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Production integrated nondestructive testing of composite materials and material compounds – an overview

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Abstract. Composite materials and material compounds are of increasing importance, because of the steadily rising relevance of resource saving lightweight constructions. Quality assurance with appropriate Nondestructive Testing (NDT) methods is a key aspect for reliable and efficient production. Quality changes have to be detected already in the manufacturing flow in order to take adequate corrective actions. For materials and compounds the classical NDT methods for defectoscopy, like X-ray and Ultrasound (US) are still predominant. Nevertheless, meanwhile fast, contactless NDT methods, like air-borne ultrasound, dynamic thermography and special Eddy-Current techniques are available in order to detect cracks, voids, pores and delaminations but also for characterizing fiber content, distribution and alignment. In Metal-Matrix Composites US back-scattering can be used for this purpose. US run-time measurements allow the detection of thermal stresses at the metal-matrix interface. Another important area is the necessity for NDT in joining. To achieve an optimum material utilization and product safety as well as the best possible production efficiency, there is a need for NDT methods for in-line inspection of the joint quality while joining or immediately afterwards. For this purpose EMAT (Electromagnetic Acoustic Transducer) technique or Acoustic Emission testing can be used.

1. Introduction

As the demand for environmental-friendly production and application of products is consequently increasing, composite materials like Carbon Fiber Reinforced Polymers (CFRP) or Metal Matrix Composites (MMC) are of gaining relevance for achieving efficient lightweight designs due to their high specific strengths. But as long as damage mechanisms and their progress of such complex materials are still under investigation, reliable NDT methods to detect a minimum damage size to still ensure safe conditions have to be identified and established in production as well as during the application. On the other hand the necessity of realizing lightweight construction concepts places high demands on joining technology as appropriate methods for example to weld dissimilar materials have to be established or even developed. NDT techniques offer the great potential not only to prove the joint quality after the welding process (post-process) but also to realize process monitoring concepts, which enable to identify necessary adjustments of different process parameters while welding (in-process) in order to achieve high quality and less waste. X-ray and ultrasound (US) techniques are still state of the art for the inspection of composite materials and material compounds. But both are rather difficult to integrate into a production line, as X-ray methods require a special shielding and conventional ultrasound methods need to work in contact and with coupling media (e.g. by water immersion). For this reason in most cases the nondestructive testing takes place in the post-process, where no more corrective actions can be done in case of defects or irregularities. However, X-ray and ultrasound are suitable and essential as reference methods for any other NDT method due to the achievable high resolution. But other NDT techniques like for example EMAT, eddy current and acoustic emission testing have great potential to speed up the inspection process by an automated implementation into production processes.

2. Post-process NDT methods for composite materials and material compounds

With respect to the achievable resolution and detection sensitivity conventional US techniques are often not able to detect sufficient small irregularities, as it is necessary in regard to efficient and safe lightweight design constructions. To overcome this, special high-frequency ultrasound techniques (HF-US) have been developed, which are working in the frequency range from 10 MHz to 200 MHz. This increase in ultrasound frequency and therefore in resolution and sensitivity can be achieved by performing the measurements in a water-filled immersion tank due to the difference in ultrasound velocity in comparison to air [1]. As a result, irregularities with a size up to 0.2 mm can be detected, what makes this method a fast alternative to destructive, metallographic investigations. But nevertheless HF-US is not applicable as inline NDT-method for most applications due to corrosive effects, which cause that the parts cannot be used or forwarded to the next production step anymore.

Figure 1 shows the results of HF-US measurements on magnetic pulse welded aluminum/steel-joints. On the left side the C-scan of a faultless weld seam is demonstrated, whereas the C-scan on the right exhibits significantly higher intensities of the reflected amplitudes in the area of the weld seam indicating the presence of welding defects. In this case so-called kissing bonds were present at the interface between aluminum and steel, which are generally very difficult to detect. HF-US proved itself to be capable to identify such bonding defects in welded joints.

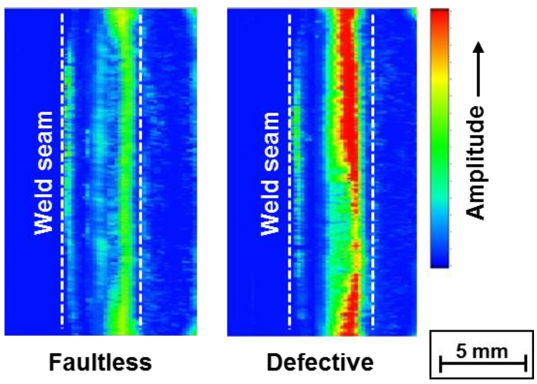

Figure 1. Nondestructive detection of kissing bonds in magnetic pulse welded aluminum/steel-joints using high-frequency ultrasound.

X-ray measurements are imaging methods using X-rays and mathematical algorithms to generate images or sequences of the investigated specimen [2]. While in X-ray radiography only 2D-images can be achieved, X-ray computed tomography (CT) can provide 3D-models of the samples. For this purpose numerous radiographs of the specimen are taken while it is rotating between the X-ray source and the detector. Afterwards the model of the sample gets calculated and visualized [3]. In this manner high resolutions can be achieved, which generally predestine X-ray measurements for the nondestructive identification of nearly every irregularity in materials and welding areas. But depending on the investigated material and its thickness such measurements are often very time-consuming and due to the required rotation of the parts in the course of the beam often not applicable with regard to the geometry of the parts. Therefore X-ray radiography and CT can often only be realized in the post-process as reference methods. An alternative to CT is the computed laminography (CL) which enables the inspection of bigger parts with high resolution. In contrast to CT the X-ray source and the detector are moved in CL-measurement which reduces the physical, geometric restrictions [3, 4]. Considering this, in addition with the adoption of enhanced reconstruction methods, the testing time can be considerably reduced and this method can generally be applied even for inline testing in the production line for several applications [4].

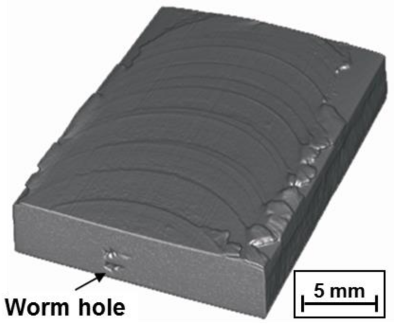

Figure 2. Detection of a worm hole in a friction stir welded Al-joint by 3D-CT.

As figure 2 demonstrates it is possible to detect very small-sized defects inside the volume of a specimen with X-ray techniques, like in this example a so called worm hole inside a friction stir welded Al/Al-joint by 3D-CT. However not only to detect existing defects but also to characterize different material or joint properties X-ray methods are suitable. For example the orientation of the fibers in composite materials or, like shown in figure 3, the degree of material mixing in welded joints can be visualized. In this case figure 3 compares the mixing levels of Al/Mg hybrid joints which are produced by conventional friction stir welding (a) and ultrasonic enhanced friction stir welding (b) using computed laminography with faded out aluminum contents. It can be clearly realized, that the superimposition of the friction stir welding process by ultrasonic energy leads to an intensified material mixing in the joining area [5].

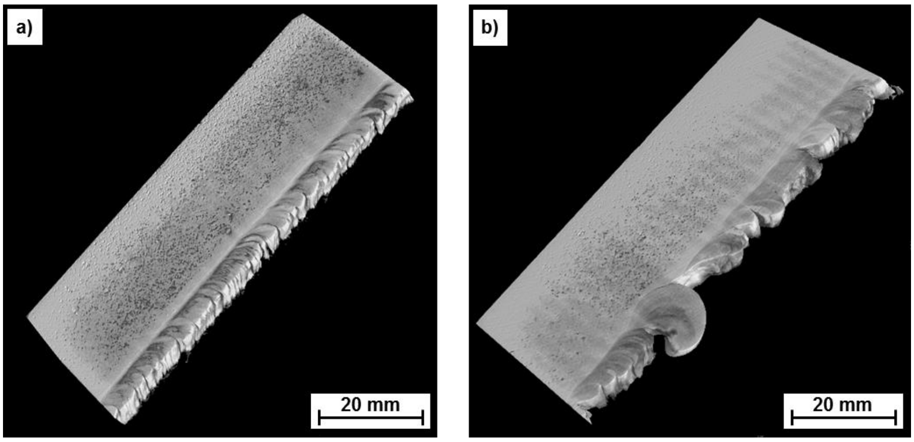

Figure 3. Visualization of the material mixing in the stirred area of a friction stir welded (a) and an ultrasonic enhanced friction stir welded (b) Al/Mg-joint by computed laminography (Al faded out) [5].

3. Production integrated NDT of composite materials

Composite materials like metal or polymer matrix composites, aim to combine the advantageous properties of different materials. Relating to lightweight construction this means to achieve the highest possible strength with the lowest possible density. In order to exploit the lightweight potential of such complex materials in an optimal way, appropriate NDT methods to monitor the material condition have to be developed and used during the application and already in the material or component production. Characteristic defects that may occur in composite materials are for example delaminations, debonds, porosity or fiber breakage. Following several methods will be presented which are suitable to realize a nondestructive testing of such reinforced materials.

3.1 Sampling Phased Array (SPA)

Sampling Phased Array (SPA) is an ultrasonic NDT method which operates in transmitter-receiver mode and uses the signals of different transducers in the array to characterize the material. A signal that is transmitted by one of these transducers of the array is received by all the other transducers. Due to this a great advantage of SPA is the ability to investigate comparatively big volume sections in very short time. In addition SPA enables to focus on different investigation depths simultaneously which is not possible in conventional phased array measurements. By combining this technique with the Synthetic Aperture Focusing Technique (SAFT) it is possible to generate a real time imaging of the investigated material area. Using the Reverse Phase Matching it is even possible to analyze complex and anisotropic materials, like for example CFRP or austenitic steel welds by determining the velocity distribution of the wave propagation using the elastic constants of the materials. Figure 4 illustrates the detection of various artificial defects of different size and at different depths on a CFRP specimen with a thickness of 14 mm [6].

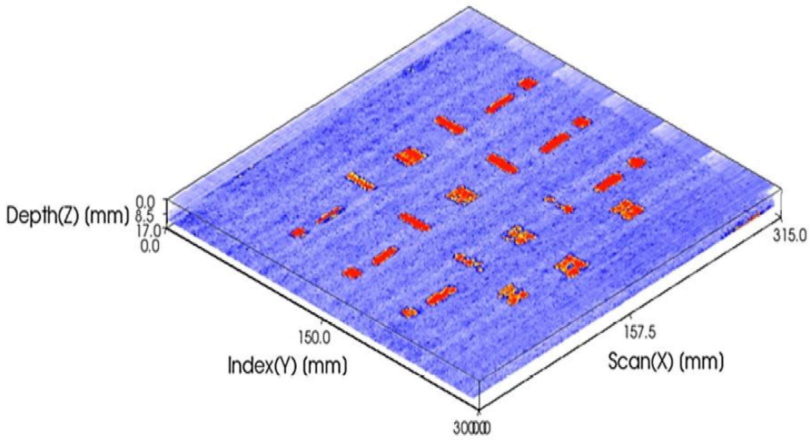

Figure 4. Detection of artificial defects in CFRP by Sampling Phased Array method with Reverse Phase Matching and 3D imaging [6].

3.2 Non-linear Ultrasound

Non-linear Ultrasound describes a method that uses the interaction between ultrasonic waves propagating in the sample and the mechanical properties of materials in defect-near areas to characterize the sample condition. Existing micro cracks, for example in CFRP components, may be closed if no stress or compressive stress is applied and therefore these defects are very difficult to detect in such an early stage of damage. By transmitting an ultrasonic wave of adequate intensity to the sample, tensile components are able to achieve temporary crack opening, which can be detected due to its effect on the amplitude of the received ultrasonic signal [7].

3.3 Eddy current

Eddy currents can be induced in conductive materials by placing a coil on or near the surface which is excited with an alternating current and generates an alternating magnetic field around the coil. These induced eddy currents generate an opposed magnetic field to the one resulting from the excitation coil. Any defect or irregularity in the investigated area of a sample leads to a disturbance in the flow of eddy currents and the resulting magnetic field, which can be measured by the impedance signal of the receiving coil [3]. In [3] and [8] the ability but also the restrictions of eddy current testing to detect defects in CFRP were investigated. In both cases defects which directly affect the conductive fibers, for example by fiber cracking, could be identified [3, 8]. In addition delaminations at the interface between fibers and matrix material could be proven. But nevertheless this technique is not able to detect inhomogenities which only affect the nonconductive components in composite materials, like i.e. pores in the polymer matrix of CFRP [8]. This method is a very fast, cheap and robust NDT technique, but limited in detection depth as the penetration depth of the magnetic field depends on the operating frequency of the eddy current system [3].

3.4 Lock in thermography
As a result of a temporally or locally periodic modulation of the thermal excitation, i.e. sinusoidal, a so called "thermal wave" can be induced in a material or a component. This wave propagates through the material and gets reflected at the boundaries of defects. The result is an interference of the reflected proportion of the wave with the modulated excitation wave which leads to a measurable temperature variation at the surface and can be detected by a thermographic camera. By applying a Fourier transformation the amplitude and the phase information of the measured signals can be evaluated which enables an imaging of defects inside the volume of the investigated samples [3, 9]. As described in [3] this method is very suitable for application on complex structures but limited concerning the detection depth. In this case artificial defects with a dimension of 4 x 4 x 0.5 mm^3 could be proven up to 8 mm in depth. Figure 5 demonstrates exemplarily the ability of lock in thermography to detect artificial defects of different sizes in a CFRP plate.

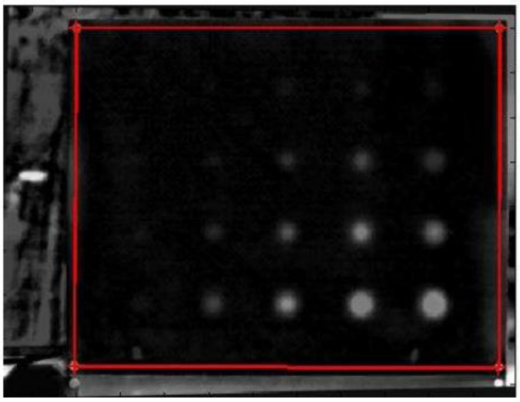

Figure 5. Detection of artificial defects in CFRP by lock in thermography [8].

4. Production integrated NDT of material compounds
To fulfill the requirements of modern lightweight construction, innovative joining technologies have to be developed or established that enable the realization of multi material design and avoid additional joining elements or overlapping material sections. But also conventional and widespread joining techniques have to be optimized regarding their efficiency in order to achieve an optimal resource usage. An important tool to optimize and to monitor or even control joining processes is the application of different NDT techniques, which will be presented exemplarily for different welding methods in the following.

4.1 Electromagnetic Acoustic Transducers (EMAT)
Nondestructive testing with Electromagnetic Acoustic Transducers (EMAT) describes a special method of ultrasonic testing. In contrast to conventional ultrasonic testing, EMAT enables contactless testing without any couplant as the ultrasonic waves are generated directly in the material, which has to be investigated, by electromagnetic induction. This is realized by a RF coil that is located below a permanent magnet and induces eddy currents in the material (see figure 6a). Due to this operating principle the EMAT technique is suitable for inline- and in-process inspection, but can only be used to investigate electrically conductive materials [10]. The principle of defect detection is similar to conventional ultrasonic testing. Figure 6 illustrates the investigation of weld seams by EMAT. Whereas a faultless weld seam exhibits no additional ultrasonic reflection between the echo of ultrasonic wave generation and the edge of the investigated sample (figure 6b), any defect in the weld seam causes reflections of the ultrasonic waves and weakens the proportion of ultrasonic energy which

is transmitted through the welding area (figure 6c). In the case of a complete material separation, like shown in figure 6d, the ultrasonic waves are reflected at the interface of the defect completely and no edge echo of the sample can be attained.

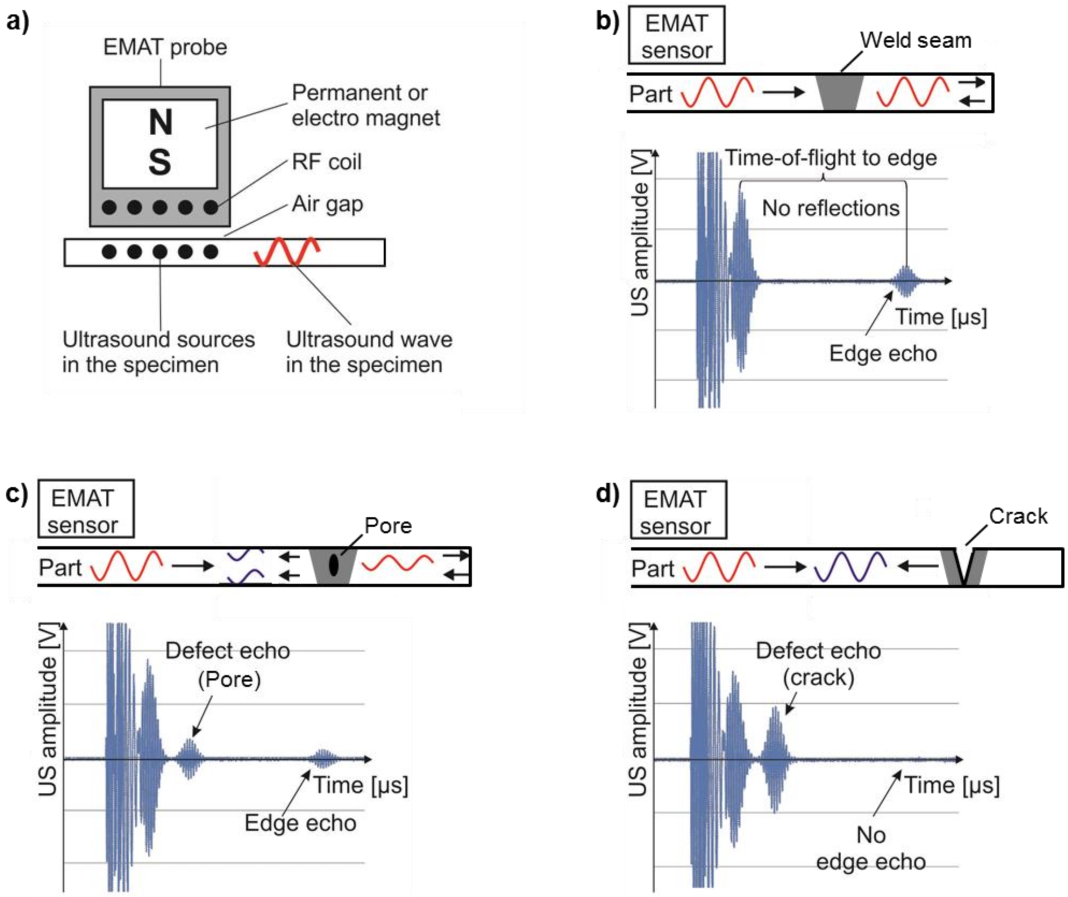

Figure 6. Schematic illustration of the detection of defects in weld seams by EMAT; a) physical principle, b) signals of a faultless weld seam, c) signals of a defective weld seam, d) signals of a weld seam with complete material separation.

4.2 Conventional ultrasonic testing

An example of a process monitoring concept in resistance spot welding is shown in figure 7. In contrast to EMAT, conventional ultrasound has to be transmitted to the investigated parts by a contacting transmitter. This is realized by implementing the US transmitter into one of the welding guns, which has to get in contact with one of the joining partners anyway. The other welding gun is equipped with an appropriate receiver to detect the ultrasonic waves, which pass the welding area during the process. In this case the ultrasonic testing is performed in transmission mode. The detection of defects and therefore the monitoring of the spot weld quality take place in a similar way than described for the EMAT´s as any irregularity in the welding process or the welding spot leads to measurable changes in the signal that is detected by the US receiver.

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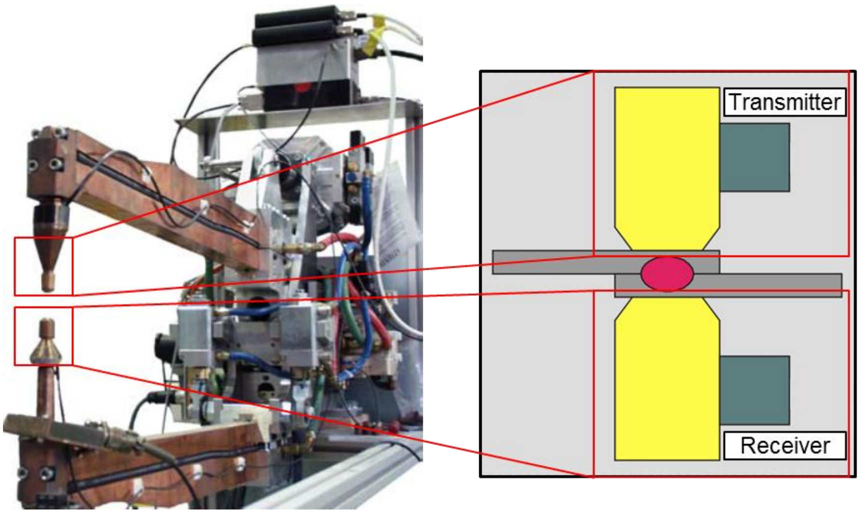

Figure 7. Ultrasonic Weld Monitor (USWM) in resistance spot welding.

4.3 Evaluation of process-intrinsic characteristics

A possibility to obtain direct feedback on possible process and thus quality variations of the corresponding component in the sense of an inline in-process procedure is the determination of process intrinsic characteristics. For example, the monitoring of the laser welding process on steels is carried out in [11, 12] by recording and anlalyzing the acoustic emissions of the process. This can be achieved by measuring the structure-borne acoustic emissions, e.g. by applying a corresponding sensor to the sheets to be joined or by measuring air-borne acoustic emissions. Particularly advantageous in this context is the detection of the signals in the high-frequency range from several hundred to approximately 1000 kHz, since this can eliminate disturbing environmental influences. Figure 8 illustrates this method using the example of the air-borne acoustic emissions of a laser weld with artificial as well as natural welding defects. It can be seen that the amplitude of the measured signal reacts significantly to deviations resulting from process variations or the presence of a defect and exceeds the limits of a previously determined tolerance band [11, 12].

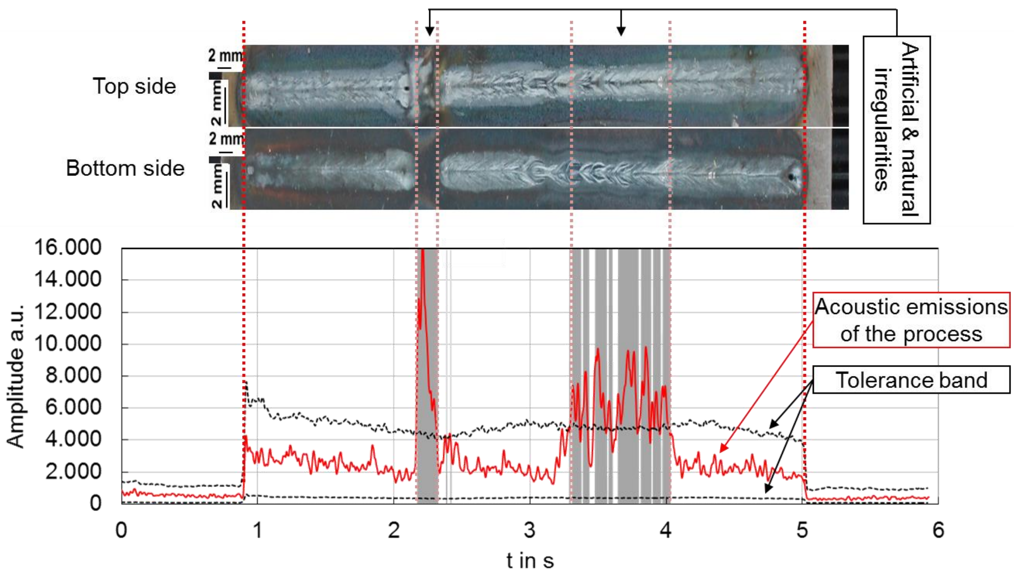

Figure 8. Process monitoring in laser welding by air-borne acoustic emissions [12].

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Another example of the use of process-intrinsic characteristics for the purpose of process monitoring is described in [13] on the basis of the Friction Stir Welding process (FSW) of aluminum alloys. As FSW is a pressure welding method, a welding tool has direct contact to the joining partners, resulting in process forces in all three spatial directions. The axial welding force of the tool in the z-direction is a main process parameter of Friction Stir Welding, which is also used as control variable to realize a force-controlled process. However, the forces in the plane of the joining partners (x - and y-direction) can be recorded and evaluated in the sense of a real time process monitoring, as represented in figure 9. So, process fluctuations, as well as the occurrence of defects in the weld seam are expressed in deviations of these forces as illustrated by the black circled area. A subsequent analysis of the data by means of a short-time Fourier transform (STFT) facilitates the identification of relevant critical areas through the representation of temporal changes of the frequency spectrum which are highlighted by red circles in figure 9. The knowledge obtained in this way can also be used as the basis for the realization of appropriate process control algorithms. In addition to the schematic representation of this process monitoring approach, called "MonStir®", figure 9 shows the proof of the identified defect in the weld by means of ultrasonic testing and a microscopic view of a metallographic cross section [13].

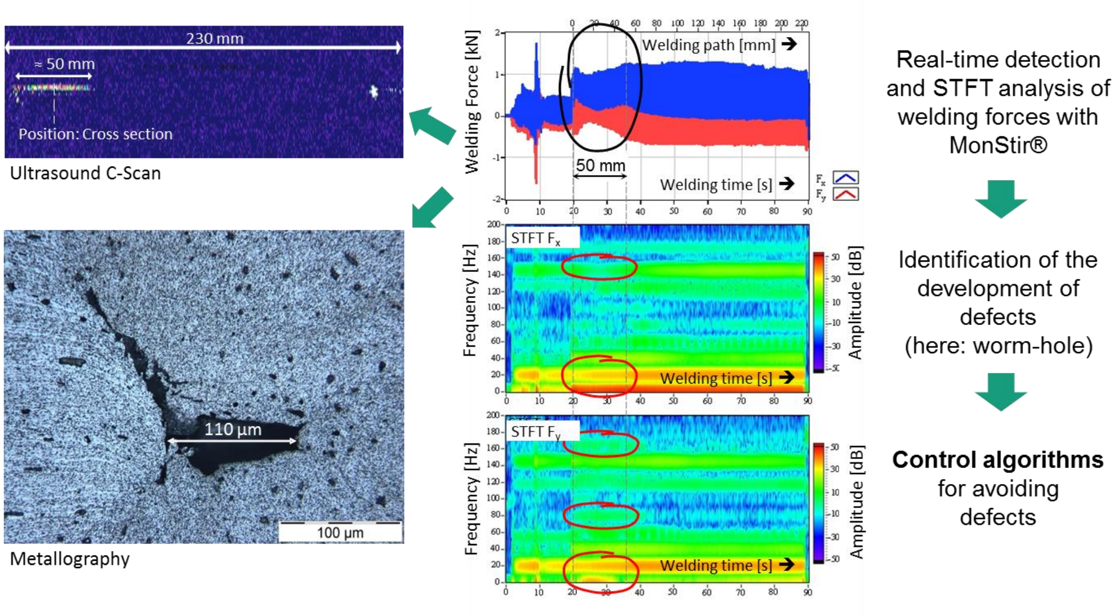

Figure 9. Schematic illustration of the MonStir® concept for process monitoring and control of the Friction Stir Welding process [13].

4.4 Measurement of mechanical and microstructural properties by micro-magnetic methods

In addition to the possibilities presented for the detection of imperfections, qualitative and quantitative determinations of mechanical and microstructural properties of materials can also be made using NDT methods. To achieve this, the 3MA technique (Micromagnetic Multiparameter Microstructure and stress Analysis) makes use of the correlation between the micro-magnetic properties of ferromagnetic materials and their mechanical or microstructural properties. On the basis of destructively determined reference values, a polynomial is calculated by means of a regression analysis which describes this relationship mathematically and thus enables the nondestructive determination of mechanical and microstructural properties such as, for example, hardness, tensile strength or diffusion layer thicknesses. In order to make the determination as accurate as possible, 41 measurement variables are measured by the combination of the methods: incremental permeability, harmonic analysis, Barkhausen noise and multi-frequency eddy current. Figure 10 shows on the left the comparison between destructive and nondestructive determination of the hardness over a laser welding seam. In the right-hand part of the figure, the residual stresses measured longitudinally and transversely to the seam are shown in a comparative manner over the weld seam. In both cases, there is a very good correspondence between destructive and nondestructive measurement values.

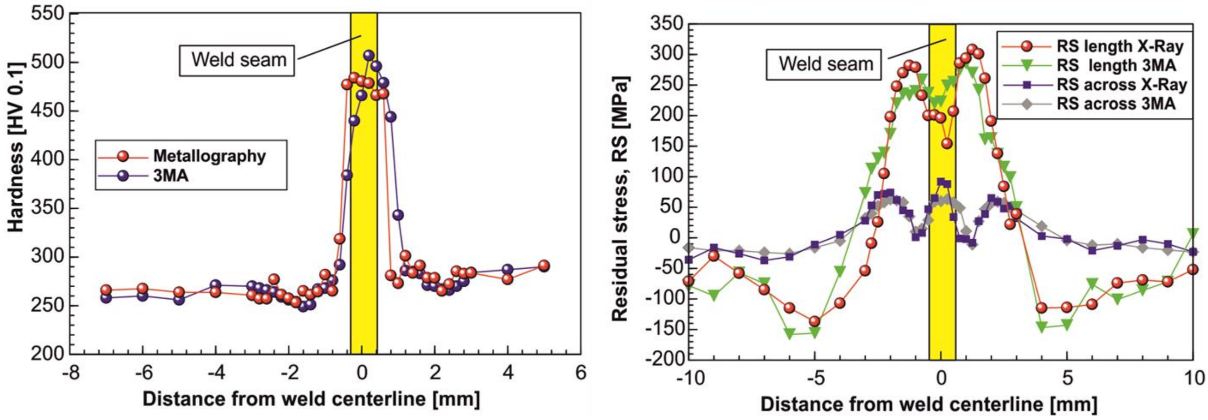

Figure 10. Nondestructive quantitative evaluation of hardness and residual stresses across a laser welded seam using 3MA technique.

5. Conclusions

As clarified by this article, the NDT has a high relevance to ensure adequate material quality as well as joint quality in the sense of lightweight construction. Due to the large number of available methods, as well as their constant further development and also new developments in the field of NDT, the challenges of the quality assurance of composite materials and material compounds can be overcome and thus a substantial contribution to a resource-saving product design can be provided.

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References

[1] Netzelmann U 1993 Nondestructive testing of ceramic-metal joints by high-frequency ultrasound techniques *Joining ceramics, glass and metal* (Frankfurt/Main: Deutsche Glastechnische Gesellschaft) pp 168–175

[2] Verein Deutscher Ingenieure (VDI) 2009 Computertomografie in der dimensionellen Messtechnik - Grundlagen und Definitionen *VDI/VDE 2630 Blatt 1.1.* (Düsseldorf: VDI-Verlag)

[3] Beine C, Boller C, Netzelmann U, Porsch F, Venkat R, Schulze M, Bulavinov A and Heuer H 2010 NDT for CFRP aeronautical components a comparative study *2nd International Symposium on NDT in Aerospace (Hamburg)*

[4] Maisl M, Schorr C, Porsch F and Haßler U 2010 Computerlaminographie, Grundlagen und technische Umsetzung *Industrielle Computertomografie: Zerstörungsfreie Bauteilprüfung, 3D-Materialcharakterisierung und Geometriebestimmung* (Aachen: Shaker Verlag) pp 261–266

[5] Straß B 2015 Ultraschallunterstütztes Rührreibschweißen von Al/Mg-Verbunden: Prozess-analyse, mikrostruktureller, mechanischer und korrosiver Eigenschaftsvergleich *Werkstoffkundliche Berichte* vol 36 (Kaiserslautern: University of Kaiserslautern)

[6] Ramanan S V, Bulavinov A, Pudovikov S, Boller C and Wenzel T 2010 Quantitative non-destructive evaluation of CFRP components by sampling phased array *2nd International Symposium on NDT in Aerospace (Hamburg)*

[7] Helfen T B 2014 Nichtlinearer Ultraschall zur Charakterisierung von Ermüdungsschäden während der Hochfrequenz-Beanspruchung von C-Faser-Kunststoffverbunden *PhD Thesis* Universität des Saarlandes

[8] Müller W 1993 Erhöhung der Aussagefähigkeit von zfP-Prüfergebnissen an CFK-Platten durch Einsatz und Kombination unterschiedlicher Sensortechnik *Seminar über die Qualitätssicherung von Faserverbundwerkstoffen (Darmstadt)*

[9] Zöcke C, Stössel R, Langmeier A and Arnold W 2007 Automatische Erkennung und Charakterisierung von Defekten in CFK-Werkstücken unter Verwendung thermischer Aufnahmen *DGZfP-Berichtsbände* (Berlin: Deutsche Gesellschaft für zerstörungsfreie Prüfung (DGZfP))

[10] Salzburger H-J, Niese F and Dobmann G 2012 EMAT pipe inspection with guided waves *Welding in the world* **56** 35–43

[11] Bastuck M, Herrmann H-G, Wolter B, Böttger D and Zinn P-C 2016 AkuProLas: Acoustic Inline Process Monitoring for Laser Welding Applications *World Conference on Nondestructive Testing (19): WCNDT 2016* (Berlin: Deutsche Gesellschaft für zerstörungsfreie Prüfung (DGZfP))

[12] Bastuck M 2016 In-Situ-Überwachung von Laserschweißprozessen mittels höherfrequenten Schallemissionen (Saarbrücken: Universität des Saarlandes)

[13] Jene T 2008 Entwicklung eines Verfahrens zur prozessintegrierten Prüfung von Rührreibschweißverbindungen des Leichtbaus sowie Charakterisierung des Ermüdungsverhaltens der Fügungen *Werkstoffkundliche Berichte* vol 21 (Kaiserslautern: University of Kaiserslautern)