Investigation on the suitability of laser-excited thermography to detect cavities in metallic components

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Abstract
Active thermography has become a widely used technique in non-destructive material testing and numerous excitation sources are applied. One field of application is the testing of joints. Especially the detection of defects in welds is a challenging tasks as two-dimensional defects like cracks can occur as well as volumetric inner defects as cavities.
Recently, the suitability of lasers as a contactless excitation source has been investigated and it was shown, that cracks can be detected. As the specimens are locally heated, a heat flow is initiated. Those heat flows can be used to detect crack-like defects that are perpendicular to the surface. However, the suitability of the laser-excited thermography to detect inner defects like voids and the influence of geometric as well as excitation parameters on the test result has not been fully investigated. Therefore, this study focus on the detection of inner defects in metallic components.
In a first step, thermographic measurements with varying excitation parameters were performed. The obtained results were than used as a basis for the numerical simulation of the testing process. A parametric FE-model has been implemented and the influence of excitation as well geometric parameters on the testing results were determined. Different approaches to evaluate the resulting surface temperatures were considered as well. The simulation results were than compared to the experimental data that was obtained by testing idealized specimens with cavities. Based on these results, the most relevant parameters are determined and limiting factors resulting from the experimental setup are discussed.

Keywords: Laser, Thermography, FE-Simulation, aluminum testing

1. Introduction

The non-destructive testing of welds is highly standardized. Beside the definition of welding defects that are defined in ISO 6520-1 for fusion welds and in 6520-2 for press welds, the corresponding quality levels are defined in ISO 5817 for steel, titanium and nickel and their alloys and in ISO 10042 for aluminum and its alloys. Some of the most common imperfections are cavities and their allowed size depends on the required quality level as well as the thickness of the weld. In order to assure the quality of these welds, the testing standard ISO 17635 defines non-destructive testing methods and their suitability for the evaluation of the weld. However, active thermographic testing methods are not considered within these standard although numerous investigations concerning the applicability of thermographic testing methods for welded joints have been investigated within recent years and some studies report the successful application of active thermographic methods for the detection of inner volumetric defects.
Several studies have been conducted to determine the detection boundaries of laser excited thermography. Most studies focus on the detection of cracks. Experimental tests [1, 2] as well as simulations [3, 4] were performed and it could be shown, that cracks within the low micrometer range can be detected. In order to detect void inner defects, exemplary results are shown in [5] for flaws in laser powder deposition components and in [6] for carbon fiber reinforced plastics.
In order to qualify laser based thermographic methods for the non-destructive testing of welds, a critical evaluation of the potential of these method to detect inner volumetric defects such as voids and their suitability to fulfil the existing standards for the quality levels in welds is required. Therefore, this investigation propose a numeric model to evaluate the influence of excitation parameters as well as some geometric properties on the resulting surface temperature

and evaluates the suitability of laser excited thermography for the testing of butt-welds according to the existing testing standards.

2. Methods and Materials

In order to determine the suitability of laser excited thermography for weld inspection, a simulation based approach was chosen to eliminate the influence of excitation and recording equipment. The outcome of thermographic measurements with laser excitation depend on the utilized excitation source and the excitation parameters, the thermal and geometrical properties of tested specimens as well as the applied IR-camera. As it was intended to make a general statement on the suitability of the testing method, in a first step the functionality of the measurement principle was demonstrated. In order to be able to define the influence of several parameters, a simulation based approach was chosen. Experimental investigations on the influence of excitation parameters on the heating behavior were performed as a basis for the simulations. The accuracy of the proposed simulation model was shown and finally the influences of the parameters were computed using finite element method. The experimental setup and the simulation model are described below.

2.1 Experimental setup

A sketch of the experimental setup used in this investigation is and is displayed in Figure 1. The test bench consist of a laser based excitation, the IR-camera as a recording device and an even specimen placed on a scissor lift as well as control units for and a device for data processing.

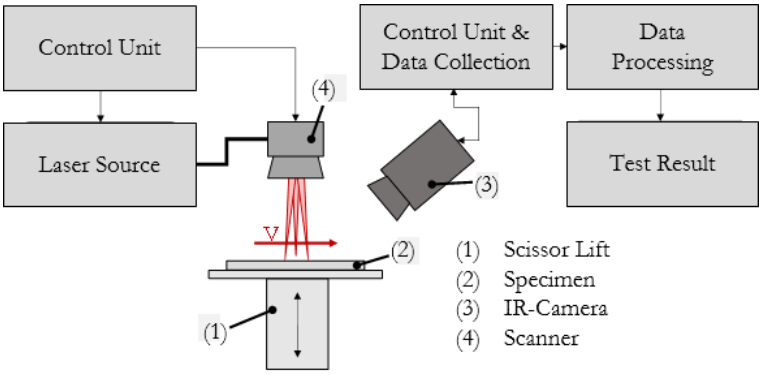


Figure 1: Sketch of the experimental setup used within the experiments

Within this study, a redEnergy G4 fiber laser by SPI Lasers UK Ltd. emitting radiation at a wavelength of 1062 nm with an average output power of 70 W was utilized in continuous mode. The laser source generates the monochromatic light and is connected to a laser scanner via glass fiber. The scanner is positioned perpendicular to the surface of the specimen to be heated. The scanner attached to the laser was an Axialscan-20/-30 by Raylase AG allowing the guidance of the laser beam across the surface of the specimen. The excitation parameters were defined using the control software weldMARK3 by Raylase AG. Within this study, the average output power as well as the scanning speed were varied. While the average output power was set in between 14 W and 70 W, the scanning varied between 10 mm/s and 100 mm/s. When the test is started, the laser beam travels over the surface of the specimen with a predefined average output power and scanning speed along a given path. Within the experiments, the path was chosen to be a straight line with a length of 50 mm.

The specimen consisted of the aluminium alloy EN AW 6082-T6. It hat a quadratic shape with a side length of 50 mm to avoid heat accumulation on the edges and a thickness of 8 mm. This was chosen, as the thinnest category of metal sheets within ISO 17635 is defined up to this

thickness. The surface of the specimen were blackened to suppress reflections and to allow an accurate temperature measurement. The specimen was placed on a scissor lift that allows the variation of the distance between the surface of the specimen and the scanner. Therefore, a variation of the spot size can be achieved. The deflection from the focal level of the laser beam was varied between ±25 mm.
An IR-camera records the heating process. The IR-camera was a VarioCAM® HD produced by Infratec GmbH. The framerate within the measurements was set to 240 fps. The associated image size was 640 × 120 px and one pixel represents a sixe of approximately 100 x 100 µm. The results of the measurements were proceeded using the software Irbis 3.1 bx Infratec GmbH, Germany.

2.2 Finite Element Simulation

The numerical simulations were performed using the commercially available software Simufact Welding 8.0 by simufact engineering GmbH. This software was developed for the simulation of welding processes and offers implemented heat sources that can be tailored to the application. Within this investigation, a circular surface heat source with varying diameter was applied. The material used in the simulations was EN AW 6082 and the properties were assigned to the model from the databank included in Simufact Welding 8.0.
Two different models were considered within the simulations. The models were prepared using the software Abaqus CAE 2018. On one hand, an even plate with dimension 50 x 50 x 8 mm was used to demonstrate the accuracy of the simulation compared to the experiments. The size of the models was chosen based on pre-tests that showed no heat accumulation appeared on the edges with this size of specimen. On the other hand, models with an artificial cuboidal cavity with varying dimensions were prepared. The size of the cavities was chosen in conformity with the requirements of the testing standards. Permitted cavities with sizes lower than the required diameters were as well considered as larger, inadmissible cavities. The sizes differed between 0.1 mm and 4.307 mm. The distance of the cavities was also varied between 0.1 mm and 4 mm. The cuboidal shape of the cavities was chosen as a constant heat introduction required a uniform distribution of surface nodes to suppress excitation caused irregularities from superimposing with the cavity caused temperature changes. Furthermore, the cuboidal shape allowed a consideration of the influence of the projected surface compared to the cavity volume. The mesh size within the excitation area was chosen to 50 µm and increased continuously from the surface.

3. Experimental Results

Within this chapter, first a measurement of a specimen with artificial cavities is show. Then, exemplary results of the experimental tests to characterize the laser heating process are shown. Therefore, the maximum temperature of each pixel was determined and the temperature increase compared to the initial temperature was calculated. This was done to eliminate variations of the initial temperatures within the experimental measurements. To display the differences in the maximum temperature increases, measurement lines were placed across the specimen perpendicular to the scanning line. In order to evaluate the accuracy of the simulations, three measurement lines were placed in a steady distance from each other within the experiments and a mean value was calculated out of three measurements.

3.1 Detection of artificial voids

In Figure 2, an example of a thermographic measurement and a µ-CT measurement are shown. The depth of the artificial voids was 1 mm. The path of the laser is illustrated by the red line in the µ-CT picture. The results indicate, that the larger voids with a diameter of 8 mm and 4 mm are detectable, while the smaller void with a diameter 2 mm cannot be detected. This is caused

by the smaller size and the larger distance of the scanning line to the void. However, the measuring principle can be demonstrated.

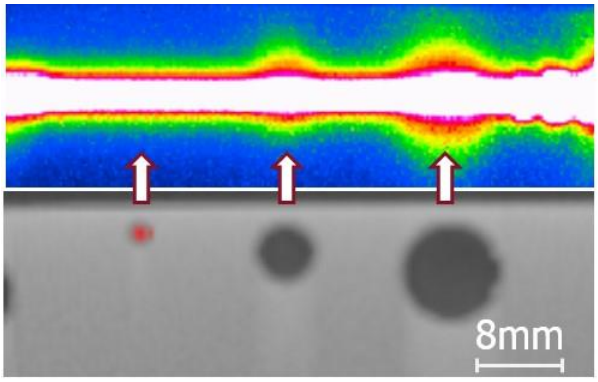
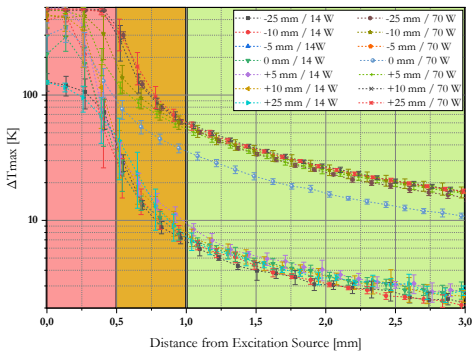


Figure 2: Comparison of thermographic measurement (scanning speed 10 mm/s spot size 1 mm and average output power 21 W) and µ-CT-measurement

3.2 Influence of Excitation Parameters on Heating Properties

As described, in a first step the influence of different excitation parameters on the heating of the specimens was determined. Exemplary results of these experiments are given in Figure 3. Figure 3a.) displays the influence of the average output power and the distance from the focal level (and therefore the spot diameter) on the maximum temperature increase ΔT_{max} while Figure 3b.) shows the influence of the scanning speed. While the influence of the scanning speed and the average output power can be measured over the whole measuring section, the influence of the varying spot diameter is only significant within the region of the heat introduction.

a.)



b.)

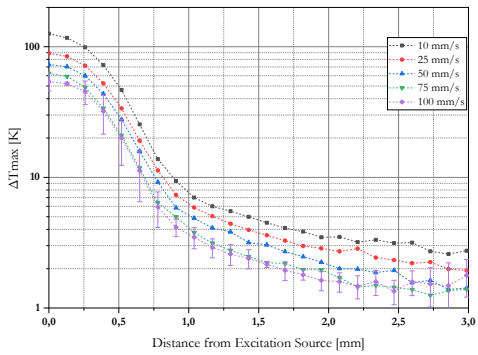


Figure 3: Influence of excitation parameters on maximum temperature increase: a.) Influence of distance to focal level and average output power (scanning speed: 10 mm/s) and b.) influence of scanning speed (focal level: 0 mm; average output power; 14 W)

It can be derived from the results, that an increase in the applied average output power results in a significant increase in energy input and therefore, the maximum temperature increase is obvious. In addition, an influence of the focal level can be observed within the heated area (red) as well as in a small zone next to it (orange). Due to the change in spot size resulting from the different focal levels, the heat introduction changes as the power per area increases. The closer the distance to the focal level is, the higher are the resulting temperatures. However, within the green area, which starts, independent from the applied power, in a distance of approximately 1 mm to the middle of the laser source, no influence of the focal level (and the spot diameter) can be observed. In addition, a decrease in temperature can be observed for one of the test series with an average output power of 70 W within the focal level can be observed. This is caused

by ablation of the black paint and damages on the surface of the aluminum specimen as the energy input is too concentrated.
In comparison to the influence of the laser power, the influence of the scanning speed is rather small. However, an increased scanning speed results in a decrease in energy input and therefore lower temperature increases. This can be explained by the lower changes in energy per unit length.

4. Simulation Results

In a first step, the accuracy of the simulation model is demonstrated. Corresponding to the experimental test, simulation were computed and the results were compared to the experimental findings. Then, a short overview of different approaches for the processing of the date is given based on a exemplary simulation result. In a next step, the influence of different cavities is shown. On one hand, the size of the cavities was varied and on the other, the shape was modified. Finally, the influence of excitation parameters is shown.

4.1 Accuracy of the Simulation Models

As the average output power was identified as the main influence on the resulting maximum temperature differences of the specimen, a variation of this parameter was used to demonstrate the accuracy of the simulation model. In Figure 4, simulation and experimental results are compared. The focal plane in the experiments was kept constant at +25 mm which resulted in a spot diameter of approximately 1 mm. The experiments were conducted with an constant scanning speed of 10 mm/s. The simulation was performed using exactly the same excitation parameters and as can be seen in the diagram, the maximum temperature increase of the simulations and the experiments correlate sufficiently. However, within the area of the heat introduction, the experimentally measured temperatures exceed those of the simulations, but the overall energy introduction seems to be the same. The differences may be explained by a vaporization of the paint used to blacken the specimen that overlay the measurements without leaving significant marks on the surface. In a distance of 1 mm to the center of the excitation, the temperature increase in simulations and therefore, the simulation is considered accurate to examine the suitability of the laser based thermography to detect cavities in metallic components.

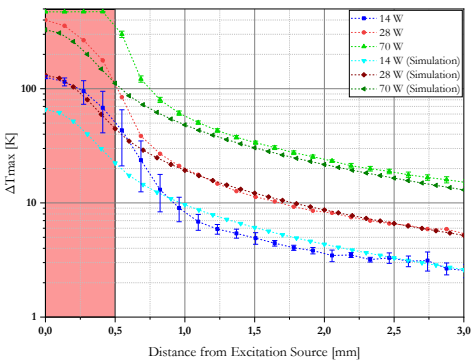


Figure 4: Comparison of experimental and simulation results depending on average output power (focal level: +25 mm; scanning speed: 10 mm/s)

4.2 Simulation Results – Result Processing

Different approaches for the visualization of the cavities have been investigated. Exemplary results are shown in Figure 5. As can be seen from the illustrations, the cavity (edge length of 0.1 mm and 0.1 mm under the surface) can be visualized using adequate data processing.

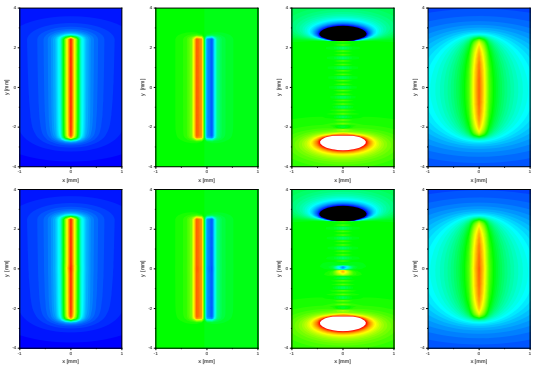


Figure 5: Approaches for cavity visualization – Reference samples (a.) T_{max}, (b.) d T_{max} /dx, (c.) d T_{max}/dy, (d.) mean temperature) and e.)-h.) Sample with cavity (e.) T_{max}, (f.) dT_{max}/dx, (g.) T_{max}/dy, (h.) mean temperature

While mean temperatures (d.) and h.)) for each measurement point suppress resulting temperature changes and therefore a detection of the cavity is impossible, a further processing of the maximum temperatures T_{max} by using derivations shows good potential to increase the signal. Especially results obtained by using the first derivation of the T_{max} in the scanning direction are quite significant (c.) and g.)). It has to be notices, that it is possible to detect the cavities by comparing the maximum temperatures as well, also the picture above indicate otherwise. This approach preferably used in the within this paper.

4.3 Simulation Results – Detection of Cavities Depending on excitation parameters

The proposed simulation model enables the variation of the spot diameter, the scanning speed and the applied power. The effect of these parameters on the detectability of the cavities is shown in Figure 6. The cubic cavity in this simulations had an edge length of 0.2 mm and was placed in a depth of 0.1 mm. The reference simulation were performed using a solid sample. The scanning speed for this simulations was 10 mm/s, the spot size was 400 µm and the power was 7 W.

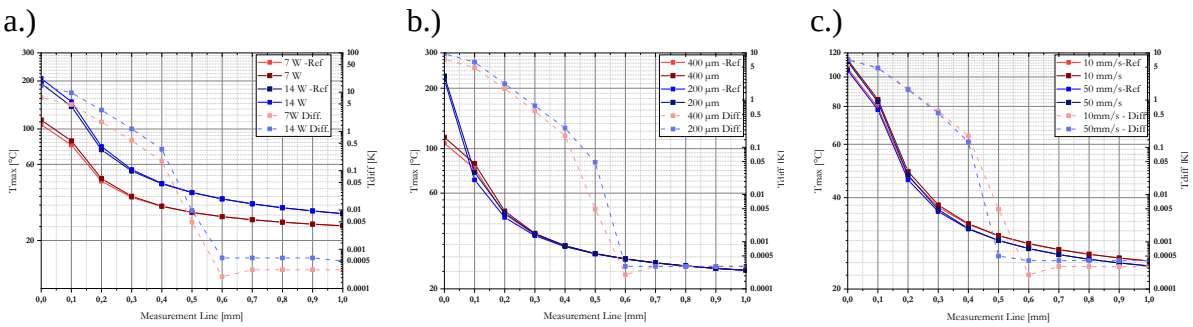


Figure 6: Influences of excitation parameters on detectability of cavities – a.) Influence of laser power; b.) Influence of spot size and c.) Influence of scanning speed

As the result show, the excitation parameters influence the heating of the specimen significantly. An increase of the laser power increase the resulting maximum temperatures and the maximum energy input, as well as a lower scanning speed. In contrast, the spot diameter influence only the maximum temperatures within the heated area as lower a lower spot diameter the intensity of the heating increase. However, it has to be noticed, that the excitation parameters do not affect the detectability of the void significantly. The example shown in the diagrams demonstrate, that the differences in maximum temperatures are significant ($T_{diff} > 0.1$ K) within a distance of 0.4 mm from the center of the excitation.

Therefore, it seems to be suitable to use lower excitation powers and larger spot diameters to improve the experimental results as the ablation can be avoided and the experimental test should be more accurate. In contrast, lower scanning speeds should be preferred to receive accurate date. The scanning speed should be chosen with respect to the framerate of the IR-Camera

4.4 Simulation Results – Influences of Geometric Properties on the Detection of Cavities

In Figure 7, the influence of two different geometric properties are shown In Figure 7a.) the size of a cavity placed in a depth of 0.1 mm is shown while Figure 7b.) displays the effect of the shape of a cavity with a constant volume of 1 mm³. All simulations were performed using a scanning speed of 10 mm/s, a spot diameter of 400 µm and a laser power of 7 W.

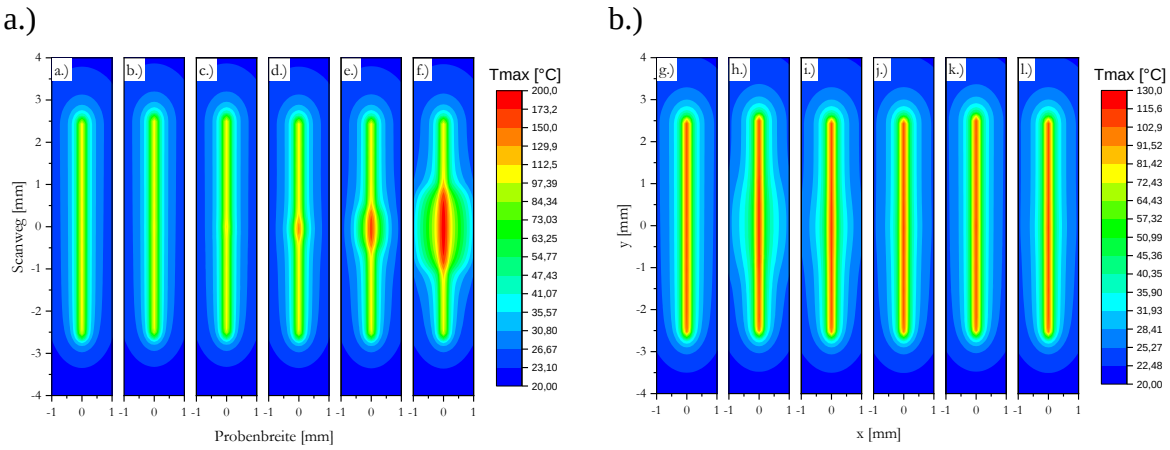


Figure 7: Influence of geometric properties –a.) Influence of size of cavity compared to a reference sample and b.) Influence of shape of cavity compared to a reference sample

As can be seen from the results, the size of the cavity has a mayor influence. While smaller cavities with edge length smaller 0.2 mm ((b.) and (c.)) can hardly be detected, larger cavities result in a local increase in temperature giving a clear indication of the cavity. However, not only the size, but also the shape influence the detectability. As can be seen from Figure 7b.), the projected area of the cavity is more important than the volume. The larger the projected area is, the larger is the probability of detection as the temperature differences increase. A void with a projected area of 10 mm² in a depth of 0.5 mm can be detected (h.), while a cavity with equal volume but smaller projected area of 1mm² cannot be identified (k.).

5. Conclusion

First of all, it can be shown that basic measurement principle is suitable to detect subsurface defects. The cavities shown in the example in chapter 3.1 are quite big and do not fulfil the requirements of the testing standards, but they are suitable to demonstrate the basic approach of the testing concept. The main influences of the excitation source were identified and the resulting effects of parameter variations are displayed. It was found, that the laser power has the largest impact on heating of the specimens. The effects of the scanning speed are much lower and it was found, that the influence of the spot diameter is negligible.

A simulation model was proposed and the accuracy was demonstrated by comparing simulation and experimental results. There a difference in the area of heat introduction that are suspected to be caused by an interaction of the paint used to improve the measurement results within the experiments and the laser radiation. In addition, it was found, that the basic properties of the heating process are well covered. Finally it was shown, that geometric have the largest effect on the detectability of the artificial defects while excitation parameters determine the heating of the specimen, but do not influence the detectability. Therefore, these parameters should be

chosen to minimize the possibility of ablation. It was found, that the shape of the defect is more important than the actual size of the cavities.
As a basic result it can be stated, that the measurement principle is suitable to detect small defects. The influence of the excitation source might be neglected and therefore further studies will focus on the influence of the recording device on the test results of experimental test to validate the simulation results.

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