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RESEARCH PAPER

Review of NDT and process monitoring techniques usable to produce high-quality parts by welding or additive manufacturing

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Abstract
The main objectives of applying NDT techniques are to ensure the quality of an assembly or a part according to a given specification including known acceptance criteria. It generally enables not only to detect an indication, but also to classify it (size, position, nature…). Many non-destructive testing (NDT) techniques are effective in testing welded components. Radiography, ultrasonic testing, penetrant testing and magnetic particle testing are widely used and standardised. Phased arrays, TOFD and multi-elements eddy current are more and more extensively applied. Tomography, acoustic emission, ultrasonic guided waves, laser ultrasonic and optical techniques continue to be a strong topic of interest. Each of these techniques is based on different physical principles to detect defects on the surface of the part or over its whole volume. However, the geometry, physical and material properties of the part being tested are key factors in the applicability and performance of a given NDT technique. To date, the development of reliable NDT methods for additive manufacturing (AM) parts is still a major challenge. The process may generate various defects such as cracks, voids, inclusions and porosities. NDT techniques need to be optimised or developed to address singular features of the AM processes: complex geometry, special internal structures, anisotropic material properties, typical defects. Knowledge of the potential occurring imperfections produced by the various AM process needs to be improved in order to be able to select the best suited NDT techniques.

Keywords Welding · Joining · Additive manufacturing · NDT · Process monitoring · Case study

1 Introduction

Any mechanical parts having to provide a service must offer optimal guarantees of safety and endurance to the conditions of service, either for new or already in service equipment. To ensure the quality of a manufacturing process, there is a wide variety of NDT techniques that are generally implemented after the manufacturing stage.

The main objectives of applying NDT techniques are to ensure the quality of an assembly (welded, bonded, mechanical…) or a part according to a given specification including known acceptance criteria. It generally enables not only to detect an indication, but also to classify it (size, position, nature ...)

2 Content

This paper reviews:

- NDT methods and techniques and compares them in terms of capability, and applicability for welded and metallic additive manufacturing (AM) parts at the manufacturing stage
- Some monitoring techniques applicable either to weld or AM parts and advanced processing data (support vector machine …)
- Some advantages of these techniques for providing interesting hints to the mechanical engineer

Examples of NDT applications on welded and AM parts are given as a short focus on the NDT standardisation progress.

This article is part of the collection Welding, Additive Manufacturing and Associated NDT

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3 Review of weld imperfections

ISO 6520-1 [1] classifies welded imperfections into six main groups:

1. Cracks
2. Cavities
3. Solid inclusions
4. Lack of fusion and penetration
5. Imperfect shape and dimension
6. Miscellaneous imperfections

In each group, each type of imperfections is defined and numbered according to its group. For example: 1001 is a micro- crack, 2012 corresponds to linear porosities, 2013 to an elongated cavity …

The main welding imperfection causes are:

- Inappropriate selection of welding process, welding parameters drifts
- Type/nature of parts/material to be welded
- Filler material
- Working environment
- Human factors related to welder

As a starting point this standard is also a good guideline to review the potential imperfections generated in the various AM process. The main difference is that for AM there is no more need to make differences between parent metal, heat affected zone (HAZ) and welded zone because the whole part is melted.

4 What is NDT?

4.1 Introduction

Non-destructive testing (NDT) consists of examining objects without destroying them, in order to detect local detrimental imperfections generating malfunctions in a device, to which the objects belong. These detrimental imperfections are then called “defect” (Fig. 1).

Whatever the NDT technique applied, the aim is to detect and assess the imperfection located in a melted or heat affected zone inside a part, by means of a physical phenomenon interacting with the imperfection. The result of this interaction is generally observed by means of a signal or an image and is then called an indication. The indication is often confused with the imperfection itself. It is very important to keep in mind that the indication is a representation of the imperfection that can be very different from the imperfection itself.

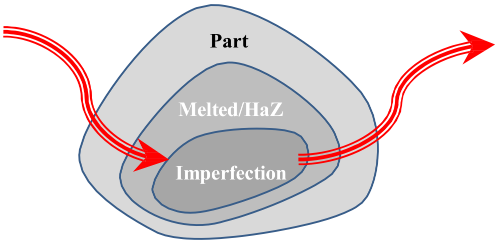


Fig. 1 The defect/weld/part system [2]

NDT is not only applied at the manufacturing stage but also for in-service inspection especially to provide integrity assessment. In-service inspection requirement can vary and the procedures to be applied are not the same: the defects to detect are no more those generated by the manufacturing process but by the ageing of the component.

Each NDT technique gets its specific capabilities and limitations. Some are only able to perform detection and to measure the length of the indication, while others also have the capability to assess the indication height. NDT techniques also vary in their capacity to characterise a discontinuity, i.e. to determine whether it is voluminous, planar, sharp etc. The different physical principles and the conditions of application may cause differences in performances.

Inspection procedures are often made up of a mix of NDT techniques, setting procedures or calibrating principles, decision steps, scanning systems, recording and illustration tools and software. They often involve a process of interpretation of indications depending on the skill of the operator. As a result, they cannot be considered simply as measurements. NDT performance for detecting, locating, classifying and sizing defects cannot be represented by simple confidence intervals. Higher sophisticated probability of detection (POD) procedures may have to be developed and taken into account.

4.2 Factors of influence [2]

The capabilities and performances of the various NDT techniques are then dependent on three main families of factors:

- Type 1: factors related to the inherent properties of the system made up by the imperfection/melted zone/part
- Type 2: factors related to the operating settings allowed by the type of NDT technique applied
- Type 3: human factors

A short list of the main type 1 factors of influence is given in Table 1. NDT people have little control over these factors. Manufacturers may have a limited influence: to improve the test piece surface conditions and to get benefit from the heat processing applied to decrease for example the grain sizes.

Table 1 List of the mains factors of influence (type 1)

Part	Melted zone and HAZ	Imperfections
Surface conditions	Surface conditions	Facies/morphology
• Roughness	• Roughness	• Smooth
• Ripple	• As welded	• Rough
Shape-geometry	Shape-geometry	Shape-geometry
• Plane	• Plane	• Planar
• Regular and 2D	• Regular and 2D	• volumetric
• 3D	• 3D	• Linear
• Complex	• Complex	• Point like
• Faces //		• Straight
• Constant section		
Dimensional and other	Dimensional and other	Dimensional and other
• Thickness	• Thickness	• Height
• Size	• Size	• Length
• Weight	• Weight	• Distance from surfaces, depth, location
		• Tilt
		• Skew
Material and metallurgical properties	Material and metallurgical properties	Type
• Grain sizes	• Grain sizes	• Cracks-decohesion
• Texture	• Texture	• Cavities
• Grade of parent metal	• Filler metal composition	• Solid inclusions
• Structures	• Structures	• Lack of fusion
• Preferred orientation	• Preferred orientation	• Lack of penetration
		• Imperfect shape and dimension
		• Miscellaneous
		• Rogue materials
Other	Other	Other
• Stain	• Stain	• Stain
• Stress	• Stress	• Stress
• Temperature		

NDT people may work a little bit more over type 2 parameters by selecting the best NDT operating parameters adapted to the scope and testing conditions.

In some cases design modifications can make testing easier but unfortunately it is often too late because NDT engineering is not enough known by designers. An attempt to build bridges between these two communities was carried out through a European project [3] and IIW guidelines [4].

Human factors are often not taken into account, but they may have a strong influence on the NDT performances.

An accurate study of the factors of influence shall be performed case by case and may require a long time study depending on the scope to address. Simulation tools such as CIVA®, COMSOL® are very useful to study the impact of type 1 and 2 factors on the NDT performances and to speed up the analyses.

5 Current NDT methods and techniques used for weld testing

5.1 General

NDT purist people make a difference between method and technique. A method is defined in ISO 9712 [5] as a "discipline applying a physical principle in NDT" and a technique as a "specific way of using a NDT method". As an example ultrasonic testing is a method, but when phased array ultrasonic probes are used it is then called the Phased Array ultrasonic technique (PAUT). However there are some "grey areas" between a method and a technique particularly when historical methods are applied, i.e. UT method generally means now Manual ultrasonic technique (MUT).

This wording difference is of importance according certification of NDT personnel. As a matter of fact ISO 9712 specifies requirements for principles for the qualification and certification of NDT personnel for the following methods: acoustic emission testing (AT), eddy current testing (ET), infrared thermographic testing (TT), leak testing (LT) (hydraulic pressure tests excluded, magnetic testing(MT), penetrant testing (PT), radiographic testing (RT), strain gauge testing (ST), ultrasonic testing (UT), visual testing (VT) (direct unaided visual tests and visual tests carried out during the application of another NDT method are excluded).

The system specified in ISO 9712 can also apply as written in the standard "to other NDT methods or to new techniques within an established NDT method, provided a comprehensive scheme of certification exists and the method or technique is covered by International, regional or national standards or the new NDT method or technique has been demonstrated to be effective to the satisfaction of the certification body".

So, in the following we will try to keep the definition provided by ISO 9712 but without being more papist than the pope.

5.2 Introduction to the "NDT family"

Table 2 compares the main NDT methods according to their general scope of testing and their main limitations.

Table 2 General comparison according to the area coverage

Method/ technique	Part surface	Part volume	Part in its whole	Observations
VT	1	0	0	For open imperfection only but process drifts leading to potential imperfection may also be deduced
PT	1	0	0	For non-porous material only and open imperfection
MT	1	0	0	For magnetic material only—subsurface imperfection may be detected
ET	1	2	0	For conductive material only—depth of penetration may range 0.1 to 10 mm
RT	2	1	1	May be impossible on material having high X or γ ray attenuation a whole part may be tested depending on the size ratio: part/detector
UT	2	1		May be impossible on coarse grains or material having high ultrasound attenuation
AT	(1)	(1)	(1)	Limited to detect propagating defects
TT	(1)	(1)	(1)	Generally used on non-metallic material

0: not applicable; 1: recommended by general standards; (1): recommended by product standards; 2: considered in the scope of general standards but generally not to apply as a stand-alone method

5.3 Visual testing

VT is the oldest form of testing method. It is generally performed by the naked eye. The first courses provided by Institut de Soudure (formerly the Central Office of Acetylene) were given during the 1910s by R. Amédéo on carbon steel plate welded by an oxyacetylene torch. An extract of this course [6] is given in Figs. 2 and 3.

This highlights that, at that time, VT was not only taught as a way to detect surface imperfections but also as a means to sentence welding process drift and its consequences. These aspects are often forgotten in many 2010s VT courses.

VT is now often assisted by tools such as magnifying glasses, mirrors and endoscopes. Testing may be performed both from the outside and, with the aid of specialised tools such as endoscopes, from the inside of constructions. Since only the surface is observed, only the surface indication dimensions can be measured; a large choice of welding gauges is available on the market for: checking alignment, verifying weld dimensions, assessing surface breaking defect…. Profilers (using laser or not) may be used instead weld gauges (laser profilers are more expensive and generally not so versatile and can be limited on complex geometries such as nozzles). Their characteristics (resolution, accuracy, dimensions …) shall be carefully chosen in accordance with the inspection objectives, available access and software capabilities.

5.4 Methods and techniques for surface testing

Penetrant testing (PT) was after VT the first NDT surface testing method applied and is still widely applied in many industries.

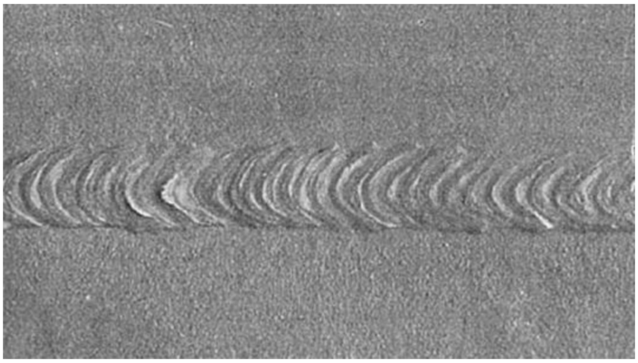


Fig. 2 An experienced observer recognises from the simple aspect of this weld that it lacks penetration: protrusion of the added metal, visibly unconnected with the plates: too fast work or use of a filler wire with a too large diameter

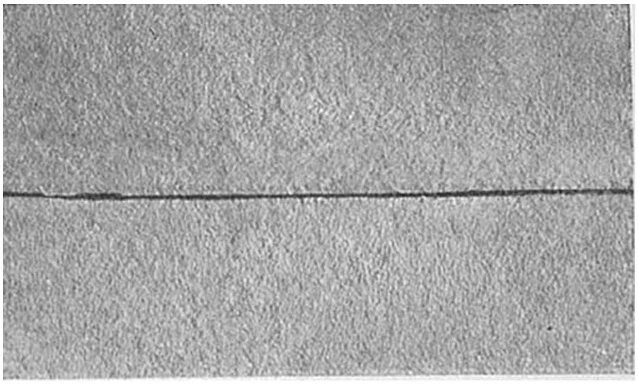


Fig. 3 Here is the back of the same weld demonstrating the absolute lack of penetration—weld of no mechanical value and break initiation along its entire length

Magnetic particle testing (MT) is another surface testing method widely used. It consists in exposing the zone to be tested to a continuous or alternate magnetic field. The possible imperfection will produce a leakage field on the surface of the part to be tested, making it visible by means of a medium containing ferromagnetic particles.

Eddy current testing (ET) may also be used for surface testing because imperfections have other electrical conductivity and magnetic properties than the parent material. Eddy current testing array (ETA) is more and more used and offers major benefits compared with single coil ET: imaging records, sizing capabilities, flexible sensors able to match complex shaped parts.

P. Nennig [7] made a comparison of PT and ETA capabilities on various kinds of samples. Figures 3 and 4 illustrate the results obtained on the cracked sample No. 2 according to ISO 3452-3 [8]. The five areas with cracks are clearly detected. The resolution obtained by ETA is not as high as fluorescent PT, but may be satisfactory for many industrial applications. The first area, having cracks with the smallest depth, is even better detected, probably because some subsurface imperfections are present (Fig. 5).

The main advantages of ETA testing vs PT are:

- Subsurface imperfections may be detected.
- No need to recycle effluents.
- Immediate results.
- Permanent records.

Table 3 compares NDT surface methods according the influence of the part surface conditions.

5.5 Radiographic testing methods and techniques

ISO 17636-1 [9] specifies fundamental techniques for examination of fusion welded joints in metallic materials by conventional X and gamma-ray techniques with a film.

5.5.1 Computed radiography technique

In computed radiography technique (CR) the film is replaced by an imaging plate. Its principle is based on the characteristic of some phosphorus crystals (phosphor layer consist in a mix of bonded fine grains of fluor, barium and bromium doped with europium) to capture a latent image when they are exposed to an X or gamma photon flux. This latent image is formed by the trapped electrons at a higher energy level when phosphorus crystals interact with photons incident on the plate. Then the plate is scanned by means of a high resolution laser beam which stimulates the trapped electrons. That is photo stimulated luminescence, which entails a brightness located in the visible spectrum. This light is then measured with a photomultiplier, digitized and then stored in the computer's memory as a function of the laser beam position on the plate. The plate can then be erased by an internal white light source inducing a return of the trapped electrons to their original energy level.

The number of measured light photons is proportional to the number of trapped electrons being proportional to the number of X or gamma photons which interacted with the plate.

Due to the proportionality of the latter mechanisms, the characteristic curve of this plate is a straight line, contrary to the line of the traditional silver ions film having an S shape. Using high sensitive CR plates with X-rays allows to obtain sensitivity in very close agreement to one obtained with film.

ISO 16371-1 [10] specifies the fundamental parameters of digitized radiographic systems with storage phosphor imaging plates and classifies IP plate in 6 groups from IP1 to IP6. IP6 has the highest resolution and the lowest SNR.

ISO 16371-2 [11] specifies the general principles for testing metallic materials using X-rays and gamma rays with CR ISO 17636-2 [12] specifies the requirements for digital radiographic X- and gamma-ray testing by either computed radiography (CR) or radiography with digital detector arrays (DDA) of the welded joints of metallic plates and tubes for the detection of imperfections.

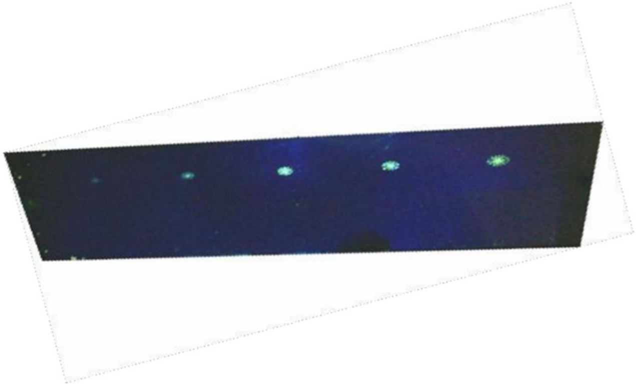


Fig. 4 PT results on a cracked sample [7]

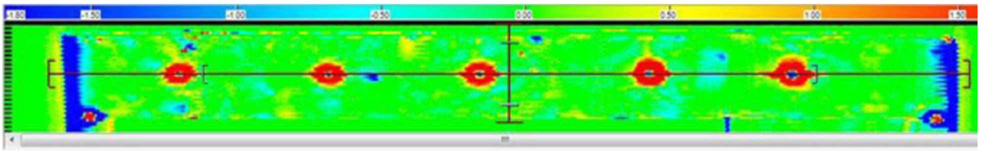


Fig. 5 ETA results on a cracked sample [7]

Note: IP plates are more sensitive to low energy scatter than conventional film. Careful control of backscatter is required.

5.5.2 Digital radiography system (DR)

The conventional radiographic film is replaced by a digital detector providing a digital grey value image. This image cannot be viewed and evaluated by means of a light-box. A computing system is required.

With DR [13], there is an immediate conversion of radiation intensity into digital image information. The radiographic image is almost immediately available. Some systems even provide a true real-time (radioscopic) mode with display rates up to 30 images per second.

In direct detection, the amount of electric charge created by the incident X-ray photons is directly detected in semiconductor materials.

In indirect detection, the X-ray photons are absorbed by a scintillator emitting visible light photons, which are then detected by a photo detector being the second layer, thus providing an indirect detection method.

With linear detectors, the image is acquired by a detector unit containing a linear array of closely spaced sensing elements. The objects under observation need to be moved relative to the detector. It thus accumulates a two-dimensional image line-by-line as the object travels across its field of view.

2D detectors are made with a panel of photo detector arrays. Small 2D detectors are often based on crystalline silicon integrated circuit, optically mated to a powdered scintillator screen. CCD'S and CMOS technologies may be used. Larger 2D detectors (up to the size of common films) are usually made from photo diode arrays of amorphous semiconductors.

Table 3 NDT surface methods comparison

Surface conditions	PT	MT	ET	ETA
Coated/painted with thin non-conductive layer	0	1	1	1
Coated/painted with thick non-conductive layer	0	0	2	2
Coated/painted with conductive layer	0	(1)	2	2
Uncleaned (degreasing, brushed…)	0	0	1	1
Blasted	0	1	1	1
As welded	1	1	2	2

0: not possible; 1: possible with standard procedure; 2: to assess with specific procedures (generally limited)

EN 13068-1 [14] specifies the measurement operations to define the specifications of the imaging device relating to the imaging properties.

EN 13068-3 [15] specifies general rules for industrial X- and gamma-radioscopy for flaw detection purposes, using radioscopic techniques, applicable for testing of metallic materials.

5.5.3 Image processing

To enhance the visibility of imperfections, CR and DR systems always include image processing capabilities. The systems currently available on the market provide basic image processing such as brightness and contrast enhancement and filtering (Figs. 6, 7 and 8).They may also include advanced algorithms adapted to specific tasks. In any case image processing shall be carefully used. As an example, a longitudinal defect is enhanced by the processing applied on Fig. 8 but a transverse one would be hidden by the same processing.

5.5.4 Computed tomography

Classic radiography cannot deliver accurate depth information of an imperfection from single X-ray images. RT inspectors well trained for welds testing may deduce depth positions hints. Some special RT techniques (i.e. parallax technique) were developed a long time ago, based on two or three shots on the same film allowing through geometrical known considerations, to assess the depth of an indication.

Computed tomography (CT) principle is in it spirit based on these early principles but with much more shots and more complex reconstruction algorithms.

Fig. 6 Raw CR image on a weld

Fig. 7 CR image on a weld after basic image processing

Full 3D reconstruction of the object and of its content is then now possible. This allows not only to perform NDT but also advanced metrological analyses of the parts and its internal items and then comparison with CAD design.

When an indication is detected by CT, and any acquisition and reconstruction artefacts avoided, the indication may be considered quite as the imperfection itself. Then sizing the positions and dimensions may be accurate. It is then possible for example, to calculate the volume of an imperfection and to apply a coloured threshold allowing displaying out of acceptance imperfections (Fig. 9).

J. Waller [16] summarised advantages to use CT for Ti-6Al-4V specimens manufactured by AM as follows:

- Detection of deep or embedded defects
- Interrogation of inaccessible features
- Confirmation effectiveness of post-process, treatments often required to make usable parts
- Characterisation and qualification as manufactured parts

However, the inability of CT to reliably detect cracks is pointed out (since cracks oriented perpendicular to the X-ray beam may not be detected).

CT is also based on the differential attenuation and is not able to detect an imperfection providing a too weak attenuation such as:

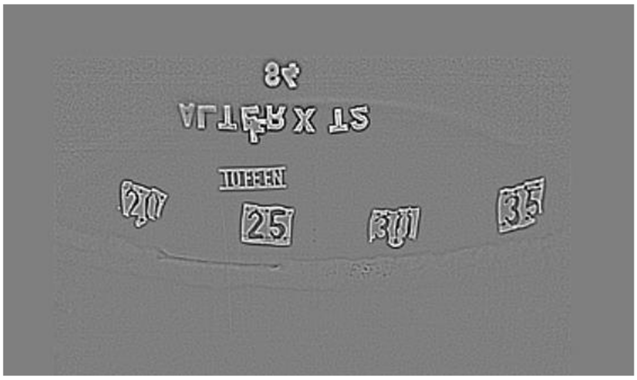


Fig. 8 CR image on a weld after filtering

- Close atomic number between imperfection and parent metal
- Different metallurgical phases

5.6 Ultrasonic testing methods and techniques

Physical principle of the historical manual ultrasonic testing (MUT) is very similar to the acoustic echo generated when somebody shouts in front of a wall; the wall reflects the voice and after a lapse of time the echo of the voice may be heard. When using ultrasounds, it is a little bit more complicated because several phenomena occur: reflection, transmission, mode conversion and diffraction when the wave length is in the same range than at least one dimension of the imperfection.

Reflection and transmission coefficients are driven by acoustic impedance. Diffraction is driven by other factors and laws.

To be detected, the imperfections have to be wide enough and be impinged by the ultrasonic beams at the right angle. Imaging capabilities have been added to the historical manual UT methods, to make imperfection assessment easier. Time-of-flight diffraction (TOFD) technique and phased array ultrasonic testing (PAUT) are now widely used and standardised.

5.7 Other NDT methods

Thermographic testing (TT) deals with detecting and locating surface temperature variations. An infrared camera associated to image processing software produces a 2D image of the inspected zone, called thermogram. The colour of each image pixel can be linked to the temperature at each point of the object, assuming hypothesis on the emissivity value of the surface. Basic testing is conducted on the passive mode (using the temperature variation related to the object)

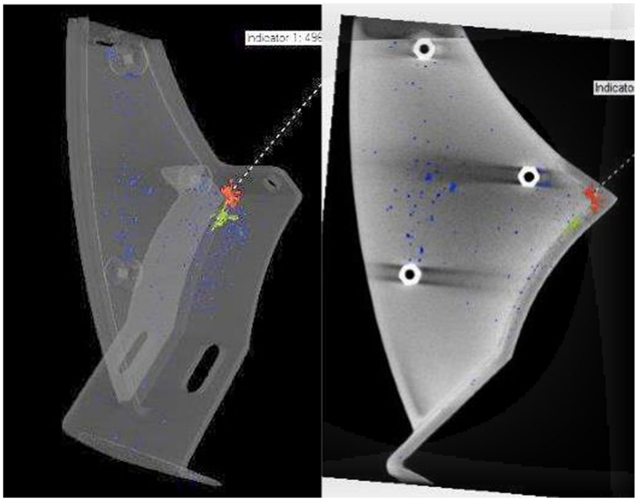


Fig. 9 CT on aluminium alloy casted parts

Advanced thermography testing techniques use various types of external heating source in order to create a thermal flow. The heat applied on surface generates waves inside the part to be tested. The dissipated heat is monitored using a high resolution IR camera (few mK). The presence of imperfections creates inhomogeneity in the thermal area and may be observed in the thermal image. Several excitation sources may be used and should be chosen according to the size, type and orientation of potential imperfections and to the material of the part. The most common heating sources are: flash light, IR lamp, halogen lamp, induction. Mechanical stimulations (ultrasonic, vibration…) may also be used.

Instead of heating, cooling may also be used; observations during the process cooling cycle may also be of interest.

This method is mainly used to detect imperfections in composite parts such as: delamination, disbonding, cracks and porosity. Thermography is also a good approach to monitor different kinds of manufacturing processes: welding, additive manufacturing, mold filling … see § 9.

Acoustic emission testing (AT) is another very useful method able to test a whole part.

The measuring principle of acoustic emission consists in detecting ultrasonic waves resulting from the structure activity. Detection is generally carried out through probes of the piezo-electric type secured to the structure. Acquisition and processing of recorded data are thereby carried out by the system itself.

AT is a valuable method for replacing hydrotest on pressure vessels.

6 Focus on capabilities of NDT techniques

6.1 UT in mastered coupling conditions

The test pieces are either set inside an immersion tank (Fig. 10), or between two probes fed by a water squirter device. The probe (or the probes) which can be focused moves mechanically according to a pre-established raster scanning. When a favourably orientated defect is present inside the part, the scanning cycle can be stopped at the location of the indication. The ultrasonic signal can also be recorded in the testing system with the corresponding position of the mechanical system, thus allowing production of ultrasonic images such as B-scan, C-scan ….These techniques require good surface conditions in places where the ultrasonic beam impinges the part to be tested.

Fig. 10 Ultrasonic immersion tank

Water squirter UT devices are mainly used to test honey comb composite parts, but the mechanical device may hold other kinds of probes than the UT one and also be used for developing new NDT techniques. There are potential synergies for testing strategies applied to additive manufacturing lattice parts.

The advantage of the squirter presented in Fig. 11 is that it is based on two poly-articulated arms allowing to test parts having very complicated shape.

High frequency ultrasonic testing also called acoustic microscopy is adapted for detecting very small defects. D.Flotté et al. gave examples [15] of applications:

- Ceramics
- Testing assemblies with thin parts (thickness < 5 mm)
- Bonds on micro-assemblies
- Laser welds on thin plates (thickness < 2 mm)
- Ceramic/metal assemblies (brazed, thermo-compressed) the ceramic can be up to 10 mm thick with a frequency of 50 MHz

The advantages of such a technique is the high resolution obtained but the gantry shall be accurate and the part inspected shall have very good surface conditions.

Figure 12 shows the results obtained after scanning a coin, highlighting the resolution that can be obtained.

Fig. 11 Squirter UT equipment

Fig. 12 HF UT C-SCAN on a coin

Figure 13 shows porosities and inclusions ranging from 10 to 80 μm and Fig. 14 shows two cracks. The bigger one has a length of 7.2 mm and a width of 20 μm. A good correlation was obtained with micro-focus RT.

6.2 Laser ultrasonic technique

The main phenomena involved in laser ultrasonic wave generation in a solid are characterised by two regimes:

- Thermoelastic: this mode is characterised by three main steps:
  - Emission of a laser beam impacting a material partially absorbing the optical power
  - This power is converted into heat, inducing rapid and localised heating
  - This heated zone leads to a dilation and then a localised thermal contraction generating ultrasonic waves in the medium

- Ablation: when the emitted beam power becomes higher than the ablation threshold, some particles of the surface reach the vaporisation temperature. This ejection of material introduces normal forces at the surface of the part, making it possible to generate ultrasonic waves.

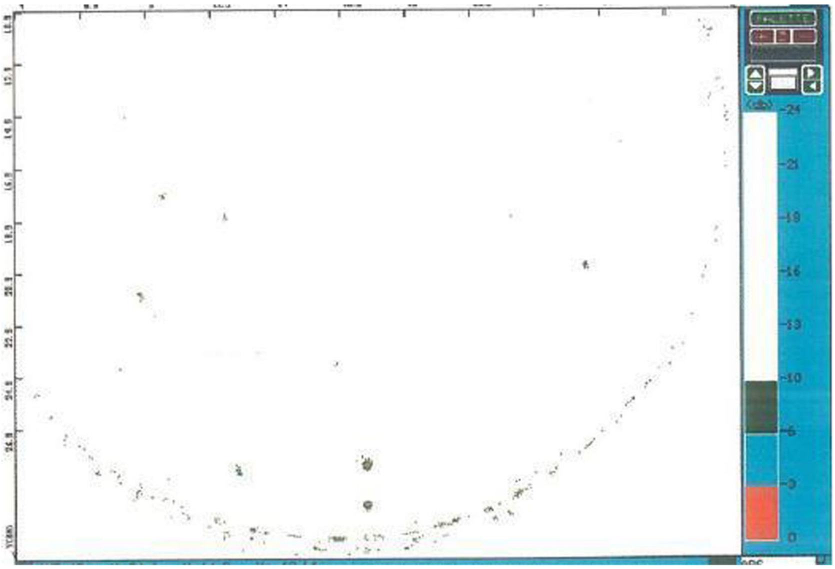
For both regimes, several types of waves are generated, namely: Rayleigh, longitudinal, transverse... In addition, the pattern of wave directivity varies according to the generation regime. Thus, as different modes can propagate in the part, a better performance of detection may be reached. However, it may be more tricky to perform discrimination between imperfections and artefacts.

Figure 15 illustrates the two laser ultrasound generation regimes.

One of the main benefits of using laser ultrasonic technique (LUT) is that the testing technique can be implemented without contact and coupling medium. The detection is also ensured by optical elements (generally an interferometer is used). This allows to detect the variations of the characteristics of the incident beam (frequency, phase, etc.) generated by the interaction with the ultrasonic vibrations present on the surface of the part to test. Figure 16 shows a lab equipment allowing to produce and receive laser ultrasonic waves.

An example of the result obtained on a surface breaking notch introduced in a carbon steel reference block (Fig. 17) is

Fig. 13 HF UT C-SCAN on a Si3N4 sample (porosities) [17]



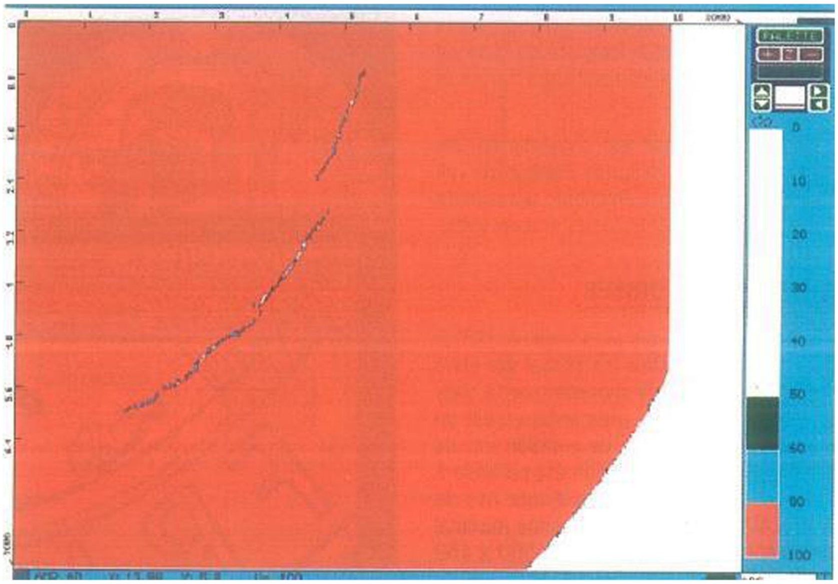


Fig. 14 HF UT C-SCAN [15] on a Si3N4 cracked sample [18]

given in Fig. 18. The top and bottom of the notch are clearly detected allowing to accurately size the notch.

6.3 Guided waves

This technique has been developed for about 20 years. It relies on guided waves which are mechanical waves propagating through the wall of a structure and is mainly used for pipes and pipings testing or monitoring in order to detect corrosion. The main advantage of this technique is to make it possible to test a wide length of pipe (up to 100 m) at a time and to assess areas non accessible by other NDT techniques. Inspection of pipes embedded in high attenuating medium such as bitumen or cement, remains a challenge.

For pipe/pipings inspection, two experimental arrangements may be used. In pulse-echo measurement, the transducer plays in general case a dual role: emission and reception. However, in pitch-catch case, two transducers are needed, and should be placed on either side of the area to be tested. This arrangement is not preferred in inspection field because it needs baseline data, which are not easy to get in most cases.

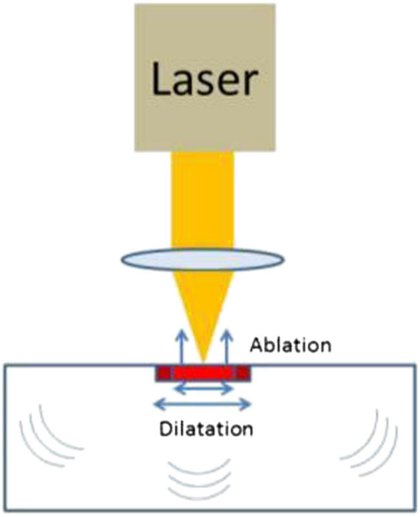


Fig. 15 Principle of laser UT generation [19]

Ultrasonic guided waves [20] have two behaviours (dispersive and multimodal) which can make the interpretation of testing results problematical. An infinity of propagative and evanescent modes with different degrees of dispersion may exist. Among them T (0, 1) mode is frequently used because it is easy to generate and receive, has a not-or-weak dispersive behaviour, and provides an equal probability of detection over the pipe circumference.

6.4 TFM/FMC technique

The full matrix capture (FMC) is a specific acquisition methodology applied on PAUT probes associated to a specific

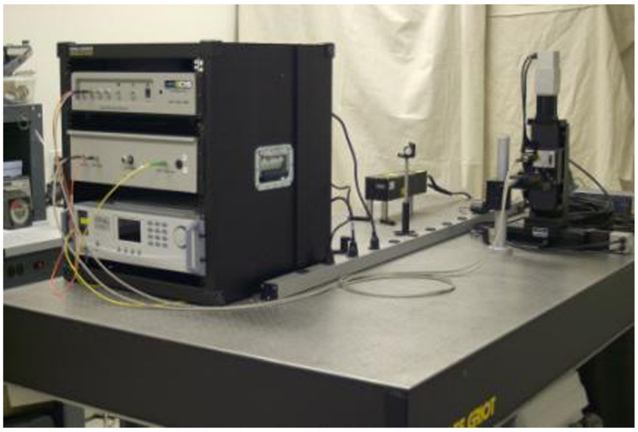


Fig. 16 Laser UT equipment

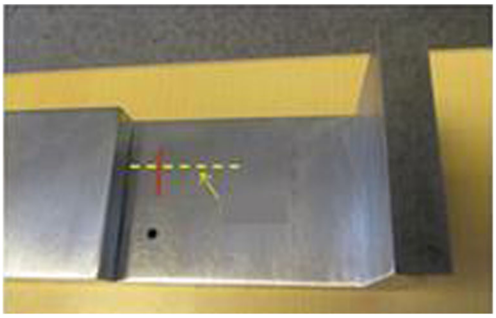


Fig. 17 Calibration block with holes and a notch [19]

processing called total focusing method (TFM). FMC consists in recording all the ultrasonic signals from all the possible pairs of transmitting-receiving elements on the array. Each element is successively fired and at each step the signals received on all the active elements are recorded. The outcome of this operation is the “full” matrix of signals Sij (t) where (i, j) represents the T-R pair of elements. After the data have been collected, they may be as a second step processed in many different ways [21]. Recently the application of TFM/FMC has been booming.

The main advantages of such an approach are:

- No more need to apply a focal law at the emission
- Quite equal resolution in the region of interest
- Multimodal representation of the imperfection
- Better representation of the imperfection

Figures 19, 20 and 21 show examples of results obtained on a carbon steel weld root defect by applying this special technique with Gekko ® in real time (Fig. 21). The plate thickness is 25.4 mm. The probe used has 64 elements and a frequency of 5 MHz. With TTT mode, the defect representation and the defect height assessment are accurate (better than 0.1 mm in lab conditions).

ISO 17636-1 [9] compares the range of thickness according to the type of radio element used for RT. Testing level B is more stringent and the thickness range is then more limited (see Table 4).

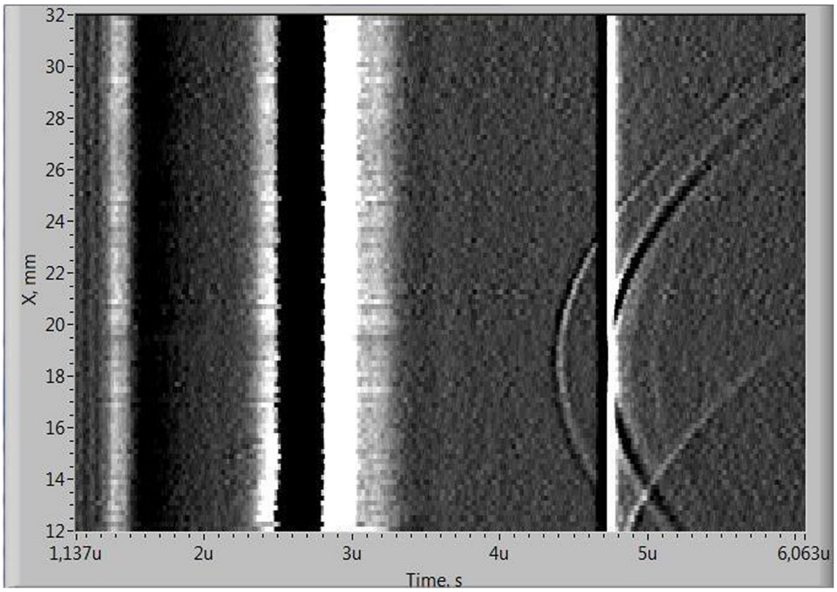
When comparison is performed aiming at replacing a NDT technique by another, the said OPC approach [23] may be used. It consists in driving a systematic analysis taking into account: the Occurrence of imperfection liable to appear while welding, the detection Performance of such an imperfection for each of the used NDT technique/method, the consequence(s) liable to result from the non-detection of these imperfections by the NDT techniques to apply considering the scope of application of the welded construction. Then, risks are assessed for each NDT technique combining parameters by means of a set of rules. The interest of such an approach is that the final decision takes into account the whole quality scheme and not only the NDT performance of each technique. This leads to re-address why NDT is applied. The OPC approach is based on FMECA (failure modes, effects and criticality analysis) principles and may be applied for other fabrication processes such as additive manufacturing.

7 Standardisation

7.1 ISO and EN organisation for weld testing

ISO and European standardisation are organised in technical committees (TC) entrusted to write standards. In Europe, activities of both TC are more and more merged. ISO/TC135 “Non-destructive testing” covers NDT standardisation as

Fig. 18 B-Scan obtained on the notch [19]



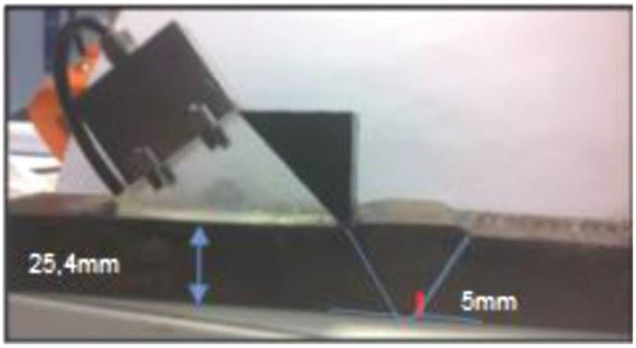


Fig. 19 Root defect on a carbon steel welded plate [22]

applied generally to constructional materials, components and assemblies. ISO/TC44 "Welding and allied process" covers standardization of welding, by all processes, as well as allied processes. The SC5 of this TC is dedicated to standardise "Testing and inspection of welds."

7.2 ISO standards for weld testing, how it works?

ISO standardisation is organised around quality levels standards as summarised in Table 5. These standards are for NDT purpose the "mothers" standards.

These quality levels are related to the actual size and nature of welded imperfections. The rejected defects and the acceptance values are based on historical good practice and not on Engineering Critical Assessment. Values do not equate to the capabilities of the different NDT techniques. It was agreed between ISO TC committees, that there is a fundamental difference between quality levels of a welded construction and NDT acceptance levels. The former limits the size and the number of welded imperfections in a given weld, including their actual physical size, while the latter limits the type, size and/or number of NDT indications. As already explained, they may be far different from the actual welded imperfection. That is why ISO 17635 [24] was issued. It specifies how to link quality level to acceptance levels.

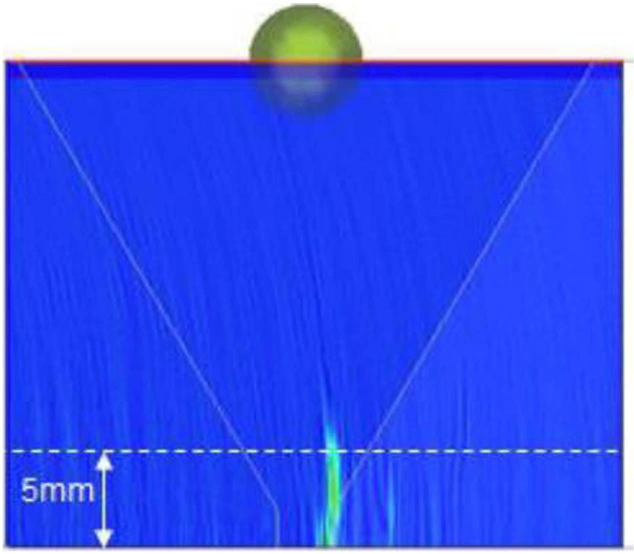


Fig. 20 TFM/FMC display on TTT mode [22]

Fig. 21 Example of portable equipment able to perform TFM/FMC in real time

ISO 5817 [25] provides quality levels of imperfections in fusion-welded joints (except for electron beam welding) in all types of steel, nickel, titanium and their alloys. It applies to material thickness ≥ 0.5 mm. It covers fully penetrated butt welds and all fillet welds. Its principles can also be applied to partial-penetration butt welds.

Three quality levels B, C and D are defined, where B is the more stringent. The main ISO weld standards to apply, when ISO 5817 is specified, are summarised in Table 6.

ISO 10042 [26] is the equivalent of ISO 5817 for arc-welded joints in aluminium and its alloys. It applies also to material thicknesses above 0.5 mm. It covers full-penetration butt-welds and all fillet welds and the principles may also be applied to partial-penetration butt welds. Quality levels for electron beam-welded joints are not covered. They are given in ISO 13919-2 [27].

In Europe, EN TC products may add complementary requirements. A product can be: pressure vessel, pipings, pipe, welded structures….

For example for pressure vessel, characterization of indications detected by UT shall be carried out according to ISO 23279 [28].

Table 4 Recommended thickness range for steel and Ni alloys according to radio element types

Radio element Testing level	Tm 170	Yb 169	Se 75	Ir 192	Co 60
Class B (mm)	≤ 5	2–12	14–40	20–90	50–180
Class A (mm)	≤ 5	1–15	10–40	20–100	30–200

Table 5 ISO quality levels standards

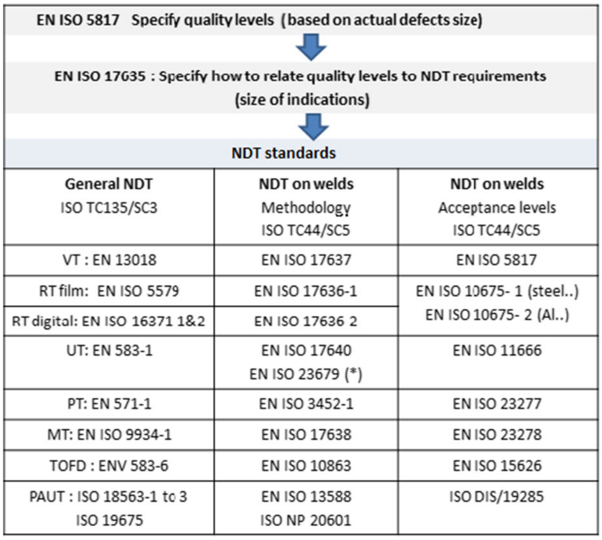
Quality levels standards	Materials	Welding process
ISO 5817	Steel, nickel, titanium & alloys	Fusion welded except EB
ISO 10042	Aluminium alloys	Fusion welded except EB
ISO 13919-1	Steel, nickel, titanium & alloys	Electron beam
ISO 13919-2	Aluminium alloys	Electron beam

7.3 What is new in NDT standardisation for additive manufacturing?

ASTM is currently running a project called WK47031 [29] aiming at writing a "New Guide for Non Destructive Testing of Additive Manufactured Metal Parts Used in Aerospace Applications."

This guide lead by Jess Waller from NASA, discussed the application of established and emerging (NDT) techniques such as: computed tomography, neutron diffraction, process compensated resonant testing (PCRT), used during the life cycle of additive manufactured metal parts. The scope of this guide covers aerospace applications therefore; the requirements may be more stringent than used in other industries. The metals under consideration include but are not limited to aluminium alloys, titanium alloys (Ti-6Al-4V), nickel-based alloys, cobalt-chromium alloys, and stainless steels. The AM processes under consideration include but are not limited to electron beam free from fabrication (EBF3) also called EBAM (electron beam Additive manufacturing), electron beam melting (EBM), Direct Metal Laser Sintering (DMLS), and selective laser melting (SLM). Some acceptance criteria are proposed but solely for purpose of refinement and further elaboration of the procedures described in the Guide and not for procurement.

Table 6 Relations between ISO 5817 and NDT standards for welds



EN ISO 5817 Specify quality levels (based on actual defects size)

EN ISO 17635 : Specify how to relate quality levels to NDT requirements (size of indications)

NDT standards

General NDT ISO TC135/SC3	NDT on welds Methodology ISO TC44/SC5	NDT on welds Acceptance levels ISO TC44/SC5
VT : EN 13018	EN ISO 17637	EN ISO 5817
RT film: EN ISO 5579	EN ISO 17636-1	EN ISO 10675- 1 (steel..) EN ISO 10675- 2 (Al..)
RT digital: EN ISO 16371 1&2	EN ISO 17636 2	
UT: EN 583-1	EN ISO 17640 EN ISO 23679 (*)	EN ISO 11666
PT: EN 571-1	EN ISO 3452-1	EN ISO 23277
MT: EN ISO 9934-1	EN ISO 17638	EN ISO 23278
TOFD : ENV 583-6	EN ISO 10863	EN ISO 15626
PAUT : ISO 18563-1 to 3 ISO 19675	EN ISO 13588 ISO NP 20601	ISO DIS/19285

Another guideline is also currently in progress through ISO TC 261 JG59 [30]. The project is called: "Additive Manufacturing—General Principles —Non-Destructive Testing of Additive Manufacturing Parts" reviews the ISO standards (welding and casting) usable for AM at the post-process stage. The scope of this "best practice" document covers metallic parts, but a similar framework can be applied to other materials (e.g. ceramics, polymers, etc.). Potential imperfections in direct energy deposition (DED) and powder bed fusion (PBF) are listed and an image catalogue of these imperfections is provided. This guide reviews existing standards and covers mostly the imperfections that can be generated by DED except some imperfections generated by PBF process: unconsolidated powder; layer; cross layer and trapped powder. New standards are then necessary to deal with these imperfections.

8 Monitoring techniques

8.1 Introduction

The two main areas of development are process monitoring (PM) used at the manufacturing stage and structural health monitoring (SHM) used to assess service life. Both areas may benefit from the same progress in sensors, signal processing and data science and may have valuable synergies.

On line NDT and process monitoring have some overlapping because some families of sensors may provide both: soundness assessment (NDT) and data collection related to process variations (monitoring).

8.2 Process monitoring

Process Monitoring (PM) is mainly focused on existing signals generated by the process and provides real-time control possibilities based on regulation loops identified as necessary for the process. It is possible to collect a lot of data during the process.

An optimum choice should be made between PM and NDT. Strong link between PM and the quality of the parts can be established by capturing the adequate information during the processing stage. However NDT is not generally fully replaced to verify the quality of a part. Adequate PM strategy will ensure that the quality of the parts will remain in the acceptable level avoiding applying 100 % NDT on the produced parts, thus reducing production cost.

Ideal techniques/sensors in process monitoring should provide the right information without:

- Being disturbed by the process
- Introducing malfunctions of the process

According to visibility/accessibility of the building scene, the sensors may receive either direct or indirect information. The sensors can be used in passive or active mode.

Several techniques may be used to collect direct information:

- Visual observations with or without processing. Lighting shall be carefully adapted to get the optimal information
- 2D or 3D reconstruction of the building scene; laser profilometry is often used for that purpose
- Thermal measurement due to variation of the extent/shape of typical hot spot generated by the process
- Eddy current
- Sound and ultrasound
- X-rays

W. J. Seufzer et al. [31] used thermal measurements to control EBF_3 process. They also compared the advantages of the possible regulation loops to apply.

Indirect information may also be collected due to:

- Thermal variations: as a wide range of processes is based on heat transfer, monitoring the heat exchanged through one constitutive material may be correlated to something wrong happening in the building scene.
- Mechanical stress (force or local pressure) or deformation may be transmitted through a component used in the process and may provide interesting hints related to process drift.
- Ultrasonic/acoustic wave generation or modification may be transmitted outside the building scene and be used as good hints of process deviation.

H. Rieder et al. [32] used ultrasound with sensors set underneath the building platform in order to monitor the SLM process.

The information provided by a sensor can be used either in a close-loop or as an independent control measurement. In an operational close loop, the value of the sensor should fit a setpoint and has therefore no more interest than checking the settings and stability. However, the actuator level in the close loop is seldom recorded and is often a good indicator of a process drift. The sensor choice and location has also to be taken into account according to the using mode. A passive monitoring sensor can be closer to the material to be transformed and more sensitive to variations without disturbing the long-term stability of process. An active/passive sensor couple is also very useful for information redundancy helping to detect possible sensor drift or damage.

8.3 Structural health monitoring

Structural health monitoring (SHM) can be defined as a discipline aiming at surveying continuously the integrity of a structure. To do so, sensors/actuators should be set permanently with the said structure during its full life. An easy-to-use software can be used to automatize the monitoring. Decision to use this software is based on thresholds which are closely related to the collected database. The collected data are unfortunately vulnerable to environmental and operational changes (EOC), which can cause false alarms. Reducing these EOC effects is a challenging task and needs the development of algorithms either analytical or statistical (Table 7).

M. El Mountassir et al. [33] have made a review of these EOC factors, their associated effects and the various strategies to compensate for or eliminate these effects.

Analytical strategies may be used, based on optimisation algorithms that rely on the minimisation of the residual error between the baseline signal and the current signal (which may contain information related to damage). Other strategies are based on using statistical methods which seem to be more reliable and can be easily implemented.

These methods can be divided into two categories: supervised and unsupervised learning algorithms:

- Supervised learning is used when different damage levels and scenarios are available. It can be used for the identification of the type and the damage severity. But in general, data from the damaged structure are not usually available.
- Unsupervised learning does not need an a priori on the structure, due to its behaviour with time, damage characteristics (shape, dimensions, orientation, type, location, etc.).

An example of application of such algorithms is given in §10.

Table 7 EOCs factors and their associated effects [33]

EOCs factors	EOC effects			
	Time shift	Amplitude drift	Dilation	Distortion
Temperature	✓	✓	✓	✓
Flow rate	✓	✓	✗	✗
Humidity	✗	✓	✗	✗
Rain	✓	✓	✗	✗
Loads	✓	✗	✗	✓

9 Cases studies

9.1 Tomography testing of SLM parts

A nozzle was manufactured by a laser beam melting with a SLM 250 HL (from SLM Solutions GmbH). The material used is a Ti-alloy (TiAl6V4). A section of this nozzle is presented in Fig. 22 where the internal channels are shown. The internal channels are used for some cooling medium (e.g. air or water).

A nozzle as built was investigated by CT investigations. The x-ray-images and the CT-scan were taken with a XRH222-S equipment.

The main settings are:

- Acceleration voltage: 225 kV
- X-ray current intensity: 3,6 mA
- Used filter for beam-hardening: 0.5 mm Cu
- Pixel size of the detector 139 μm
- CT-scan:

– 1600 steps—duration of the scan: 3.5 h
– voxel size: 95.4 μm
– magnification × 1.4

No soundness imperfections were detected.

The benefit of CT to investigate this kind of part is also in its capability to measure the internal channels dimensions (Figs. 22 and 23).

9.2 PAUT of austenitic welds

The presence of austenitic weld metal can seriously affect the ultrasonic testing of a part because of:

Fig. 22 Section of a Nozzle made by SLM (Courtesy of VisiConsult X-ray Systems & Solutions GmbH and IFW - Günter-Köhler-Institut für Fügetechnik und Werkstoffprüfung GmbH)

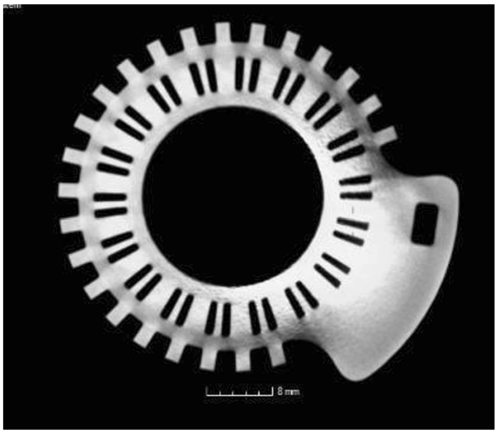


Fig. 23 X-ray tomography slice (Courtesy of VisiConsult X-ray Systems & Solutions GmbH and IFW - Günter-Köhler-Institut für Fügetechnik und Werkstoffprüfung GmbH)

- Distorted wave propagation within the weld material
- Reflection of ultrasound at the fusion boundary between the parent material and the weld

UT procedures have to deal with [34]:

> Anisotropy: the properties of the melted material, e.g. ultrasonic sound velocity, vary with the direction in which they are measured. Choice of appropriate type of wave and ultrasound angle beam generation may limit this effect
> Beam deviation: Beam deviation is said to occur when an ultrasonic beam propagates in a direction which is not perpendicular to the wave front. This phenomenon can cause unexpected changes in beam direction and shape. Using focus beam generally limits this effect.
> Scattering: Welds in austenitic materials have coarse macrostructures which cause significant scattering of ultrasonic beam that even may occur at relatively low frequencies, e.g. 2 MHz. This can lead to very low signal-to-noise ratios for some ultrasonic testing.

That is why UT testing of austenitic welds should follow the recommended flow chart (Fig. 24) [35].

The following case study, reported by S.Demonte et al. [31], deals with the testing of nozzle butt welds of high pressure vessels, DN 50 and 75, thickness 25mm + 3mm weld overlay SS 316. The filler material is inconel 625. The construction code refers to EN1714 (now ISO 17640 [32]). ISO 22825 [33] was used as guidelines. Basic modelling (Fig. 25) was carried out to define appropriate scan plans able to meet the testing zones coverage requirements (Figs. 26 and 27).

The main benefits of using PAUT compared to RT are the following:

- A better detection of critical imperfections: all joints were acceptable by RT, 5 joints were rejected by PAUT. Several

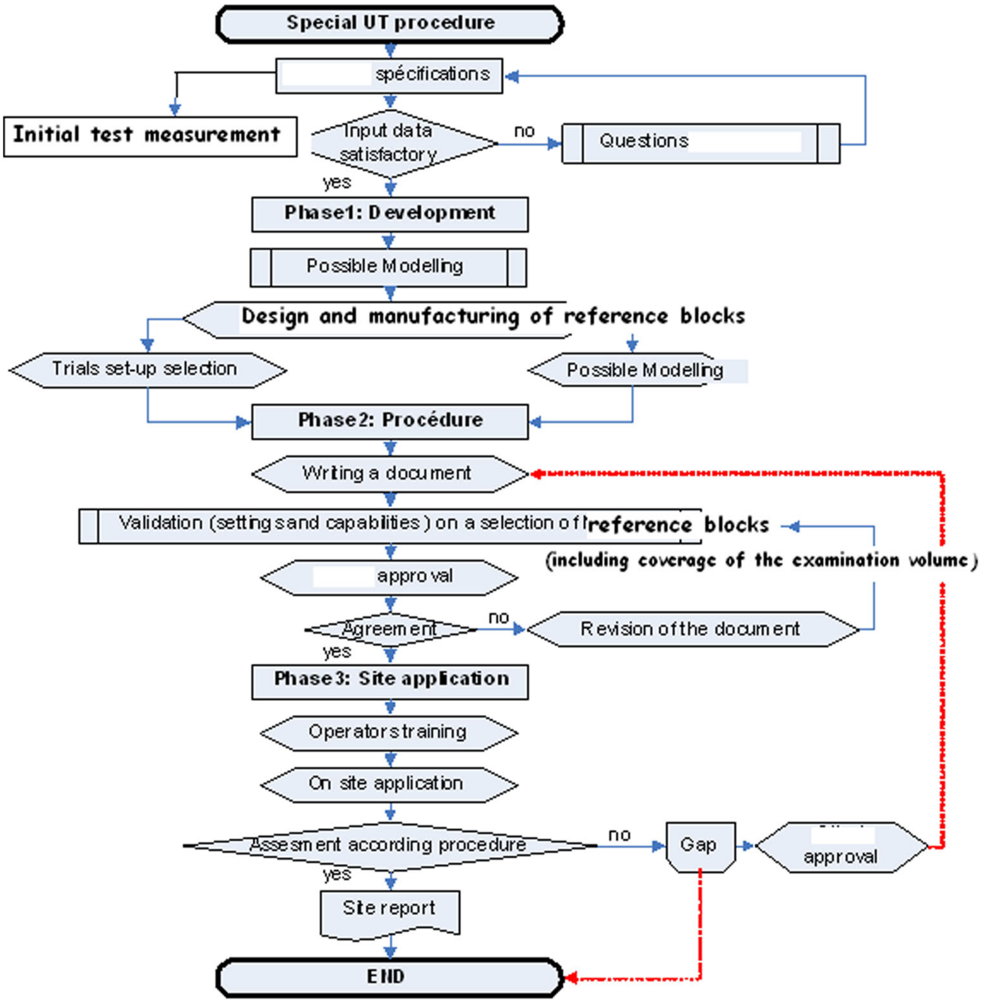


Fig. 24 Flow chart for UT testing of austenitic welds [20]

rejectable indications were discovered on the same joints. Defects not detected on RT films were mainly side wall or inter-run lack of fusion).

- the examination time is reduced:

– RT requires 5 h shooting time (Ir 192-1 TBq)

– PAUT ranges from 1 to 2 h depending on the number of indications detected

- PAUT results are given in real time (no offline analysis), defect location directly marked on the weld, allowing immediate repair.

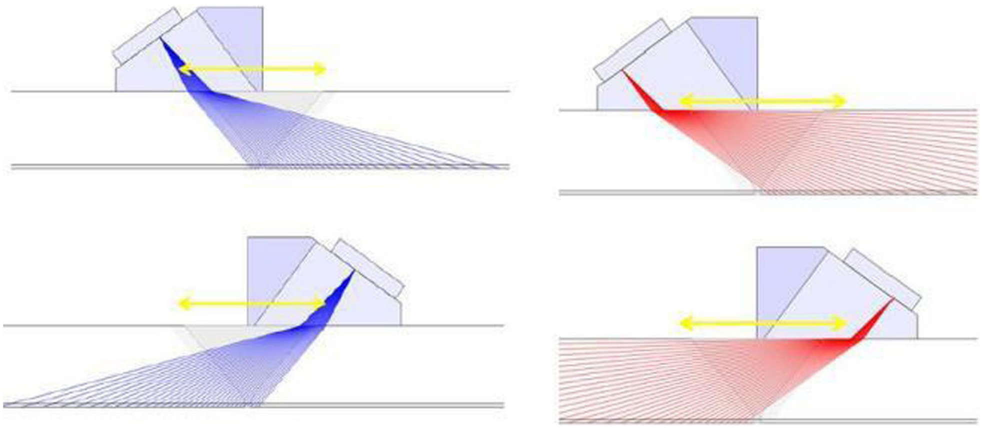


Fig. 25 Zones coverage study by modelling [36]

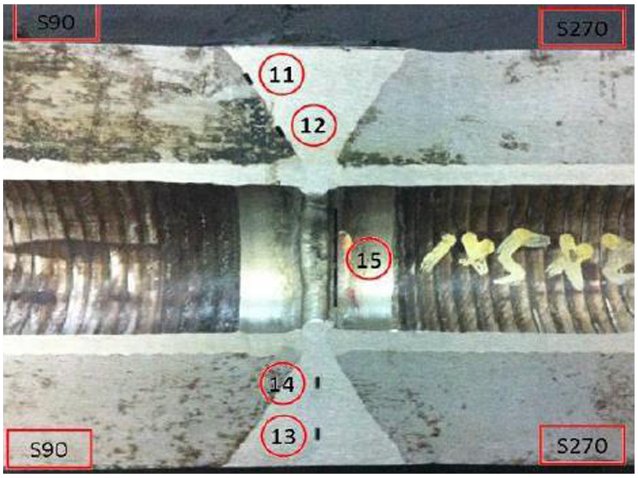


Fig. 26 Calibration-qualification blocks [36]

9.3 Testing on steel parts made by WAAM

9.3.1 3D reconstruction

There is a broad variety of technologies for digital acquisition of 3D object shapes. Each device has its own specifications and works differently. Figure 28 shows an example of reconstruction made with the Handyscan ® system on a carbon steel object made by WAAM at Institut de Soudure.

Handyscan® 3D is a hand-held scanner manufactured by Creaform®. It is a portable and versatile self-positioning 3D scanner, based on stereo principle allowing simultaneously observing reflective targets (for positioning) and laser projection (for geometry detection). Once the object and the scanner position have been located with targets, the surface acquisition is completed through the camera. The camera sees the two laser lines, crossing each other, projected on the surface. As the surface is swept over by the laser, data are recorded, based on the triangulated position. The output file format is a STL file.

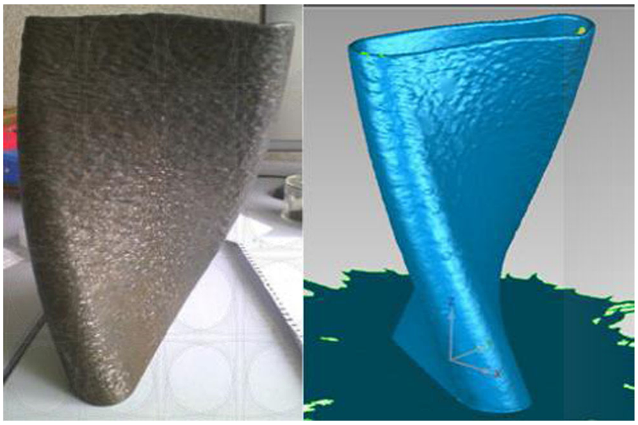


Fig. 28 Waam object and corresponding 3D scan

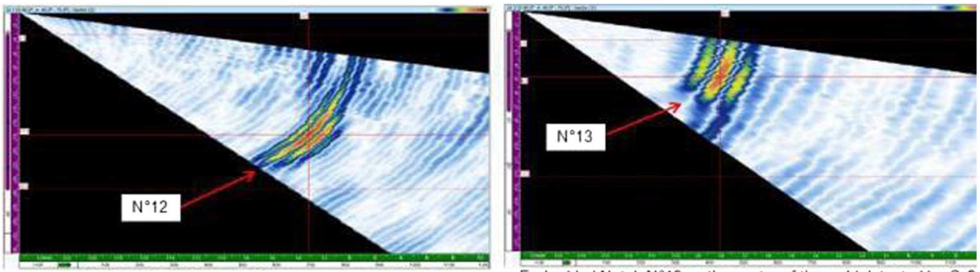
The interest of such a reconstruction may be to verify that the depth of ripples doesn't exceed values leading to get surface breaking imperfections after machining (when required). In any case it allows checking the shape and main dimensions are within the required tolerances.

9.3.2 Immersion C-scan UT scanning

Figure 29 shows a carbon steel cylinder machined after WAAM manufacturing. In this sample internal and external surface breaking notches were introduced.

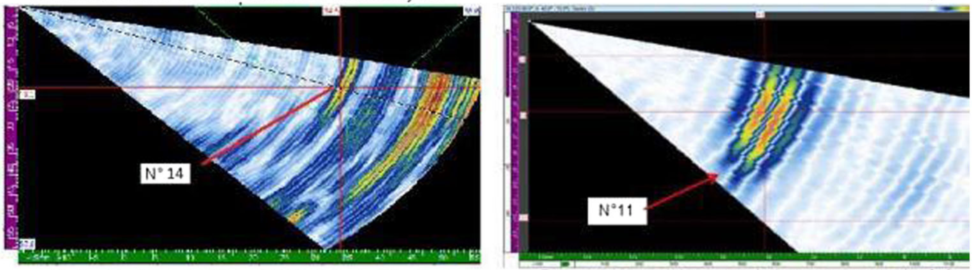
In such a case, there is no main difference on ultrasonic procedures with a part manufactured by other kind of processes. Generally, scans at different angles are used as well as appropriate calibration and reference block.

Fig. 27 Sectorial scans used to check UT settings on the blocks [31]



Embedded Notch N°12 on the fusion zone detected by Gr1

Embedded Notch N°13 on the center of the weld detected by Gr2



Embedded Notch N°14, at WCL detected by Gr 1

Embedded Notch N°11 on the fusion zone detected by Gr2

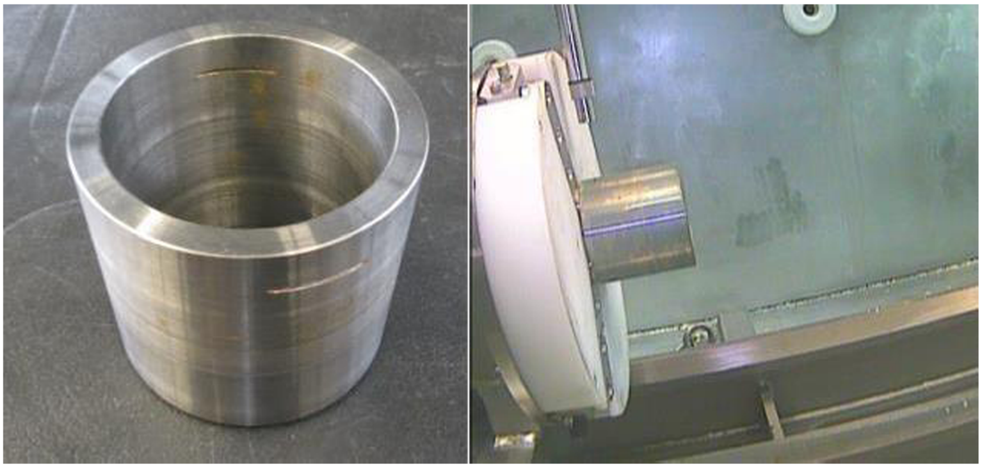


Fig. 29 Carbon steel WAAM sample in immersion UT [37]

Figure 30 [37] shows the result obtained from one scan performed by means of longitudinal waves generated perpendicularly to the cylinder generatrix.

The two notches are clearly identified on the C-Scan presented on Fig. 30.

9.4 Laser profilometry used in robotised TIG

Studies carried out at Institut de Soudure in the 1990s had made it possible to define dynamic 3D models in robotic MAG welding in self-adaptive seam tracking mode. These early studies had proven that it was possible to correct the welding path and to take into account the gap and geometrical variations of the steel plate to weld.

Recently, T.Trantien and S.Pernodet [38] have developed a new self-adaptive dynamic model for TIG welding. This model was successfully applied on Airbus components called “Lower Pan”. These components act as heat shield on the A380 Airbus reactor masts. They are made of titanium alloy. The geometrical characteristics of the joint associated with numerous welding positions have required the development of this new welding model (Fig. 31).

During the robotised welding operations a laser profilometry system was used to make corrections with the learning points. The robot previously performed a first run before welding, stopping at each learning point of the initially programmed path. The laser system is placed downstream of the TIG torch, and measures successively the difference between the programmed point and the effective position of the joint to determine the new position of the torch by taking into account the deviations. The industrial feedback for several years of use, has highlighted the following benefits compared to manual testing: better welds quality, higher productivity, less consumables. It was also demonstrated that this process was able to weld in extreme geometrical conditions where manual welding failed.

9.5 FSW monitoring

9.5.1 On line temperature measurement [39, 40].

Today, the level of maturity of the FSW process allows it to be used in various industrial sectors (rail, naval, automotive…). The aerospace industry has also a great interest for this process and is keen on any means able to increase the reliability. It is well known that changes in temperature have a significant impact on the quality of the welds (Figure 32), so monitoring of this key factor is highly relevant.

A. BenAttar et al. [39] developed a WiFi device introduced into the welding head to achieve this task (Fig. 33).

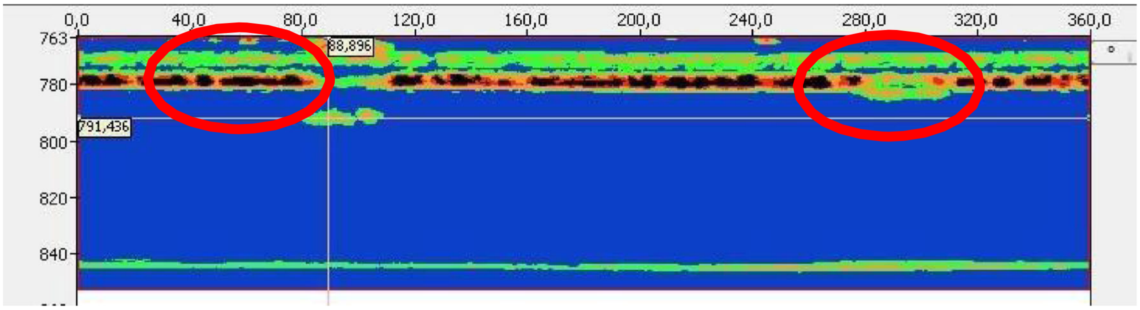


Fig. 30 C-scan [37]

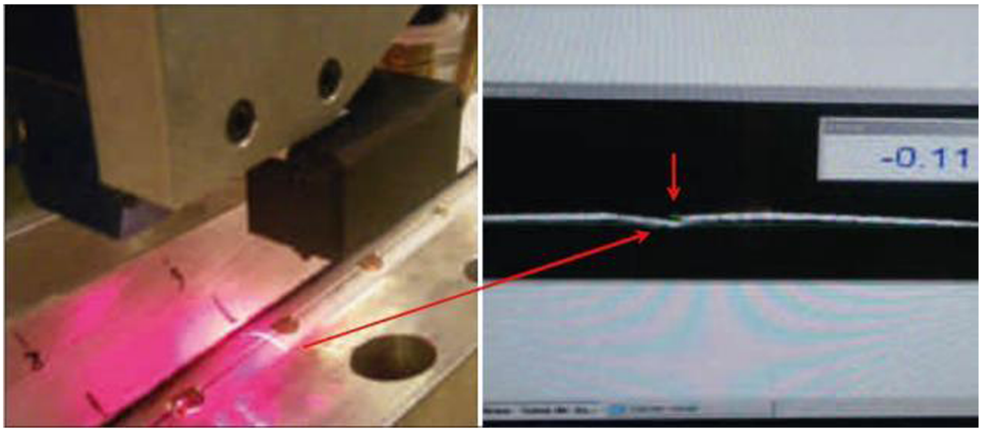


Fig. 31 Laser profilometry used during robotised TIG [34]

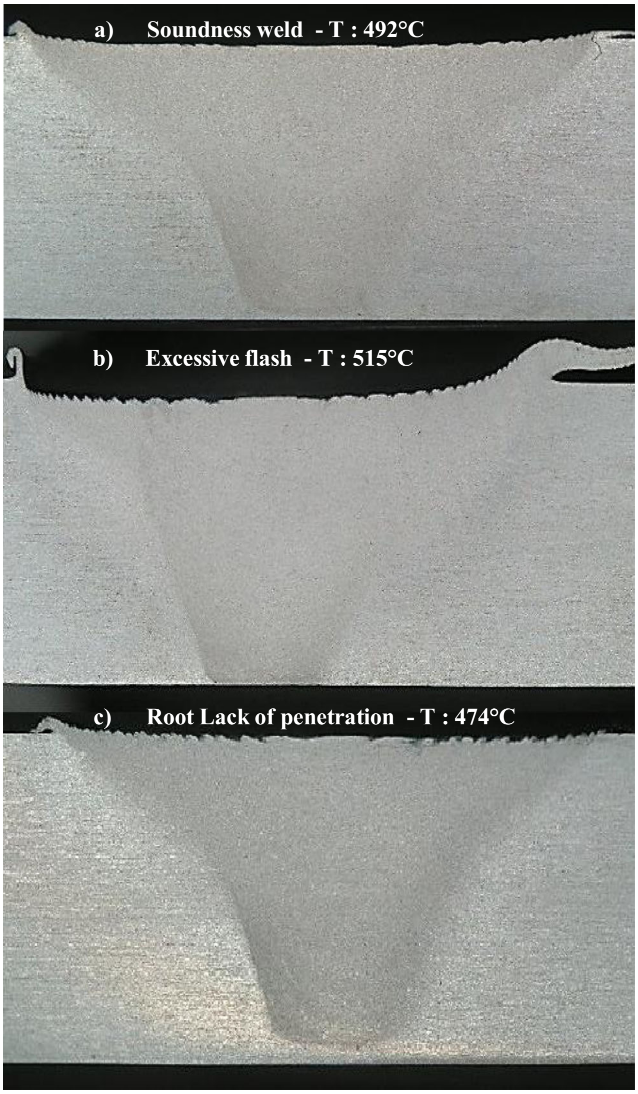


Fig. 32 Macrographic sections of welds [36]

9.5.2 On line process parameters measurement

A. Ben Attar et al. [39] have developed a methodology aiming at achieving robotic online trajectory corrections.

> Forces applying on the tool (Figure 34) during welding are recorded in the 3 directions (Figure 35). The tool rotational speed is also recorded. From these data and taking into account the dynamical interaction of the tool with the material, it is possible to determine (through an estimator) the real position of the robot and to calculate a compensation factor. This compensation factor may then be used in real time to correct the robot trajectory (Table 8).

9.5.3 Data base

A data base is now used and fed with the operating parameters (temperature, forces…) collected during the studies performed at Institut de Soudure on the fully instrumented FSW welding gantry machine. This makes it possible to correlate the recorded forces and temperatures variation, collected during FSW operations with the weld quality assessed by NDT.

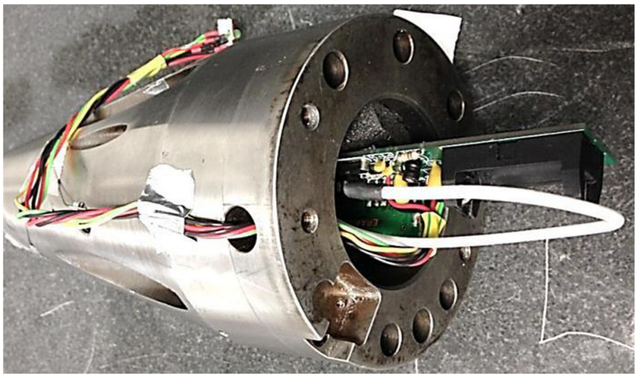


Fig. 33 Wifi temperature measuring device set on the welding head [36]

Fig. 34 FSW head of the huge IS gantry machine [41]

Table 8 compensation factor [40]

Variable	Definition
q_d (x, y, z, i, j, k)	Robot programmed position
$\hat{q}$ (x, y, z, i, j, k)	Robot real position
Δq_d (x, y, z, i, j, k)	Compensation

9.6 Smart welds concept

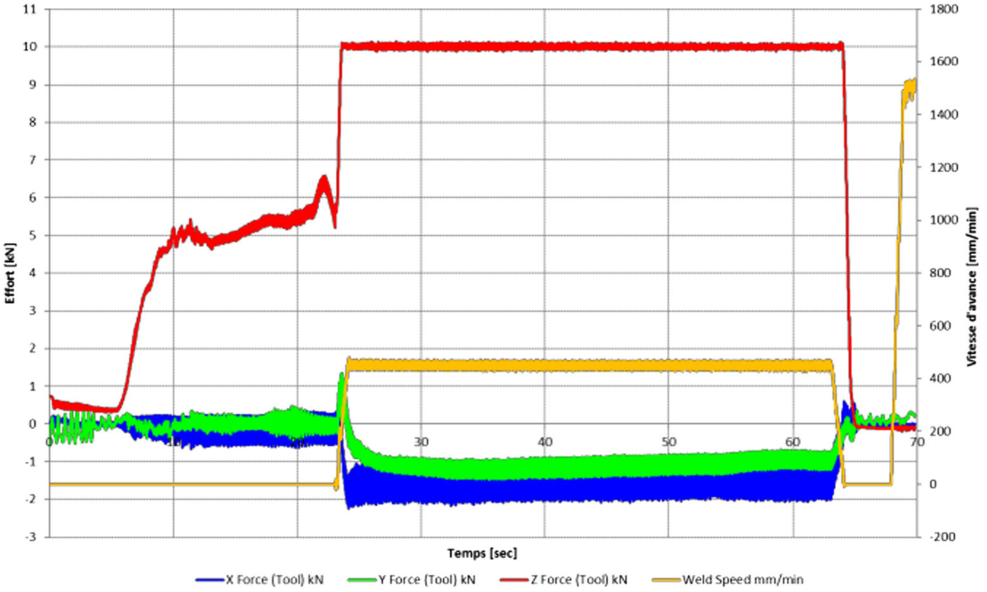
In current guided waves monitoring, the sensor/ actuator is attached permanently to the structure that is being monitored. As the sensor is generally bonded by adhesive, the question of sensor ageing may be a concern to keep reliable data collected during the whole life of the structure to monitor. SHM techniques compared generally the anterior data with the current one to determine the state of the structure. Ageing of the bonding may generate stochastic behavior complicating the analysis, and then cause false calls. Full disbonding may also happen, making the monitoring impossible leading to make the monitoring impossible.

That is why Institut de Soudure [42] has developed the smart weld concept: the weld itself, or a part of the structure, might be used as the passive part of an alternative sensor. Prototypes (Fig. 36) were developed based on enhancement of the magnetostrictive effect of a weld and/or a structure at the manufacturing stage. Several solutions were tested and patented based on incorporating adequate elements during welding, applying appropriate spraying on the surface, applying heat treatment. Trials using these prototypes have been carried out, and generation and detection of waves have been proven.

9.7 Guided waves monitoring with statistical algorithm

M.E1 Mountassir et al. [33] applied a statistical algorithm on a case of study where data acquisition (emission and reception of guided waves) was performed using MsS ® System

Fig. 35 Example of FSW data recorded with IS equipment (welding forces in three directions and welding speed) [36]



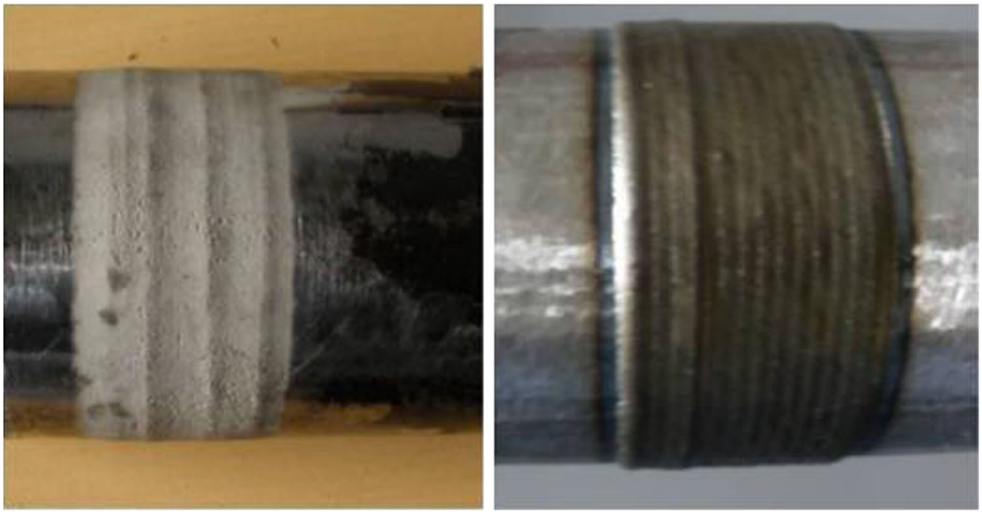


Fig. 36 Smart weld prototypes [43]

(designed for pipeline guided wave inspection). Damage was simulated by changing the local mass and stiffness by attaching magnets to the surface of the pipe, the algorithm may be applied together with either a univariate analysis or a multivariate one.

A univariate analysis explores each damage sensitive feature separately, while a multivariate analysis combined all features in a multi-dimensional vector. Using univariate analysis doesn't guarantee that all the damages-sensitive features will have the same response in terms of detectability. In other words, some features could for example indicate the presence of a defect and others not. This fact reduces the applicability of such a method and leads to prefer using a multivariate analysis. As a matter of fact, Figure 37 demonstrates the capability of such an analysis:

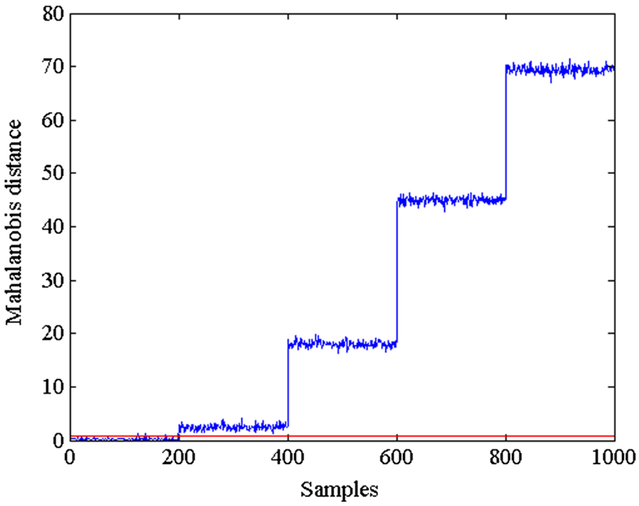


Fig. 37 Multivariate analysis of several level of damages

- To improve the sensitivity to damage
- To achieve a good discrimination between all damage types

10 4. Conclusion

There is an extensive range of NDT methods and techniques. No one is universal, but only suitable for a given scope. There is no technique to guarantee the detection of all imperfections in a welded joint or an AM part. Knowledge of the welding process and of the associated imperfections is therefore preponderant for the choice of the NDT technique to be implemented. The issue is the same for testing parts manufactured by the various AM processes. Monitoring is already used during welding and is also highly valuable for AM.

Welding assemblies and additive manufacturing (AM) parts have in common to deal with melting zones. The experience gained by the NDT community involved in welding inspection is highly valuable to develop suitable testing for AM parts.

AM standardisation is in progress, but quality levels need to be defined for each of the main family process. A better knowledge of the imperfections generated by the various AM processes and how defects are critical is still needed to achieve this task.

Some NDT standards designed for welds may be adapted for AM but new imperfections are generated and need to be specifically addressed.

Reliable low cost testing of as built parts made by WAAM and EBM needs to be developed. Testing lattice parts by other techniques than CT needs also to be studied.

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