Laser excited Thermography – Simulation based Determination of detection thresholds in aluminum welds depending on geometrical and excitation Properties

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Abstract

Active thermography has become a widely used technique in nondestructive material testing. However, the testing results strongly depend on the excitation technique. Especially optical excitation sources are frequently used as they allow contactless measurements and have advantages concerning the access. Halogen lamps as well as flash lamps are the preferred excitation sources as they are cost efficient and easy to integrate into the testing system. However, those excitation sources heat the whole surface of the test object resulting in a very insensitive excitation and therefore they are limited in detecting crack-like defects. To overcome this disadvantage, laser excited thermography has become an alternative to the traditional optical heat sources.

The lasers used to heat the specimens partially create heat flows on the surface. Those heat flows can be used to detect crack-like defects that are perpendicular to the surface. The suitability of those methods has been shown in various studies, but the limitations have not been explored yet. Therefore this study aims to determine the limitations of laser excited thermography to detect crack like defects in aluminum based on a FEM-approach. Therefore a parametric FE-model of a laser scanning process has been developed that covers the characteristics of an experimental heating process.

Consequently, this model is used to simulate the heating process and to determine theoretical process limitations for crack detection depending on geometrical as well as heating parameters. Based on the simulation results, the theoretical detection thresholds are defined and an outlook on the consequences for the laser excited thermography is given.

1. Introduction

Laser excited thermography has gained importance in recent years as it neglects the disadvantages caused by other excitation methods used for active thermography. The most important advantage of lasers compared to other optical excitation sources like flash lamps or halogen lamps is the local and therefore sensitive energy input. This provides the opportunity to detect cracks perpendicular to the surface as the crack forms a heat barrier and therefore disturbs the heat flow. Compared to other excitation techniques that enable the detection of these defects, the testing method is contactless and quite flexible. However, the test result depends on several different parameters that can be divided into the six fields given in Figure 1 which are strongly related. As an example, the power introduced into the test object not only depends on the applied laser power, but also on other parameters like scanning speed or the material of the test object resp. its reflectivity for the laser beam. Therefore, the aim of this study is to introduce a simulation based

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approach that offers the opportunity to determine the detection thresholds depending on geometrical and excitation properties.

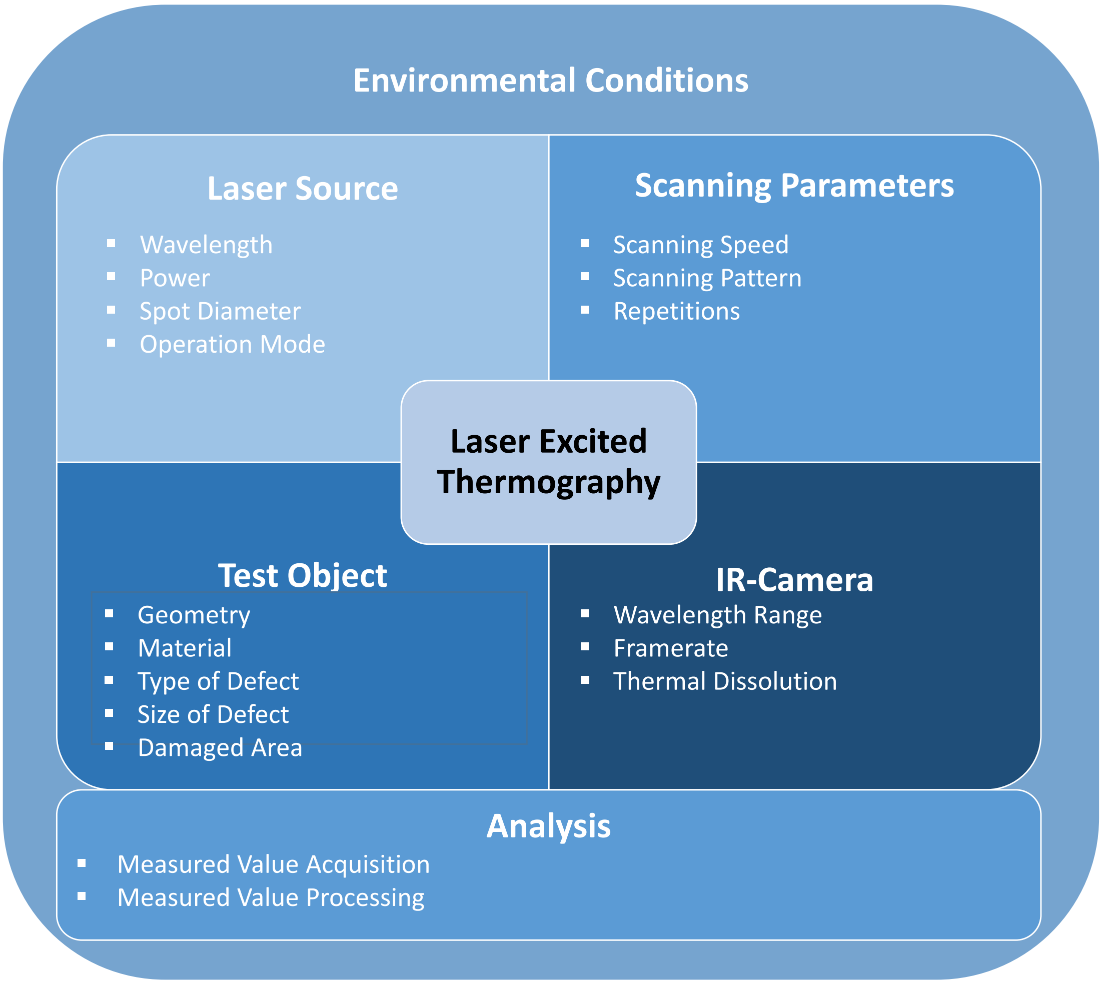


Figure 1: Overview of parameters that influence the results of active thermography using a scanning laser process as excitation source

Several studies, have been conducted to determine the detection boundaries of laser excited thermography. Experimental tests were performed (1, 2, and 3) and it could be shown, that cracks within the low micrometre range can be detected. In (4, 5), 3D finite difference modelling results are presented for a scanning laser process. It was derived, that cracks with a diameter of few micrometres can be detected. In (6) a 2D FEM model was used to simulate heat diffusion phenomena and the effect of the presence of a known surface crack on a sample with a width of 12 µm. Based on this studies it can be stated, that laser excited thermography is a suitable method for crack detection.

However, the mentioned studies use different laser sources with different laser powers and scanning speeds. As a result, the detection boundaries depending on the process parameters as well as the geometrical properties of the crack have not been defined yet. Furthermore, the mentioned studies focus on steels and other materials while aluminium has not been considered yet. Due to lightweight construction, aluminium has gained importance in recent years. Especially in automotive as well as aerospace industry, aluminium alloys are commonly used and cracks might appear in welds. As the thermal properties of aluminium differ significantly from those of other steel, the detection of defects in aluminium is a challenging task. Therefore, this study focus on the possibilities to detect cracks in aluminium and aims to define thresholds depending on geometrical and excitation properties.

2. Basic Experiments

Experimental test were performed to determine the basic properties of the laser based heating process. The test were performed on a quadratic aluminium plate with dimension 100x100x8 mm. The plate was made of the aluminium Alloy EN AW 6082.

To determine the basic heating characteristics, a redEnergy G4 pulsed fiber laser by SPI Lasers UK Ltd., United Kingdom, emitting radiation at a wavelength of 1062 nm with an average output power of 70 W was used. The laser was operated in continuous mode to avoid ablation during the heating process. A galvano-scanner was attached to the laser (Axialscan 20/30 by Raylase AG, Germany) to vary the scanning speed and to enable a heating along a predefined line. Three different scanning speeds (10 mm/s, 60 mm/s and 100 mm/s) and three different laser powers (70 W, 42W and 21W), were considered within this study. The length of the scanning line was held constant at 50 mm. In addition, the distance between the scanner and the specimen was varied. The test series consisted of tests that were made in the focal plane of the laser as well as tests that were made out of focus. The tests were conducted using three different spot diameters of appr. 150 µm, 320 µm and 450 µm. All tests were recorded using an IR-Camera (Flir SC655 by Flir Systems Inc., USA) with a framerate of 200 fps.

3. Experimental Results

From the tests it was found, that the main influence on the heating properties are the scanning speed and the laser power, while the spot diameter had a negligible effect. Exemplary results are shown in Figure 2. The results show the maximum temperatures increases taken from the middle of the scanning line during the heating process. However, the temperatures measured within the area of the laser spot cannot be measured accurately as the surface conditions change as the black paint is ablated. Furthermore, the maximum temperatures occur when the laser travels through the measurement line which prevents a proper measurement.

a.) b.)

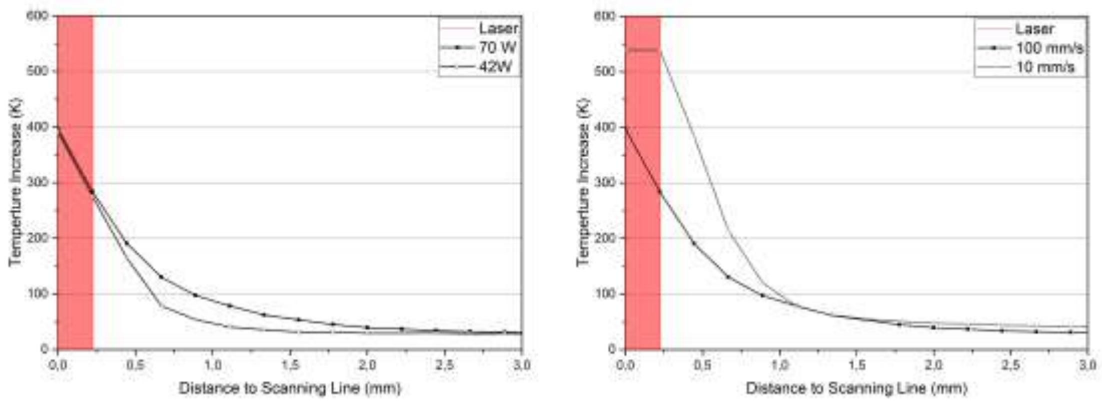


Figure 2: Influence of process parameters on resulting temperature increase on a measurement line in on one side of the laser source: a.) Laser power and b.) Scanning speed

As can been seen from the graphs, an increase in the laser power results in an increase in energy input. Due to the limitations in the measurement within the area of the laser, the differences close to the laser source are not that significant. In comparison, the influence of the scanning speed differs more significantly. The profiles were then used for the evaluation of the heat source used in the simulations. In addition, it was found that larger temperature increases could only be detected within a range of up to 1 mm around the laser beam.

4. Finite Element Simulation

For the finite element simulations, the commercially available software Simufact Welding 7.0 by simufact engineering Gmbh, Germany. The models were prepared and meshed using Hypermesh 16.0 by Altair Engineering Inc., USA. The material used in the simulations was EN AW 6082 and the properties were assigned to the from the databank included in Simufact Welding 7.0. The dimension of the specimens were set to 100x100x8 mm for all simulations to match the experiments. Two different types of simulations were conducted.

First, simulations on a solid plate were conducted. For this simulations, cubic elements with an edge length of 1 mm were used. During the process, a mesh refinement was applied in the area of the heat source to get more appropriate results. The results were compared to the results of the experiments to show the suitability of the defined heat source in the simulations.

Following this, simulations on models with idealized cracks were performed. The width of the cracks varied between 1 µm and 10 µm. The depth of the crack was 2 mm and the length was 10 mm. The meshing was chosen according to the width of the crack. However, the element size varied over the model to reduce the computing time. Therefore, the fine meshing was limited to the area of the crack. In the area of the heat source, mesh refinement was carried out during the calculation.

The heat source used within this study was a predefined surface heat source. The circular heat source can be varied in diameter and applied energy. It distributes the energy that should be applied within the defined diameter on the surface. The heat source diameter was set to 320 µm as an intermediate value derived from the experiments. Three different laser powers (21 W, 42 W and 70 W) were used within the simulations.

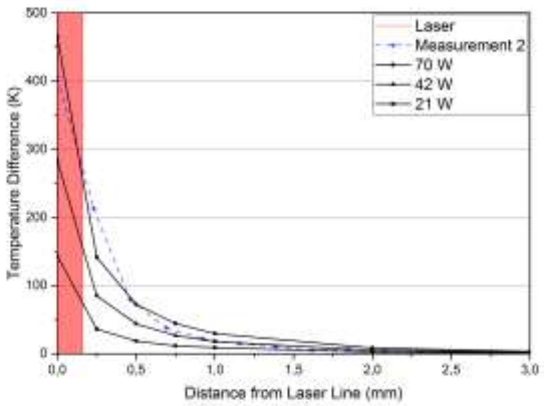
5. Results of Simulations

Subsequently, exemplary results of the simulations are shown. First, a comparison of the experimental results and the simulation is shown. Then exemplary results of the simulations are shown and briefly discussed. As the laser power and the scanning speed were found to be the dominating excitation parameters, the results discussion focus on this parameters.

4.1 Comparison of Experimental and Simulated Results

In Figure 3 the results of three simulations with different laser powers (70 W, 42 and 21 W) are compared to two experimental measurements conducted with a laser power of 70 W and a scanning speed of 100 mm/s. As can be seen, the results of the simulation and the experiments correspondents sufficiently. However, within the area of the laser, significant differences occur.

The measured temperature exceed the simulated temperatures within the area between 0.16 mm and 0.5 mm. The power introduced into the specimen in the experiments has to be lower than 70 W as not the whole laser power applied is converted into heat. Therefore the temperatures derived from the experiments are expected to be lower than the simulated temperatures. An explanation might be an inaccurate measurement that is affected by the scanning laser source as described in chapter 3.



Comparison of Experiments and Simulation

Crack Size:	-
Distance Laser to Crack:	-
Scanning Speed:	100 mm/s
Scanning Length:	50 mm
Laser Power:	42 W

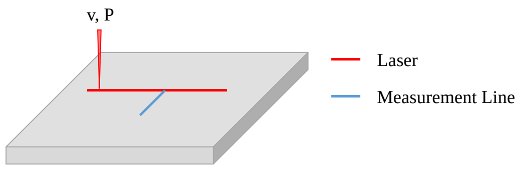


Figure 3: Exemplary comparison of experimental data and simulation results for definition of heat source

The area of the highest temperature increase correspond well and the area that seems to be suited for thermographic measurements is within a distance of 1 mm from the centre of the laser. The reason for this is, that the slop of the graph is high and therefore temperature drops caused by inhomogeneities might be identified well.

4.2 Results of Simulation

As stated before, several parameters influence the heat distribution. Therefore, the approach of a numerical simulation is beneficial. Consequently, within this chapter, the influence of the scanning speed and the laser power on the crack detection is shown. The evaluation is done by comparing the maximum temperature on both sides of the laser. A sketch of the method used to identify the crack is given in Figure 4.

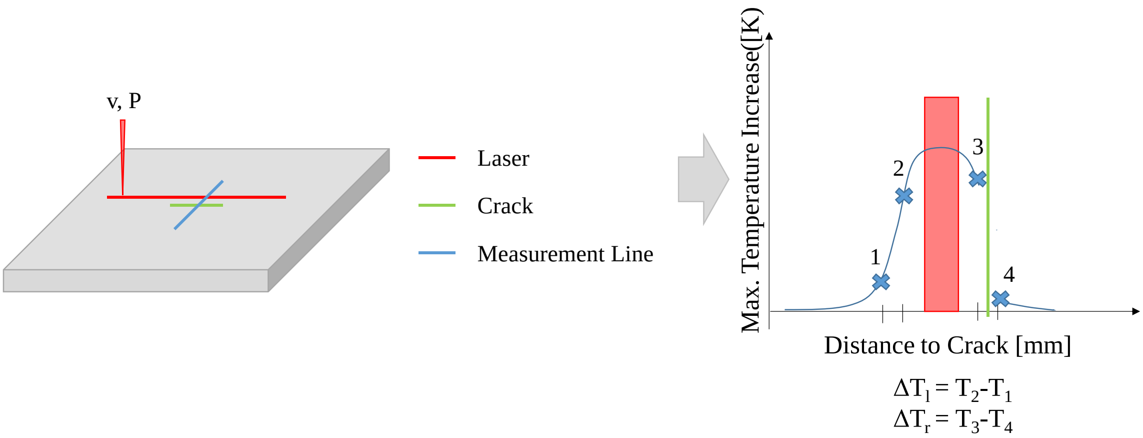


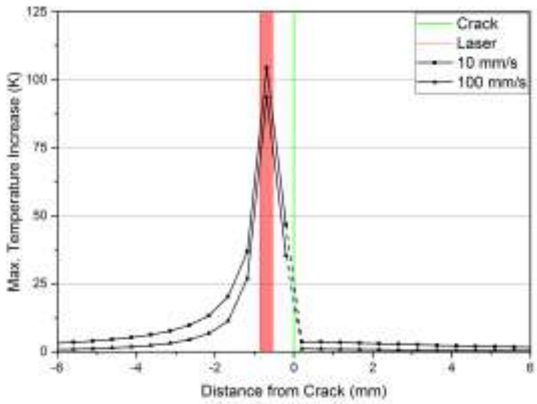
Figure 4: Definition of temperature differences based on reference points on both sides of the laser source

First, the maximum temperatures along a measurement line across the middle of the scanning line and the idealised crack are identified. Then the temperature differences ΔT_r

and ΔT_l between two points on both side of the laser source are determined. Both sides differ due to the presence of the crack on the right side of the laser. The crack is placed right between the reference points. The distance for the reference points to the laser source are 0.9 mm (for 1 and 4) and 0.5 mm. (for 2 and 3).

4.2.1 Influence of Scanning Speed on Crack Detection

In Figure 5 the exemplary results concerning the influence of the scanning speed on the crack detection. As it can be seen from the graph, the idealised crack, although it has a quiet small width, has a significant influence on the simulated heat flux within the specimen and the resulting surface temperatures differ significantly on both sides of the laser.



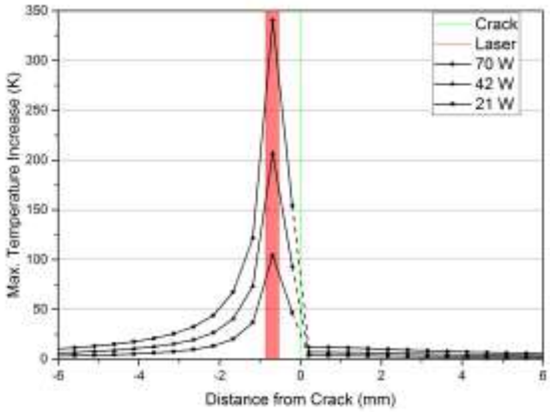
Influence of Scanning Speed	
Crack Size:	10 x 2 x 0.001 mm
Distance Laser to Crack:	0.7 mm
Laser Power:	21 W
Scanning Length :	50 mm
Laser Power:	42 W

Figure 5: Influence of scanning speed on the maximum temperature increase

The differences between ΔT_r and ΔT_l indicate the crack clearly. If a crack is present, the temperature difference ΔT_r is 43.1 K in case of a scanning speed of 10 mm/s and 34.4 K in case of a scanning speed of 100 mm/s. In comparison, the temperature difference at the defect free side of the specimen shows is only a temperature difference ΔT_l = 16.4 K in case of a scanning speed of 10 mm/s and ΔT_l = 15.6 K in case of a scanning speed of 100 mm/s. Therefore, both scanning speeds are suited to detect cracks. The variations in the temperature differences are caused by the different scanning speeds. Using a scanning speed of 10 mm/s the energy per length is increased as well as the overall applied energy increase. This results in higher temperatures. However, this effect is overlapped by a faster compensation of thermal gradients caused by the high thermal diffusivity resulting. Therefore, lower scanning speed shows a slightly higher temperature difference.

4.2.2 Influence of Laser Power on Crack Detection

In Figure 6 the exemplary results concerning the influence of the laser power on the crack detection is shown. The graph shows, that the power has a large impact on the crack detection. As the surface temperatures increase due to higher laser powers, the temperature differences between the reference points increase. While a laser power of 70W results in temperature differences of 142.1 K for ΔT_r and 54.2 K for ΔT_l, a laser power of 42 W gives only temperature differences 85.8 K for ΔT_r and 32.8 K for ΔT_l. A further decrease of the laser power to 21 W results in even lower temperature differences of 43.1 K for ΔT_r and 16.4 K for ΔT_l. However, with all laser powers applied, the crack like defect can be identified clearly.



Influence of Laser Power

Crack Size:	10 x 2 x 0.001 mm
Distance Laser to Crack:	0.7 mm
Scanning Speed:	10 mm/s
Scanning Length:	50 mm
Spot Diameter:	320 µm

Figure 6. Influence of laser power on the maximum temperature increase

5. Conclusions & Outlook

From above mentioned results it could be derived, that the simulation correspond satisfactorily with the experimental results. Especially within the area of beside 1 mm to the laser source, significant temperature differences can be observed and used to detect crack-like defect. Therefore, the crack should be no more than 1 mm away from the laser source. The simulation based approach allows the identification detection threshold and their dependence on the excitation parameters while other parameters like the IR-Camera (which difficulties have briefly been discussed) or the variances in test specimen are faded out. This is the basis for a better process understanding and the development of model of the laser excited thermography. Furthermore, it helps to define excitation parameters for in practice measurements.

The simulated results show that laser excited thermography should be capable to detect small cracks in aluminium which is a challenging task due to the high thermal diffusivity. Even cracks with a width of 1 µm were be detected within the simulations. The results presented were derived with crack length of 10 mm and a depth of 2 mm. However, if these values are reduced, the temperature differences decrease. Further results show that cracks with a length of 2 mm and a depth of 1 mm can also be detected, although the differences in ΔT_r and ΔT_l decrease.

The results presented indicate, that higher laser powers and lower scanning speeds result in higher temperature differences and therefore ease the crack detection. But it has to be considered, that ablation has to be avoided in practice. This limits the increase in power and the decrease in scanning speed. But based on the shown result, it can be stated, that higher scanning speeds and lower powers should be suitable to detect cracks.

Ongoing studies focus on the reduction of scanning speed and laser power and the determination of the optimal excitation parameters. In addition, experiments are conducted to confirm the simulation results. Therefore, specimens with defined defects have been manufactured using electron beam welding and friction stir welding.

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