Control strategies and inspection methods for welded part

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Abstract
Present and future demonstrator designs were used to demonstrate the quality assurance of welds. The NDT methods tested on prototype demonstrator parts are: visual inspection, radius gauges, throat size gauge, liquid-penetrant testing, magnetic particle testing and ultrasonics with pulse echo and phased array. The other methods like eddy current, time of flight diffraction, radiography, impression test, macro test and infrared thermographs are currently being analyzed along with their inspection costs.

The control plans for present and future designs with corresponding present and future NDT methods are suggested to minimize a shift in process.

- Magnetic particle testing revealed a lack of fusion and cracks for fillet welds, whereas ultrasonic pulse echo and phased array identified an internal lack of fusion, inner pores/slag inclusions on butt welds.
- Ultrasonic PAUT & TOFD could be used for accurate defect identification and thermography for online identification of lack of penetration, depth of penetration and weld parameters.

Keywords:
Visual inspection, WPS, impressions, throat size gauge, radius gauge, liquid penetrant test, magnetic particle testing, eddy current, radiography, ultrasonic (PAUT & TOFD), thermography, control plan, cost per hour.

1. Introduction
Volvo construction equipment (VCE) is one of the world’s leading companies, which produces heavy machinery equipments for construction such as roads, forest-related equipment, cranes, building industry and many others. More than 60-80% of the machine weight is from steel plates and castings with different thicknesses (6-70mm), with welding as primary joining technology. These complex welded components are continuously subjected to amplitude loading in operations, which are designed for longer service life using the right design rules to minimize weight in order to increase productivity and decrease fuel consumption. Residual stresses introduced at design cracks, negatively influence the fatigue life of fillet welds. Improved production standards and the quality approval methods are maintained for all structures before being outbound. Currently produced demonstrator parts and weight reduction by improved weld quality
demonstrator parts (demo optimized-X) are used as demonstrators for quality assurance, using Non-Destructive Testing (NDT) methods.

The aim is to examine appropriate control strategies and inspection methods for quality assurance of welds for selected welded part. Different NDT methods, which are tested on prototype demonstrator part, are visual inspection, radius gauges, throat size gauge, liquid-penetrant testing, magnetic particle testing and ultrasonics with pulse echo and phased array. Other methods like eddy current, time of flight diffraction, impression test, macro test and infrared thermographs are currently being analyzed. Cost calculations for each method are analyzed. Control plans are suggested for present and future designs using NDT methods, which could be practiced on welded parts for continuous day by day improvements.

Today manufacturing, maintenance and infrastructure are the main challenges to fulfill basic human requirements to accomplish these welding and non-destructive testing are playing dominant roles almost in every industry. These improve the quality and overall life of all the products [1].

2. Background

2.1. Welding

Today, engineering industries economize profoundly on welded components and structures, goodness of weld are important for acceptable and reliable performance of components and structures. Weld is reliant on base material, filler material, and weld process specifications. “Welding is defined as a localized coalescence of the metal wherein coalescence is produced by heating to suitable temperature, with or without the application of pressure and with or without the use of a filler metal”, melting point of filler metal can be same or below the base metal and products obtained by welding are called weldments [2].

2.2. MAG welding

A flux cored filler wire electrode is fed through a torch at controlled speeds and current, continuously striking base material, shielding gases flow through the torch at selected speeds, which acts as a blanket over the weld, to protect it from atmospheric inclusions. Gas metal arc welding can be semi-automatic or mechanically performed; with solid wire or with flux core [2].

It is difficult to produce a perfect weld, but a satisfactory weld is possible in many ways. The factors for appropriate welding process are: given below

- Workmanship, Joint design, residual stress, pre & post –heat treatment
- Right welding consumables
- Require necessary heat input for the weld joint
- Weld joints faces have to be free from surface contamination
e. Free from atmospheric gases (such as oxygen)
f. Base material and filler wire material properties must be the same for a particular weld process

To minimize the problem during welding the metallic faces need to be mechanically (metal brush) or chemically cleaned before welding and the duration between cleaning and welding must be as short as possible to prevent the formation of non-metallic films caused by prolonged exposure to atmosphere. Weld types are selected on complexity of structures, selected welding process, plate thickness and welding positions. In spite of the advanced welding techniques and processes, defects still occur in the welds. The selection of proper weld parameters may not give defect free weld but can minimize the defects occurring during process [2]. Most frequent faults are spatter and cold laps may lead to fusion defects, as lot of spatter sticks to the nozzle leading to irregular gas flow causing porosities, oxides, voids and lack of fusion at spatter/base interface [2, 3].

2.3. Weld imperfections

During welding, the weld metal will cool much faster due to the heat sink provided by the base metal that results in thermal stresses which leads to cracks and entrapment of gases or inclusions in the weld region.” A discontinuity is not necessarily a defect”, a defect can be a discontinuity in part, which is unable to meet standard weld specifications [2]. See the types of weld imperfections in table 1 mentioned below.

3. New weld standard

Volvo’s (STD 181-0004) new weld standards for weld shapes have maximum allowable values for various weld defects, depending on their estimated fatigue life. This new weld classes allows the designer to select appropriate weld demands for fatigue stressed areas of the demonstrator part and provide a basis in quality control inspection of welds to standards STD 5605 and STD 180-0001. Two important weld demands introduced in new weld standards are; transition radius and root defect. Fatigue life of fillet welds is affected by introducing design cracks which have little or no penetration, and are approximately of the same size as of the plate thicknesses at its root. The introduced crack joints are dependent on penetration, as we know that there is no post treatment procedure possible, so it is excluded from standards and is communicated on drawing with i (penetration) [4-6].

Even transition at weld toe is inspected visually along radius gauges. Toe radiuses for different weld classes are mentioned in the new standard. Outer transition radius increases step by step from R>0.25 mm in VD class, to R>1 mm in VC class, to R> 4 mm in VB class which requires post treatment. In the new weld standards; four different weld classes are categorized for static and fatigue load cases. Weld class VS is
assigned for static load case and the other three weld classes VD, VC, VB for fatigue load cases. VD and VC are for as weld condition and VB for post treated welds. If weld class is increased by one step from VD to the next higher class VC and VB; at each step, fatigue life is doubled and results in an increase of 25% higher stresses at specified positions (say life expected is N at VD, will be 2N at VC and 4N at VB) [5].

3.1. Type of imperfection

The imperfections mentioned in standards are internal and external cracks, cold laps, internal and external lack of fusion, undercuts, throat size, misalignment of plates, surface pores etc. are presented within allowable design limits, criticality level, throat size and penetration are indicated in drawing sheet [6].

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3.1.1. Internal and external cracks

Cracks are one of the harmful weld defects that causes possible danger under stresses during product service life, their possibility to occur is in different forms and orientations within or over the surface of weld geometry, cracks occur in linear direction under the stress applied, can be of different sizes from macro-
sized cracks to micro cracks [5]. Depending on the temperature these cracks are termed as hot cracking or cold cracking. Cracks must be detected and removed [2].

### 3.1.2. Overlap and cold lap

![Fig. 1. Cold lap weld defects; a) line cold lap, b) spatter cold lap [7].](image)

It occurs in the following situations such as; when molten material doesn’t coalesce with the cold plate surface, the weld exceeds beyond the toe, incomplete or insufficient penetration and lack of fusion which is mostly seen in fillet welds refer above fig 1. It is caused by improper welding techniques, torch angle and mostly high welding speed, changes in welding current and in some cases local round laps are produced by spatter [5]. Cold lap is somehow resulted with spatter, presence of cold lap in weld geometry reduces weld quality [6].

### 3.1.3. External & internal lack of fusion

It occurs when weld metal doesn’t form a cohesive bond with base metal; lack of fusion could be present in any size from the root to the surface of the weld and so are the sensitive areas from fatigue point of view [5]. It is caused due to low amperage, fast travel speed, short tip to working distance, abrupt torch angle, preheating, unclean base metal, arc-off seam and mainly due to voids and oxides composed of silicon and manganese and carbon at interface [6]. The defective area(s) must be re-welded.

### 3.1.4. Outer transition radius

Transition area is the area between the weld toe and plate. Weld toes must have even transition between cohesive bond and base metal. Transition radius must be above 0.25 mm for even transition in case of
normal quality and TIG treated for smoother transition in case of post treated welds. It is caused due to low travel speed [5].

3.1.5. Undercut

A notch or a groove at the toe of the weld left unfilled. Undercut is one of the worst defects for causing mechanical failures because the undercut creates a notch effect at toe sides. It is caused by changes in weld parameters such as low travel speeds [5].

3.1.6. Under passed throat (a-dimension)

Throat sizes are a major concern to fillet welds; they measure height of the triangle and check if the welds have same leg lengths and their faces may be flat, convex or concave. It is recommended to have throat size above 3 mm otherwise there will be an impact on the toe and the root side of the weld, it is caused due to applied heat input and travel speed [5].

3.1.7. Non-filled weld

It is an incomplete weld fill where the weld face is below the adjacent base metal, due to improper weld techniques.

3.1.8. Edge displacement

Two plates produced at wrong positions and wrong angles leads to misalignment, generally the misalignments in plates are at root side, and are due to differences in plates thickness [5].

3.1.9. Inner porosities/Slag inclusions & surface porosities

These are entrapments of voids, gases or oxides in the weld region, formed during solidification. Slag inclusions, pores and blow holes are generally present on the surfaces at root side, close to the weld surface and in between the layers [5].

3.1.10. Pipe (craters)

Caused by changes in volumetric contraction of molten metal during solidification, shrinkage stresses are severe enough to cause cracks and they depend on the interaction of arc to base metal [2].
3.1.11. **Leg deviation**

Leg deviation is caused due to the changes in weld positions at flange and web. Here, we can see the differences in throat size with leg lengths.

3.1.12. **Weld reinforcement**

The amount of weld exceeded beyond the plate surfaces at both face and root of the weld, caused due to low travel speed.

3.1.13. **Bad fit-up**

It is recommended to have proper fit-up between the plates for good weld; a bad fit-up has too large gap between the plates which indirectly results in incomplete penetration at root side and changes in throat size. A more than required fatigue life is reached with a proper fit-up [8].

3.1.14. **Incomplete root penetration**

Weld metal doesn’t reach the required depth into the joint root. It is due to high welding speeds, wire feed and tip to working distance.

Discontinuity is defined as imperfection in a particular weld. It can be in-homogeneity of physical, mechanical or metallurgical characteristics of the weld; here discontinuity in material doesn’t mean the presence of defects. Discontinuity is categorized into two; they are dimensional and structural discontinuities.

   a. **Dimensional discontinuity:**
      Discontinuities are a shift in size and shape of the weld or misalignment or improper positioning of joint parts [9].

   b. **Structural discontinuity:**
      These are due to lack of material or excess material in the weld. Examples of structural discontinuities are porosities, a lack of penetration and lack of fusion [9].

4. **NDE**

Non-destructive evaluation (NDE) is generally used interchangeably with NDT. NDE interprets the measurements that are perceptible in nature, for instance, NDE methods would detect the defects as well as measures the size, shape, orientation and locates the position of the defects. It explicates material properties such as fracture toughness and inspects defects at an early stage of processing, to minimize the cost of the product. Below mentioned NDT methods are being used to detect external and internal defects in
weldments, methods inspecting external defects are visual inspection, radius gauge, and throat inspection gauge, liquid penetrant testing, near surface and internal defects detection methods are magnetic particle testing, eddy current testing, radiography, ultrasonics and IR thermograph(y). Advances in NDT methods have improved reliability in quality inspection of weldments [10].

4.1. Visual inspection

Visual inspection even today is a worthwhile and most commonly used technique in all types of manufacturing sectors for quality inspection of welds. In this case, weld examination is done by a qualified inspector; which is an inexpensive, easy and quick task. Visual inspection reveals surface defects and the acceptance or rejection of a component by saving much time and money. Visual inspection is mostly conducted after the completion of welds which reveals many surface imperfections, but it would be good idea to carry a visual inspection before and during various stages of welding. Many things can be learnt by seeing a weld during process; one can observe torch angle, plate’s alignment, different seams and its divergence, so an inspection carried before, during and after welding gives a good quality weld. Many non-critical welds are evaluated by visual inspection [2, 11].

The basic procedure of an inspection is by naked eyes, mirrors, magnifier and lighting device with sufficient brightness for viewing low corners and it is quite important that the welds must be clean before test. It also gives an idea of commonly occurring surface imperfections that must be kept in mind during inspection. Time period for visual inspection must not exceed two hours on a continuous basis otherwise it decreases accuracy [2, 11].

A good visual inspection during welding depends on the following factors:

a. The rate at which an electrode melts [2].
b. The way the weld metal flows [2].
c. Sound of the arc.
e. Shape of electrode during melt (according to welding expert at PTC).

An examination of weld on completion will reveal the following:

a. Visual inspection checks if the right fusion has been obtained between the weld and the parent metal.
b. Undercut along transition between the parent metal and weld joint (and sharp notches).
d. Weld having concave, convex or flat face.
e. Weld appearance with regards to surface roughness, weld spatter and overlaps [5].
f. Position of cracks, orientation of cracks, cracks related to various zones in welds.
g. Surface porosity, unfilled craters, contours of weld beads.
Various faults during welding are lack of technical skills, experience of welder and personnel fatigue.

Disadvantages

a. It is unreliable in detecting subsurface flaws and internal defects in weldments.

4.2. Macro Etch Testing

In this method, a small sample is sliced from the welded joint for inspection. The sliced sample is polished on a selected cross-section and etched with mild acid mixture depending on base material. Etching reveals the internal structure of weld using optical microscopy. An even transition between a weld and a base material can be clearly seen and it reveals all types of defects such as incomplete root penetration, depth of penetration, lack of fusion, internal porosity, internal cracks, slag inclusions etc. Generally, it is the best method used for sampling of production welds [12].

Olympus optical microscopy connected to weld estimation software calculates the geometry of weld (i.e. throat size, transition radius, required penetration, leg lengths, weld face either concave, convex or flat, penetration at leg lengths). This method visually shows extended weld and can be controlled before the actual production run. Welding procedure specification (WPS) is the optimum method to verify if the process is altered (or not), see fig 2.

4.2.1. Weld Break Test

An alternate method of destructive testing is by breaking a weld (fillet weld or butt weld), by applying load on transverse direction of the un-welded portion, a sample is inspected for detection of penetration with digital callipers to find discontinuities visually through the weld length. This destructive test can detect imperfections such as lack of fusion, internal porosities and slag inclusion; see tables 3 and 4 for different types of imperfection. This testing is simultaneously used with the macro test. These combined tests, provide a detailed evaluation of welds [12].
Advantages

- It reveals all types of imperfections in weld.
- Estimation software shows incomplete and defective weld areas.

Disadvantages

- It cannot be performed at production area.
- Time consuming and expensive.

4.3. Impression test

- Clay is mixed
- Firmly placed on weld face
- Allow the clay to dry
- Remove the clay
- Cut the clay with Knife
- Investigation of slit face with optical microscopy using weld software
- Weld measurements and imperfections are estimated using software

Fig. 2. a) Flow chart for macro etch test b) etch test result c) weld estimation using software database.

Fig. 3. Flow chart for impression test using silicon clay.
Impression testing methods of welds is done in the following manner: clay is mixed and firmly placed on the sliced weld face for few minutes till the clay dries and the dried clay takes the impression of the weld face which is then sliced with a knife. The slit side face is investigated using optical microscopy and weld estimation software connected to a display screen. All types of surface imperfections are possibly detected; refer tables 3 and 4 for different types of imperfection.

Disadvantages

a. Internal defects are not detected
b. Time consuming

4.4. Throat size gauge

Fig. 4. Fan-shaped Gauge for inspecting throat size of weld.

Many gauges are available to check throat size of weldments. Today operators and auditors use fan shaped gauge and automatic weld size weld gauge, shown in the above figure. These gauges are for measurement of concave, convex and flat weld faces with reference to Volvo’s new weld standards. See types of imperfections and considerations in tables 3, 4, 5 and 6 [5]. The weld faces in reality may not look the same as shown in drawing. Difficulties with the types of weld faces are listed below.

a) Concave welds face: Using fan shaped gauge, operators/auditors measure throat size at center of weld face and it is important to know if they knew the exact center on face. Other problem is at toe sides, toes may have very smooth surface (nearly 1-2mm). In this smooth surface where do the operator/auditor measure.

b) Convex weld face: Fan shaped gauge can be used in case of convex welds from toes. If the welds have different leg lengths then operators/auditors may choose the shorter leg length for throat size measurement but it may give wrong results because the real throat size is hidden by the longer leg length. Throat size can be calculated, but cannot be measured.

c) Flat face: This will have the similar problem as mentioned in concave weld face.
4.5. Radius gauge

Transition radius is the most important at weld toes (sides); otherwise undercut at the toes will lead to failure of the structure before its estimated fatigue life. Toe side is evaluated using radius gauges, for reference the gauge is first placed on master block then allied on the weld toe, and light draining between the gauge and the toes, results in a mismatch, as in figure below [13]. Least count radius gauge is 0.25mm but transition radius above 1mm is considered for normal VD class according to Volvo weld standards and 4mm for VB class. Please refer types of imperfections and considerations from tables 3, 4, 5 and 6 [5].

![Image of weld sample indicating penetration, throat size and toe radius](image1.png)

![Image of master block and radius blades used for weld toe radius evaluation](image2.png)

**Fig. 5.** a) Weld sample indicating penetration, throat size and toe radius b) Master block and radius blades used for weld toe radius evaluation [13].

4.6. Liquid (Dye) Penetrant Testing (LPT)

Liquid penetrant testing is a cost-effective NDT method, which detects surface and near surface defects in weldments, a penetrating liquid is applied over a cleaned surface of the component, the liquid enters discontinuities under capillary action, and a test procedure consists of pre-cleaning the component surface for dirt, grease, spatter, welding flux and rust. A penetrant spray is applied over the component surface and is left over for a sufficient time (60 seconds), so that penetrant seeps into the surface defect. Excess penetrant is wiped off from the surface. Developer sprayed enters in root passes and sequential passes to detect surface and near surface defects [2]. Refer flowchart in fig 6. Different types of defects like external porosity, external fatigue cracks can be detected, refer tables 3, 4, 5 and 6. A later cleaning of surface is necessary to avoid corrosion [11]. The dwell time must be followed using the dwell time chart. Penetrant must not be allowed to dry and it shouldn’t be wet. Penetrants are water washable and can be removed by tap water and others using special solvents and paper, it is used during production, processing and maintenance [14]

Surface defects like cracks, tears, cold-shuts, shrinkage, seams and laps are not acceptable in critical components as subjected to dynamic loading; defects such as gas porosity are acceptable to some extent as
they do not affect mechanical properties and are in specified limits as in Volvo standards [5]. It is recommended to use fluorescent dye penetrant for inspection [2].

**Fig. 6. Penetrant test flow diagram[14].**

Advantages

a. Detects surface discontinuities in weldments.
b. Easy to perform the test, inexpensive, easy to clean, portable, applied on region of interest (ROI).
c. This method can locate tight cracks using fluorescent penetrant and considered an absolute method for high production.

Disadvantages

a. The application and true indications require good skill and practice. For example, cracks, seams, laps show continuous lines, the flaw may be partially closed at surface and same in case of porosity, blow holes and inclusions.
b. Penetrants containing toxic chemicals may have deleterious effect on weld material.
c. Dry developers could be a health hazard, testing should be performed in ventilated area.

Limitations

a. Dwelling time differs for defect types.

**4.7. Magnetic particle testing**

Magnetic particle testing technique is extensively used in case of Ferro magnetic materials in locating and evaluating surface defects and sub-surface defects which are not open to surface; this method enables to find defects of 2-3mm from surface, in processing and maintenance. Materials are magnetized by a permanent magnet or along magnetic field produced by an electric current [11]. Principle method is when a Ferro magnetic material is under test, discontinuities which lie in perpendicular will transverse the magnetic field
causing leakage around discontinuity, see fig 8, white contrast sprayed will be left for dwell time (2-3 minutes) then a finely divided ferrous magnetic particles (dry, wet) are sprayed on surface with no dwell time required, these suspended particles are gathered over imperfection to indicate the location, shape, size of discontinuity in material. It is a sensitive method for identification of small and shallow tight surface cracks. Sharp and fine discontinuities close to surface such as non-metallic inclusion can be identified. Pre-cleaning is needed to have a dry surface. Demagnetization is important otherwise strong residual magnetic field may deflect the arc during welding. Testing is performed using yoke poles placed on opposite sides of the weld in inspection as shown in below fig 7b [2]. Discontinuities such as slag inclusions, internal & external pores, and incomplete penetration at root side and other imperfections are shown in detail in the tables 3, 4, 5 and 6.

![Magnetized material flow chart](image1)

**Fig. 7. Magnetic penetrant test a) Testing flow chart b) Yoke test using suspended metallic particles spray on component [15].**

![Magnetic flux leakage around suitably oriented flaws attract magnetic particles](image2)

**Fig. 8. Effect of near surface discontinuity in magnetic field a) Discontinuity causes disruption in magnetic lines of flux, leaving material b) Disruption in magnetic fields is very little [15].**

Material retentivity must be low, the harder the material, the higher is their retentivity; low carbon steels have little or no retentivity and are frequently used with alternating current. The other methods in magnetic particle inspection are the wet and dry continuous methods, using circular magnetization and longitudinal magnetization with direct current, alternating current and half-wave current are also possible [2].
Advantages

a. There is little or no limitation on the sizes and shapes of the parts inspected.
b. Cracks filled with foreign materials can be detected.
c. Variable current control can be used for MPI for variety of applications.
d. Indications may be produced at the cracks that are large enough.

Disadvantages

a. A machine with higher amperage output is needed to detect the discontinuities lying deep and on a large area.
b. Wider cracks will not produce the particular pattern if the surface opening is too wide for particles to bridge.
c. If discontinuity is deeper then indication of the cracks will be little difficult.
d. Detection is not possible when the direction of the crack is parallel to the direction of the magnetic lines of forces, refer b in fig 8.
e. Sensitivity is reduced as the inclination in angle is reduced.
f. Human interpretation is subjective, inconsistent and sometimes biased, so a computer automated image processing technique cannot be used due to liquids used for testing and is no good to automate [16].

Limitations

a. It’s portable but equipment has limited current supply.
b. Local heating and burning of electrical contact testing surfaces.
c. Testing sensitivity is optimum when the direction of the crack and the magnetic force lines meet at an angle of 90 degrees. The work piece has to be magnetized in multiple (90 degrees) directions, so that all cracks oriented in different directions can be detected in a single test, refer a in fig 8.
d. Tiny lack of fusion between seams must be taken care along ROI.

4.8. Eddy Current Testing

Eddy current is based on the principle of electromagnetic induction. This method with application of probe detects surface and near-surface discontinuities for conductive materials; application of probe on component surface is similar to acoustic testing method (ultrasonic), can be used as reference to ultrasonics. An alternating current (frequency 1KHZ - 2MHZ) in a conducting materials can reveal crack sizes of 15-20 microns and the eddy currents in probe does not make direct current contact to inspection surface [11].

Eddy current conductivity measurement depends on shorting, hardness, material composition, heat treatment, microstructure, grain size, segregation, surface condition, dimensional changes, plating, coating and the plate or sheet thickness. Imperfections such as cracks, inclusions, external & internal porosities, cold laps and others are presented in tables 3, 4, 5 and 6 below. Defects can be detected by wrapping a test coil
around plates or probes. As frequency is increased there will be decrease in accuracy because for plates depths greater than 3-3.5mm makes it lose its accuracy [2, 11].

![Diagram of eddy current testing](image)

**Fig. 9. Eddy current a) flow chart sequence of testing b) generation of an eddy current [17].**

An alternating magnetic field is produced when a probe or coil is brought near the electrically conductive surface; eddy currents (electric currents) flow into the material due to electromagnetic induction (normally have circular paths at right angles in a primary field). These eddy currents are parallel to the inspection probe or coil. The presence of any defect or discontinuity disturbs the eddy current flow. These eddy currents in turn, generate an alternate magnetic field in opposite directions to the probe’s primary magnetic field. The direction of the current changes in a magnetic field during inspection as can be seen in fig 9 [2, 11].

Eddy currents are being used in the detection of fatigue cracks and corrosion of complex aircraft geometries. Eddy current c-scan can detect fatigue cracks about 3-3.5 mm from the inspection surface. FEM analysis proves that the low densities of currents are a good choice for deeper penetration inspection and low frequencies for higher sensitivity on selected stressed regions (ROI). ROI may be defined as location of possible damages [18]. It requires skill and an experienced inspector to test and interpret results.

**Advantages**

1. The eddy current probe provides a good alternate to magnetic particle testing.
b. It can detect surface and near surface defects without the removal of coatings.
c. Sensitive to small cracks and other defects.
d. Environmental friendly, offers immediate results, no effluent and cleaning needed.
e. Easily portable equipment.
f. Near surface defects missed by radiography can possibly be detected with an eddy current [19].

Disadvantages

a. Only conductive materials can be inspected.
b. Skill and training is required, refer tables 3 and 4.
c. Density of current decreases with increasing penetration depth [18].
d. More noise due to coarse microstructures.

Limitations

a. Depth of penetration is dependent upon the conducting frequency of eddy currents in the material under inspection [18].
b. Frequency, geometry of test, electrical conductivity, temperature and dimensions [2].

4.9. Radiographic Testing (RT)

In weld testing method using source of radiation as x-rays, gamma rays and neutrons, where x-rays are produced by an x-ray tube, gamma rays by radioactive isotopes and neutrons by fission reaction of uranium elements in a nuclear reactor are invisible and are not affected by magnetic or an electric field, can pass through space without any transfer of matter [11]. Industrial radiography works with the same principle as that of medical radiography; in a medical radiography, the radiation is passed over the human body whereas in an industrial radiography, the radiation is passed over a 3-dimensional weld component, and the resulting internal image structure is printed on a radiograph. The amount of radiation energy absorbed by a
component depends on its thickness and density. For e.g. tungsten, a material with high density shows light images on the film for inclusions. The areas in a weld where less or no energy is absorbed will appear to be dark. Imperfections such as internal and external porosities, cracks, lack of penetration and inclusions will appear as dark regions on film [21]. Almost all types of imperfections mentioned in Volvo standard are possible to detect but lack of fusion is case sensitive, refer tables 3, 4, 5 and 6. Both sides of the weld joint can be inspected, surface preparation is very important and must be free from oil, grease or dirt else it will adversely affect the interpretation results. It is recommended to follow ASTM, IIW and BS for references because evaluations have to be done with standard references to check the difference in degrees of each defect [11]. Radiography is one of the best methods for detecting internal defects of a 3-dimensional weld and the most important thing is the interpretation of results which requires a suitably trained, qualified and an experienced inspector. The working environment is important for interpreting radiographic images because incorrect interpretation can be so expensive that it can affect productivity. Image quality indicators are kept on components to check radiographic sensitivity; IQIs are made of similar materials of component that is to be inspected. Three types of radiography testing are:

- a. Film radiography
- b. Computer radiography
- c. Digital radiography

The overall function of these three is same, but resolution, signal to noise ratio and sensitivity differ.

<table>
<thead>
<tr>
<th>Film radiography and computer radiography (CR)</th>
<th>Digital radiography (DR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The achievable contrast sensitivity is only 5% of the penetrated material thickness.</td>
<td>Contrast sensitivity of digital detector is much better than film and computer radiography.</td>
</tr>
<tr>
<td>The contrast sensitivity (CS) in CR improves with exposure time, after certain level sensitivity cannot be improved even though exposed for longer time or high dose power.</td>
<td>Contrast sensitivity of DDAs improved with exposed time or dose power due to better quantum statistics. High contrast sensitivity achieved in DDAs better compared to X-ray film and CR must be calibrated carefully.</td>
</tr>
<tr>
<td>Quantum correction of flaw size is same in both the cases.</td>
<td>Quantitative correction of flaw sizes is improved using digital measurement tools but the results differ from film and computer interpretations.</td>
</tr>
<tr>
<td>X-ray films and imaging plates are limited to structural fixed pattern due to its crystalline structure &amp; in-homogeneities in test objects contribute to the noise. This effect limits the best achievable contrast sensitivity of CR systems.</td>
<td>If calibrated correctly, DR can achieve more than 100 times signal to noise ratio (SNR) and with 10 times better contrast sensitivity to film and computer radiography if no noise is generated from in-homogeneities in test objects.</td>
</tr>
<tr>
<td>Lack of sharpness in film and computer images.</td>
<td>SNR in DDAs compensate lack of sharpness. Reliable sharpness is achievable by film and computer radiography.</td>
</tr>
<tr>
<td>The performance of CR systems is limited by its fixed pattern structure.</td>
<td>If the voltage of the tube is increased above its limits, the efficiency is improved.</td>
</tr>
</tbody>
</table>

The essential parameters are basic spatial resolution; signal-to-noise ratio (SNR) and specific contrast (scatter effects). The sensitivity of radiographs is typically evaluated by image quality indicators (IQI) and other important parameters could be the viewing conditions, monitor brightness, and pixel size which
influence the visibility of image quality indicators (IQI). IQI sensitivity is based on detection camera or human eye. Applied to pipeline welds, castings, electronic assemblies, wheels, rails, aerospace, nuclear reactors, bridges and many other industrial uses [22]. Refer tables 3, 4, 5 and 6.

Advantages

a. Minimum maintenance is sufficient [2].
b. Testing technique does not depend on material type and its density.
c. Possible to inspect assembly components.
d. Inspection data can be permanently saved.
e. Source output can be increased by increasing the current input.

Disadvantages

a. It cannot detect lack of fusion [19].
b. Expensive and slow method [22].
c. X-rays and gamma rays have serious effects on health and safety, radiations results in undesirable somatic and genetic effects [11].
d. Viewing of the radiographs requires a dark room, otherwise films can be damaged.
e. If the density of inclusion size is the same as that of the component, then its data is hard to interpret using radiograph and it is not an effective method for detecting planar defects [11].
f. Defects sizes are larger on radiographs when compared to real-time [2].

Limitations

a. If radiation is directed obliquely to the plane of the crack then the image will be faint and even disappears if the angle of incidence increases.
b. The interpreter must have adequate eye sight, able to identify the images of various weld conditions.
c. Technique sensitivity varies for pores, cracks and density of material.
d. Penetration over surface is necessary.
4.10. Ultrasonics Testing

![Ultrasonic testing flow diagram.](image)

High frequency sound waves introduced into a material reflect back from defective surfaces, the relative sound energy is displayed versus time in a CRT screen build within. An equipment inspector can anticipate a cross section of the specimen showing the depth, shape and size of defects. A couplant is applied on a component before inspection so that the air between the probe and the component does not disturb the sound waves; else they get dissipated into air.

Acoustics is attributed to time varying deformation or vibrations in material, ultrasonic non-destructive testing works on acoustics. It is composed of many atoms that move in concordance, yielding mechanical waves into the material for inspection. These waves do not disturb the mechanical properties of the material; they propagate as elastic oscillations through solid medium, these waves cannot travel through liquids and gases. Sound waves in solids propagate in four modes:

- *a.* Longitudinal waves
- *b.* Shear waves or transverse waves
- *c.* Surface waves
- *d.* Plate waves (i.e. in case of thin materials)

Among the four modes, longitudinal and shear waves are extensively used in ultrasonics. The wavelength of sound changes if the frequency is altered but sound velocity will be fixed because these waves are reliable in detecting discontinuities. Higher frequencies have shorter wavelengths that increase sensitivity for detecting defects. Resolution has the ability to locate near surface defects, both frequency and resolution are interrelated because resolution and frequency increases reliability in finding defects whereas other variables
that have reliability in detection are pulse length, type of voltage applied to the crystal, properties of the crystal, backing material, transducer diameter, and the receiver circuitry of the instrument. It is important to know that the discontinuity in material must be larger than one-half the wavelength to detect the defects [11].

**Longitudinal waves:** Longitudinal waves oscillate in direction of wave propagation because compression and dilatational forces are active in longitudinal waves. These waves are called as pressure waves, compression waves and density waves because particles in waves fluctuate as they oscillate in medium [2].

**Shear waves:** Shear waves or transverse wave particles oscillate at right angles or in transverse to the direction of propagation. These waves are originated using some of energy from longitudinal waves; shear waves are weak when compared to longitudinal waves; during testing, majority of transmitted energy is lost due to absorption and diffusion by the material under test [2, 23]. Angle beam transducers are used for converting longitudinal waves to shear waves. Longitudinal waves get refracted and converted to shear waves which propagate in the material medium. In this process, the probe scans the surface of material around the weld. These refracted sound waves will bounce back or reflect from discontinuities in their path showing the orientation of the defects. AWS D1.1 standard can be followed by the inspector for inspection as many AWS inspections are performed using refracted shear waves. The operator must use proper angle techniques for detecting discontinuities [24].

Generally ultrasonic testing used for in-service and maintenance of mill rolls, rail-road rolling-stock axles, mining equipment, welded pipes in chemical and nuclear plants, boilers etc. If the operator is not well trained and experienced, the inspection results may interpret gross errors. Online testing of welds is possible using ultrasonics but gives fluctuating results, tested at Brunei University using pulse-echo method [2].

**Conventional or pulse echo technique:** A longitudinal wave hits the surface at an angle, during mode conversion; energy changes the movement of particles from transverse to shear waves. This method is also called as traditional pulse echo technique, of detecting defects using the selected angle probes (i.e.70 or 60 degree probes). Probe is moved between skip distance and half skip distance on one side of weld using A-scan for detection, refer fig.13. Defects are detected if sound waves are perpendicular to flaw. The size of discontinuity is estimated by comparing the signal amplitudes obtained from known and unknown reflectors. Defects outside a selected probe angle cannot be detected [24].
**TOFD technique:** Time of Flight Diffraction (TOFD) works on the same principle (shear waves) as pulse echo and is considered the fastest method of non-destructive testing for characterization of weld with a single scan along with linear direction (B-scan) with two probes on either sides of the weld [24]. It is a fully computerized scan, which can store and indicate the height, length and position of defects accurately. Accuracy of flaw detection is higher when compared to other ultrasonic techniques, TOFD can detect defects if they are perpendicular to ultrasonic sound beam, direct, reflected, diffracted waves are used for accurate sizing of defects because the material attenuation and orientation of defects are less critical when compared to pulse echo method [2, 25]. The first echo that passes over the surface of specimen is referred to as a lateral wave. If there is a flaw then the diffraction echo will be seen between the lateral wave and the back wall echo. For a better understanding, refer to the fig below [26]. TOFD has two dead zones one at top surface (ID) and other at bottom surface (OD), where defects cannot be detected. These two dead zones are located near the Lateral Wave and near the Back wall reflection. The depth of these two dead zones depends on the TOFD configuration, frequency and damping. For example, at 7.5 MHz, the lateral wave (OD) dead zone is around 3mm, while the back wall (ID) dead zone is around 1mm [27].

![Fig. 12. Schematic representation of ultrasonic TOFD [26].](image)

TOFD detects the defects which can also be detected by other methods such as pulse echo technique and radiography. If their images are compared TOFD shows much more reliable results [23]. One transducer pair can detect up to 50 mm plate thickness in a single pass. To increase the probability of detection, multiple transducers can be used [27]. Different algorithms can be used in TOFD, such as principle component analysis (PCA) & Karhunen-Loève (KL) transformation expansion technique to detect lack of fusion, lack of penetration and porosities [28].

**4.10.1. Phased array technique**

The ultrasonic phased array (PAUT) technique makes use of transducers consisting of multiple ultrasonic elements that can be driven independently [29]. Phased array transducers can have a different geometries,
for e.g. linear, matrix and annular; and the beams can be steered, scanned and focused electronically. A couplant is applied between the transducer and the test part [30]. A great advantage about the phased array when compared to the TOFD & pulse echo is its competency of having both A-scan and sectorial scan, a transducer with multiple elements is the heart of PAUT, the range of elements being 16 to 256 [31]. PAUT is a tightly focused transducer which works like a search light in welds. It can possibly detect all defects using different angles; images show the sliced view of hidden defects. Frequency of transducers generally used is 2 MHz to 10 MHz [29, 32]. Ultrasound attenuation occurs if the inspection distance increases. Other factors that attenuate probability of detection are coarse grain, grain boundaries, in-homogeneity and inclusions. Refer the tables 3, 4, 5 and 6 for different defects and consolidations [33]. Welds can be tested by straight beam and angle beam techniques. Angle beam technique is commonly used and straight beam technique requires weld beads to be ground for flat scanning surface [11]. The probe needs to be taken closer to the weld to see the defects present in the range of angles (from S to S/2). The reflected beam to the transducer gives the defect details from the plates. In sector scan, we look at the entire angle at the same time. \( P \) is the distance from the probe to the defect in the weld and \( D \) is the depth to the defect from the surface, \( S \) is the velocity, \( t \) is the thickness of plate and \( x \) is the distance from output to the front of the probe. See fig below. Scanning techniques generally used in PAUT are linear scanning, dynamic depth focussing and sectorial scanning.

![Fig. 13. Sectorial scan using PAUT.](image)

**4.10.2. ** **PAUT & TOFD technique**

Phased Array Ultrasonic Testing (PAUT) and Time of Flight Diffraction (TOFD) can be combined into a single equipment which gives high probability for detecting (POD) and is more reliable in providing the exact size, location and orientation of the defects. It is an algorithm integrated with ultra-vision 3 software which gives information regarding the PAUT sectorial top view, side view and end view of the ROI (region of interest) along with TOFD images. An inspector using this equipment can double check the PAUT (side
view, top view and end view) along with the TOFD data. It is an optimum method for detecting orientation, size and exact location of defects and can function well with different algorithms (i.e. neural network algorithm) [34, 35].

![Fig. 14. S-Scans & TOFD data acquired with the ZIRCON [34].](image)

**Advantages**

a. PAUT can detect the grain size in a single plane [33].

b. High sensitivity in detecting extremely tight cracks [2].

c. Automated defect detection algorithms work very well for detecting flaws during welding while using the ultrasonic time of flight diffraction (TOFD) method.

d. TOFD is a powerful technique allowing good midwall defect detection, accurate sizing, detection of oriented defects, and fast linear scanning [27].

**Disadvantages**

a. Coarse grains inclusions and in-homogeneities in the material are the reasons for ultrasonic attenuation, reduced ultrasonic ability to penetrate, causing reduced echo height and scattering losses [11, 33].

b. Alignment of the probe carrier is critical during scanning, and a misalignment of only 2 or 3mm can also invalidate the examination [34].

c. Probes quickly degrade after exposing to high temperatures for more than 2 minutes during online inspection.

d. Conventional ultrasonics cannot detect several defects detected by radiography.

e. Couplant chemicals can cause corrosion.

f. In online detection of welds, a liquid-solid interface fails to provide reflected signals (fluctuating results).

g. Difficult to find a reliable NDT-method for cold laps [6].
Limitations

a. An inspector must make a decision about the frequency of the transducer that will be used. TOFD limitation is the dead zones [27].
b. The combination of PAUT sectorial scanning and TOFD is a robust inspection technique that should be preferred over RT for a wide range of weld types [34].
c. Limitations are often experienced with conventional ultrasonic transducers when dealing with sensitivity, reliability and for complete imaging of defects [29].
d. Ultrasonic research examinations are carried on a butt weld, it is even important to see if they could detect fillet welds.
e. Parameters of the interpretation software required some 'tuning' between scans of different resolutions because different spatial resolutions occupied by the defect and their differing signal-to-noise ratio of the ultrasonic signals.
f. Equipment has to be calibrated regularly.

4.11. Thermography

All objects emit electromagnetic radiations at or above ambient temperatures; these radiations are referred to as infrared radiations which are extensively used in NDT method with IR resolution of 320 × 240 pixels and spectrum range of about 0.8–20μm. The hotter the object, the more intense is their emission of infra-red radiation. IR radiations are invisible to the naked eye but with the help of an external detector, defects up till 5mm deep can be detected [36]. The image and measure areas during an inspection show the problems and their severity. The component surface temperature changes are conceived using thermal images. IR spectrum intensity depends on the body temperatures and is a non-contact mode of detection using high resolution thermographic camera [2]. It is widely used in the petroleum industry, piping, refining furnaces, welding, food industry, blast furnaces. Thermography is put down into two categories, which are active and passive.

Passive technique: The measurement of heat distribution and inspection during welding [2]. Non-destructive IR-thermography is the best choice for weld control and process monitoring. It monitors the variations in arc positioning and heat input using IR camera as a differentiator in spatial and temporal surface distributions [2, 37-39]. IR-camera can be fixed at a distance of 1 meter from the component surface on the torch during welding, the entire weld can be seen during the process and it is possible to see the variations in temperature at weld pool. Images viewed during process can be recorded using a flash disk that can be reviewed and analyzed later for justification. To detect ability of defects such as misalignments, voids, inclusions, layer thicknesses, and lack of penetration and depth of penetration which are dependent on the physical properties (heat capacity, heat conductivity, density, and
emissivity) of the component. Abnormal temperature changes on a component indicate the hidden problems which are clarified by setting absolute process parameters [37].

Online weld analysis has been performed using two TVs, an IR camera, and the voltage and current details as shown in fig below. IR and TV1 camera will observe the weld area and the pool as it cools down whereas TV2 is placed parallel to the torch to have a clear image of the welding process. It can be a good idea to point out the region of interest (ROI). ROI could be the highly stressed portions in the structure [39]. Thermal imaging of incomplete penetration and lack of penetration depth are clearly visible from below fig 15 and fig 16 that shows lack of material (air gap) at root which appears as a cold spot at the centre of weld, depth of penetration in fig 16 a) depends on heat input and distribution of heat energy as the graph represents that thermal profile across the weld pool and area under thermal distribution curve have linear relation which can be used as indicator, since the area under thermal curve is in direct relation to the weld input power, this parameter can be used as feedback for control. The resultant data, acquired after a thermography test is accurate, as it depicts that a weld can be cross-tested by destructive testing, as shown in fig 16 [37].

**Fig. 15.** IR-thermographic a) test flow diagram b) position for observing weld process c) lack of penetration detection [37, 39].

**Fig. 16.** Penetration depth captured using a) IR-thermographic camera for 100 % and 60% penetration b) double checked by destructive testing c) graph shows thermal area Vs input power of welding machine [37].
**Active technique:** External heat is applied using laser, lamp and induction on the completed weld surface and the change in temperatures over the surface are captured as images by a thermographic camera [2]. External heat is supplied to the test surfaces for detecting the changes in thermal contrast. Other active methods in IR detection are by sonic or ultrasonic energy using welding horn which in this case is known as vibrometry or sonic infrared. In this case, excited energy vibrates the material undergoing inspection, due to this vibration, crack faces rub against each other and mechanical energy is converted to heat energy, thereby identifies the surface defects [40]. The vibration and rotation of atoms and molecules increase as their temperatures rise, thereby increasing their kinetic motion, in turn generates more infrared energy [41].

### 4.11.1. Eddy current and lasers in thermography

Eddy current thermography is one of the appearing technologies in non-destructive testing. The testing is carried out in combination of eddy current and thermography camera for faster detection of defects in complex geometries. Infrared thermography gives quantitative information from analyzed images in inspection. This technique occurs with advanced signal analysis for defect detection in many critical areas of inspection. Identification of sub-surface defects where the heat is deposited on inspection surface using induction heater coil where current (Eddy currents, joule’s law) propagates through the material for defect identification based on thermal distribution thus thermographic images indicate major defects in short time [40]. Similarly IR lasers can be used to heat the surfaces for detecting smaller cracks above 0.5 mm, the amount of energy absorbed depends on the width of the crack, wider the crack more the radiation absorbed, if the wavelength of the light is larger than the width of the crack then light will not enter the crack, if the length of the crack is shorter than 0.5mm, it is difficult, as it depends on the resolution of the IR camera and the time of heating is nearly 2ms, larger cracks can be seen without excitation. Oxides on the weld are good absorbers for thermal distribution [16].

Infrared thermography is a powerful method in parameter identification of welding process. IR thermography is the working concept of blackbody and the Planck’s law [42].

Signal to noise ratio (SNR) determines which processing algorithm is more suitable in detecting the defects because it is necessary to have sufficient thermal contrast between defective and non-defective areas. The defective area is considered as “signal” and sound area considered as “noise”. Skewness and Kurtosis based algorithms provides information regarding detection of defects due to changing gas flow pressure which gives poor results to other methods, such as pulsed phase transform (PPT) method which detects gas flow pressure, inclusions and lack of penetration with inaccuracy. Principle component analysis (PCA) is the best
among the methods because it detects all types of defects including lack of penetration due to inadequate welding and inconstant thicknesses [38].

![Eddy current thermography system setup and temperature distribution](image)

Fig. 17. Eddy current thermography a) system setup b) temperature distribution after 100ms of heating for rail head sample [40].

Advantages

- **a.** Wide area inspection can be carried out in a short time when compared to other NDT techniques [40].
- **b.** Visualization can be done immediately for quantitative evaluation of recorded images [40].
- **c.** Direct contact using Eddy current can increase detect ability but may damage the material under inspection [40].
- **d.** Thermography could be attached a few millimeters back of the torch, and as the HAZ cools quicker, it may be possible to detect the defects faster.
- **e.** Detects arcmisalignment, helps to differentiate between good and bad welds [2].
- **f.** Reduce the cost of rework.

Disadvantages

- **a.** Issues with SNR: the amount of heat reflected from material under inspection using IR thermography can conflict with the measured signal [40].
- **b.** It is difficult to heat the material surface in very short time for detection using thermography.
- **c.** Deception in contact between material surface and welding horn gives unpredictable results from contact to contact [40].
- **d.** Relation between the eddy current heat generation and the temperature (thermal contrast) is unclear because there is a decrease in conductivity with an increase in temperature [40].
- **e.** Angle oriented defects in some cases interpret false results [40].
- **f.** Constantly changing shielding gas pressure and insufficient heat input [38].
- **g.** Lack of fusion will be difficult to detect, the detect ability would depend on the field of view, spatial resolution and thermal contrast sensitivity.

Limitations

- **a.** Taking a thermogram of an object at an earlier or later time may result in a very different temperature distribution; which differs if the object is in a heated or a cooled condition.
b. The surface appearance by infrared system must represent a uniform temperature over the whole surface during an examination.

c. Inspections in presence of shadows in not permitted, and may give unpredictable/confusing results.

d. The angle of observation is very important during active and passive testing techniques [36].

e. Lot of manpower, money and time is consumed to know soundness of the weld [37].

4.12. **Reliability of NDT methods**

Human factors have a negative effect on the reliability of NDT methods; variations can be observed in individual testing, differences in testing procedures and the accuracy of the equipment being used. A human factor refers to the things that need to be controlled to obtain optimum unfailing performance such as human qualification, technology, organization and manufacturer. It was also seen that the inspector’s attitude will have effect on inspection [43]. Increased scattering depends on experimental condition like:

a. Time pressure (heat, noise, limitation to perform the task) decreases the quality of inspection, hence giving scattering results.

b. Variations in individual performances, inspectors with ≥ 8 years of experience have higher reliability in results when compared to the inexperienced.

c. Higher demands for selected demonstrator results in mental work load and performance.

d. Error in identification of defects, sizing and its location, problems in taking decision because of limitations in software and hardware of the equipment and operator individuality differences [44].

It is observed that an operator puts less effort in group work than in working individually which is referred to as “social loafing” [45]. The above results will have effect on safety and cost. To achieve consistency in NDT inspection, the organization must have reliable equipment, right procedures and skilled inspectors; because the huge amount of variations can be found in between the inspectors as they are the ones who interpret the results from the equipment. Independence between two skilled inspectors during inspection lessens variations. From previous researches, it was stated that automation bias occurs [46, 47].

5. **Analysis**

The above table’s 3 and 4 are matrix with types of imperfections and non-destructive testing methods for identification of reliable method for defect detection. All NDT methods can’t detect all types of imperfections. Types of imperfections listed in standard are analyzed with yes, no and not always, that are shown in tables 3 and 4. It shows that macro test and thermography can detect almost all imperfections. Tables 5 and 6 are the matrix with other considerations and non-destructive testing methods. It describes
type of defects, time of results, skill, training, equipment portability, equipment cost, inspection cost, material composition, automate, effect of geometry, consumable cost and equipment sensitivity. These are the results from testing and theoretical analysis.

### Table 3. Detection of defects using NDT methods

<table>
<thead>
<tr>
<th>S.no</th>
<th>Types of imperfection</th>
<th>Visual inspection</th>
<th>Macro test</th>
<th>Impressions</th>
<th>Throat size gauge</th>
<th>Radius gauge</th>
<th>LPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Internal and external cracks</td>
<td>External</td>
<td>Internal</td>
<td>External</td>
<td>No</td>
<td>No</td>
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<tr>
<td>102</td>
<td>Overlap and cold lap (is kind a lack of fusion)</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
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<td>Internal lack of fusion</td>
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<td>No</td>
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<td>No</td>
<td>No</td>
</tr>
<tr>
<td>114</td>
<td>Surface porosities</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>115</td>
<td>Pipe (craters)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>201</td>
<td>Leg deviation</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>202</td>
<td>Weld reinforcement</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>203</td>
<td>Arc strikes and spatter</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>204</td>
<td>Bad fit-up</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>301</td>
<td>Excessive penetration</td>
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<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>302</td>
<td>Incomplete root penetration</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>303</td>
<td>Root defect</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
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</table>

### Table 4. Detection of defects using NDT methods

<table>
<thead>
<tr>
<th>S.no</th>
<th>Types of imperfection</th>
<th>MPT</th>
<th>Eddy current</th>
<th>Radiography</th>
<th>Ultrasonic's</th>
<th>IR-Thermography</th>
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</thead>
<tbody>
<tr>
<td>101</td>
<td>Internal and external cracks</td>
<td>External</td>
<td>External</td>
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<td>Yes</td>
<td>Yes</td>
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<tr>
<td>102</td>
<td>Overlap and cold lap (is kind a lack of fusion)</td>
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<td>Yes</td>
<td>Yes</td>
<td>Not always</td>
<td>Yes</td>
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<td>103</td>
<td>External lack of fusion</td>
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<td>Yes</td>
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<td>Yes</td>
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<tr>
<td>104</td>
<td>Internal lack of fusion</td>
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<td>Not always</td>
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<tr>
<td>106</td>
<td>Outer transition radius</td>
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<td>No</td>
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<td>No</td>
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<tr>
<td>107</td>
<td>Undercut</td>
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<td>Yes</td>
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<tr>
<td>108</td>
<td>Underpassed throat (a-dimension)</td>
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<td>No</td>
<td>No</td>
<td>No</td>
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<td>109</td>
<td>Non-filled weld</td>
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<td>110</td>
<td>Edge displacement</td>
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<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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<td>112</td>
<td>Inner porosities/Slag inclusions</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>114</td>
<td>Surface porosities</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>115</td>
<td>Pipe (craters)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>201</td>
<td>Leg deviation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Not always</td>
</tr>
<tr>
<td>202</td>
<td>Weld reinforcement</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>203</td>
<td>Arc strikes and spatter</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>204</td>
<td>Bad fit-up</td>
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<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>301</td>
<td>Excessive penetration</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>302</td>
<td>Incomplete root penetration</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Not always</td>
<td>Yes</td>
</tr>
<tr>
<td>303</td>
<td>Root defect</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
### Table 5. Considerations with NDT methods

<table>
<thead>
<tr>
<th>Considerations</th>
<th>Visual Inspection</th>
<th>Macro</th>
<th>Impression</th>
<th>Throat size gauge</th>
<th>Radius gauge</th>
<th>Liquid penetrant testing</th>
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<tbody>
<tr>
<td><strong>Type of defects</strong></td>
<td>External</td>
<td>All</td>
<td>All</td>
<td>External</td>
<td>External</td>
<td>Surface cracks</td>
</tr>
<tr>
<td><strong>Time of results</strong></td>
<td>Immediate</td>
<td>Delayed</td>
<td>Delayed</td>
<td>Immediate</td>
<td>Immediate</td>
<td>Short delay</td>
</tr>
<tr>
<td><strong>Training</strong></td>
<td>Medium</td>
<td>Important</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Skill</strong></td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
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<tr>
<td><strong>Equipment portability</strong></td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td><strong>Equipment cost</strong></td>
<td>D</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td><strong>Inspection cost</strong></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Dependant on Material composition</strong></td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Automate</strong></td>
<td>Not possible</td>
<td>Not possible</td>
<td>Not possible</td>
<td>Not possible</td>
<td>Not possible</td>
<td>Fair</td>
</tr>
<tr>
<td><strong>Effect of geometry</strong></td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Not important</td>
</tr>
<tr>
<td><strong>Consumables cost</strong></td>
<td>NIL</td>
<td>High</td>
<td>Medium</td>
<td>NIL</td>
<td>NIL</td>
<td>C/D</td>
</tr>
<tr>
<td><strong>Equipment sensitivity</strong></td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>

### Table 6. Considerations with NDT methods

<table>
<thead>
<tr>
<th>Considerations</th>
<th>Magnetic particle testing</th>
<th>Eddy current</th>
<th>Radiography</th>
<th>Ultrasonic’s</th>
<th>Thermo grapy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of defects</strong></td>
<td>External</td>
<td>External</td>
<td>All</td>
<td>Internal</td>
<td>Internal</td>
</tr>
<tr>
<td><strong>Time of results</strong></td>
<td>Short delay</td>
<td>Immediate</td>
<td>Short delay</td>
<td>Immediate</td>
<td>Immediate</td>
</tr>
<tr>
<td><strong>Training</strong></td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td><strong>Skill</strong></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Equipment portability</strong></td>
<td>Medium/High</td>
<td>Medium/High</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Equipment cost</strong></td>
<td>D</td>
<td>C</td>
<td>A</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td><strong>Inspection cost</strong></td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Dependant on Material composition</strong></td>
<td>Magnetic</td>
<td>Conductive</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Automate</strong></td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Effect of geometry</strong></td>
<td>Not important</td>
<td>Important</td>
<td>Not important</td>
<td>Important</td>
<td>Important</td>
</tr>
<tr>
<td><strong>Consumables cost</strong></td>
<td>C/D</td>
<td>D</td>
<td>B</td>
<td>B/C</td>
<td>NIL</td>
</tr>
<tr>
<td><strong>Equipment sensitivity</strong></td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
Tables 7 and 8 show the inspection cost per hour for each NDT testing method, which includes equipment cost, electricity cost, consumables cost, labor cost, maintenance cost, training cost/safety cost, range and all these gives inspection cost per hour, inspection cost increased due to labor cost and electricity cost. Electricity cost is included in MPT, eddy current, ultrasonics and IR-Thermography because their battery needs to be charged before testing. Per hour cost for each method is shown. If we divide the cost per minute by defects per minute, we get the cost per defect. Per minute cost in tables 7 and 8 are excluding electricity cost and labor cost for all methods.

6. Case study: Demonstrator part

6.1. Product description

Articulated hauler with six-wheel drive was founded in 1947, based on the marriage between a tractor and a loading unit and is still the brand leader. Demonstrator part carries a load of an articulated hauler from the
rear axles into the frame and the reason of using a demonstrator part with two rear axles is to climb over
hinders like stones where other conventional trucks are unable to perform. Besides the six-wheel drive, one
necessary feature of the hauler is the rear suspension system to enable the mobility in difficult terrain and
the passing of a high hinder the rear axles will move in the vertical direction. At the same time, the weight
of the body is distributed to the rear axles under driving conditions by a rotatable demonstrator part. The
demonstrator part is connected to the rear axles, separated by rubber springs called “Supports”, see fig 18.
The centre of rotation is the rubber-metal composite bearing, while the demonstrator part is bolted to the
axles. As the demonstrator part sometimes may have slightly different leg lengths casted iron end-caps are
applied at the ends of the demonstrator part to achieve a quasi-symmetric structure, see below schematic
diagram of demo; due to this it is not necessary to distinguish between a left and a right beam in production.
The biggest machine has a load capacity of 40 tons today in production.

![Articulated hauler [4].](image)

### 6.2. Production of current demonstrator part

Production of a present demonstrator part starts with a laser beam cutting (0.2mm tolerance) plates with
15mm and 10mm for flanges and web, steel grade with 350Mpa yield strength. The turning of the sleeve
bearing partly built with rubber, is fixed, and followed by attaching the bend lower flange plates.
Demonstrator parts are assembled and checked for misalignment, and they are tack welded in the fixture for
fixed assembly and low distortions. The process is continued by a robot welding with flux-cored wire.
Where a robot cannot reach at all corners of the assembly, so the start and stop positions are welded
manually. Flux-cored MAG welding shows compressive residual stresses at the weld toe (40-180 Mpa).
almost nil to very less weld defects (cold laps < 0.03mm) and high fatigue strength (110Mpa) [6]. If needed, post treatment can be carried out with a VB type weld class which can be used in specific sub models (transition radius, sleeve, lower corner and centre upper flange) as shown in fig.20. The overall demonstrator quality is assured by experienced quality auditor using non-destructive testing methods such as visual inspection, radius gauge, throat size gage and ultrasonic pulse echo for weld reliability for selected demonstrator from production samples. Refer fig.19 for today’s testing plan. After quality inspection, the demonstrator is shot blasted and painted. Until here the production process is the same for all demonstrator designs. In this thesis, the box type demonstrator welded structure in the hauler is used i.e. the machine has a loading capacity of 30 tons and current weight of the demonstrator part is 183kg [4, 6]. Till date there are no failures experienced in the present demonstrator parts.
6.3. **Weight reduced demonstrator parts**

Weight reduction in a demonstrator part is connected to WIQ and LOST projects where a weight reduction of 20% was intended. Demo optimized-X demonstrator parts are obtained by choosing appropriate material choices with increased material properties, improved calculations and design changes which depend on component functioning and its loading conditions with present process facilities [4]. Steel structure welding is the most common and efficient technology practiced in welding. Reduced plate thickness demonstrator structure could be used in Haulers. Dynamic loading conditions of demonstrator results in stress concentrations at toe and root of weld which will affect the overall fatigue life of the structure leading to a failure before its estimated service life. New Volvo weld standards are in practice to improve quality assurance in production and to ensure safety against failure, in accordance to right design using right weld demands on demonstrator joints. In an optimized-X demonstrator parts the design has been changed with increased radius at transition, sleeve casted to have butt weld and lower flange changed to one single piece, the casted end caps replaced with plates of flange thicknesses, design has been modified to increase the stiffness of the structure at critical fatigue positions with reduced plate thicknesses of 12/6, 12/5 and 10/5 where a 12mm and a 10 mm is for the selected flange with selected yield strength of 500Mpa and 600Mpa and a 6mm and a 5mm are the thicknesses of the webs for selected yield strength of 600Mpa. The equivalent stress at the centre of upper flange is 360Mpa for which the safety factor against yielding is 1.6, whereas the
safety factor for plasticity for an original demo design was 1.5 with yield strength of 355Mpa and maximum equivalent strength of 232Mpa at centre of upper flange [4].

Different weld types are tested at different stress positions of demonstrator with different designs using design software; ANSYS with global FEM model using von misses stress due to complex stress states in most cases the critical one [4]. Design of experiments and sub modeling technique proceeded by FEM analysis was performed by effective notch method for toe and root of weld because stress concentration at these positions arise due to complex geometric loading conditions. Structural failure analysis for weight reduced demonstrator part under extreme load conditions were carried by buckling analysis, see sub model in fig 21 for present demonstrators. See fig. 22 sub models for WIQ demonstrators. In proposed light-weight designs the above production process is similar as in case of present demonstrator parts and is recommended to post-treat welds by TIG treatment (Tungsten inert gas welding) because light weight structures will have 25% higher stress levels in dynamic loading. Based on the data from previous thesis and project ‘LOST’, the overall weight of demonstrator parts were reduced by 39% using thinner plates of 10mm for flange and 5mm for web without changing the overall dimensions [4].

6.4. Post treatment

During welding different defects such as geometrical discontinuities and weld defects are introduced in the weldments that will have a negative effect on the fatigue life of a demonstrator. To minimize these defects, welds are post-treated. Multiple loading will introduce compressive residual stresses at surfaces and removes some of the cold lap and spatters [6]. Fatigue life can be improved by introducing smoother (even) transition between weld and parent material at toe sides. Minimum defects and compressive residual stresses will reduce the stress concentration at the root [49]. Due to a smoother transition radius, the starting positions of cracks are suppressed by re-melting the transition area at the weld toe. Re-melting is done using tungsten electrode arc welding with argon or argon-helium mixture as the shielding gases. It is important to remember that the root side of a weld cannot be post-treated. A lack of penetration is the main cause at the roots; therefore it is highly recommended to have the required penetration at root [4].

6.5. Design limits for fatigue assessment

To evaluate the fatigue life of a structure as well as to design the machine for customer needs, a realistic design load database is used. VCE uses an own test track reflecting the real life working conditions. During testing, the machine is equipped with strain gauges at position of interest and is driven one hour on the test track, the strains are continuously recorded while driving, the gauges make it possible to calculate the forces acting at these positions, and the load time history is then scaled to estimated operating time. The forces are
categorized using rain flow counting. The result of this counting are the magnitude forces respective to cumulative number of cycles; a concept of fatigue equivalent load is used [50]. Dynamic simulations are carried out to develop extreme load cases for light-weight structures [4]. The fillet weld size in design is decided. Generally it is said that the guideline is very simple ‘‘Rule of thumb’’ s7a5 in the present demonstrator part. It is according to old standards. i2a5 (s7a5) is the most ordinary requirement that a production technician recommends the design department and they always start with i2a5 (s7a5). In this production phase, the design department has learnt that penetration is more important than throat size. Years earlier, production did not have much influence in the design phase, so the basic start for the design taken here is i2a5, as from a robotic welding a 3mm penetration could be achieved and the design department later reduced it to 2mm. An effective notch analysis is run, if it is ok, it is then used and if not, they check if the error is in the toe side or the root side. i2a5 is a start point and at lowest to see if it lasts for 100,000 hrs. This is the lowest weld demand production have today. The test track at braås plant tests the machines and it really worked on hinder's terrain. A signal size of 1000 cycles/hrs could give approximately the same amount of damage, which is called equivalent load, and an equivalent load of 1 is kept as fatigue load. Recorded load time histories of torsion cases, driving of the demonstrator on terrain are extracted using computational simulations with ADAMS-CAR from an earlier project [4, 50]. A (DU [3]) shows correlation between criticality and stress level in a weld (refer STD 105-0001), from old standards D is Weld class, U is Fatigue (even transition) and [3] is criticality (repairing without stopping vehicle). A criticality of [3] can be removed from the drawing because it is not of much significance. Production can have drawings with criticality level indicated for hot spot stress areas of the demonstrator part. NDT-ultrasonic can be on level [2] (leading to stoppage of vehicle) in a drawing and to look at the points which have high criticality and monitor the criticality. The hot spots mentioned in the drawing with the criticality levels in production and a quality control.

In the present demonstrator parts, the global weld type of i2a5 does not show any failures in real service life. Different weld positions in a demonstrator will have different fatigue life estimations, due to the maximum stress levels acting at these positions different weld types are accounted for weight reduced demonstrators.
6.6. Optimized demonstrator parts

The design and weld demands for the light-weight demonstrator part is confined to keep same chassis clearance distance between lower corners, upper flange to the centre. The demonstrator structure is subjected to torsion load, and to reduce torsion stiffness, it was suggested to conventionalize box type demonstrator part structure, by removing end caps on both sides with end plates with the same thickness that of flanges, and adding a top plate of rubber spring from support near transition radius, for weight and cost savings. The critical fillet weld between sleeve and web geometry changed to butt weld to achieve a higher penetration. DOE’s (design of experiments) was performed for parameter identification and interactions at the toe and the root.
Reasonable weld types are obtained for weight reduction; the changed design parameters are detected and evaluated using a design of experiments. On this basis, the best set of parameters and weld demands are selected for three different plate thicknesses. Optimized 10/5 is demonstrator with 10mm flange and 5mm web thicknesses, in this the stiffness of structure is decreased due to higher stresses in a demonstrator which needs higher weld requirements to satisfy over all life of a demonstrator and a high strength steel material selected for the design in yield strength of 600Mpa with a safety factor for plasticity is 1.6. The weld types for the design are 5/8i4 along the lower flange up to the end of transition radius, 5/8i2 weld type at centre part of lower flange, 5/8i3 at the rear part of upper flange and a4i1 in the middle section. All the above weld types are within the VD weld class, but weld toe above the support is not satisfied with 5/8i4 which may require a post-treatment. The weld class VB may be necessary in this case because double fatigue life is expected if weld class is increased by one step. FEM analysis shows that the above weld demands are satisfactory, see demo optimized – X in above fig.22 [4, 5].

The weight saving of a demonstrator part to reduce the production cost with different light-weight designs was proposed in project ‘Lost and previous’ thesis. The reduced weld demands are proposed for weight reduced demonstrator parts, with this we will have a less deposition material in a weld i.e. an estimated reduction of 28% deposition material could be obtained when compared to the actual design. These reduced weld requirements can possibly be achieved with a higher welding speed, as well as a reduced welding time decreases the action period of a welding robot with increased productivity at the welding station. Generally the demonstrator part production process as mentioned earlier starts with tack welding, finish welding and
post-treatment with TIG treatment, but at present there is no prototype produced with weight-reduced demonstrator parts, different weld types show that the fatigue life could be increased if penetration at root side is increased. It is also important to check if the different weld types satisfy the weight-reduced demonstrator parts in real-time [4].

6.7. Shakedown analysis

Shakedown analysis was performed to check if there was any plastic deformation during cyclic loading. As we remember the residual stresses are present in the weld component, these residual stresses prevents plastic deformations for consecutive load cycles. More load must be needed to cross over localized stresses, if the next cyclic load history does not exceed the residual stress level; the stress field will relax causing elastic behavior. Shakedown analysis was performed by applying maximum load limit until the plastic deformation occurs; maximum load case and torsion loads are applied on the optimized demonstrator part structure. Under maximum load conditions, the highest stressed area is at transition radius in horizontal part of the web at the centre of transition radius and at the sleeve located at 8 ‘o’clock position with 483.76Mpa [4]. For torsion load cases, the most critical position are at the web between the upper rare flange to the transition radius close to the top plate of support, at transition radius from start to end, and on the sleeve at 12 ‘o’clock position. This analysis was performed for “demo optimized -12/6” and the data are similar for other two cases of optimized designs [4]. Analysis was carried out to identify potentially critical welds in demonstrator parts.

7. Result

Below are the test results for prototype with available non-destructive methods with VCE at Arvika. Tests are performed using visual inspection, magnetic particle testing, pulse echo (conventional testing) method and phased array.

![Diagram of testing process]

*Fig. 23. Prototype testing of demonstrator part with MPT, Pulse echo and PAUT.*
7.1. Visual inspection

The prototype demonstrator flange is 15mm and web is 10mm thick. Throat size was a3 and a toe radius is r>3mm which is within standards. The undercut and sharp radius at weld region was visible. Butt welds at lower corner have cold laps. In general, as discussed with weld coordinator (Braås), the weld demands are sufficient for required service life.

7.2. Magnetic particle test

Powder magnetic spray Bycotest 104A (white contrast paint) is sprayed on the complex weld surfaces, the liquid is left to dry for 3 minutes then Bycotest 103 (black magnetic ink) containing fine metal particles in sprayed. Yoke method (48Volts) magnets are placed on either side of weld in inspection using above testing flow chart see fig 7. Lack of fusion throughout weld is detected on transition radius and lower corner, whereas long cracks at upper corner front were seen. Testing was carried on multiple directions so that the direction of crack meets the magnetic lines of forces at 90 degrees. No test conducted at sleeve as it is tack weld and i was able to see visible cracks at tacks.

7.3. Ultrasonic Testing

Selected region of interest (ROI) on a demonstrator part is tested with conventional pulse echo and phased array, the region of interest were upper flange and lower corner butt welds, other portions cannot be tested.

Fig. 24. a) Crack at upper flange front b) lack of fusion at transition radius.
7.3.1. *Conventional pulse echo method*

**Upper flange**

- Pulse echo with 0° and 5mm width probe on 15mm flange at rare side did not indicate the defects because the source from 5mm probe diverges and the defects must be larger than the sound beam. We were able to measure the leg length (7mm) but couldn’t detect defects in between this leg length. Here PAUT can be used with 4 elements but they don’t know to test.

- 70° angle probe with skip distance from 30-70mm were able to see lack of fusion around 70mm in direction of weld with depth of 11.44mm and 42mm distance from probe to defect region. No defects recognized on front flange.

*Fig. 25. Lack of fusion at 11.44mm deep and 42mm distance from probe at upper flange rear.*

**Lower corner**

Defect depth 10mm, 38.36mm length, may be very small lack of fusion in weld.

7.3.2. *Phased array (PAUT)*

PAUT detected root defect at lower corner that was not found by pulse echo, refer fig. 28. Distance from probe, depth of the defect in the plate can be calculated. Lack of fusion at upper flange rare was detected by PAUT and pulse echo.
Fillet welds: Ultrasonic phase array testing is mainly used for butt weld but it is also possible to test some fillet welds. All types of fillet welds are unable to be tested because of the complexity of joints between components. Normal probe transducer from horizontal member indicates the defect in the fillet welds. Angle
probes can also be used to test the defects in fillets. There are certain limitations in testing fillet welds, see page 90, fig 3.38 in [11]. They are Pulse echo & PAUT, normal probe transducer for fillet welds give differing results (variation in 1mm to 2mm).

VCE is undergoing research trying to make the tolerances to measure, because they have done a lot of tests by comparing the values of destructive and ultrasonic tests, in which it was found that the values are closer to each other. It is not possible to see the root defect because there is big gap (2-3mm). It may be somehow possible to see the tips but hard to make a decision. Sound reflects at these points and vibration at these areas creates ultrasonic pulses. The longitudinal waves (5900 m/s) get converted to shear waves (3250 m/s).

The sound beam is quite broad, normally, since there is no accessibility to the surface, echo from root tip can be seen because the tip generates longitudinal tube wave and is difficult to say exactly where it is because transmitting shear waves are at back side of plate, tip generates longitudinal waves as it has high velocity.

8. Control plans

It is an organized collection of documents, files and procedures given to process owners. It is similar to a user manual for process owners to enhance day by day improvements. It is a way for better audits and documentation of data, analysis and reasoning for adjustments. A control plan enables process owners and performers on the timelines such as; when to do what, what measurement is no longer required and who needs to do what, why and where. It is a living document for the process and its further improvements.

8.1. Control plan for each imperfection in standards

Suggesting a control plan for present and future designs using NDT-methods for each imperfection listed in Volvo’s standards.
### Table 9. Control plan with present and future NDT methods for each imperfection

<table>
<thead>
<tr>
<th>S.no</th>
<th>Types of imperfection to be controlled</th>
<th>Specification limits/requirements</th>
<th>Measuring methods</th>
<th>selected method (present)</th>
<th>Control method</th>
<th>Sample size</th>
<th>Frequency for selected method</th>
<th>Who/What measures</th>
<th>Recorded Containment (10 days to dispatch)</th>
<th>Adjustment</th>
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<tr>
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<td>Internal and external cracks</td>
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<td>Weekly</td>
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<td>p-chart</td>
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<td>MPT</td>
<td>p-chart</td>
<td>1</td>
<td>Weekly</td>
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<td>Radius gauge</td>
<td>Radius gauge</td>
<td>X-bar &amp; R chart</td>
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<td>Daily</td>
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<td>MPT</td>
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<td>MPT</td>
<td>p-chart</td>
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<td>Daily</td>
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<td>Weekly</td>
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<td>100 &amp; 1000</td>
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<td>VI</td>
<td>p-chart</td>
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<td>VI, MPT, IRT</td>
<td>MPT</td>
<td>p-chart</td>
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<td>Weekly</td>
<td>Operator data sheet</td>
<td>Data sheet</td>
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<td>VI, MPT, IRT</td>
<td>MPT</td>
<td>p-chart</td>
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<td>Weekly</td>
<td>Operator data sheet</td>
<td>Data sheet</td>
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<td>Arc strikes and spatter</td>
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<td>VI</td>
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<td>Weekly</td>
<td>Operator data sheet</td>
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<tr>
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<td>VI, IRT</td>
<td>VI</td>
<td>X-bar &amp; R chart</td>
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<td>Daily</td>
<td>Operator data sheet</td>
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<td>Weekly</td>
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<td>Daily</td>
<td>Operator data sheet</td>
<td>Data sheet</td>
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</table>

### 8.1.1. Internal and external cracks

MPT at ROI for selected number of demonstrators can determine the size of cracks using a ruler. As per standard, cracks are not permitted, rework is required.

### 8.1.2. Overlap and cold lap

Overlap and cold lap can be tested weekly once with WPS by auditor. Percentage defectives can be taken out to minimize this issue by resetting weld parameters.

### 8.1.3. External lack of fusion

MPT reveals external lack of fusion. Lack of fusion is not permitted as per standard, so % check area at ROI would work for improvement. Auditor may test one sample weekly. Data have to be documented.

### 8.1.4. Internal lack of fusion

Ultrasonic pulse echo & PAUT can be used to find the variation after inspection on same sites. Later a suitable angle for the type of inspection can be selected.

### 8.1.5. Outer transition radius

Radius gauges have to be used daily by robot welding operators to make sure that they have the right transition radius. Variations with gauge and operation can be seen in x-bar & R-charts. Repeatability and reproducibility shows changes in process and inspection. We then come to know that there is a shift in process which has to be adjusted. WPS and impressions can be double-checked by a weekly inspection.
8.1.6. **Undercut**

These must have $A<0.05\text{mm}$; if undercuts are $0.03\text{mm}$, then it is within transition radius. A maximum undercut of $1\text{mm}$ is permitted in VD class. If they are greater than $1\text{mm}$ then we have to verify with WPS to see if arc heat input has been increased. It can be measured in percentage of undercuts along welds.

8.1.7. **Under passed throat (a-dimension), Non-filled weld and Edge displacement**

A throat size gauge will be used by operators to verify a-measure. Throat measurements with SPC can see the variation of the process, as we know extra material deposited can increase the cost of the product. Operators must calibrate their gauges twice a day. Once in a week we could use impression test and calculate with weld software to see if the process has shifted. As we monitor every week we come to know what parameters are shifting. Gauge repeatability and reproducibility can be analyzed but there is no right gauge for a-measurement. Impressions can be used twice a week.

8.1.8. **Internal & external porosities/Slag inclusions**

Total internal pore/slag inclusion area is max $6\%$ of check area and $3\%$ for external pore/slag inclusions at ROI. Anything more than this is unacceptable and the weld needs to be redone. Testing performed by auditors and percentage of defectives will be documented in data sheets for future reference.

8.1.9. **Pipe (craters)**

Pipes are acceptable if the welds satisfy throat dimensions. The commonly occurring size of pipe which is acceptable has to be listed because it is seen as unavoidable in all cases. A robot welder must check these. Generally, pipes are visible at start and end of every weld. A sample can be tested every week.

8.1.10. **Leg deviation**

Here the extension of leg length shouldn’t be greater than $3\text{mm}$. Throat size measure from shorter leg side will give wrong measurements. WPS can be done once a week; and impressions, twice a day.

8.1.11. **Weld reinforcement**

Variation in measurements collected using a comb that has metal needles. An auditor can exclude the percentage of defective area.
8.1.12. Arc strikes and spatter

Spatter is a very common problem with MAG. Operators has to make sure that they use the right process parameters at single pass and multiple passes. A wire with a small diameter for first pass and a larger diameter for multi-pass can give the right welds. A daily inspection of percentage check area at ROI by operators may reduce the occurrence of spatter.

8.1.13. Bad fit-up

This has to be properly adjusted before and during tack welding of assembled parts on fixture. These may not be seen due to complex geometry of the finished part and are difficult to detect with NDT methods. Bad fit-up if open for detection and can be measured with a ruler. Testing can be carried out daily, and operators during the assembly have to be very clear about fit-up gap, because this could result in lack of penetration.

8.1.14. Excessive penetration

Excessive penetration according to standard must be less than 2mm. It can be measured with a scale, x-bar and r-chart can be prepared with an excel solver. A weekly inspection can result the variations by which we could reduce the heat input or see if plates are of right geometry.

8.1.15. Incomplete root penetration

It is one of the major concerns in welds. IRT is an appropriate method in detecting root penetration for future design by operators. In the case of present design, WPS can be done weekly once by an auditor and will adjust the process shift.

8.1.16. Root defect

As per standard, it is not applicable in welds because it effects penetration. IRT is better used for tracking, whereas UT can only show the edge of root, but cannot accurately determine the defect. An operator must keep track to avoid root defect by monitoring the captured videos for future design. At present WPS will be done for adjustments in input parameters.
8.2. Control plan for present design with present NDT-methods

Table 10. Control plan for present design with present NDT-methods

<table>
<thead>
<tr>
<th>S.no</th>
<th>Process step</th>
<th>Characteristics</th>
<th>LSL</th>
<th>Target</th>
<th>USL</th>
<th>Method</th>
<th>Sample size</th>
<th>Frequency</th>
<th>Who/What measures</th>
<th>Recorded</th>
<th>Containment (10 days to dispatch)</th>
<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boogie beam</td>
<td>All defects</td>
<td>i2a5</td>
<td>i2a5</td>
<td>i2a5</td>
<td>WPS</td>
<td>2</td>
<td>Weekly</td>
<td>Auditor data sheet</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>2</td>
<td>Upper flange</td>
<td>Throat size, LF, Pores</td>
<td>i2a5</td>
<td>i2a5</td>
<td>i2a5</td>
<td>UT, MPT, impression</td>
<td>1</td>
<td>daily/Weekly</td>
<td>Auditor data sheet</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>3</td>
<td>Transition radius</td>
<td>External cracks</td>
<td>i2a5</td>
<td>i2a5</td>
<td>i2a5</td>
<td>MPT</td>
<td>1</td>
<td>daily</td>
<td>Operator data sheet</td>
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<td></td>
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<tr>
<td>4</td>
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<td>ILF, Internal Pores</td>
<td>i2a5</td>
<td>i2a5</td>
<td>i2a5</td>
<td>UT</td>
<td>2</td>
<td>daily</td>
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<td>5</td>
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<td>i2a5</td>
<td>i2a5</td>
<td>i2a5</td>
<td>MPT, radius gauge</td>
<td>1</td>
<td>daily</td>
<td>Operator data sheet</td>
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</table>

Weld procedure specification is a document that describes how welding is to be carried out in production. Before introduction of a new part, WPS test is performed to evaluate all types of internal and external defects. Appropriate welding parameters are set for mass production. The cost of inspection will depend on the number of specimens and the time consumed for testing. Sample size of 2 demonstrators weekly on ROI will evaluate the shift in process (may be after every 20 frames), which can be recorded on a data sheet. If there is a discontinuity during process, it can be documented if the shift was due to changes in process parameters, material, machine, operator or environment. The weld type requirement for present design is i2a5.

Process steps for demonstrator ROI are selected to see if the discontinuities are found and adjustments are made. In this case testing is done after welding by auditors or operators.

1. **Upper flange**: In case of an upper flange, the front and rear sides are butt welded. Throat size is measured with gauges (no appropriate gauge till date), external lack of fusion tested with MPT and internal porosity with ultrasonics pulse echo method daily for one demonstrator. According to standards, external lack of fusion is not permitted, ROI have to be reworked. In case of internal porosity, size of pore and % of pores as per standards must be less than 6% of inspected area; if not then rework is necessary. Another idea could be p-chart to see the percentage of defectives in a selected area. Throat size deviations can be taken by impression testing to see deviation from actual size, which will be done once or twice a week. Control chart could show the variation.

2. **Transition radius**: Here ultrasonics cannot be used. In case of external cracks, MPT can be used. According to standards, cracks are not permitted. If there is variation in the crack sizes then the process shift can be checked for changing parameters and it requires rework. This can be tested once a day.

3. **Lower corner**: Butt weld at lower corner can be tested with pulse echo for internal porosities and internal lack of fusion (lack of fusion according to standard is not permitted). Daily two samples can
be tested. In case of internal lack of fusion, rework is necessary but for internal porosities the percentage check area as per standard and size of the pore with p-chart can keep the track on process, which may be caused due to changes in process parameters, material, machine, operator or environment.

4. **Sleeve**: Lower semi-circle at sleeve for outer transition radius is checked with radius gauges and undercuts are tested with MPT. Control charts can be used to monitor outer transition radius to avoid sharp transition, which can be done daily for one selected demonstrator. Undercut problem can be reduced by using p-charts for monitoring. As welding itself is a defect introducing process, in that sense defects can be reduced to a certain limit but cannot be totally eliminated. SPC can be done by operators with their gauges (gauges must be calibrated).

The costs involved for the methods used can be taken into account, depending on inspection time, basically continuous inspection time must not exceed more than 2 hours.

**8.3. Control plan for present design with future NDT-methods**

The designer and production technicians together decide the stress areas in the demonstrator. The operator before the process can check for plate’s alignment and after welding, they can visually inspect for surface defects. Depending on weld type they suggest future NDT methods on present demonstrator. The lower corner is tested with PAUT and TOFD, whereas online testing at transition radius and sleeve with thermography is conducted by operators in presence of experienced auditors. Inspection flow diagram for the present demonstrator is shown in fig 28.

![Inspection flow diagram for demo 2 demonstrator part](image-url)
WPS is very similar before and after welding as mentioned in present design with present NDT-methods.

1. **Upper flange**: PAUT and TOFD every day for two samples can be tested to detect internal lack of fusion and internal porosities. Testing has to be done by auditors as inspection requires experienced personnel. SPC is used for monitoring internal lack of fusion and p-charts for monitoring internal porosities and slag inclusions. Adjustments must be made as there is shift in process, double-checked by eddy currents.

2. **Transition radius**: External cracks, undercuts, outer transition radius related problems can be solved by the impression method. Indented dried clay will reveal these defects, percentage defectives can be calculated weekly during the testing for one sample.

3. **Lower corner**: This is similar as in case of upper flange.

4. **Sleeve**: Incomplete root penetration (lack of penetration and depth of penetration) and root defects as of today are defined by WPS and destructive testing. In future these can be tested with infrared thermography during welding. Testing must take place weekly once by operators and evaluation must be done in presence of experienced auditors. During this stage the shift in process while welding will reveal defects that could be adjusted by resetting parameters.

Future testing methods will be performed by auditors, tested data and shift in process will be documented for further improvements in future. Perhaps the whole demonstrator can be tested during welding using IR-Thermography.

<table>
<thead>
<tr>
<th>S.no</th>
<th>Process step</th>
<th>Specification</th>
<th>LSL</th>
<th>Target</th>
<th>USL</th>
<th>Method</th>
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<th>Frequency (once in week)</th>
<th>Who/What measures</th>
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8.4. Control plan for future design with present NDT-methods

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<tr>
<td>3</td>
<td>Elephant foot (Above)</td>
<td>overlap, outer transition</td>
<td>5/8i4</td>
<td>5/8i4 (VB)</td>
<td>5/8i4 (VB)</td>
<td>Impression</td>
<td>1</td>
<td>Weekly</td>
<td>Auditor/Operator</td>
<td>data sheet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Upper flange</td>
<td>ILF</td>
<td>5/8i3</td>
<td>5/8i3</td>
<td>5/8i3</td>
<td>MPT</td>
<td>1</td>
<td>Weekly</td>
<td>Auditor</td>
<td>data sheet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Center sleeve</td>
<td>ILF, internal pores</td>
<td>S6</td>
<td>S5</td>
<td>S5</td>
<td>UT</td>
<td>2</td>
<td>Daily</td>
<td>Auditor</td>
<td>data sheet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12. Control plan for future design with present NDT-methods

LSL, Target and USL values are weld types taken from proposed weight reduced design from previous thesis for a demonstrator part.

1. **Lower flange**: Cracks are not permitted, the only way is to rework. Percentage defectives (p-chart) can be taken for external lack of fusion and undercuts using magnetic particle testing. This can be done on selected ROI for one sample weekly by auditors. Undercuts, external lack of fusion and cracks can be tested by operator daily on each and every sample. Tested data can be documented for correction and future verification.

2. **Lower flange (center)**: Deviations in throat size and leg deviation shown by impression testing. SPC can be plotted for one sample weekly by auditor.

3. **Support (above)**: Overlap or cold lap can be tested using impressions and outer transition radius with radius gauges. The variations in smooth transitions can be evaluated using control charts. Double check for laps can be done by MPT. Operators can take care of outer transition radius using gauges and the auditor tests with impressions and MPT.

4. **Upper flange**: Internal lack of fusion using MPT and pulse echo will not work for fillet welds. Monitoring using control charts audited once a week by the auditor with WPS, may work.

5. **Sleeve**: Pulse echo can be used to detect internal lack of fusion and internal pores by auditor. Daily two samples can be tested. Root defect and incomplete penetration can be checked by WPS only.

By using these control plans, we don’t control the input. We only monitor the output of the process to make changes in input parameters at later stage.

8.5. Control plan for future design with future NDT-methods

Designer and production technicians together decide the stress areas in the demonstrator. Before the process, the operator can check for the plate’s alignment and after welding they can visually inspect for surface defects. Depending on the weld type they suggest NDT methods for future design. The sleeve is tested with
PAUT and TOFD, whereas the upper flange, path lower flange and support are tested online with thermography by operators in presence of experienced auditors. Inspection flow diagram for optimized demonstrator part is shown in fig 31.

**Fig. 29. Inspection flow diagram for optimized demonstrator part.**

**Table 13. Control plan for future design with future NDT-methods**

<table>
<thead>
<tr>
<th>S.no</th>
<th>Process step</th>
<th>Specification</th>
<th>LSL 12/6</th>
<th>Target 12/5</th>
<th>USL 10/5</th>
<th>Method</th>
<th>Sample size</th>
<th>Frequency (once in week)</th>
<th>Who/What measures</th>
<th>Recorded</th>
<th>Containment</th>
<th>Adjustment</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>Lower flange (center)</td>
<td>undercut, Leg deviation</td>
<td>Nil</td>
<td>Nil</td>
<td>5/8/2</td>
<td>Impression</td>
<td>1</td>
<td>Daily</td>
<td>Auditor</td>
<td>data sheet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Upper flange (Rear)</td>
<td>root defect, IP</td>
<td>5/8/3</td>
<td>5/8/3</td>
<td>5/8/3</td>
<td>IRT</td>
<td>1</td>
<td>Daily</td>
<td>Operators</td>
<td>data sheet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Center sleeve</td>
<td>ILF, internal pores</td>
<td>S6</td>
<td>S5</td>
<td>S5</td>
<td>NDT (PAUT+TOFD)</td>
<td>2</td>
<td>Daily</td>
<td>Auditor</td>
<td>data sheet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. **Lower flange**: Cracks, internal lack of fusion and undercuts can be seen with thermography during the weld transition from liquid to solid state. In this case, using a p-chart may be a good idea to monitor the percentage of defectives during welding at this point of interest. Eddy current can double check internal lack of fusion sizes with that of thermography data. One sample daily can be tested. Weld operators can use thermography and auditors will use eddy current equipment. The deviations are noted and corrective actions like proper sizes of plates, process parameters have to be set.

2. **Lower flange (center)**: Undercuts and leg deviation can be checked by impression testing. SPC can be plotted for one sample weekly by auditor.
3. **Support (above):** Outer transition radius can be checked by the operator after weld and fine control charts can be plotted to show the shift in process. One sample has to be checked daily. Overlap and cold lap can be tested using IRT by the operator during welding. This could be done weekly once for the selected sample(s).

4. **Upper flange:** Root defect and incomplete penetration can be checked by IRT. Percentage of root defect and lack of penetration can give a good idea that the right amount of heat input is necessary to have good penetration. Weekly once by operators.

5. **Sleeve:** It is an easy method to detect internal lack of fusion and internal pores with PAUT and TOFD. Again we could use p-chart. Defect found by PAUT can be double checked by other methods at the same time within same equipment with TOFD. Testing must be done by experienced auditors. Daily two samples can be evaluated.

Misalignment with fixtures, tack welding must be carried out carefully. Control plans monitor output, it has more output when compared to the input to the process [51].

9. **Discussion**

For demonstrator, it is necessary to have minimum throat size of $a \geq 5\text{mm}$, which is acceptable. This is being used from several years and is still being continued in production and no problems detected so far. It is always a problem for the quality department to know which area is more critical or important and requires special inspection. In previous research demonstrators without cast part is similar to a bigger size as demo 2 demonstrator part. Presently the inspection of a demonstrator part is totally done by visual inspection and ultrasonic pulse echo testing at upper flange rear and front i.e. at butt joint between flanges, web and cast part, which is critical position as known today. The production technician decides criticality in welds and directs the quality team’s focus. Quality inspectors today understand that there are critical regions which need attention, in this case the designer needed to indicate the criticality on the drawing to focus on quality for improvement as it will not be a good idea to consider whole demonstrator for NDT inspection, so that the inspector can do frequent checks in those areas, The gauges used by the quality in Arvika and Braås differ, which makes difference in measurement and may not exactly connect to the prescribed guidelines. Auditors can start impressions testing instead throat size gauges. As mentioned in section 4.4, throat size gauges give wrong results.

Visual inspection, macro test, impression test, ultrasonic and IR-thermography presents reliability in identification of defects. Radiography can detect similar results as of thermography but could be excluded due to harmful and genetic effects to human (from tables). Multiple directions testing with MPT showed
defects that were difficult to understand; whether it was a lack of fusion, very small cracks; the liquid just stuck on the surfaces. Magnetic particle testing for single pass robotic welds will reveal cracks, deviations from actual geometry.

Lack of fusion tested in weld; sometimes there are oxides on the surface which enhance the risk for lack of fusion, it may be during cutting, high welding speeds with high heat input during welding. It is possible to reduce the weld area to about 25% and we can still retain the same fatigue life of the structure [4, 6]. A good look and a good quality are not necessarily the same, the costs that add up to make a weld appear good will not translate into profits, since customers do not pay for good looking welds; rather they pay for good quality welds. If a customer wants the good-looking demonstrator part it may costs 500 SEK extra, the most important welds are those with high penetration and sometimes need to control undercuts and radius. As of today, most of the demands on the demonstrator parts are not relevant, whether it has direct influence to the fatigue life of the product from previous research work [4]; it was found that around 80% of welds have either too large penetration or too large a-measure which are found during the initial audits. Different parameters are checked on different parts; a minimum of 10 parameters are checked within a single weld. For a demonstrator part, penetration is an important parameter. In general, in this product 80% of the demands are overestimated and huge amounts of financial investments are required to fulfill all these demands (according to welding coordinator at Braås).

Testing can be carried with eddy current, PAUT & TOFD for detection of defects. Thermography could be good idea but different algorithms are required during testing, all algorithms do not give information regarding all types of defects. Thermography detect ability would depend on field of view, spatial resolution and thermal contrast sensitivity. Most frequent faults during testing are undercuts, external pores, and external lack of fusion and throat size.

Magnetic particle testing at ROI on demonstrator part showed cracks and lack of fusion. Ultrasonic pulse echo and phased array (PAUT) at its best detects lack of fusion as radiography and IR-thermography will have difficulty, it is not easy to say if thermography will detect defects on present prototype demonstrator because many researches based tests are performed on butt welds. From previous ultrasonic test data, it shown that there is inconsistency with different angle probes (pulse echo), about 2-3mm probe misalignment with this method will give varying results and it even depends on ability of inspector. Phased array with sectorial scan takes much less time than pulse echo. Echo’s from root tip can be seen with PAUT and pulse echo methods as the tip generates longitudinal wave, it is difficult to say exactly where it is because transmitting shear waves to back side of the plate and the tip generates longitudinal wave as it has high velocity, so we get different sound velocities with this tip, refer fig 13. Penetration and its depth not possible for detection using ultrasonics for prototype demonstrator part as it has many fillet welds, it is then
recommended to go with passive thermography, ultrasonic with PAUT & TOFD for butt joints whereas magnetic particle testing, thermography for fillet welds.

In eddy current testing sample surfaces needed to be very smooth for inspection (as seen in laboratory test at PTC), otherwise lot of noise appear which was seen on Volvo test samples at PTC. It is difficult to determine defect areas if that is upper or lower peak in the x-y plane in cct screen on equipment, refer fig 30.

![Eddy current testing on a Volvo test sample and cct screen showing peaks for defect.](image)

**Fig. 30. Eddy current testing on a) Volvo test sample b) cct screen show peaks for defect.**

Eddy current testing depends on permeability, electrical conductivity and frequency. Probes with different frequencies have to be selected depending upon the weld surface, orientation of grains, homogeneous grain structure, conductivity, else we only see noise. If the surface are rough (spatter and cold laps) then the defects peak and noise peak look similar, that gives unpredictable results. This method with low frequencies reveals defects at greater depths and at high frequencies is similar to magnetic particle inspection. Eddy current testing require lot of training and is one of the good methods in detecting fatigue related defects. The cost of right eddy current equipment will be as costly as ultrasonics.

10. **Conclusion**

In the case of present demonstrator parts and weight reduction with improved weld quality for demo optimized 12/6, 12/5, 10/5 it may be possible to do ultrasonic test on sleeve, transition radius, above support and upper flange. But these have to be tested in real-time for weight reduced demonstrator parts, because the prototype is of 15/10 flanges and web plates with fillet weld at sleeve. The best method is chosen based on the features of the problem, so passive thermography will be good to use during welding. However, this process still requires a lot of study and experimental work.

Control plans are proposed for present and future boogie beams with present and future NDT methods.
11. Further work

- Multiple coils in a single probe could be an idea to see the defects at toe. Other idea could also be to introduce notch of mm range with EDM at toes to see if eddy current could detect defects at toe, see fig 1.
- Normal video cameras with filters can be used to see the arc and weld surface but it still requires investigation to see if it can show the defective areas during welding. Here we saw droplets of melting electrode, shape of electrode. So we could probably decide the parameters for the process. 100% testing performed at laboratory as same cannot be done during production. Further research in fields of eddy current and thermography are necessary.

12. References


[21] Shaikh AM. Applications of various imaging techniques in neutron radiography at BARC, Trombay.


[32] !!! INVALID CITATION !!!


[34] Frédéric LAPRISE JB, Guy MAES. Sectorial Scan PAUT Combined with TOFD, a Robust Weld Inspection Technique in Lieu of RT. 18th World Conference on Nondestructive Testing; 16-20 April 2012; Durban, South Africa. p. 1-10.


Appendix A: Standard 181-0004
### 4.1 Imperfections affecting the static strength and the fatigue strength

<table>
<thead>
<tr>
<th>No. Nr</th>
<th>Type of Imperfection</th>
<th>Weld classes</th>
<th>Weld classes for static strength</th>
<th>Weld classes for fatigue strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diskontinuitetstyp</td>
<td>Svetsklasser</td>
<td>Svetsklasser för statisk hållfasthet</td>
<td>Svetsklasser för utmattningshållfasthet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VS</td>
<td>VD Normal quality</td>
<td>VC High quality</td>
</tr>
<tr>
<td>101</td>
<td>Internal and external crack</td>
<td>Not permitted Tillåts ej</td>
<td>Not permitted Tillåts ej</td>
<td>Not permitted Tillåts ej</td>
</tr>
<tr>
<td></td>
<td>In- och utvändig spricka</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>Overlap and cold lap</td>
<td>Permitted Tillåts</td>
<td>A &lt; 0,5 mm</td>
<td>A &lt; 0,1 mm</td>
</tr>
<tr>
<td></td>
<td>Överrunnen svets och kallflytning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. Nr</td>
<td>Type of Imperfection</td>
<td>Weld classes for static strength</td>
<td>Weld classes for fatigue strength</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>----------------------</td>
<td>---------------------------------</td>
<td>----------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diskontinuitetstyp</td>
<td>Svetsklässer för statisk hållfasthet</td>
<td>Svetsklässer för utmattningshållfasthet</td>
<td></td>
</tr>
<tr>
<td>VS</td>
<td>Normal quality</td>
<td>Normal kvalitet</td>
<td>Very high quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mycket hög kvalitet</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. Nr</th>
<th>Type of Imperfection</th>
<th>Weld classes for static strength</th>
<th>Weld classes for fatigue strength</th>
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<tr>
<td>103</td>
<td>External lack of fusion</td>
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<td>Not permitted</td>
</tr>
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<td></td>
<td>Yttre blodfäl</td>
<td>Tillåts ej</td>
<td>Tillåts ej</td>
</tr>
<tr>
<td>104</td>
<td>Internal lack of fusion</td>
<td>A &lt; 0,2t</td>
<td>Not permitted</td>
</tr>
<tr>
<td></td>
<td>Inre blodfäl</td>
<td>Tillåts ej</td>
<td>Tillåts ej</td>
</tr>
<tr>
<td>106</td>
<td>Outer transition radius</td>
<td>No requirements</td>
<td>r &gt; 0,3 mm</td>
</tr>
<tr>
<td></td>
<td>Yttre övergångssradie</td>
<td>Inget krav</td>
<td>r &gt; 1 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>r &gt; 4 mm</td>
</tr>
<tr>
<td>No. Nr</td>
<td>Type of Imperfection</td>
<td>Weld classes for static strength</td>
<td>Weld classes for fatigue strength</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------</td>
<td>---------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Svetsklaser</td>
<td>Svetsklags för statsk hålfasthet</td>
</tr>
<tr>
<td>107</td>
<td>Undercut</td>
<td>A &lt; 0.2t but max 2 mm / men max 2 mm</td>
<td>A &lt; 0.05t, but max 1 mm</td>
</tr>
<tr>
<td></td>
<td>Smalltäcke</td>
<td>Undercut radius acc. to Imperfection type 106 required</td>
<td>Radiekrav för småldike enligt diskontinuitetstyp 106</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>For hollow-section tubular profiles t = 6 mm</td>
<td>A &lt; 0.2t</td>
<td>A &lt; 0.1t</td>
</tr>
<tr>
<td></td>
<td>För håliga rörprofiller t = 6 mm</td>
<td>Undercut radius acc. to Imperfection type 106 required</td>
<td>Radiekrav för småldike enligt diskontinuitetstyp 106</td>
</tr>
<tr>
<td>108</td>
<td>Underpassed throat dimension, a-dimension (including weld stop)</td>
<td>Locally min throat ≥ 0,8a</td>
<td>Permitted locally if: Min throat ≥ 0,8a. Deviation not to exceed -2 mm</td>
</tr>
<tr>
<td></td>
<td>Underskridande av a-mått (inklusive svetsavslut)</td>
<td>Lokalt min a-mått ≥ 0,8a</td>
<td>Tilåts lokalt om: Min a-mått ≥ 0,8a. Avvikelse får dock ej överskrida -2 mm</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. Nr</td>
<td>Type of Imperfection</td>
<td>Weld class for static strength</td>
<td>Weld class for fatigue strength</td>
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<tr>
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<td>----------------------</td>
<td>--------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td></td>
<td>Diskontinuitetstyp</td>
<td>Svetsklasse</td>
<td>Svetsklasse för utmättningshållfasthet</td>
</tr>
<tr>
<td></td>
<td>Non-filled weld, not permitted for additional symbols (Including weld stop)</td>
<td>A ≤ 0,2t, but max. 2 mm/dock max 2 mm</td>
<td>A ≤ 0,05t, but max 1 mm/dock max 1 mm</td>
</tr>
<tr>
<td></td>
<td>Utbytta svets, tillåtats ej vid tilläggsymbol (Inklusive svetsavslut)</td>
<td>Radius acc. to Imperfection type 106 required</td>
<td>Radiekrav enligt diskontinuitetstyp 105</td>
</tr>
<tr>
<td></td>
<td>För hull-section tubular profiles t = 6 mm</td>
<td>A ≤ 0,2t</td>
<td>A ≤ 0,2t</td>
</tr>
<tr>
<td></td>
<td>För ihåliga rörprofiler, t = 6 mm</td>
<td>Radius acc. to Imperfection type 106 required</td>
<td>Radiekrav enligt diskontinuitetstyp 105</td>
</tr>
<tr>
<td></td>
<td>Edge displacement</td>
<td>Kantskurenning</td>
<td>A ≤ 1,5 + 0,25t, but max 5 mm/ dock max 5 mm</td>
</tr>
<tr>
<td></td>
<td>För hull-section tubular profiles, t = 6 mm</td>
<td>Not permitted</td>
<td>Tillsås ej</td>
</tr>
<tr>
<td>No. Nr</td>
<td>Type of Imperfection</td>
<td>Weld classes</td>
<td>Weld classes for fatigue strength</td>
</tr>
<tr>
<td>-------</td>
<td>----------------------</td>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>111</td>
<td>Single internal pore / single slag inclusion</td>
<td>Max extension of pore/inclusion in any direction &lt; 0,4t, but max 4 mm</td>
<td>Porens/enskild slags största utsträckning i någon riktning &lt; 0,4t, dock max 4 mm</td>
</tr>
<tr>
<td>112</td>
<td>Inner porosities / slag inclusions</td>
<td>Total pore / slag inclusion area max 6 % of check area</td>
<td>Total pore / slag inclusion area max 6 % of check area</td>
</tr>
<tr>
<td>No. Nr</td>
<td>Type of Imperfection</td>
<td>Weld classes for fatigue strength</td>
<td>Weld class for static strength</td>
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<tr>
<td>-------</td>
<td>----------------------</td>
<td>-----------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>113</td>
<td>Single surface pore</td>
<td>Normal quality</td>
<td>Normal kvalitet</td>
</tr>
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<td></td>
<td>Ensta ytpor</td>
<td>Normal kvalitet</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Mycket hög kvalitet</td>
<td></td>
</tr>
<tr>
<td>114</td>
<td>Surface porosities</td>
<td>Total pore area max 3 % of check area</td>
<td>Total pore area max 3 % of check area</td>
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<td>Yttrh parningsar</td>
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<td>115</td>
<td>Pipe</td>
<td>Permitted if 108 and 109 are compiled with tillåts om 108 och 109 uppfylls</td>
<td>Permitted if 108 and 109 are compiled with tillåts om 108 och 109 uppfylls</td>
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<tr>
<td>116</td>
<td>Non-existing weld</td>
<td>Not permitted tillåts ej</td>
<td>Not permitted tillåts ej</td>
</tr>
</tbody>
</table>
### 4.2 Imperfections affecting the static strength but with no/little effect on the fatigue strength

#### Table / Tabell 3

<table>
<thead>
<tr>
<th>No. Nr</th>
<th>Type of Imperfection</th>
<th>Weld classes for static strength</th>
<th>Weld classes for fatigue strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diskontinuitetstyp</td>
<td>Svetsklasse för statisk hålfasthet</td>
<td>Svetsklasse för utmattningshålfasthet</td>
</tr>
<tr>
<td>201</td>
<td>Leg deviation</td>
<td>VS</td>
<td>VD</td>
</tr>
<tr>
<td></td>
<td>Kafetavvikelse</td>
<td>For one-pass weld/För ensträngssvetsar:</td>
<td>A ≤ 2 + 0,2a</td>
</tr>
</tbody>
</table>

#### Note
- Not permitted for additional symbols. OBS! Tillåts ej vid tilläggsymbol.

<table>
<thead>
<tr>
<th>No. Nr</th>
<th>Type of Imperfection</th>
<th>Weld reinforcement</th>
<th>Occasional arc strikes, max one per check length, are permitted. Spatter which has stuck is permitted. Tändmärken tillåts, max 1 per kontrollsträcka. Fastsittande svetssprut tillåts</th>
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</thead>
<tbody>
<tr>
<td>203</td>
<td>Arc strikes and spatter</td>
<td>Svetsstråle</td>
<td>Occasional arc strikes, max one per check length, are permitted. Spatter which has stuck is permitted. Tändmärken tillåts, max 1 per kontrollsträcka. Fastsittande svetssprut tillåts</td>
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### 4.3 Root imperfections

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<tr>
<th>No. Nr</th>
<th>Type of Imperfection</th>
<th>Weld for static strength Svets för statisk hålffasthet</th>
<th>Weld for fatigue strength Svets för utmattningshålffasthet</th>
</tr>
</thead>
<tbody>
<tr>
<td>301</td>
<td>Penetration bead/ Excessive penetration Rotvikt/Genomträdning</td>
<td>A ≤ 1,5 + 0,3c</td>
<td>A ≤ 1,5 + 0,3c</td>
</tr>
<tr>
<td>302</td>
<td>Incomplete root penetration Oftuistålig genomsvetsning</td>
<td>A ≤ 0,2 t, but max. 2 mm</td>
<td>Not applicable, controlled by the s-dimension (minimum dimension)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A ≤ 0,2 t, dock max. 2 mm</td>
<td>Ej tillämpligt, styrs av s-måttet (minimår)</td>
</tr>
</tbody>
</table>

---

### 4.3 Rotdiskontinuiteter

<table>
<thead>
<tr>
<th>No. Nr</th>
<th>Type of Imperfection</th>
<th>Weld for static strength Svets för statisk hålffasthet</th>
<th>Weld for fatigue strength Svets för utmattningshålffasthet</th>
</tr>
</thead>
<tbody>
<tr>
<td>301</td>
<td>Penetration bead/ Excessive penetration Rotvikt/Genomträdning</td>
<td>A ≤ 1,5 + 0,3c</td>
<td>A ≤ 1,5 + 0,3c</td>
</tr>
<tr>
<td>302</td>
<td>Incomplete root penetration Oftuistålig genomsvetsning</td>
<td>A ≤ 0,2 t, but max. 2 mm</td>
<td>Not applicable, controlled by the s-dimension (minimum dimension)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A ≤ 0,2 t, dock max. 2 mm</td>
<td>Ej tillämpligt, styrs av s-måttet (minimår)</td>
</tr>
<tr>
<td>303</td>
<td>Root defect</td>
<td>Locally permitted $A \leq 0.2a$</td>
<td>Not applicable, controlled by the i-dimension (minimum dimension)</td>
</tr>
<tr>
<td>-----</td>
<td>-------------</td>
<td>-------------------------------</td>
<td>--------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Root defect</td>
<td>Tillåts lokalt $A \leq 0.2a$</td>
<td>Ej tillämpbart, styrs av i-måttet (minimimått)</td>
</tr>
</tbody>
</table>

![Diagram of root defect](image)
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDT</td>
<td>Non-destructive testing</td>
</tr>
<tr>
<td>WIQ</td>
<td>Weight reduction by improved weld quality</td>
</tr>
<tr>
<td>STD</td>
<td>Standard</td>
</tr>
<tr>
<td>NDE</td>
<td>Non-destructive evaluation</td>
</tr>
<tr>
<td>WPS</td>
<td>Welding procedure specification</td>
</tr>
<tr>
<td>ROI</td>
<td>Region of interest</td>
</tr>
<tr>
<td>LPT</td>
<td>Liquid penetrant testing</td>
</tr>
<tr>
<td>MPT</td>
<td>Magnetic particle testing</td>
</tr>
<tr>
<td>MPI</td>
<td>Magnetic particle inspection</td>
</tr>
<tr>
<td>ET</td>
<td>Eddy current testing</td>
</tr>
<tr>
<td>RT</td>
<td>Radiography testing</td>
</tr>
<tr>
<td>ASTM</td>
<td>American society for testing and materials</td>
</tr>
<tr>
<td>IIW</td>
<td>International institute of welding</td>
</tr>
<tr>
<td>BS</td>
<td>British standards</td>
</tr>
<tr>
<td>IQIs</td>
<td>Image quality indicators</td>
</tr>
<tr>
<td>CS</td>
<td>Contrast sensitivity</td>
</tr>
<tr>
<td>CR</td>
<td>Computer radiography</td>
</tr>
<tr>
<td>DDAs</td>
<td>Digital detector arrays</td>
</tr>
<tr>
<td>DR</td>
<td>Digital radiography</td>
</tr>
<tr>
<td>VCE</td>
<td>Volvo construction equipment</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>PAUT</td>
<td>Phased array ultrasonic testing</td>
</tr>
<tr>
<td>TOFD</td>
<td>Time of flight diffraction</td>
</tr>
<tr>
<td>POD</td>
<td>Probability of detection</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge couple device</td>
</tr>
<tr>
<td>SPC</td>
<td>Statistical process control</td>
</tr>
<tr>
<td>UCL</td>
<td>Upper specification limit</td>
</tr>
<tr>
<td>LCL</td>
<td>Lower specification limit</td>
</tr>
<tr>
<td>EDM</td>
<td>Electro-discharge machining</td>
</tr>
</tbody>
</table>
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