Competition Between Surface Defects and Residual Stresses On Fatigue Behaviour of Shot Peened Forged Components

Benjamin Gerin[a,b,] ,Etienne Pessard[a, *], Franck Morel[a], Catherine Verdu[b]

[a] *LAMPA, Arts et Métiers ParisTech Angers, 2 Bd du Ronceray, 49035 Angers, France*
[b]*MATEIS, INSA Lyon, Université de Lyon, CNRS UMR 5510, 25 av. Capelle, F-69621 VILLEURBANNE CEDEX, France*

Abstract

The present study focusses 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, 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, microstructure and hardness. The aim of this work is to develop a fatigue design approach that can take into account both the effect of the surface defects and that of the residual stresses on fatigue.

Keywords: High-Cycle Fatigue, Surface Defects, Kitagawa-Takahashi Diagram, Shot-Peening

1. Introduction

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 forging and shot-peening 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. In order to study a sample relevant of the forging process, 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. Prior to shot-peening, these were cleaned of scale by hand with a metal brush.

Shot-blasting and shot-peening affect many properties of the treated surface in addition to modifying its topography. The process affects the microstructure of the component, its hardness and roughness and introduces 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 by McKelvey et al. (2012) and Bhuiyan et al. (2012). However, in addition to the homogenous roughness, the 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 of defects on fatigue behaviour have been separately studied, and the main focus of this study is the combined effect of both shot-peening and forging surface defects.

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.

2. Material characterization

An industrial shot-blasting treatment was applied to the as-forged specimens. The surface integrity is characterized through residual stress measurements (X-ray diffraction), EBSD and surface topography scan. 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 (Fig 1) will have a large beneficial impact on the fatigue behaviour.

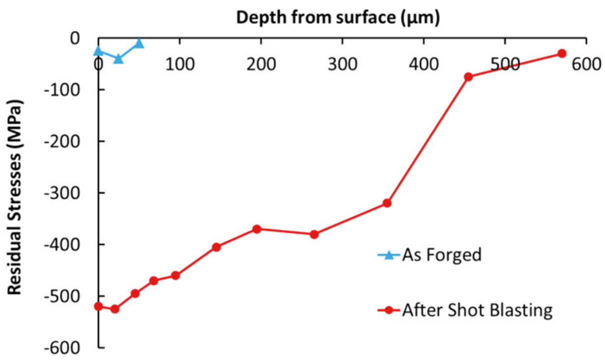

Fig 1 Residual stresses in the as forged and shot-blasting surface states.

The surface aspect of the connecting rods is also heavily affected by the surface treatments. However, the differences between the two surface states are poorly reflected by standard roughness parameters such as the Ra (Table 1). The surface states have a similar Ra (between 6 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 process the smooth areas disappear, leading to a smaller standard deviation for the Ra.

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

	As-forged	**Shot-blasting**
R_a µm	6.4	7.8
Std. Deviation µm	2.0	0.9

The effects of shot-blasting 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 Ra values of the shot-blasted/peened surfaces are similar but their surface aspects are different, giving each process a recognizable surface texturing.

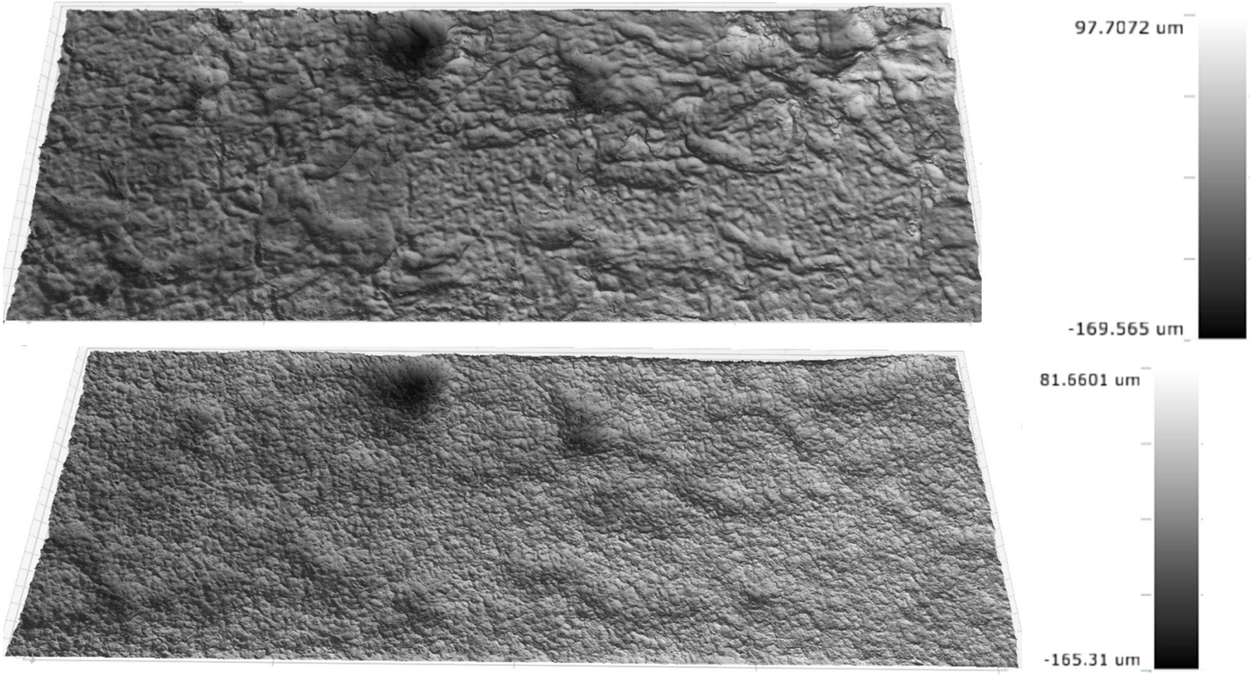

Fig 2 Surface scans (20x7 mm) of the same fatigue specimen, before (top) and after shot-peening (bottom). The residual scale in the top right corner has been removed during the shot-peening. A large defect (2.5 mm wide and 150 µm deep) can be seen.

The shot-blasting process produces a smoothing of the edges of local defects, without affecting their overall shape or depth. Previous studies conducted by Arola et al. (1999) and Suraratchai et al. (2008) have shown that both roughness and defects 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-peened microstructure is very similar to that of shot-blasting.

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

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 core 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 3) or cracks that run parallel to the surface. They measure around 100 µm and could provide crack initiation locations in fatigue.

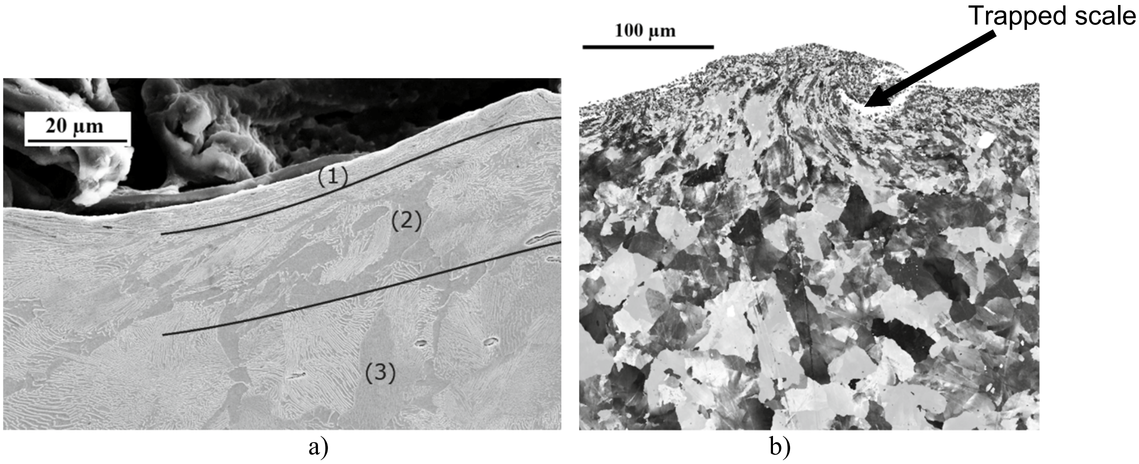

Fig 3 a) SEM image showing the microstructure in a shot-blasted connecting rod. b) EBSD map of the first 300 µm in a shot-blasted connecting rod. Scale has been trapped in a 50 µm fold during the shot-blasting.

3. 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 4) 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 so as to concentrate the stress at the surface, thus avoiding crack initiation in the centre or the sides of the specimen. The "step" method defined by Maxell and Nicholas (1999) allows to quickly determine the fatigue strength of each specimen.

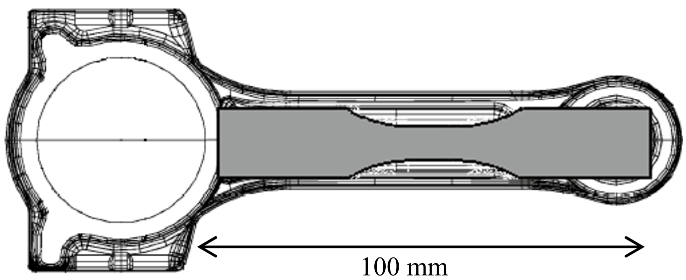

Fig 4 Connecting rod with the machined fatigue specimen. The geometry was chosen so as to extract a flat surface area from the connecting rod.

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.

The forging defects have a large impact on the fatigue behaviour of the specimens. Average 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).

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

	Polished	**As-forged**	**After Shot-blasting**
Fatigue Strength MPa	424	333	475
R_a µm	~ 0	6.4	7.8
Residual stresses MPa	~ 0	~ 0	- 500

Fracture analysis showed that the crack initiation point was always located 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 5). They are at least 150 µm long and 20 µm deep.

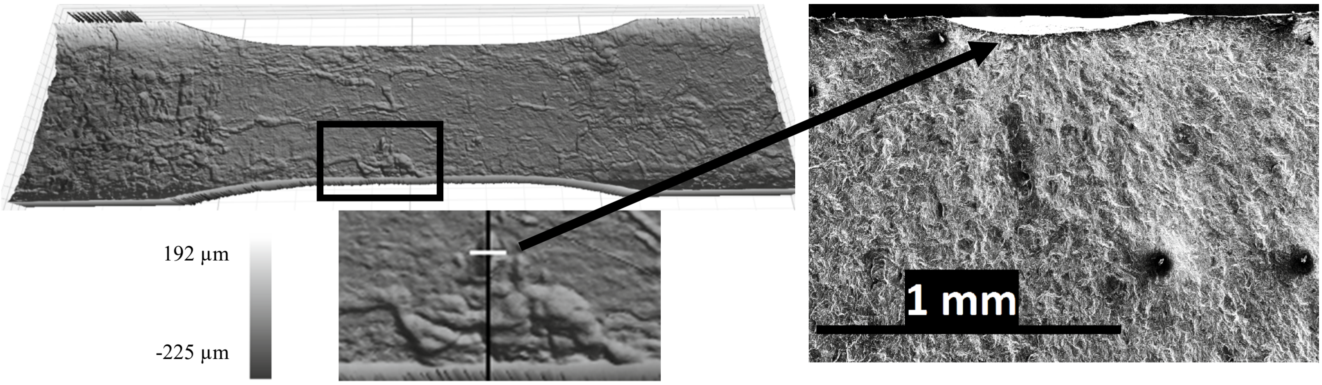

Fig 5 Surface scan of an as-forged specimen, showing the crack initiation and propagation, with SEM image of the associated fracture surface (defect size: 875 µm long and 60 µm deep).

The defect size at the initiation site is measured using the $\sqrt{area}$ parameter proposed by Murakami (2002) on each specimen fracture surface for the two batches: as forged and after shot-blasting.
Plotting all the experimental results in a Kitagawa Takahashi diagram (Fig.6) shows the influence of the defect size on the fatigue strength.
For shot-blasted specimens, the edge of the specimens has been machined and do not contain any residual stresses. During the fatigue test in bending, the first tests showed that the cracks initiates on the edge of the specimens. To be sure to initiate on the shot-blasting surface, connecting rods with large defects have been specifically selected for this study. In the fig 6, the fact that shot-blasted specimens contain largest defects compared to the as-forged specimens is only due to the prior selection of the connecting rods.

4. Analysis

For the as-forged batch, knowing the Vickers hardness of 292 HV, the experimental results can be compared to predictions with Murakami's model (Eq 1).

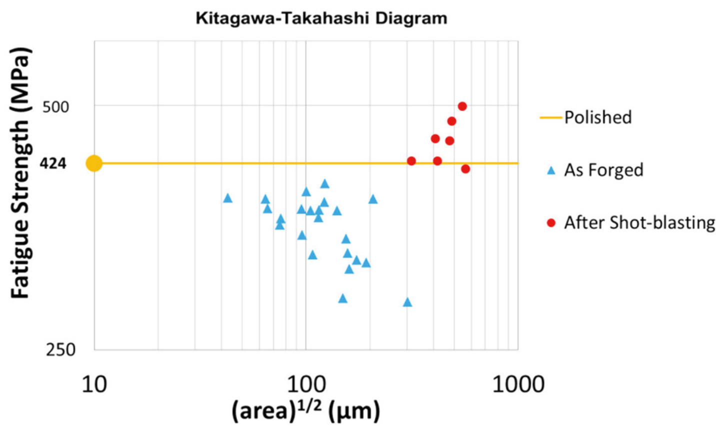

Fig 6 Kitagawa-Takahashi diagram of the fatigue results obtained on As-Forged and Shot-Blasted specimens

$$\sigma_D = \frac{1{,}43(H_V + 120)}{\left(\sqrt{area}\right)^{1/6}} \tag{1}$$

Fig 7 shows a Kitagawa Takahashi diagram where the experimental results for the as-forged specimens are compared to Murakami's model. The model underestimates the fatigue limit by around 75 MPa, however the data points generally follow the model's slope of 1/6. To obtain a more accurate prediction, the criterion is expressed as:

$$\sigma_D = \frac{A(H_V + 120)}{\left(\sqrt{area}\right)^{1/6}} \tag{2}$$

Where A is Murakami's constant, determined using the least squares method so as to minimise the prediction error. With a value A = 1.89, the average error is 6% and the maximum error is 17% (Fig 7).
The model's slope intersects the nominal fatigue limit at a defect size of 38 µm. This value seems to be the critical defect size below which a defect has no influence on fatigue behaviour. None of the tested specimens had the crack initiation on a defect of this size, and only one initiated on a defect with a size smaller than 50 µm. It is therefore not possible to confirm this value of critical defect size.

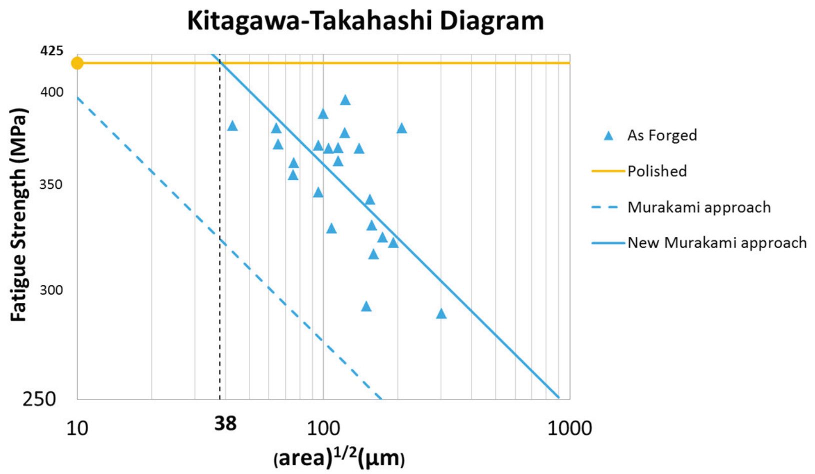

Fig 7 Kitagawa-Takahashi diagram with predictions using Murakami's model.

For the shot-blasted specimens, the Kitagawa-Takahashi diagram (Fig 6) shows that the influence defect size is less clear and that despite the large defects on the specimens, the compressive residual stresses introduced by shot-blasting are enough to improve the final fatigue strength of the specimen.

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 (initiating a crack) 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 introduced by shot-peening. Combining both approaches would reduce the need for fatigue tests on components.

References

Arola, D., Ramulu, M., 1999. An examination of the effects from surface texture on the strength of fiber reinforced plastics. Journal of Composite Materials, 33(2), 102–23.

Bhuiyan, M. S., Mutoh, Y., McEvily, A., 2012. The influence of mechanical surface treatments on fatigue behavior of extruded az61 magnesium alloy. Materials Science and Engineering A, 549(0), 69 – 75.

McKelvey, S. A., Fatemi, A., 2012. Surface finish effect on fatigue behavior of forged steel. International Journal of Fatigue, 36(1), 130–45.

Maxwell D.C., Nicholas T., 1999. A rapid method for generation of a Haigh diagram for high cycle fatigue. In: 23 Panontin TL, Sheppard SD, editors. Fatigue and fracture mechanics, ASTM STP 1321, vol. 29. West Conshohocken (PA): American Society for Testing and Materials; 626-41.

Murakami, Y., 2002. E_ects of small defects and nonmetallic inclusions. Elsevier.

Suraratchai, M., Limido, J., Mabru, C.,, Chieragatti, R., 2008. Modelling the influence of machined surface roughness on the fatigue life of aluminium alloy. International Journal of Fatigue, 30(12), 2119–26.