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Innovative D^Esign for Reliable PLANET bearings

IDERPLANE PROJECT REPORT

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Executive Summary

This report summarizes the work done by Brescia University (Prof. A. Mazzu) and INSA Lyon (Prof. J-Y Buffiere and Dr C. Xiao) within the project IDERPLANE to characterize in 3D the formation of sub surface cracks during rolling contact fatigue tests performed using a bi-disk test configuration. To foster crack initiation, two cylindrical artificial defects with various depth and diameters were machined on the rolling track. Two materials conditions (heat treated and untreated) and various normal pressure P were investigated. The tests were stopped when a spall on the rolling track was detected or when a given number of cycles was reached (10^6 or 10^7). Thin slabs containing the surface of the disk close to the defects were cut from the disks and characterized using X-Ray tomography. Two types of X-ray sources were used: laboratory source, synchrotron source. The crack size was measured for each specimen at the bottom of the hole along two orthogonal directions. The 3D reconstructed images are available at <https://doi.org/10.5281/zenodo.6351387>.

1. Introduction

1.1 Disc shaped specimens

18 disc shaped specimens were machined. The material of six specimens was left as it was after the first machining; other specimens were heat treated on the surface. Artificial holes of two different geometries were made by EDM in 14 specimens. The two geometries are identified by the diameter of the holes ($\varnothing 0.2$ mm and $\varnothing 0.4$ mm); the depths of all holes were 0.27 mm. The geometry of the specimens and the holes is shown in Figure 1; the complete list of the specimens with their specifications in terms of heat treatment and artificial defect is given in Table 1.

Table 1: List of the specimens and artificial defect specifications.

Specimen ID	Series	Heat treatment	Artificial defect
1-2-3-4-5-6	B	Yes	Hole $\varnothing 0.4$ mm
7-8	C	Yes	Hole $\varnothing 0.2$ mm
13-14-15-16		Yes	None
17-18-19-20-21-22	A	No	Hole $\varnothing 0.4$ mm

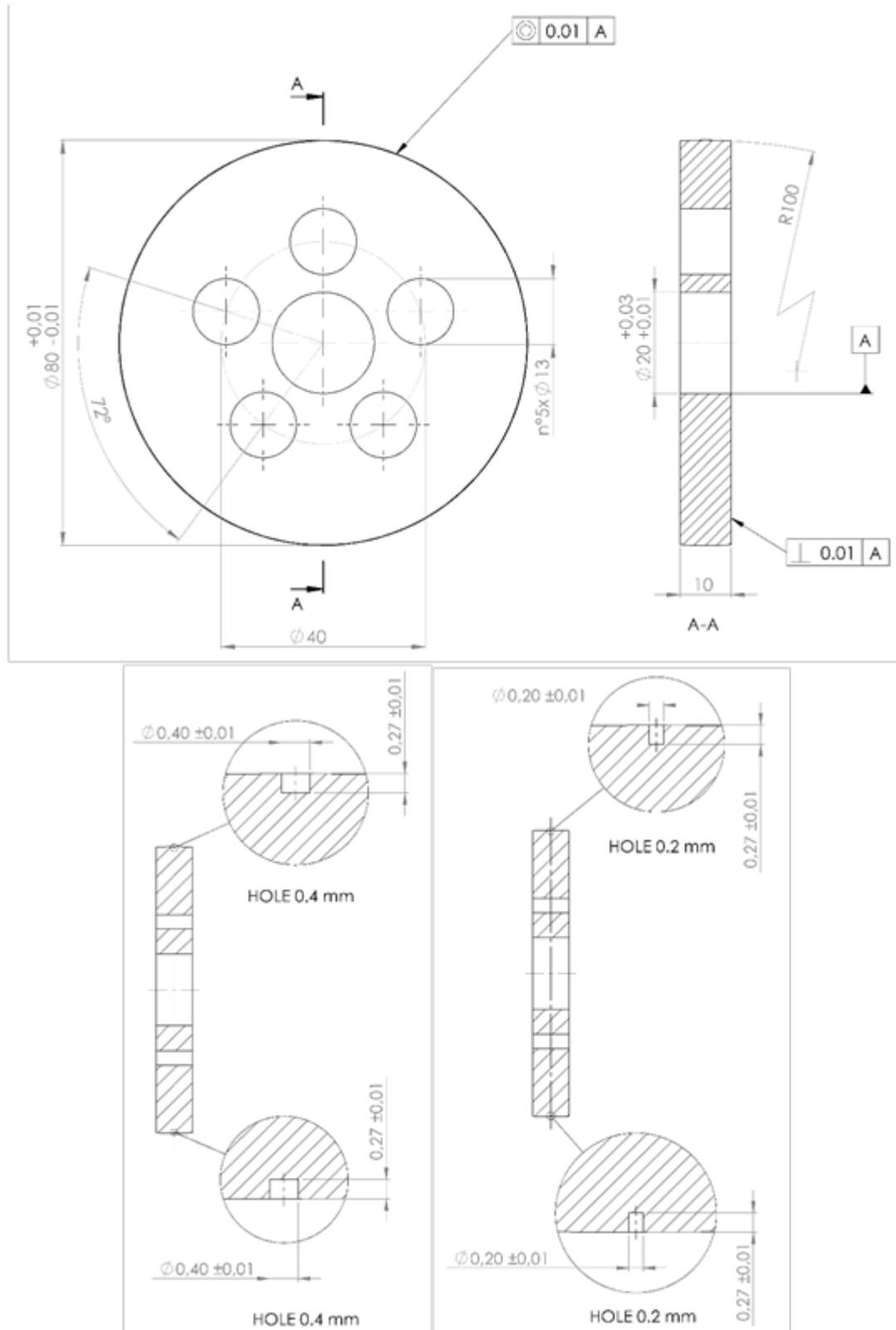


Figure 1. Nominal geometry of the crowned disc-shaped specimens and artificial holes.

The tests were carried out by means of the bi-disc machine shown in Figure 2: it is a bi-disc machine where the specimens are fixed to independent shafts. One of them can be displaced orthogonally to the shaft axis by a hydraulic cylinder, which applies the imposed contact load

as well. The specimens with the artificial defects were coupled with defectless one, in oil-lubricated pure-rolling contact at 900 r.p.m. rolling speed.

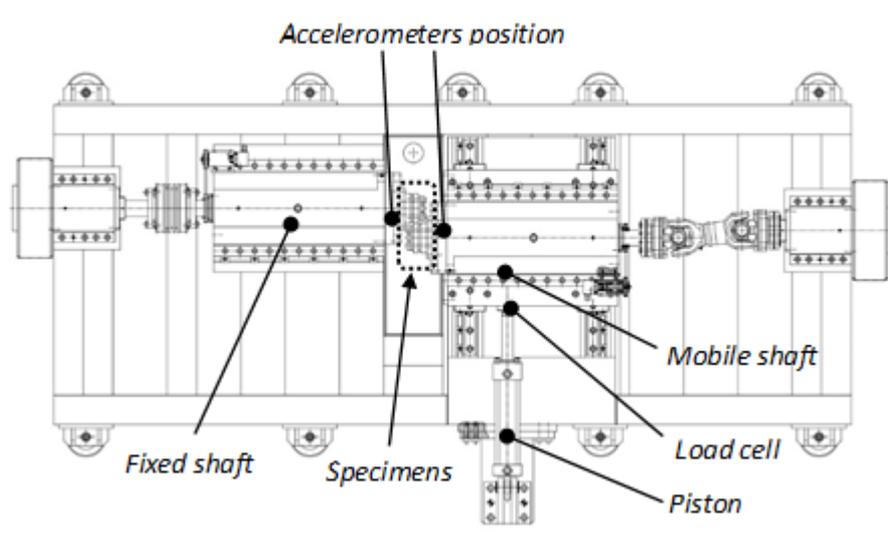


Figure 2. Schematic of the twin-disc test bench

For the tests on the untreated specimens (series *a*), the contact loads were chosen to obtain a representative S-N curve of the material. The list of the normalized contact pressure P applied in the tests is given in Table 2.

Table 2: Contact load data in the tests on the untreated specimens

Specimen ID	Normalized contact pressure P [MPa]
17	0.541
18	0.624
21	0.705
19	0.794
20	0.866
22	1

The second series of tests (series *b*) was carried out on the heat-treated specimens with $\varnothing 0.4$ mm holes. Two levels of contact pressure were imposed. For the test at the maximum pressure level, two different test duration were imposed: 10^6 cycles and 10^7 cycles. Such conditions were chosen to estimate the propagation rate of subsurface cracks at different load levels.

The third series of tests (series *c*) was done on the heat-treated specimens with $\varnothing 0.2$ mm holes. A single contact pressure level was imposed; two different durations were imposed: 10^6 cycles and 10^7 cycles. The list of the test parameters of the series *b* and *c* is given in Table 3.

Table 3: Contact load data in the tests on the heat-treated specimens

Specimen ID	Normalized contact pressure P	Hole diameter [mm]	Duration [cycles]
1	0.874	0.4	10^7
2	0.616	0.4	10^7
3	0.874	0.4	10^6
7	1	0.2	10^6
8	1	0.2	10^7

1.2 Experimental results

The six tests on the untreated specimens with $\varnothing 0.4$ hole (specimens from #17 to #22) allowed determining a life curve, where the failure criterion was based on the appearance of macroscopic damage (spall) on the contact surface within the maximum test duration. Indeed, the tests from #19 to #22 led to the formation of a spall, revealed by vibrations exceeding the fixed limit value. The images of the spalls and the number of cycles corresponding to their appearance are shown in Figure 3. The tests #17 and #18 were interrupted without apparent damage on the surface. All the tests carried out on heat-treated specimens, whatever the hole size, did not show any visible damage on the contact surface. In Figure 4 a diagram summarizing all the test results, on both heat-treated and untreated specimens, is shown.

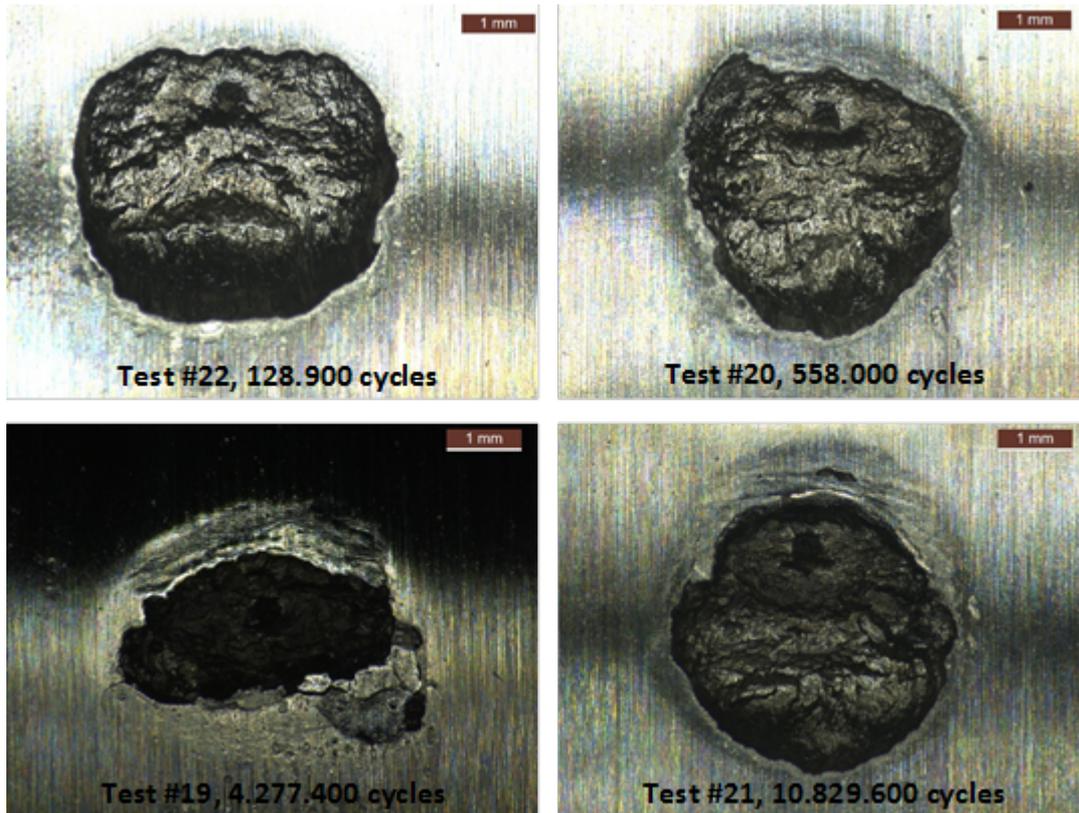


Figure 3: Spalls appeared at the contact surface in the tests on untreated specimens

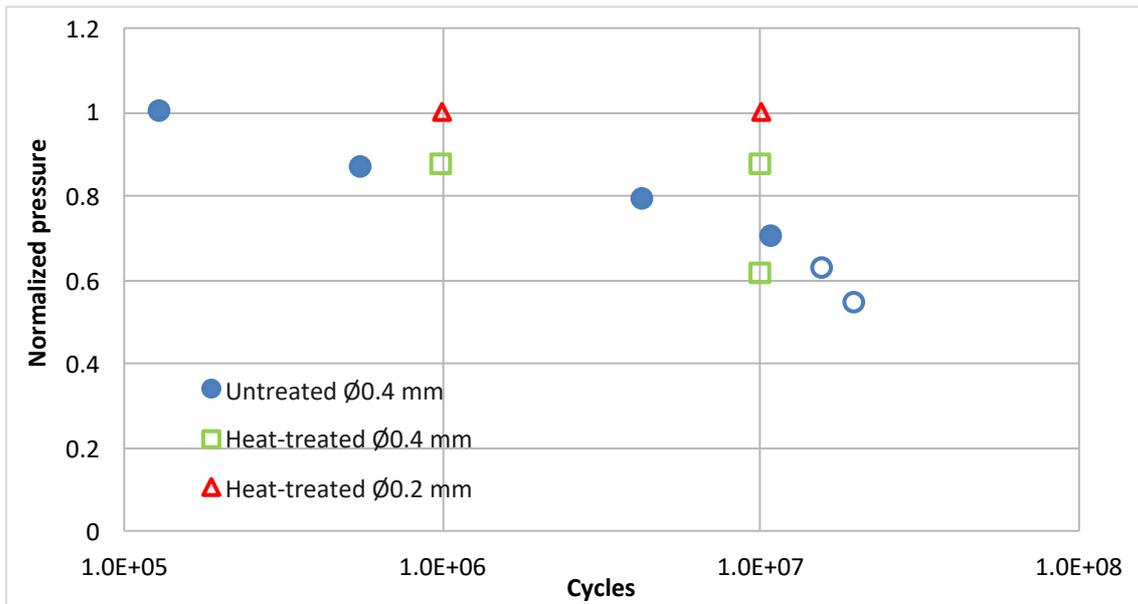


Figure 4: Results of the experimental tests on disc-shaped specimens. Full dots represent tests where spalling occurred, empty dots refer to tests ended without visible damage

2. 3D Detection of cracks

Table 4 summarizes the results obtained for the untreated material. For this metallurgical condition, cracks were observed in all the investigated samples; their relatively large size allowed to image them using laboratory tomography with a voxel size ranging from 2 to 3 μm . The crack size has been measured in two orthogonal directions as defined in section 2.1 corresponding to mode II and Mode III propagation.

Table 4: List of Lab CT results of samples extracted from untreated bi-disc specimens (Lab. = laboratory tomography)

Sample name	Defect size (mm)	Normalized Pressure (MPa)	Number of cycles	CT type	Voxel size (μm)	Crack Length \perp RD (μm)	Crack Length // RD (μm)
17-1	$\emptyset 0.4 \times H0.27$	0.541	2×10^7	Lab.	2	1044	876
17-2	$\emptyset 0.4 \times H0.27$	0.541	2×10^7	Lab.	2	1023	789
21-1	$\emptyset 0.4 \times H0.27$	0.705	1.1×10^7	Lab.	2.5	2020	1192
19-1	$\emptyset 0.4 \times H0.27$	0.794	4.3×10^6	Lab.	2.5	2048	1610
20-1	$\emptyset 0.4 \times H0.27$	0.866	5.6×10^5	Lab.	2.5	1850	1365
22-1	$\emptyset 0.4 \times H0.27$	1	1.3×10^5	Lab.	3	1568	929

Table 5 summarizes the results obtained for the heat-treated material. It can be seen that for this metallurgical condition (larger yield stress) although some cracks could be observed using the same conditions as those of the non-treated material (voxel size 3 μm) in 7 samples no cracks were detected. Those samples were sent to the synchrotron (ESRF, Grenoble) for imaging. Thanks to the smaller voxel size (0.7 μm) and to the presence of phase contrast cracks were detected in those 7 remaining samples.

The detailed results (crack sizes, rolling test conditions) for each investigated sample are presented in section 2.2. The 3D images from which those measurement have been obtained can be found at: <https://doi.org/10.5281/zenodo.6351387>.

Table 5: List of Lab/Syn CT results of samples extracted from heat-treated bi-disc specimens (Lab. = laboratory tomography, Syn. = Synchrotron tomography)

Sample name	Defect size (mm)	Normalized Pressure (MPa)	Number of cycles	CT type	Voxel size (μm)	Crack Length \perp RD (μm)	Crack Length // RD (μm)
1-1	$\emptyset 0.4 \times H0.27$	0.874	1×10^7	Lab.	3	492	370
				Syn.	0.7	902	410
1-2	$\emptyset 0.4 \times H0.27$	0.874	1×10^7	Lab.	3	575	410
				Syn.	0.7	834	417
2-1	$\emptyset 0.4 \times H0.27$	0.616	1×10^7	Lab.	2.5	No crack	No crack
				Syn.	0.7	No crack	No crack
2-2	$\emptyset 0.4 \times H0.27$	0.616	1×10^7	Lab.	2.5	No crack	No crack
				Syn.	0.7	490	No crack
3-1	$\emptyset 0.4 \times H0.27$	0.874	1×10^6	Lab.	3	No crack	No crack
				Syn.	0.7	449	No crack
3-2	$\emptyset 0.4 \times H0.27$	0.874	1×10^6	Lab.	3	No crack	No crack
				Syn.	0.7	442	No crack
7-1	$\emptyset 0.2 \times H0.27$	1	1×10^6	Lab.	3	No crack	No crack
				Syn.	0.7	369	No crack
7-2	$\emptyset 0.2 \times H0.27$	1	1×10^6	Lab.	3	No crack	No crack
				Syn.	0.7	254	No crack

2.1 Definition of Coordinate System

As shown in Figure 5, the definition of coordinate system in this document is as follow:

- x-axis is parallel to the rolling direction and perpendicular to the radial direction;
- y-axis is perpendicular to the rolling direction and perpendicular to the radial direction;
- z-axis is perpendicular to the rolling direction and parallel to the radial direction.

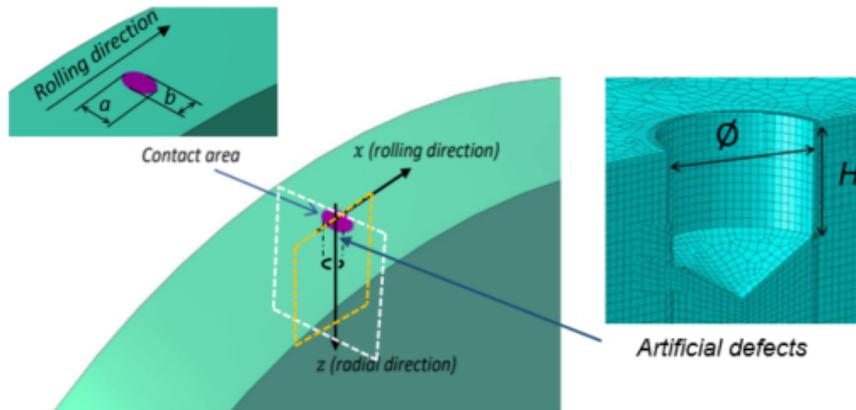


Figure 5: 3D schematic of the contact area region and artificial defects

2.2 Results

Sample # 17-1

- Normalized pressure: 0.541
- Number of cycles: 2×10^7
- Material: untreated
- Defect size: $\text{Ø}0.4 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $2 \text{ }\mu\text{m}$
- Crack length perpendicular to rolling direction: $1044 \text{ }\mu\text{m}$
- Crack length perpendicular to rolling direction: $876 \text{ }\mu\text{m}$
- Name of 3D image: 17-1-Lab.tif

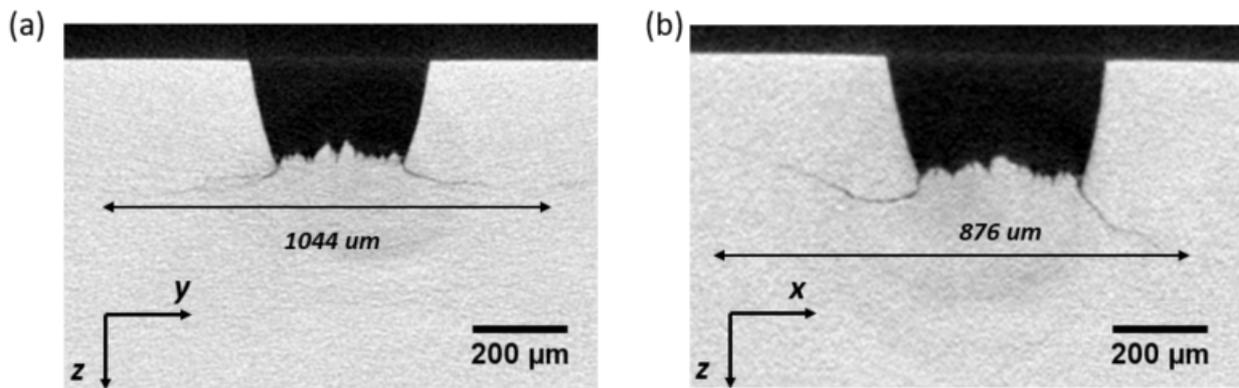


Figure 6: Lab CT results (voxel size 2 μm) of sample 17-1 taken from a bi-disc specimen run at $P/P_{max}=0.541$ and after 2×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $1044 \text{ }\mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $876 \text{ }\mu\text{m}$.

Sample # 17-2

- Normalized pressure: 0.541
- Number of cycles: 2×10^7
- Material: untreated
- Defect size: $\text{Ø}0.4 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $2 \text{ }\mu\text{m}$
- Crack length perpendicular to rolling direction: $1023 \text{ }\mu\text{m}$
- Crack length perpendicular to rolling direction: $789 \text{ }\mu\text{m}$
- Name of 3D image: 17-2-Lab.tif

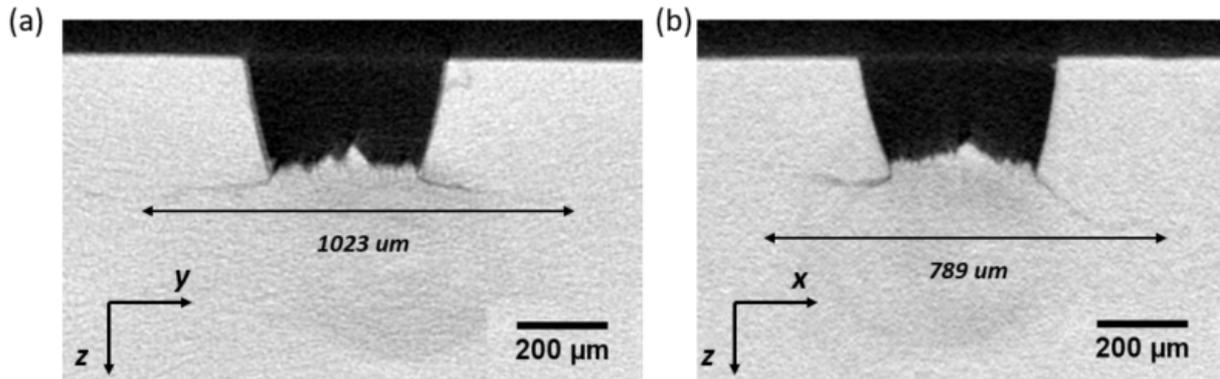


Figure 7: Lab CT results (voxel size 2 μm) of sample 17-2 taken from a bi-disc specimen run at $P/P_{max}=0.541$ and after 2×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $1023 \text{ }\mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $789 \text{ }\mu\text{m}$.

Sample # 21-1

- Normalized pressure: 0.705
- Number of cycles: 1.1×10^7
- Material: untreated
- Defect size: $\text{Ø}0.4 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $2.5 \mu\text{m}$
- Crack length perpendicular to rolling direction: $2020 \mu\text{m}$
- Crack length perpendicular to rolling direction: $1192 \mu\text{m}$
- Name of 3D image: 21-1-Lab.tif

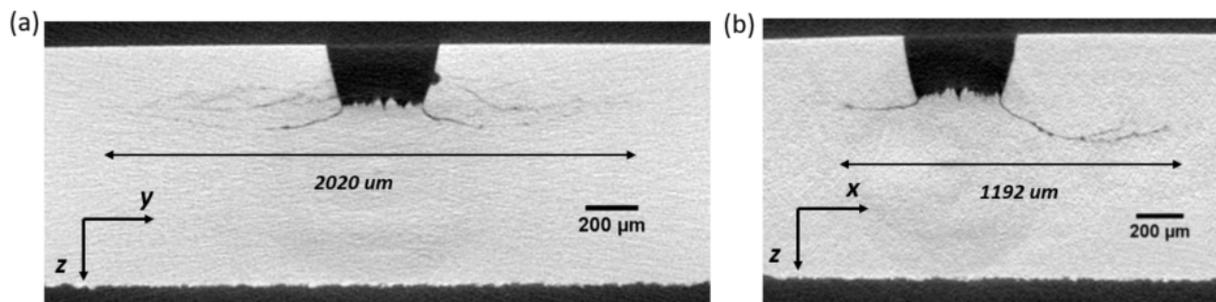


Figure 8: Lab CT results (voxel size $2.5 \mu\text{m}$) of sample 21-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.705$ and after 1.1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $2020 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $1192 \mu\text{m}$.

Sample # 19-1

- Normalized pressure: 0.794
- Number of cycles: 4.3×10^6
- Material: untreated
- Defect size: $\text{Ø}0.4 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $2.5 \text{ }\mu\text{m}$
- Crack length perpendicular to rolling direction: $2048 \text{ }\mu\text{m}$
- Crack length perpendicular to rolling direction: $1610 \text{ }\mu\text{m}$
- Name of 3D image: 19-1-Lab.tif

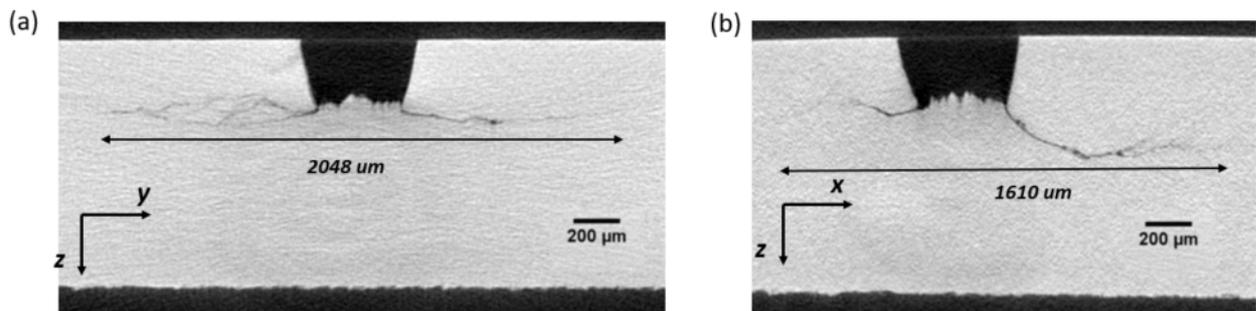


Figure 9: Lab CT results (voxel size $2.5 \text{ }\mu\text{m}$) of sample 19-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.794$ and after 4.3×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $2048 \text{ }\mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $1610 \text{ }\mu\text{m}$.

Sample # 20-1

- Normalized pressure: 0.866
- Number of cycles: 5.6×10^5
- Material: untreated
- Defect size: $\text{Ø}0.4 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $2.5 \mu\text{m}$
- Crack length perpendicular to rolling direction: $1850 \mu\text{m}$
- Crack length perpendicular to rolling direction: $1365 \mu\text{m}$
- Name of 3D image: 20-1-Lab.tif

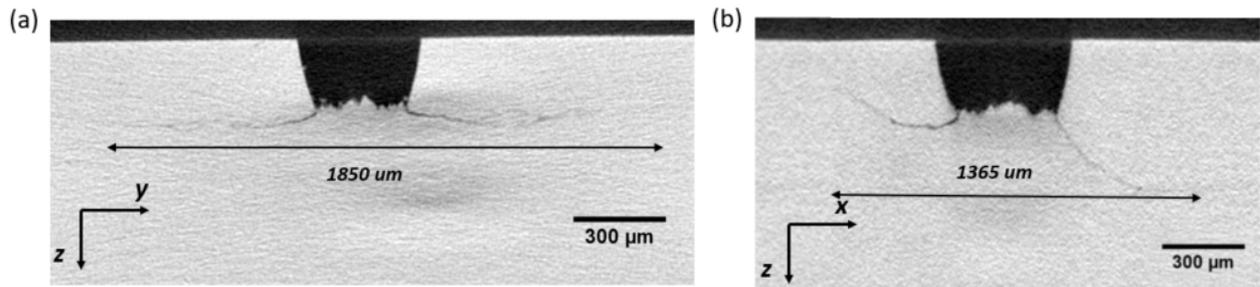


Figure 10: Lab CT results (voxel size $2.5 \mu\text{m}$) of sample 20-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.866$ and after 5.6×10^5 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $1850 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $1365 \mu\text{m}$.

Sample # 22-1

- Normalized pressure: 1
- Number of cycles: 1.3×10^5
- Material: untreated
- Defect size: $\text{Ø}0.4 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $3 \mu\text{m}$
- Crack length perpendicular to rolling direction: $1568 \mu\text{m}$
- Crack length perpendicular to rolling direction: $929 \mu\text{m}$
- Name of 3D image: 22-1-Lab.tif

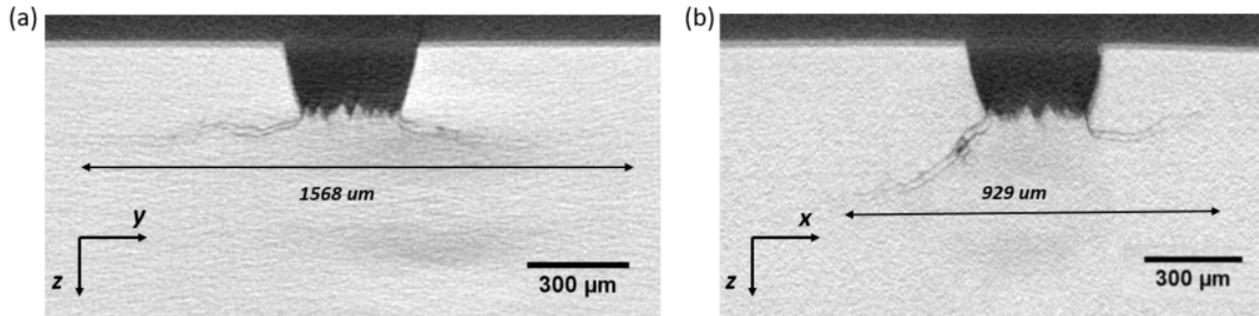


Figure 11: Lab CT results (voxel size 3 μm) of sample 22-1 taken from a bi-disc specimen run at $P/P_{max}=1$ and after 4.34×10^5 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $1568 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $929 \mu\text{m}$.

Sample # 1-1

- Normalized pressure: 0.874
- Number of cycles: 1×10^7
- Material: heat treated material
- Defect size: $\varnothing 0.4 \text{ mm} \times H0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $3 \mu\text{m}$
- Crack length perpendicular to rolling direction: $492 \mu\text{m}$
- Crack length perpendicular to rolling direction: $370 \mu\text{m}$
- Name of 3D image: 1-1-Lab.tif

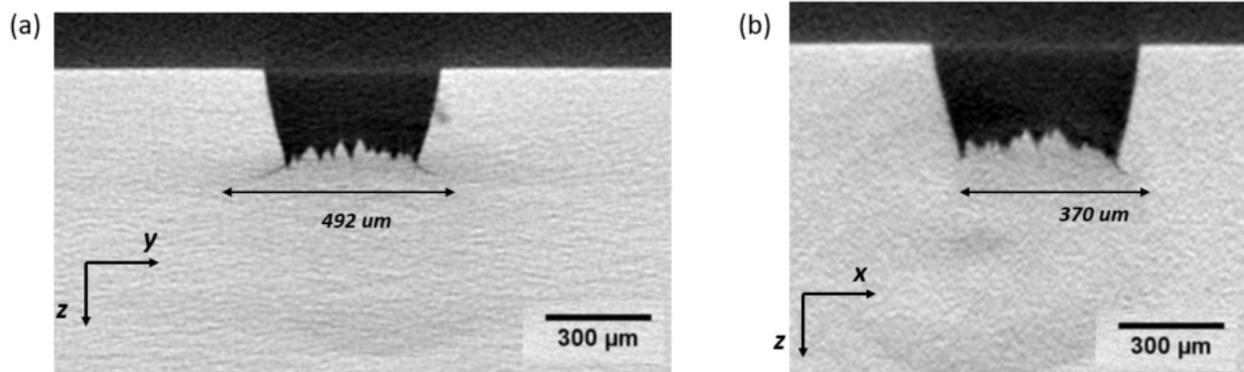


Figure 12: Lab CT results (voxel size $3 \mu\text{m}$) of sample 1-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $492 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $370 \mu\text{m}$.

- CT type: synchrotron tomography
- Voxel size: $0.7 \mu\text{m}$
- Crack length perpendicular to rolling direction: $902 \mu\text{m}$
- Crack length perpendicular to rolling direction: $410 \mu\text{m}$
- Name of 3D image: 1-1-Syn.tif

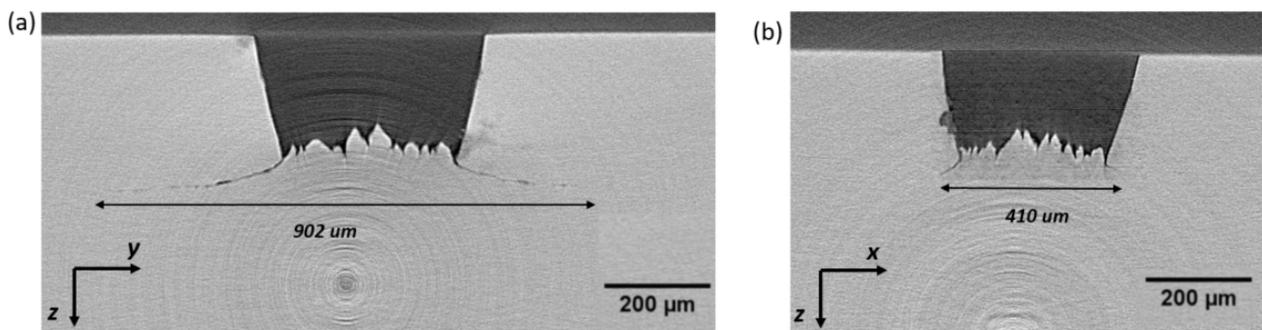


Figure 13: Syn CT results (voxel size $0.7 \mu\text{m}$) of sample 1-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $902 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $410 \mu\text{m}$.

Sample # 1-2

- Normalized pressure: 0.874
- Number of cycles: 1×10^7
- Material: heat treated material
- Defect size: $\varnothing 0.4 \text{ mm} \times H0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $3 \mu\text{m}$
- Crack length perpendicular to rolling direction: $575 \mu\text{m}$
- Crack length perpendicular to rolling direction: $410 \mu\text{m}$
- Name of 3D image: 1-2-Lab.tif

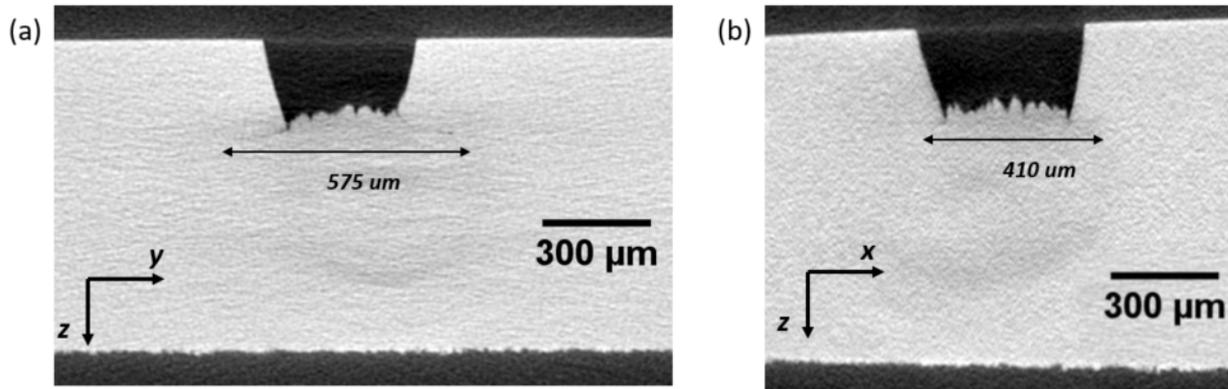


Figure 14: Lab CT results (voxel size $3 \mu\text{m}$) of sample 1-2 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $575 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $410 \mu\text{m}$.

- CT type: synchrotron tomography
- Voxel size: $0.7 \mu\text{m}$
- Crack length perpendicular to rolling direction: $834 \mu\text{m}$
- Crack length perpendicular to rolling direction: $417 \mu\text{m}$
- Name of 3D image: 1-2-Syn.tif

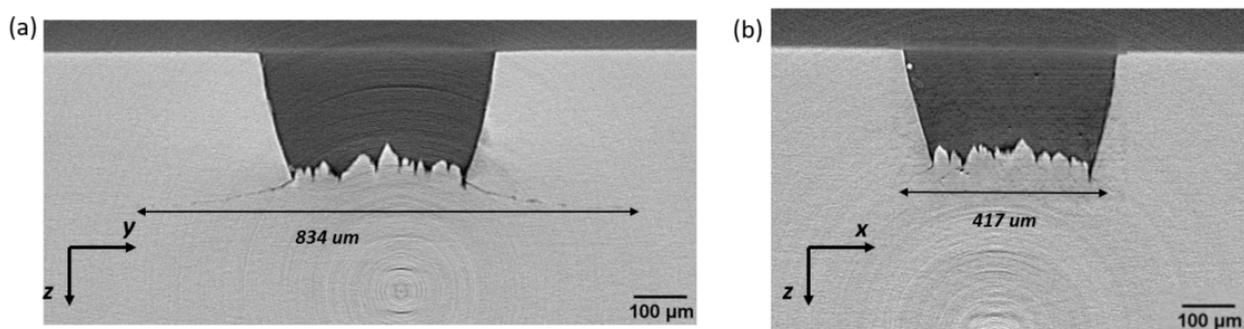


Figure 15: Syn CT results (voxel size $0.7 \mu\text{m}$) of sample 1-2 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $834 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, crack length: $417 \mu\text{m}$.

Sample # 2-1

- Normalized pressure: 0.616
- Number of cycles: 1×10^7
- Material: heat treated material
- Defect size: $\varnothing 0.4 \text{ mm} \times H0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $2.5 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 2-1-Lab.tif

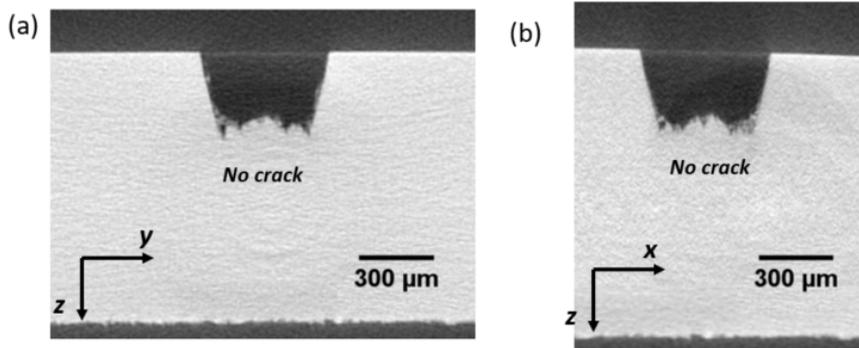


Figure 16: Lab CT results (voxel size $3 \mu\text{m}$) of sample 2-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.616$ and after 1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, no crack has been observed. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

- CT type: synchrotron tomography
- Voxel size: $0.7 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 2-1-Syn.tif

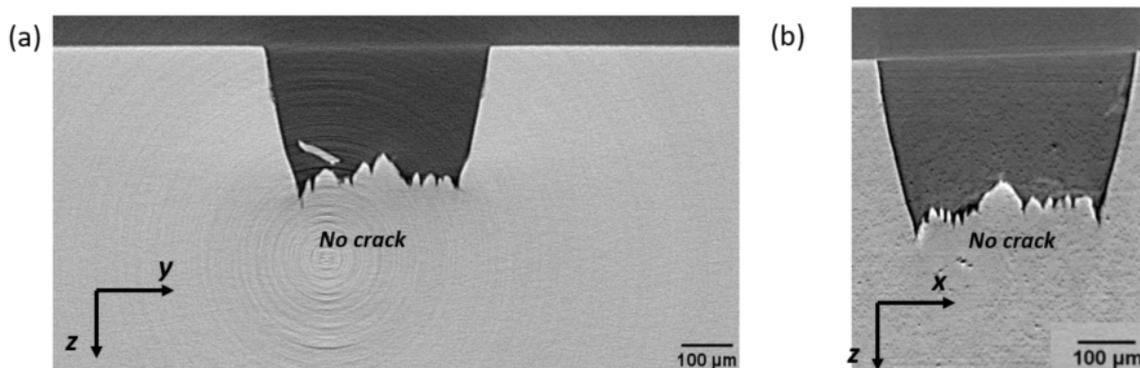


Figure 17: Syn CT results (voxel size $0.7 \mu\text{m}$) of sample 2-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.616$ and after 1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, no crack has been observed. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

Sample # 2-2

- Normalized pressure: 0.616
- Number of cycles: 1×10^7
- Material: heat treated material
- Defect size: $\varnothing 0.4 \text{ mm} \times H0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $2.5 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 2-2-Lab.tif

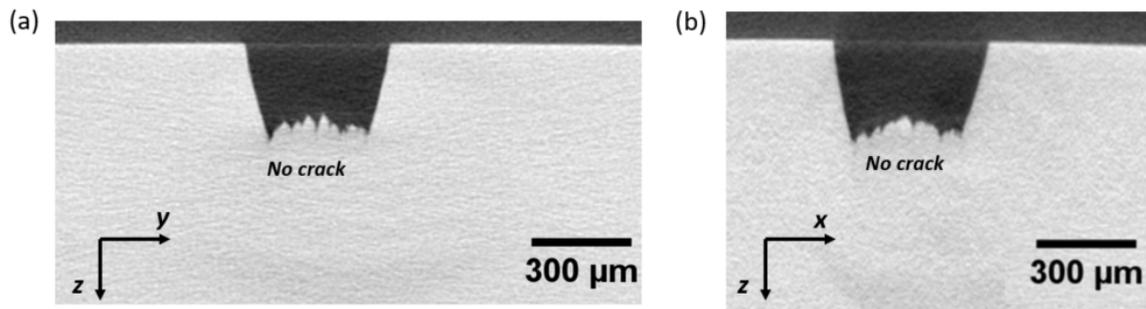


Figure 18: Lab CT results (voxel size $3 \mu\text{m}$) of sample 2-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.616$ and after 1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, no crack has been observed. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

- CT type: synchrotron tomography
- Voxel size: $0.7 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 2-2-Syn.tif

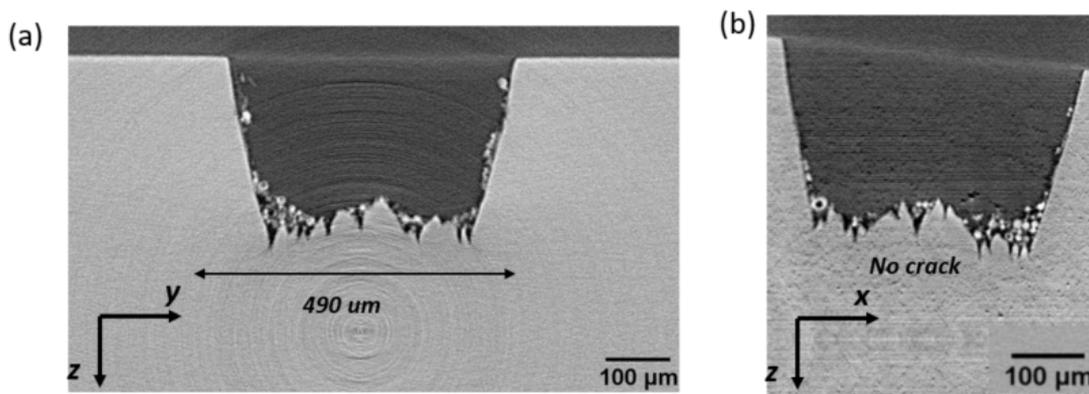


Figure 19: Syn CT results (voxel size $0.7 \mu\text{m}$) of sample 2-2 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.616$ and after 1×10^7 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $490 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

Sample # 3-1

- Normalized pressure: 0.874
- Number of cycles: 1×10^6
- Material: heat treated material
- Defect size: $\text{Ø}0.4 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $3 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 3-1-Lab.tif

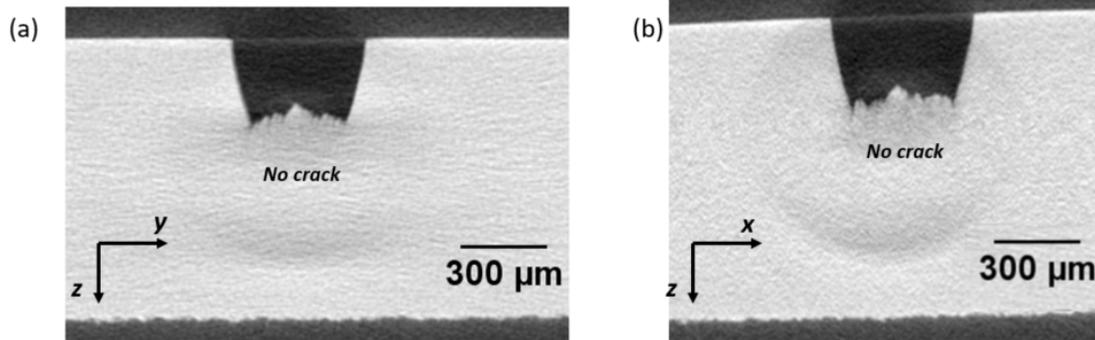


Figure 20: Lab CT results (voxel size $3 \mu\text{m}$) of sample 3-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, no crack has been observed. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

- CT type: synchrotron tomography
- Voxel size: $0.7 \mu\text{m}$
- Crack length perpendicular to rolling direction: $449 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 3-1-Syn.tif

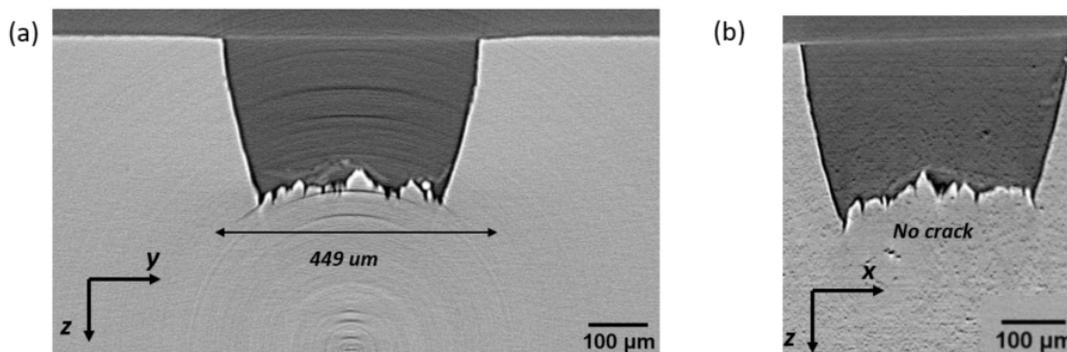


Figure 21: Syn CT results (voxel size $0.7 \mu\text{m}$) of sample 3-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $449 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

Sample # 3-2

- Normalized pressure: 0.874
- Number of cycles: 1×10^6
- Material: heat treated material
- Defect size: $\varnothing 0.4 \text{ mm} \times H0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $3 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 3-2-Lab.tif

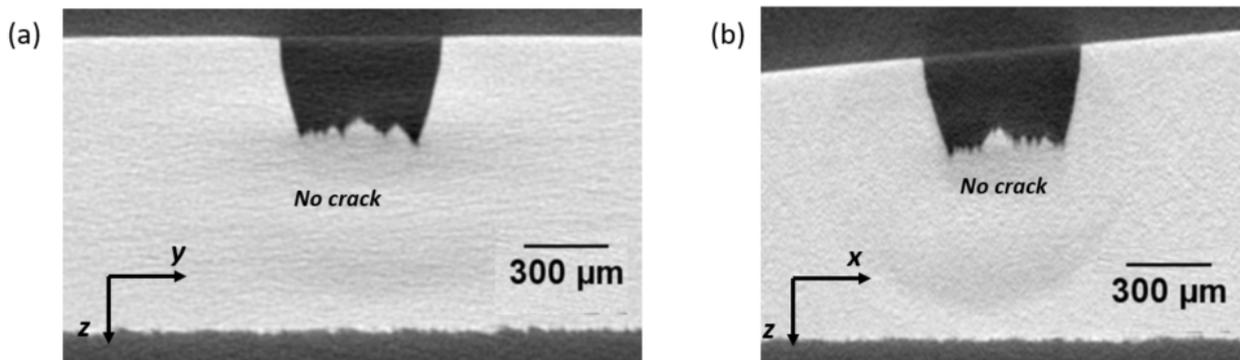


Figure 22: Lab CT results (voxel size $3 \mu\text{m}$) of sample 3-2 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, no crack has been observed. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

- CT type: synchrotron tomography
- Voxel size: $0.7 \mu\text{m}$
- Crack length perpendicular to rolling direction: $442 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 3-2-Syn.tif

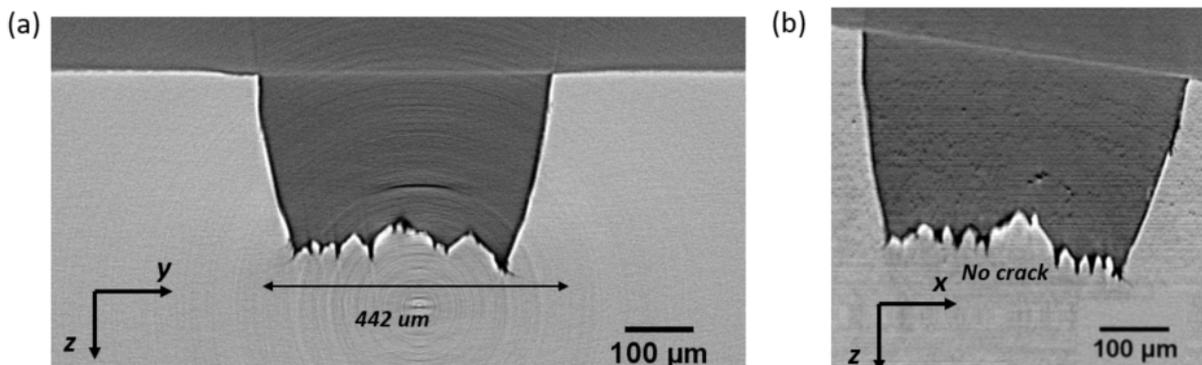


Figure 23: Syn CT results (voxel size $0.7 \mu\text{m}$) of sample 3-2 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $442 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

Sample # 7-1

- Normalized pressure: 1
- Number of cycles: 1×10^6
- Material: heat treated material
- Defect size: $\text{Ø}0.2 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $3 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 7-1-Lab.tif

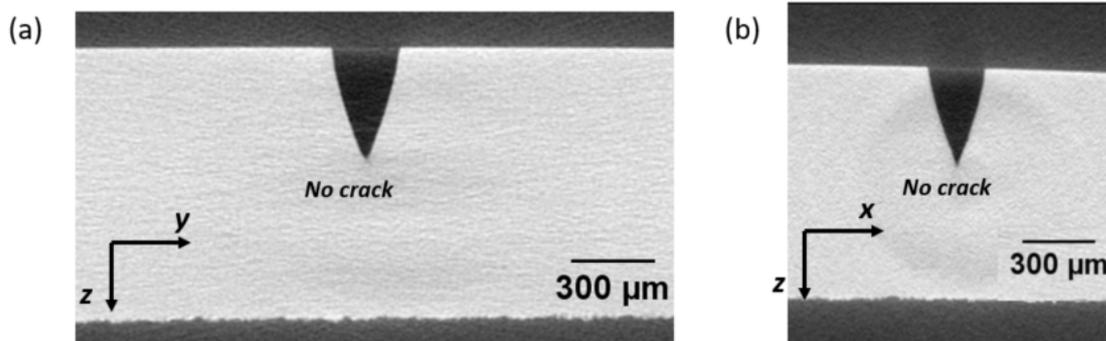


Figure 24: Lab CT results (voxel size $3 \mu\text{m}$) of sample 7-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=1$ and after 1×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, no crack has been observed. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

- CT type: synchrotron tomography
- Voxel size: $0.7 \mu\text{m}$
- Crack length perpendicular to rolling direction: $369 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 7-1-Syn.tif

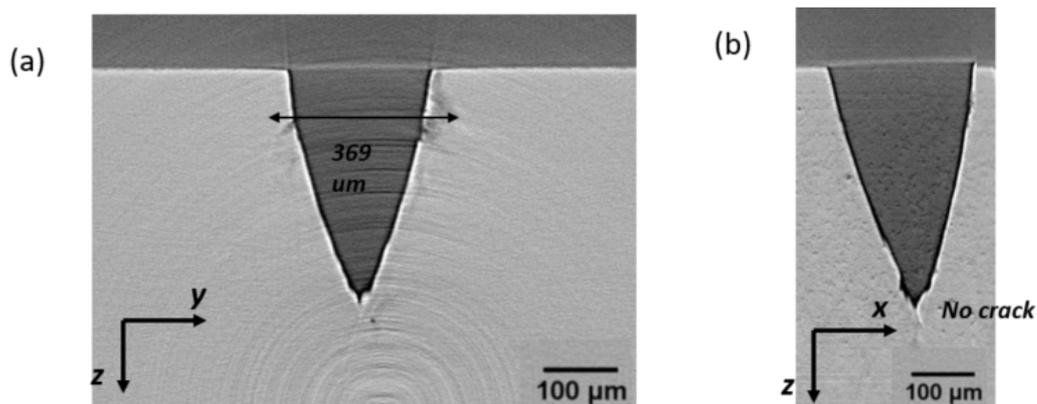


Figure 25: Syn CT results (voxel size $0.7 \mu\text{m}$) of sample 7-1 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $369 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

Sample # 7-2

- Normalized pressure: 1
- Number of cycles: 1×10^6
- Material: heat treated material
- Defect size: $\text{Ø}0.2 \text{ mm} \times \text{H}0.27 \text{ mm}$
- CT type: laboratory tomography
- Voxel size: $3 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 7-2-Lab.tif

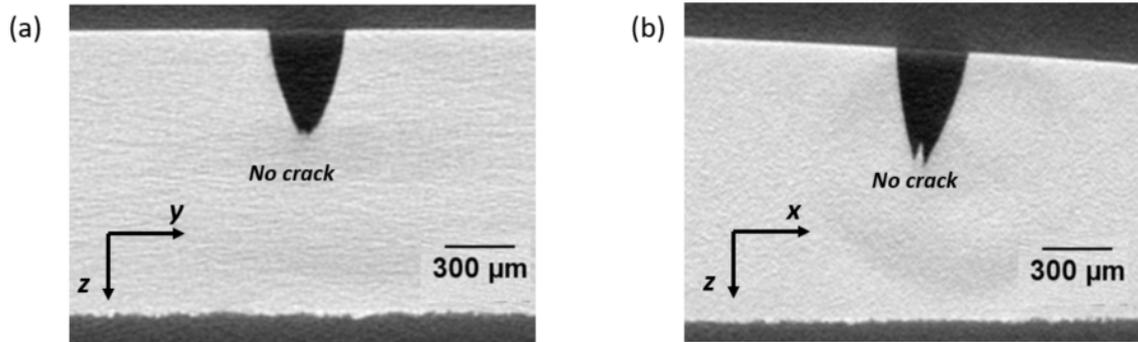


Figure 26: Lab CT results (voxel size $3 \mu\text{m}$) of sample 7-2 taken from a bi-disc specimen run at $P/P_{\text{max}}=1$ and after 1×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, no crack has been observed. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

- CT type: synchrotron tomography
- Voxel size: $0.7 \mu\text{m}$
- Crack length perpendicular to rolling direction: $369 \mu\text{m}$
- Crack length perpendicular to rolling direction: no crack
- Name of 3D image: 7-2-Syn.tif

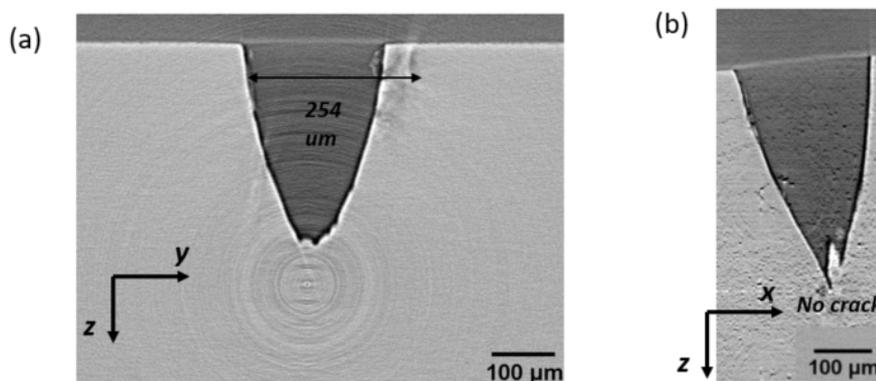


Figure 27: Syn CT results (voxel size $0.7 \mu\text{m}$) of sample 7-2 taken from a bi-disc specimen run at $P/P_{\text{max}}=0.874$ and after 1×10^6 cycles. (a) C Reconstructed slice corresponding to the dashed white line in Figure 1, crack length: $254 \mu\text{m}$. (b) Reconstructed slice corresponding to the dashed yellow line in Figure 1, no crack has been observed.

3. Conclusions

Rolling contact fatigue tests were performed using a bi-disk test configuration. To foster crack initiation, two cylindrical artificial defects with various depth and diameters were machined on the rolling track of one disk. Two materials conditions (heat-treated and untreated) and various normal pressures P were investigated. The tests were stopped when a spall on the rolling track was detected or when a given number of cycles was reached (10^6 or 10^7). For all the test conditions investigated, sub surface cracks initiated at the bottom of the artificial holes. Their length was measured along the rolling direction (mode II propagation) and perpendicular to it (mode III). For the material with the higher yield stress, the smaller size of the cracks required some synchrotron observations with higher resolution (smaller voxel size) while for the material in the untreated condition cracks could be observed using laboratory tomography.