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NON-DESTRUCTIVE TESTING (NDT) FOR INDUSTRIAL APPLICATIONS – SYSTEMATIC APPROACH TO IMPLEMENTATION, OPPORTUNITIES AND LIMITATIONS OF NOVEL NDT METHODS, NEW TRENDS

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Abstract. *Non-destructive testing (NDT) methods are valuable for ensuring the quality and integrity of industrial components and structures. NDT allows examination without destruction and offers detailed information about material and internal structure condition. Thus, NDT can lead to great cost savings by efficient quality control in production processes. The implementation of NDT methods in industry poses challenges due to unique requirements and the need for specialized equipment and expertise. The first part of this paper proposes a systematic approach to implementing NDT solutions in industrial environment. To ensure a reliable NDT solution, a step-by-step approach is derived from normative regulations in automotive industry. A checklist for implementation is provided. The basic principles of the procedure can mostly be transferred to other industries like aerospace, power generation and construction industries. The second part of the paper provides an overview of conventional and advanced NDT methods. The varying feasibilities and challenges of selected NDT methods are indicated, highlighting both their specific advantages and limitations. New trends and innovative NDT solutions complete these considerations. Successfully implemented NDT applications in current production processes are presented as well as innovative NDT approaches to quality control in novel industrial processes of additive manufacturing. Tailor-made NDT solutions for individual inspection task offer opportunities to expand the boundaries of actual NDT. Special focus in this paper lies on thermography and its application.*

Keywords: *Novel non-destructive testing (NDT) methods, opportunities and limitations, new trends, approach to implementation, industrial requirements, additive manufacturing, active thermography*

1. INTRODUCTION

The use of non-destructive testing (NDT) methods is of great value to industry particularly for quality assurance or ensuring the integrity of industrial components and structures at various stages of technical development. NDT allows examination without destruction and offers a wide range of benefits. On the one hand, its use allows to obtain more detailed information about the material condition and internal structures of manufactured parts, assemblies or properties of joints, etc.. On the other hand, it leads to substantial cost savings as result of more efficient production control through non-destructive testing and the related reduction of scrap and personnel costs for example compared with former manual, destructive testing processes. NDT methods provide rapid and accurate analysis, preventing potential failures and improving the part quality. Therefore, they have a high attractiveness for various industries including aerospace, automotive, power generation and construction. Recent progress in novel NDT, mainly due to advanced technical capabilities and customization to individual inspection tasks, are opening up additional opportunities leading to further breakthroughs in industry.

2. NDT IMPLEMENTATION IN INDUSTRY

The industrial use of non-destructive testing methods is generally motivated by different aspects: 1. Replacing costly destructive or less efficient non-destructive testing procedures that are currently used in series production, 2. Establish non-destructive testing procedures in new projects or production concepts with state of the art or with innovative methods. In previous work (Siemer, 2011) examples from the body shop in automotive industry are shown. Regardless the motivation the use of an NDT method subject to special requirements. In the following, a systematic proceeding for a reliable introduction of NDT, developed in automotive industry, is presented. The considered normative regulations originate mainly from European area and apply to automotive industry. The developed procedure, however, ensures fundamental requirements and can therefore in its basic features also be transferred to other branches of industry.

2.1 Requirements for NDT

Fig. 1 shows an overview of normative regulations that describe the requirements to be observed when introducing non-destructive testing technology in processes of the automotive industry. Requirements range from general guidelines for quality management systems to specifications for the calibration of measuring systems.

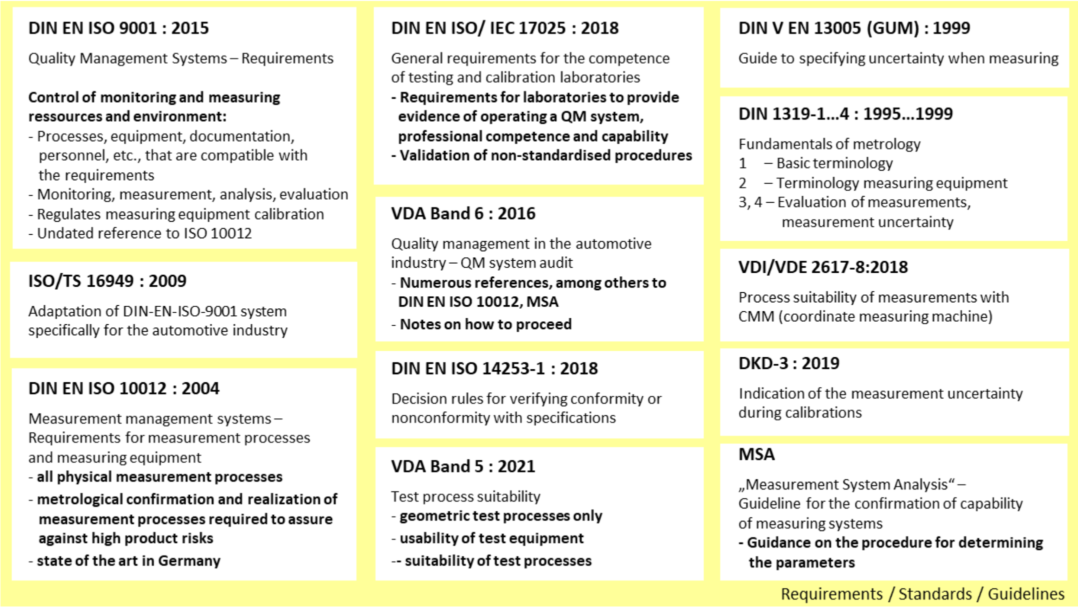

Figure 1. Normative environment (European automotive industry): requirements, standards, guidelines for NDT.

2.2 Systematic approach for implementation

Taken the requirements of foregoing standards into account, a comprehensive qualification process of NDT methods was derived (Siemer, 2010). Fig. 2 describes the systematic approach with several steps from bottom to top which ensure, that important actions were done, necessary aspects are considered so that a reliable NDT setting is introduced to industry.

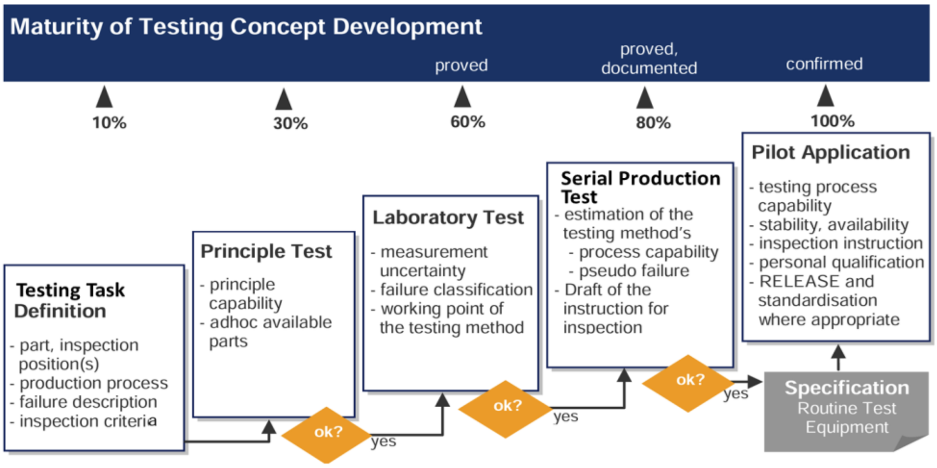

Figure 2. Qualification steps for the implementation of non-destructive testing methods for industrial applications.

Beginning with the testing task definition all relevant defects (cracks, delamination, cavities, etc.) of the test object must be described including their positions and critical dimensions for failure, respectively the minimum required NDT sensitivity. The test object geometry, the accessibilities and restrictions for NDT methods must be listed in detail. The principle test serves to postulate general capabilities and to identify the most potential NDT method for the present testing task. In the laboratory test the best conditions for the defect detection is evaluated, the testing configuration and parameter will be defined. With the serial production test, further, increasingly specific and detailed insights into possible influences are gained and a robust handling of disturbance variables is developed. The pilot application completes the analysis and proves the feasibility of the NDT setting under comprehensive real operating conditions.

2.3 Influence and effect analysis

In order to introduce an NDT method and using it as a reliable quality control instrument, all relevant parameters that may have an influence on the measurement result must be investigated very carefully. Extensive tests to get important knowledge about significant effects are mainly made in the stages "laboratory test, series production test and pilot application". With an increasing level of detail, the main influences are examined. Fig. 3 shows an ISHIKAWA diagram exemplary for a thermographic application, offering worked out influences and effects for respective test settings.

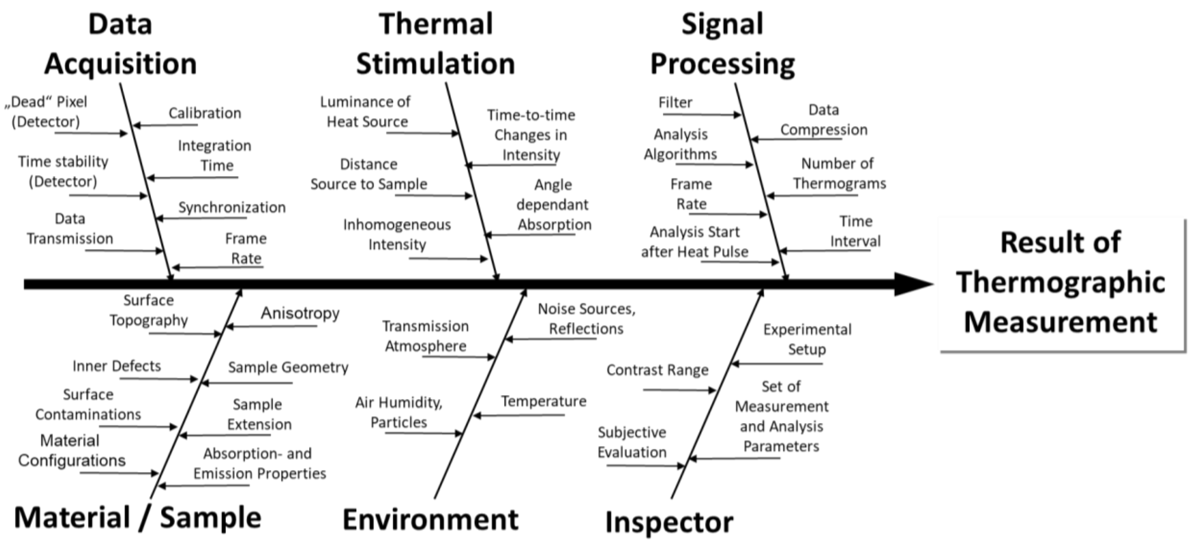

Figure 3. Ishikawa diagram as result of an influence and effects analysis for thermographic applications.

The determined significance of the influence parameter and effects and how to deal with them will be documented in later test specifications for the NDT application.

2.4 Checklist

The following checklist in Fig. 4 provides guidance on how to proceed for a successful NDT implementation. All important points are listed and queried in a chronological way. The complete version of the checklist can be found in (Siemer, 2010).

Checklist for NDT Implementation		Maturity of Testing Concept			
procedures based on VDA Bd. 5:2003 / CEN/TR 14748:2004		Consulting Testing Task	Principle Test	Laboratory Test	Serial Produ Test
Meßverfahren					
Measuring principle					
	measured variable	suggest	name		
	physical effect/ context	describe	confirm	investigate	
	Influencing factors			name	investigate
Principle test capability					
	test characteristics/ features		confirm		
	failure detectability		confirm		
	failure classification (type, location, distribution, size)		estimate	confirm	
Features measuring devices					
	availability			name / test	confirm
	parameterisation			name / test	confirm
	resolution			name / test	confirm
	accuracy			name / test	confirm
Device measurement uncertainty					
	calibration uncertainty			estimate	confirm
	repeatability uncertainty			estimate	confirm
	linearity uncertainty			estimate	confirm
	device stability				estimate / demand
	Ishikawa diagramm (influence variable analysis)			create	confirm
	further contributions from failure influence analysis			estimate	confirm
	test equipment capability				confirm

no action / no results available
testing task with preliminary result/ preliminary result available
testing task with binding result/ binding result available

Figure 4. Excerpt of checklist for implementation an NDT application in industry (cf. Siemer, 2010).

3. NDT METHODS

3.1 Overview of NDT methods and general capabilities

Tab. 1 contents a selection of NDT methods, that have manifold use cases in industry or are in transfer status. Although the table covers conventional NDT methods like e. g. penetration or magnetic powder testing, as well as advanced or novel techniques like e. g. computed tomography or microwave testing, the aim is to provide assistance to select probably suitable NDT methods for present testing tasks. General feasibilities, opportunities and constraints of these NDT methods are listed, mainly based on physical capabilities and restrictions of each NDT method.

Table 1. NDT methods (conventional, novel and advanced) with general feasibilities, opportunities and constraints regarding possible applications.

NDT method	**conventional** **advanced**	**test configuration**	**defect position**	**material**	**defect types**	**sensitivity**	**further specific opportunities & constraints**
Visual testing (VT)	eye viewing	- one side - non-contact	only at surface, no inner defects	all	- surface inhomogenities	depending on optional optical tools	+ easy procedure + fast testing + low costs - susceptibility to interference
	automated image proccessing						
Ultrasonic testing (UT)	single spot sensor	- reflection or transmission - contact	inner defects, low and high depths	(all)	- cracks - delamination - volume errors	good resolution, depends on test frequency	- partlially subjective Testing
	phased array technique, EMAT, air coupling	- 3D beam steering - contact or non-contact	+ better local defect reconstruction				
Radiographic testing (RT) / Computed tomography (CT)	transradiate	- transmission	inner defects, low and high depths	all	- volume errors - no 2- dimensional defects	good resolution, influenced by material contrasts	+ very high resolution - long testing - high costs - harmful radiation
	360° recording and computed images	- circumferential accessibility required	all		- volume errors - (delamination) - cracks	very high resolution (up to nm)	
Penetration testing (PT)		- one side	only surface opened, no inner defects	no porosity	- only surface opened		+ easily interpretable + low training effort
	+ automated image proccessing						
Magnetic powder testing (MT)		- one side	only near surface, no inner defects	permeable	- cracks		+ very fast + easily interpretable
	+ automated image proccessing						
Eddy current Testing (ET)	single sensor	- one side	only near surface, low penetration depth	permeable	- cracks		+ very fast
	sensor fusion (e. g. micro-magnetic 3MA), sensor arrays						
Thermographic testing (TT)	passive methods	- reflection or transmission	higher penetration depth leads to less resolution	(all)	- volume errors, - delamination	for active methods much higher than for passive testing, decreases with defects depth	+ harmless radiation
	active methods (optical, kovective, ultrasonic, inductive excitation)				- volume errors - delamination - cracks		
Acoustic emission testing (AT)	passive methods	- diverse	integral	(all)	- cracks	highly specific	
	active methods				- highly specific		
Microwave or Terahertz testing (MWT/ THzT)		- reflection or transmission	medium penetration depth	dielectric	- volume errors, - delamination, - cracks	medium or low resolution	

The table provides a rough classification for which application cases the NDT methods are suitable or not. Especially for novel NDT methods effective potentials can only be determined in subsequent practical analysis. Thus, right after the testing task definition the most promising NDT method is chosen for initial principle tests (cf. chapter 2.2) to figure out, whether a further approach with this NDT method is purposeful.

3.2 Novel NDT opportunities, limits and new trends

Novel opportunities as result of recent development in NDT offer new potentials for industrial applications. New trends for selected NDT methods as well as their actual limits are presented in the following. Particular attention is paid to thermography with relatively young industrial solutions and remaining large implementation potential.

Visual testing (VT): Focus of development lies in automation and optimisation of image recognition systems and image processing. The consequence is an objectification of test results as well as a high reduction of personnel costs. Limits are still the restriction of only being able to detect surface defects and being disturbed by surface irregularities.

Ultrasonic testing (UT): The inspection technology has evolved enormously. New trends include for example the use of phased array sensors with typically 16…256 single element transducer. Thanks to differentiated sensor control and signal processing from one array position, almost any point in the test object can be controlled. Sufficient computing power is needed. Other novel developments refer to special coupling methods of the ultrasound. Electromagnetic acoustic transducers (EMAT) employ a magnetostrictive effect to transmit and receive ultrasonic waves (Niese et al., 2020). Caused by the advantages of no contact to the test sample and no coupling medium is needed, interest of industry in other air-coupling methods also increase, but this is for example restricted to highly damping materials (Pfeiffer et al., 2020). Water coupling techniques like squirter- or immersion techniques offer more flexibility in local steering, but it is mostly associated with more effort. Potential of combination of both air coupling and phased array sensors are shown in (Hufschläger et al., 2022).

Radiographic testing (RT) / Computed tomography (CT): Conventional radiographic transmission testing still remain important for many areas. X-ray films and their development is mostly substituted by digital solutions with instantaneous evaluation possibilities. Highly time and cost intensive computed tomography solutions are meanwhile regarded irreplaceable due to its extraordinary resolutions and reliability to detect inner irregularities. Further trends lead to inline CT and robot solutions, see for example (Holub et al., 2020). Laminographic methods for example reduce the computation effort and attempt to accelerate testing procedures while keeping sufficient detection accuracy (Krumm et al., 2018).

Penetration or Magnetic powder testing (PT or MT): Even with further developments, the testability of both methods remains limited to defects that are open to the surface (PT) or close to the surface (MT). In the case of MT in particular, new developments lie in the area of automation and automatic image analysis for the evaluation of components.

Eddy current Testing (ET): Lot of activity and potential can be found in development of sensorarrays (Mook and Simonin, 2020) and in sensorfusion, not least with help of combined information together with magnetic interaction of the material (Khazi et al., 2020). For example, micromagnetic testing (3MA) can be used for non-destructive determining the hardness of shape-hardened components in automotive body shop.

Thermographic testing (TT): This method analyses infrared radiation from objects and is characterised by its particular diversity. It is distinguished into passive and active methods (DIN, 2018), without or with additional thermal excitation for testing. Several excitation sources and the basic active test procedure are shown in Fig. 5.

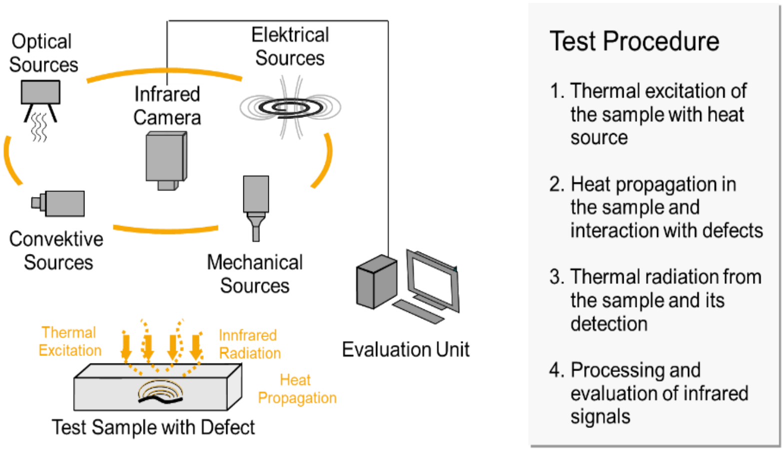

Figure 5. Basic test procedure and excitation sources for active thermographic testing.

For active thermography the excitation source has a great influence to the detection capabilities of the NDT method. The kind of thermal excitation and its modulation determines which defect types and sizes can be analysed. Other performance improvements can be achieved by optimizing the signal acquisition with infrared cameras and the signal processing and evaluation. All this variation result in a wide range of test possibilities with each very specific opportunities and limits. Thermographic testing offers a number of advantages, including the relatively fast inspection of larger areas or the absence of potential hazards such as ionizing radiation. A disadvantage is the limited penetration depth respectively the decreasing detection sensitivity with higher penetration depth.

Acoustic emission testing (AT): Different methods, contact or non-contact, with or without external acoustic excitation, are possible. A sound arising suddenly from a part can indicate occurring cracks. Controlling such sounds offer methods suitable for example health monitoring (Prokofyev et al., 2023). Even though, acoustic waves can be extra induced into a part. Resulting acoustic resonance pattern will be different, if defects are presents or not. Deviations of recorded acoustic emission gives advice of possible defects in the part. New developments, so called “acoustic cameras”, additionally achieve a local resolution about the position of the defect in the part. Those 3-dimensional methods require either a high number of microphones or moving the sensors around the object (Vonrhein et al., 2020).

Microwave or Terahertz testing (MWT/ THzT): These non-contact testing methods use electromagnetic waves, adjacent to infrared radiation towards longer wavelengths, that means from frequencies of approx. 0,3GHz…300GHz (MWT) up to 0.1…10 Thz (ThzT) and wavelengths of 1m…1mm (MWT) down to 3mm…30µm (THzT). Due to its comparatively low energy, the radiation is harmless to the human organism. Applications are restricted to dielectric, i. e.

electrical insulating materials. Possible areas of industrial application are monitoring of curing processes for adhesives, layer thickness measurements, delamination control as well as foreign inclusion or object detection. Many plastics and ceramics are quasi-transparent in microwave or terahertz frequency range, which makes it possible, to detect for example internal metal reinforcements. While microwave testing has a bit higher, but still a medium penetration depth, the resolution for terahertz testing is better than for microwave testing. For both compared to other foregoing methods the resolution is rather low (cf. Becker et al., 2021).

4. NDT APPLICATIONS IN INDUSTRY

As seen in the foregoing chapter most NDT methods are strongly different. For some specific materials or structures may be difficult to inspect, especially if they possess complex geometries or are made of composite materials for instance. Interpretation of test results often requires a high level of expertise and experience. NDT methods can be expensive to purchase and require specialized equipment and trained personnel. Feasibility must be thoroughly investigated to ensure reliable solutions that can withstand the high demands of industrial manufacturing. Exemplary applications will be presented for already established thermographic applications or for thermographic testing methods in different stages of technical maturity. Then, potential of advanced NDT methods for new adaptions in additive manufacturing as an emerging technology with special needs for NDT will be discussed.

4.1 Thermograpic applications in current industry processes

First, an example from the power generation industry, which has already reached the stage of global roll-out, is cited (Goldammer et al., 2015), The turbine blade test shown in Fig. 6 is certainly one of the pioneer applications in industrial use of active thermography. A coated turbine blade for use in gas turbines is inspected within one test cell using different methods needed for its quality assurance. Shown is the delamination inspection of the turbine’s coating using pulse phase thermography and hot air excited thermography to check the continuity of the cooling air holes. A systematic way to qualify the NDT setting for worldwide use was successfully completed.

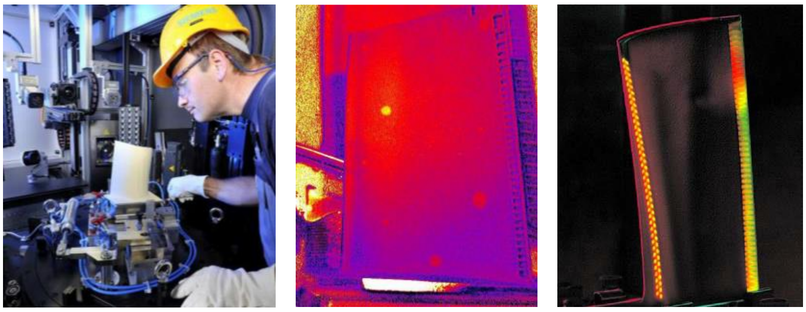

Figure 6. NDT test cabin with coated turbine blade (left), amplitude image with areas of delamination as result of flashlight pulse phase thermography (middle), result image after hot air flooding with intact and blocked cooling air holes (Goldammer et al., 2015).

Also already qualified for industrial use, is the passive thermographic testing of dashboards in automotive industry (Fig. 7). 100% online testing objectifies the previous visual and haptical manual testing, avoids failure slippage in production and reduces personnel cost. The comprehensive proceeding for implementation (cf. chap. 2.2) and so the introduction of the NDT process was successfully completed. With passive thermography, the heat transfer in the component is only induced by the process temperature in the mold. Defects that can be detected are pores and cavities in the polymer foam of the dashboard structure. Minimum detected sizes of failures go down to diameters of about 10 mm.

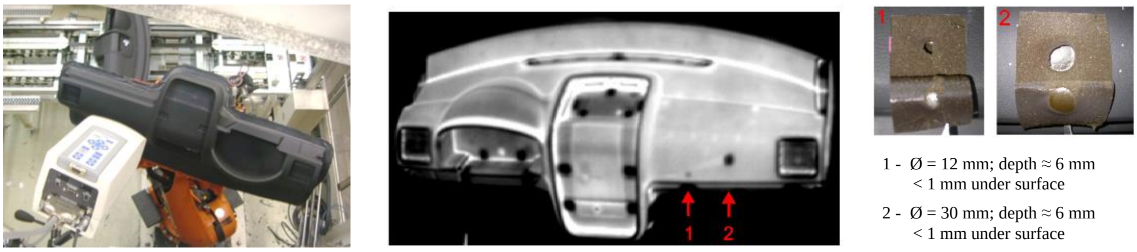

Figure 7. Passive thermographic testing of dashboards: online process integration (left), thermal image (middle), cut open defects (right).

An established application of active thermography can be found in the automotive body shop. Fig. 8 shows a test setting for the quality control of laser welds in a metal sheet car body structure, replacing foregoing highly personnel and scrap intensive destructive chisel test procedure. For laser welded car bodies, the thermographic pulse technique with optical flashlight excitation in transmission mode represents a sufficiently robust testing method for a half-automated sampling inspection under production line conditions.

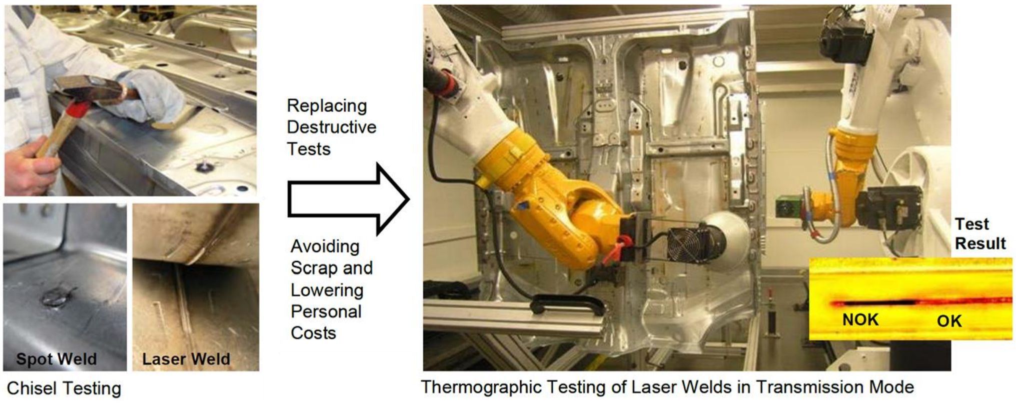

Figure 8. Quality control of welded joints in car body structures: Replacing destructive chisel testing (left) with non-destructive active thermographic offline testing of laser welds with flashlight excitation (right)

In the stage of a principle test Fig. 9 shows a metallic chassis part in an ultrasound excited thermographic test configuration. Clearly visible in the thermal result image, as well as in the infrared signal path, is the heat effect while ultrasound excitation. Mechanical vibrations induce friction between the inner crack surfaces, so that the developed heat can be attributed to existing, or to with the ultrasound emerging cracks.

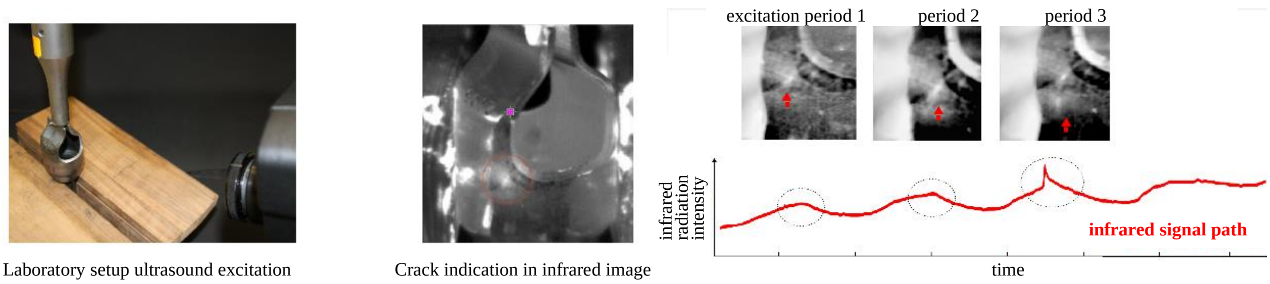

Figure 9. Ultrasonic excited thermographic testing of chassis part: test setup (left), infrared result image (middle), infrared signal path while excitation with ultrasound (right).

The principle suitability of the test method for detecting cracks has been demonstrated. However, in order to replace present quality tests, a large number of investigations and verifications still have to be carried out.

4.2 Innovative NDT applications in novel industry processes

To discuss opportunities of NDT for novel industry production processes, the focus lies on additive manufacturing (AM). Offering great advantages for generating innovative parts, AM is under close observation by industry. NDT testing solutions for later quality control of AM processes are desired. If needed for a differentiated discussion about feasibilities of NDT methods, considerations will be initially focused on metallic parts. First industrial applications demonstrate typical framework conditions and requirements of AM for NDT, as seen in Tab. 2. Main irregularities that must be detected for quality control in AM are listed in Tab. 3.

Table 2. Typical framework conditions of AM for NDT.

Typical framework conditions of AM for NDT
- small series production
- complex geometries of the parts, often with winding hollow interiors
- poor accessibility to part's structure and shape
- relatively rough surfaces

Table 3. Main irregularities that needs to be controlled in AM.

Main irregularities to be detected for quality control in AM
- lack-of-fusion, inclusions, cracks and pores after AM process
- cracks occurring while AM process
- residual powder in inner hollow interiors

Various NDT methods offer particular potential for the tasks described above. Of course, computed tomography (CT) is the method with the best possible resolution over the entire sample volume. All relevant irregularities can generally be detected. However, inspection times and costs are still very high, so that the effort of detailed CT analyses is usually only justified in the development stage of components. For production monitoring, systems are conceivable that reduce the inspection effort in some way, either by reduced accuracy due to lower data depth, e. g. CT laminography (cf. Maisl et al., 2010), or by concentrating the measurement on limited areas. In the ENABL3D research project, a robotic monitoring system for the verification of potential defects in critical regions (ROI-scan) was developed to maturity comparable to the described "laboratory test" stage. Pores, inclusions, or lack-of-fusions in powder-bed-fusion components were detected in the critical size ranges (Dedyaeva et al., 2023).

Investigations in the Multisurv research project (Herzer and Schilp, 2020) promise, for active thermographic testing (TT) with flashlight excitation and for powder-bed-fusion multimaterial AM processes, abilities to distinguish different powder materials, coating defects from 100 µm and coating thickness differences from 50 µm. The maturity of the NDT setting can be estimated by the "serial production test" stage. To learn more about NDT crack detection and how it works for rough surfaces of additive manufactured parts, investigations from (Srajbr et al., 2022) provides helpful insights. For the qualification of active thermography for welded joints, AM test specimens were produced with artificial cracks in different sizes and then, examined both using CT as reference method and active TT methods with inductive, laser and ultrasonic excitation sources. Promising results were found for active thermal excitation with inductive and with laser sources. The detected artificial cracks had sizes between 0.7-0.8 mm, but positions were limited to near surface regions. As already the principle test of the chassis part in Fig. 9 implicates, also with an ultrasound excitation detectable cracks in metallic parts are restricted to the near surface. Cracks in the deep inner structure, not unusual for AM, are very bad or not detectable caused by the excellent heat transfer properties of the material.

Most challenging for NDT of AM parts are probably the particularly complex component geometries, on one side a great advantage of this technique, on the other side making the accessibility for NDT testing very difficult or not possible. For this reason, the studies by (Hansen, 2023) show a possibility to check the part’s quality “inline”, i. e. within the running AM process. Each or a certain number of layers are tested step-by-step with an inline test configuration, that combines additionally two NDT methods EMAT ultrasonic testing and eddy current testing (UT+ET). With this sensor fusion residual stresses and microcracks in the layers were successfully determined. Because in the meantime turbine blades also are being AM manufactured, the test setting in Fig. 6 can probably be transferred to AM parts too. Flashlight excited thermography should be investigated for the in-situ testing during layer build-up.

The hot air excited thermography to check the continuity of the cooling air holes (Fig. 6) should show similar results also for equivalent AM turbine blades. Therefore, the test setting to check residual powder in inner hollow structure is a promising NDT solution also for other comparable structures. It makes sense to combine this thermographic method with the present measure flow technique.

Another attractive idea to detect cracks, is monitoring the AM process with acoustic emission (AT) methods. Probably, inline integrated acoustic sensors can indicate occurring cracks. Also potential of AT with external acoustic excitation should be tested (cf. Ritter, 2023). Because of eventually high process noise, a sensor contact method should be preferred.

The microwave and terahertz testing (MW+THzT) methods were not further discussed, because of their low potential for only metallic materials. Because of the limitation to surface opened or surface near cracks of penetration or magnetic powder testing (PT or MT) the established methods can be used but offer no new potential for the quality control in AM.

The considerations identified some purposeful approaches to achieve an NDT testing solution for AM. But they also give advice, that challenges have to be solved until a robust NDT process control is available. Since single methods rarely can detect all relevant faults at once, a combination of different methods can often lead to a solution. The adaption of advanced NDT methods to the AM process means, today, great effort not at least due to highly tailor-made solutions.

5. RESUMEE AND OUTLOOK

Advanced NDT methods or novel NDT testing solutions still can lead to significant cost savings in industry, especially because much new potential has not yet been realised. The implementation of NDT methods in industrial processes poses challenges due to unique requirements and the need for specialized equipment and expertise. According to a systematic approach for NDT implementation less efficient quality control measures in current processes can be reliably replaced through innovative NDT methods. The concise characterization of several advanced NDT methods, new innovative trends as well as presented applications in several stages of maturity offer valuable information to learn for further applications.

A comprehensive NDT solution for monitoring AM processes is not yet available. Currently, there are only perspectives to test only single defect types or to supplement existing inspection concepts. From the consideration of possibilities with innovative NDT configurations, the reduced CT inspection, various method combinations or sensor fusion and especially the applications of active thermography should be highlighted. More opportunities through NDT method combination should be examined in detail. In order to master the geometric complexity of parts when inspecting material insufficiencies, the TT in-situ step-by-step testing approach should be pursued. For the inspection of residual powder, the thermographic approaches shown can represent the more cost-effective solution in comparison to CT. However, highly tailor-made solutions with often the combination of different NDT methods must be assumed. But tailored solutions and individual adaptations also have the potential to expand actual boundaries of conventional NDT, offering new possibilities and overcoming limitations.

6. ACKNOWLEDGEMENTS

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