Non-Destructive Online-Testing Method for Friction Stir Welding Using Infrared Thermography

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Abstract. The aerospace as well as the traffic sector are always searching for efficient and reliable technologies, also in the field of joining methods. Friction stir welding (FSW) is a pressure welding process during which a rotating tool is moved through the joint area of the joining partners. These heat up due to the friction and are then stirred together. This results in a metallic joint with a high seam strength. As FSW needs no auxiliary or additional material, weight is generally reduced which, in turn, makes this joining method very interesting for the welding of aluminium for lightweight designs.

Just as in other welding methods, local imperfections within the weld seam can occur despite of the constant procedural welding parameters. These imperfections reduce the mechanical-technological properties of the weld seam. To prevent a possible failure of these seams and to ensure a constant quality of the weld seam, it is important to detect these critical flaws non-destructively. This is all the more the case in security-relevant applications.

A promising non-destructive testing (NDT) method for FSW is IR thermography. By detecting the infrared radiation, the weld seam can be examined without contact. Irregularities that might occur during the welding process can be detected online, respectively passive, due to small differences in the temperature at the surface of the seam. According to DIN EN ISO 25239-5, significant irregularities of friction stir welding are „wormholes“ and „lack of penetration“. These inhomogeneities cannot be detected by visual inspection but can reduce the quasi-static strength of the weld by more than 50%.

In this publication, we would like to present an online evaluation of a lap joint seam during the cooling process. The aim of NDT is the detection of critical defects and their quick evaluation. Besides naming the smallest detectable irregularities, our investigations also verify these flaws using other destructive testing methods.

1. Introduction

Friction stir welding is a comparatively young pressure welding process in which a rotating tool, made out of a pin and a shoulder, plasticizes the base material at about 75-80% of the melting temperature. Under axial load application, the tool is moved along the joint. Both join partner are stirred together through the tool rotation, thus, forming a material closure.
join (see fig. 1). Friction stir welding is used for material with low melting temperatures such as aluminum, copper but also steel.

Fig. 1: Depiction of the principle of friction stir welding

A main advantage of FSW is that no auxiliary or filler materials are necessary for the process. Furthermore, between 80 – 100% of the tensile strength of the base material can be achieved. In contrast to fusion welding processes, the join has a flat weld without weld splatter on both sides. This is advantageous economically and as regards the production process, the weld does not have to be post-treated. In addition, this welding process is easily automatable and needs no process-adapted preparation of the joint. [1]

It is a common procedure to record the force progression during the welding process in order to detect imperfections. However, imperfections can still occur within the welds which are caused by deviations of singular, non-detectable parameters. These imperfections, however, reduce the technological and mechanical properties of the friction stir weld. [2] To secure a constant weld seam quality and to avoid the unforeseen failure of the weld, it is necessary to detect critical imperfections non-destructively.

A method for the non-destructive testing and evaluation of imperfections should offer quick results and the possibility of monitoring 100% of the welds. Within the field of FSW, this task has already been taken up by using several non-destructive testing methods (e.g. ultrasonic testing (UT), acoustic emission (AE)). However, these methods have several specific disadvantages. Depending on the testing method, this includes a small testing area, low detectability of critical imperfections, long testing period or limited automatability. [3, 4] Currently, there is no NDT method which enables the examination of the weld seam during the process. This paper would like to introduce passive thermography as an online NDT method which can monitor friction stir welding to 100%.

2. Experimental Setup

The infrared camera FLIR SC5600-M was used for thermographic measurements during the process. This actively cooled camera features an indium antimonide (InSb)-sensor with a high resolution of 640 Pixel x 512 Pixel, a recording frequency of 100Hz and a spectral range of 2.5µm – 5.1µm. Due to the smallest detectable noise equivalent temperature difference (NETD) of < 20mK, this camera is especially suited to detect smallest differences in temperature. [5] By reducing the measuring window, a recording frequency of 200Hz could be achieved. This recording frequency enabled the recording of sufficient pictures for a detailed evaluation of the welding process even at a feed rate of up to 1000mm/min.
A construction was built which positioned the camera directly over the weld seam so that its position to the tool stayed the same during the entire welding process. By following the tool, the cooling process could be monitored in a constantly large area (min. 90mm x 100mm). Due to this position, occurring flashes had no effects on the measurements. As shown in figure 2, the distance of the camera lens to the tool \( r \) was about 270mm, the angle of the camera \( \phi \) to the welding surface was about 55°.

![Fig. 2: Position of the thermographic camera to the welding tool](image)

To increase the measuring signal, measures to improve the thermal isolation were taken in order to shield disturbing reflections from the measurements. For this purpose, the welding area was encapsulated. All surfaces (e.g. clamping devices) were coated with matt black varnish. As the tool heated itself up, it radiated a lot of heat. In order not to disturb the measurements, the tool and its fixture were encased into a thin matt black hollow cylinder so that the gap between the sleeve and the aluminium sheet was less than 1mm. Although the emissivity was low, the aluminium sheets were deliberately uncoated. Thus, a contamination of the weld seam with the varnish and the resulting influence on the weld could be avoided and, simultaneously, the conditions stayed close to what they would be in practice.

3. Test Procedure

The wrought aluminium alloys EN AW-5754 H22 and EN AW-6082 T6 were examined as industry-related materials. From the thermographic perspective, the difference between the two alloys was their thermal conductivity (EN AW-5754: 140-160 (W/m K), EN AW-6082: 170-220 (W/m K)). [6] The size of the aluminium plates was 500 x 120 mm so that a weld seam length of 430mm was generated which could be analysed. The material thickness depended on the type of impact, for lap joints, a material thickness of 1mm, 2mm, and 3mm was examined, for butt joints a thickness of 2mm, 3mm and 5mm was examined.

3.1 Validation of Repeatability of Data

Before weld seam imperfections were examined, tests for the validation of the reproducibility of the thermographic measurements were performed. Here, identical, flawless weld seams were generated for both types of joints and recorded using the thermographic camera. To avoid the challenge posed by the low and not entirely known emissivity during the whole welding process, the intensities were evaluated instead of the temperatures. The depiction of a thermogram of a sound weld seam of a lap joint and a three dimensional image of the intensity are shown in figure 3.
Mean values and the corresponding standard deviations were calculated at various intervals from the recorded data. As shown in figure 4, the averaged intensity values of the process matched the data from the single welding process in figure 3. This was also confirmed by the standard deviation, which was comparatively low when seen in relation to the highest recorded intensity values (see fig. 4, right). For butt joints, the intensity values of the individual weld seams corresponded similarly highly to the mean values and the standard deviation was still low. Thus, reproducibility of the thermographic data could be proven.

3.2 Generation of Imperfection

In friction stir welding, imperfections and defects can occur due to faulty system parameters or local disturbing factors in the weld seam. Significant imperfections are defined by the standard AWS D17.3/D17.3M [7] as well as DIN EN ISO 25239-5 [8]. Especially critical imperfections are those defects which cannot be detected by visual inspection, such as wormholes and lack of penetration (see fig. 5).
A wormhole is a tubular cavity within the weld metal which has its biggest dimensions parallel to the axis of the weld seam. Thus, a wormhole can go along the entire weld seam. A wormhole is caused by insufficient material flow during the welding process.

A lack of penetration (LoP) is the consequence of an inadequate mixture of the workpieces at the root of the weld. It is caused by an insufficient plunge depth of the pin into the material. Thus, the resulting weld is flatter than the set value, the full penetration depth is not achieved.

As wormholes only rarely occur in stable process sequences, local imperfections were inserted into the weld seam which caused wormholes or insufficient material flow. Wormholes were created using two methods. In the first, paper was inserted along the joint of the weld seam which then locally disturbed the mixing of the materials. In the second method, holes of different diameters were drilled into the base material from the bottom which then caused a lack of material during the welding process. When the drilled holes were filled with the base material, the missing material caused small wormholes and lack of fusion in the weld. Incomplete penetration was achieved by shortening the pin of the tool.

4. Detection of Imperfection

As the position of the detector to the tool stayed the same and the testing sample was passed along the IR-camera in a uniform movement during the entire welding process, the algorithm according to Thiemann and Zäh [10] was applied.

The procedure of the evaluation was structured into 4 steps (see fig. 6). In the first step, the cooling friction stir weld was moved along the field of view of the camera. In this case, no additional loading needed to be inserted as the heat left over from the welding process was used. The spatial distance of each camera line relating to the weld tool was a defined point of evaluation after the energy input. The recording of the sequence of images, the chronological sequence of the cooling process, happened in the second step. Here, an inserted defect (see fig. 6, green spot) moved through the single images at a given time. In the third step, a column extraction was performed in which each image to each interval was split into the individual line values in order to string together the measured values of the same line. In the last step, this resulted in the cooling sequence for the entire component. Now, the entire measurement object could be seen in one singular depiction and could be evaluated at a given time $t_1$, $t_2$, … $t_n$. 

![Fig. 5: Depiction of some relevant imperfections in FS-welds, according to Völlner [9]](image-url)
The advantage of continuous in-line testing lies in the generation of an analysable individual picture for the different times $t_1, t_2, \ldots, t_n$ for the entire length of the object, even if this is clearly bigger than the field of view of the IR-camera.

4.1 Detection of Wormholes

Locally caused wormholes were analysed with the aforementioned algorithm. As can be seen in figure 7, even the smallest imperfection in a weld seam length of 5mm could be detected safely. As the parts in which the imperfections were induced had an insufficient mixing of materials, the heat dissipations to the surface of the seam changed. This could be detected using thermography. The proof of the smallest imperfections with a cross section can also be seen in figure 7.

4.2 Detection of Lack of Fusion

In the following, locally caused lacks of fusion were examined. Figure 8 shows the forms of imperfections of different sizes. Even the smallest imperfection, which had a diameter of 1.5mm, could be detected. Lack of fusion occurred where the imperfections were. These, in turn, disturb the heat dissipation for which reason they can be detected at the surface of the weld seam due to the change in the heat dissipation. Figure 8 also shows the cross section of the smallest imperfection.
4.3 Detection of Lack of Penetration

The shortening of the pin lead to lack of penetration along the entire weld seam. No indications of this defect could be seen on a singular thermogram. However, when comparing the thermogram with a thermogram of a reference weld, the difference in the radiation from the surface of both weld seams is clear (see figure 9). As the join area is reduced if a lack of penetration exists, the heat which is generated during the process dissipates slower. Thus, slightly higher intensity values could be measured with thermography along the weld seam. A cross section of the flawed seam is also shown in figure 9.

5. Results

Imperfections and defects of the weld could be detected directly during the welding process with the help of passive thermography. Critical defects include wormholes could be detected online during the welding process. This also revealed that the smallest detectable dimensions of wormholes was the same as the distance of the wormhole to the weld seam surface. Insufficient plunge depth could be safely detected, if the depth of the pin was reduced by more than 20% in relation to the set depth of the pin. Contaminations of the weld seam with grease and oil could also be identified clearly. Lack of fusion changed the heat dissipation just as grease and oil did and could therefore also be detected. In addition, the failure of the tool as caused by the breaking of the pin could also be identified directly during the process. Furthermore, it could be observed that the aluminium alloy with the higher thermal
conductivity showed an increased signal contrast for weld defects. Thus, there is a higher probability to detect imperfections and defects. However, flash and surface imperfections make the thermographic evaluation difficult.

6. Conclusion

In this paper, it could be shown that passive thermography can be successfully applied for online detection of imperfections during the friction stir welding process. The presented thermographic data shows a high reproducibility. To reduce disturbances in the online thermographic measurements, environmental and procedural disturbance variables need to be shielded off, especially the tool. Furthermore, surface characteristics can falsify the thermographic measurements as they cause higher heat radiation and then prevent the detection of underlying imperfections. With the method presented here, lack of fusion, lack of penetration, contamination during the welding process and failure of the tool can be detected under the described conditions during the welding process.

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