Characterising the impact of surface integrity on the fatigue behaviour of a shot-peened connecting rod

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Abstract

The present study focuses on analysing and modelling the influence on fatigue behaviour of the surface of a hot-forged C70 connecting rod which undergoes a shot-blasting treatment. The shot-blasting heavily affects the surface and thus the fatigue properties. In addition, the forging process introduces large defects which also have an effect on the fatigue strength. So as to be able to determine which aspects of the surface integrity are the most influential in fatigue, additional surface states were generated by shot-peening the as-forged surface. The various surface states were thoroughly characterised and then tested in high cycle fatigue in bending. The various aspects studied are the surface roughness and large defects, residual stresses, and microstructure.

Keywords High cycle fatigue, residual stresses, large defects, roughness, microstructure.

Introduction

Shot-blasting and shot-peening affect many properties of the treated surface in addition to modifying its topography. They affect the microstructure of the component, its hardness and roughness and introduce residual stresses. This leads to a modification of the component's behaviour in high cycle fatigue. The effects of shot-peening on fatigue behaviour have already been extensively studied [1,2]. However, in addition to the homogenous roughness, the studied components feature large defects before and after shot-blasting or shot-peening, which also have a noticeable effect on fatigue. The effects of shot-peening and defects on fatigue behaviour have been separately studied, and the main focus of this paper is the combined effect of both shot-peening and forging surface defects.

This study is part of a French national research project, DEFISURF, involving nine partners from the metal supplier to the final user (French car maker). Its object is to study the influence of surface integrity on the fatigue behaviour of two forged components. The first is a hot-forged connecting rod and the second is a cold-forged fatigue test specimen.

The project has two parts: simulation of the industrial processes, and modelling the fatigue crack initiation and propagation in the forged surface. The current paper will focus on the fatigue aspect of the first component: a C70 pearlitic steel hot-forged connecting rod which is then shot-blasted to clean off the scale. This shot-blasting process has a very large influence on the fatigue strength of the component. Some connecting rods feature large forging defects which have an impact in fatigue. 500 consecutive as-forged connecting rods (without the usual shot-blasting process) were sampled from the production line, as were an additional 500 consecutive shot-blasted connecting rods. This large sample allows for a statistical study of the surface integrity and the extrapolation to the entire production. To investigate other surface integrity conditions, various shot-peening treatments are performed on as-forged specimens. These were cleaned of scale by hand with a metal brush.

Fatigue tests on specimens with various surface conditions are performed in addition to a thorough analysis of the different surface states. The fatigue specimens are machined out of connecting rods prior to surface treatment. Fatigue tests are performed in plane bending with a min/max stress ratio of $R = -1$ and serve to quantify the effect of surface integrity on the fatigue strength in high cycle fatigue.

Surface characterisation

Two shot-peening treatments were applied to as-forged specimens. These two treatments were chosen in order to replicate the residual stresses introduced by the shot-blasting while having different surface roughness parameters. With the as-forged surface, this leads to four different surface states. The surface integrity is characterised through residual stress analysis (X-ray diffraction), EBSD and surface topography scans. The surface state of the shot-blasted connecting rods is very close to the observations of shot-peened surfaces [3].

The residual stresses of the four surface states are given in Fig 1. The two shot-peening treatments correctly replicate the residual stress profile of the shot-blasting treatment. The as-forged surface has negligible residual stresses, therefore the high compressive residual stresses (-500 MPa) introduced at the surface by the shot-blasting/peening will have a large beneficial impact on the fatigue behaviour.

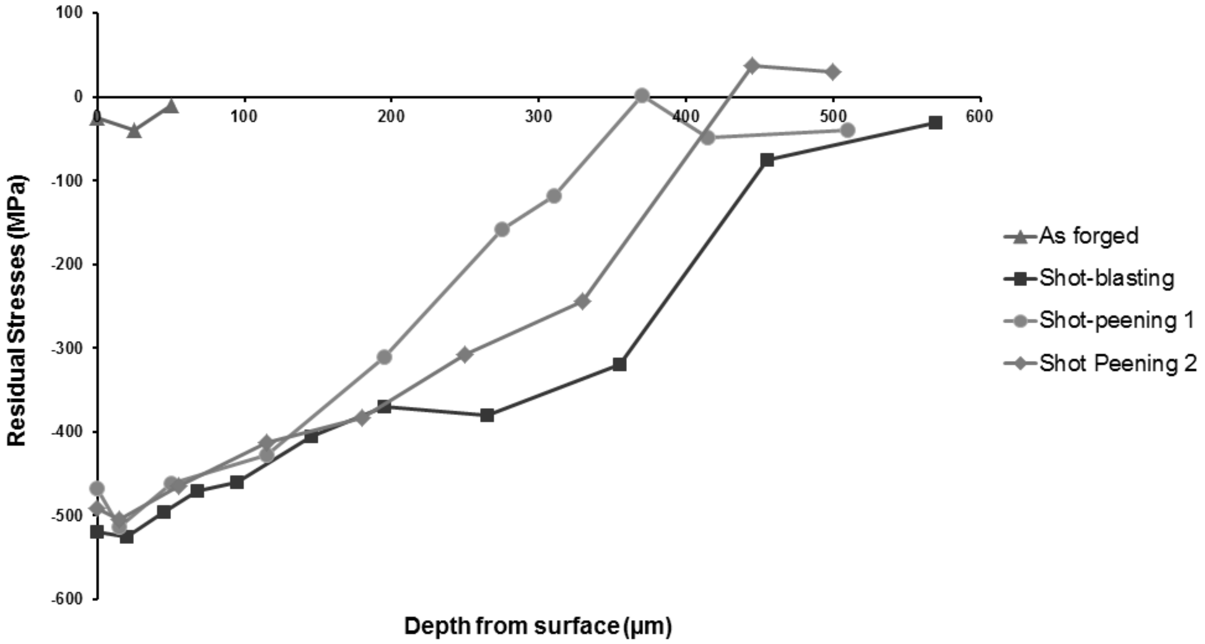

Fig 1 Residual stresses in the various surface states. The shot-blasting/peening residual stresses are similar; with their peak very close to the surface and affect the first 500 µm in depth.

The surface aspect of the connecting rods is also heavily affected by the surface treatments. However, the differences between the various surface states are poorly reflected by standard roughness parameters such as the R_a (Table 1). All the surface states have a similar R_a (between 4 and 8 µm) with the as-forged surface having the highest standard deviation. This is because the as-forged surface is an assortment of smooth areas and pitted patches. These defects appear during the forging process when scale sticks to the die, altering the final surface state (Fig 2). During the shot-blasting/peening process the smooth areas disappear, leading to a smaller standard deviation for the R_a.

	As-forged	Shot-blasting	Shot-Peening 1	Shot-peening 2
R_a µm	6.4	7.8	4.3	7.6
Std. Deviation µm	2.0	0.9	1.2	0.8

Table 1 Roughness values for the various surface states. The shot-blasting/peening only has a small effect on the average R_a parameter but reduces the standard deviation by affecting the smooth patches on the as-forged surface. Cut-off distance: 2500 µm.

The effects of shot-blasting/peening on roughness are more apparent with surface scans, where the roughness aspects introduced by local ball impacts can be seen (Fig 2). The surface scans were obtained with an optical confocal profilometer. The R_a values of the shot-blasted/peened surfaces are similar but their surface aspects are different, giving each process a recognisable surface texturing.

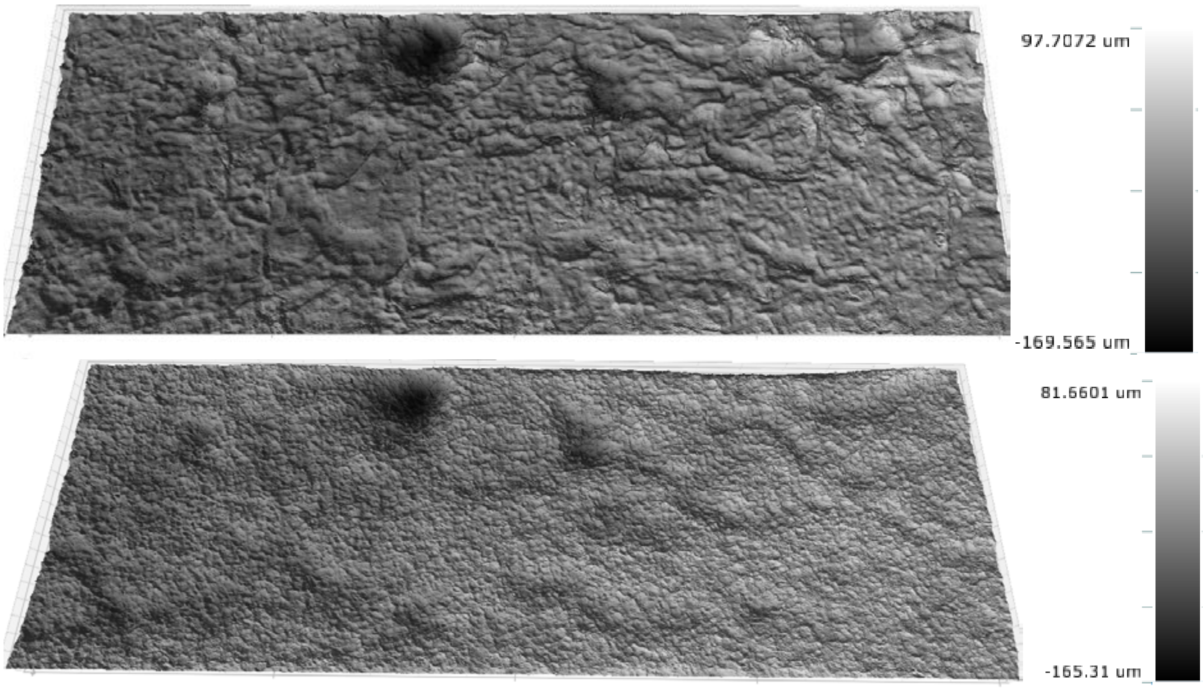

Fig 2 Surface scans (20x7 mm) of the same fatigue specimen, before (top) and after shot-peening (bottom). The residual scale in the top right corner has been removed during the shot-peening. A large defect (2.5 mm wide and 150 µm deep) can be seen.

The shot-blasting/peening process produces a smoothing of the edges of local defects, without affecting their overall shape or depth. Previous studies have shown that both roughness [4,5] and defects [6] can have a negative effect on the fatigue behaviour.

In addition to the topography, the surface microstructure is also studied through SEM and EBSD images. These show how the shot-blasting/peening affect the surface microstructure and the grain orientation.

The as-forged microstructure is homogenous with no grain size gradient at the surface. Shot-blasting heavily affects the microstructure up to a depth of 200 µm from the surface. The shot-peening microstructure is very similar to that of shot-blasting.

Four layers can be observed in the microstructure (Fig 3 & 4):

1 The utmost surface layer is 5 to 10 µm deep and is comprised of extremely small grains.
2 The second layer is 10 to 20 µm deep and has heavily deformed grains.
3 This layer is the transition between the surface and the unaffected centre material. Grains are progressively larger and less deformed, up to a depth of 150 to 200 µm.
4 Unaffected centre material, starting from 150 to 200 µm from the surface.

In addition to the microstructure gradient, shot-blasting also introduces micro defects near the surface. These can be folds (Fig 4) or cracks that run parallel to the surface. They measure around 100 µm and could provide crack initiation locations in fatigue.

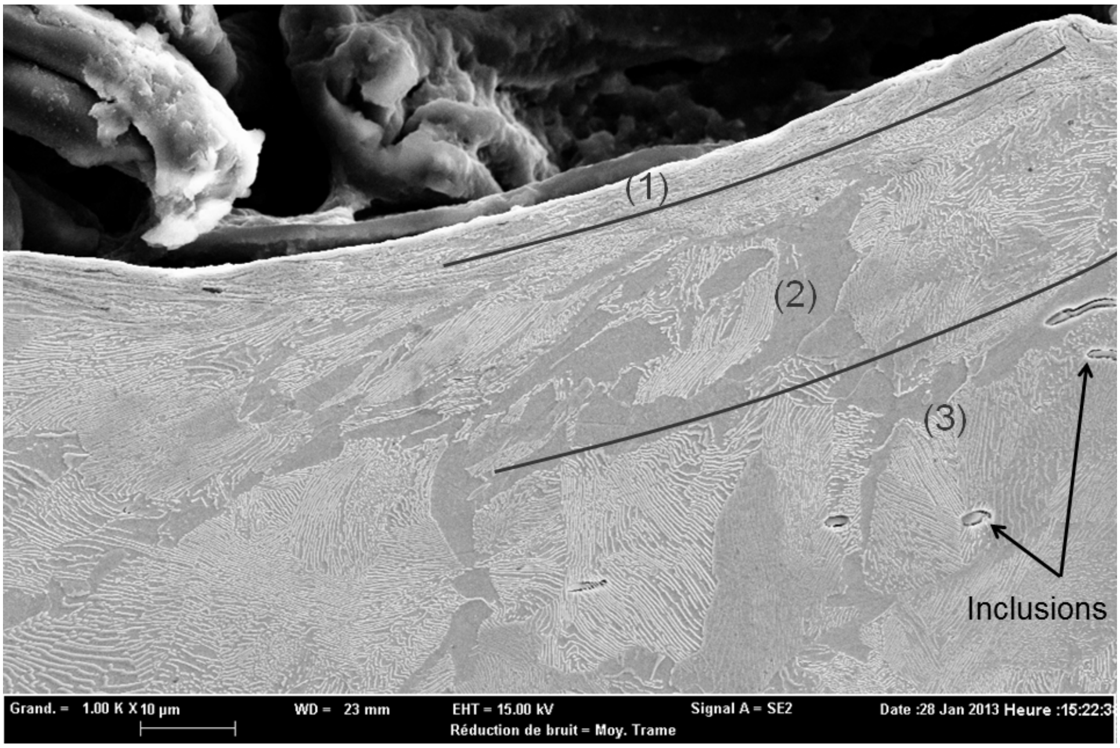

Fig 3 SEM image showing the microstructure in a shot-blasted connecting rod.

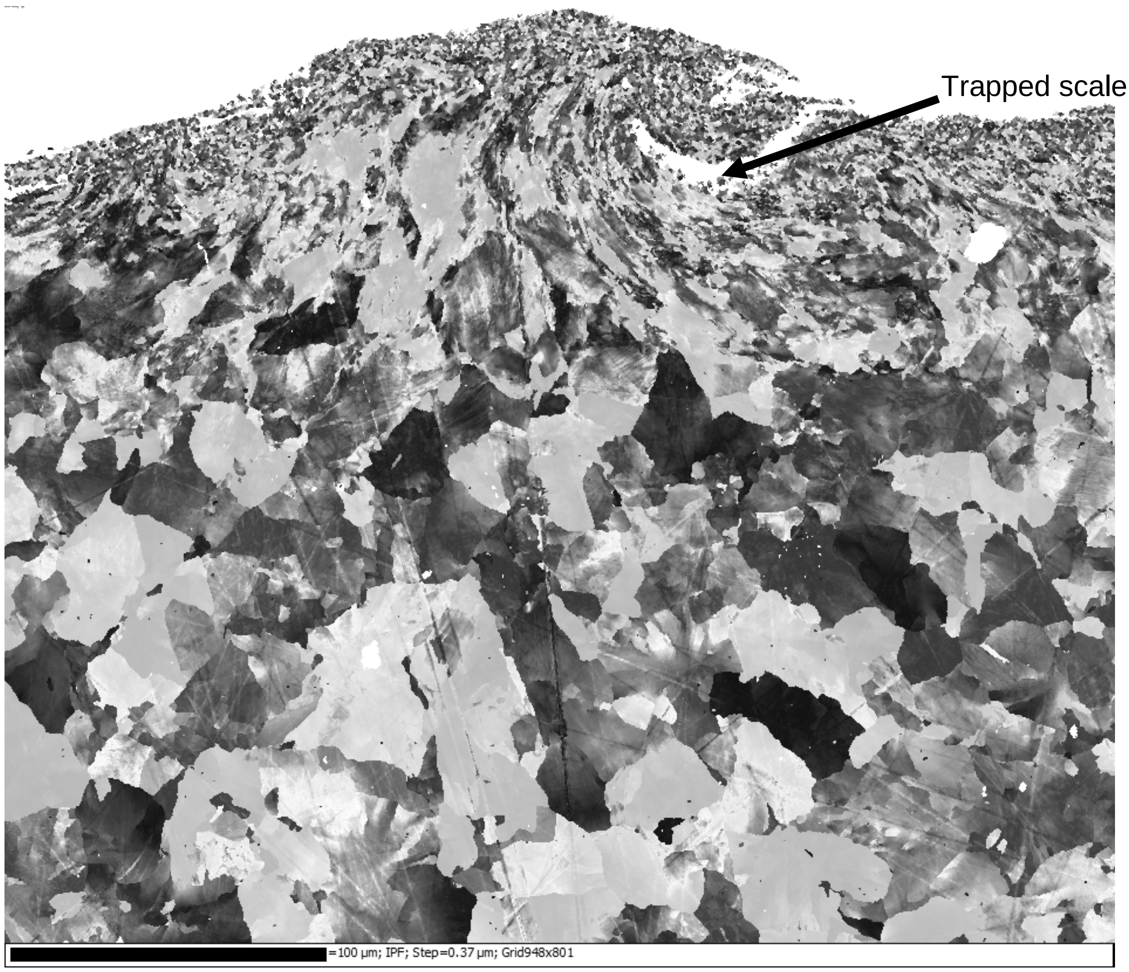

Fig 4 EBSD image of the first 300 µm in a shot-blasted connecting rod. Scale has been trapped in a 50 µm fold during the shot-blasting.

Fatigue Tests

To quantify the effects of the previously stated surface aspects on the fatigue behaviour of the component, fatigue tests were performed. Fatigue specimens were machined out of the connecting rods (Fig 5) by spark machining. The fatigue tests were performed in bending with a min/max stress ratio of R = -1 at a frequency of 70 Hz. The fatigue strength was determined at 2.10^6 cycles. Bending was chosen to concentrate the stress at the surface, thus avoiding crack initiation in the centre or the sides of the specimen. The "step" method [7] allows to quickly determine the fatigue strength of each specimen.

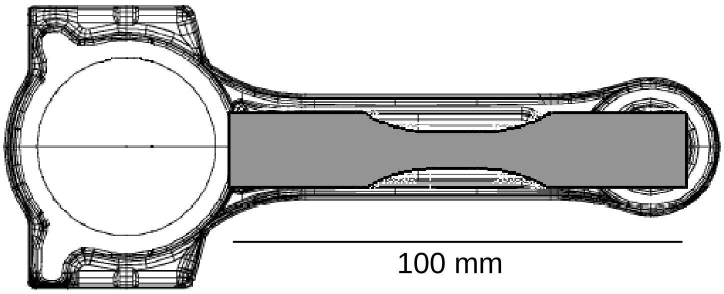

Fig 5 Connecting rod with the machined fatigue specimen. The geometry was chosen so as to extract a flat surface area from the connecting rod.

In order to have a fatigue reference, machined and polished specimens were also tested in fatigue. This additional surface state has negligible roughness, residual stresses and microstructure gradient.

Fracture analysis showed that the crack initiation point was always on a large forging defect, for all surface states (except for the polished surface). The defects can be clearly seen on the surface scans and the fracture surface (Fig 6). They are at least 150 µm long and 20 µm deep.

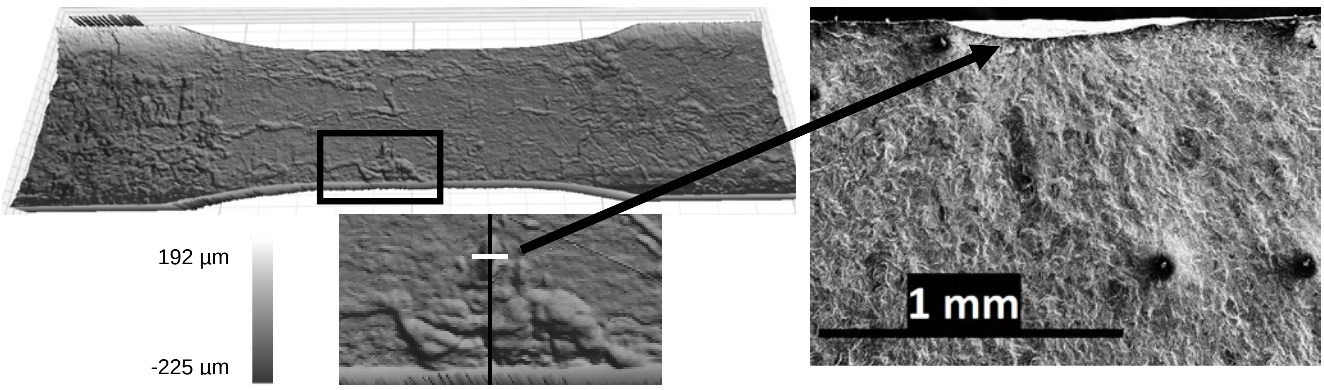

Fig 6 Surface scan of an as-forged specimen, showing the crack initiation and propagation, with SEM image of the associated fracture surface (defect size: 875 µm long and 60 µm deep).

The forging defects have a large impact on the fatigue behaviour of the connecting rod. Provisional fatigue limits (Table 2) show that the presence of the forging defects decreases the fatigue strength by 22% compared to the polished surface. After shot-blasting treatment, the defects are still present but the high compressive residual stresses increase the fatigue strength by 43% (12% compared to the polished surface).

The shot-blasted and shot-peened surfaces have very close fatigue limits. This shows that the influence of the roughness is secondary compared to the influence of the defects and the residual stresses, unless the roughness values are too similar for the effect to be noticeable.

Additional fatigue tests are needed to confirm this trend, and tests on a shot-blasted surface with no residual stresses are needed to determine the influence of the microstructure.

	Polished	**As-forged**	**Shot-blasting**	**Shot-peening 1**	**Shot-peening 2**
Fatigue Strength MPa	424	333	475	480	480
R_a µm	~ 0	6.4	7.8	4.3	7.6
Residual stresses MPa	~ 0	~ 0	- 500	- 500	- 500

Table 2 Provisional fatigue limit (at 2.10^6 cycles), roughness and surface residual stresses for each surface state.

The fatigue tests combined with the surface scans allow for the easy detection of the critical defects and their associated fatigue strength. Combined with finite element simulations of the defects, this will lead to a fatigue criterion based on the defect shape and size. This approach will also lead to a statistical distribution of the defects in the component. Using extreme value analysis, it would then be possible to predict the largest defect size (and its associated fatigue strength) on the whole connecting rod production.

The next step will then be to introduce in the model the residual stresses present in the shot-blasted surface. The goal of this approach is to be able to predict the critical defect and the fatigue strength of a specimen without resorting to a fatigue test, simply by analysing the surface of said specimen. In addition, another lab in the project is working on the finite element simulation of shot-peening; initial results are promising and show that it could be possible to accurately predict surface topography, residual stresses and hardening. Combining both approaches would reduce the need for fatigue tests on components.

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