0			
13xx	G13xx0			
40xx	G40xx0			0.20-0.30
41xx	G41xx0		0.80-1.10	0.15-0.25
43xx	G43xx0	1.65-2.00	0.40-0.90	0.20-0.30
46xx	6xx0	0.70-2.00		0.15-0.30
48xx	G48xx0	3.25-3.75		0.20-0.30
51xx	G51xx0		0.70-1.10	
61xx	1xx0		0.50-1.10	
86xx	6xx0	0.40-0.70	0.40-0.60	0.15-0.25
92xx	2xx0			

<sup>a</sup>The carbon concentration in weight percent times 100, is inserted in the place of "xx" for each specific steel.

<sup>b</sup> Except for 13xx alloys, manganese concentration is less than 1.00 wt%.

Except for 12xx alloys, phosphorus concentration is less than 0.35 wt%.

Except for 11xx and 12xx alloys, sulfur concentration is less than 0.04 wt%.

Except for 92xx alloys, silicon concentration varies between 0.15 and 0.35 wt%.

**Typical Applications and Mechanical Property Ranges for Oil-Quenched and Tempered Plain Carbon and Alloy Steels**

<i>AISI</i> Number	UNS Number	Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
<i>Plain Carbon steels</i>					
1040	G10400	605-780 (88-113)	430-585 (62-85)	33-19	Crankshafts, bolts
1080 <sup>a</sup>	G10800	800-1310 (116-190)	480-980 (70-142)	24-13	Chisels, hammers
1095 <sup>a</sup>	G10950	760-1280 (110-186)	510-830 (74-120)	26-10	Knives, hacksaw blades
<i>Alloy Steels</i>					
4063 4340	G40630 G43400	786-2380 (114-345) 980-1960 (142-284)	710-1770 (103-257) 895-1570 (130-228)	24-4 21-11	Springs, hand tools Bushings, aircraft tubing
6150	G61500	815-2170 (118-315)	745-1860 (108-270)	22-7	Shafts, pistons, gears

### References

1. Philip A.Schawetzer. *Metallic Materias. Physical, Mechanical, and Corrosion Propertyies.* – N.Y., Pennsylvania, USA. – 2003. – 702 p.
2. Michael F. Ashby, David R.H. Jones. *Engineering Materials 2. An Introduction to Microstructures and Processing.* – Published by Elsevier Ltd. – 2013. – 545 p.
3. Callister, William D., *Fundamentals of materials science and engineering : an integrated approach / William D. Callister, David G. Rethwisch.*—4th ed. p. cm.  
a. Includes index 2011. – 1221 p.
4. Schweitzer, P. *Metallic materials. Physical, Mechanical, and Corrosion Properties /Philip A. Schweitzer, P. E.* –New York, Basel. – 2003. – 704 p.
5. Kakani S. Kakani A. *Material Science / S. Kakani, A. Kakani.* – New age int.Ltd.– 2004. – 639 p.
6. Bin Wu. *Manufacturing Systems Design and Analysis.* 1994.-459p.
7. J. Datsko. *Material Properties and Manufacturing Processes.*
8. Katsundo Hitomi. *Manufacturing Systems Engineering: a unified approach to manufacturing technology, production management and industrial economics.*
9. R. Thomas. *Wright manufacturing systems.*
- 10.J. Beddoes, M. Bibby. *Principles of metal manufacturing processes.*
- 11.De Garmo, Black and Kosher. *Materials and processes in manufacturing.*
- 12.**Singh R. Introduction to basic manufacturing processes and workshop technology/ Rajender Singh.** – New age int.Ltd.– 2006.–483 p.
  
- 13.C.F. Walton, *Gray and Ductile Iron Castings Handbook*, Iron Founder’s Society, 1971, p 193
- 14.C.F. Walton and T.J. Opar, *Iron Castings Handbook*, Iron Casting Society, 1981, p 235 & p 297-321
- 15.“Chrome-Moly White Cast Irons,” Publication M – 630, AMAX, Inc., 1986
- 16.Davis, J.R., *Cast Irons*, ASM International, Materials Park, OH, 1996
- 17.G. Lambert, Ed., *Typical Microstructures of Cast Metals*, 2nd ed., The Institute of British Foundrymen, 1996, p 47
- 18.H.T. Angus, *Physical and Engineering Properties of Cast Iron*, BCIRA, 1960, p 21
- 19.<http://www.msm.cam.ac.uk/doitpoms/miclib/index.php>
- 20.<http://www.matweb.com/search/GetSubcat.asp>
- 21.<http://www.wynndanzur.com/glossary.htm>