New NDT - approaches to monitor the friction stir welding process and to inspect the welding quality

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Introduction

Numerous reports concerning recent scientific and industrial activities on friction Stir Welding (FSW) reflect the broad advantages of this upcoming welding technique [1, 2, 3, 4]. In particular, FSW is interesting for small and medium-sized enterprises (SME), because it does not necessarily require the additional purchase of expensive special machinery. Often it is possible to use a slightly modified CNC milling machine for FSW [5].

FSW is well known for its reproducibility and freedom from traditional fusion welding imperfections such as shrinkage cavities or slag inclusions. But, if FSW should be widely accepted as a joining method, reliable but also cost-effective process-specific quality assurance activities have to be developed. So far there is neither a common standard defect catalogue for FSW, which summarizes all relevant irregularities and describes their allowable sizes for different applications nor a standardized test specification for FSW welds. Moreover, it is even not fully understood, how different imperfections of the weld are affecting its mechanical properties during static and dynamic load [6].

Like for established welding techniques it is necessary to provide non-destructive testing (NDT) for assuring the integrity of structural welds by identifying cracking, porosity and other "well-known" flaws that can compromise weld strength. The NDT methods proposed for FSW so far, like ultrasound and eddy-current arrays and x-ray techniques [7, 8, 9, 10, 11] are suitable to only a limited extent for application in SME production, because they are expensive, time-consuming and not flexible enough. In addition, however, there are some FSW-specific irregularities affecting fatigue behaviour and corrosion resistance, such as flat worm-holes, oxides lines and blisters (small pores near to surface), which are difficult to identify with "conventional" NDT. Therefore, there is still exists the need for further development of NDT techniques.

This is especially true for in-process NDT methods, which allow the automatic joint quality inspection during welding [12]. Such devices offer the possibility for a 100% monitoring of welds. Integrated into a feedback control algorithm, they will help to reduce weld imperfections. This is important especially for oxide lines - sometimes also referred as kissing bonds or joint line remnants - which are difficult to inspect in a post-process inspection. Process optimization is required in order to prevent such imperfections.

Post-Process Inspection

FSW Imperfections

Figure 1 summarizes the most frequent FSW irregularities.

The detection of "conventional" flaws, like LOP and LOF is an important NDT task but they can be reduced / avoided by a suitable clamping, tool pin length and machine set-up. Similar "simple" preventive measures do not exist for process-specific flaws, like collapsed nugget, blisters, worm-holes and oxide lines.

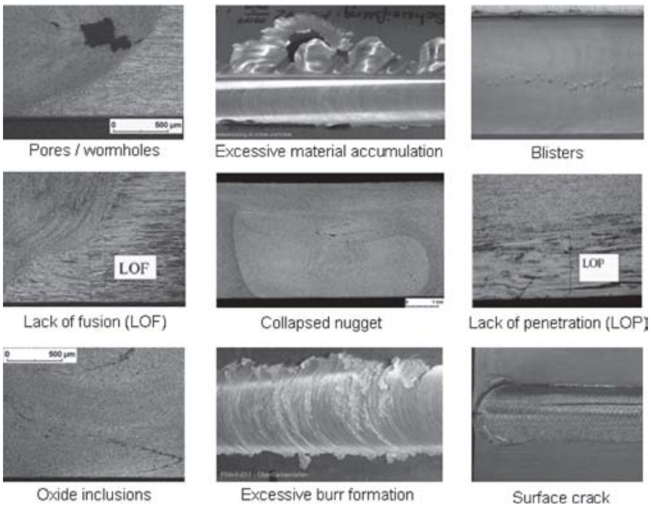
Pores / wormholes
Excessive material accumulation
Blisters
Lack of fusion (LOF)
Collapsed nugget
Lack of penetration (LOP)
Oxide inclusions
Excessive burr formation
Surface crack

Figure 1. FSW weld imperfections

If the pin geometry and its immersion depth are not adjusted to the weld, a collapsed nugget with a strong asymmetric shape can result [13]. If the welding force in z-direction is not adapted correctly, an excessive burr formation can result. Blisters may arise from the fact, that material is distributed over pre-welded areas, which subsequently do not connect cohesively anymore [14].

For FSW, worm-holes are process-specific too, because, unlike to fusion welding, they are not formed by gases. Here, their formation is dependent on the material flow around the tool pin and the generated frictional heat [15, 16]. Worm-holes have a significant impact on the fatigue properties. Fatigue tests show, that they act as an initiator for a crack network and result in a forced fracture of the weld [17].

Generally, there is a trend that worm-holes emerge, if the feed rate is too high and the pin rotation speed is too low. The optimum machine parameters set to prevent worm-holes is dependent on the specific combination of the welded sheet thickness and materials. Often, extensive experiments are required in order to determine the narrow window of optimum parameters. Anyhow, even in this case, the formation of worm-holes can not be prevented completely, because non-controllable parameters, like material thickness variations or tool wear can have a detrimental effect on the process [17]. Therefore, there is a need to detect worm-holes with NDT. This can be difficult, because worm-holes are often flattened to almost zero height (~ 0.1 mm) due to the high z-forces.

But also oxide lines, i. e. particles conglomerating along characteristic lines / bands can have a significant impact on the mechanical properties of FSW welds. Yield strength, tensile strength and fracture elongation are reduced for a weld with oxides [18]. Compared to welds with oxides, oxide-free welds show 50 to 100% higher number of cycles to failure [17]. Therefore, these weld irregularities have to be avoided or at least to be identified too. But these imperfections are difficult to detect, because there is little disruption to direct passage of sound through this flaw and there is only a negligible amount of matter with a lower density that would enable X-ray detection [8].

X-Ray Microscopy

Except oxide lines, x-ray micro-focus radiography and computer tomography (CT) allows to identify all types of relevant weld flaws in the volume. In the present work, radiography, 2D- and 3D-CT has been used as "reference" for other NDT methods. For small samples, the used x-ray device is capable to resolve features of about 5 µm. In case of welded sheets with an area of 100 x 100 mm2 a spatial resolution of about 50 µm was achieved.

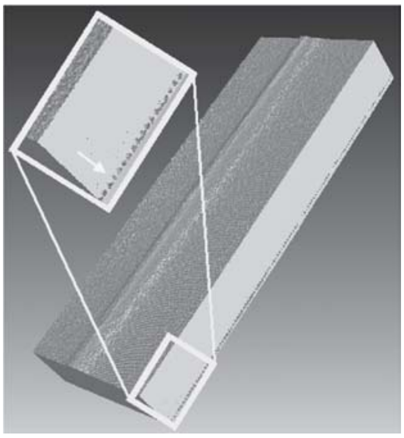

Figure 2. Identification of a worm-hole with x-ray 3D-CT

As shown in figure 2, size, position and orientation of a very thin worm-hole can be determined with 3D-CT. But the inspection time for a weld was between 40 min and 1 hour.

High-Frequency Ultrasound

The principle of high-frequency ultrasound (US) immersion testing is shown in figure 3. The ultrasound transducer and the specimen are immersed in water. For the following results, an 80 MHz transducer was used, which scans a 200 x 30 mm2 area of the specimen in a meandering pattern with a step width of 0.5 mm. The inspection time is about 1 hour.

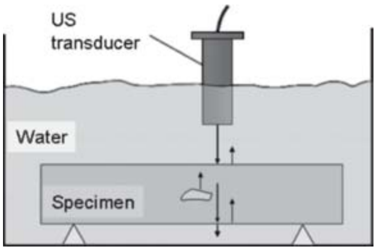

Figure 3. Ultrasound immersion technique

Based on test specimens, equipped with blind holes of different diameters and depths, it was verified, that equivalent flaw sizes down to 0.5 mm could be detected up to a depth of 9.5 mm. As shown in figure 4, the worm-hole from above was detectable again. Additionally, it was possible to detect pores, blisters and root flaws with this method.

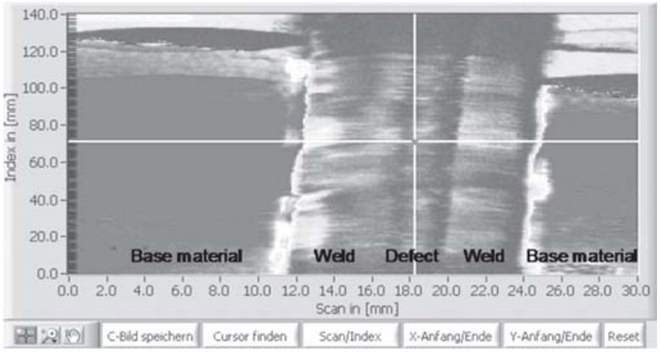

Figure 4. Identification of a worm-hole in an US C-Scan

Ultrasound Backscattering

None NDT methods so far is suited for a reliable identification of oxide lines. An approach for the direct detection of these defects could be US backscattering.

This measuring principle is based on the scattering of an US wave at boundaries of grains and phases, with an acoustic impedance, which is different to the base material. This method is commonly used for determining the hardening depth in induction hardened steels [19]. It was also used for determining the distribution of ceramic reinforcements in Al-based metal matrix composites [20].

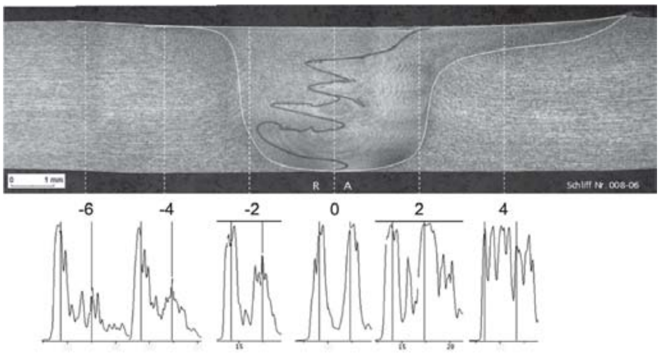

Figure 5. Backscattered US signal of a weld with oxide lines

In order to identify oxide lines with this method, an US frequency has to be selected, which corresponds with the

Rayleigh scattering range for the size of the oxide fragments (~ 5 µm) but not for the grain size in the weld nugget (~ 15 µm).

One result of some first experiments is shown in figure 5. There seem to be an increase of the backscattered signal in the area of the weld with a high amount of oxide lines. This promising result has to be verified by further experiments.

Ultrasonic Residual Stress Determination

Complementary to the established techniques to evaluate stress states, ultrasound (US) techniques permit the evaluation of stresses in the volume. One advantage of this technique is the possibility of a fast evaluation of stress states, enabling a continuous analysis along traces in order to get information about the stress distribution and the stress inhomogeneities. This technique has been developed for different cases of application on components and set-ups for the automated evaluation of stress states are in industrial use.

The evaluation of stress states using US assumes the knowledge of the acoustoelastic constants. These constants describe the interdependency between the US measuring quantities (sound velocity or time-of-flight) and the strain or stress states. The influences of the microstructure state and texture on US velocities and on the acoustoelastic constants have been studied using material samples with known mechanical properties and well described microstructure states. Lists of the relevant constants of different Al alloys and steel grades are available as well as techniques and sensors for specific applications [21].

One well described application is the determination of residual stress in fusion welds [22]. Based on the same procedure FSW welds have been investigated concerning their residual stress distribution. Some exemplary results for five welds with different sheet thicknesses between 1 and 3.5 mm are shown in Figure 6. The profiles are asymmetric in regards to the centre line of the weld. This interesting feature, not detectable for fusion welds, probably reflects the different conditions at retrieving and advancing side of the weld.

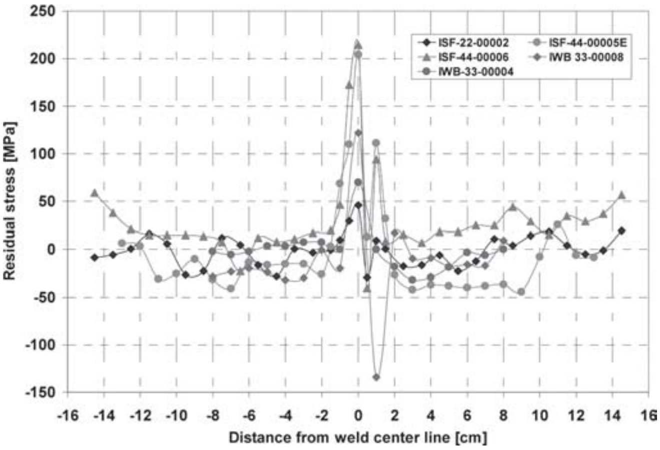

Figure 6. Residual stresses of five different FSW welds, determined with an ultrasonic technique.

Process Monitoring and Control

In-line Weld Inspection with EMAT's

Electro-magnetic acoustic transducers (EMAT's) are a well known type of ultrasonic probes used for NDT of electrically conductive materials. US waves generated with EMAT's can propagate as guided plate waves in flat sheet construction joined with FSW. In case of these waves the whole sheet thickness is under vibration. This is favourable for detecting volume as well as surface defects in a FSW weld.

EMAT's are advantageous, because they do not require the use of a couplant, i. e. they can be applied non-contacting, which make them ideally suited for use in an in-line inspection system. Therefore EMAT weld inspection can be integrated into the production process in order to check joint quality directly after welding (see figure 7). High inspection speeds of more than 0.5 m/s can be achieved at moderate costs.

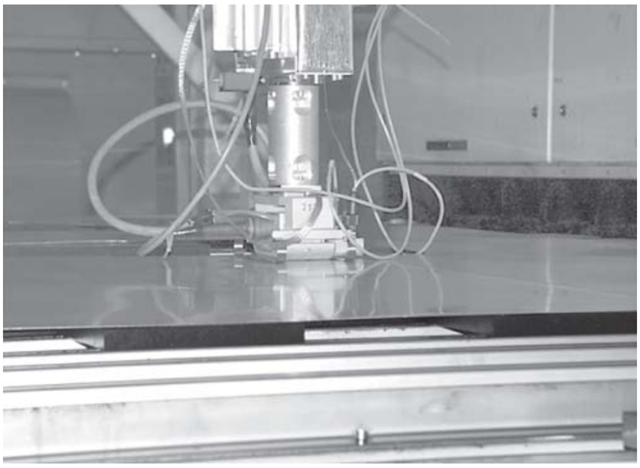

Figure 7: In-line weld inspection with EMAT in a gantry

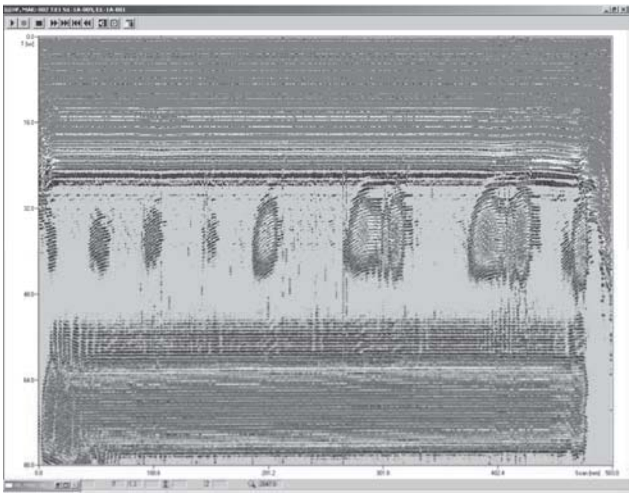

Figure 8: Indication of different flaws in an US B-Scan determined with EMAT's

Figure 8 shows the result of measurement on a test specimen, equipped with blind holes. An equivalent flaw size of 0.5 mm was still barely detectable.

FSW Monitoring with MonStir®

Today, the welding forces perpendicular to the sheet plane are commonly recorded to enable a force control during FSW. Despite the availability of this data, which can provide information about the developing material structure in a friction stir weld, the data are not used so far in detail. The software package MonStir® is appropriate for monitoring and analyzing the welding forces in the x-, y- and z-directions in their time and frequency domains.

These data give an explicit indication of the presence of worm-holes and their formation in the weld. Figure 9 shows the frequency spectrum of the force Fz, determined with MonStir®. The results between point a (x = 120 mm) and point f (x = 200 mm) indicate, that a worm-hole is developing.

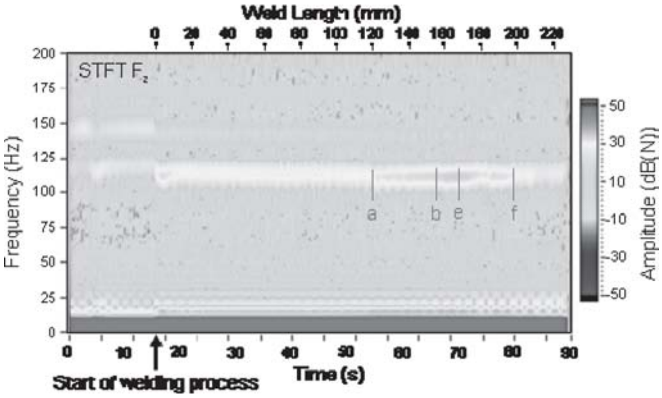

Figure 9. Fz frequency spectrum of a weld process with a worm-hole, detected between point a and point f.

Later this weld was inspected with US immersion technique In the US C-scan, the worm-hole is clearly visible (see figure 10). But results from US inspection as well as from later destructive tests could detect this worm-hole not before point b (x = 165 mm). That means, with MonStir® it was possible to predict this weld imperfection before it actually occurs. Therefore MonStir® gives the possibility to take corrective actions, i.e. to adjust the welding parameters, in order to avoid the formation of such imperfections.

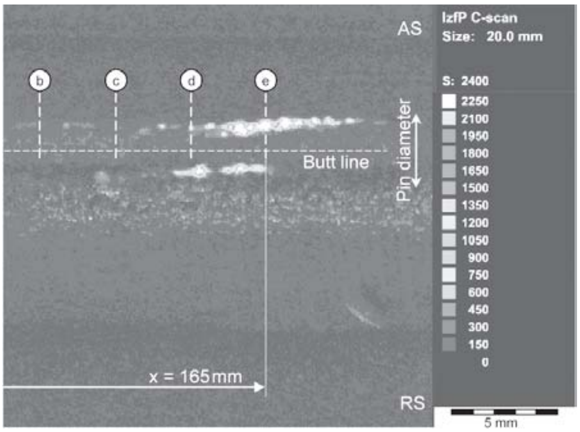

Figure 10. US C-Scan of the weld from figure 7

A significantly different pattern appeared when other welding imperfections, such as pores, blisters occurred. Furthermore, it could be shown, that there is a close correlation between the oscillating welding forces and the distribution of oxide particles within the weld nugget. In particular, the ratio of the feed rate to pin's rotational speed could be correlated with the periodic length of the measured forces as well as with the distribution of the oxide particles. Therefore, it can be concluded, that monitoring the welding forces could be used to predict the oxide distribution in the microstructure of the weld [12].

In addition to the prediction of welding imperfections, tool breakage seems to be predictable, as well. The tool could be replaced before it breaks off in the part, thus preventing the part from being later rejected.

Process Optimization

Reducing the Amount of Oxide Inclusions

Oxide / hydroxide inclusions in the weld originate from the sheet surfaces. During welding, the amorphous oxide layer is disrupted and stirred in the form of small particles into the weld nugget. Depending on the feed rate per rotation speed of the pin, the oxide particles arrange in characteristic pattern. Supported by other adverse conditions (e. g. high humidity) these particles eventually agglomerate within the unwanted characteristic lines / bands.

Hence, in order to minimize the oxide amount in the weld it is necessary to remove the oxide layers on the sheet surfaces before welding. If the opposite edges of both join partners are sawn cut and polished, it reduces the surface available for oxidation. After sufficient grinding with fine grain and subsequent polishing down to a roughness of Ra < 0.4 microns, oxides can not be observed in the micrograph of the weld nugget anymore.

Ultrasound Supported Friction Stir Welding

Grinding and polishing of the edges are additional process steps, which may not be accepted in each case for reasons of cost-, time-efficiency. A second possibility to prevent the formation of oxide lines is to superimpose high power ultrasound (US) during welding [23].

In order to couple the US into the weld, a sonotrode was pneumatically attached with a force of 500 N to the joint line of the welding set-up (see figure 11). By this, US is transferred into all three spatial directions of the sheets. Nevertheless, with modern milling centres, it should be possible to directly couple the US into the FSW tool.

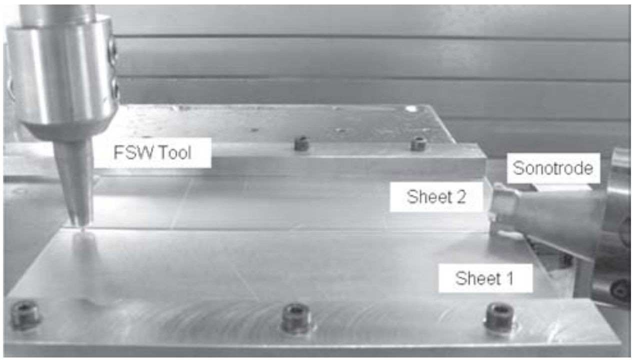

Figure 11. .FSW with superimposed high power ultrasound

Usually the oxides arrange in the weld nugget according to the low-frequent oscillation of the pin rotation (~ 20 Hz). If US is applied, an additional high-frequent (~ 20 kHz) vibration is superimposed. As a consequence oxide particles are spread over a larger volume of the weld. Thus, the agglomeration of detectable amounts of particles is less probable, resulting in less oxide lines. The absence of oxide lines was approved in micrographs. Besides the prevention of oxide lines, superimposing US seems to improve the microstructure in the weld nugget by grain fining too.

Conclusions

X-ray microscopy and high-frequency ultrasound (US) are adequate NDT methods for the detection of FSW relevant weld flaws, except oxide lines. High-frequency US backscattering seems to be an approach in order to detect oxide lines in the weld nugget. US time-of-flight measurements allow to determine the residual stress distribution across the width of the weld. Nevertheless, usually these methods are not suited for in-line inspection during welding.

For the in-line detection of weld flaws US monitoring systems based on couplant-free EMAT's have been proposed. Such systems allow high inspection speed at moderate costs. The detection and even the prediction of the formation of weld irregularities, like pores, worm-holes but also the prediction of tool breakage seems to be possible by monitoring and analyzing welding forces based on the process monitoring software MonStir®.

Possibilities to reduce the occurrence of oxide lines in the weld nugget have been developed based on findings about the influence of process parameters and sheet surface preparation. Reducing the amount of unwanted oxide lines was realized either by reducing the surface roughness of the join partners or by superimposing high power ultrasound during welding.

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