3D Observation of Rolling Contact Fatigue Crack Network in Nitrided Alloyed Steels

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Context

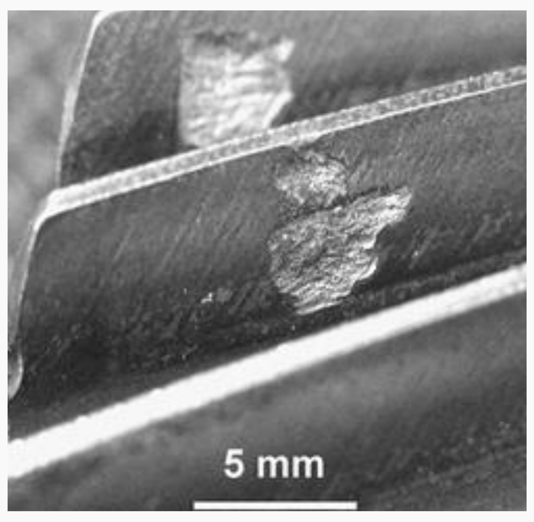


Fig.1 Pitting on tooth flanks

Gas nitriding increases the hardness and introduces compressive residual stresses to the component surfaces. It is therefore widely used by gear manufacturers **to avoid Rolling Contact Fatigue (RCF) crack initiation and propagation** at the origin of failures called **micro-pitting** and **pitting** (Fig. 1).

Nitriding some alloyed steels as the 33CrMoV12-9 grade however **precipitates intergranular carbides, specifically flat compared with the surface, which seem to make RCF crack growth easier** as revealed by previous 2D experimental analysis **[1].**

To support this last statement, this study focuses on **3D observations of the whole crack network** by using high energy X-ray (XR) tomography. This would finally help **understanding RCF behavior differences of various nitrided layers with different intergranular carbide network morphologies, while mechanical properties are similar** (Fig.6).

Test rig and procedures of analysis

A twin-disc machine was used (Fig.2). Contact conditions were defined to reproduce a specific RCF gear failure called **surface initiated pitting.**

Hertz pressure	Rolling speed	Slide to roll ratio	Oil temperature	Roughness	Material
2.1 GPa	3000 rpm	6.5%	80°C	Ra 0,05 µm	33CrMoV12-9

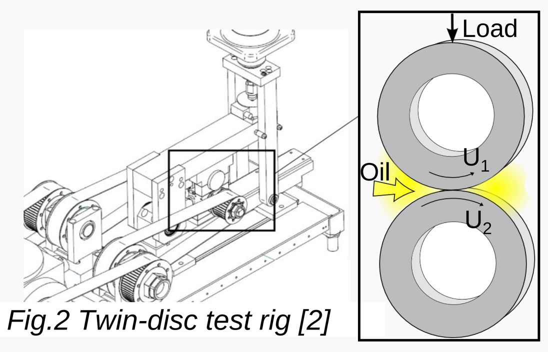


Fig.2 Twin-disc test rig [2]

At the end of the tests, samples displaying surface damages were extracted from the nitrided discs, mounted, and polished in order to observe cracks on 2D cross sections (Fig.3).

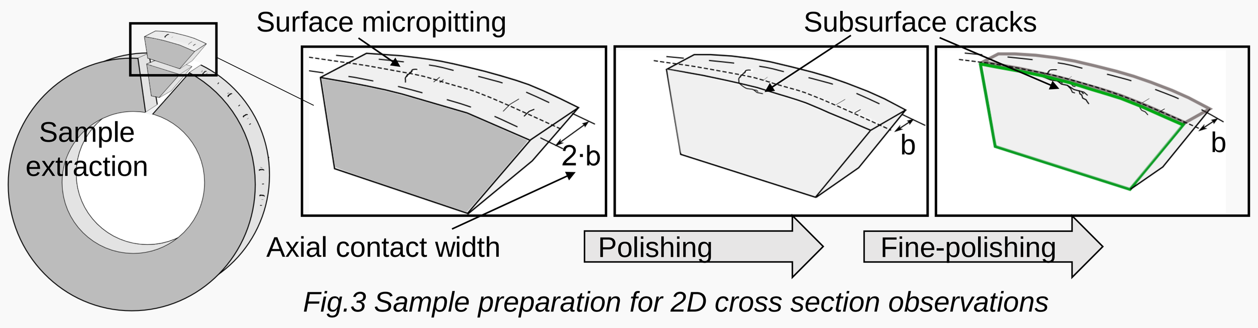


Fig.3 Sample preparation for 2D cross section observations

One of those samples was reduced to a smaller volume containing half of a RCF crack network for 3D analysis (Fig.4).

High energy XR tomography is then used to **observe the non-destructed remaining part of the crack network inside the sample**, by collecting non-absorbed XR going through the volume [3]. More exactly, ***n*** 2D scanned images of the sample in ***n*** positions were recorded by a sensor and computed to generate a **3D image** (Fig.5).

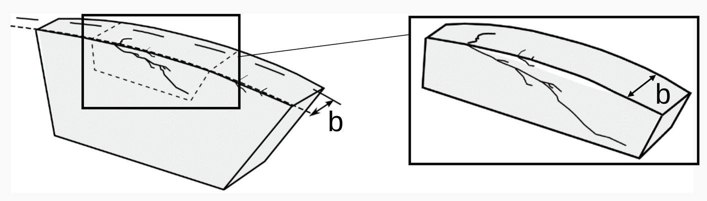


Fig.4 Extraction of a smaller sample containing half of the crack network

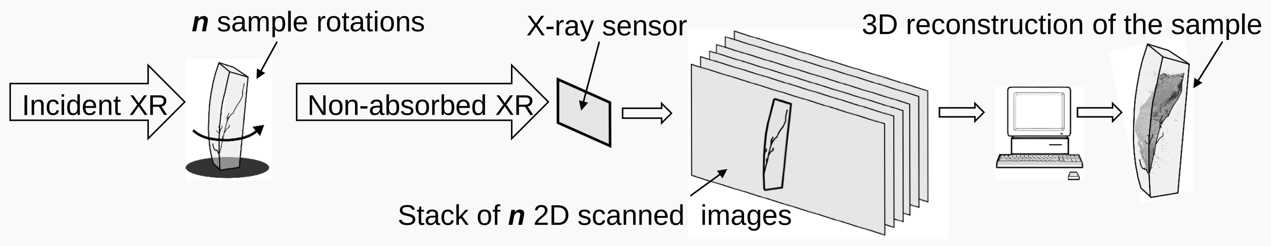


Fig.5 X-ray computed tomography, a 3D imaging technique

Resistance of the tested nitrided layers to surface initiated pitting

Two batches of specimens were austenized at two temperatures to obtain two grain size steels (thin and coarse) compatible with the material qualities recommended in standards [4]. After nitriding, their **carbide network morphologies are different** (Fig.6, a), while their **hardness and compressive residual stress profiles are equivalent throughout** the nitrided layers (Fig.6, b).

After the tests, specimens show similar surface micropit and subsurface crack lengths at a larger number of cycles for the thin microstructures.

Surface initiated pitting resistance is then greater for thin grains and carbide networks (Fig.6, c).

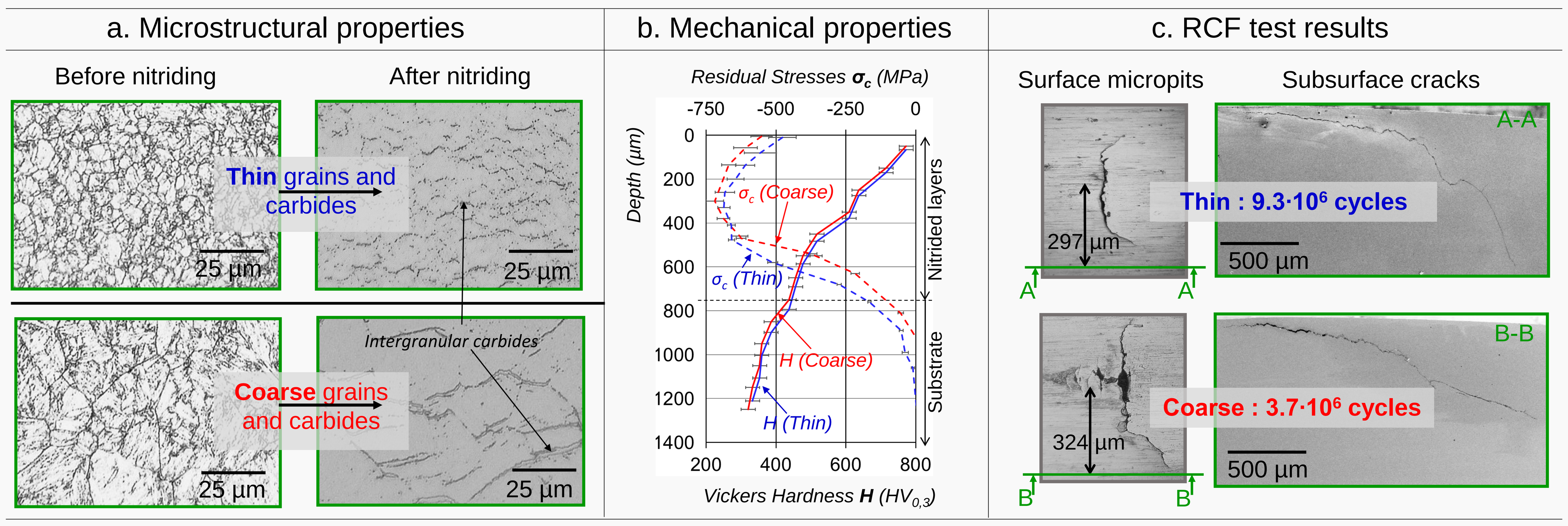


Fig.6 Microstructural and mechanical properties of the tested thin and coarse microstructure nitrided layers, and their resistance to surface initiated pitting

Influence of intergranular carbide on RCF crack propagation

3D-view of the crack network reveals that **two crack propagation mechanisms** occurred during RCF tests throughout the nitrided layers. They are illustrated by a first **cup-shaped fracture surface** separated by the dashed-blue line from a second **striped fracture surface** (Fig.7).

Comparing with a cross section parallel to the surface realized within the nitrided layer where carbide are present (Fig,8), **the shape of the intergranular precipitates seems to match the cup-shaped fracture surface.**

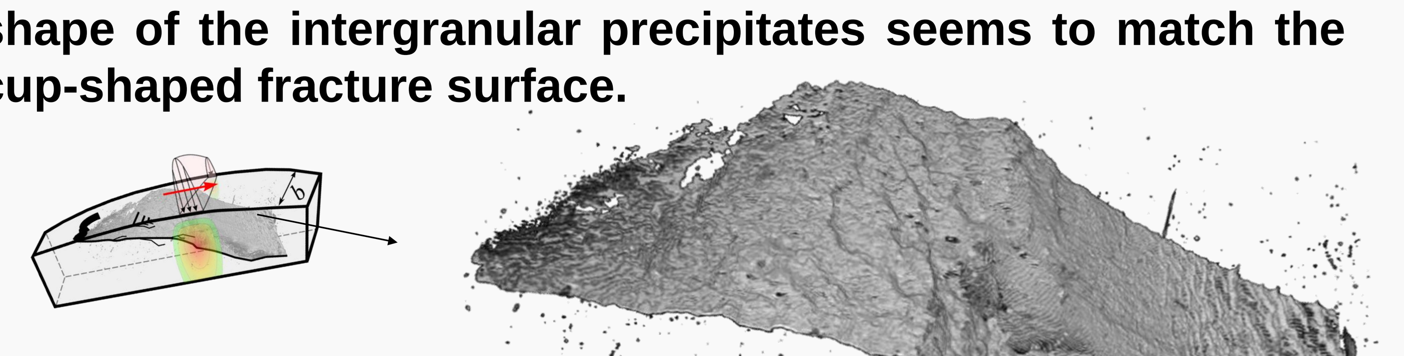


Fig.7 3D view of the crack network within the RCF tested nitrided layer

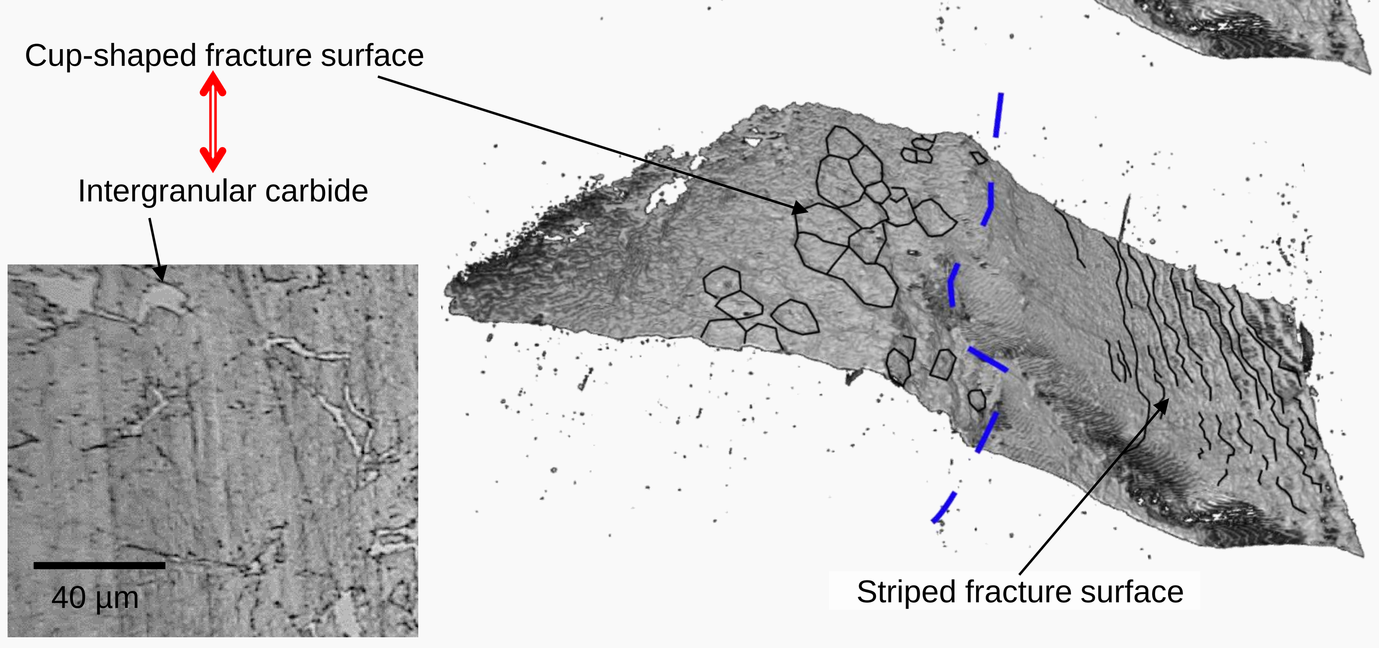


Fig.8 Cross section parallel to the surface in a nitrided layer

Superposition of all the RX scanned images parallel to the surface gives rise to an image which appears like a fractography captured by SEM (Fig.9). This figure also highlights the fracture surfaces described above.

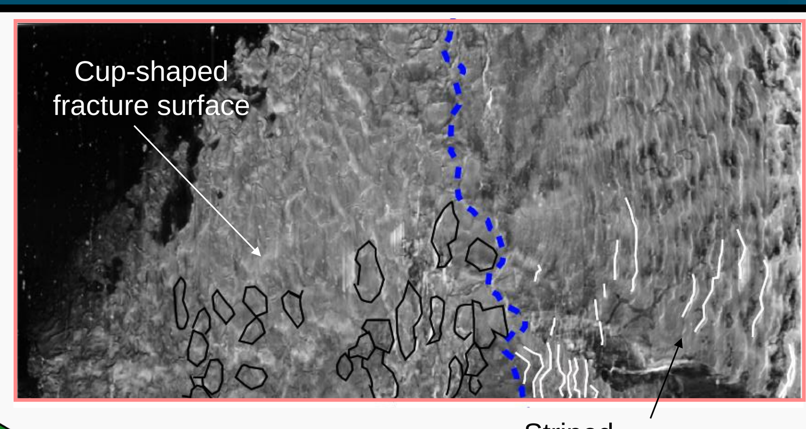
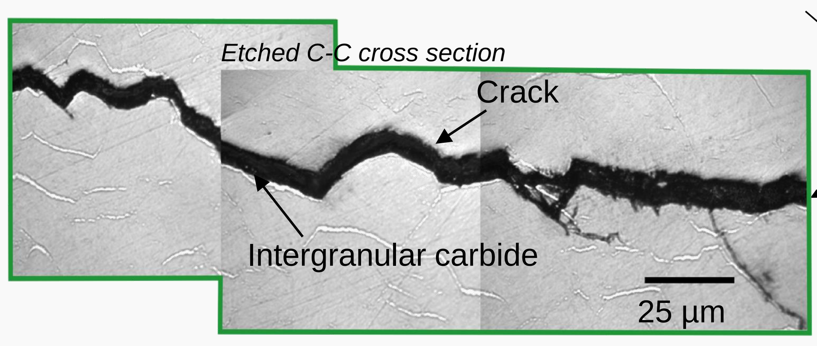


Fig.9 Superposition of scanned images parallel to the surface

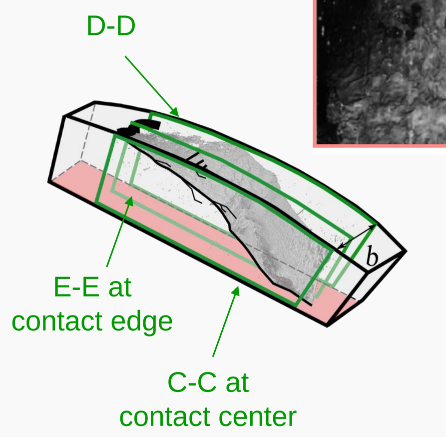
2D scanned images at different distances from the contact center also show the presence of two fracture mechanisms (Fig.10).

The etched C-C cross section near the contact center reveals **carbides along some crack path parts in the nitrided layer,** confirming **the role of carbides on the cup-shaped fracture surface**.



Moreover, scanned images near the contact center show that the limit between the two fracture mechanisms corresponds to the limit of the presence of carbides within the nitrided layer. Thus, **cracks propagate through the carbides near the initiation site as long as the crack network dimension is small.**

In contrast, on scanned images towards the contact edge, the cup-shaped fracture surface boundary is limited to a flat path more or less parallel to the surface like the carbides, which is besides located in a superficial stress-free zone. Hence, **when cracks grow away from the contact center, the network gets wider and the crack path is affected by the carbides only where contact shear stresses are low.**



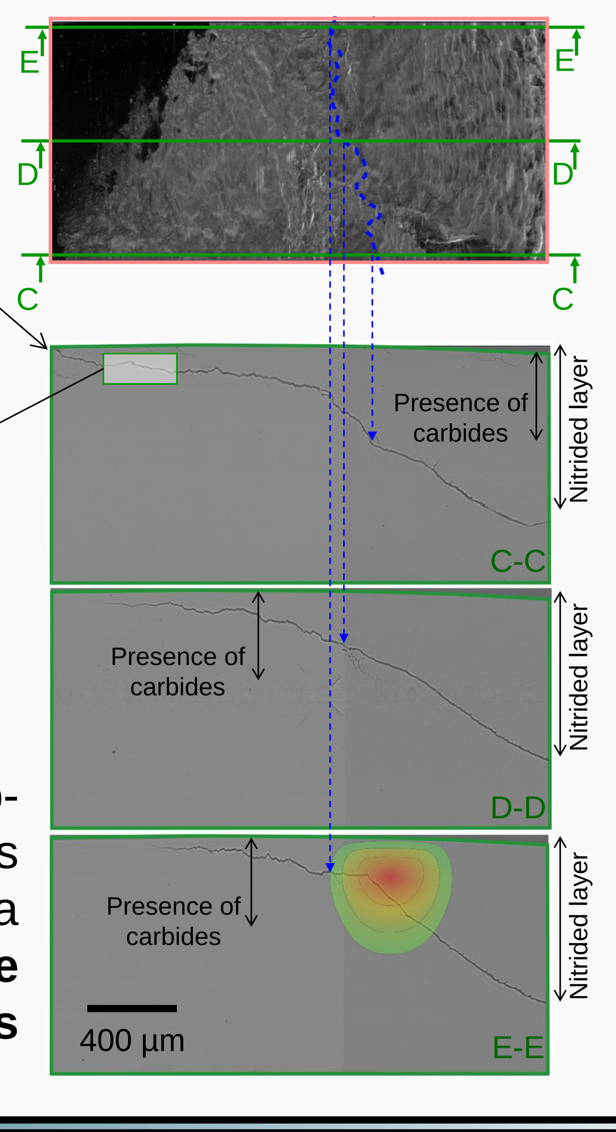


Fig.10 Scanned images at different distances from the contact center

Conclusion and future work

- Surface initiated pitting resistance is greater for nitrided specimens with thin grains and carbide networks compared with coarser microstructures, even if their mechanical properties are equivalent.
- 3D analysis are consistent with previous 2D studies, confirming that the carbides make crack growth easier **when crack lengths are small** and **where contact shear stresses are low**. These observations explain why different nitrided layers with similar mechanical properties but different carbide network morphologies do not equally resist to RCF failures.

Ongoing work aiming to test other microstructures and contact conditions would help better understanding the crack propagation scenarios.

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