

Ministry of Education and Science of Ukraine

**KHARKIV NATIONAL AUTOMOBILE AND HIGHWAY
UNIVERSITY**

**DEPARTMENT OF METAL TECHNOLOGY AND MATERIALS
SCIENCE NAMED AFTER O. M. PETRYCHENKO**



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STRUCTURE EXAMINATION

Lecture Notes

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1 INTRODUCTION

The failure of machine parts and structural components under various loads, which in many cases is accompanied by corrosive and thermal effects, leads to the breakdown of critical assemblies or even of an entire structure or mechanism. For this reason, considerable attention has been paid in recent years to the study of deformation and fracture processes, both under laboratory conditions and in service, as functions of mechanical, physical and physicochemical factors. Nevertheless, despite the numerous valuable results of these studies, the laws and causes of actual fracture and failure of materials are still far from being fully understood.

Engineering and technological examination is one of the most complex types of engineering and technical expert examination.

In terms of its legal status, technical examination is carried out on the instructions of both investigative authorities and courts.

By purpose, the examination of equipment is classified according to whether the equipment is intended for industrial, household, gaming, construction or medical use.

By place of manufacture, the examination of equipment is divided into the examination of domestically produced and foreign-made equipment.

Forensic technical examination is in demand in disputes concerning the supply of substandard (faulty, defective or damaged) equipment.

Judicial technical examination is conducted in cases concerning the termination of supply contracts for machinery and equipment for civil, industrial or medical use.

Basic definitions

Industrial safety examination (hereinafter, examination) is an assessment of the conformity of the object of examination with the industrial safety requirements imposed on it, the result of which is an expert opinion.

Objects of examination are design documentation, technical devices, buildings and structures at a hazardous production facility, industrial safety declarations and other documents related to the operation of a hazardous production facility.

Industrial safety examination system (hereinafter, the Examination System) is the totality of participants in industrial safety examination, together with the norms, rules, methods, conditions, criteria and procedures within which expert activity is organised and carried out.

Licence is a special permit to carry out a specific type of activity, subject to mandatory compliance with licensing requirements and conditions, issued by a licensing authority to a legal entity or an individual entrepreneur.

Expert organisation is an organisation holding a licence from the national state technical supervision authority to conduct industrial safety examination in accordance with current legislation.

Expert opinion is a document containing substantiated conclusions on the conformity or non-conformity of the object of examination with industrial safety requirements.

Expert is a specialist who conducts industrial safety examination.

Client is an organisation that has submitted an application for an examination.

Materials science examination is a discipline that integrates the knowledge acquired in the study of materials science, physical metallurgy, the technology of metal production and processing, and the methods of investigation and analysis of metals.

The main objective is to establish the composition, structure and origin of materials and to identify the causes of their failure. Therefore, fractography is an integral part of materials science examination. The principal document summarising the results of an expert analysis is the expert opinion.

This document contains unambiguous answers to the questions submitted for examination. In conducting an examination, all known methods of materials analysis are used in order of increasing locality. The locality (resolution) of a method is considered sufficient if it makes it possible to give an unambiguous answer to the questions submitted for examination.

The main tasks of materials science examination are:

1. Determination of the chemical composition of a substance.
2. Determination of the structural characteristics of a substance.
3. Atomic structure of a substance (crystal structure, establishing whether the substance is amorphous).
4. Presence of macro- and microdefects.
5. Determination of the causes, conditions and energy intensity of fracture of a substance.
6. Determination of the suitability of materials for their service conditions.
7. Conformity of a material to its certified (specification) characteristics.

Metallurgical examination is a constituent part of materials science examination. It deals with the examination of metals (alloys) and is carried out in order

to detect metal particles and traces of metallisation on objects, to investigate the qualitative and quantitative composition of metals, alloys and articles made from them, and to establish the technology and time of manufacture of metal and alloy articles, their service conditions and any changes associated with the circumstances of the event under investigation.

The objects of metallurgical examination are highly diverse. The most common are steel articles and their blanks: home-made and factory-made knives, daggers, dirks, knuckle-dusters and other steel objects used as instruments of crime, as well as their fragments and pieces; splinters and parts of explosive devices, shells and mines; parts of failed components of motor vehicles and other mechanisms, etc.

Objects of metallurgical examination are seized in virtually all categories of criminal and civil cases. They may be investigated not only within an examination of this kind but also within comprehensive metallurgical examinations and examinations of other classes and types: trace (tool-mark), electrical engineering, fire-technical, ballistic, explosives and automotive technical examinations.

1.1 Documentation of the expert opinion. Grounds for conducting an examination

Materials science examination may be carried out by staff experts and by appointed experts. The ground for conducting an examination is an order signed by the prosecutor of the district or city where the offence was committed, drawn up on the basis of a corresponding application from the investigative authorities substantiating the need for a materials science expert analysis.

The following documents and materials are handed over to the expert for the examination:

- the order appointing the examination;
- case materials containing information on the nature of the offence and the conclusions of other types of expert analysis;
- the questions submitted for examination, in which the main purpose of the analysis and the propositions to be *confirmed* or *refuted* are clearly formulated;
- the material evidence forming the basis of the expert analysis. All documents and materials are handed over in sealed form, in accordance with an enclosed inventory. When conducting the examination, the expert is obliged to check the documents against the attached inventory.

The period for conducting an examination shall not exceed one month. The expert opinion must contain the following sections:

1. General description of the problem to be solved.
2. List of the questions submitted for examination and enumeration of the methods of analysis used in performing the work.
3. Detailed description of the actions taken and interpretation of the results obtained for each of the questions submitted for examination.
4. Photographs and graphs obtained in the course of the work (photo tables) must be included.
5. Conclusions giving brief answers to the questions posed.
6. Supplementary materials of the expert analysis.

2 METHODS USED IN MATERIALS SCIENCE / METALLURGICAL EXAMINATION

All methods are divided into two groups:

1. Destructive analysis:
 - macro- and microscopic analysis by means of optical systems (determination of the structural parameters of a material and determination of its phase composition by selective etching).
2. Non-destructive testing (ultrasonic flaw detection, X-ray diffraction analysis, certain methods of spectral analysis).

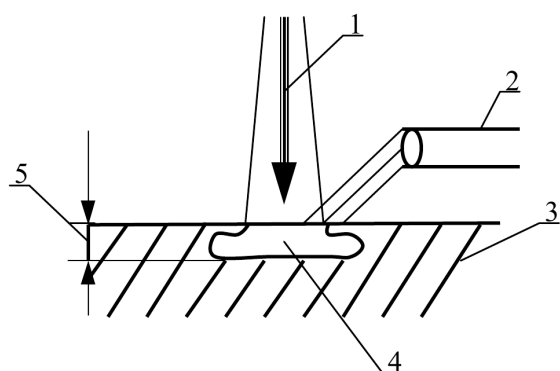
The first group includes:

- transmission electron microscopy, which permits fine analysis: it makes it possible to determine the degree of crystallinity of a material and the number and types of defects, and to determine the crystal structure quantitatively by electron diffraction (resolution down to 0.1 Å);
- scanning electron microscopy (large depth of field, resolution down to 15–30 Å = 1.5–3 nm);
- determination of the chemical composition of a material:
 - a) macroscopic methods – spectral methods and methods of analytical chemistry;
 - b) microscopic methods:
 - electron probe X-ray microanalysis;
 - mass spectroscopy (for impurity contents down to 0.001 %),

and Auger spectroscopy (Figure 2.1, a);
– ion and field-ion microscopy (Na^+ ions).

Auger spectroscopy. The essence of Auger electron spectroscopy is that the surface of a material is irradiated with an electron beam of a certain energy, which excites the atoms of the substance under study; as a result, they begin to emit secondary Auger electrons. These electrons are recorded by a spectrometer. Auger electrons are characteristic: their energy is specific to each element, and therefore the chemical composition of the object under study is determined from the lines of the energy spectrum.

Auger electrons are electrons belonging to atomic shells that are excited by electromagnetic radiation. They are generated during the transition of electrons from one electron level to another under the action of the energy of incident high-energy electrons (Figure 2.1).



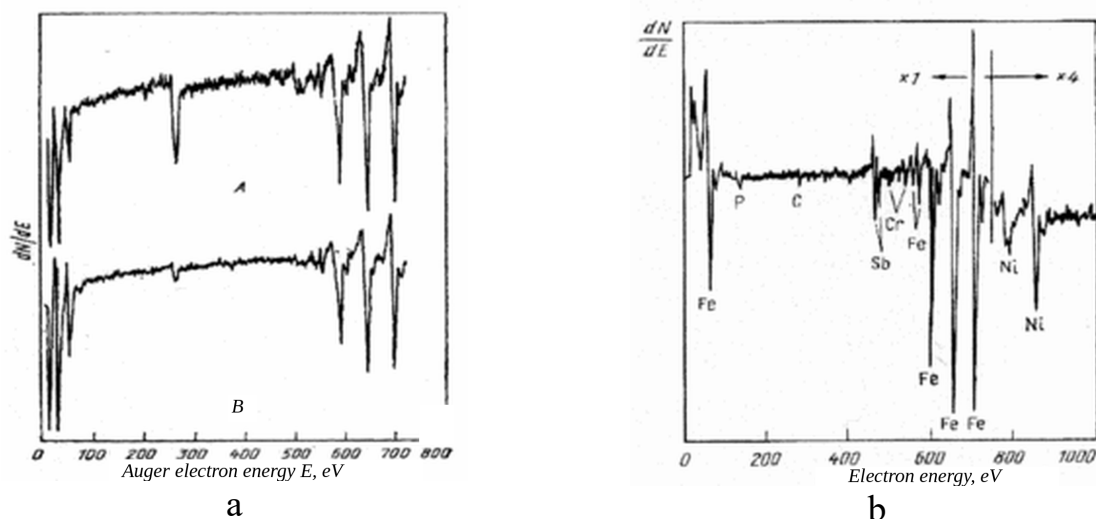
1 – electron probe, 2 – Auger electron detector, 3 – substance under study, 4 – Auger electron excitation region, 5 – thickness of the excitation region, 1–10 Å
Figure 2.1 – Schematic diagram of the Auger spectroscopy investigation

The energy of Auger electrons is low, so they are intensively absorbed by the material under study, and only the Auger electrons emitted by atoms of the surface layers of the specimen (to a depth of about 10 atomic layers) are recorded by the spectrometer. This determines the effectiveness of Auger electron spectroscopy (AES) for determining the chemical composition of the surface of metallic materials. In addition, the small diameter of the primary electron beam provides a lateral locality of the method of 5 to 50 μm^2 . The method is easily combined with scanning electron microscopy, which makes it possible to perform targeted chemical microanalysis of fracture features directly while studying the morphology of the fracture surface.

The method is distinguished by high sensitivity in the chemical analysis of surface layers up to 2–3 nm thick and by the speed of analysis. It can detect all chemical elements except hydrogen and helium. The method is particularly effective for

identifying sulphur-containing non-metallic inclusions in steels (the sensitivity for sulphur reaches 10^{-4} %) and antimony and arsenic impurities.

Figure 2.2 shows Auger spectra of the fracture surface of a steel with a pearlitic structure and of film inclusions that cause the appearance of brittle areas of the fracture.



a – Auger spectrum of the fracture surface of rolled 30KhN steel with a pearlitic structure: A – spectrum in a cementite area; B – spectrum in a ferrite area; b – Auger spectrum of an antimony-containing film inclusion on the fracture surface of rolled steel of the 30KhGSNA type

Figure 2.2 – Auger spectra of various metallic materials

3 FUNDAMENTALS OF FACSIMILE PHOTOGRAPHY

The expert analysis begins with the mandatory photographing of the objects submitted for examination.

Facsimile photography is photography that reproduces the image of an object without distortion of its shape and structure.

The main factors causing distortion of the shape of an object when it is photographed are as follows:

1. Non-uniform refraction of light rays in the lens systems of cameras – *spherical aberration*, i.e. different refraction of monochromatic rays passing through different zones of a lens (Figure 3.1).

2. Non-uniformity and distortion of the colour gamut of the object owing to the dependence of the refractive index of lens systems on the wavelength of light – *chromatic aberration* (Figure 3.2). It arises because, when non-monochromatic light is used, rays of shorter wavelength are refracted by the lens more strongly than rays of longer wavelength. As a result, images of different sizes are formed.

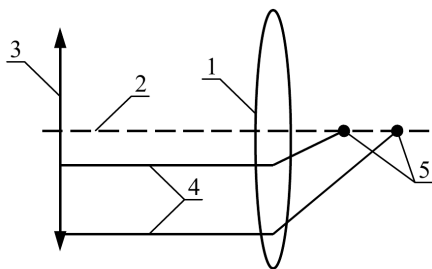
3. Reduced image sharpness owing to the limited depth of focus of lens systems.
4. Distortion of the object shape when the optical axis of the camera and the geometric centre of the object are misaligned (Figure 3.3).
5. Incorrect illumination of the object and the associated change in its apparent shape.

Focus, or *focal length* F , is the maximum distance to the object being photographed at which the object is seen sharply and its contours are not blurred. The reciprocal of the focal length is called the optical power of the lens D (measured in dioptries):

$$D = 1 / F, \quad \text{where } F = 15\text{--}600 \text{ mm.}$$

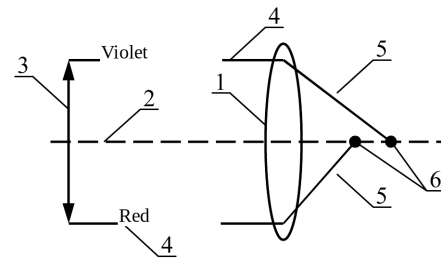
The effect of spherical aberration is manifested as follows:

1. Image sharpness decreases from the geometric centre of the object towards its periphery;
2. In the same direction, the shape of the object is distorted towards an increase in its size.



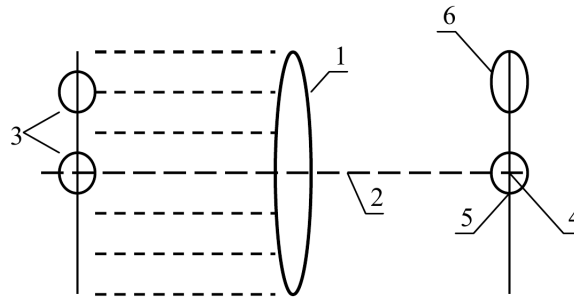
1 – lens, 2 – optical axis, 3 – objects, 4 – light rays, 5 – different foci of the rays refracted in different zones of the lens

Figure 3.1 – Spherical aberration



1 – lens, 2 – optical axis, 3 – object, 4 – light rays of different wavelengths, 5 – refraction of the light rays by the lens, 6 – different foci of the refracted rays

Figure 3.2 – Chromatic aberration



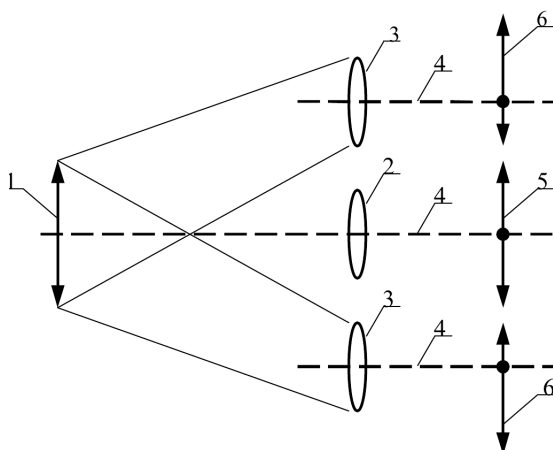
1 – lens, 2 – optical axis, 3 – objects, 4 – lens focus, 5 – image of an object located on the optical axis, 6 – distorted image of an object located off the optical axis
Figure 3.3 – Blurring of the object shape with increasing distance from the lens focus

Spherical aberration can be eliminated by stopping down the aperture, and *chromatic* aberration by special lens coatings.

3.1 Distortions of the object shape associated with the relative position of the object and the lens

In any object being photographed, a geometric centre can always be identified, which is regarded as its optical centre in subsequent photographing.

Facsimile photography is photography taken with a lens located on the same line as the optical centre of the object. If the camera lens is located above or below the optical centre of the object, the image of the object in the photograph will be distorted (Figure 3.4).



1 – object, 2 – front lens, 3 – lenses located above or below the optical centre of the object, 4 – optical axes of the lenses, 5 – facsimile image of the object, 6 – distorted images of the object

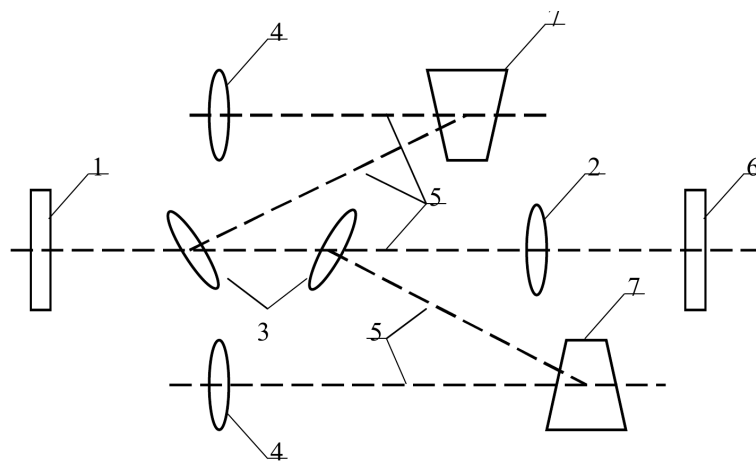
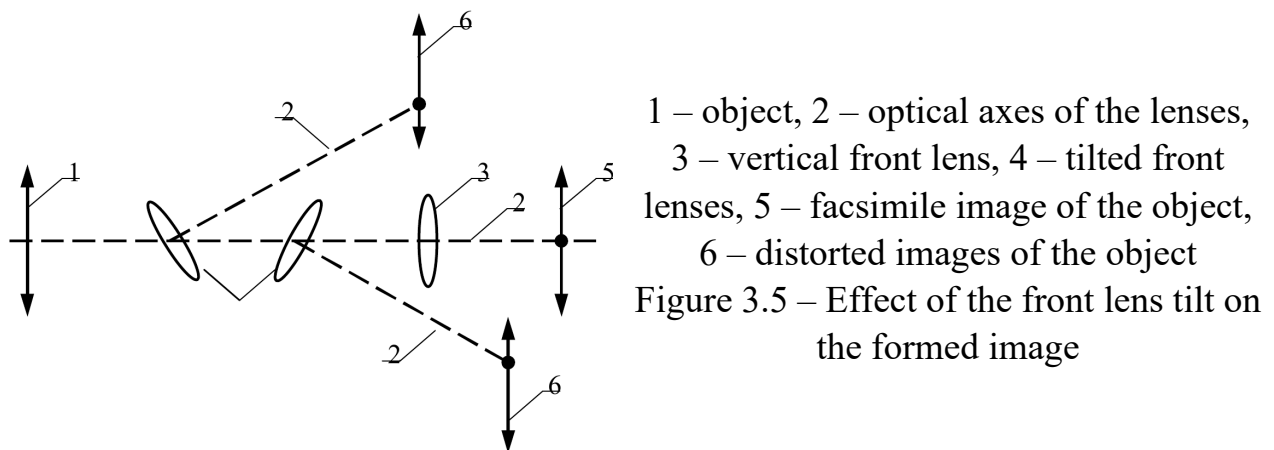
Figure 3.4 – Effect of the lens position on the image

As can be seen from Fig. 3.4, if the lens is located above the optical centre of the object, the lower half of the object will be reduced in size in the image, while the upper half, on the contrary, will be enlarged; if the lens is located below the optical centre of the object, the distortions will follow the opposite pattern.

Tilting the front lens of the objective relative to the optical centre has a similar effect (Figure 3.5).

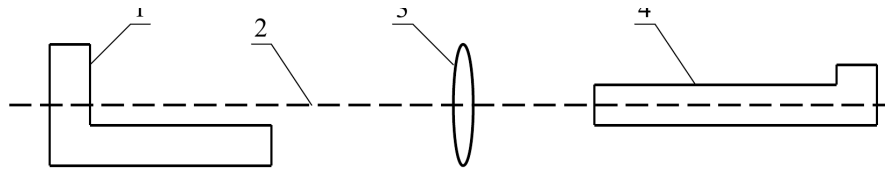
Thus, a facsimile image is obtained when the lenses are parallel to the axis of the photographed object; the position of the front lens likewise affects the image of the object cross-section (Figure 3.6).

Tilting of the lens will lead to similar changes in the shapes of objects. Distortion of the longitudinal dimensions of an object is achieved by means of special photographic lenses (Figure 3.7).



1 – object, 2 – vertical front lens, 3 – tilted front lenses, 4 – lenses located above or below the optical centre of the object, 5 – optical axes of the lenses, 6 – facsimile image of the object, 7 – distorted images of the object

Figure 3.6 – Effect of the lens position and tilt on the cross-section of the object

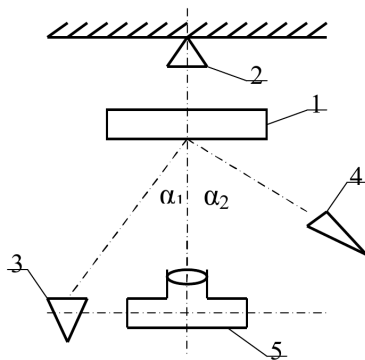


1 – object, 2 – optical axis, 3 – lens, 4 – image of the object

Figure 3.7 – Distortion of the longitudinal dimensions of the object

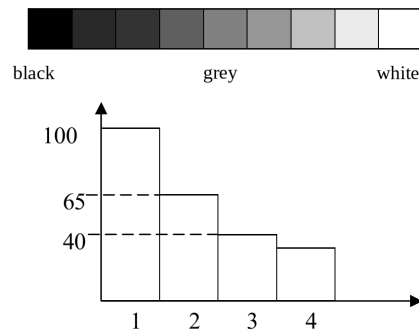
3.2 Illumination of the object

To obtain a properly illuminated object, at least three light sources are used (Figure 3.8): a background source, a modulating (fill) source and a modelling (key) source.



1 – object, 2 – background light source, 3 – modulating (fill) light source, 4 – modelling (key) light source, 5 – camera,
 $\alpha_1 = 5-10^\circ$; $\alpha_2 = 15-45^\circ$

Figure 3.8 – Illumination of the object



1 – human eye, 2 – black-and-white photograph, 3 – colour photograph, 4 – digital camera

Figure 3.9 – Diagram illustrating the level of light perception by various devices

The background source separates the image of the object from the background and serves to obtain sharp external contours of the object in the photograph.

The modulating source, like the modelling source, serves to illuminate the object to a degree sufficient to obtain a good-quality projection on the photosensitive layer. In addition, the modelling source is intended to form a shadow pattern from the relief of the object in order to increase sharpness and contrast.

Figure 3.9 presents a diagram illustrating the level of light perception by various photographic devices in comparison with the human eye. As can be seen from this diagram, the human eye has the highest level of perception, since it can not only distinguish colours and shades but also create in the brain a three-dimensional picture with correct scaling. Cameras, even digital ones, do not give a complete picture,

especially when quantitative and scale comparisons of the sizes of the objects shown in an image are required.

3.3 Selection of photographic equipment and materials

The main unit of a photographic device is the lens (objective). Depending on their focal length, lenses are divided into:

1) Short-focus lenses with a focal length of less than 35 mm:

- provide a wide angle of view;
- have a large depth of focus.

Such lenses are also called ultra-wide-angle lenses. They make it possible, for example, to photograph a high-rise building without moving a considerable distance away from it. Disadvantage: distortion of the object, especially when the lens is positioned incorrectly.

2) Medium-focus lenses with a focal length of 35–80 mm. These are the most frequently used lenses. Their angle of view is smaller, and when viewed through the viewfinder it can be seen that they somewhat "bring closer" the image in comparison with short-focus lenses.

3) Long-focus lenses with a focal length that can in principle be increased indefinitely (from 60 mm to several metres). Advantages:

- provide strong magnification of the object;
- distort its shape to a lesser extent.

Disadvantage: a small angle of view.

4) Variable focal length (zoom) lenses, usually 35–100 mm.

Thus, the longer the focal length of a lens, the narrower its "angle of view" and the more it "brings objects closer". The shorter the focal length, the wider the "angle of view" and the smaller the objects appear.

Since lens systems always exhibit spherical and chromatic aberrations, photographic objectives include, in addition to the main (front) lens, up to 10–15 biconvex and convex correcting lenses. Besides lenses, objectives always include an aperture stop. The aperture stop determines the depth of field of the objective and regulates the luminous flux reaching the photographic emulsion.

Depth of field is the distance along the shooting direction within which the image does not go out of focus. The smaller the diameter of the aperture stop, the greater the depth of field of the objective.

Choice of exposure. Since the sensitivity of photographic materials is limited, the luminous flux reaching the photosensitive layer must be strictly limited in order to obtain a good-quality image. This limitation is called exposure; it depends on the size of the aperture stop and the shutter opening time (shutter speed).

Use of light filters and photographic attachments. Light sources are divided into natural and artificial. Natural light (sunlight) has a different spectral composition depending on the height of the sun above the horizon. Thus, when the sun is low, the red part of the spectrum predominates in the light. Solar radiation may be direct or diffuse.

Artificial lighting is provided by incandescent lamps, fluorescent daylight lamps, discharge lamps and pulsed (flash) light sources. The light of fluorescent, discharge and pulsed lamps is closest in spectral composition to natural light. Black-and-white photographic emulsions are most sensitive to the yellow-green part of the spectrum. Multicolour emulsions have different sensitivities to light radiation.

Light filters are used to match the spectral composition of the illumination to the spectral sensitivity of photographic materials. In black-and-white photography, light filters make it possible to change the spectral composition of the light source considerably.

The use of yellow-green filters increases image contrast. Red filters darken the areas of the object that are blue-cyan in colour. Blue filters are used to darken orange-red areas of the object.

4 METHODS FOR INVESTIGATING THE QUALITY OF WELDED JOINTS

4.1 Leak-tightness tests

Welding is widely used in the manufacture of various tanks for storing liquids and gases, as well as of pipelines and cylinders. To determine the leak-tightness of welded joints, hydraulic pressure testing and air testing are used. In the air test, air at an excess pressure of 10–20 kN/m² is pumped into the vessel under test, and the outer surface of the weld is wetted with soapy water. Where discontinuities are present, soap bubbles form at these locations.

For welded parts of large dimensions, the tightness of the welds is checked by blowing a jet of compressed air at a pressure of at least 0.4–0.5 MN/m² onto them, with the distance from the end of the hose to the weld under test not exceeding 30 mm; the opposite side is wetted with soap foam.

Kerosene test. Since kerosene has high wettability, it easily penetrates the finest cracks. When the tightness of a weld is checked, one side of the weld is coated with chalk and the opposite side is wetted with kerosene. At discontinuities, the chalk darkens owing to the kerosene that has penetrated.

Ammonia test. The tank is filled with compressed air with the addition of ammonia (1–2 %), and a paper strip impregnated with mercury nitrate or phenolphthalein is glued onto the weld from the outside. If there is a leak, dark or violet spots form on the paper.

Vacuum method. The weld is wetted with soapy water and covered with a transparent cap sealed with a rubber gasket. Air is then pumped out of the cap, and soap bubbles, visible through the transparent cap, form at discontinuities.

Leak detector method. Compressed air with added halogens (e.g. CCl_4) is pumped under low pressure into the vessel under test, and the weld is scanned with a leak detector that responds to the presence of halogens. When halogens are detected in the air at discontinuities, the leak detector emits sound signals or the reading of its pointer indicator changes.

Investigation using a mass spectrometer. Hydrogen is pumped under pressure into the vessel under test, and air samples are taken from the outside with a probe and analysed with a mass spectrometer for the presence of hydrogen. Owing to its small atomic radius, hydrogen is able to penetrate discontinuities a few nanometres in size.

4.2 Methods for testing welded joints

Mechanical tests. Both individual fragments of welded structures and whole structures are subjected to them, with static, vibration and impact loads applied.

Metallographic methods. Macro- and microstructural analysis methods are used. Metallographic investigations give the most complete picture of the quality of a welded joint. In addition to known defects, metallographic examination makes it possible to see structural changes in the weld and in the weld zone and to determine their effect on the properties of the metal.

Chemical methods. In chemical investigation, the chemical composition of the deposited metal is determined and, in some cases, the corrosion resistance of the weld is tested.

Physical methods:

X-ray methods, or investigation using gamma radiation. X-rays (from an X-ray tube) can be used to radiograph metals with wall thicknesses of 50–100 mm.

Gamma radiation from radioactive isotopes (Co, etc.) makes it possible to radiograph metals up to 400 mm thick.

Magnetic methods. These methods are usually used for parts after machining of the weld.

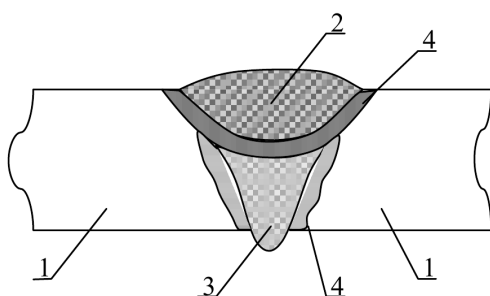
The magnetic particle method consists in sprinkling magnetic powder onto the artificially magnetised surface of parts; opposite defective areas, the powder forms a pattern different from that over defect-free areas.

The induction method consists in acting on the part with an electromagnetic field supplied by alternating current, while a probe, which is a magnetic coil, is moved along the opposite side; its signal is fed through an amplifier to a pointer instrument or headphones. Over a sound weld, the sound in the headphones is monotonous, whereas over defective areas it is intermittent.

Ultrasonic flaw detection. This method is based on an ultrasonic generator feeding, through a transducer, a signal into the weld zone; the signal is reflected from surfaces and picked up by an instrument with a cathode-ray tube. With this instrument, the size of a defect and its location can be determined. Flaw detectors that display a three-dimensional image of the weld with its defects on the screen are currently produced commercially.

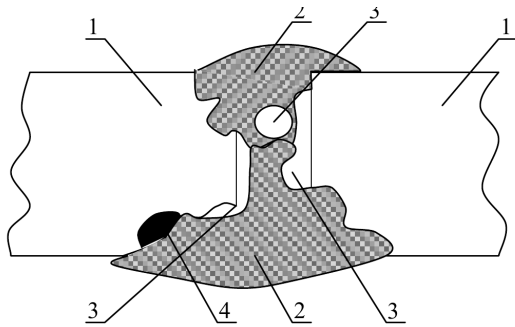
4.3 Analysis of weld structure

Figure 4.1 shows a diagram of a defect-free weld. Judging by the structure, weld 3 was made first, and then weld 2. The quality of this weld can be considered good; its only drawback is the presence of a heat-affected zone, which can be eliminated by annealing the whole article, if possible, or by annealing the weld zone. In practice, however, ideal welds are not always encountered. Thus, Figures 4.2 and 4.3 show diagrams of welds with various defects.

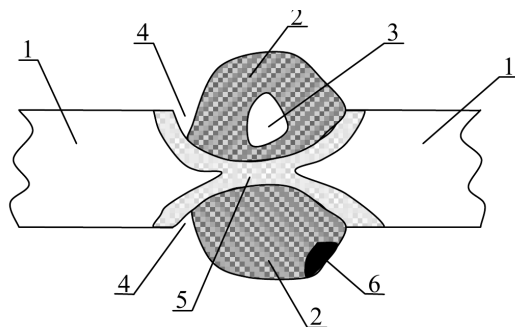


- 1 – base metal,
- 2, 3 – weld metal,
- 4 – heat-affected zone

Figure 4.1 – Diagram of a defect-free weld



1 – base metal,
2 – weld metal,
3 – lack of penetration,
4 – slag inclusion
Figure 4.2 – Weld with defects



1 – base metal,
2 – weld metal,
3 – lack of penetration, 4 – undercuts,
5 – heat-affected zones,
6 – slag inclusion
Figure 4.3 – Weld with defects

The presence of lack of penetration in a welded joint and lack of fusion of the base metal edges leads to a sharp decrease in the strength of the weld. The welding was probably performed at too low a current (the edges of the base metal were partially unmelted).

Owing to the undercuts of the base metal at the bottom and at the top, the cross-section of the base metal is reduced, which is unacceptable. The quality of the weld is unsatisfactory. This defect (undercuts) can be corrected by additional welding. The welding was carried out at too high a current; the welding parameters must be changed.

Nowadays, different steel grades are increasingly joined by welding. Let us consider such a case using the following example.

Example. Butt welding was performed, followed by annealing to improve the quality of the welded joint by diffusion (Figure 4.4). During annealing, carbon was redistributed in the welded parts. The question to be answered is: in which direction did the carbon migrate?

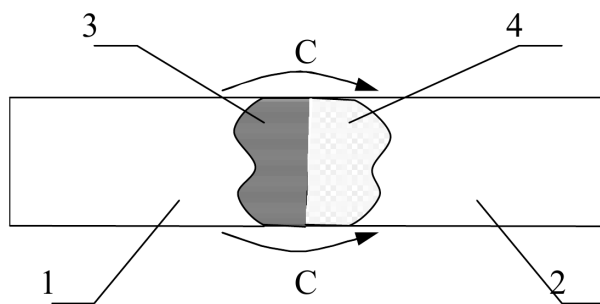
Fick's law is known: $J = -D \cdot dc / dx$, where:

D – diffusion coefficient;

c – concentration of atoms of the substance per unit volume;

x – minimum distance over which the atoms of the substance move.

According to Fick's law and to common sense, carbon should have moved from the region of higher content to the region of lower content, but the opposite occurred.



1 – steel with 2 % Si and 0.4 % C,
 2 – steel with 3 % Cr and 0.8 % C,
 3 – decarburised layer,
 4 – layer with increased carbon content

Figure 4.4 – Diagram of carbon migration in the weld

This is because the silicon in the first steel increases the activity of carbon, that is, it effectively expels carbon from the solid solution, while in the second steel the carbide-forming chromium lowers the chemical potential of carbon. Thus, carbon from steel 1 will migrate into steel 2, and at the interface a decarburised zone forms in steel 1 and a zone with increased carbon content forms in steel 2.

4.4 General principles for evaluating the structures of welded joints

Primary crystallisation.

Primary crystallisation refers to the growth of crystallites from the melt during solidification of the weld pool. This results in the formation of the so-called primary structure. In metals such as aluminium, copper, nickel and their alloys, the primary structure does not change, or changes only slightly, on further cooling. Therefore, the properties of the weld depend on it. To determine the primary structure, it is necessary to know the conditions of its formation and the factors influencing it.

In metals and alloys with allotropic (polymorphic) modifications, for example in steels, secondary crystallisation, or recrystallisation, takes place in the solid state during cooling. In this case, the properties of the secondary structure are determined by the modifications that are stable at lower temperatures.

There is a certain relationship between the primary and secondary structures; therefore, investigation of the primary structure is also necessary for alloys with allotropic transformations. Moreover, before recrystallisation the primary structure is subjected to loads, for example shrinkage stresses. Cracks forming in welds cannot be explained by secondary crystallisation. Therefore, for metallographic investigations it is important to understand the processes of primary crystallisation.

In the crystallisation of metal melts, a distinction is made between supercooling of the melt, nucleation and growth of nuclei.

Crystallisation is impossible without supercooling. Supercooling may be thermal or constitutional (concentration-induced). Thermal supercooling of technically pure metals is significant only for nucleation. However, ready-made crystallisation centres are always present in welds. Therefore, owing to the reduction in the energy of nucleation, the required supercooling may be smaller or may not be needed at all. Of particular note in this respect are the unmelted crystals of the base metal, on which epitaxial crystallisation from the liquid phase may occur, i.e. crystallisation with the same crystallographic orientation.

The growth of crystallisation nuclei is associated with constitutional supercooling. It develops only in alloys or in heavily contaminated metals. The melt crystallises over a certain temperature range, and alloying elements or impurities lower the liquidus temperature. They accumulate ahead of the crystallisation front and lower the liquidus temperature still further (Figure 4.5).

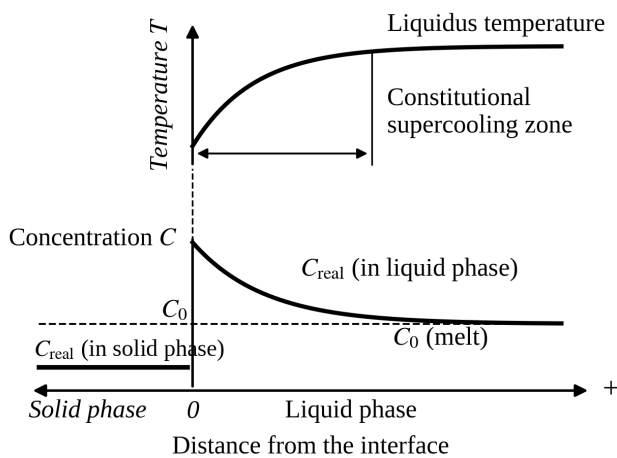


Figure 4.5 – Diagram of constitutional supercooling

This effect increases with increasing crystallisation rate. Favourable conditions in this respect are created in electroslog welding (low temperature gradients) and in resistance spot welding (high crystallisation rate).

In accordance with the spatial distribution of temperature gradients and crystallisation rates in the weld, constitutional supercooling increases continuously from the fusion boundary towards the weld centre. In this zone the probability of nucleation is highest; as a result, under certain conditions, a second crystallisation front may arise in the middle of the weld owing to constitutional supercooling.

The first crystallisation front arises as a result of the growth of crystals from partially melted grains of the base metal bordering the weld pool, which act as ready-made centres (Figure 4.6).

They grow fastest perpendicular to the isothermal boundary surfaces and parallel to the directions of the most intensive heat removal. As a result, oriented columnar crystals are formed. Crystallites of the second crystallisation front, which form from nuclei produced by constitutional supercooling, have, on the contrary, an equiaxed structure (Figure 4.7).

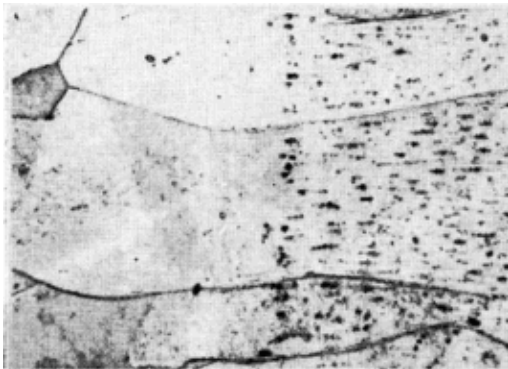


Figure 4.6 – Epitaxial growth of base metal grains at the first crystallisation front of a copper weld made by plasma welding

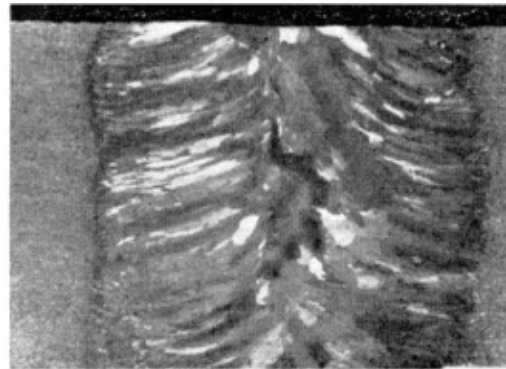


Figure 4.7 – Crystallisation front with globular misoriented crystals inside an alloy weld made with a tungsten electrode in argon

Constitutional supercooling also plays a certain role in the formation of crystals at the first crystallisation front. Pure metals form (especially at high solidification rates and low temperature gradients) crystals that are bounded laterally by comparatively flat surfaces. Such crystal growth is called cellular (Figure 4.8).

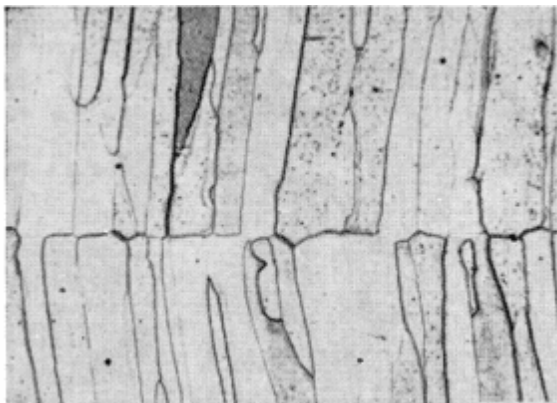


Figure 4.8 – Cellular crystallisation of a tungsten weld made by resistance spot welding

Conversely, at low cooling rates and high temperature gradients, as well as at increased contents of segregating (i.e. non-uniformly distributed) impurities, the

boundary surfaces of the crystals exhibit considerable irregularities: the growth of the crystallites becomes dendritic.

The tips of the growing crystallites penetrate into the zone of constitutional supercooling (Figure 4.9).

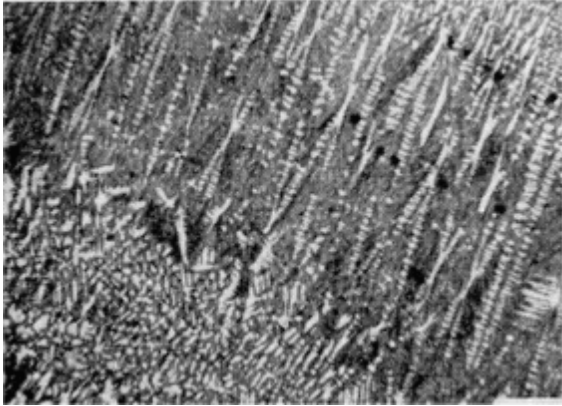


Figure 4.9 – Dendrites of an iron–chromium–boron–carbon alloy weld in a section parallel to their longitudinal axes

However, the direction of the weld crystals cannot be determined precisely from a metallographic section. Therefore, in the microstructure of welds that do not undergo allotropic transformations, the boundaries of cellular and dendritic crystals are usually revealed in the form of a more or less ordered network (Figures 4.10 and 4.11).

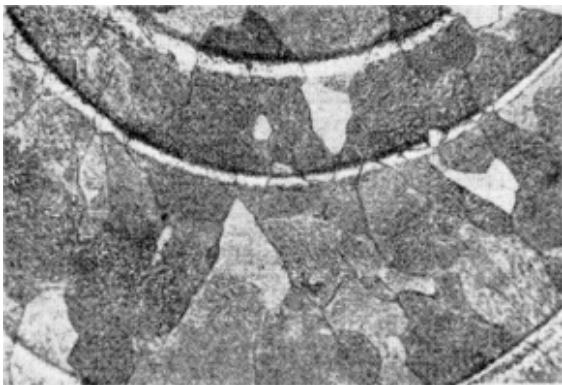


Figure 4.10 – Cellular crystals of a weld in a section not parallel to their longitudinal axes (granular structure). Electron beam welding of copper

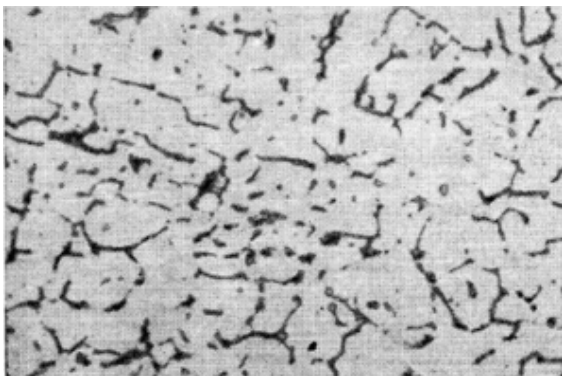


Figure 4.11 – Dendrites in a section not parallel to their longitudinal axes (cellular structure). Consumable-electrode welding of austenitic chromium–nickel steel in argon

If a dendrite is formed, the cross-sections of the branches of identical crystallites cannot be distinguished from one another. In this case, the cross-sections of the branches (Fig. 4.10) are called cells. The cross-sections of crystals that crystallise in a cellular manner (Fig. 4.11) are called a "granular structure" (unlike the former, they form a closed network).

Under favourable circumstances, conclusions about the structure of the primary crystals can also be drawn from the secondary structure of alloys undergoing allotropic transformations. Single-pass welds in structural steels can serve as examples. During the recrystallisation of the metal of these welds, hypoeutectoid ferrite forms along the boundaries of the primary grains and is clearly revealed by etching.

The orientation of the crystals of the first crystallisation front relative to the longitudinal axis of the weld depends on the welding speed and the solidification rate. In welds produced at low welding speeds and solidification rates, the crystallites are located almost parallel to the weld axis and form dendrites. A high welding speed changes the crystallisation pattern (Figures 4.12 and 4.13).

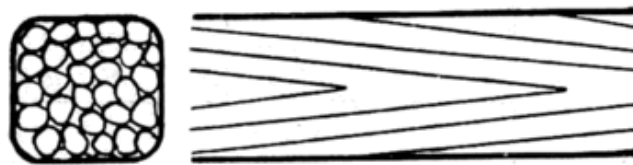


Figure 4.12 – Arrangement of crystals in welds at low welding speeds and solidification rates

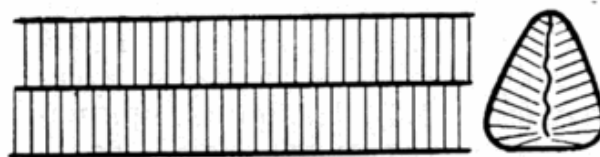


Figure 4.13 – Arrangement of crystals at a high welding speed

A special case is the formation of "feathery" crystals in welds of aluminium and its alloys. A low welding speed with a high heat input leads to the formation of large primary crystals, while a high speed with a small weld pool volume leads to the formation of fine primary crystals.

The cell size of the primary weld structure is an essential characteristic that determines the strength properties. In steels this parameter is of secondary importance owing to allotropic transformations. Nevertheless, the finer the primary grain, the finer

the grain of the secondary structure. Usually, the aim is to obtain the finest possible grained (or fine-cellular) misoriented structure.

5 FUNDAMENTALS OF THE METHODOLOGY FOR ESTABLISHING THE CAUSES OF FAILURE OF PARTS

As already noted, fracture analysis is only one of the main stages of the work carried out to identify the causes of failure of parts.

Other equally important stages are: assessment of the damage to related parts or parts adjacent to the failed one in order to establish the sequence of failure and any abnormalities in the operation of the machine or mechanism before the accident or breakdown; flaw detection of the part; and investigation of the quality of the material. To establish the causes of failure, it is sometimes necessary to examine the condition of similar machines or mechanisms that have not failed, to collect statistical data on defects and full-scale tests, and to review the strength calculations of the parts and the results of previous investigations of similar failures, etc.

The content and scope of specific work depend on the nature of the accident, the type of part, the branch of engineering and the service conditions. Since a full account of the methodology for establishing the causes of failure of parts is beyond the scope of this manual, we shall confine ourselves to the main principles.

The investigation plan for establishing the causes of failure of parts consists of the following 5 main stages:

- 1) assessment of the general condition of the object of investigation;
- 2) analysis of the external condition of the failed or damaged parts and of the parts related to them;
- 3) assessment of the quality of manufacture and of the material of the part by inspection, flaw detection, metallographic, mechanical and other investigations;
- 4) analysis of the operating conditions by assessing the external condition of the parts, observing the operation of the structure, machine or mechanism before its failure, full-scale, bench, operational and special tests, strength calculations, experimental stress analysis methods, etc.;
- 5) generalisation and analysis of the investigation results and development of recommendations for preventing the causes of such failures.

Let us consider in more detail the methodology of each stage of the investigation.

5.1 Assessment of the general condition of the object of investigation

Work to establish the causes of failure of parts begins at the place where the failure was discovered and usually ends in the laboratory, often not by the persons who started it. Therefore, to distinguish the work performed at the failure site from the laboratory *investigation*, this work is referred to as the *inquiry*.

The correctness of establishing the causes of failure of a part in the investigation largely depends on the thoroughness and completeness of the inquiry.

The inquiry includes a general inspection of the object of investigation in order to identify existing fractures and damage to individual parts, assemblies and the structure or machine as a whole, as well as a study of the circumstances of their failure or damage and of the external signs that accompanied it.

Damage or failure may be accompanied by obvious fractures or may manifest itself indirectly in the form of vibration, smoke, leakage and so on.

The inquiry begins with questioning the operating personnel, technical staff or chance witnesses who discovered the accident or defect, and with studying all the circumstances under which the disruption of normal operation occurred and the external signs that accompanied it. These include the total duration and mode of operation and the nature of the deviation from the normal mode. Thus, the failure of the automobile bearing ring shown in Figure 5.1 occurred as a result of vibration of the garage floor caused by the operation of a nearby two-stroke engine.

To obtain a fuller picture of the nature of the defect that led to the machine breakdown, it is recommended, where possible, to test the machine in operation. Thus, vibration of a piston engine may be temporary, for example owing to "sticking" of a cylinder valve in its guide bush, but it may also be caused by the failure of individual parts or by the malfunction of individual units (Fig. 5.1).

In the case of a major accident with individual fragments widely scattered, their relative positions and the location of the explosion, impact or fall of the structure or machine must be marked on a site plan. For example, from the relative positions of aircraft wreckage on the ground it is possible to establish the direction of flight during the fall and the angle of impact, and to identify the structural elements with which the aircraft first touched the ground. The purpose of the inquiry is to identify the part or assembly that failed first, to establish the probable causes of the accident or defect, and to describe all the circumstances of the event as fully as possible in order to help determine the true causes of the failure during the subsequent investigation.



Figure 5.1 – Dents on the raceways of bearing rings caused by bearing vibration

An essential feature of this stage of work is that the results of the inquiry cannot be repeated or supplemented in the course of the subsequent investigation. This is because the machine, assembly or part is sent for investigation, the fuel and lubricant are drained, the fragments are mixed up, and the accuracy of the testimony of witnesses and operating personnel rapidly decreases with time. Therefore, at the first stage of work, investigators are required to have an excellent knowledge of the equipment, the specifics of its operation and maintenance, and the technology of its manufacture and repair.

Once the possible causes of the defect have been established at the scene and the site of the primary fracture has been determined, the parts, their positions and all observed defects that may be useful in establishing the causes of failure are photographed. A detailed description is compiled of all observed abnormalities in the operation of the equipment, the circumstances of the failure, the established sequence of fracture, and the evidence or assumptions regarding the site of the primary failure.

5.2 Analysis of the external condition

Analysis of the external condition of failed or damaged parts should begin with identifying the part that failed first. This is followed by establishing the sequence of failure of all parts and identifying the fracture origins and stress concentrators. Stress concentrators are assessed by their shape and by the fracture features. Great importance is attached to establishing the acting loads and the degree of overload under repeated loading, and to identifying abnormalities in the operation of the failed part. Such abnormalities can often be judged from the mutual damage of parts.

Investigation of mutual damage makes it possible to characterise the striking object – its shape, speed and direction of motion. A correct assessment of mutual

damage sometimes allows the cause of failure to be established without any additional investigations.

Thus, in the delayed brittle fracture of bolts and other parts, misalignment of a bolt or stud in service can be established from traces of non-uniform contact.

For a correct assessment of mutual damage (abrasions, dents), it is necessary to establish, at least approximately, the time at which these defects formed during the operation or failure of the parts. Where the nature of the mutual damage shows that it formed before the failure of the parts, it can be concluded that such damage may have contributed to the failure. Sometimes it can be established that the damage occurred during the failure of the parts and is associated with a disruption of normal operating conditions.

When determining the part that failed first, all the damage present on the parts must be divided into two groups according to its origin.

The first group includes all damage that arose during the failure process. Analysis of this damage, taking into account the kinematics of the assembly and the loading conditions of the parts, makes it possible to determine the sequence of failure of the parts and the part that failed first.

The second group includes damage that arose during the operation of the machine or mechanism before the failure, for example excessive wear, wear grooves, abrasions, traces of severe corrosion, fretting corrosion, etc. In a number of cases, such damage may indicate a violation of the normal operating conditions of the part, and establishing its connection with the failure then plays an essential role in determining the causes of failure.

The expediency of such a division of damage into two groups is obvious and requires no further explanation. Indeed, investigation of failed parts shows that, when determining the part that failed first, the greatest difficulties arise in the failure of fast-moving and kinematically linked parts.

Thus, the combined failure of the piston, connecting rod and piston pin of an internal combustion engine may begin with any of these three parts. If the piston fails, the piston pin released from it produces characteristic longitudinal scores on the working surface of the cylinder liner. Failure of the piston pin is accompanied by intensive wear of the holes in the piston bosses and in the connecting rod. If the connecting rod failed first, the piston detached from it may be damaged by the rotating crankshaft parts. Consequently, in this case, longitudinal scores, worn holes or traces

of the piston being crushed by the crankshaft counterweights indicate the primary failure of one of these three parts.

Signs of the primary failure of parts can be highly diverse, and therefore no general recommendations can be given for identifying such parts. In any case, the presence of a fatigue fracture can in most cases serve as sufficient evidence of the primary failure of a part. The area of primary failure of a part is identified by the fracture features and, if the fracture is severely damaged, by indirect signs, for example by the degree of deformation of individual fragments, the degree of failure of the part in different areas, the intensity of carbon deposits, etc.

As an example, Figure 5.2 shows an articulated connecting rod of a piston engine that failed at two sections (the shank and the head).

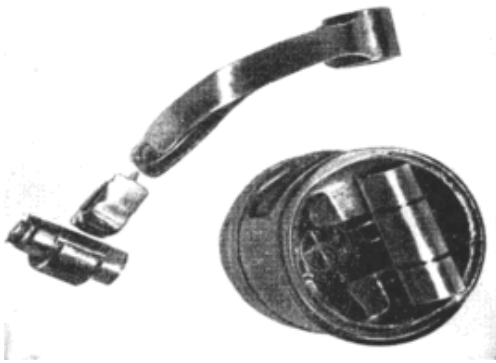


Figure 5.2 – Articulated connecting rod of an engine that failed at two sections

Although the fracture surfaces are severely battered, the site of the primary failure can still be determined. Analysis of the operating conditions of the connecting rod shows that its primary failure could only have occurred at the head, since after the rupture of the shank the force stretching the connecting rod, which could have caused the rupture of the head, disappears.

In other cases, the site of primary failure can be determined by identifying various external signs near the fracture origin, such as material defects, traces of abnormal wear indicating that the machine operated with a fracturing part, characteristic local crushing of the fracture edges, and traces of residual deformation.

The stress concentrator is identified and assessed from the fracture or from indirect signs. The stress concentrator that served as the fracture origin is located in the area of primary failure. Where the fracture is severely damaged, the stress concentrator can be established by metallographic analysis, by flaw detection or by assessing the location of the fracture on the part. Thus, the detection of metallurgical defects (grinding cracks) in the area of primary failure may prove that the failure of the part began from these stress concentrators. A spring fracture surface that is not inclined at

45° to the coil but shows longitudinal splitting indicates failure of the spring along a longitudinal defect (a scratch or a hairline) or owing to sharply reduced strength across the grain flow.

One should not insist on finding a stress concentrator in every case, since a failure may result from general overstressing of the part or from reduced strength and ductility caused by the effect of the environment, temperature, etc. The stress concentrator is assessed from the fracture, by calculation, by strain gauging or full-scale testing, and by comparing the nature of failures and the service lives of parts of the same type.

The nature of failure is assessed from the position of the fracture surface relative to the acting forces and the external contours of the part. For example, if the fracture surface of a crankshaft lies at 45° to its axis, the failure originated from alternating torsion. If the crankshaft fracture occurred at an angle close to 90°, it originated from single or repeated torsion under considerable overloads, or from repeated bending loads.

When assessing the nature of the acting forces, the loading conditions of the part must be taken into account. The position of the fracture surface relative to the shaft axis is determined by the magnitude of the overload and the effect of the stress concentrator. Under very high overloading of a shaft by torsional vibrations or under single twisting, for example on instantaneous engine stoppage, a fracture almost perpendicular to the shaft axis is formed. Likewise, in the presence of a sharp stress concentrator oriented perpendicular to the shaft axis (a thread, a sharp groove), the fracture initiates on a surface perpendicular to the shaft axis. On further propagation, most often under small overload and with a not very sharp stress concentrator, the fatigue crack usually turns into a helical one. A shaft fracture at 45° or the primary formation of longitudinal cracks is observed under relatively small cyclic overload. Fracture of rods, studs, tubes and tie-rods under bending or tension occurs along a plane perpendicular to the axis. In this case, without analysing the loading conditions of the part and its operation, it is difficult to establish which loads caused the fracture.

Overloading of a part under repeated loading can be assessed by fracture analysis, check strength calculation, testing or experimental stress analysis. To determine the nature of the acting loads in fatigue failure, an indicative table of fracture features is given (Table 5.1).

5.3 Assessment of the quality of manufacture and of the material of the part

At this stage of the investigation, the following are performed:

- 1) measurement of the parts to establish their compliance with the requirements of the technical specifications;
- 2) assessment of the surface finish quality;
- 3) flaw detection to reveal cracks and metallurgical defects;
- 4) checking of the material quality to establish whether its mechanical properties meet the specified requirements and to reveal metallurgical defects in the material.

Table 5.1 – Indicative table of fracture features

Type of loading	Low nominal stress			High nominal stress		
	Weak local stress concentrator	Weak circumferential stress concentrator	Strong circumferential stress concentrator	Weak local stress concentrator	Weak circumferential stress concentrator	Strong circumferential stress concentrator
Tension and one-sided bending						
Two-sided (reversed) bending						
Rotating bending						

Measurement includes not only the measurement of individual parts but also the checking of adjustment clearances during disassembly. Therefore, measurement begins during the disassembly of the assembly, that is, already at the first stage of the investigation. The importance of checking clearances can be seen from the following example. An inlet valve head failed in an aircraft engine. Measurement showed that the adjustment clearances between the valve and the tappet were increased approximately eightfold. Calculations and tests established that such an increase in clearances leads to up to a threefold increase in dynamic loads.

In the case of failure of a part at a design stress concentrator, the fillet radii are measured with gauges, by taking replicas with their subsequent examination on a profile projector, or by cutting templates. The surface finish class and the depth and

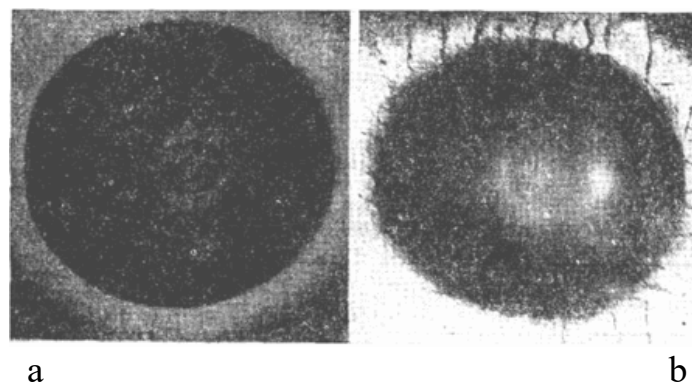
sharpness of surface defects are also determined, which is especially important if the part failed along machining marks, dents or corrosion pits.

Flaw detection of failed parts is usually performed by the same physical inspection methods that are used for flaw detection of parts during their manufacture or repair. It is advisable to examine parts visually and also with a magnifying glass or a binocular microscope. In some cases, the surface of the part is lightly etched to reveal cracks and other defects better.

In flaw detection, the areas located near the fracture origin are inspected particularly thoroughly.

Investigation of the material quality includes standard mechanical tests, metallographic and chemical analyses, and various technological and other tests of the material. These investigations are performed by standard methods, but their application to failed parts has certain specific features. If standard specimens cannot be made, tensile, bending and torsion tests can be performed on micro-testing machines.

In the reverse bend test, it is more important to determine the moment at which the first cracks appear than the number of repeated bends to complete fracture, as is usually done. In a buckling (longitudinal stability) test, it is important to determine the nature of the loss of strength, not only the magnitude of the critical force, etc. Figure 5.3 shows indentations produced by pressing a steel ball into satisfactorily and unsatisfactorily chromium-plated parts.



a – metal with satisfactory chromium plating, b – metal with unsatisfactory chromium plating

Figure 5.3 – Photographs of indentations produced by pressing a steel ball

As can be seen from Fig. 5.3, the chromium layer cracked on indentation only on the failed part, which became one of the proofs that the chromium coating was defective. To reveal surface layers with properties (hardness) different from those of the core, it is advisable to measure microhardness on taper sections.

5.4 Analysis of the operating conditions of the part

Analysis of the operating conditions includes the assessment of design, manufacturing-technological and operational factors. Assessment of design factors is mandatory in the case of mass failures of the same parts, and also in the case of failures of parts of prototype machines. Failures of parts due to insufficient strength are, as a rule, characterised by a short service life.

Sometimes insufficient strength may become apparent only after long-term operation, when the acting stress increases or the mechanical properties of the material deteriorate, for example as a result of wear or when the part operates at elevated temperatures.

Design shortcomings that can lead to failures of parts include an unsatisfactory assembly design, expressed, for example, in the designer specifying grooves, welds, etc. in the most heavily loaded zones of the part, incorrect selection of materials for friction pairs, unsatisfactory lubrication conditions, incorrect specification of clearances, etc.

As a result of incorrect selection of materials for friction pairs, the contacting surfaces of parts may wear or undergo fretting corrosion. Incorrect specification of clearances leads to parts catching on one another or being overloaded.

Manufacturing-technological factors are assessed on the basis of the results of measurement and in-service testing of machines, run-out checks, inspection of similar parts in service, investigation of the material and other methods that make it possible to reveal defects introduced during the manufacture or repair of the part, machine or mechanism. The manufacturing-technological group includes not only production defects that arose during the manufacture of the part but also repair defects.

Nevertheless, in the investigation of failed parts it is in most cases possible to distinguish manufacturing defects from repair defects.

The service life of a part or machine from the start of operation and after repair is indicative in this respect. If a defect arose during repair, failure usually occurs shortly after the repair.

Generalisation of the actual data on the analysis of failures of machine parts shows that the manufacturing-technological causes of failures are as follows:

- material defects;
- defects of heat treatment and electroplating;
- machining defects;

– assembly defects.

Machining defects include distortion of the geometric shape of a part during manufacture, damage during repair, undercutting of fillet transitions, traces of rough machining, tears and cracks, grinding cracks and grinding burns, etc.

The group of assembly defects includes misalignments, incorrect fits, over-tightening, loosening of threaded connections, etc. A special group consists of accidental defects, for example the installation of a part in the unhardened condition, damage to parts by dents and nicks, mixing-up of materials, etc. Assessment of operational factors usually causes the greatest difficulties, because violations or changes in the normal operation of a machine that occurred during operation or maintenance are detected with difficulty and often remain undetected. One may point to well-known cases of failure of connecting rods and other parts of piston engines caused by hydraulic lock (hydraulic shock). The latter is caused by "overfilling" of the combustion chamber with oil or fuel, which results in the piston striking the liquid.

If the engine operation is monitored carelessly, hydraulic lock may go unnoticed, and the engine will continue to operate with a deformed connecting rod. This leads to an increase in the stress acting on the connecting rod and to its subsequent fatigue failure after a more or less long period of time.

Whereas repair and manufacturing defects can in most cases be established directly (measurement, flaw detection, etc.), operational violations (hydraulic lock, overheating, "oil starvation", etc.) are usually established only indirectly.

Therefore, in the analysis of operational factors, the study of the operation and maintenance documentation is of great importance. In assessing operational factors, account should be taken of the qualifications of the personnel servicing the machine, the service life of the machine, the operating modes, the nature of the machine failure, and the reasons for replacing parts and assemblies. This list is not exhaustive and in each specific case should be refined and supplemented in accordance with the specific operating features of the machine.

5.5 Generalisation of the investigation results

A final conclusion on the causes of failure can in most cases be drawn only after generalising all the investigation results: the analysis of the external condition, the operating conditions and the fracture of the part, the assessment of the material and, in some cases, strength calculations or experimental stress analysis.

The main purpose of analysing the investigation results is to substantiate the sequence or pattern of failure of the parts and to establish the cause of failure.

On the basis of the conclusions drawn from the investigation results and the conclusion on the cause of failure, recommendations are developed for preventing similar failures in the future. The need to develop recommendations or claims to industry, the designer, or repair or operating organisations is determined on the basis of the tasks set for the investigation, the hazard of the failure, the recurrence of similar failures, etc.

The development of measures to prevent similar failures is the final stage of the investigation.

Recommendations for eliminating the causes of failures may provide for:

- improvement of the design of parts and assemblies;
- improvement of the quality of manufacture and repair, as well as amendment and supplementation of the existing technology and technical specifications for manufacture and repair;
- amendment and supplementation of the operation and maintenance instructions;
- elimination of shortcomings and violations that may occur during operation and maintenance.

6 DETERMINING THE CAUSES OF CRACK FORMATION IN METAL FROM THE MICROSTRUCTURE

6.1 Determining the causes of cracking from fractures

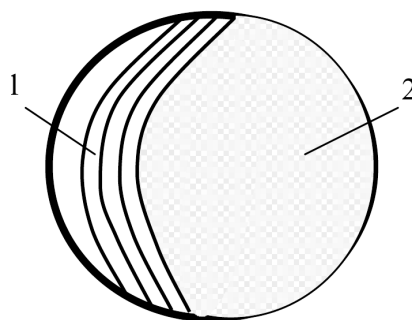
Cracks in metal parts may be caused by the failure of parts in service due to applied loads exceeding the permissible values. The fracture of the part may then be brittle or ductile, depending on the structure and properties of the metal. In ductile fracture, considerable plastic deformation of the metal occurs, and owing to this plastic deformation the structure of the metal cannot be discerned in the fracture. In brittle fracture, the crystalline structure of the metal can be seen in the fracture – the grain size (coarse-grained structure) and the fracture mode (transgranular or intergranular). In transgranular fracture, failure propagates through the grain bodies. In intergranular fracture, failure propagates along the grain boundaries.

With a ductile fracture structure, it can be stated with certainty that the failure occurred due to excessive loads; in this case, the party responsible is whoever operated the article.

With a brittle fracture, when the fracture is predominantly intergranular, the manufacturer of the part or those performing the heat treatment of such parts may be held responsible. Intergranular fracture is most often obtained in structures in which a brittle phase has precipitated as a result of heat treatment, or in the case of burning, when during heating for heat treatment the part was heated to high temperatures and oxidation of the grain boundaries occurred.

When a part operates under alternating loads, fatigue fractures may form (Figure 6.1).

A characteristic feature of fatigue fractures is a two-zone macrostructure. The fatigue zone has a smooth, as if polished, surface with radial marks, whereas the final fracture zone has the structure of either ductile or brittle fracture and a rough surface.



1 – fatigue zone
2 – final fracture zone

Figure 6.1 – Diagram of the two-zone macrostructure of a fatigue fracture

The causes of fatigue failure may be cracks on the surface of the part formed during its heat treatment or surface treatment. When a fatigue fracture is present, the manufacturers of the part, rather than those who operate it, are usually considered responsible for the failure. In some cases, it is necessary to establish the cause of crack formation.

6.2 Possible causes of crack and microcrack formation during heat treatment of parts

Cracks and microcracks often form during the heat treatment of parts owing to non-uniform heating, especially of parts of complex shape with abrupt transitions from massive sections to thin sections. Cracks may form at the very beginning, during heating of the part, or at the end of heat treatment during accelerated cooling. Cracks formed during heating are called *hot* cracks, and those formed during cooling are called

cold cracks; the latter also include cracks that may form not only during cooling but also during holding after heat treatment owing to considerable internal stresses.

Characteristic features of *hot* and *cold* cracks:

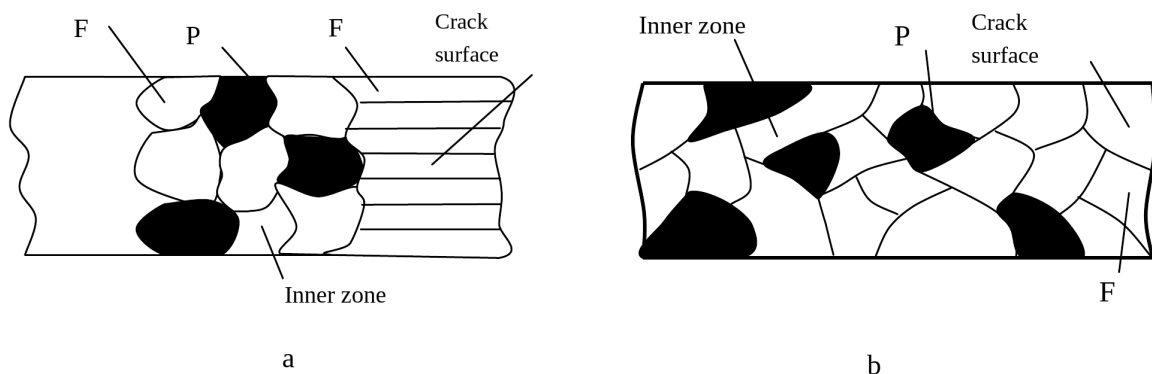
– *hot* cracks, formed at the beginning of heating of the part: the crack edges oxidise during heating, and the crack is filled with oxides. If a microsection of the crack edges is prepared, the crack surface often has a decarburised structure. The decarburising medium is the oxide filling the crack (Fe_2O_3). The temperature at which decarburisation took place can be determined from the structure of the decarburised layer.

For example (Figure 6.2), in the first case, steel with a carbon content of $\sim 0.4\%$ was heated to a temperature below 910°C . On heating to a temperature below 910°C , steel 40 acquired an austenitic structure.

When carbon is removed from the surface, a polymorphic transformation of austenite into ferrite takes place at the surface. The ferrite nuclei formed grow into the depth of the structure as carbon is removed, forming columnar ferrite grains.

On heating above 910°C (Fig. 6.2, b), the removal of carbon from the surface of the part does not lead to the polymorphic $\text{A} \rightarrow \text{F}$ transformation, and the austenitic structure is retained at these temperatures both at the surface and inside the part.

The surface austenite will differ from the austenite of the central zones only in its carbon content. In the surface austenite the carbon content will be very low, while in the inner layers it will remain at the initial level. On cooling, the low-carbon austenite at the surface transforms into ferrite, forming equiaxed grains. In the central zone, a polymorphic transformation of austenite takes place, first with the precipitation of excess (proeutectoid) ferrite and then of pearlite.



a – heating below 910°C , b – heating above 910°C ; F – ferrite, P – pearlite
Figure 6.2 – Schematic microstructure of the metal in the crack formation zone

The transition from the zone with a pure ferrite layer to the initial structure is gradual in terms of carbon content, i.e. the number of pearlite colonies increases smoothly up to the initial state, and there is no sharp boundary as in the first case.

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