LVQ-WP-group

members of the LVQ-WP group:

- LVQ-WP Werkstoffprüfung GmbH
- LVQ-WP Prüflabor GmbH
- LVQ-WP Werkstoffprüfung GmbH & Co.KG

140 employees, 10 Mio € sales; 3 x business locations (Mülheim/Ruhr, Magdeburg und Bremen)

business activities: 1. training/education 2. testing service 3. inspection

Magdeburg

Mülheim/Ruhr

Bremen
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5. review: development of testing cast components
1. Introduction

Due to the high number of cast materials, cast defect types and non-destructive test technologies a detailed presentation of all fundamental facts is not the focus of this lecture. Assuming that the basics of the NDT technologies are well known this lecture will concentrate on special aspects being important for solving an industrial test problem. As an example the application of eddy current testing of cast components will not be explained as the industrial use can be neglected in comparison to other NDT technologies. Furthermore the use of non iron cast materials will be ignored. This is due to the fact that the industrial application is very special and will overspread the intention of this lecture. Additionally all acceptance procedures of cast components relating to special standards and technical guidelines like ASME-CODE, all different production techniques of casting (being important for the occurrence of different defects types) as well as all the defects types being generated by an insufficient heat treatment or by a mismatched machining cannot be taken into account due to the limited time of this presentation.

2. Casting process and cast materials

All components with complex geometries in power plant technology like for example a valve housing cannot be manufactured by a conventional assembling technique like welding. Therefore, complex geometries of components have to be produced by a casting process. Normally this will be done using a foundry mold which will be destroyed (lost mold) after the finish of the casting process. Alternatively the application of a metal chill mold is possible for using it several times. To build up an adapted chill mold the sand will be cemented using a design model representing the geometry of the part. As cast parts are hollow a casting core has to be inserted after the removal of the design model. To avoid a shift of the casting core during the melt process the cast core has to be fixed by a backup. Every chill mold is build up by a minimum of one sink head and one riser. The liquid metal will be inserted into the chill mold via the sink head; the riser is necessary to allow exhausting of air and cast contaminations.

After the finish of the casting process the microstructure of the cast components and linked to this the mechanical properties can only be manipulated by a special heat treatment and not by any type of a mechanical forming. The optimal selection of the chill mold, the mold material and the casting temperature will define the mechanical properties of the final cast component. For example the cooling rate is fixed by the mold material and the volume of the mold. Thereby, the target is defined to reach a fine grain size microstructure on the surface (casting skin) in order to realize a high strength and a high corrosion resistance.

Using a high temperature of casting the tendency of dendrite generation by chill casting is preferred and the tendency of coarse grain size by sand casting. An optimal compromise is given for example by a microstructure with a chilling layer, an inhibited dendrite generation and a globilite subsurface structure. This can be achieved by reducing the temperature of the casting process. The casting temperature range for different cast materials is documented in Tab. 1.

<table>
<thead>
<tr>
<th>temperature of casting (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>gray cast iron</td>
</tr>
<tr>
<td>cast steel iron</td>
</tr>
<tr>
<td>cast aluminum</td>
</tr>
</tbody>
</table>

Tab. 1: casting temperatures for different cast materials [1]

The generation of cast crystal germs will start on the cold surface. Due to the fact that the temperature difference is high many crystal germs will be generated simultaneously. The liquid cast will solid at the crystals, whereby crystal germs will grow perpendicular to the surface into the liquid cast (FIG. 1). The growing orientation is given by the direction of the best heat transmission. In case of a very high heat transmission (mold casting) the generation of longitudinal oriented dendrites will result. In case of a very low heat transmission (without a preferred orientation) a globular or round structure of the crystals will result (sand casting).
At the end of the steel manufacturing process melt will be casted to steel slabs for further forging, milling or pressing process or to final cast components having a complex geometry.

In general the following technologies for the cast processing are known:

- ingot / slab casting
- strand casting
- chill casting
- die casting / high-pressure casting
- centrifugal casting
- sand casting

3. Defects by the casting process

The defects are defined as discontinuities limiting the applicability of the cast components. If this is not proven all indications and discontinuities have to be accounted as inhomogeneities. All inhomogeneities in semi-finished products are caused by a mismatching in melting, casting and solidification of the material (slab) before the final processing. In case of cast components the temperature of casting, the alloy composition (especially the iron accompanying elements like sulphur and phosphor) are of high importance for the generation of inhomogeneities. Thereby, the inhomogeneities are initialized by the typical influencing factors like an incorrect casting, a mismatched assembling of the cast component, an increased or decreased temperature of casting and enclosed gas or sand particles. Beside the technological influences especially the mold material and the cast material will play an important role.
3.1 surface defects

3.1.1 heat cracks

In case of a high-alloyed material the residual melt between the crystals is consisting of low-melting material. This melt material is consisting of sulphur, oxygen or phosphor compounds in a liquid condition (so called segregation) between the grains, whereby based on the volume contraction in the cast component a high mechanical stress is present (FIG. 2).

![FIG. 2: heat cracks](image)

Due to this situation the material is unable to compensate the mechanical stress and the cracks will be generated in the direction of the liquid areas. Similar mechanism are known during the cooling down in a welding process (cracks at the crater end zones). The surface open cracks (independent of their origin) are always displayed in the penetrant test by linear indications. Those types of PT indication are prohibited in several international standards (for example AD-Standard HP 5/3).

3.1.2 pores and gas cavities

In contrast to the solid status the melt includes a high amount of dissolved gas. This gas has to disappear in case of the solidification. Normally it will concentrate on the interface liquid/solid in type of gas cavities and it will exhaust via the liquid melt to the air or into the mold sand. This process needs a defined time duration. In case of a short-timed solidification of the melt the gas cavities will be frozen and this will lead to internal pores. Fig. 3 is documenting the gas cavities in a slab of rimmed steel.

![FIG. 3: gas cavities in a slab of rimmed steel](image)
3.2 subsurface defects

3.2.1 shrink holes

During the cooling-down process the material volume will be reduced. This is also valid for the casting process, whereby three steps of the volume reduction can be fixed (Tab.2):

1. reduction of volume in the liquid condition (can be compensated by the rate of inflow and the type of riser),
2. reduction of volume in plastic /"pasty" condition
   shrinkage: inter side: liquid; external side: pasty;
   melt will compensate the volume reduction from inner side,
3. reduction of the volume in the solid condition
   material depending volume contraction

The volume reduction from the liquid to the solid is very strong. In this case contraction holes, so called shrink holes, can be generated (Fig. 4).

![Diagram of shrink holes]

**FIG. 4:** generation of shrink holes

<table>
<thead>
<tr>
<th>material</th>
<th>shrinkage in %</th>
<th>contraction in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>gray cast iron</td>
<td>2,8</td>
<td>1,0</td>
</tr>
<tr>
<td>cast steel iron</td>
<td>4,5</td>
<td>3,0</td>
</tr>
<tr>
<td>cast aluminum</td>
<td>5,0</td>
<td>1,3</td>
</tr>
</tbody>
</table>

Tab. 2: shrinkage and volume contraction for different cast materials [1]

Shrinkage cracks will be generated mainly in areas of high differences in the wall thickness. In the chill mold the material solidification is starting first at the wall surface and later layer wise. By the transition liquid/solid the volume reduction must be compensated by the liquid inside, whereby the level of the melt is declined and a so called head shrink will occur. In case of sand casting the raiser and in case of chill casting the slab end will compensate this effect (FIG. 5).
In case of a globular solidification on the inner side the possibility is still present that in between single grains residual melt will cause shrink holes of dendrite type. The result will be micro shrink holes, gas cavities and a sponge like microstructure (FIG. 6).

FIG. 6: micro shrink holes on the inner side of a bearing seat of cast iron. [1]

3.2.2 inclusions caused by sand and slag/dross

A spalling of the mold sand during the melting process is generating nipple type effects on the surface (so called "Schüppen") and sand inclusions inside the material. Additionally a desoxidation process or reaction by heat-resistant coating material will initialize non metal products which will be frozen inside the material (slag).

3.2.3 core backups

In case of hollow cast components so called core backups are used to fix the chill mold. By this no shifting of the core will occur and the geometrical accuracy is guaranteed. The core backups will be out of the same material as the cast component under process and will be “joint” with the cast material. In case of corrosion, oil or dust the "joining process" will fail and a so called "lack of fusion" between the cast material and the backup will result. A "lack of fusion" has to be classified as a defect ("not joined core backup") minimizing the life time of the component in a significant way.
3.2.4 segregations

Normally slab segregations will not be displayed by a material control as they are generated by remixing effects during the solidification process. Nevertheless the test operator will detect secondary effects by non metallic inclusions, slag and cracks, which are located favored in those areas.

4. NDT test technologies

4.1 Penetrant Testing (PT), Magnetic testing (MT), Visual Testing (VT)

4.1.1 Penetrant Testing (PT)

The penetrant testing \[ \text{[1], [8]} \] is only sensitive for inhomogeneities which are open to the surface. Therefore, the test technology is unable to detect subsurface/volume-type defects.

Using the penetrant technology the operator will detect non metallic inclusions, slag or cracks which are favored located in the segregation zone. A porosity is displayed as a round-type indication; cracks or separation type indications are displayed as longitudinal indications. Therefore, the international standards and the technical guidelines distinguish between linear and non-linear indications.

4.1.2 Magnetic Testing (MT)

The magnetic testing \[ \text{[2]} \] can only be applied on ferro-magnetic materials having optimal magnetic values (for example permeability \( \mu_r \geq 100 \) or magnetic flux \( B \approx 1 \) Tesla). The technology is based on the difference of permeability between iron (test part) and air (inhomogeneity). The test sensitivity is optimal if the difference of permeability is a maximum.

The magnetic testing is able to find the inhomogeneities which are open to the surface or in a very surface-near zone. The test sensitivity and the test limits are strongly depending on the surface condition and are influenced by the condition of the magnetization.

In case of an optimal constellation, for example the depth of inhomogeneity is higher than the surface roughness (but less than 0.2 to 0.4 mm in depth) and the ferro-magnetic test part will be under sufficient magnetic field strength a test sensitivity of approx. 10 \( \mu \text{m} \) depth can be achieved \[ \text{[2]} \].

The penetration depth of the magnetic testing respec. the detection of subsurface inhomogeneities is a point of controversial discussion. It is fixed, that the sensitivity will be less by increasing depth based on the system equipment, the type and the shape of the inhomogeneity as well as by the physical conditions of the magnetization.

It has to be stated that a quantitative information about the depth of the inhomogeneities is not achievable \[ \text{[6]} \]. Additionally based on the physical background the sensitivity will be higher for the surface near inhomogeneities by an AC-magnetization. A higher penetration depth can be achieved by a DC-magnetization.

The background for the higher penetration depth by a DC-magnetization is the uniform evaluation of the total test part cross section, whereby the detection sensitivity is depending not only on the surface condition but also by the orientation of the inhomogeneity within the magnetic flux and by the volume of the inhomogeneity. In case of a complex geometry of the part under test the realization of a sufficient detection sensitivity can be critical as the test parts need to be checked by a variation of field strength and different clamping positions \[ \text{[7]} \].

The detection of inhomogeneities cannot be realized in the direct environment of the clamping/contact areas. This is based on the fact that the test medium (magnetic powder) cannot reach this test area due to the necessary mechanical contact and by the fact that the magnetic field emission in the pole area is perpendicular and will not produce a stray flux which is necessary for a detection.

The only possibility to overcome this problem is a multi-magnetization by different orientations.
In case of a non-destructive testing procedure, four test statements can be fixed in general:

1. A defect is present and will be detected in the right way (true-positive),
2. No defect is present and no defect will be detected (false-negative),
3. A defect is present but will not be detected (true-negative),
4. No defect is present but a defect indication will be detected (false-positive).

Under the pre-condition that the statement 1 and 3 will describe "the test part with defects" and the statement 2 and 4 will describe "the test part without a defect", the quality of the applied test system can be evaluated independent from the test parameter set-up by the attached diagram (FIG. 7).

The diagram will allow a conclusion about the probability of true and false indications.

FIG 7: probability of true (tp) and false (fp) indications of different test systems [6]

A test system with the characteristic of line 0 will achieve true and false test results with the same probability and therefore, can be not applied. In contrast, a test system with the characteristic of line 5 will achieve 10% resp. under the calibration to 70%, only 3% of false indications.

Thereby, the area under the different lines will display information regarding the quality of a test system with 50% (not sufficient test system) up to 100% (optimal usable test system). This way to check the probability for a defect detection is known as the ROC-method (Receiver Operating Characteristics [6, 10]).

The test sensitivity of the non-destructive technologies will be adjusted by the use of defined test defects. The test potential will be estimated by the capability that defect indications higher than the operating threshold will be identified without problems and defect indications below the operating threshold level will not give any alarm. The range around the operation threshold, which is combined with uncertainty lower 95% and higher 5%, is called the critical range or "gray area". A test technology with a limited critical range is more qualified than a test technology with a broad critical range (Fig. 8). In the magnetic testing the quantitative critical range is always near to the limit of the detection potential.
The crack detection potential is strongly depending on the total permeability. The total permeability itself is depending on the magnetic field strength. The application limits will allow that in practical use different materials, cross sections and orientations can be magnetized and magnetization can be calculated with the known formula.

Due to the fact that the test data evaluation in the magnetic testing will be done by operators a human error is always present. Therefore, a defined residual risk for sorting out defective parts is still existing. For example a statistic evaluation on a high number of test parts by the automotive industry has documented that in contrast to destructive testing and existing real defects a 100% recognition of all defects is not possible applying non destructive test technologies. Different statistical evaluation document the reliability and test sensitivity of the magnetic testing. The technique will allow to separate subjective and objective influences and to analyze faults in the production and in testing.

A special aspect is given by the vision quality of the operator. The total capacity of the human eye has to be considered under the aspects that drugs, diabetes or affection of the eyes will reduce the capacity. A permanent testing time of several hours is stressing the eyes in a significant way.

Regarding the fluorescent testing is has to be kept in mind that the testing will be done in shadowed rooms. Having a shadowed field of vision the sensitivity of the eyes is increasing (mesopic vision). The time up to a total adaption of the eye in case of a shadowed field of vision add up to around 40 minutes. Any failures in the eye adaption might influence the testing confidence.

In case of a high irradiation (> 30 W/m²) the test cabinet or the working environment has not to be shadowed in order to have an equivalent contrast between the indication and the environment. Beside this the design of the working environment is very important regarding the field of vision of the operator and the avoidance of a direct glare in case of metallic shining test parts.

The necessary magnetic flux leakage for detecting the inhomogeneities is depending on the type and the geometry of the inhomogeneities. Thereby, for example wide open surface inhomogeneities with rounded-down edges and a flat bottom are difficult to detect as they will generate a low or even no magnetic leakage flux and therefore no defect indications.

Also flat angled shells and forging imperfections or gaps filled by ferro-magnetic slag (iron oxide) are producing "weak" indications based on the minimal magnetic stray flux generation.
4.1.3 visual testing (VT)

The optimal vision is not only for the human people a basic requirement to map the environment; it is also a basic requirement for all testing procedures in order to detect and to analyze inhomogeneities. In order to qualify the normal vision as a visual testing the test problem has to be known beside the normal interaction between the light and the test part. Thereby, the inspection features whom the operator has to follow by the test procedure have to be settled in a defined way. This will result in a reproducible testing with a defined standard for evaluating the inhomogeneities. By this the visual testing is integrated in many other NDT technologies.

Visual testing will be performed for example in case of a surface inspection by the detection and analysis of indications. Prior to the testing start the operator has to check the test area for visible inhomogeneities [13]. Since the validation of the European Standard EN 473 several years ago the visual testing is established as an independent test technology and will be used in the industrial practice [3]. The revaluation of the visual testing in the last years which is manifested in international standards is based on the fact that everyone is sure to perform this complex testing by himself under the only pre-condition to be able "to realize an adequate vision". Based on this understanding EN 473 has settled defined test requirements [19].

- VT testing by level 1, 2 or 3 needs qualified and certificated staff,
- the test procedure has to be fixed by a written inspection instruction
- the final test result has to be fixed by a protocol, a tests statement or a document.

The test area representing the part of the surface to be tested is not only defined by the dimensions. In addition test material, the condition of the test part surface, the illumination, the direction of electric lightning angle of inspection as well as several inspection features like dimensions of defects, deviations from normal standards etc., must be known.

In many application a so called integral or overview test will be performed first. Thereby, abnormalities will be picked up and an overall picture of the part under test will be fixed. In addition a specialized visual test with a defined test target and test specifications will be worked out. For this specialized visual test the test conditions and the testing scope have to be settled. A concrete time duration for a visual testing is not possible based on the variability and flexibility of the technology. A scheduled integration of the technology in technical test sequences is to be preferred. This can be realized by continuous VT tests from start to the end during a technical cycle or in case of periodic inspections or during a damage check.

It has to be noticed, that the test parts might consist also of inner test surfaces. Thereby, hollow areas must be accessible. At a minimum an entrance port for the insert of an endoscope should be available.

In order to qualify and to evaluate the surface inhomogeneities the so called "Gussfehleratlas des Vereins Deutscher Gießereifachleute" [14] can be consulted offering the displayed examples in FIG. 9 to FIG. 16. In this atlas information is given for the reorganization of typical surface inhomogeneities and their nature of occurrence, whereby information about acceptance or inadmissibility is missing.

FIG. 9: vein and free nipples ("Schulpren") in wet cast iron
surface and subsurface control on cast components

FIG. 10: angled blows in cast iron steel

FIG. 11: "cold" cracks in gray cast iron

FIG. 12: heat crack in cast iron steel

FIG. 13: cold shut in gray cast iron

FIG. 14: wrinkle in cast iron steel
In the atlas of cast faults different defects will be discussed regarding their nature, location on or in the cast component and regarding their typical visual occurrence.

The quality of the cast components will be defined prior by the roughness of the surface based on the following standards:

- DIN EN 1370 [16] testing of the surface roughness by the use of reference samples

In order to perform a visual examination of the surface roughness of cast components real replicas of existing surfaces (or even photos) or reference master parts will be used (Tab. 3).

<table>
<thead>
<tr>
<th>reference master</th>
<th>class</th>
<th>quality of surface</th>
<th>performance level</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCRATA</td>
<td>A</td>
<td>unfinished casting surface</td>
<td>1 to 5</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>grinded surface</td>
<td>1 to 5</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>special treated surfaces</td>
<td>1 to 5</td>
</tr>
<tr>
<td>BNIF 359 [15]</td>
<td>S1</td>
<td>unfinished casting surface (for all alloys)</td>
<td>4/0, 3/0, 2/0, 1/0 1 to 8</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>grinded surface (for all alloys)</td>
<td>4/0, 3/0, 2/0, 1/0 1 to 8</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>special treated surface (only for thermal and mechanical treated cats components)</td>
<td>4/0, 3/0, 2/0, 1/0 1 to 8</td>
</tr>
</tbody>
</table>

Tab.3: reference master for visual examination of the surface roughness of cast steel via DIN EN 1370
Based on DIN EN 12454 the set of reference master parts is consisting of six classes with a decreasing performance level from 1 to 4. The types of defects are: surface inclusions, gas porosity, cold shuts, nipples ("Schlüpe"), core backups, welding effects (no cracks!).

The standard is requiring an order specification for the visual inspection regarding the performance level and the different test locations as well as the status of production for surface testing. Additionally within a protocol the following information has to be fixed: the testing sequence and -based on the requirement of the customer- a test sample identification, the name and the qualification level of the operator staff, the evaluated class and the performance level of the test area.

**Inhomogeneities to be not recorded** are testing characteristics, which might be estimated as an inhomogeneity or displayed by the optical system as a color change or a visual shadow. In case of an uncritical result no registration will be done.

**Inhomogeneities to be recorded** are divided into acceptable inhomogeneities having no influence on the safety and the application efficiency of the component and not acceptable inhomogeneities having a significant influence on the safety and the application efficiency.

### 4.2 radiographic testing (RT) and ultrasonic testing (UT)

#### 4.2.1 radiographic testing (RT)

The actual valid standards for the radiographic testing of cast components [4][18] for example EN 444 are divided into two test classes:

- test class A: basic technology (for example: standard subsurface/volume-type defects)
- test class B: advanced technology for higher sensitivity (for example: testing with high performance level)

The technologies of the test class B will be applied if the test class A is to low in the test sensitivity. More sophisticated technologies as the test class B can be discussed between the contract partner whereby all necessary test parameter have to be fixed. The final selection of the radiographic technology must be agreed between the contract partner.

The required number of single photographs is depending on the size of the area to be tested. In case of a small sized cast component it should be tried to evaluate the component by a single "overview" photograph. The bigger the size of the cast component the more single photographs have to be done. In this case a X-ray film map for example by a grid on the cast component (FIG.17) and a X-ray radiation map (FIG. 18) will be necessary.

*FIG. 17: film map (grid on the cast component)*

*FIG. 18: X-ray radiation map (testing of a cast housing)*

The quality of a radiographic test photograph will be documented by the so called penetratermeter described in the standard EN 462. The penetratermeter has to be placed on the radiator near side of the test sample, in the middle of the test zone and in a zone of identical wall thickness.
The evaluation of the image quality will be done according to the standard EN 462. Thereby, the number of the smallest wire or hole dimension of the penetrator which can be separated by the radiographic test photograph will be evaluated. The wire size of the penetrator will be noticed as classified if the wire will be indicated in the area of a constant density by a minimal constant length of 10 mm.

For classifying and evaluating inhomogeneities the technical guidelines are divided in the object-related technical guidelines for acceptance and the test-related technical guidelines for defined procedures (FIG. 19).

FIG. 19: object-related and test-related technical guidelines for a radiographic test of cast components

Today, all cast components produced by cast iron steel, aluminum, copper as well as copper alloys and magnesium will be tested based on EN 12681. Depending on the wall thickness and the type of radiation the inhomogeneities (defect code) and their acceptance will be reviewed by 8 quality classes. Qualifying the defects has to be done by a comparison with master X-ray photographs mainly based on US technical guidelines (ASTM atlas).

After the selection of the master X-ray comparison photographs the square test area with the inhomogeneities has to be compared to the master X-ray photograph. In case that the square test area with the inhomogeneities is bigger than the area of the master X-ray photograph the square area with the inhomogeneities has to be divided into square sections similar in dimension as the master X-ray photograph.

In case of different types of inhomogeneities of the X-ray photograph comparison has to be done type by type using the relevant master X-ray photographs (for example A indications and B indications fixed by comparison master X-ray photograph A/level II and B/level III) [9].
4.2.2 ultrasonic testing (UT)

The ultrasonic testing is the most applied technology for the testing of cast components [5] [11] [12]. This is based on the fact that the ultrasonic testing will be used during the production process as well as on the installation and inspection side.

**cast iron steel**

Initialized by the segregation contaminations, non metallic inclusions, oxides will deposit in-between the dendrites. This effect is presenting for the ultrasound a phase reflection. Thereby, the ultrasound will be deposit in sound direction and cannot be detected.

Similar effect occurs using X-ray radiation which will be degraded by the dendrites, whereby this "microstructure type indication" will lead to a misinterpretation on the X-ray film.

In contrast to forged components the testing of cast components is strongly influenced by the material, the microstructure, the geometry of the part under test and the type of defect. The material and the microstructure are linked inseparably and they define the test technology to be used. The test geometry and the defects types can be examined independent form the test material. Regarding the test geometry in ultrasonic testing is can be stated that limits are fixed by the surface condition, the geometry of the cast part, changes in cross-section, non-parallel walls and by the wall thickness. Although the testing of higher wall thickness is an advantage of the ultrasonic testing against the X-ray testing this is only effective for testing cast steel and in a limited way for testing globular gray cast iron.

Tab. 4 is displaying an overview about the most common defect types in ultrasonic testing, the nature of their appearance and the detectability.

The detectability of defects in cast material is strongly related to the reflexion factor. As the reflected content of the transmitted sound beam is very low for most defect configurations the ultrasonic echo height cannot be used to evaluate the indications. Therefore, the shadow-minimizing effect of the defects to the back wall echo will be evaluated. By this the signal to noise ratio of inhomogeneities to microstructure indications will have an significant importance.

<table>
<thead>
<tr>
<th>defect group</th>
<th>defects type</th>
<th>nature of appearance</th>
<th>detection by ultrasonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>voids</td>
<td>pores cavities</td>
<td>casting mold, core and binding material are not dry, missing deoxydation of the cast nappe and the molding sand, missing air vent of the cores, to high amount of gas within the mold, air in the cast nappe</td>
<td>low reflection potential, can only be detected in high quantity, high ultrasonic scattering based on the nodular size; low reflection to the ultrasonic test head</td>
</tr>
<tr>
<td></td>
<td>metallic inclusions</td>
<td>dissolution of alloy elements or different metal</td>
<td>not detectable</td>
</tr>
</tbody>
</table>

Tab. 4
<table>
<thead>
<tr>
<th>defect group</th>
<th>defects type</th>
<th>nature of occurrence</th>
<th>detection by ultrasonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>voids</td>
<td>non metallic inclusions, slag</td>
<td>deposition of the de-oxydation elements or the sulfur, swept parts of mold, foundry ladle or sink head, adverse gating and mold conditions</td>
<td>more sensitive to detect in contrast to pores or cavities based on the bigger size with two-dimensional or linear content perpendicular to the ultrasonic beam</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>based on the rough, irregular inner surface of the voids or by the spongy microstructure with micro cavities always reflecting or shadowing ultrasonic contents are present. By this the voids can be detected by a missing back-wall echo.</td>
</tr>
<tr>
<td>cavities</td>
<td></td>
<td>volume shrinkage during solidification, high casting temperature, significant changes in cross sections, micro cavities by microstructure bulking</td>
<td>If the voids are subsurface and if there will be no break-through to the surface, the voids are only to be detectable if their orientation is known. If they are perpendicular to the ultrasonic beam they will be detected in a sensitive way like a two-dimensional defect.</td>
</tr>
<tr>
<td>cracks</td>
<td>heat cracks</td>
<td>intercrystalline tension and shrinkage cracks during solidification caused by the shrinkage of the mold material, not optimal construction, high sulfur amount and high casting temperature</td>
<td>Are always oriented from outer to inner side and divide in many cases the total cross section in tension critical zones.</td>
</tr>
<tr>
<td></td>
<td>cold cracks</td>
<td>after solidification of cast by expansion limitation, different cooling rate, early evacuation of the cast box, external tension (cutting of feeder head)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not welded areas</td>
<td>iron chill (cooling element) for defined solidification or core backups are not melted before finish of solidification</td>
<td>If the orientation of the iron chill (cooling element) or the core backups in the cast component is known the cold welds can be detected in a sensitive way.</td>
</tr>
</tbody>
</table>

Tab. 4: Typical defect types using ultrasonic technology for testing cast components [5]
The material of the cast component is the important factor for the testing ability as well as the test technology to be applied. Thereby, the type of alloy and the condition of the microstructure will determine the ultrasound transmission as well as the potential of inhomogeneity detection. Therefore, the test technology and the extent of testing have to be examined in relation to the cast material.

Taking the geometry of the component into account non-alloyed and low-alloyed cast iron steel materials can be tested well if the cast components are in a normalized or quenched/tempered heat treatment condition. FIG. 20 is documenting the microstructure of cast iron steel in an unfinished condition and FIG. 21 in a normalized heat treatment condition.

Without a defined heat treatment only components of a wall thickness lower than 20 mm can be tested and evaluated. In case of increasing wall thickness more and more an acicular type of crystal grains so called "Widmannstätten’sche" microstructure (Fig. 20) will limit the ultrasound transmission. Therefore, using this type of cast material the result of the heat treatment should be verified by a separate microstructure check before starting the ultrasonic testing.

For instance some special areas of a cast component might have no ultrasound transmission based on their bad positioning in the heat treatment oven. Thereby, in case of a lack of knowledge of the actual microstructure defects might be assumed. On the other hand in case of a surface finishing problems will arise by local spots of high hardness based on low strain and tensile ductility.

Usually, high-alloyed cast iron steel materials can be tested only in case of a ferrite microstructure. In case of an austenitic material a sophisticated test technology must be applied in order to realize a sufficient ultrasound transmission.

For the optimization of the ultrasound transmission in industrial testing large-sized diameter of ultrasound test heads and low test frequencies will be used.

gray cast iron

Normally in case of gray cast iron a testing by ultrasound is not possible. This is based on the one hand on the chemical composition of the microstructure and the conversion of the carbon to graphite which will generate a significant deviation of the ultrasound velocity and the ultrasound attenuation. On the other hand defined heat treatments for optimizing the microstructure are in contrast to the cast iron steel not or only to a minor degree applicable.

Depending on the shape of the graphite the gray cast iron will be divided in lamellar graphite (GG/FIG.22), nodular graphite (GGG/FIG.23) and vermicular graphite as the mixed version.
Surface and subsurface control on cast components

Special types of gray cast iron exist by annealed cast iron (GT) and white iron (GH) or chilled cast iron. In case of the annealed cast iron the graphite flake will be generated by a heat treatment (annealing) under a decomposition of the cementite; in case of white iron/chilled cast iron (for example for roll production) a high-speed cooling will be applied to achieve a white, hard and ductile solidification layer combined with subsurface layer of lamellar graphite.

The penetration depth of this solidification layer will be marked as chill depth and can be detected by ultrasonic probes (transmitter/receiver configuration) as better as the change over between white and gray microstructure zones is more abrupt.

The graphite form (shape, size and amount) is affecting the ultrasound velocity in a significant way. The more the graphite is in a finely spread nodular shape the higher is the ultrasound velocity.

FIG. 24 is displaying this relation.

FIG. 22: gray cast iron with lamellar graphite

FIG. 23: gray cast iron with nodular graphite

FIG. 24: longitudinal und transverse ultrasound velocity in cast gray iron [5]
The limit of cast gray iron with nodular graphite can be fixed by $c_{\text{long}} \approx 5500$ m/s and a minimum of approx. 90% nodular graphite. In the range of $c_{\text{long}} \approx 5400$ to 5500 m/s the microstructure will show irregular and disturbed sphaerolites (nodular graphite) and in the range of $c_{\text{long}} < 5400$ m/s burst and abnormal sphaerolites. In comparison the ultrasound velocity of gray cast iron with lamellar graphite has to be calculated in the range of approx. 3800 to 4500 m/s.

If an ultrasonic production control will determine a percentage of 70% to 90% of nodular graphite a defined perlite annealing process can be applied in order to achieve or to optimize the mechanical values similar to a 100% nodular graphite.

The ultrasonic test series have been done predominant on test components of gray cast iron with nodular graphite; rarely on gray cast iron with lamellar graphite or annealed cast iron.

In general statements for the testing and the evaluation of inhomogeneities are similar to the testing of cast steel. Nevertheless the graphite will generate additional problems as the lamellar graphite has to be seen as a center for ultrasonic scattering and this will increase the ultrasound attenuation already present by the microstructure. By this the detection of small-sized defects will be more critical.

In case of industrial testing of gray cast iron with nodular graphite typical inhomogeneities will be dross, slag, sand inclusions, cold shuts and cavities generated by a accumulation of pores leading in combination with dross to an expansion up to the surface of the test component.

As a principal rule it can be stated that cast components are worse to be tested if wall thickness is increasing, if strength is decreasing and if lamellar graphite is bigger in size and high in numbers.

### Ultrasonic testing of cast components by standards and guidelines

<table>
<thead>
<tr>
<th>Type of cast iron</th>
<th>Standards and guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron steel</td>
<td>DIN EN 12680-1 und -2, SEP 1922 u. DIN 1690, T.2, SEP 1924</td>
</tr>
<tr>
<td>Gray cast iron with nodular graphite</td>
<td>DIN EN 12680-3</td>
</tr>
<tr>
<td>Gray cast iron with lamellar graphite</td>
<td>No standards and no guidelines</td>
</tr>
</tbody>
</table>

The two standards DIN EN 12680-1 and -2 are nearly identical. This is also valid for DIN EN 12680-3 [20].

### 5. Review: Development of testing cast components

The regenerative energies like wind, water or sun become more and more important. Thereby, the contribution for energy power supply is increasing worldwide.

For an effective and economic operation of energy plants it is absolutely necessary that the quality is guaranteed for all components. This is affecting the quality of production of the components by subcontractors, the quality during the production process of the materials and the quality during the inspections.

In case of the production of a wind energy systems a defined production control will prevent momentous production problems.

Global sourcing - around the world new production plants will be build up; new production techniques will be developed. Only if a mismatching will be detected as early as possible a standstill of the operation and additional cost can be avoid.

The key aspects which have to be checked are critical processes in the production, the qualification of the operator staff as well as the internal quality control of the producer including all internal testing and incoming inspections [4].
Components of gray cast iron with globular graphite will be tested by:
ultrasonic testing by DIN EN 12680, magnetic testing by DIN EN 1369 and DIN ISO 9934,
penetrant testing by DIN EN 1371 and DIN EN 571 as well as DIN ISO 3354,
visual testing by DIN EN 1370 and DIN EN 12454
whereby, nature, orientation and visual appearance of surface defects can be extracted by the atlas of cast defects of the foundry publishing Haus Düsseldorf "Gussfehleratlas des Gießereiverlages Düsseldorf"[8].

- Main beam (Maschinenträger),
- Base frame (Bodenplatte),
- shaft hub joint (Naben),
- machine base (Maschinenfundament),
- Gear housing (Gehäuse),
- brake disks (Bremsscheiben),
- Yaw beam (Unterlegscheiben),
- Torque arm (Trägerarme),
- Bearing house (Gehäuse)
- axle journal (Achszapfen),
- cast nods (Knoten) for wind energy systems and off shore platforms.

The importance of the non destructive testing of cast components will be documented by the fact that new standards as well as guidance rules will be established permanently. This will be done in order to guarantee the qualification level of the operator staff and to secure the quality of cast components by the evaluation of the acceptance of different types of inhomogeneities.

6. Literature:
[1] Skript Eindringprüfung LVQ-WP Werkstoffprüfung GmbH Stufe 3
[9] Purschke, Die Röntgen-Prüfung (RT/RS), Castell-Verlag GmbH Wuppertal 2001
[10] Deutsch, Autorenkollektiv, Informationsschriften zur Zerstörungsfreien Prüfung
[15] BNIF359, Vergleichsmuster als Beispiele zur Bewertung des Oberflächenzustandes
[16] DIN EN 1370, Gießereiwesen, Prüfung der Oberflächenrauheit mit Vergleichsmuster 1997
[18] DIN EN 12681, Gießereiwesen, Durchstrahlungsprüfung 2003
THANKS FOR YOUR ATTENTION