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DIAGNOSTICS AND CASTING QUALITY CONTROL

(lecture notes)

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STUDY REGULATIONS

Subject name:

DIAGNOSTICS AND CASTING QUALITY CONTROL

For the subject Diagnostics and Casting Quality Control in the 3rd semester of the field of study Modern Metallurgical Technologies you have obtained an educational packet including integrated lecture notes for the combined study comprising also study regulations.

1. Prerequisites

The subject has no prerequisites

2. The objectives of the subject and outputs from the education

A student will become an expert for management of casting quality in foundry plants.

After studying the subject, a student should be able to -

Acquired knowledge:

characterize basic defects in castings, i.e. those occurring most frequently in operation in foundry shops

know basic procedures of diagnostics of casting defects, to identify causes of defect formation using statistical methods

Acquired skills:

be able to apply theoretical knowledge for proposals of preventive measures for quality improvement

be able to apply the knowledge of procedures of defect diagnostics and testing of casting properties

For whom the subject is intended:

The subject falls within the Master's study of the field of study Modern Metallurgical Technologies of the Metallurgical Engineering study programme, but it can also be studied by applicants from any other branch, on condition of having met the demanded prerequisites.

Recommended procedure for studying each chapter:

To read subchapters

To read-over each chapter with detailed focusing on flowcharts, figures and particularly equations.

A way to communicate with lecturers:

You can contact the lecturer through e-mail: jiri.hampl@vsb.cz or by telephone: +420 597 324 206.

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1 INTRODUCTION TO QUALITY CONTROL. QUALITY OF CASTINGS. CLASSIFICATION OF CASTING DEFECTS

Subchapters:

- ✓ Casting quality
- ✓ Classification of casting defects
  - Development of the classification
  - The present state of the art
- ✓ Quality of products in foundry plants
- ✓ Literature

Time needed for the study: individual

Objective: After studying this chapter a student will be able to:

- Define a term “casting defect”
- Classify defects in classes and groups
- Define peculiarities of foundry production

The basic terms are included in the part “Subchapters”

Lecture

Many organizations spend 20 to 30 % of their income to correct errors and drawbacks originated during their activity, which applies above all for manufacturing companies. A company must replace defective products, provide repairs of defects, solve claims from customers, compensate their losses etc. Today all of us want high quality products and services. One of definitions of quality says that it is a determining value of a thing, human or phenomenon. Quality is “good”, if it meets or exceeds our requirements and expectations. If it is not like that, we talk about “bad” quality. Bad quality harms a reputation of a company and may result in a customer finding another supplier. Clients and users are more and more demanding and are not willing to tolerate off-grades. Moreover, they can choose goods and services from a wide offer on the market.

Therefore companies and organizations worldwide implement extensive programs oriented on quality continuous improvement, prevention of failures and defects. At the same time, they innovate their products and improve their parameters to the customer’s higher satisfaction. No organization or company can ignore quality. Investment to quality enhancement also brings along a financial situation improvement and stability of companies. Regarding ever increasing demands to the management system in organizations, quality management system standards ISO 9000 have been elaborated by ISO, the International Standardization Organization.

Many of the present-day as well as potential clients of foundry industry have often a false idea of what can be achieved by casting and what can be expected from a cast semi-product. Foundry processes are widely used for the manufacture of parts by a highly economic way.

Through this direct way complicated shapes requiring only little or even no machining can be achieved. The manufacture of a cast semi-product involves many steps, the first of which is a design of the component construction and specification of materials from which the semi-product is to be made. Then elaboration of a casting technological procedure comes, including determination of a casting position during casting, a gating system design and other measures for a casting to be compact and "sound", i.e. without surface and inner defects. A decision on an adopted procedure is governed mainly by a final casting quality determining the production cost. Mere meeting requirements of a customer and his designer need not to result in an optimal solution as to costs. It is often a foundryman's responsibility to find a more cost saving solution through a change in a shape or material of the component.

Compared to foundry industry, we can hardly find another production process so much susceptible to changes. Various defects are an accompanying phenomenon of a material transition from the liquid to solid state of matter. From raw materials to a casting, metal goes through melting phases, casting into moulds, solidification and shrinkage and may change – a worker cannot influence the process directly from a moment of casting the metal into a mould as long as the product is not cooled-down completely. Further, castings are manufactured from raw materials and other materials, quality of which cannot always be defined exactly. We often rely on various a priori chosen technological actions, which are often contrary to each other according to the cast alloy. A casting temperature of metal can be an example. Its increase supports metal fluidity and perfect filling of a cavity in a mould, on the other side, metal may penetrate intergrain areas of a sand mould and a high casting temperature results in coarsening of a primary structure during crystallization. An improper casting temperature may cause three types of casting defects at minimum. This implies instability of the process and necessity to adopt compromising solutions. Otherwise defects occur in castings, which, in the extreme, cannot be corrected and a respective piece or a whole batch has to be discarded. Then the production has to be repeated; but before this, defect diagnostics has to be performed.

A procedure to determine a diagnosis is often chaotic and based on a risky "trial – error" strategy. This method is usually insufficient for discovering a hidden cause of a defect. If a systematic approach is used for a proper diagnostics of a casting defect and to find an appropriate corrective and preventive action, an applicable solution for defect minimization can be found quickly, saving time and money.

That's why in the next chapters of these lecture notes we deal with the diagnostics of defects, their classification and description.

1.1 Casting quality

In 2003 Hüttenes Albertus, a world-wide known supplier of foundry materials and raw materials, within their advertising campaign has brought a slogan "PERFECT CASTINGS, SOUND CASTINGS, MAGIC CASTINGS". During his professional career, an author of this textbook has dealt with production quality in foundry plants and solutions of various casting defects on a long-term basis [4]. Actually, those were "ILL CASTINGS"; a "disease" had to be diagnosed, then "cured" and prevention had to be suggested at the end. To be able to cure a disease, exactly like in medicine, it has to be identified properly – diagnosed. This fact was evidently known just 300 years ago by doctors when treated their patients, as the quote below illustrates:

Qui bene cognoscit, bene curat, hinc diagnosis morbi est summa necesitas.

Who recognizes properly, cures properly. Therefore a disease diagnosis is the highest necessity!

Surgeon Hassler, Krems, 1684 [1]

To be able to manage quality means to be able to determine a nonconformance (defect). A proper and fast diagnostics of a nonconformance – defect is a key to cost reduction in a foundry shop.

A casting defect is a deviation (nonconformance) from

- appearance
- shape
- dimension
- weight
- structure
- compactness (homogeneity) and agreed conditions and standards

Casting defects can be:

- Apparent – detectable when inspecting a non-machined casting by a naked eye or simple measuring devices. These are mostly surface defects (outer).
- Latent – detectable no sooner than after having machined the casting, after having measured the dimensions or using applicable devices and instruments. These are mainly subsurface defects (inner).

A term “casting defect” has a conditional meaning. Pursuant to provisions of appropriate standards or agreed technical conditions, each deviation can sometimes be an acceptable defect, or sometimes a non-acceptable defect, a repairable or removable one. From this point of view, we can distinguish casting defects as follows:

- ***Acceptable defects*** do not hinder applicability of castings and have to be either explicitly permitted or at least must not be explicitly interdicted.
- ***Non-acceptable defects*** are usually namely stated and their occurrence signifies a non-conformant product, i.e. spoilage.
- ***Repairable defects*** are defects that can be removed by applicable additional operations carried out in a foundry shop at their own expenses.

A casting with a non-acceptable defect is called a scrap, i.e. a spoiled, rejected piece. Depending on a place where a scrap is found out, we can distinguish internal scraps – found out before dispatching a casting to a purchaser and external scraps – found out after delivering a casting to a purchaser (after invoicing). In addition, we distinguish inner defects (subsurface defects) and outer defects (surface defects).

In foundry industry, more than in other fields, it is important to distinguish terms *defectless product, quality casting, non-conforming product, delivery without defects, production without defects.* By the above mentioned reasons, for the time being, production of defectless castings is only a goal to achieve. On the other side, it is possible to find latent defects before dispatching and ensure deliveries without defects (without external scraps). A quality casting conforms to standards and conditions prescribed by a customer; it does not mean that a product must be defectless. Certain defects in specified quantity and in defined places need not to hamper the product functionality; these are not non-conforming products (scraps). A simple rule applies, which expresses a relation between quality and cost at the same time:

**A QUALITY CASTING = SO GOOD,
AS NEEDED AND SO CHEAP,
AS POSSIBLE**

1.2 Classification of casting defects

1.2.1. Development of the classification

When finding a certain casting defect, it is important to determine a type of the defect properly, and then following activity is performed to determine an origin of the defect, to determine causes and corrective actions to prevent its recurrence. This situation can be compared again to treating a sick human. Recovery of a patient, mitigation of his pain and disorders depends on a fast determination of a diagnosis as accurately as possible. Medical diagnostics comprehends a disease determination, that a clinical picture of a disease is categorized in a known and learned classification system according to features (including results of particular investigations) [2]. Medical science uses a very extensive terminology of diseases, ever extending along with development of scientific knowledge.

Foundry experts also deal with the defect classification – the first works were published in the first half of the 20th century already. Along with development of technology and knowledge of foundry procedures for creating cast semi-products, the classification of casting defects had been further made more and more accurate and extensive.

The first atlas of casting defects was published by the British foundry institute in 1946. The second revised edition in 1961 [2] described 54 defects, arranged in the alphabetical order without a systematic sorting. A casting defect manual was published in the USA in 1947 and this edition was reworked several times during next decades [3]. Czechoslovakia in the 50ies also produced high quality monographs with guidelines for assessment of casting defects with practical instructions for removal of these defects thanks to Plešinger for grey cast iron [4] and Přibyl for steel castings [5]. On the basis of these two manuals, a casting defect standard ČSN 42 1240 was published in 1955, amended in 1965 [6]. As shown in Tab. 1.1, it contains 37 defects classified in 7 groups, sorted to types. The shown defect classification applies for all kinds of cast materials, neglecting a manufacturing method and casting technology.

The most detailed atlas of casting defects so far has been published in France as a common work of acknowledged specialists from 18 countries under the patronage of the International Committee of Foundry Technical Associations (CIATF); a German translation was published in 1955 and 1956 [7, 8]. These two volumes have covered 200 defects occurring in castings from iron and non-ferrous metals alloys. They were classified in 9 groups and designated by a four-figure number code. 135 defects were common for castings of all alloy types. 40 defects were typical for grey cast iron and 25 for the rest of alloys. In 1965, a Committee of foundry properties and metallurgy at CIATF charged a French and German organization with a task to publish an amended edition of this work. The German edition was elaborated under an editorial leadership of Schneider, Reuter and Siieben [9D], the French edition was edited by Hénon, Mascré and Blanc [9F]. The English edition of the atlas edited by Rowley was published in the USA in 1973 [9EN]. Thus the most elaborated classification of casting defects for all kinds of cast alloys was created. The described defects have been classified to 7 categories, 17 groups, 41 subgroups with 109 defects. Each defect has been identified by a four-figure denomination. Defect classes have been designated with large letters of the alphabet:

A. Metallic projections
B. Cavities
C. Discontinuities
D. Defective surface
E. Incomplete casting
F. Incorrect dimensions or shape
G. Inclusions or structural anomalies

Tab. 1.1 Classification of casting defects according to groups and types in ČSN 42 1240

Number of the group of defects	Name of the group of defects	Numerical designation of a defect	Defect type name
1	Defects of shape, dimensions and weight	11	Misrun
		12	Shift
		13	Flash
		14	Swell
		15	Warping
		16	Mechanical damage
		17	Deviation of dimensions
		18	Deviation of weight
2	Surface defects	21	Burning-on
		22	Cold shuts
		23	Expansion scabs
		24	Erosion scabs, sand buckles
		25	Veining
		26	Eutectic sweat
		27	Scale
		28	Dents, contusions, bruises
3	Discontinuities	31	Hot tears
		32	Cold cracks
4	Cavities	41	Gas holes
		42	Pinholes
		43	Shrinkages
		44	Shrinkage porosities
		45	Microshrinkages
		46	Microgasholes
5	Inclusions	51	Slag inclusions
		52	Sand inclusions
		53	Non-metal inclusions
		54	Cold shots
		55	Metallic inclusions
6	Structure defects	61	Segregation
		62	Defective fracture
		63	Hard spots
		64	Inverse chill
		65	Incorrect structure
7	Defects of chemical composition, anomalies in physical or mechanical properties	71	Incorrect chemical composition
		72	Unsatisfactory mechanical properties
		73	Unsatisfactory physical properties

At the same time as in our country, in the former USSR a manual from a collective of authors under the leadership of Lakedemonskij was published [10]. This contained 36 defects classified in 9 groups. Poland had a highly detailed standard covering 64 defects in 5 groups with names and classifications of defects [11]. A Bulgarian monograph of Todorov and Peshev from 1980 was translated into Russian [12]. Casting defects were divided to 8 groups. One of the groups covered defects of castings manufactured by new casting methods or these were castings for special purposes. As this work suggested, specific defects should also be taken into account for the classification of casting defects. In the Czech literature a systematic analysis of defects of precision castings was performed in a book from a collective of authors under the leadership of Doškář [13].

1.2.2. The present state of the art

New foundry technology findings also brought in new knowledge on causes and a mechanism of defects [14,15,16]. Therefore a simple defect classification with a two-digit designation used in the Czechoslovak standard ČSN 42 1240 became out-of-date. Within activities of specialized committees of ČSS (the Czech Foundry Association) in the 80ies a revision of this classification was performed and a proposal for the defect designation with a three-figure code was suggested, which enabled to extend a number of defects. The proposal was issued as a publication of the Czech committee of the foundry association in 1987 [17]. The classification was extended by new defects, some of the existing defects were further assorted according to causes of their origination, and in comparison with the classification based on ČSN 42 1240 standard, 108 possibilities in total were created to describe a nonconformance of a foundry product. Defects were classified in 7 classes designated with numbers 100 to 700, in 38 groups of defects, 20 from this identified just a defect, 18 were divided to 70 particular defects. Thus there are 90 defects (70+20) or 70 + 38 = 108 options to describe a nonconformance – defect. This classification respects a nomenclature of the International Atlas of Casting Defects as well as its categorization [9]. The defect terminology and the basic numeric designation of defects from ČSN 42 1240 has also been maintained to the maximum extent. The defect list is summarized in Tab. 1.2. At the end, a cooperation of authors of the new defect classification has resulted in publishing a monograph about defects of castings of iron alloys [18]. In spite of the fact that the new classification has not been issued as a national standard, it is used in lots of foundry plants. It was also supported by a body of editors of "*Slévárenství*" (Foundry industry) journal, who published a series of articles on casting defects from 1997 to 2005. Later on they were published as a whole by the *Association* of *Foundries of* the Czech Republic on CD ROM [19]. The casting defects analyzed in these lecture notes are also based on the new defect classification.

In recent 20 years further monographs on quality and defects of castings have emerged based on development in the knowledge of foundry procedures, application of up-to-date laboratory and detection procedures for inspection of defects and the use of mathematical modeling. Hasse elaborated a detailed and rich monograph [20] and among numerous works of Campbell, there is a practical manual for defect prevention [21]. In our country, Otáhal has published the Atlas of defects of ferrous and non-ferrous alloys on an electronic carrier [22].

Tab. II List of classes, groups and types of casting defects

Casting defects in a class 100					
Class of defects		Group of defects		Types of defects	
Number	Name	Number	Name	Number	Name
100	Defects of shape, dimensions and weight	110	Missing part of the casting without a fracture	111 112 113 114 115 116 117	Misrun Short run Run-out metal, bleeding Mould repair error (dash) Excessive cleaning Mechanical damage Improper handling in cleaning shop
		120	Missing part of the casting with fracture	121 122 123	Breaking part of hot casting Breaking part of cold casting Broken in runners, risers
		130	Variance in dimensions, incorrect shape	131 132 133 134	Incorrect pattern Shift, cross joint Incorrect dimensions Warping, deformation
		140	Incorrect weight		

Tab. II continue 1

Casting defects in classes 200, 300 and 400					
Class of defects		Group of defects		Types of defects	
Number	Name	Number	Name	Number	Name
200	Surface defects	210	Burning-on, adherence sand	211 212 213	Rough surface Burn-on Burn-in, penetration
		220	Expansion scabs	221 222 223	Scab on cope surface Bottom (expansion) scab Rat tails
		230	Swells	231 232 233 234	External or internal swell Crush, friction Mould drop Erosion or wash
		240	Veining or finning		
		250	Eutectic sweat, sweating		
		260	Metallic projections in the form of fins	261 262 263	Joint flash or fins (Raised mould) Cracked core Craked mould
		270	Irregularities of a casting surface	271 272 273 274 275 276 277	Orange peel Elephant´s peel Small pox, local or bar Scale, Scaled casting Fine drops Pitting or channel-type corrosion Chemical corrosion
		280	Defects of painting protection of a casting		

300	Discontinuities	310	Hot tears	311 312 313	Superficial hot tears Subsurface hot tears Internal hot tears
		320	Cold cracks		
		330	Discontinuities due to mechanical damage	331 332	Hot rupture Cold rupture
		340	Discontinuities caused by lack of fusion	341 342	Cold shut Incorrect welding
400	Cavities	410	Blow holes , gas porosity	411 412 413 414 415	Oxygen-caused blowholes Hydrogen-caused blowholes Nitrogen-caused blowholes Entrapped gas Superficial netting of blowholes
		420	Pinholes		
		430	Boiling, blowholes	431 432 433	Blowholes (boiling) from a mould, a core Boiling from chills and metallic inserts Blowholes (boiling) from inclusions
		440	Shrinkages	441 442 443 444 445 446	Open shrinkage cavity Internal shrinkage cavity Shrinkage porosity Shrinkages cavities from core or mould edges Shrink mark, sink Shrinkage blowhole

Tab. II continue 2

Casting defects in classes 500, 600 and 700					
Class of defects		Group of defects		Types of defects	
Number	Name	Number	Name	Number	Name
500	Macroscopic inclusions and macrostructural defects	510	Slag inclusions	511 512	Exogenous slag Secondary slag, dross
		520	Non-metallic inclusions	521 522 523 524 525 526	Drop, sand holes Sand inclusions Blacking holes (scab) Oxide inclusions, film Graphite or lustrous carbon inclusions Black stains (primary graphite)
		530	Macro-segregations	531 532 533 534	Gravity segregation Physical segregation “A” segregation “V” segregation
		540	Cold shots		
		550	Metallic inclusions		
		560	Defective texture of fracture		
600	Microstructural defects	610	Micro-cavities	611 612 613	Micro shrinkages (shrinkage porosity) Micro blowholes (gas porosity) Micro tears/cracks
		620	Micro inclusions		
		630	Incorrect grain size		

		640	Incorrect microstructure components
		650	Chill spots. Hard edges
		660	Inverse chill
		670	Surface decarburization
		680	Other microstructure defect
700	Defects of chemical composition and properties of castings	710	Incorrect chemical composition
		720	Non-conformity value of mechanical properties
		730	Deviations values of physical properties
		740	Inconvenient casting homogeneity

1.3 Quality of products in foundry plants

The foundry production character is determined by approach of foundry plants to quality, as suggested in the items below.

- Foundry industry produces final products in a limited extent only, few of foundries sell their products according to a catalogue. This is a typical sub-suppliers field. A customer must be a “commodity expert” more than in other fields. An entire company has to make marketing.
- Therefore there is a close relationship to customers and a fast feedback from them.
- Goods are made in accordance with a customer’s documentation – “tailor-made”. Today there is a trend to entre even a development phase of a product and take part in documentation and influence properties of goods – castings.
- Implementation of the quality management system pursuant to ISO 9000 international standards, as well as its regular certification, is commonplace today.
- A customer often relies on own audits and monitors the quality system: there are system audits at the beginning, a product audit follows (specimen approval) and then process audits.
- Clients urge a company to a continuous improvement; they monitor quality plans, cost reduction plans.
- Nowadays, foundry plants enter also development phases of new products within simultaneous engineering. This can only be achieved by companies with highly skilled staff, with available computer technology with programs supporting 3D designing, structural calculations and mathematical modeling of foundry procedures, with the aid of simulation programs, the so-called virtual casting. Of course, they have to possess modern manufacturing technologies and advanced testing and diagnostic equipment.

1.4 Literature

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Σ Summary of terms of this chapter

– Mentioned in the part “Subchapters"

Questions to the topic

- Questions to this topic correspond to titles of the subchapters in the part “Subchapters”

2 TOOLS FOR QUALITY MANAGEMENT AND IMPROVEMENT

Subchapters:

- ✓ Cause-and-effect diagram
- ✓ Check sheet
- ✓ Histogram
- ✓ Pareto chart
- ✓ Scatter diagram
- ✓ Flow chart
- ✓ Control chart
- ✓ Literature

Time needed for the study: individual

Objective: After studying this chapter a student will be able to:

- Apply the cause-and-effect diagram for solving casting defects
- Apply Pareto chart for solving casting quality
- Create and apply control charts for the casting production process control

Lecture

In the previous chapter it was stated that in quality standard requirements a high emphasis is placed on management and improvement of processes and products. The quality continuous improvement procedures are based on various quality tools. These represent certain quantitative procedures, allowing better monitoring of processes and product realization control, better identification, diagnostics and troubleshooting issues related to quality. For management of series, line flow manufacturing, seven basic tools for quality improvement are applied [1.2]. They arose in Japan and they are known in English as Seven Basic Tools of Quality. They are helpful in monitoring of wastage caused by personnel, technology and machines. They can be also used in a single-part production or a small-lot production. Therefore they are applicable even for foundry production. These are simple tools, preferable to exact statistical methods, some of which being presented in a next chapter. This is a set of graphical methods that can be used to solve the vast majority of quality-related issues. These methods are as follows:

1. Cause and effect diagram, known also as the Ishikawa diagram or the Fishbone Chart
2. Check sheet, or also a data collection sheet, a tally chart
3. Histogram of the frequency distribution

4. Pareto analysis (Pareto Chart)
5. Scatter diagram or a regression or correlation analysis
6. Flow Chart
7. Control Chart

2.1 Cause and effect diagram

This considers all the likely causes of problems. A brainstorming session is required in order to find all main components of a problem area and all possible causes. To carry out the diagram, a problem (e.g. a casting defect) is the so-called fishbone head and main bones leading from the backbone signify areas or categories in which a problem may occur. Side bones represent actual factors – causes of a defect. This way the diagram can be carried out in more levels of causes and sub-causes. The Ishikawa diagram is used above all for curing "operational blindness". To create the diagram, the following procedure is recommended:

1. Agree on an identification of a problem that is a "head" of a fishbone and draw a horizontal arrow running to it.
2. Brainstorm the major categories of causes of the problem (phenomenon). If this is difficult, you can use general causes occurring in the given production area and use the following generic headings:

Methods
Workers, manpower
Management
Materials
Inspection and testing
Environment

3. Write the individual categories of causes (factors) as branches from the main arrow.
4. Brainstorm all the possible causes of the problem and ask: "WHY did this happen?" Draw each detailed idea as a branch from the appropriate category. Causes can be written in several places if they relate to several categories.
5. Again ask "WHY did this happen?" about each causeand write another cause. When the group runs out of ideas, focus attention to places on the chart where ideas are few.
6. What is brainstorming? It is a type of teamwork, the so-called "brain squeezing". Participants are encouraged to provide ideas; each participant has an equal right both to express his/her idea and to assess ideas of other participants. It is a directed process, guided by a facilitator.

Let us look at two examples of application of the Ishikawa diagram. The first one is for the manufacture of cores and the second one for an undesirable phenomenon of occurrence of pinhole defect (420) in a casting. Fig. 2.1 shows in details the factors affecting the manufacturing process of sand cores, which determine casting quality significantly.

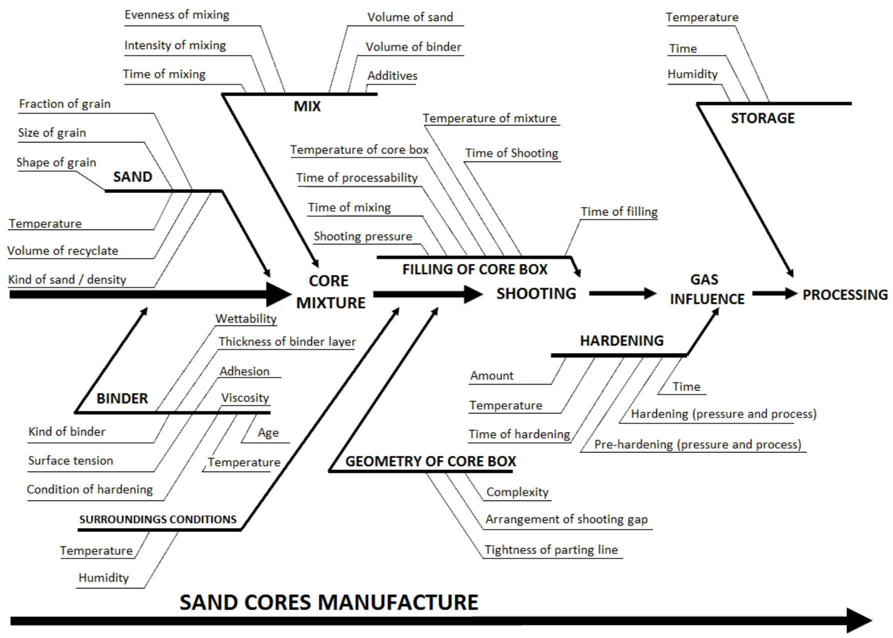


Fig. 2.1 Cause and effect diagram for the technological process of the sand cores manufacture

The cause and effect diagram for occurrence of pinholes in castings from spheroidal graphite iron in Fig.2. 2 is focused on factors affecting the formation of the casting from molten metal to the final product. These effects are divided into 5 groups and have to be taken into account at each assessment of the course of these procedures. They are [3]:

1) Casting material (chemical composition, thermal conductivity, specific weight, specific heat, viscosity surface tension etc.)
2) Mould material (type and granularity of base sand, type and amount of a binder, specific weight, heat absorbing capacity coefficient, moisture, permeability, gassiness of a mixture etc.)
3) Casting method (a position of a casting in a mould, pressure and speed conditions of metal flow, flow rate, metal casting temperature, risering, application of chills etc.)
4) Casting design (thicknesses of walls and a shape, requirements for casting material properties, material mechanical properties etc.)
5) Surrounding atmosphere (temperature, pressure and other geo-climatic conditions)

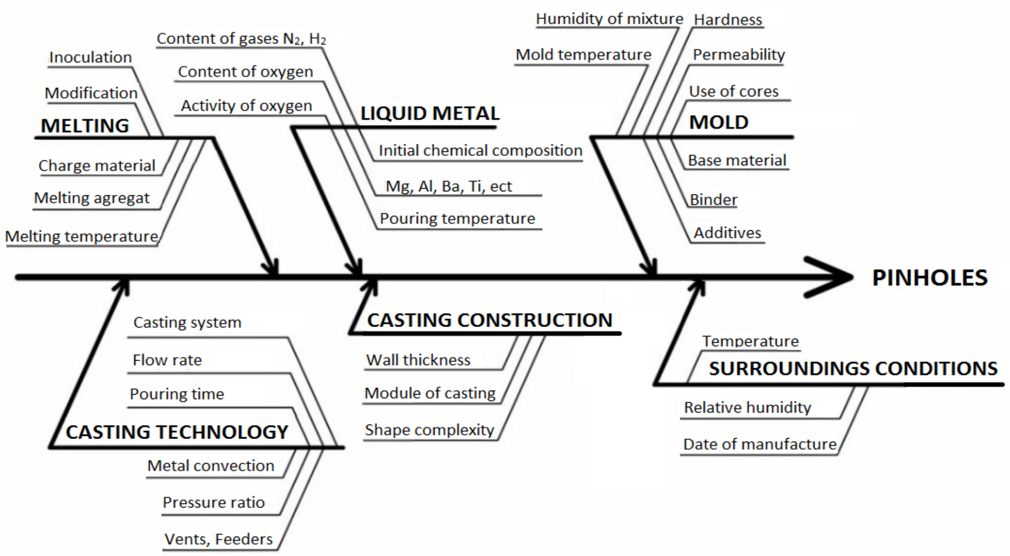


Fig. 2.2 Cause and effect diagram for occurrence of pinholes in castings of spheroidal graphite iron

2.2 Check sheet

A check sheet (see an example) or a data table serves for collecting and organizing primary quantitative data on quality, such as a number and type of defects during a manufacturing process or at an output control. The goal is to obtain an overall overview on the quality condition and to give persons in charge a possibility to make decisions based on facts. When designing the table, collecting and recording data, the following viewpoints are to be considered.

- Stratification principle – a process of data sorting, the aim of which is to separate data from various sources, so that an origin of each item can be identified quickly and thus an origin of a possible related problem as well.
- Principles of simplicity, standardization and visual interpretation – data should be recorded simply, so that everybody can do it. A record has to be performed simply by making check marks instead of numerical data. Data should be recorded in such a way, so that they do not have to be rewritten into other blanks.

Example of a check sheet for solving casting defects in different shifts and on different calendar days

OUTPUT CONTROL DOCUMENT CASTING, NUMBER: 220.351-2 MONITORED FROM 18/11 TO 22/11						
MOULD NUMBER	DAY	NUMBER OF NON-CONFORMING PRODUCTS (pcs)				
		Shift A	Σ	Shift B	Σ	Σ
1	Mon Tue Wed Thu Fri	xxxxxxxx xxxx xxxx xxx xxxxx	8 4 4 3 5	xxx x xx 	3 1 0 2 0	11 5 4 5 5
Σ1			24		6	30
2	Mon Tue Wed Thu Fri	xxxxxx xxxxxxx xxxxx xxxxxx xxxxx	6 7 5 6 5	xx xxx x xx x	2 3 1 2 1	8 10 6 8 6
Σ2			29		9	38
3	Mon Tue Wed Thu Fri	xxxxxx xxx xx xxxx xxx	6 3 2 4 3	xx x x x	2 0 1 1 1	8 3 3 5 4
Σ3			18		5	23
Total			71		20	91
EVALUATED BY:						

2.3 Histogram

A histogram is an often used graphical display of data distribution through a chart with columns of the same width, expressing a width of intervals (classes), while a height of columns expresses frequency of the monitored quantity in the given interval. It is important to choose a proper width of an interval. An improper width of an interval may decrease an information value of the diagram. A histogram is used when numerical data on a course of a certain phenomenon (process) are available. This way we can determine, if the distribution is about normal. Also, we can see whether a process change has occurred from one time period to another, possibly to compare outputs from two different processes. Then these two sets can be subjected to tests of significance of their differences. A histogram is advisable for easily comprehensible display of a process data distribution (Fig. 2.3.). For a histogram construction, you should collect at least 50 consecutive data points from a process. An interval width has to be chosen properly. Some properties of the process and data can be assessed from the histogram shape, for example two peaks instead of one show that data from two different processes have been put together.

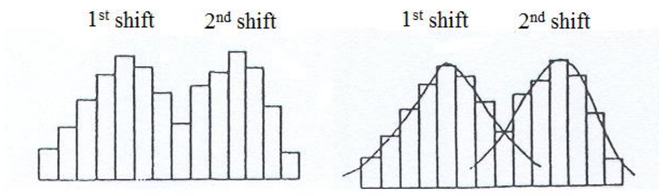


Fig. 2.3 Example of a histogram application for a comparison of working crews for sand mixture mixers in the 1st and 2nd shift

2.4 Pareto chart

The Pareto chart is a type of a graph that combines a bar chart and a line chart, where bars representing frequency for particular categories are arranged in an order from the highest to the lowest (the longest bars to the left, the shortest to the right) and a line represents a cumulative frequency in percentage. The Pareto chart is used for visual depicting of importance of particular categories. It is applicable when analyzing the nonconformance frequency in the given process, when there may be more causes and the most significant ones need to be determined. Therefore we can often see it in foundry plants when assessing casting wastage. For setting-up the Pareto chart, you need to decide what categories you will use to group items, what quantities are to be measured and what period of time the chart will cover. It is also suitable for analyses of losses, claims, nonconformance causes. According to the chart, for a specified problem we can determine a “non-useful minority” and “useful majority” of causes, which is above 80 %. Look at the example (Fig. 2.4.) of an analysis of non-conforming products in a grey iron foundry shop per one quarter.

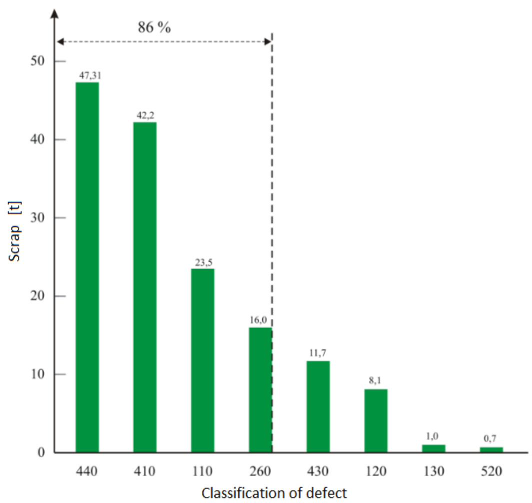


Fig. 2.4 Example of the amount (%) of non-conforming products in a grey iron foundry shop per one quarter

2.5 Scatter diagram

A scatter diagram or also a point graph is a mathematical scheme using Cartesian coordinates for a depiction of a data set of 2 variables. Data is depicted as individual points where the horizontal axis is determined by an independent variable value and the vertical axis is determined by a dependent variable value. This is a simple way to find a relationship (correlation) between both the variables, possibly to interpolate this relationship (by a straight line, curve or another type of a correlation), as shown in Fig. 2.5.

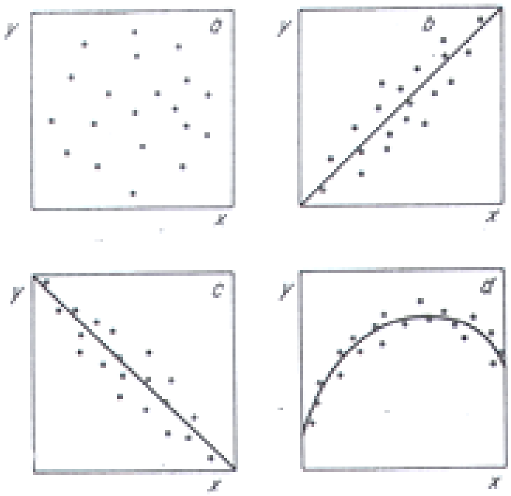


Fig. 2.5 Examples of point graphs with a different course of correlation

The scatter diagram can be used when you have paired numerical data, when your dependent variable may have multiple values for each value of your independent variable. The scatter diagram can easily answer a question, whether the two variables are related or not. Using advanced statistical methods of regression and correlation analysis, we can quantify relationships of two quantities. Fig. 2.6 shows an example of such a procedure.

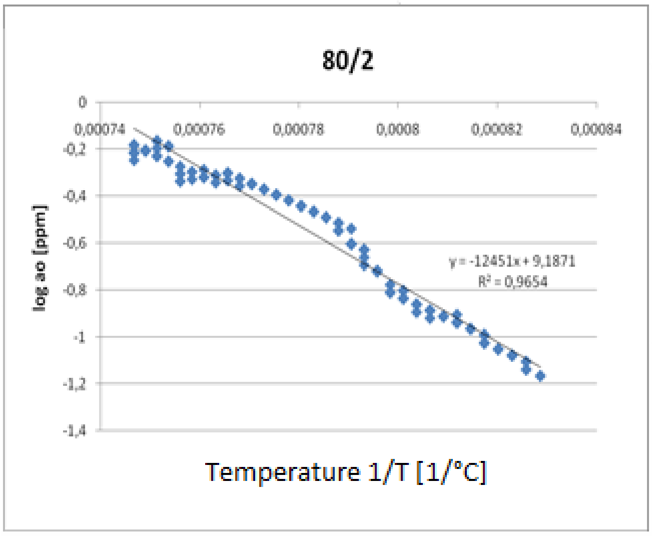
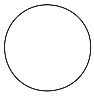
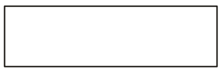
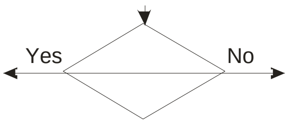
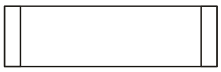
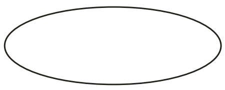


Fig. 2.6 Relationship of the oxygen activity on a temperature inverse value during cast iron solidification

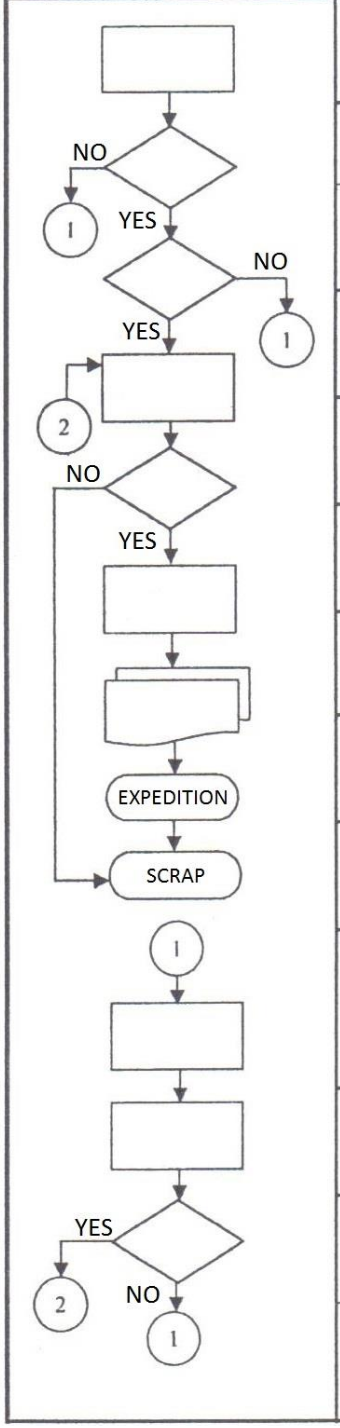
2.6 Flow chart

A flowchart is a visual representation of algorithms or processes and can be used to better understand complex processes and their relationships. The flowchart uses symbols for depiction of individual partial operations – Tab.2.1.I, which are interconnected through oriented arrows. The used symbols are included and defined in the Czech standard ČSN ISO 5807. The flow chart maps out a logical sequence of events that take place sequentially or in parallel, join each other again or repeat in some case, until in all variants the beginning and the end, i.e. input and output, are connected.

Tab. 2.1 Symbols used to create flow charts and their meaning

Symbol	Meaning
	Connection, transfer to another part or continuation of the flow chart
	Operation performance, activity
	Decision process – always one input and only two outputs
	Sub-process described in another sub-chart
	Beginning or end of the process
	Document

Tab. 2.2 Flow chart of the casting defects identification [5]

Chart	Work process	Performs
	Assessing defect by appearance, standards, design and approved technical conditions	Controller
	Decide to defect is apparent (YES), or hidden difference (NO)	Controller
	Assessing, whether defect is clearly definable	Controller
	Determine the type of defect, define a cause, made a arrangements	Controller or expert committee
	Assess repair options - can be repaired?	Supervisor, Technologist or Chief
	Perform a repair, modification	Specialized plant
	Make a note about used processes, the extent, identification	Chief
	Release the castings for customer	Supervisor or dispatcher
	Elimination of casting, scrapping	Supervisor, Chief
	Supplementary analysis, destructive and non-destructive control	Laboratory or specialized plant
	Assess the result of analysis, appearance of defect, comparison with directive	Controller or expert committee
	Is it possible now clearly identify the defect?	Controller or expert committee
	Repeat the process with the use of other control methods, external experts etc., Pending a final decision	

Tab. 2.2 Flow chart of determination of a defect cause [5]

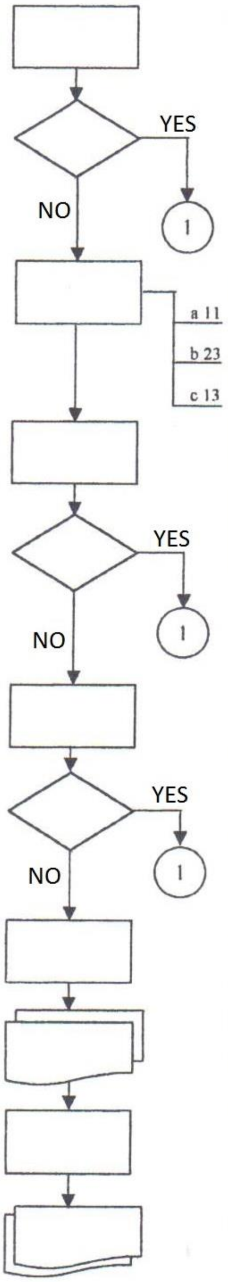


Chart	Work process	Performs
	Assess the defect due to potential causes	Controller
	Is possible clearly define the causes of defect according to definition of this defect?	Controller
	Define the causes of defect and implementation prevention measures	Controller, production plant
	Determine possible causes (variant of solutions)	Controller or expert committee
	Evaluation of data from production conditions (parameters input, process and output control) or the results from special analyzes and tests (1st level SQC)	Controller or expert committee
	Is possible clearly define the causes of defect?	Controller
	Define the causes of defect and implementation prevention measures	Controller, production plant
	Analyzed further result - 2nd level SQC	Controller or expert committee
	Is possible clearly define the causes of defect?	Controller or expert committee
	Define the causes of defect and implementation prevention measures	Controller, production plant
	Analyzed further result - 3rd level SQC, or implement special monitoring of serial production of castings	Expert committee
	Make a note about used processes, documentation of results	Authorized technician
	Decision of management about the cause (causes) of the defect, implementation prevention	Controller or expert committee
	Develop a final report	Authorized technician

2.7 Control chart

A control chart as a tool of the Statistical Process Control (SPC) is a graph used to display how a process changes over time. The control chart always has a central line for the average value (CL – Central Line), an upper line for the upper control limit and a lower line for the lower control limit (UCL – Upper Control Line and LCL – Lower Control Line), the so-called action limits, which are determined from historical data or represent an objective target determined by an ordinance. The so-called warning limits can be marked as well, the upper warning limit (UWL – Upper Warning Limit) and the lower warning limit (LWL – Lower Warning Limit). From the diagram course (Fig.2.7), you can draw conclusions about whether the process variation is consistent (under control) or is unpredictable (out of control).

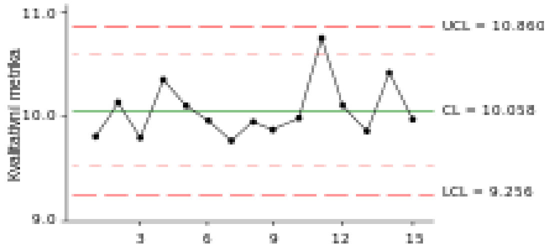


Fig. 2.7. Example of a Control Chart

Control charts can be used e.g. for the process stability control; they can determine whether the process is a stable system with non-routine events in a small range (inherent variability system), designated also as a process in a statistically managed condition, or whether this condition is improved or impaired. Further, control charts can be used for monitoring trends, iterations and cycles of a system behavior, thus determining predictability of the system and to predict whether the system meets determined requirements. They can also be used for identification and possible elimination of adverse influences, for a feedback for the process setting-up and for assessing the measurement system efficiency. The control chart provides users with on-line view to the process behavior and its advantage is simplicity of its construction and ease of its application. The control chart can be also used for controlling ongoing processes and correcting problems „as they occur“.

For control charts further decisive criteria apply to determine the process stability, or more precisely a need to intervene in the process. These are the so-called nonrandom clusters, i.e. special clusters of points. Such a cluster may be:

- One or more points are outside the range of action limits
- A certain number of points in a row are outside the range of warning limits
- A certain number of points in a row are on the same side of the mean value
- A certain number of points in a row are on the same side of the mean value and exhibit more than one exceeding of warning limits
- A certain number of points in a row are continually increasing, or decreasing
- A higher number of points in a row are all within the limits
- A higher number of points in a row alternate in direction, decreasing then increasing
- A certain number of points in a row exceed the range of warning limits
- Implementation of a number of points may vary in different cases The so-called Nelson rules can be an example

2.8 Literature

[1] NENADÁL, J., et al.: Moderní management jakosti (Modern quality management). Management Press, Prague, 2008.

[2] PLURA, J.: Plánování a neustálé zlepšování jakosti (Quality planning and continuous improvement), 1st ed., Computer Press, Prague 2001.

[3] ELBEL, T, HAVLÍČEK, F.: Hospodárné konstruování odlitků – co by měl vědět konstruktér o vzniku odlitku (Cost-saving design of castings). *Slévárenství (Foundry industry journal),* vol. LV, 2007, no. 4, p. 149-155.

[4] ČSN ISO 5807 Zpracování informací (Processing of information). Dokumentační symboly a konvence pro vývojové diagramy toku dat, programu a systému, síťové diagramy a diagramy zdrojů systému

[5] ELBEL, T.: Vady odlitků – Identifikace vad odlitků a příčin jejich vzniku (Casting defects – identification of casting defects and causes of their occurrence). *Slévárenství (Foundry industry journal),* no. 9, 2001, p. 539-543.

[6] TOŠENOVSKÝ, J., NOSKIEVIČOVÁ, D.: Statistické metody zlepšování jakosti (Statistical methods of quality improvement). Montanex publishing, Ostrava, 2000.

[7] HUTYRA,M. et al.: Management jakosti (Quality management), CD ROM, VŠB - Technical University of Ostrava

Σ Summary of terms of this chapter

– Mentioned in the part "Subchapters"

? Questions to the topic

– Questions to this topic correspond to titles of the subchapters in the part "Subchapters"

3 DEFECT TESTING METHODS AND CASTING QUALITY INSPECTION

Subchapters:

- ✓ Visual control (inspection)
- ✓ Measuring, weighing
- ✓ Defectoscopy
- ✓ Chemical analyses
- ✓ Structure analyses
- ✓ Analysis of material properties
- ✓ Literature

Time needed for the study: individual

Objective: After studying this chapter a student will be able to:

- Determine applicability of various inspectional processes for casting defect testing
- Principle and application of ultrasonic defectoscopy
- Principle and application of radiological methods

Lecture

A choice of optimal inspection and testing methods, an analysis and evaluation of test results, to a large extent depends on knowledge and experience and must always be based on an exact formulation of demands for observed data and their range. Various methods are used for casting defects testing, so that deviations in a shape and dimensions, weight, surface quality, discontinuity, homogeneity, structure variance, mechanical and physical properties and chemical composition can be found out [1]. Tab.3.1 shows an overview of methods for testing of casting defects. There are 6 groups shown, which are divided to 21 partial methods for casting defects testing. For each of them, frequency of applications for some of 90 types of defects is shown in the last-but-one column in the table. The total number of 168 possibilities of applications highly exceeds the number of defects, because in some cases of identification of a defect more testing methods can be used, which is even necessary for defects difficult to identify. In the last column an abbreviation of a method is shown (created mostly of the initial characters of a name), which is then used in the following chapters dealing with analyses of individual defects. In the text below, short characteristics of respective methods are described; for more detailed information see the work of Ptáček [2] and a manual [3], these sources have been used by the author when writing this chapter.

3.1 Visual inspection (control)

A visual inspection of a casting (VC) is the simplest defectoscopic inspection and up to 78 % of defects can be found and identified this way. The visual control can be divided according to used tools to:

- Direct control – inspection through a naked eye or using a magnifier (VCM) at a magnification of 3 to 6 times.
- Indirect control using more sophisticated optical and optoelectronic apparatuses and devices. This covers endoscopes, periscopes and TV cameras. These are used above all for observing cavities not available for VC.

A condition for application of VC is good illumination, good eye-sight of the inspecting worker and sometimes also suitable surface finishing.

3.2 Measuring, weighing

Dimension control (DC) belongs among common methods of casting acceptance. Measuring of all dimensions and comparison of the measured results with a drawing is performed. Many foundry shops perform measurements by manual marking-out of castings using slide gauges, micrometers, calibers and check templates. More advanced and complicated instruments based on light or laser optics have found ever increasing application. These coordinate measuring machines, known under the abbreviation CMM, in a combination with digitalization and following processing of measured values and their comparison with 3D pattern (drawing), are able to generate a protocol with found-out deviations.

Surface roughness measurement (SRM**) -** a demand for this inspection is rather rare in foundry shops. Roughness testers are used (workshop types, portable and laboratory types). Roughness testers measure surface roughness on a pre-defined sample length of a surface. A measuring stylus is mechanically drawn across the surface, its transversal movements are recorded. The measurement should get near the standard definition pursuant to an appropriate standard.

Casting weight determination (CWD) is performed by weighing and concerns a defect/nonconformance number 140 “Deviation of weight”. Standard weighing devices are used, which must be calibrated and certified on a regular basis.

Tab. 3.1. Defect testing methods

Group	No.	Name	Frequency	Abbreviation
1. Visual control of a casting	1	Visual inspection of a casting	70	VC
	2	Casting inspection using a magnifier or an industrial endoscope	11	VCM
2. Measuring, weighing	3	Dimension control	4	DC
	4	Casting surface roughness measurement	2	SRM
	5	Weight determination	1	WD
3. Defectoscopy	6	Sonic testing	1	ST
	7	Ultrasonic defectoscopy	7	USD
	8	Radiological testing	10	RTG
	9	Capillary penetration testing	4	CPT
	10	Electromagnetic testing	2	ELT
	11	Permeability testing (pressurizing)	4	PT(P)
4. Chemical analyses	12	Determination of material chemical composition	5	CHEM
	13	Determination of gas content	4	DGC
	14	X-ray spectral microanalysis	8	SEM
	15	Methods for phase composition determination	5	PCD
5. Structure analyses	16	Fractography	6	FRA
	17	Determination of macrostructure	4	DMA
	18	Determination of microstructure through optical microscopy	14	DMI
	19	Electron microscopy	4	EMI
6. Analysis of material properties	20	Determination of mechanical properties	1	DMP
	21	Determination of physical properties	1	DPP

3.3 Defectoscopy

Each defectoscopic method has an exactly determined area of possibilities for indication of a certain type of a defect specified by its physical principle. There is no universal method enabling recognition of all types of defects. Application of particular methods is often limited by a different type of casting material (e.g. ferromagnetic material, paramagnetic material). If supposed defects have to be found out perfectly in the testing procedure, an appropriate suitable method or a combination of 2 or more methods, which complement one another, need to be chosen.

Sonic testing (ST)

This is one of archaic methods for detection of a defect by hearing an audible sound through knocking on a casting. It is based on a difference in acoustic resonance from a homogenous “sound” casting and from a casting with a discontinuity. This is a less reliable to unreliable method for detection of defects of a type of “hot cracks” and “cold cracks”.

Ultrasonic defectoscopy (USD)

There are four basic defectoscopic ultrasonic methods, the first two of them are the most widely used in foundry industry:

- Transmission method
- Pulse reflection method

- Resonance method
- Method enabling imaging of an inner defect

The **transmission** method is based on measurement of a value of ultrasonic energy propagating through a tested object. There are two ultrasonic probes always placed co-axially on the opposite surfaces of the material to be tested; one of them works as a transmitter of the ultrasonic energy and the second one as a receiver. In the case of the presence of a defect or other inhomogeneity in the material, propagating waves act upon the area, a shade emerges behind the defect and a drop in the acoustic pressure appears. The defect is detected by a comparison of values of energy propagating through consistent and defective material. This method is applicable for testing of materials with less thickness. However, its use is limited for testing of objects accessible from the both sides on which probes can be set co-axially.

The **pulse reflection** method is the most widely-spread one. It is based on an impulse operation of an ultrasonic source. Short ultrasonic pulses are transmitted into an inspected casting; the pulses are reflected from the casting surface and inner defects. After the reflection in the material, the ultrasonic waves are returned either to the same or the other probe (one-probe or two-probe operation), which operates as a receiver. The time behavior of the pulse in the material is displayed on a monitor. At the moment of transmitting the ultrasonic pulse, an initial echo appears on the screen. The defect echo is in such a distance from the initial echo, which is displayed on a time base as a time period within which the pulse passed from the surface to the defect and back. The end echo is a record of a pulse reflection from the opposite wall of the tested casting. A distance between the initial and end echo is proportional to the casting wall thickness and a distance between the initial and defect echo is proportional to the depth under the surface in which a defect occurs.

Radiological testing (RTG)

Exposing castings to radiation is an important method of non-destructive testing of materials and castings. X-rays, gamma-rays and neutron rays are the most frequently used types of radiation. X-ray machines, betatrones and radioisotopes are used as radiation sources. Due to its documentary character, the radiological inspection is an evidential test and is conditioned by obtaining a quality image of the tested object for final conclusions in the defect classification. All radiological methods of testing are based on a difference in radiation intensity during its passing through a casting wall with/without a defect. This phenomenon is supported by the attenuation law:

$$I = I_0 \cdot e^{-\mu\rho},$$

where I_0 is intensity of the impacting radiation, I is intensity of the passed-through radiation, μ is a linear attenuation coefficient and ρ is density of the tested material.

Radiological tests have gained considerable significance particularly in foundry industry. Methods using radiation are divided according to a type of the used radiation source and according to a method of the tested product image recording:

- Radiographic methods, involving recording the tested casting image on a photographic film:
  a) X-ray photography
  b) Betatronography
  c) Gammagraphy
  d) Special radiographic methods – radiophotography (photofluorography), x-ray cinematography, stereoradiography, tomography, xeroradiography

- Radioscopic methods – tests displaying the tested material image in a fluorescent image – x-ray radioscopy
- Ionization method – radiation intensity passed through a tested material is registered by a radiation indicator

In the large-lot manufacture of castings with no inner defects allowed, e.g. vehicle chassis components, 100 % inspection by radiological methods must be performed. In this field a significant advance has occurred, where computer technology and robotization have found applications. Programs for assessment of radiological images have been created. Radiological lines operated by robots have been constructed for castings to pass through (e.g. aluminum wheel discs for cars). After subjecting a casting to radiation and assessment of the image, the computer program decides about releasing or rejecting (scrapping) a non-conforming casting. Another innovation is a possibility of spatial imaging if inner defects using computer tomography [4].

Capillary penetration testing (CPT)

Liquid penetrant capillary tests are used to detect discontinuities of material and product surfaces, namely such defects relating directly to the surface and open to the surface, such as surface cracks and pores. A principle of these tests lies in application of a suitable capillary active liquid which can seep into a discontinuity (crack) and after the removal of the excess penetrant from the tested object surface it rises back by effect of capillary forces and makes a surface discontinuity and its shape visible. Liquid penetrant testing depends mainly on a liquid effectively wetting the surface, so advisable detection liquids are only those with a low surface tension (e.g. petroleum or turpentine). There are several modifications of liquid penetrant tests, which are mostly divided according to the chemical activity of the used detection liquid:

- Testing with application of a chemically passive detection liquid, i.e. non-disturbing the tested metal surface:
  a) Visible colour dye testing
  b) Fluorescent dye testing
  c) Other (e.g. oil, petroleum testing)
- Testing with application of a chemically active detection liquid – etching test

A layer of pigment is saturated with a detection liquid, which either makes it coloured (a colour liquid is most frequently red – sudan red) or an indication of a defect in pigment fluoresces and can be seen under ultraviolet radiation. In the case of application of chemically active liquids, a chemical reaction between the liquid and the pigment layer occurs.

Electromagnetic testing (ELT)

Tests based on magnetic and electric induction can be used for detection of surface defects or near-surface defects on semi-products and products. Common testing methods can be divided according to a used basic testing principle:

- Flux leakage methods (for ferromagnetic materials only)
- Eddy current methods

This group of defectoscopic tests has found wide application in a receiving and output control of castings in foundry and engineering plants. Some variations of these tests can be fully automated. The proper application of electromagnetic tests requires knowledge of magnetism and ferromagnetism theories and knowledge of magnetic properties of tested materials.

One of widely used methods for testing of surfaces of various products from magnetic materials is a magnetic powder method, which is based on the flux leakage principle, where the magnetic field rises above the tested object surface in a place of a defect. Due to this phenomenon, the detected defect can be made visible using a proper tool – dry magnetic powder or a solution of magnetic powder suspension in water. This is a magnetic liquid method.

Magnetic particle testing, similarly as the penetrant method, is used to make surface defects visible, moreover, enables to identify near-surface discontinuities not open to the surface. This method imposes similar demands on a surface quality as the penetration method. Testing is carried out for different types of materials – anyway, the materials must be ferromagnetic.

Permeability testing (pressurizing) of castings (PT (P))

This is a testing method to detect and locate leaks and to check whether a casting is pressure-tight and impermeable for a pressure medium (gas or liquid) during its further operation service. If a casting is permeable during the test, this indicates defects (shrinkage porosities, microporosity). This relates mainly to thin-walled castings manufactured form aluminum alloys by casting under pressure. For each type of a tested casting, a fixture to supply the compressed air must be made. The tested piece is immersed into a tank with water or another liquid and a compressed air inlet is opened. The air pressure ranges from 0.1 to 2 MPa according to an agreement with a customer. If a component is permeable, both a pressure decrease occurs and we can locate a defect location according to bubbles in water. Such a casting must be scrapped or, in a case allowed by a client, can be repaired by impregnation.

3.4 Chemical analyses

Determination of material chemical composition (CHEM)

An analysis of chemical composition enables above all:

- To control the melting process run
- To observe the prescribed range of individual elements in accordance with requirements in appropriate material data sheets. Two basic analytical methods are commonly used for chemical composition determination:
  - Classic chemical “wet” analysis
  - Spectral analysis

The classic chemical analysis allows determination of a content of all basic and accompanying elements present in alloys. Analytical values of the analysis can only be considered determining, if a specimen was taken-off and prepared in accordance with standards. Sampling consists of a sample take-off, this is a coarse sample, which is further processed to a fine, analytical specimen.

The main disadvantage of the classic chemical analysis is considerably high work and time consumption. These disadvantages can be eliminated in a spectral analysis using physical methods based on the electrical assessment of an intensity of a selected spectral line of an analyzed element. Used apparatuses are called automatic spectrometers (sometimes quantometers). They can be divided to:

- Optical emission types
- X-ray types

Optical emission spectrometers analyze light spectrum, which is a set of electromagnetic irradiation emmited as vapourized atoms from the given specimen. During the very analysis procedure a discharge is generated between a specimen and a silver or tungsten electrode and a small proportion of the analyzed sample gets evaporated. A part of the evaporated atoms are brought to an excited state and emit light. The light beam passes through a spectrometer (diffraction grating) and is split according to wavelengths. Appropriate spectral lines of each element (according to the intensity and position in the spectrum) are isolated by an outlet aperture. The light beam incidents the photomultiplier, where the light energy changes to the electrical energy for charging a condenser. The condenser voltage level indicates the concentration of the analyzed element.

X-ray spectral analysis uses a fact that x-ray radiation generated by the electron beam excitation has a characteristic wavelength for each element. Its intensity is also proportional to the quantitative composition of the analyzed specimen. From the analyzed specimen the polychromatic radiation is emmited, the intensity of which cannot be measured directly. The individual special lines are separated from the others using adapted single crystals of various substances [5].

Determination of gas content in metal (DGC)

Gases in metals – this means hydrogen, oxygen and nitrogen. Hydrogen determination in metals belongs among relatively complicated methods above all due to strict demands for the sampling procedure and a preparation of samples. Hydrogen is typically analyzed in solid samples of a round cross section with a diameter of 6 to 12 mm. When choosing a sample dimension, you have to keep in mind that a velocity of hydrogen releasing increases along with a temperature increase, with a decrease in a sample diameter and an increase in the hydrogen content.

In operation it is recommended to keep samples in a solid carbon dioxide. Prior to the very analysis, samples need to be ungreased, the surface cleaned to the clean bright metal and quickly heated to room temperature. Handling procedures related to sampling and sample preparation need to be observed, so that adequate accuracy can be ensured. If conditions for sampling and sample preparation are not met, results of the hydrogen content determination may not be accurate and may be lower than real values, because hydrogen atoms have the smallest dimensions and the highest diffusion rate of all elements.

In most apparatuses for determination of the hydrogen content in molten metal, at first the hydrogen extraction from the sample is performed, either in vacuum or in a carrier gas flow, mostly argon. The very analysis is performed additionally.

Oxygen and nitrogen contents in samples are usually determined all at once in apparatuses of a similar principle. Extraction is mostly performed in a carrier gas flow, usually helium. Modern devices also allow analyses of oxide and nitride phases in samples. Demands for sampling and sample preparation are not as strict as for the hydrogen determination. Oxygen can be preferably analyzed from solid samples, nitrogen can be analyzed even from chips.

X-ray spectral microanalysis (SEM)

A principle of the x-ray spectral microanalysis consists in an analysis of the characteristic x-ray radiation, which is excited by an incident of an electron beam on those elements in a sample surface layer the excitation potential of which is lower than the used beam accelerating voltage. The excited x-ray radiation is processed by two methods:

a) Selection according to x-ray radiation wavelengths – the wavelength dispersion analysis
b) Selection according to x-ray quanta energy – the energy dispersion analysis

The devices, electron microanalyzers ("microprobes") using either the first or the second method of x-ray signal processing, differ both in a design and in an analysis methodology. The wavelength dispersion type microanalyzers have x-ray spectrometers of a complicated construction, the measuring procedure is more complicated from the mechanical point of view, measuring is slower, however, results are more accurate and reproducible. In comparison to them, the energy dispersion type microanalyzers are smaller in dimensions, the measuring procedure is fast and automated to a considerable large extent, however, results are not so accurate and reproducible as with the above mentioned type devices. As to basic kinds and possibilities of analyses, both the types of microanalyzers are comparable to one another.

A method of ETG spectral analysis is applied for analyses of dendritic microhomogeneity of alloys, for analyses of inclusions and phases and can be also used for analyses of slags, oxide layers, particles extracted from fracture surfaces etc.

Methods for phase composition determination (PCD)

These experimental methods of x-ray and electron diffraction use the Bragg's law, which describes a reflection of monochromatic radiation from a set of parallel atomic planes. The x-ray diffraction methods also enable to determine quantities related to elastic and plastic deformations of a crystal structure and its disorders. Besides lattice parameters of a measured polycomponent system, these are residual stress values, dislocation density, stacking fault frequency, values of interstitial concentrations in a solid solution of quenched steels (martensite) and other parameters. The method has also found its application in measurements of moulding material phase composition and its changes during casting and cooling of castings.

3.5 Structure analyses

Fractography (FRA)

Fractographic analysis is used for evaluation of morphology of material fracture areas. It is based on a fracture area image. If a low magnification is involved, this is macrofractography, if a high magnification, this is microfractography. Optical or electron microscopy is used for making images. The scanning electron microscopy is perfectly suitable. Fractography enables to detect causes of defects and failure of materials and to evaluate complicated events of diagnostics of defects and faults.

Determination of macrostructure (DMA)

This is one of optical microscopy methods examining material macrostructure at a low magnification or performing a visual inspection of defects on a human eye visibility limit. A macrostructure inspection is performed pursuant to a client's requirements and may involve for example the following standardized procedures:

- Determination of grain size in steels and non-ferrous metals
- Determination of size of austenitic grain on a fracture
- Deep etching testing of steel macrostructure etc.

Macroscopic testing also includes inspection of defects no. 443 and a group no. 610 on a binocular microscope at 10x to 20x magnification.

Determination of microstructure through optical microscopy (DMI)

Methods and technologies of optical microscopy belong to the most frequently used experimental additional methods when looking for defect causes [6]. Metallographic scratch patterns are commonly prepared by wet grinding using special grinding papers and are polished mechanically, electrolytically or chemically. In order to observe microcleanness, i.e. inclusions, micro-shrinkage porosities, micro-shrinkages and others, specimens are polished mechanically using diamond pastes and usually are not etched. To be able to observe a structure, a structure relief needs to be produced using applicable agents. Scratch patterns can be observed in a reflected light, either in a bright field or a dark field. The achievable useful magnification of optical microscopes is about 750x for common objectives. Optical microscopes feature a very low contrast in comparison with electron microscopes. Present-day metallographic microscopes are usually fitted also with equipment for a polarized light, interference and phase contrast and microhardness tester.

The metallographic analysis using light microscopy methods is a base for other special analyses. It is of considerable significance as an additional and inspection method for the manufacture of castings and it is advisable not to disparage its importance. This is a relatively easily available method and if used properly, its price is usually adequate to the obtained results. Except the essential application as a laboratory investigation method, it is also adapted for observing structures just in operating conditions.

Electron microscopy (EMI)

At present, two types of microscopes are used. These are electron microscopes with a solid-state electron bundle (transmission microscopes) and with a scanning electron bundle (scanning microscopes). However, this classification is not quite exact, because modern types of electron microscopes enable to work in both of the ways. A great advantage of electron microscopes is a high contrast and a possibility to have the resolution ability an order-of-magnitude higher, and thus also an effective magnification compared to light microscopes.

The transmission electron microscope operates on the same basic principle of imaging as the light microscope; we can observe either a replica of a scratch pattern surface or a thin metal foil. A specimen can be observed either on a fluorescent screen or on a photographic plate. The intensity of displayed primary electrons decreases with an increasing thickness of a specimen. In electron microscopes with accelerating voltage to about 100 kV, the primary electron bundle has not enough energy to penetrate a thin metal foil and therefore replicas are used. The most frequently used replicating processes are one-stage (commonly carbon) and two-stage (commonly collodion/carbon) methods. The metal foil technology is highly laborious and only sporadically used for analyses of defect causes.

A principle of imaging in a scanning electron microscope differs from the above mentioned. A focused beam of electrons scanning across a specimen surface ejects secondary electrons from the specimen surface layer and their intensity is transferred to a display screen in a form of brightness. Scanning electron microscopes play an important part in verification of casting quality and in determining causes of their defects. A preparation of specimens is simple. For observing in secondary electrons, the specimens must be electrically conductive. Nonconductive surfaces need to be coated by evaporation with a thin metal layer prior to the observing, whereas technically pure copper in a layer of 5 nm thickness is enough. Surfaces which are to be analyzed also for chemical composition are coated by evaporation with carbon in a layer of c.30 nm thickness.

3.6 Analysis of material properties

Determination of mechanical properties (DMP)

Except for exceptions, tests of mechanical properties during the manufacture of castings are an essential part both of the very manufacturing process and of the quality testing of manufactured alloys and castings. Tests of mechanical properties are generally divided according to:

a) State of stress (at uniaxial and multiaxial state of stress)
b) Loading process (tensile tests, compression tests, bending tests, torsion tests, shear tests)
c) Time behavior of the loading force (static and dynamic tests)
d) Effect of loading upon the test specimen (destructive tests where an object is deformed or damaged and non-destructive tests where a non-permissible damage of an object or casting does not occur)

Among the nowadays wide choice of tests of mechanical properties the essential ones can be considered tensile tests, hardness tests, notch toughness tests and fracture toughness tests. For these and others, look for information in a special literature [3,6,7].

Determination of physical properties (DPP)

Testing of castings with specific properties is usually concerned. These include increased corrosion resistance, magnetic properties, stability at elevated temperature, requirements for thermal and electrical conductivity, increased wear resistance etc. Physical properties are tested at a client’s requirement.As a summary, below is a survey table Tab.3.2.of defectoscopic methods and their applicability from Ptáček publications [2,6].

Tab. 3.2. Survey and applicability of defectoscopic methods for testing of defects typically occurring in foundry and metallurgical products [2]

Physical quantity used for testing				Principle	Superficial hot tears	Internal hot tears	Subsurface hot tears	Internal rapture	Chill spots	Cold shut	Blowholes	Pinholes	Shrinkage	Shrinkage porosity	Microshrinkage	Microblowholes	Incorrect welding	Slag inclusions	Drop, sand holes	Nonmetallic inclusions	Cold shots	Metallic inclusions	„V“, „A“ segregate	Segregation	Incorrect physical properties
energy	electrical energy	electro-magnetic waves	X-ray	registering local changes of X-ray intensity	○	○	○	○	○	○	●	●	●	●	◑	◑	●	●	●	●	◑	◑	○	○	○
			gamma rays	registering local changes of intensity gamma rays	○	○	○	○	○	○	●	●	●	◑	◑	◑	●	●	●	●	◑	◑	○	○	○
		Electromagnetic fields	magnetic flux	registration dispersion of flux	●	○	●	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
			magnetic force	change intensity of magnetic field	●	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
			eddy currents	change impedance of coil	●	○	●	○	○	◑	○	○	○	○	○	○	○	○	○	○	○	○	●	◑	◑
		electric current	alternating current (AC)	potential step in material discontinuous	●	◑	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
			direct current (DC)	potential step in material discontinuous	●	◑	●	○	◑	◑	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	mechanical energy	elastic wave	audible sound	change frequency and interference of sound waves	◑	◑	◑	◑	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
			ultrasound	registering of reflected ultrasonic waves and the ultrasonic wave intensity change	○	●	○	●	●	●	●	●	◑	●	●	●	●	●	●	●	○	○	◑	○	◑
matter	liquid	passive	colored liquid	capillary elevation of colored liquid from defects	●	○	●	○	○	◑	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
			fluorescent liquid	capillary elevation of fluorescent liquid from defects	●	○	●	○	○	◑	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
		active	acid	etching the surface and capillary elevation of acid from defects	●	○	●	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

● certain indication ◑ less certain indication and fallible indication, restricted use ○ impossible indication

3.7 Literature

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Summary of terms of this chapter

- Mentioned in the part “Subchapters"

Questions to the topic

- Questions to this topic correspond to titles of the subchapters in the part “Subchapters”

4 DIAGNOSTICS AND CASTING QUALITY CONTROL

Subchapters:

- ✓ Technical diagnostics
- ✓ Diagnostics of casting defects
    - Anamnesis
    - Defect identification
    - Differential diagnostics
    - Determination of causes of a defect formation, proposals of actions to eliminate the defect
    - Preventive actions against a defect formation and their realization
    - Summary
- ✓ Introduction to the characteristics of casting defects
- ✓ Literature

Time needed for the study: individual

Objective: After studying this chapter a student will be able to:

- Characterize basic principles and procedures of casting defects diagnostics
- Apply an anamnesis for identification of casting defects
- Determine a procedure for determining a cause of a defect
- Determine general preventive actions to eliminate casting defects

Lecture

4.1 Technical diagnostics

A term diagnosis was originally taken-over from Greek for medical investigations only and much later it was also used for technical applications. Dia-gnosis in Greek stands for “through knowledge”. As Kreidl and Šmíd [1] state, the technical diagnostics is an independent field dealing with non-demounting and non-destructive methods and tools for determination of a technical condition of an object. In contrast to the medical diagnostics, the technical diagnostics is based on knowledge, which, aside from a heuristic character, has a causal character, and even on mathematical models of diagnosed objects. Fundamental tasks of the diagnostics are as follows:

a) Detection of a defect or failure, i.e. identification of a defect or identification of a complete or partial failure of an object

b) Localization of a defect or failure, i.e. determination of a location of a defect or failure in an object

A diagnosis is an evaluation of a momentary technical condition of an object. From the point of view of terminology of reliability, this is an assessment of operability of an object under defined technical conditions. Reliability, as one of essential features of quality of each technical device, is conditioned by rational monitoring of a technical condition of an object and well-timed detection of physical changes and processes. The definition implies that the technical diagnostics deals with monitoring of various objects (for instance technical devices) during their operation.

According to Popper and Keleman [2], making a diagnosis is a process of determination of a condition of a system on the basis of spontaneous or induced, directly or implicitly observable, phenomena in a context of circumstances of its existence. In a case the condition is not standard, i.e. the system has failed, the diagnostic process usually involves also an explanation of causes of this failure. The very process of making a diagnosis has, independently from a kind of diagnosed systems, common characteristics. Failures or defects and their causes are assessed on a basis of observable features of behavior of a specified system. A character of data, their availability, costs and risks related to their acquisition, may be considerably different in different events.

A diagnostics conception, as defined by the technical diagnostics, can be only partially applied for diagnosing defects of castings. For this event, the medical diagnostics is an advisable model, which is a science on determining diseases (in foundry industry - defects). Determination of a diagnosis consists in specification of a disease of an ill human, figuratively it is also recognition of causes.

4.2 Diagnostics of casting defects

A diagnosis and an analysis of a casting defect is a complex problem. A recognition of a defect is a key to its removal. In this chapter a systematic approach to identification of a defect, determination of causes and recommendation for their elimination and prevention is defined. A procedure for diagnosis and prevention of casting defects can be divided to eight steps:

1. Anamnesis
2. Identification
3. Differential diagnostics
4. Special material analyses (chemical, structural, defectoscopic)
5. Final diagnosis
6. Determination of causes of a defect formation, a proposal of an action to eliminate the defect (“therapy”)
7. Preventive actions against a defect formation and their realization
8. Evaluation

A procedure for determination of a diagnosis of a casting defect is shown in the block diagram in Fig.4.1.

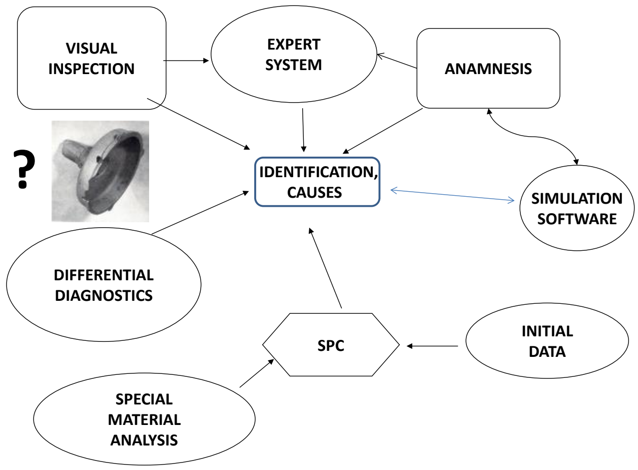

Fig. 4.1 Diagram of the casting defect identification

4.2.1 Anamnesis

An anamnesis = "prior to a disease", a recall, a set of information for an analysis of a situation. For a defective casting, all data on material, a melt, production and material of moulds and cores and the foundry technology (gating system, risers, exhausts) need to be prepared. Records from a longer time are applicable, too (a trend analysis). The information needed for setting an anamnesis have been mentioned by Hasse in his monograph [3]. When defining an anamnesis, we have to find out all circumstances foregoing prior to the casting defect formation and we have to ask the following questions:

- Did manufacturing conditions of the "ill" casting differ from an ordinance? Make a comparison from the long-term point of view.
- Can you remember what changed? Were suppliers of raw materials and additional materials changed?
- Have you ever met such a defect in other castings?
- If this is a repeated manufacture, what has a proportion of non-conforming products (scraps) been now and before?
- When did the defect emerge for the first time?
- Is this a single case or does it occur epidemically in a large scale?
- Can the defect occurrence be assignable to a specified time (a work shift)? Are the non-conforming pieces the first ones or the last ones from the ladle?
- How many pieces from a moulding box, a melt, a mould, a ladle are non-conforming?
- Have manufacturing technological procedures been changed?

4.2.2 Defect identification

At first, here is a story told by T. Bex as an introduction to his work on identification of casting defects [4]. It happened at the time of the cold war in the USA. One reporter got dressed in a uniform of a Red Army officer. He was walking around Washington, went by a passenger train to New York, was hanging around Wall Street and Times Square, spoke English with an exaggerated Russian accent and waited for reactions from people. He asked policemen and passers-by questions and got answers and information how to get to various sensitive localities and freely accessible public buildings. Nobody checked him. The reporter gave up an idea to write an article about how he was caught as a spy and instead he wrote about people who watched but did not see. He came to a conclusion that people usually see what they expect to see or are accustomed to see. At the times of the cold war people did not expect to see an "enemy" officer among them. So they considered him an ally soldier in their minds. Well, what a Russian officer would do in the USA in 1953? Bex further wrote that an approach of technicians to casting defects in a foundry shop was the same as the reporter could see with his fellow citizens. Defects are easily recognizable, when somebody takes the time to recognize their "uniforms", because defects are "disguised" as something what they are not. Defects may look similar, but they are caused by completely different problems. This apparent similarity in a group of defects may lead foundry workers to conformity in opinions, but they may miss a target leading to corrective actions. A wrongly determined defect may result in a wrong "therapy".

Identification of defects is typically linked with determination of causes of their formation and with setting measures for elimination of their occurrence and for prevention. It is based on appearance (morphological) and technological features. Information resulting from collection of data on production conditions is of a decisive significance. Castings, or at least groups of castings, have to be addressed; this means fitted with a numerical or another mark in which e.g. production date, melt number and other facts important for determination of a defect origin are coded. The primary information for identification is an anamnesis. Defects can be detected through six methods.

- Visual inspection of a casting
- Measuring, weighing
- Defectoscopy
- Microscopic analyses
- Chemical analyses
- Analysis of material properties

The most frequently used method is a visual inspection of a casting, then microstructure determination follows and eventually subjecting of castings to radiation is performed. However, methods must often be combined and sometimes several methods one after another must be used for determination of a defect. Casting defects are manifold and considerably variable in their symptoms. The defect identification is a complicated intellectual performance requiring also experience and intuition aside from skill and competence [5]. Faults in the casting defect identification occur by reason of ignorance, wrong judgement and a lack of information. If a defect cannot be determined immediately in the first steps, a phase of differential diagnostics follows in which additional analyses and special methods have to be applied. These are for example defectoscopic tests of castings, the light and electron microscopy, methods of x-ray and electron diffraction, x-ray spectral microanalysis etc. These procedures help to better investigate morphology of a defect, to perform a material-point analysis of the defect etc. A revision of a casting technology is also carried out with the aid of simulation programs and other modern methods are used [6, 7]. The identification procedure has been described by the author of these lecture notes in former works [5,8] and the flow chart of a defect identification procedure and determination of causes of origination has been shown as an example in chapter 3. The experience and opinions of other experts have been used as a base for a summary of the most frequent mistakes made when identifying a casting defect and determining a therapy:

- Non-systematic approach - hit or miss
- Instead of solving a problem, a "culprit" of a disease is searched for
- Jumping into (misleading) conclusions
- In an effort for a solution as fast as possible, a casting technology is changed

- After determination of a cause, several corrective actions are implemented at once
- After having "cured the disease”, the problem is forgotten, not documented and there is no time to evaluate the situation and take a lesson for the future No preventive actions adopted

These are usually offences against ISO 9000 quality management standards – if implemented and certified in the foundry plant.

4.2.3 Differential diagnostics

At the conclusion of the identification, the final diagnosis is determined – a defect. If not sure, a preliminary working diagnosis of the most probable defects is performed. All defects that could correspond to features and appearance of the defect are then designated as differential diagnoses. If the working diagnosis is not still sure, further analyses are carried out. We can perform special analyses: chemical and metallographic analyses of the defect place, x-ray microanalysis etc. Having a simulation program for virtual casting available, we can perform modeling of several variants. We can also perform controlled experiments in castings “in vivo”, i.e. intentional changes of manufacturing conditions and monitoring of their effect. A decision about the final diagnosis is a key aspect of the casting defect identification. Tools enhancing effectiveness of accepted decisions include computer information systems, in particular systems for decision support DSS = Decision Support Systems. DSS involve above all interactive computer information systems compiling useful information based on entry data, personal knowledge, documents, simulations. They solve problems and suggest decisions. They cover e.g. knowledge-based expert systems. An example is ESVOD (Knowledge-based expert system of casting defects) [9], created not long ago in the Department of Metallurgy and Foundry of the Faculty of Metallurgy and Materials Engineering at the VŠB - Technical University Ostrava. 13th chapter of these lecture notes deals with expert systems.

4.2.4 Determination of causes of a defect formation, proposals of actions to eliminate the defect

Let us have a lesson from Jan Amos Komenský: “Let us see everything separately: Imperfections and diseases first, then causes, and medication in the end.”

An analysis of causes and origin of defects and looking for means for their elimination and prevention demands the deepest knowledge of principles of foundry processes, technology and equipment taking part in the manufacture of castings. Casting defects result from several causes and their co-acting.

Many causes have their origin in a casting design, both in improperly chosen shape and material. When assessing technological characteristics of a design, good cooperation of foundry technicians with designers is needed. Other causes for occurrence of a scrap lie in metallurgy. Preparation of material is a responsibility of a metallurgist and a furnace operator. This does not mean only to adhere to the prescribed chemical composition, but all principles of the melt control, molten metal treatment and observance of the specified temperatures have to be maintained. A majority of scraps is often caused by an improperly designed casting manufacturing procedure. This covers a proper choice of allowances, bevels, risers, gating system and also moulding materials, cooling of a casting etc. The manufacture of good pattern equipment and tools is a part of well-functioning technical preparation of production, too. The most frequent cause of the casting defect origination is usually non-observance of a technological discipline in all stages of production: in the preparation of moulding materials and in a melting shop, core-making shop, moulding shop, dressing shop, storage room and dispatch of castings.

A procedure for determination of causes of a defect formation results from data on the manufacturing process and on the manufacturing conditions of individual castings. Traceability of production should be ensured especially in the batch manufacture. To designate castings with numerical codes is usually not a problem in the single part production. The procedure is further based on a presupposition that a foundry plant performs various measurements and registers and files the results. So we know chemical composition of particular melts of metal, parameters of sand mixtures, temperature of a mould and metal and other properties. To define defect causes, a cause and effect diagram is used and all possible causes of a defect are identified. We can use teamwork through the "brainstorming" method, the Ishikawa diagram etc. [10].

If we are not able to determine defect causes from the basic statistical characteristic, then we can use varied statistical methods according to a different degree of implementation of the statistical control of a process SQC (Statistical Quality Control [11]). On the first SQC level, normality and stability of the process for the particular observed parameters is monitored. These are results from evaluation of control charts, evaluation of arithmetic diameters etc. The second SQC level uses a trend analysis of processing of data on the manufacturing process on several sequential days, weeks and months and these trends are compared to the defect occurrence. The third, analytical, SQC level uses an analysis of a statistical significance of a difference between various sets, e.g. defective and good castings, to determine a defect cause. This level is not a miraculous mean, but it is often a final possibility to determine a defect cause. However, experience and intuition of a technician performing the evaluation applies here as well. Quality management tools are also described in chapter 3.

4.2.5 Preventive actions against a defect formation and their realization

The following step is implementation of an action to eliminate a defect cause – a cure (therapy). After the corrective action implementation, an inspection of its effectivity is performed. The assessment consists in a comparison of the results achieved before and after the implementation of the action. A permanent elimination of causes follows. If the rightness of determination of the cause and selection of the therapy were confirmed, the rightness of the diagnosis is confirmed, too. In this stage, all technological and inspection documentation needs to be amended and training of employees needs to be performed. Preventive actions are accepted individually for each defect. However, there are general preventive measures:

- Implementation of the quality management, so that casting defects cannot occur
- Application of international quality standards
- Training of employees
- Application of advanced technological processes (filtration of metal, equipment for feeding a casting)
- Optimization of a casting technology using simulation programs
- Ladle treatment of metal – prevention of metal reoxidation, gas content reduction
- Stability in the use (purchase) of raw materials and other materials

Results should be documented. This phase is often neglected and a report on a solving process evidenced with the actual data, photographs and analyses is not elaborated. Neither the results, nor the procedure leading to elimination of the problem, are documented. By this a possibility for a fast solution of similar situations and quality crises in the future is lost.

4.2.6. Summary

Only through proper diagnostics of defects we can find causes of non-conformances, to begin a therapy, to adopt preventive measures for elimination of their origination. A foundry plant has to implement such a quality management system, so that, with the help of preventive measures, casting defects cannot occur and need not to be removed ("cured"). So far, we do not know how to make industrial castings without defects and non-conforming products – scraps. However, each rejected casting is a source of knowledge and should be subjected to a systematic analysis. Results should be registered and evaluated statistically according to quality tools well-known today. If a foundry plant has a Quality Management System implemented and well-kept in accordance with international standards of quality management, it can avoid quality crises and "ill castings" and in a case the system fails, we can suppose that the plant will cope with the arisen problems more quickly. Examples of intelligent procedures for management of foundry processes have emerged recently [12].

4.3 Introduction to the characteristics of casting defects

In the next chapter casting defects are described in accordance with particular classes. In each class, characteristics of particular groups and types of defects are explained according to their numerical markings. For each defect a defect scheme is shown.

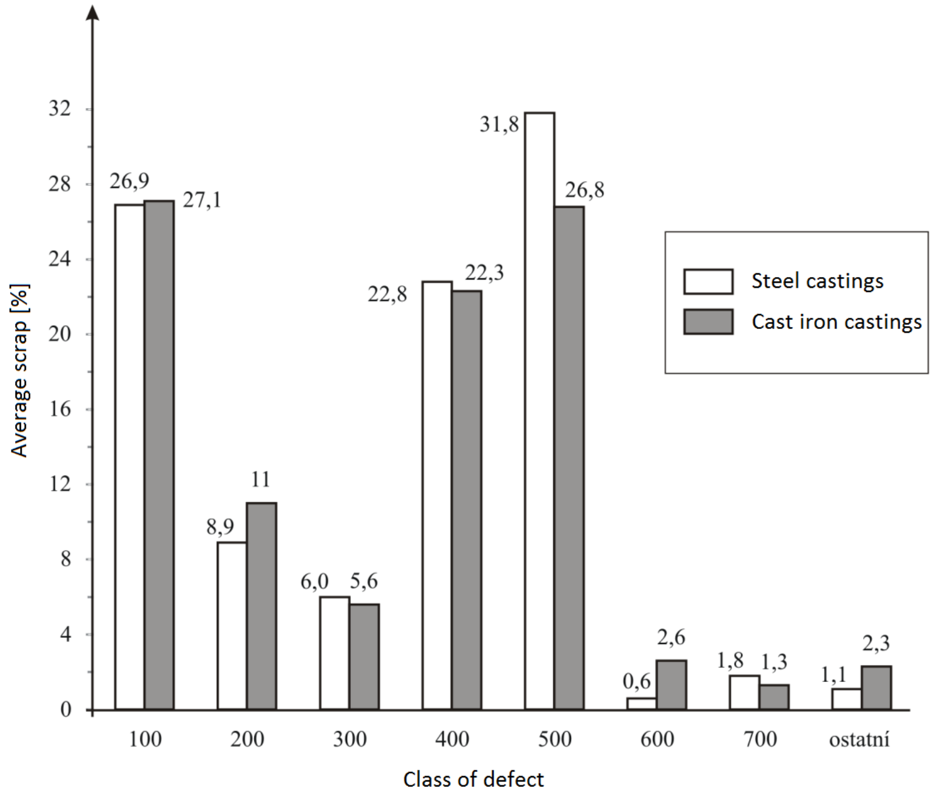

Fig. 4.2. Frequency of occurrence of unrepairable casting defects (wastage in %) in seven classes of casting defects in foundry plants of ferrous alloys

Fig. 4.2 shows a diagram of a frequency of occurrence of unrepairable defects (scraps) elaborated on the basis of a statistical evaluation in foundry plants in the former Czechoslovakia [13], when whole-national overviews compiled by technical boards in foundry plants existed. These are analyses more than 25 years old, nevertheless, I think that average values do not differ from the nowadays state too much. The particular columns in the diagram represent a number of scraps in individual classes of defects; the left-side column stands for steel castings, the right-side column stands for graphitic cast irons. Regardless of the cast material, we can see in the survey that 80 % of scraps belong to 3 classes of defects: 100, 400 and 500. Statistics from aluminum casting foundries show that non-conforming products concentrate to these 3 classes of defects as well. There are several dominating defects in each class, which are described in more details in these lecture notes.

Within a characteristic of each defect a description of the defect is given and main causes of its origination are analyzed. For a course on casting defects [14], the author of these lecture notes has elaborated a table with a description of possible causes of origination for every defect type and also for each of 7 classes. A number of causes ranged from one to ten at minimum. This was a maximum for Sand inclusions - drops (521) and Wrong homogeneity of a casting (740); 9 causes were for Secondary slag inclusions (512) and Shrinkages (440). The selection of causes and their assignation was a subjective opinion of the author. Maybe the causes (influences) could be further divided, nevertheless, as Tab. 4.1 shows, there were 17 causes. 10 from them were influences given by a technological manufacturing procedure set by a technologist. Technological influences might seem to be overvalued. Almost a half of defects are affected by the moulding material, a related influence of the manufacture of a mould is just behind that. In casting conditions, on the third place especially the metal temperature during casting is meant. As to a technological procedure, a selection of a gating system is only on the 5th place. Further influences of a technological procedure are from the 9th to 17th place. A technological manufacturing procedure is evidenced 100times in total, which is 31.5 % of 317 cases. The graphical depiction of these facts can be seen in Fig. 4.3. This Pareto analysis shows that the first 8 influences affect the casting defects most significantly.

Tab.4.1. Numbers of casting defects from various causes

	Causes	Number of defects
1	Moulding material	44
2	Mould-making/core-making	37
3	Casting conditions	35
4	Casting material	34
5	Gating system	30
6	Melting, molten metal treatment	27
7	Casting design	22
8	Finishing operations, HT	18
9	Ventilation of a mould, vents	12
10	Pattern equipment	12
11	Position of a casting in a mould	11
12	Chills	11
13	Risers	8
14	Allowances	6
15	Cast-in objects	5
16	Moulding boxes	3
17	Shrinkage	2
Total		317

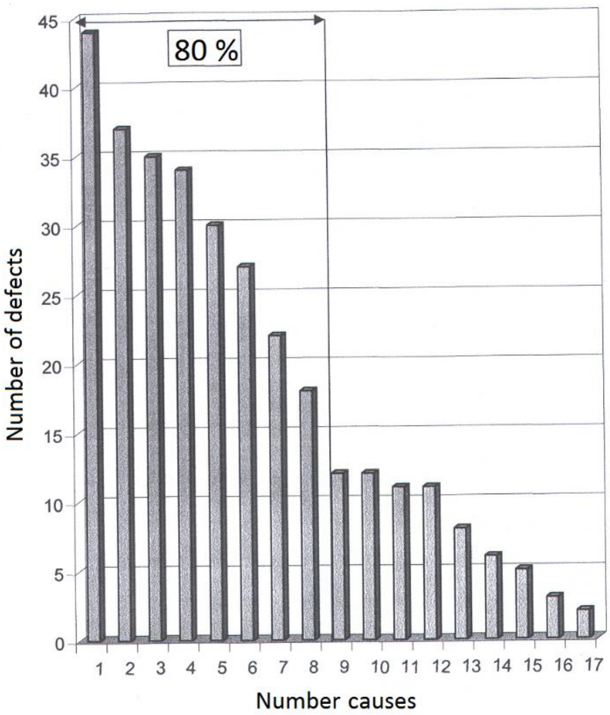

Fig.4.3. Graphic depiction of various causes (acting influences from Tab.4.1) affecting the number of casting defects

This analysis can be further developed. We can set-up an overview of factors affecting casting defects in accordance with groups of defects and classes of defects. Tab.4.1. shows an overview of a frequency of defects in groups arranged in a descending order from groups with the highest number of causes down to the lowest. A majority of causes (influences on defects) are in groups 440 and 520. These are groups with defects with as high as 10 factors affecting a casting quality (Sand inclusions - drops, Inner shrinkages).

Tab. 4.2. Frequency of possible defect causes in groups according to the classification [13]

Group of defects	Name	Number of defects V	Frequency of causes P	Ratio P/V
440	Shrinkages	6	43	7.2
520	Non-metal inclusions	6	28	4.7
610	Micro-cavities	3	22	7.3
410	Gas holes	5	21	4.2
110	Missing part of the casting, no fracture	7	16	2.3
310	Hot cracks	3	15	5
510	Slag inclusions	2	13	6.5
130	Variance in dimensions, incorrect shape	4	12	3
210	Burning-on	3	12	4
270	Irregularities of a casting surface	7	12	1.7
230	Erosion scabs	4	11	2.8
430	Blowholes	3	11	3.7
530	Macro-segregations and segregations	4	11	2.8
740	Wrong homogeneity	1	10	10
220	Expansion scabs	3	9	3

260	Flash	3	8	2.7
340	Discontinuities	2	8	4
650	Hard spots	1	7	7
120	Missing part of the casting, with fracture	3	5	1.7
320	Cold cracks	1	4	4
620	Inclusions	3	4	1.3
680	Other defects of microstructure	1	4	4
140	Deviation of weight	1	3	3
420	Pinholes	1	3	3
560	Defective fracture	1	3	3
630	Incorrect grain size	1	3	3
240	Veining	1	2	2
330	Discontinuities	2	2	1
540	Cold shots	1	2	2
550	Metallic inclusions	1	2	2
640	Defects of structure components	1	2	2
660	Inverse chill	1	2	2
670	Surface decarburization	1	2	2
250	Eutectic sweat	1	1	1
280	Painting defects	1	1	1
710	Incorrect chemical composition	1	1	1
720	Deviations from mechanical properties	1	1	1
730	Deviations from physical properties	1	1	1
TOTAL		90	317	

Other groups of defects are also on the forefront because they include defects with a high number of factors. Such defects are difficult to identify and it is demanding to reveal a cause of their unsatisfactory quality. Factors that may cause a defect, being in such a high number, may sometimes be combined. A ratio of a number of defect causes per one defect is an interesting indicator, too. From this point of view, the highest ratio (10) has a group 740 Wrong homogeneity of a casting, where the same factors as for group 440 apply.

In the end, we can analyze results in the classification in accordance with classes of defects. A summary is shown in Tab. 4.3. and a doughnut chart in Fig. 4.3. Classes 400 and 500 are dominating, where there are groups of defects with high numbers of factors influencing origination of defects in a particular group. The comparison with Fig. 4.2 is also interesting. Classes 400 and 500 belong to those with the highest wastage of castings. Class 200 “Surface defects” also includes a high number of causes but, on the contrary, this class belongs to classes with lower wastage. Surface defects are difficult to solve, however, they can often be repaired and a casting does not need to be scrapped. You have certainly noticed that defects in class 100 are on the second place in a wastage summary, but numbers of causes of defects in this class are only on the 5th place. This can be explained by a fact that there are lots of defects with only one or two causes, e.g. a wrong pattern and a mechanical damage of a casting.

Tab.4. 3. Frequency of possible causes of casting defects in classes 100 to 700

Class of defects	Name	Number of		Ratio P/V
		defects (V)	causes (P)	
100	Defects of shape, dimensions and weight	15	36	2/4
200	Surface defects	23	56	2/4
300	Discontinuities	8	29	3/6
400	Cavities	15	78	5/2
500	Macroscopic inclusions	15	59	4/6
600	Microstructural defects	10	46	4/6
700	Defects of chemical composition and properties of castings	4	13	3/3
Total		90	317	3/5

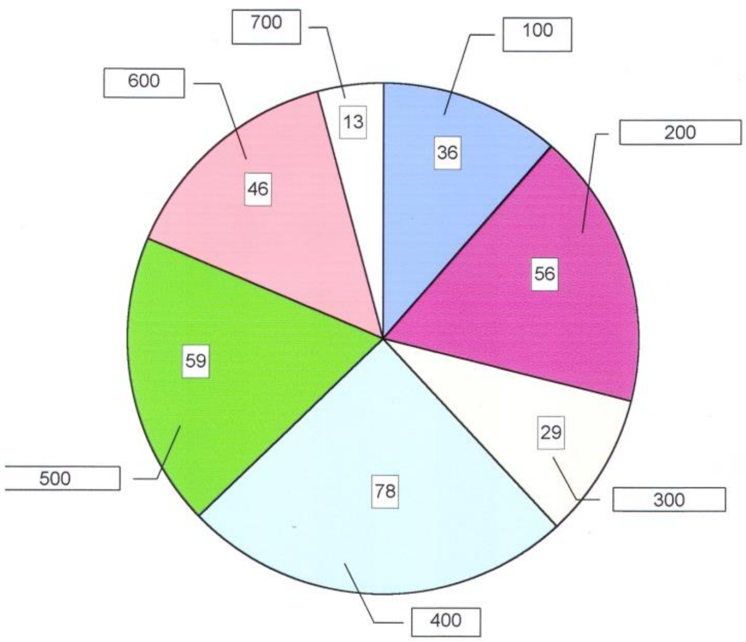

Fig. 4.4. Chart of a number of possible causes of defects in classes 100 to 700

4.4 Literature

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Σ Summary of terms of this chapter

- Mentioned in the part "Subchapters"

? Questions to the topic

- Questions to this topic correspond to titles of the subchapters in the part "Subchapters"

5. DEFECT CATEGORIES AND CLASSIFICATION

Defect descriptions and sketches

In this chapter casting defects are described in accordance with particular classes. In each class, characteristics of particular groups and types of defects are explained according to their numerical markings. For each defect a defect scheme (sketch) is done. t the end of each chapter,

There are below mentioned references for literature used for defect characteristics and recommended sources for the detailed study of casting defects.

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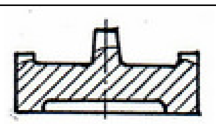
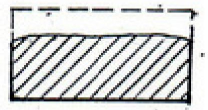
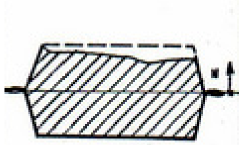
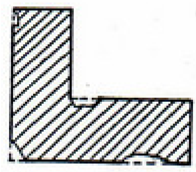
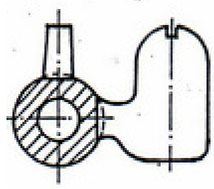
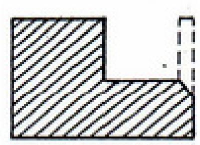
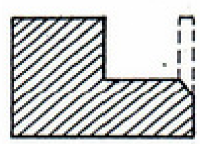
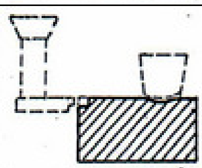
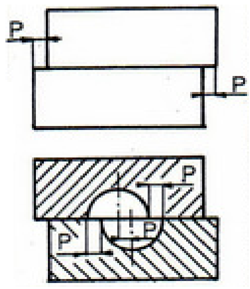
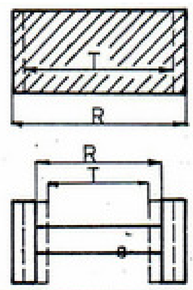
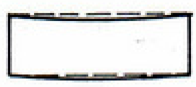
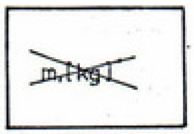
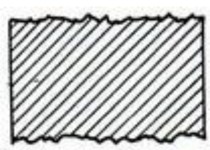
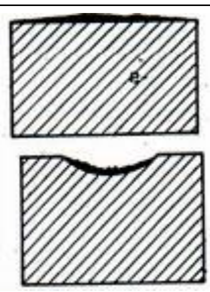
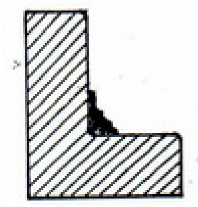
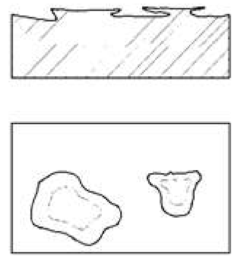
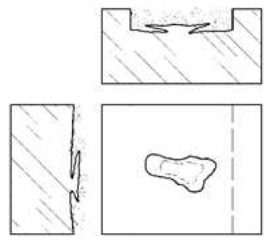
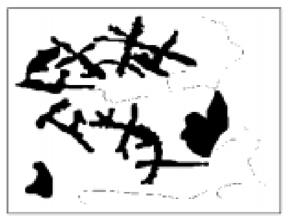
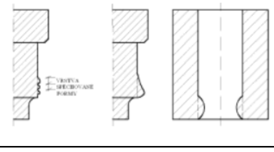
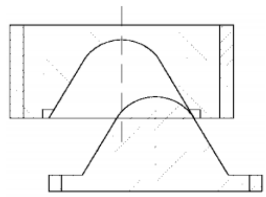
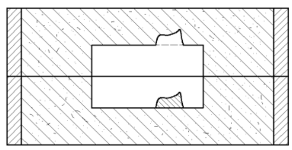
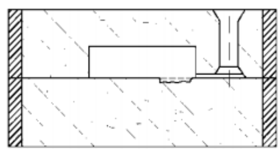
Class of Defects 100: Incomplete casting and incorrect dimensions, shape and weight

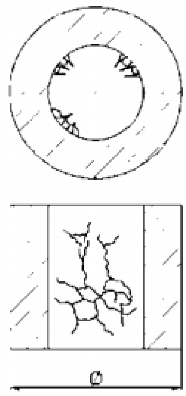
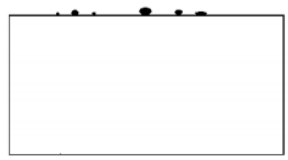
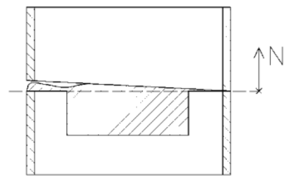
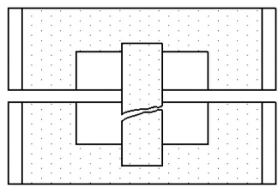
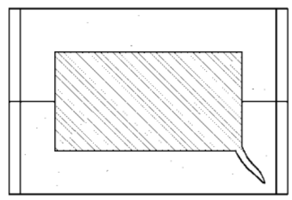
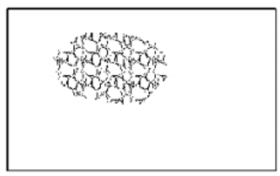
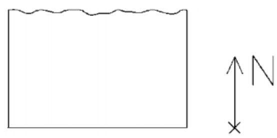
Group of Defects		Defect type		Description	Sketch
No.	Common Name	No.	Common Name		
110	Missing part of casting without a fracture	111	Misrun	Casting incomplete due to premature solidification.	
		112	Incomplete pouring, Shortrun	Casting incomplete due to insufficient metal poured.	
		113	Runout, bleeding	Casting incomplete due to loss of metal from mold after pouring.	
		114	Mould repair error	Deformed edges or contours due to poor mould repair or careless application of wash coatings.	
		115	Excessive cleaning	Significant lack of material due to excessive shot-blasting.	
		116	Mechanical damage	Significant lack of material due to bruise, crushing or cutting.	
		117	Improper handling in cleaning shop	Significant lack of material due to incorrect riser / gates removal or grinding ion cleaning shop.	
120	Missing part of casting with a fracture	121	Breaking part of hot casting	Fracture appearance indicates exposure to oxidation while hot.	
		122	Breaking part of cold casting	Casting broken, large piece missing; fracture surface not oxidized	
		123	Broken-in runners, risers	Fracture dimensions correspond to those of gates, vents, runners etc.	

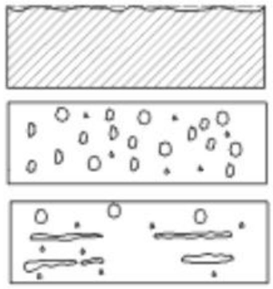
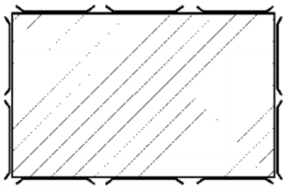
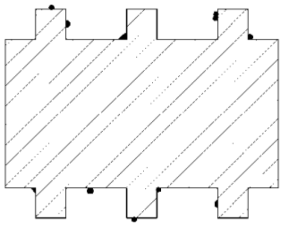
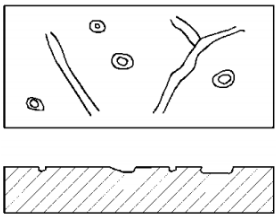
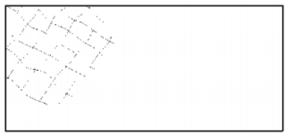
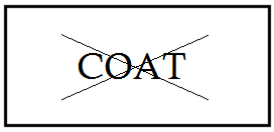
130	Dimensions default, incorrect shape	131	Incorrect pattern	Casting does not conform to the drawing shape in some or many respects; same is true of pattern	
		132	Shift, cross joint	Casting appears to have been subjected to a shearling action in the plane of the parting line.	
		133	Incorrect dimensions	Distance too great between extended projections. Dimensions too great in the direction of rapping of pattern.	
		134	Warpage, deformation	Casting deformed with respect to drawing after storage, annealing, machining. Thin casting walls over general area, especially on horizontal surfaces	
140	Incorrect weight			Nonconformity of Weight	

Class of Defects 200: Defective surface and metallic projections

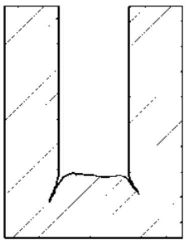
Defect group		Defect type		Description	Sketch
No.	Name	No.	Name		
210	Burn – adherence of sand	211	Rough surface	Depth of surface roughness is approximately that of the dimensions of the sand grains.	
		212	Burn on	Sand layer strongly adhering to the casting surface.	

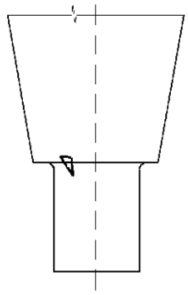
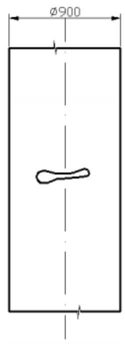
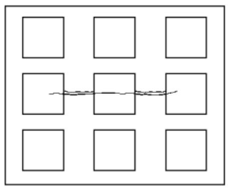
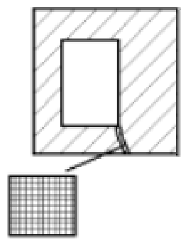
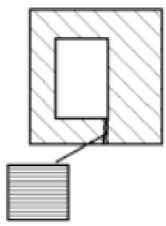
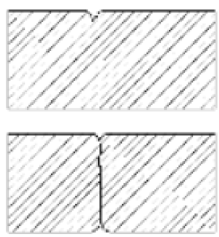
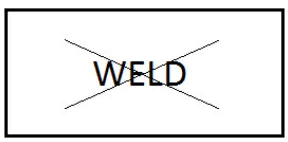
		213	Burn in, penetration	Very adherent layer of partially fused sand. Conglomeration of strongly adhering sand and metal at the hottest points of the casting (reentrant angles and cores).	
220	Scabs	221	Scab on cope surface	Plate-like metallic projections with rough surfaces parallel to casting surface; removable by burr or chisel.	
		222	Bottom (Expansion) Scabs	As above, but impossible to eliminate except by machining or grinding.	
		223	Rat - tails	Network of fine metallic projections on the casting due to the sand expansion.	
230	Swells	231	External or internal swell	Excess metal on the external or internal surfaces of the casting	
		232	Crush, friction	Metal projections in the form of elongated areas in the direction of mold assembly.	
		233	Molud drop	Metal projections on the cope surface of the casting due to mould damage.	
		234	Erosion or wash	Excess metal in the vicinity of the gate or beneath the sprue.	

240	Veining or fining			Projections in the form of veins on the casting surface.	
250	Sweating, eutectic sweat			Projections of more or less spherical form on the surfaces, corners or re-entrant angles (phosphide or lead sweats).	
260	Metallic projections in the form or fins	261	Joint flash or fins (Raised mould)	Thin fins (or flash) at the parting line or at core prints.	
		262	Cracked core	Projections in an area formed by a core.	
		263	Cracked mould	Formation of fins in planes related to direction of mold assembly (precision casting with waste pattern).	
270	Irregularity of casting surface	271	Orange peel	Casting surface entirely pitted or pock-marked. Typical defect for Shell Moulding Technology.	
		272	Elephant´s peel	Surface shows a network of jagged folds or wrinkles (ductile iron).	

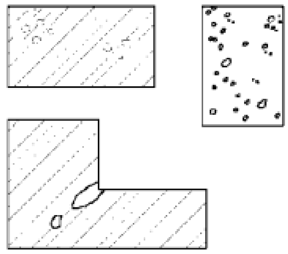
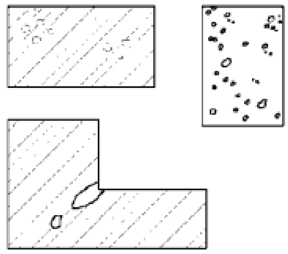
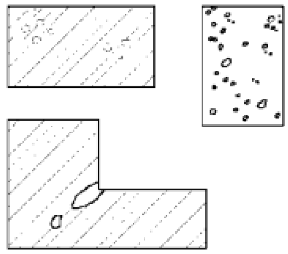
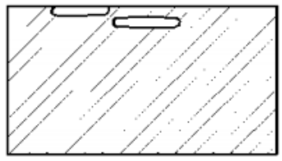
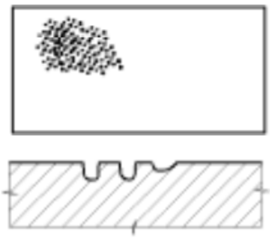
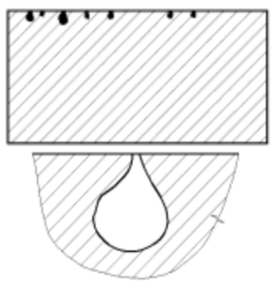
		273	Small pox , local or bar	Irregularly distributed depressions of various dimensions extending over the casting surface, usually along the path of meal flow (cast steel).	
		274	Scaled casting. Scale	Scaling after malleablizing or annealing.	
		275	Fine drops	Conglomeration of strongly adhering fine metallic balls, isolated or grouped on casting surface. The defect is typical for investment casting technology.	
		276	Channel or pitting corrosion	Surface erosion with small rounded cavities or meandering channels of various depth. The defect is typical for investment casting technology.	
		277	Chemical corrosion	Small rounded cavities due to chemical corrosion during chemical cleaning of a casting.	
280	Defects of painting protection of casting			Nonconformities of painting protection of casting	

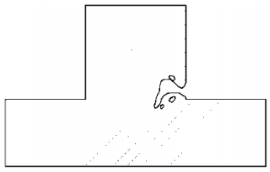
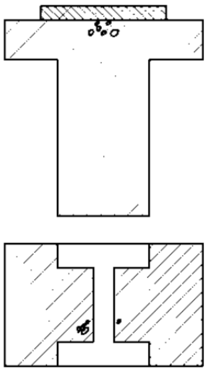
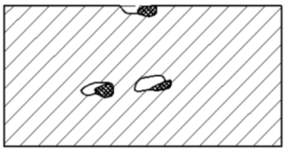
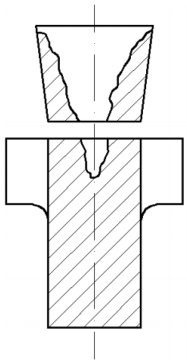
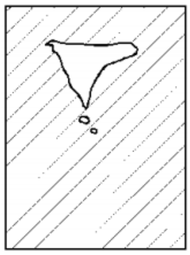
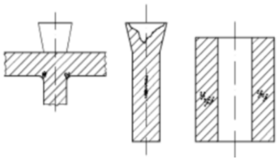
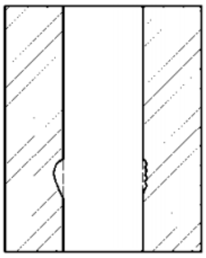
Class of Defects:300 Discontinuities

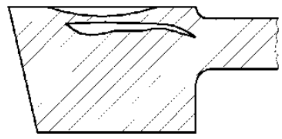
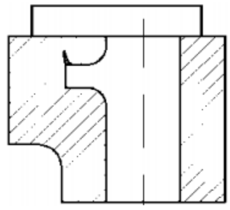
Defect group		Defect type		Description	Sketch
No.	Name	No.	Name		
310	Hot tears	311	Superficial hot tears	Irregularly shaped discontinuities in areas susceptible to tension. Surface oxidized. Intergranular fracture showing dendritic pattern. Winding (zigzag) aspect.	

		312	Subsurface hot tears	Irregularly shaped discontinuities in subsurface areas susceptible to tension. Surface oxidized. Intergranular fracture showing dendritic pattern.	
		313	Internal hot tears	Irregularly shaped discontinuities in internal areas susceptible to tension. Surface oxidized. Intergranular fracture showing dendritic pattern.	
320	Cold cracks			Discontinuities with squared edges in areas susceptible to tensile stresses during cooling. Surface not oxidized. Straight transgranular fracture.	
330	Discontinuities due to mechanical damage	331	Hot rupture	Fracture surface oxidized completely around edges.	
		332	Cold rupture	Normal fracture appearance, sometimes with adjacent indentation marks.	
340	Discontinuities caused by lack of fusion	341	Cold shut	Complete or partial separation of casting wall, often in a vertical plane. Lack of complete fusion in the last portion of the casting to fill.	
		342	Incorrect welding	Local discontinuities (tears, bubbles) after correction welding of casting.	

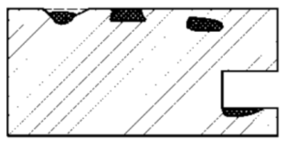
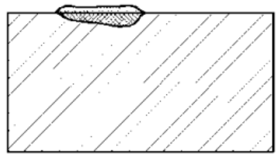
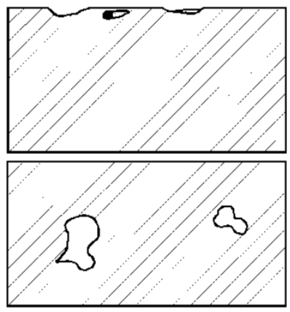
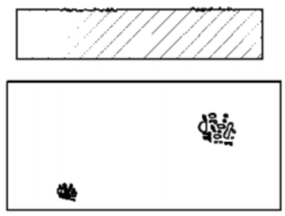
Class of Defects: 400 Cavities

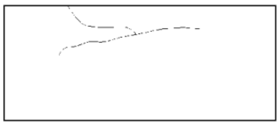
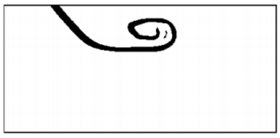
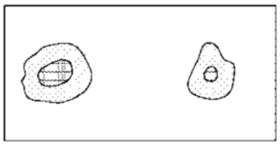
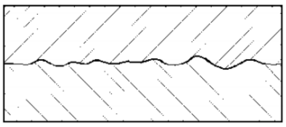
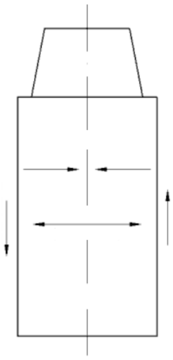
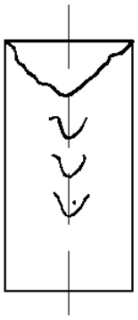
Defect group		Defect type		Description	Sketch
No.	Name	No.	Name		
410	Blowholes, Gas porosity	411	Blowholes caused by oxygen	Rounded cavities, usually smooth-walled, of varied size, isolated or grouped irregularly in all areas of the casting, distributed by oxygen.	
		412	Blowholes caused by hydrogen	Rounded cavities, usually smooth-walled, of varied size, isolated or grouped irregularly in all areas of the casting, distributed by hydrogen.	
		413	Blowholes caused by nitrogen	Rounded cavities, usually smooth-walled, of varied size, isolated or grouped irregularly in all areas of the casting, distributed by nitrogen.	
		414	Entrapped gas	Cavities of various sizes, isolated or grouped, usually at or near the surface, with shiny walls.	
		415	Superficial netting of blowholes	Network of small gas cavities on the surface of casting.	
420	Pinholes			Fine porosity (cavities) at the casting surface, appearing over more or less extended areas.	

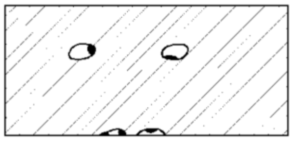
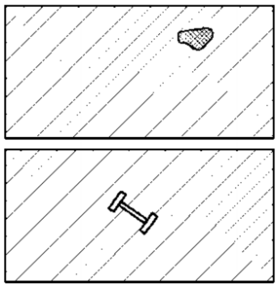
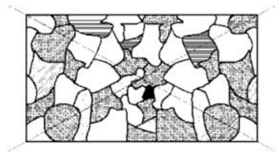
430	Boiling, blowholes	431	Blowholes (boiling) from mould, core gases	Cavities, in re-entrant angles of the casting, often extending deeply within.	
		432	Blowholes (boiling) from chills and metallic inserts	As above, but limited to the vicinity of metallic pieces placed in the mold (chills, in-serts, chaplets, etc.)	
		433	Blowholes (boiling) from inclusions	Rounded cavities, smooth-walled, of varied size, accompanied by slag or inclusions. Boiling.	
440	Shrinkage	441	Open shrinkage cavity	Funnel-shaped cavity. Wall usually covered with dendrites.	
		442	Internal shrinkage cavity	Irregular-shaped cavity. Face often dendritic.	
		443	Shrinkage porosity	Dispersed, spongy dendritic shrinkage within walls of casting.	
		444	Shrinkage cavities from core or corners	Sharp-edged cavity in fillets of thick casting or at gate location. Cavity extending from a core.	

		445	Shrink mark, sink	Casting surface depressions in the vicinity of hot spot.	
		446	Shrinkage blowhole	Shrinkage cavity combine with gas evolution from mould corner or core.	

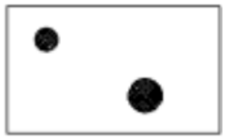
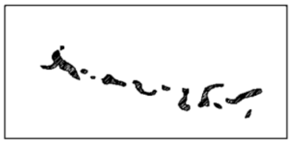
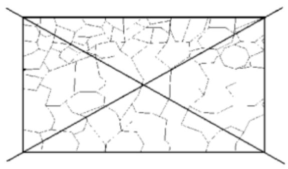
Class of Defects: 500 Macroinclusions or structural anomalies

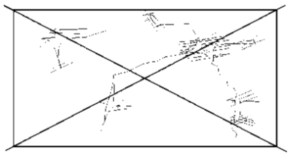
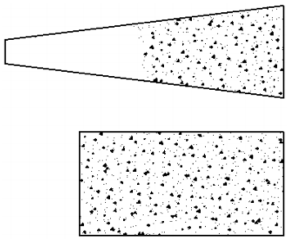
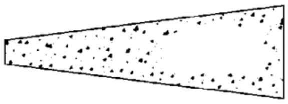
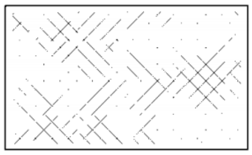
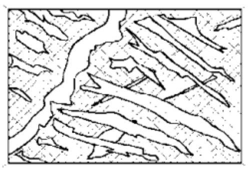
Defect group		Defect type		Description	Sketch
No.	Name	No.	Name		
510	Slag inclusions	511	Slag exogenous	Non-metallic inclusions whose appearance or analysis shows they arise from melting slag products of metal treatment or fluxes.	
		512	Secondary slag, dross	Non-metallic inclusions formed secondary during casting, generally impregnated with gas and accompanied by blowhole).	
520	Nonmetallic inclusion	521	Drop, sand holes	Holes formed from fractured mould or core sand lumps.	
		522	Sand inclusions	Sand inclusions, generally very close to the surface of the casting.	
		523	Blacking holes “scab”	Metallic projections or inclusions on the casting where mould or core washes or dressings are used.	

		524	Oxide inclusions	Inclusions in the form of oxide skins (films), most often causing a localized seam.	
		525	Graphite or lustrous Carbon inclusions	Folded films of graphitic luster in the wall of the casting.	
		526	Black stains (Primary graphite)	Clearly defined, irregular black spots on the fractured surface of ductile cast iron.	
530	Macro segregation	531	Gravity segregation	Irregularities in chemical composition in various parts of casting due to difference in densities of alloying elements. Denser constituents tend to sink toward the bottom, while lighter ones float toward the top.	
		532	Physical segregation	Irregularities in chemical composition of casting produce impurities in the enriched mother- liquor which move to central line zone (normal segregation) or near the surface (inverse segregation).	
		533	„A“ segregate	Typical macrosegregation in steel ingots and large castings. “A” segregate is formed in columnar zone. It is caused by impurities in the enriched mother-liquor infilling spaces from gas holes. Channel segregates.	
		534	„V“ segregate	Typical macrosegregation in steel ingots and large castings. The center “V” segregate is caused by impurities in the enriched mother-liquor. In horizontal zones being distorted into the characteristic “V” form infilling spaces from tears and shrinkages.	

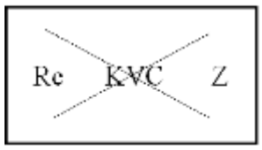
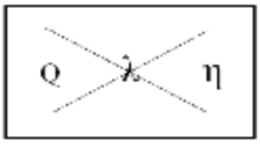
540	Cold shots	Inclusions of the same chemical composition as the base metal; generally spherical and often coated with oxide.	
550	Metallic inclusions	Inclusions whose appearance, chemical analysis or structural examination shows to be caused by an element foreign to the alloy.	
560	Defective texture of fracture	Inconvenient texture on casting fracture.	

Class of Defects: 600 Incorrect microstructure

Defect group		Defect type		Description	Sketch
No.	Name	No.	Name		
610	Micro-cavities	611	Microshrinkage (Shrinkage porosity)	Dispersed, spongy dendritic shrinkage within walls of casting, scarcely perceptible to the naked eye.	
		612	Microblowholes (Gas porosity)	Rounded, smooth walls gas cavities within walls of casting, scarcely perceptible to the naked eye.	
		612	Microtears/cracs	Irregularly shaped discontinuities within walls of casting caused by internal stresses during cooling of casting.	
620	Micro inclusions			Metallic and non-metallic microinclusions; oxides and reaction products.	
630	Incorrect grain size			Grain size nonconformity from a standard or agreed conditions.	

640	Incorrect microstructure components	Microstructure nonconformity from a standard or agreed conditions	
650	Chill spots. Hard edges	Structure partially or totally white, particularly in thin walls, projecting corners and edges, showing gradual transition to a normal structure.	
660	Inverse chill	White zones clearly outlined in the last sections of the casting to solidify. Structure at surface is gray.	
670	Surface decarburization		
680	Other microstructure defects	Other microstructure nonconformity from a standard or agreed conditions.	

Class of Defects: 700 Incorrect chemical composition or properties of casting

Defect group		Defect type		Description	Sketch
No.	Name	No.	Name		
710	Incorrect chemical composition			Nonconformity in chemical composition from a standard or agreed conditions.	
720	Nonconformity value of mechanical properties			Nonconformity in mechanical properties from a standard or agreed conditions.	
730	Nonconformity value of physical properties			Nonconformity of physical properties from a standard or agreed conditions.	
740	Inconvenient casting homogeneity			Nonconformity of casting homogeneity from a standard or agreed conditions.