Forecast of the fatigue crack initiation site of commercially pure Titanium miniature specimens with local surface topography data

L. Böhme[a,*], F. Ströer[b], A. Keksel[b], J. Seewig[b], E. Kerscher[a]

[a]Materials Testing, Gottlieb-Daimler-Str., 67663 Kaiserslautern, Germany

[b]Institute for Measurement and Sensor Technology, Gottlieb-Daimler-Str., 67663 Kaiserslautern, Germany

*boehme@mv.uni-kl.de

Abstract

Surfaces of technical components rarely appear in perfectly smooth condition. During fatigue loading, stress concentrations at surface asperities cause localized plastic deformation that can lead to crack initiation. Therefore, we have established a computer-aided method based on material ratio curves to investigate the possibility to predict the crack initiation site in fatigue tests by using detailed information on the local surface topography.

The present study shows the results of investigations on the mutual influence of the average grain size and the surface condition on the fatigue behavior of commercially pure Titanium (cp-Ti) miniature specimens. Three cp-Ti states were investigated: two types of coarse-grained cp-Ti Grade 2 with 35 µm and with 100 µm average grain size and one ultrafine-grained cp-Ti Grade 4 state with less than 2.5 µm average grain size. Confocal microscopy provided the surface topography data of all specimens and data post-processing was applied to the topography in order to locate critical areas where crack initiation may preferentially occur. These areas were compared with the actual crack initiation areas in fatigue test. Finally, scanning electron microscopy (SEM) images of the fracture surfaces were studied to analyze fatigue crack initiation site and crack path of the three microstructural states.

1. Introduction

It is well known that the local surface condition plays a major role during fatigue crack initiation. Surfaces of technical components rarely appear in a perfectly smooth condition, which leads to a stress concentration at surface asperities during fatigue loading. This stress concentration causes localized plastic deformation which can lead to crack initiation. If a crack is initiated at the surface, its ability to grow depends on the grain size and orientation of the crystallographic planes, namely those with a high Schmid factor. In consequence, these factors (surface asperities, surface grain size and grain orientation) significantly influence the fatigue limit of materials. In the past we have investigated polycrystalline cp-Ti specimens with different modified surface conditions (micro milling, laser ablation). Thereby, we showed that surface asperities do not necessarily influence the fatigue limit, when its size is considerably lower than the average grain size of the material [1-3]. This was also shown in a study where theoretical approaches, e.g. critical distance approaches, were used to predict the fatigue limit of notched specimens [4].

Now, for a detailed forecast of the crack initiation site it is necessary to know the local grain orientation, grain size, and surface topography in the fatigue loaded area of a component. Therefore, we have established a method to investigate the influence of the surface condition on the fatigue crack initiation site by detailed information on the local surface topography of the specimens. Beside the conventional standardized parameters for the characterization of the surface roughness like R_a and R_z (surface profile roughness, one-dimensional) or S_a and S_z (areal surface roughness, two-dimensional) there are other approaches standardized for profile and areal surface characterization of functional surfaces (see [5] for surface profiles and [6] for areal surfaces). Furthermore, finding notches in topography data can be subjective. A threshold has to be set manually. All measured height values below this threshold are classified as valleys. In this study, the applicability of an approach from the field of roughness measurement technique is investigated. This approach is based on calculations of function-oriented roughness parameters, which can be derived from the linear material ratio curve (Abbott curve) of a technical rough surface. Usually, such parameters are used to characterize machined surfaces with pronounced peaks, valleys, pores and plateaus, such as those present on cylinder running surfaces of combustion engines for example (e.g. [7,8]). Parameters like the core roughness depth *Rk* (surface profile characterization) or *Sk* (analogous for areal surface characterization), the reduced peak height *Rpk* or *Spk* and the reduced valley depth *Rvk* or *Svk* are appropriate for the characterization of such functional surfaces. So, the material ratio curve can be used to determine a reasonable threshold for the classification and extraction of valleys and based on this extraction, a method was developed to investigate the possibility to predict the crack initiation site of a fatigue loaded specimen.

For a detailed study of the mutual influence of the grain size and the surface condition on the fatigue limit, cp-Ti miniature specimens with different crystallographic grainsizes and surface states were investigated. Confocal microscopy provided the surface topography data of all specimens and the computer-aided topography data post-processing method was applied to locate critical areas where crack initiation may preferentially occur. These areas were then compared with the actual crack initiation areas in fatigue tests. Here, the fatigue crack initiation sites were detected by in situ observation of the local strain evolution during fatigue testing by digital image correlation. Finally, scanning electron microscopy images of the fracture surfaces were studied to analyze the fatigue crack initiation site and crack path of the three microstructural states.

2. Material and Specimens

Three cp-Ti material states with different average grain size were used in the present study (Fig. 1). An ultrafine-grained material state was produced by equal channel angular pressing technique applied to a cp-Ti Grade 4 rectangular bar, so that the average grain size measured according to [9] is less than 2.5 µm. The second material state from a hot-rolled cp-Ti Grade 2 sheet with 0.6 mm thickness shows an average grain size of 35 µm and the largest grains can be observed in the micrograph of a cp-Ti Grade 2 round bar with an average grain size of 100 µm. It has to be noticed that the three material states may also have different grain orientation distribution characteristics. Especially the hot rolled sheet material is expected to be considerably textured

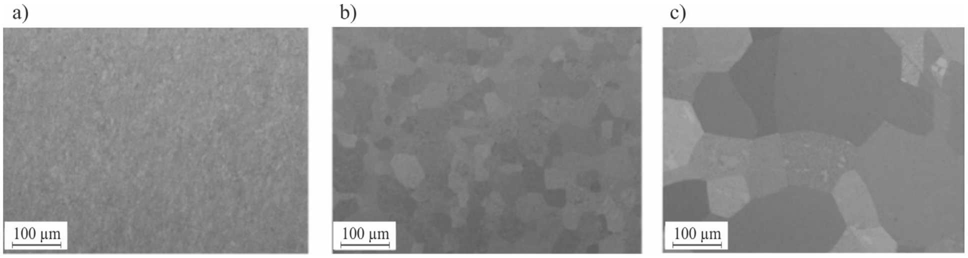

Figure 1. Polarized light microscopy images of (a) cp-Ti Grade 4 with less than 2.5 µm average grain size, (b) cp-Ti Grade 2 with 35 µm average grain size and (c) cp-Ti Grade 2 with 100 µm average grain size.

Figure 2 shows the four main steps of the surface preparation and machining of the flat miniature fatigue specimens. In a first step, thin plates were cut out of the round and the rectangular bar by using water jet cutting (step I). This technique allows for machining large and thin parallel plates and at the same time keeping the plastic deformation of the material and the heat input on a low level. Then, the surfaces of the plates were micro machined on both sides as to achieve specimens with different surface conditions (step II). The investigations include specimens with a smooth polished surface, as well as specimens with face-milled surfaces and with micro milled notches. The notches were machined by using a micro end mill. They show up a defined rectangular geometry and a specific notch depth as described in [4]. After the surface modification, miniature specimens according to the technical drawing in Figure 2 were cut out of the plates with an end mill tool (step III). Finally, the edges of the specimens are polished carefully in the measurement area (step IV)

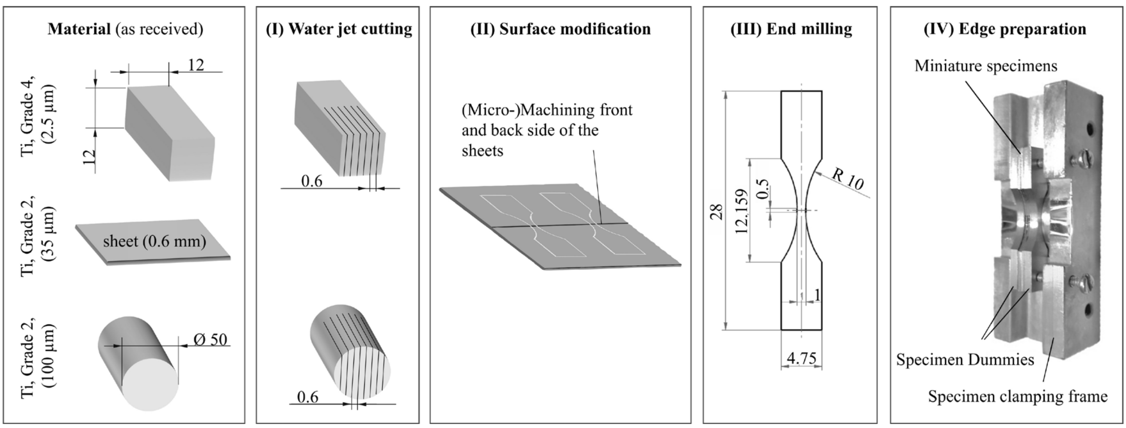

Figure 2. Machining and preparation of the flat miniature fatigue specimens

3. Methods

In order to detect areas where fatigue crack initiation may preferentially occur, the surface topography of the specimens has to be characterized with sufficient accuracy. Therefore, the surfaces of the miniature specimens were evaluated by using confocal microscopy technique. A computer-aided data post-processing method was developed and applied to detect probable fatigue crack initiation areas. These critical areas from the surface topography evaluation can be compared to the actual crack initiation areas from the digital image correlation after the fatigue tests.

3.1 Confocal Microscopy and Surface Topography Evaluation

The surface topography evaluation can be divided into three main steps, the acquisition of the topography data, the data processing as to extract measurement values belonging to a valley, and finally the determination of critical areas from these remaining valley data.

Confocal microscopy technique (NanoFocus, µsurf explorer) was used for the acquisition of the 3D topography data of the specimens. The topography measurements were conducted in the center of the specimens, where the highest stress occurs during the fatigue tests. A lens with 20x magnification was used which is adequate for measuring the surface topography with sufficient accuracy.

For the determination of the material ratio curve of a measured 3D topography, the topography data have to be filtered at first in order to eliminate any underlying basic shape. In this study, the tilt of the measured dataset was eliminated by determining a fitting plane with least squares methods. This fitting plane was subtracted from the measurement data. Figure 3 illustrates the subsequent computer-aided post-processing of the measured topography data to extract the valleys. For the determination of the material ratio curve all measured height values are sorted in descending order, assuming equidistant data points. The measured height values are plotted against the material ratio (Abbott curve, see Figure 3b). This curve is now evaluated as described in detail in [5]. The core roughness depth *Sk*, for example, is the z-range in between the points of intersection of the determined balance line with the ordinate axes, point A and point B. In order to classify and extract valley data, all measured height values that fall below the height value of point B are defined as valley data and extracted from the topography data (see Fig. 3c)

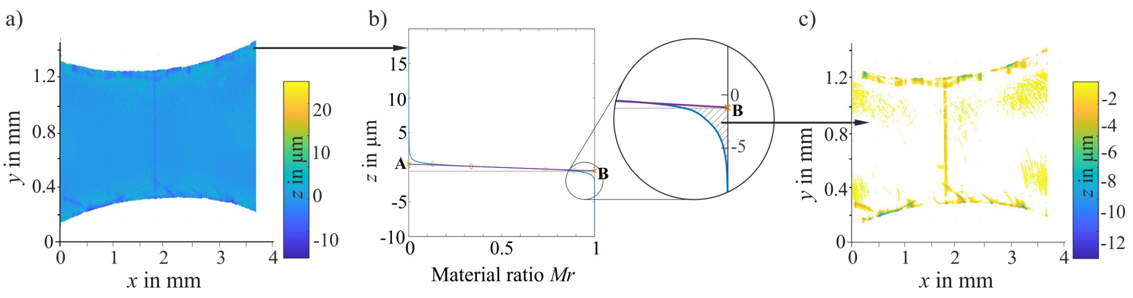

Figure 3. Illustration of the computer-aided surface topography evaluation. Complete topography data of a specimen (a), the respective material ratio curve with the linear Abbott curve and valley extraction criterion (b), and extracted valley data (c).

Now the idea was to determine critical locations of the surface topography where crack initiation may preferentially occur, simply by accumulating the remaining measurement values belonging to a valley along x-direction and along y-direction (see Figure 4a, 4b, respectively). Therefore, the remaining measurement data are interpreted as matrix values and the sum of these values in one line (or in one row) can be calculated. Then, a global minimum can be derived from both cumulated notch depth diagrams. Its location can be illustrated in the topography data plots (see Figure 4c)

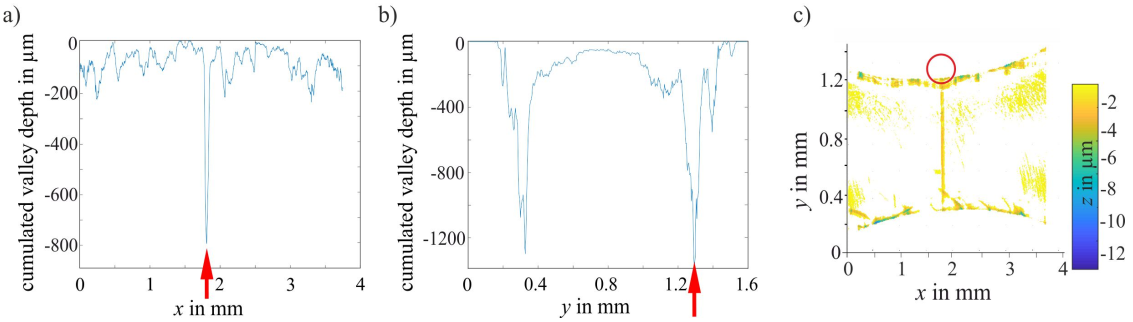

Figure 4. Detection of a critical location on the surface in Figure 3. The extracted height data (a) cumulated along *y*, plotted against x, and (b) cumulated along x, plotted against *y*, with the position of the global minima (red arrows). Extracted valley data with the

detected x-y-position of the minima (c).

3.2 Fatigue Testing

Fatigue tests were conducted on a BOSE ElectroForce® 3200 test instrument under a sinusoidal tension-compression cyclic load with a stress ratio of R = -1 at a loading frequency of 50 Hz. The tests are stopped when no fatigue failure occurs within 10^7 loading cycles and the respective specimen was classified as a runout. The results can be illustrated in a Wöhler type diagram. This way we want to find the level where no fatigue failure occurs for a specific combination of grain size and surface condition. During the fatigue tests, camera equipment was used for the acquisition of micrographs of the surface of the specimens in the measurement area. The images were taken in the moment of maximum stress of the corresponding loading cycle. Figure 5 shows the test setup. The images were investigated with the aid of digital image correlation software ISTRA 4D for the detection of local plastic deformation.

3.3 Fracture surface analyzation

SEM images of the fracture surfaces were taken with a Philips XL 40 SEM. The images were examined in order to identify the initiation site of the fatigue cracks and to analyse the underlying crack propagation mechanisms for the three cp-Ti states.

4. Results and Discussion

4.1 Influence of the surface state on the fatigue resistance

Figure 5 shows a Wöhler-type diagram, where the stress amplitude is plotted against the number of cycles to failure. The dashed lines indicate the fatigue limit from literature [2]. As can be taken from the diagram, the fatigue strength shows a strong grain size dependence. For specimens with a larger average grain size, fatigue failure occurs at lower stress amplitude values. It is commonly known that reducing the grain size usually has the beneficial effect of increasing the fatigue strength. This is because dislocations are more likely to reach and pile up at a boundary when the average grain size is small. The coarse grained cp-Ti state with 100 µm average grain size and micro milled notches of 30 µm depth shows fatigue failure at low stress amplitude values. The cp-Ti state with 2.5 µm average grain size and with polished surfaces shows the largest stress amplitude values without fatigue failure and therefore shows the highest fatigue strength. When comparing the fatigue strength of a given cp-Ti state with a smooth surface and with a micro structured surface, different observations can be made for the respective cp-Ti states. In case of cp-Ti with 2.5 µm average grain size, specimens with face milled surfaces revealed fatigue failure at lower stress amplitude values compared to the specimens with polished surfaces. In case of the cp-Ti state with 35 µm average grain size, fatigue strength is reduced by notches of the same size as the average grain size of the material. The cp-Ti state with 100 µm average grain size shows a reduced fatigue strength caused by notches, which are significantly smaller than the average grain size

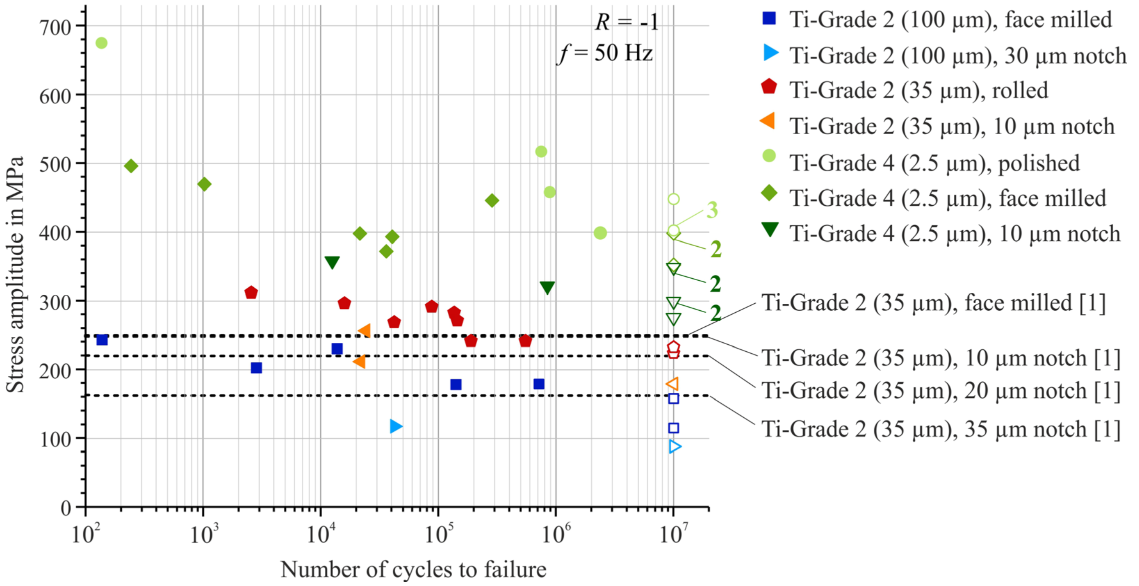

Figure 5. Wöhler-type diagram showing the results from fatigue tests on cp-Ti miniature specimens (digits indicate the number of data points that are on top of each other).

4.2 Influence of the material state on the fatigue crack propagation

The fracture surface examinations reveal that the three cp-Ti states show a different crack propagation behavior (Figure 6). In Figure 6a the three stages of crack growth can be observed by the cp-Ti specimen with average grain size of 35 µm. The observation reveals a strong influence of the microstructure on the crack path in the region of crack initiation. In the first stage of crack growth, the observations indicate transgranular shear controlled propagation of the fatigue crack. The SEM images further show radial ridges in stage II, and ductile fracture in stage III. In case of cp-Ti with 100 µm average grain size the cracks propagated mainly in the first stage of crack growth. In some cases several crack initiation areas were observed from which the cracks propagated until the crack fronts merged. The fracture surfaces of the fine grained cp-Ti states appear smooth and slight ridges can be observed running radially from the crack origin location. The cracks originate either from a surface topography characteristic or from an inhomogeneity beyond the surface

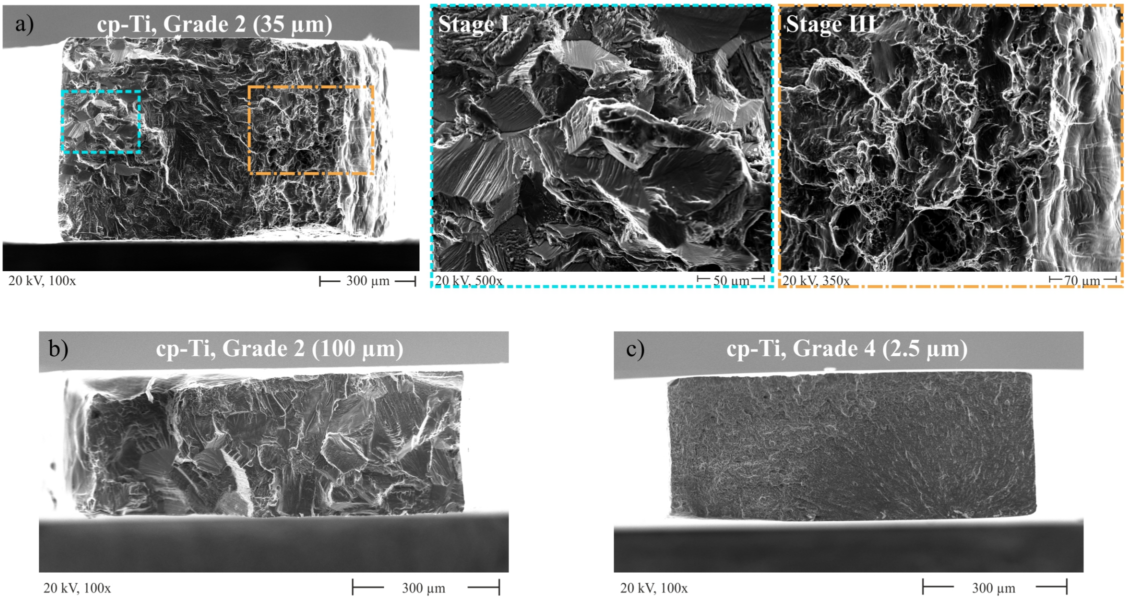

Figure 6. SEM images showing representative fracture surfaces: (a) cp-Ti Grade 2 (35 µm); (b) cp-Ti Grade 2 (100 µm); (c) cp-Ti Grade 4 (2.5 µm);

4.3 Determination of the fatigue crack initiation sites

In order to analyse the possibility of obtaining critical areas of the specimen surfaces where local plastic deformation and crack initiation may preferentially occur, predicted and respective actual crack initiation sites have to be compared. Figure 7 shows crack initiation sites of different specimen states from the topography data based prediction method, as well as the respective actual crack initiation sites from digital image correlation. When comparing the crack initiation sites of cp-Ti (100 µm) with micro milled 30 µm notches a good match can be seen (Fig. 7a and 7d). The same applies for cp-Ti (2.5 µm) with face milled surfaces (Fig. 7b and 7e). The crack initiation sites do not match in the case of cp-Ti (35 µm) with unmachined surfaces (Fig. 7c and 7f).

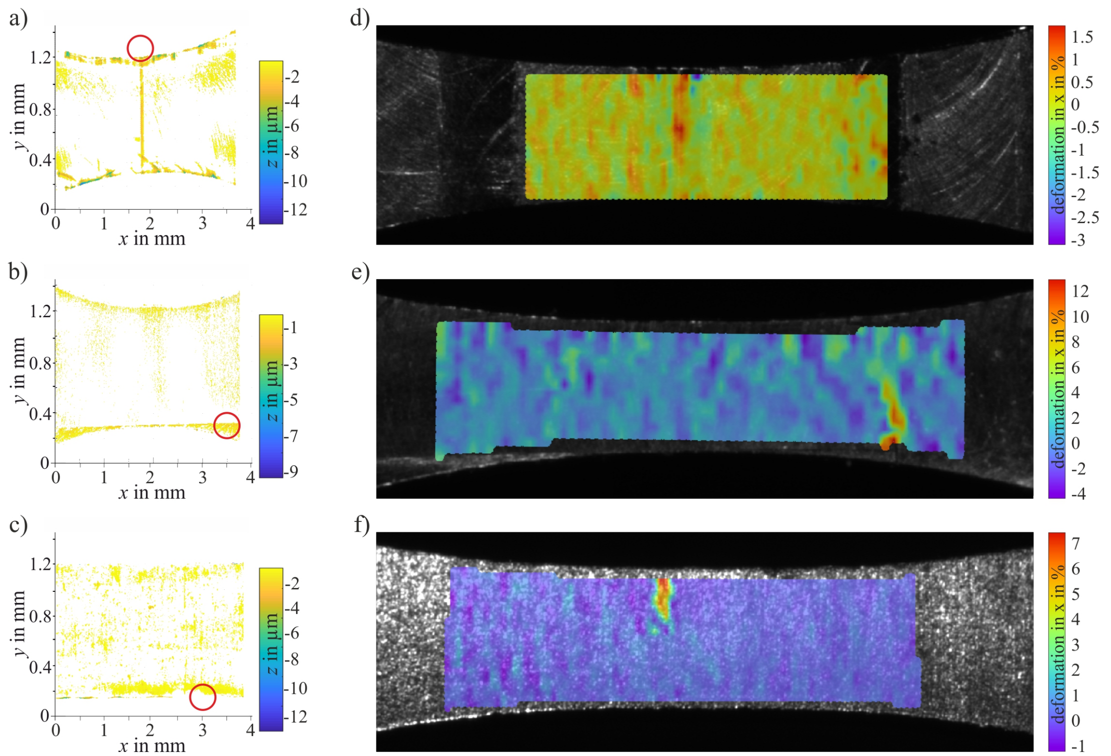

Figure 7. Crack initiation sites (a-c) from the topography data based prediction method and (d-f) the respective actual crack initiation sites from fatigue tests with digital image correlation.

6. Conclusion

A computer-aided method based on the evaluation of material ratio curves from 3D topography measurements was developed and successfully applied for the prediction of fatigue crack initiation sites. The results indicate that the crack initiation sites can be predicted when the materials microstructural characteristics are considerably smaller than the topography characteristics, or in other words, when the stress concentration occurring at a specific local topography characteristic (such as a notch) is the main reason for the initiation of a fatigue crack. Nevertheless, the topography based prediction method has to be optimized at least in one aspect. The cumulated notch depth value has to be normalized accounting for the specimen width or the global stress distribution. Otherwise, larger areas of course lead to a larger cumulated valley depth value so that the maximum cumulated valley depth value might be determined apart from the centre of a specimen where the highest stress occurs. The investigations further show that grain boundaries are barriers against fatigue crack initiation and propagation. The analysis of the fracture surface of the three material states shows that the lower the stress amplitude and the larger the average grain size, the larger is the proportion of stage I crack growth.

7. Acknowledgements

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8. References

[1] C. Kühn, E. Kerscher, Materials Science Forum, 765 (2013), 653-657.

[2] C. Godard, E. Kerscher, Procedia Materials Science 3 (2014) 440-446.

[3] E. Kerscher, Procedia Engineering 74 (2014) 210-217.

[4] L. Böhme, C. Godard, E. Kerscher, Proceedings of the International Symposium on Notch Fracture, Santander, Spain, 2017, 216-221.

[5] DIN EN ISO 13565-2:1997, Geometrical Product Specifications (GPS) – Surface texture: Profile method; Surfaces having stratified functional properties – Part 2: Height characterization using the linear material ratio curve (ISO 13565-2:1996); German version EN ISO 13565-2:1997

[6] DIN EN ISO 25178-2:2012, Geometrical product specifications (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameters (ISO 25178-2:2012); German version EN ISO 25178-2:2012

[7] S. Rief, J. Seewig, Werkstattstechnik online, 106 (2016), 823–829.

[8] K. Klauer, M. Eifler, J. Seewig, B. Kirsch, J.C. Aurich, Engineering Science and Technology, an International Journal, 21, 2018, 302-313.

[9] L. Morales-Rivas, S. Diederichs, L. Böhme, E. Gordo, A. Hebestreit, E. Kerscher, Practical Metallography, 55 (2018) 10, 678-692