



Contents lists available at ScienceDirect

## Materials Today: Proceedings

journal homepage: [www.elsevier.com/locate/matpr](http://www.elsevier.com/locate/matpr)

## Luminescence-based early detection of fatigue cracks

Falk Hille<sup>a</sup>, Damian Sowietzki<sup>b</sup>, Ruben Makris<sup>c</sup><sup>a</sup> Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany<sup>b</sup> MR Chemie GmbH, Nordstraße 61-63, 59427 Unna, Germany<sup>c</sup> Beuth Hochschule für Technik Berlin, Luxemburger Str. 10, 13353 Berlin, Germany

## ARTICLE INFO

## Article history:

Received 2 December 2019

Accepted 14 February 2020

Available online xxx

## Keywords:

Fatigue  
Crack  
Damage detection  
Luminescence  
Coating

## ABSTRACT

Classic non-destructive fatigue crack detection methods reveal the state of the fatigue damage evolution at the moment of application, generally not under operational conditions. The here introduced crack luminescence method realizes a clear visibility of the occurred and growing crack in loaded components during operation. Different established experiments show that due to the sensitive coating a crack formation can be detected even in early stage under the premise the crack reached the surface. The coating consists of two layers with different properties and functions. The bottom layer emits light as fluorescence under UV radiation. The top layer covers the fluorescing one and prevents the emitting of light in case of no damage at the surface. In case of surface crack occurrence, the luminescent light is clearly noticeable by visual observations and also by standard camera equipment which makes automated crack detection possible as well. It is expected that crack luminescence can increase structural safety as well as reduce costs and time for inspections and preventive maintenance.

© 2020 Elsevier Ltd. All rights reserved.

Selection and peer-review under responsibility of the scientific committee of the 36th Danubia Adria Symposium on Advances in Experimental Mechanics. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

## 1. Introduction

The material fatigue behavior is important in almost any field of the industry such as mechanical, plant and automotive engineering or construction for aircrafts, ships, railway vehicles, cranes, bridges and offshore constructions like oil platforms or wind turbines [1]. In structural parts under cyclic and/or dynamic loading fatigue cracks can occur after a certain number of cycles. This initiates an ongoing process of destruction and the residual lifetime of the component is limited. For safety reasons components under fatigue loading need to be inspected frequently to detect fatigue damage in an uncritical stage [2].

In dependence of the type and size of the structural components, of anti-corrosion coating and of operational circumstances conventional inspection methods can be unreliable in detecting possible fatigue cracks. The most common and generally practiced technique is the frequent visual inspection of the components for fatigue cracks, if necessary, using magnifying glasses. For reasons of increasing the detectability by visual inspection, generally two methods were adopted to intensify the cracks' recognizability: the dye penetrant testing method [3] and the magnetic particle

testing method [4]. Both methods lead to an acceptable detectability, though their application is associated with a high effort in time and considerable costs for the ingredients.

Other nondestructive testing methods for detecting fatigue cracks are ultrasonic, thermographic, radiographic as well as eddy current based. Compared to visual methods they have in common, that the inspection intervals have to be defined in dependency of the crack propagation. According to the required safety level, costs for those manual and visual inspections can be significant because well-trained experts need to be deployed.

If the vulnerable location of the expected fatigue crack is known strain measurements can be used for early crack detection. Strain measurements can be performed using strain gauges or fiber-optical sensors. They can be quite costly and only reliably, if the crack occurs at the predicted location.

To overcome the drawbacks of these established procedures, a new, so-called crack luminescence method was invented and patented at the German Federal Institute for Materials Research and Testing (BAM) [5], which provides a highly efficient solution for observing fatigue crack propagation on structural components. In a cooperative research project between BAM and MR Chemie

<https://doi.org/10.1016/j.matpr.2020.02.338>

2214-7853/© 2020 Elsevier Ltd. All rights reserved.

Selection and peer-review under responsibility of the scientific committee of the 36th Danubia Adria Symposium on Advances in Experimental Mechanics. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Please cite this article as: F. Hille, D. Sowietzki and R. Makris, Luminescence-based early detection of fatigue cracks, Materials Today: Proceedings, <https://doi.org/10.1016/j.matpr.2020.02.338>

GmbH the two main components were further developed and tested to optimize sensitivity, reliability and robustness against mechanical wear for industrial application.

The present contribution describes the principle of the method and shows its functionality by the means of two exemplary applications.

## 2. Principle and functionality

For crack luminescence, a special coating system is applied on the surface of critical locations regarding possible high stressing, for example joint weld seams. This coating system consists out of two components, a fluorescing layer and a dark layer which covers the fluorescing one [6], as shown in Fig. 1(a).

In case of crack occurrence at the steel's surface the two layers rip open due to its adhesive properties. If then energy-intensive rays (UV) enter the crack, the boundaries of the luminescing layer will emit visible radiation, as schematically illustrated in Fig. 1(b). This luminescence light can easily be seen from distance which allows for an automatized remote damage monitoring using webcams and image recognition software. This can be profitable, especially at locations that are not easy to access as well as in cases, were an interruption of the structure's operation for inspection issues is costly.

The luminescence can be seen from distance what makes remotely monitoring possible by using webcams so that there is no need of stopping any ongoing operations due to inspection issues. This can be helpful especially at locations which are not easy to access. Furthermore, an automated monitoring system is realizable by using image recognition software. Currently, the crack luminescence is limited to research application in laboratories where weather resistance is not necessarily needed but the combination of crack luminescence and corrosion prevention are part of future research.

To reproduce thin coatings in a fast and applicable way as well as to ensure a user-friendly handling MR Chemie developed an aerosol can based system. The targeted sprayed layer thickness is 60–100  $\mu\text{m}$ . The fluorescing layer makes 50–70% of the total thickness [7].

## 3. Test and exemplary application

### 3.1. Tensile test on notched specimen

In collaboration with BAM and MR Chemie different fluorescing and cover coatings were developed and tested on special test bodies which allow a measurement of the sensitivity. Thereby also the influence of the coatings thickness was determined and described [7].

Two key performance parameters of the luminescence coating are its long-life fatigue behavior as well as its sensitivity during crack formation [7]. On one hand the system should indicate the crack as soon as possible and on the other hand the coating should not signal due to a defective cover layer. These quality characteristics were investigated by cyclic tensile tests. For that, the coating was applied at thin metal sheets. In one series of tests the specimens were axially loaded 5 million times in order to detect any delamination or ripping process. As a result, no delamination in the coating layers was detected which indicates a durability of the coating layers against vibrational loading.

Another series includes cyclic loading of the sheets with a predefined notch (see Fig. 4) at the edge of the plate. It is supposed to form a crack after a significant number of load cycles origin from the notch. This crack will finally lead to the fraction of the sheet. Special attention was paid to the point in time when the crack becomes visible.

Optical changes in the coating during the test were captured in a video. Furthermore, strain gauges were applied on the specimen's surface to measure the strain throughout the whole duration of the test. Fig. 2(a) shows the test setup. The strain measurement at several specimens is shown in Fig. 4. The number of cycles is normalized and the grey area represents the moment in time when a first weak gleaming gets visible signalling the upcoming crack. Since the strain gauge is slightly behind the notch and accordingly the predefined crack, at first the measured strain values at this point increase which indicates the initiation of a crack. At point in time "2" (see Fig. 3), when the first weak gleaming is noticeable the strain increased approximately by 5%. With a growing number of load cycles the occurring crack reaches a significant length and crosses the centerline of the gauge which leads to declining strain values (point in time "3" in Fig. 3).

The evolution of strain was compared with the video material. Fig. 3 shows the progression of the crack in the specimen. Results



Fig. 2. (a) Tensile test setup; (b) Notch at metal sheet [7].

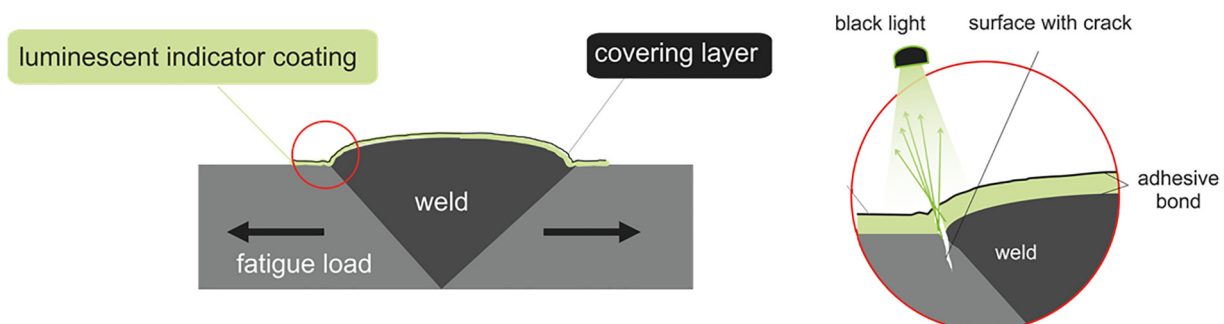


Fig. 1. (a) Application of the crack luminescence coating at a welding seam; (b) Case of a crack and the emission of visible radiation [6].

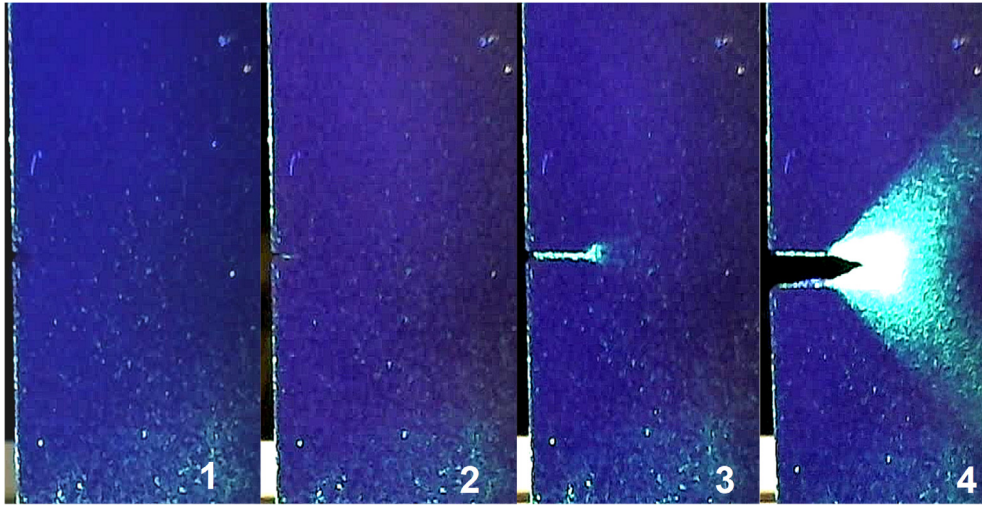


Fig. 3. Crack formation (2), growth (3) and fracture (4) while cyclic tensile test of a metal sheet with notch and luminescence coating.

of this comparison show that already small changes in strain and thereby very small cracks are displayed by the coating. Resulting, the progress of crack formation, growth and fracture can be well observed with the luminescence coating which makes this method very interesting for continuous monitoring of fatigue loaded components Fig. 4.

### 3.2. Tensile test on welded specimen

Welds almost always cause defects in cyclic loaded metal structures. Especially the edges of weld seams are fatigue vulnerable structural zones and the origin of most cracks. Therefore, the crack luminescence method was also tested on butt and fillet welds. The cross section of the steel specimen (S355J2 + N/unalloyed structural steel) is  $80 \times 40 \text{ mm}^2$  in dimension at the narrowest part of the specimen. Fatigue damage was here also caused by cyclic loading. The tests were monitored by permanent strain measurement as well as video capture. The strain gauges were applied close to the weld's edge for a sensitive detection of very small changes in strain. Fig. 5 shows the test setup. UV-lamps permanently irradiate the covering layer of the luminescent coating at the weld. The number of cycles is also captured in the video to simplify the synchronization with the measured strain. The specimens were loaded with a testing frequency of 10 Hz.

The crack formation at the fillet weld is shown in Fig. 6. First light blinking was detected after about 130,000 cycles, clearly

visible after 150,000 cycles. After 250,000 cycles the crack reached a significant length and at 274,084 cycles the specimen fractured completely.

In Fig. 7 the evolution of strain is depicted. The mentioned steps of the crack formation from Fig. 6 are marked in the graph. After a change of about  $50 \mu\text{m}/\text{m}$  in the maximum strain the curve begins to fall and a blinking of the occurring crack was clearly visible. After 250,000 cycles the value for maximum strain decreased significantly from about 1,300 to  $100 \mu\text{m}/\text{m}$ . 274,084 cycles mark the fracture of the specimen.

A very sensitive reaction of the strain measurement and the luminescence coating was observed. In order to detect a crack, the sensitivity of the strain measurement always depends on the location of the strain gauges. The closer they are to the occurring crack the faster they show changes in strain.

Also noticeable at some fillet weld specimens were the formation of a second crack at the opposite edge of the weld, which closed again after the fracture when there wasn't any loading anymore. By means of the crack luminescence coating it was possible to observe the opening and closing of a crack. After removing the coating the crack beneath wasn't noticeable at all, although dye penetrant testing and microscopic examination proved later the existence of such second crack.

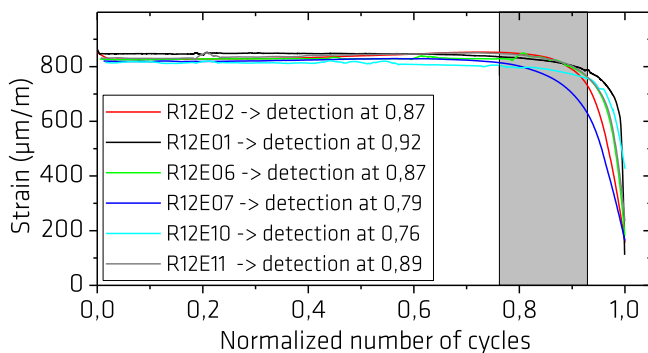


Fig. 4. Evolution of strain (metal sheets with notch).



Fig. 5. Test set up for a fillet weld specimen.

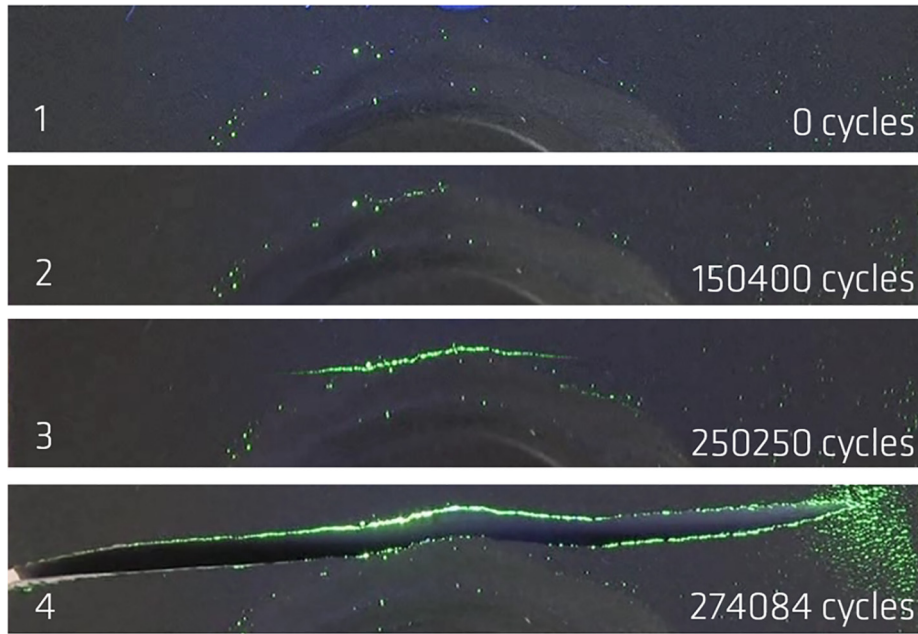


Fig. 6. Formation of fatigue crack during the test.

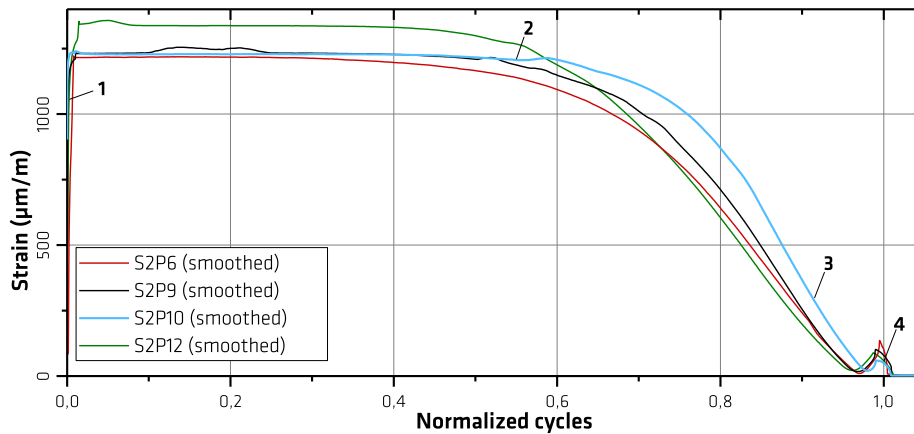


Fig. 7. Evolution of strain (tensile test at fillet welding).

#### 4. Conclusions

The results of the described studies demonstrate a high sensitivity of the crack luminescence method. All tests indicated an early detection of the crack which was in good agreement with the strain measurements or even slightly before significant changes in the measured strain. This points out that the method is suitable for examinations of crack growth behavior. The experimental procedures also demonstrate the dependency of measured strain based crack detection from the correct location of the gauges. Especially, the tests performed on the welded specimens are good examples for the limitation of crack detection by strain gauges.

Using conventional crack detection methods, uneven surfaces can increase examination costs, whereas for crack luminescence, the surface quality does not matter. The crack luminescence allows the application on any large and uneven surface without knowing the exact location of the crack in advance. This makes the method ideal for continuous monitoring by using camera technique which is useful especially at locations hard to access. The proposed

approach is promising for supporting inspections of stressed and fatigue loaded structural parts. The method is also and especially helpful for the monitoring of dark areas, where cracks in general are hard to see. Crack luminescence is not only advantageous for an application on undamaged structures or components. By applying the coating on possibly damaged parts, it is feasible to notice any further growth of existing cracks or new crack formations. For structure operating companies which are endangered crack luminescence will have a significant impact on operations and maintenance (O&M) strategies, especially coupled association with the implementation of automation technology. That can avoid the necessity to stop operating systems due to inspection issues and might also go along with an extension of the residual lifetime of such structures.

By now most applications of crack luminescence systems were realized successfully on steel structures in laboratories where the resistance against environmental influences is not relevant [8]. Future investigations and development will therefore focus on the coating's resistance against weather phenomena like wind-driven rain, hail or frost and their influences on the detection reliability.

Further functionality, sensitivity and robustness on other fatigue affected materials like aluminum and titan are on the agenda of the cooperation partners.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgements

This work was funded by the German Federal Ministry for Economic Affairs and Energy within the ZIM program; support code ZF2201092ZG4.

#### References

- [1] L. Pook, *Metal Fatigue, What it is Why it Matters*, Springer, 2007.
- [2] S. Suresh, *Fatigue of Materials*, Cambridge University Press, 1994.
- [3] EN ISO 3452-1:2013: Non-destructive testing – Penetrant testing – Part 1: General principles (ISO 3452-1:2013, Corrected version 2014-05-01), 2013.
- [4] EN ISO 9934-1:2016: Non-destructive testing – Magnetic particle testing – Part 1: General principles (ISO/FDIS 9934-1:2016), 2016.
- [5] Mehdiانpour, M. (inventor): Bundesanstalt für Materialforschung und -prüfung, assignee., Crack detection and crack monitoring by means of luminescence, European patent EP2693204 A1, 2014.
- [6] Mehdiانpour, M., Risslumineszenz – A new method for detection and monitoring of fatigue cracks, VSVI-seminar bridge- and structural engineering, Braunschweig, in German, 2015.
- [7] R. Makris, F. Hille, M. Thiele, D. Kirschberger, D. Sowietzki, *Crack luminescence as an innovative method for detection of fatigue damage*, *J. Sens. Sens. Syst.* 7 (2018) 259–266.
- [8] M. Thiele, F. Hille, R. Makris, Comparison of fatigue crack detection methods for high-cyclic loaded steel structures, Proceedings of SMAR 2019, Potsdam, Germany, 2019.