POD Improvement of Defects in Fibre Reinforced Plastics by Use of Multiply Flash Thermography with Variable Pulse Parameters

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Abstract. In the field of non-destructive testing (NDT), active flash thermography is state of the art. There, the test object is heated with a short intense thermal pulse, e.g. by means of powerful flashbulbs, radiant heaters or lasers and the heat wave propagates into the object. Defects influence the heat wave propagation and thus the temperature distribution on the object surface. Further developments have been focused on the increase of pulse energy of the excitation sources to enhance the penetration depth and the thermal contrast of defects. However, in the case of plastic components the higher amount of heat may damage the object's surface. Therefore multiple flash thermography offers a promising approach for increasing the probability of detection of defects. As a result of a currently ongoing research project between Hensel-Visit and SKZ, for the first time, it is possible to generate six sequential pulses with adjustable pulse duration between 100 µs and 3 ms and a temporal distance starting at 25 ms by using one single device. A systematic study of the mentioned parameters was carried out. The parameters of each pulse of the sequence influence its spectrum and the maximal surface temperature of the sample. Therefore, components consisting of carbon-fibers embedded in an epoxy resin matrix with artificial defects of different sizes and depth positions within the sample were investigated. As a result, the maximum surface temperature of the sample can be considerably reduced by applying consecutive pulses with the same total energy as one high-energy pulse at a constant temperature difference between the damaged and undamaged area. Furthermore the penetration depth of the resulting thermal waves can be increased by influencing the excitation spectrum. Due to the new possibility of adjusting the temporal distance between several pulses and their length by a cut off mechanism, coded signals can be applied prospectively for receiving detailed depth information. In summary, multiple pulse thermography will enhance the probability of detection of defects in the future.

1. State of the art

In active flash thermography, a sample is excited by a short energetic pulse. This results in heat wave propagation which is influenced by the sample's material and internal defects. By using thermography cameras the pulsed excitation itself as well as the cooling process can be monitored. Further developments have been focused on the increase of pulse energy of the excitation sources in order to enhance the total amount of energy input for increasing penetration depth and the presentability of defects. Possibly, the higher amount of heat may damage the object's surface, especially in case of plastics. Multiple flash thermography gives the opportunity to lower the surface temperature by applying more than one pulse. Therefore, it offers a promising approach. Some research has already been made on this topic, but most of these investigations focused on the use of two flashes to influence the spectral composition of the resulting excitation [1], to increase the thermal coupling [2] or to shape the thermal wave field [3]. The correlation between maximum surface temperature and thermal contrast of the flaw was not considered yet, even though the surface temperature is a very limiting factor of this NDT method for investigations of plastics. There are several methods to evaluate the measured temporal temperature profiles. In time domain the easiest way of evaluation is to look for the image with the highest temperature difference between an area with and without a defect [4]. Further methods which result in a better signal-to-noise ratio are thermographic signal reconstruction [5], differential absolute contrast [6] and principal component analysis [7]. With respect to frequency domain, Wavelet transformation [8] and Fourier transformation [9] are particularly relevant. Depending on the evaluation method, the result is a thermographic image with a pixel-wise plotted temperature, amplitude or phase value, respectively.

2. Processing Setup

A carbon-fiber reinforced plastic component (carbon fibers embedded in an epoxy resin matrix) with cylindrical milling grooves of different sizes and depths was investigated. The diameters of the holes are 4.5 mm, 6.0 mm, 7.5 mm, 9.0 mm and 10.5 mm with distances to the sample surface of 0.9 mm, 1.4 mm, 1.9 mm, 2.4 mm, 2.9 mm, 3.4 mm and 3.9 mm. A photon detector infrared camera FLIR X6540sc with a recording frequency of 4012 Hz, thankfully provided by AT - Automation Technology GmbH, was used to measure the maximum surface temperature during the excitation. The acquisition of thermograms, used for the defect detection, was realized with a microbolometer infrared camera Jenoptik VarioCam hr with the recording frequency of 50 Hz. For the flash excitation a pulse generator from Hensel-Visit GmbH & Co. KG in combination with the flash lamp VH3-6000 linear head in a distance of approx. 14 cm from the sample's surface was applied. This pulse generator is the result of a currently ongoing research project between Hensel-Visit and SKZ and is not commercially available yet. For the first time, it is possible to generate six sequential pulses with a total pulse energy of 10 kJ, an adjustable pulse duration between 100 µs and 3 ms, as well as a temporal distance starting at 25 ms.

3. Experiment

3.1 Single Flash Thermography

At the beginning the influence of a single pulse with different duration and voltage on the presentability of the defects in time domain was investigated. First, the component was excited by a pulse with constant pulse duration of 3000 µs and varying pulse voltages of 900 V to 400 V, respectively. After that, a constant pulse voltage of 900 V with varying pulse durations of 3000 µs, 2420 µs, 1840 µs, 1260 µs, 680 µs and 100 µs was applied.
Figure 1 shows exemplarily the temperature-time-profile (pulse duration: 3000 µs, voltage: 700 V) including heating and cooling process of a pixel with (black) and without (red) a flaw of 10.5 mm diameter and 0.4 mm beneath the surface. At 6 s in time domain the thermogram exhibit the maximum thermal contrast of the defect. In all subsequently shown results, not only the temperature difference for one pixel in a defected and defect-free part of the sample was considered, but the median values of an area of each 9 pixels.

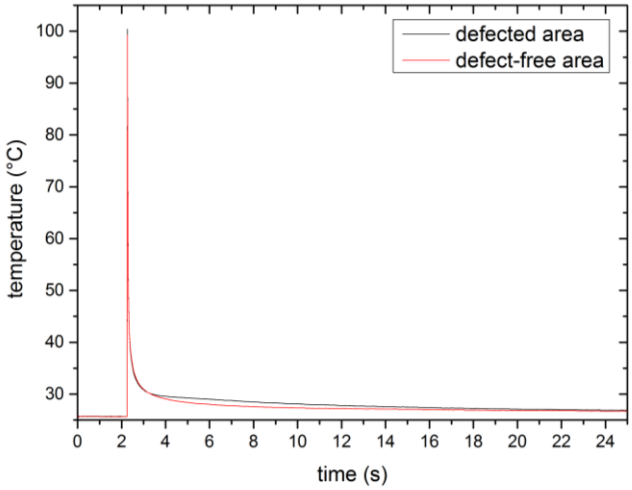

Fig. 1. Time-dependent temperature behavior of a defected (black) and defect-free area (red). The maximum temperature difference between both areas is visible in the thermogram at about 6 s.

The dependence of this temperature difference on variation of pulse voltage and duration is depicted in Figure 2. The higher both parameters are, the higher is the temperature difference, which is a measure for the presentability of the defect. The increase in the temperature difference correlates with the increase in the excitation energy due to the varying pulse voltage and duration.

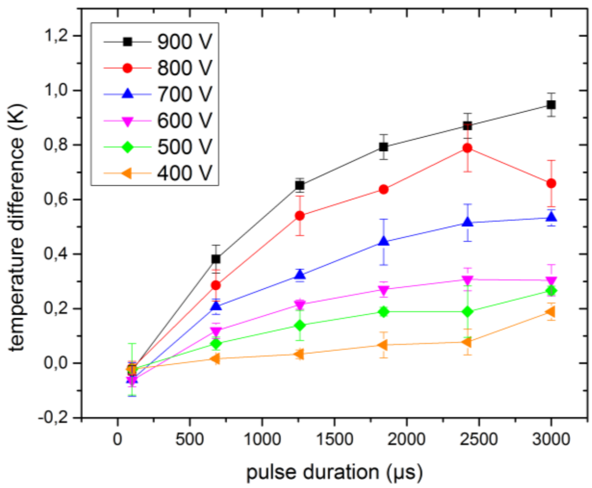

Fig. 2. Temperature difference of a defected and defect-free area in dependence of pulse voltage and duration. An increase in both parameters leads to a higher temperature difference as well as a higher maximum surface temperature during the flash (not shown in this figure).

From the data sets phase images at 23 mHz in frequency domain were calculated for further investigations of the influence of pulse duration and voltage. The frequency corresponds to a thermal penetration depth of 3 mm. Figure 3 exemplarily shows the influence of the pulse voltage in case of a constant pulse duration of 3000 µs. The defects with a diameter of 10.5 mm were considered. The phase images were calculated by Fourier transformation of 2802 thermograms recorded with a frequency of 50 Hz after excitation. It can be seen that the maximum phase difference as well as the noise level strongly depends on the excitation energy and thus the pulse voltage. The absolute values of the phase are arbitrary due to insufficient synchronization between excitation source and data acquisition. The results of the variation of pulse duration for a fixed voltage are equivalent.

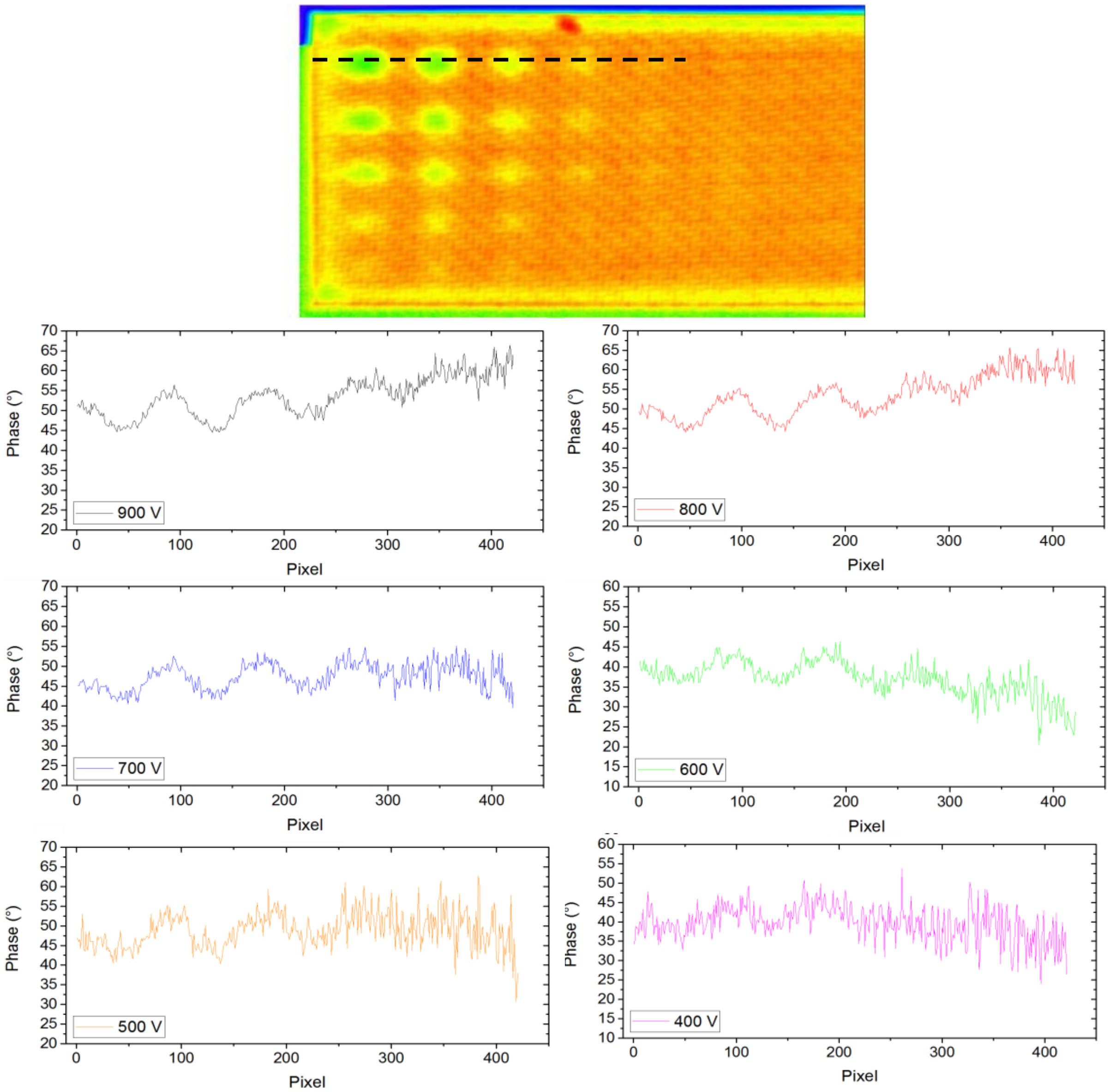

Fig. 3. Exemplary phase image for a single pulse excitation with 900 V and 3000 µs (top). The graphs below show the phase values according to the black line in the phase image. A greater distance from defect to the sample surface (from left to right) and a lower pulse voltage (s. legend) results in a higher noise level.

3.1 Multiple Flash Thermography

Contrary to the conventional single pulse method, the component was additionally excited with a pulse sequence. In the first step the influence of the pulse number and the temporal distance between the pulses was investigated. The device was excited with one to six pulses, applying a temporal distance of 25 ms, 70 ms, 150 ms, 250 ms, 500 ms and 1000 ms. Figure 4 shows exemplarily a temperature-time-profile for a six pulse excitation with a temporal distance of 850 ms. Again, the maximum temperature difference between the defect (diameter of 10.5 mm and distance to the surface of 0.4 mm) and the defect-free area was evaluated in time domain. In general, an increasing number of pulses results in an increasing averaged temperature difference between a defected and a defect-free area. Like before, a correlation with the total energy input can be found. Furthermore, it can be seen that the influence of the temporal distance between the pulses increases with an increasing total pulse number (see Figure 5).

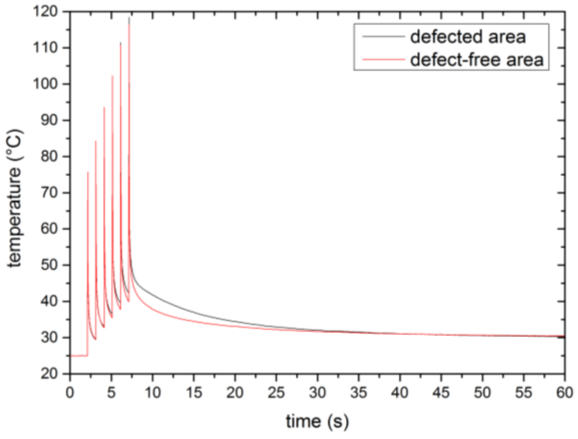

Fig. 4. Time-dependent temperature behavior of a defected (black) and defect-free area (red) excited with six pulses in a temporal distance of 850 ms. The maximum temperature difference is at about 11 s.

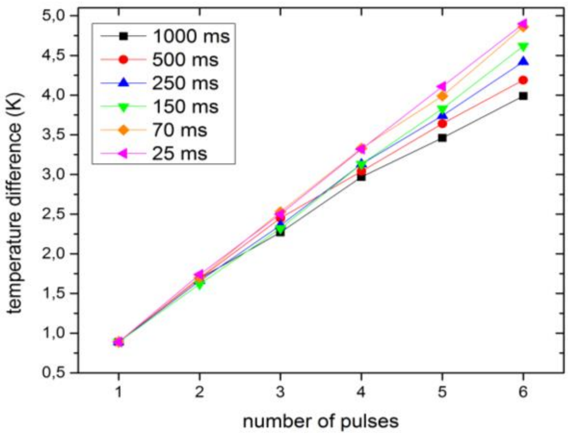

Fig. 5. Temperature difference of areas with and without a defect as a function of the pulse number and for different temporal distances. The higher the number of pulses and lower the distance between the pulses, the higher is the temperature difference and also the maximum surface temperature during the flash (not shown in this figure).

All results show, that the presentability of the defects is improved by a higher amount of excitation energy. However, a greater amount of energy is accompanied by a higher thermal load of the sample. The short-term maximum surface temperature is particularly important for plastics, since their melting or decomposition temperatures are in the order of only a few hundred degree Celsius. Regarding metals, a coating of the sample is often used to increase the degree of emission of the surface and its homogenity. This coating also generally consists of polymeric structures with similar temperature stabilities. In addition, the excitation energy limits the service life time of the flash tube. Especially for industrial application the service life and the corresponding costs are very important factors for the acceptance of NDT methods. The following investigations show, that it is possible to significantly reduce the thermal load of the excitation source and the component by applying a sequence of pulses while the temperature difference remains the same. Therefore, the required total energy with increasing number of pulses has to be increased only slightly. Moreover, it can be seen that the maximum surface temperature correlates asymptotically with the total pulse energy. A greater temporal distance between the pulses has to be compensated with a higher total energy in order to obtain the same presentability of the defect (see Fig. 6 and 7). The maximum surface temperature of the sample, measured by the infrared camera, can be significantly reduced by a multiple pulse excitation approach.

The absolute temperatures are not representative as the camera also detects the radiation of the plasma of the flash tube due to the camera-sensitive wavelength and the emissivity of the surface. However, experience has shown that during the pulse, the maximum surface temperature get up to several hundred degrees Celsius for a very short time. For instance with the multiple flash approach, the total required energy in case of use of six pulses and a temporal distance of 25 ms has to be increased by only 5 %, while the maximum detected surface temperature decreased by approx. 30 %.

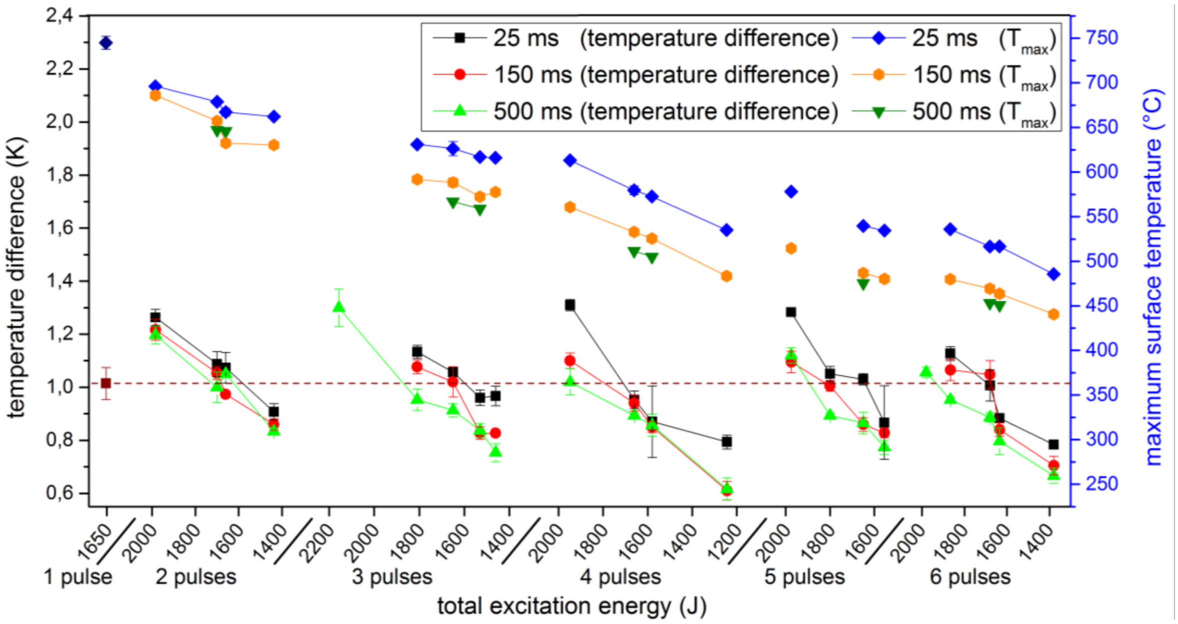

Fig. 6. Temperature difference (left) and the corresponding maximum surface temperature of the sample during excitation (right) in dependence of the number of pulses, their total pulse energy for excitation and their temporal distances of 25 ms, 150 ms and 500 ms.

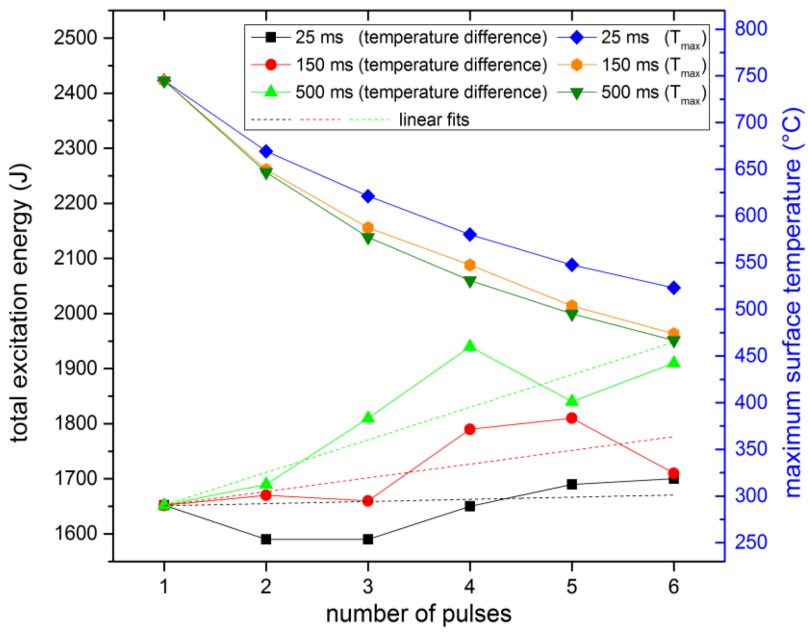

Fig. 7. Total pulse energy (left) for receiving the same temperature difference of the defect and maximum surface temperature (right) in dependence of the number of pulses. It can be seen that the total pulse energy has to be slightly higher while the maximum surface temperature decreases significantly.

4. Conclusion

It was shown that a higher amount of excitation energy caused by a greater pulse duration, voltage or number of pulses results in a better feasibility of defects. However, the maximum surface temperature and hence the thermal loading increase linearly with the excitation energy. Especially plastics and partially required coating systems, frequently needed for metals, may be damaged by this short-term highly energetic flash. Furthermore, the life service time of the flash lamps decreases with increasing excitation energy, resulting in significant running costs. The maximum surface temperature can be considerably reduced by applying consecutive pulses with nearly the same total energy as one high-energy pulse to achieve a same temperature difference between the damaged and undamaged area. In addition, the signal-to-noise ratio and thus the probability of detection of defects can be significantly increased at a constant maximum surface temperature. Due to the new possibility of adjusting the temporal distance between several pulses and their length by a cut off mechanism, coded signals can be applied prospectively for receiving detailed depth information. In summary, multiple pulse thermography will enhance the quality of non-destructive evaluation of components in the future.

5. Acknowledgment

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6. References

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