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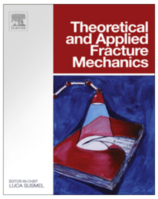

A non-local approach to model the combined effects of forging defects and shot-peening on the fatigue strength of a pearlitic steel

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ABSTRACT

This study focuses on the influence on fatigue behaviour of the surface integrity of a steel connecting rod. The component is hot-forged and shot-blasted, producing a complex surface state with large surface defects and high residual stresses. In a prior study, the surface was thoroughly characterized and fatigue tests were performed. Several different surface states were analysed in order to quantify the influence of the various surface aspects. These tests showed that the forging defects and the residual stresses are the most influential aspects of the surface. The goal of this paper is to develop an approach capable of taking into account the influence of both these aspects on fatigue behaviour.

Two methods were developed. First, using surface scans of the fatigue specimens, the forging defects were fitted with ellipsoids so as to determine their size and shape. This allows to easily compare the numerous defects and test various criteria in order to identify the critical defect of each specimen. The second method used was the finite element simulation of the defects based on real topography scans. Using a non-local approach based on the theory of critical distances, the simulations were used to accurately predict the influence of the defects' geometry. The residual stress profiles were integrated in the simulations using Dang Van's criterion. The predictions are accurate and show the importance of taking into account the real defect geometry when estimating the fatigue strength.

1. Introduction

The high cycle fatigue behaviour of industrial components can be affected by material characteristics but also by the production process. These elements must be taken into account during the design process.

Because crack initiation is usually located at the surface, a large number of articles in the literature focus on how surface integrity affects fatigue behaviour. The term "surface integrity" includes various aspects that can all affect fatigue behaviour:

- Surface roughness
- Surface defects
- Residual stresses
- Hardening
- Microstructure

Surface integrity is very dependant on the process being used, so studies on this subject usually focus on a specific process: machining [1–3], stamping [4], punching [5]. A large number of papers also deal with the impact of localised natural or artificial defects on fatigue strength. A classic example is Murakami's work [6,7]. More recently, studies have been performed on steel [8–10], on cast iron [11–13], on cast aluminium alloys [14–16] and cast titanium alloys [17]. Most investigations on defects are performed on homogeneous materials, without residual stresses. However, in the case of hot-forged steel, shot-blasting is generally used to clean off the scale. Shot-blasting is akin to shot-peening and affects surface integrity by introducing residual stresses, hardening and surface damage, and changing the microstructure. Numerous articles have been published on how shot-peening affects surface integrity and fatigue behaviour. Gariépy et al. [18] conducted a thorough characterisation of the surface of a shot-peened aluminium. Bhuiyan et al. [19] investigated shot-peened magnesium alloy specimens, some of which were stress-relieved after peening. McKelvey & Fatemi [20] studied the effects of decarburisation and shot-cleaning of the surface of steel specimens. Sakamoto et al. [21,22] studied the influence of surface cracks introduced by shot-peening on steel specimens Kim et al. [23] showed that

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in high cycle fatigue, surface residual stresses show little stress-relief during fatigue cycling.

In order to take into account the influence of the various aspects of the surface integrity, different approaches have been suggested. The majority of the studies on the effect of surface integrity on fatigue behaviour are performed on machined components. Machined surfaces typically have a periodic roughness profile. Arola & Ramulu [24] have therefore suggested a model based on the roughness values and on the estimation of the stress concentration factor suggested by Peterson [25]:

$$K_f = 1 + q(K_t - 1) \text{ with } K_t = 1 + n\left(\frac{R_a}{\rho}\right)\left(\frac{R_y}{R_z}\right) \text{ and } q = \frac{1}{1+\gamma/\rho} \tag{1}$$

where ρ is the notch curvature radius and (n, γ) are material parameters. Extending this model, Suraratchai et al. [26] suggested estimating the stress concentration with 2D simulations of the roughness profiles. Using 3D simulations from 3D surface scans to estimate the stress distribution was first performed by Shahzad and then used on surface states from other processes like forging or punching [5]. Guillemot and Souto Lebel suggest taking into account the stress concentration using a statistical model which considers micro-defects as pre-existing population of defects. Also worth mentioning is the original work of Le Pecheur [27] and Guilhem [28] based on evaluating the surface effects using crystal plasticity. When studying defects, the Kitagawa–Takahashi diagram [29] is a very useful tool, as it allows to illustrate the effect of defect size on the fatigue strength.

Fathallah et al. [30] studied the effect on fatigue behaviour of shot-peening coverage (100% or 1000% surface coverage). To model the fatigue behaviour, they performed 2D finite element simulations, taking into account the specimen geometry, the surface defects, the surface damage, the residual stresses and the hardening introduced by shot-peening. To study the influence of surface defects, other authors have used non-local approaches based on the theory of critical distances defined by Taylor [31,32]. This method has the advantage of using the elastic stress distribution to predict fatigue strength. It has been used in a number of applications [33,34], such as welded joints [35,36], fretting [37], cast alumium [38], punching defects [5], corrosion defects [39] and vapour deposition defects [40]. This approach has been combined with a multiaxial fatigue criterion and applied to shot-peened specimens [41]. It has also been used to develop a non-local damage model for shot-peened turbine blades [42].

The component studied in this paper is a hot-forged connecting rod, which is shot-blasted after forging. The connecting rods therefore exhibit localised surface defects introduced during forging in addition to hardening and residual stress gradients generated by the shot-blasting. The goal of this paper is to develop a fatigue approach which can account for the specific surface integrity of hot-forged and shot-peened components. This work is based on the results of a large experimental campaign, detailed in a previous article [43]. The various studied surface states and the fatigue results will first be quickly summed up. These results will then be used to model the fatigue behaviour of the specimens. Two approaches will be detailed in this article. The first uses ellipsoids to fit the shape and size of the forging defects present on the fatigue specimens. The defect dimensions are then used to try and detect the critical defect and its fatigue strength. In addition, the statistics of extremes are used to predict defect sizes on larger sample sizes. The second approach is based on finite element (FE) simulations using the geometry of real defects. The theory of critical distances combined with the residual stress profiles is used to predict the specimen's fatigue strength.

2. Fatigue testing results

In the previous study, fatigue specimens were machined out of connecting rods (Fig. 1a). Several different surface states were analysed in order to quantify the influence of the various aspects of surface integrity. The various surface states used in this study are as follows:

- As-forged surface, manually cleaned of scale
- Shot-blasted, the surface state of industrially produced connecting rods
- Shot-peened with shot diameter 800 μm, Almen intensity 30–60 A with 200% coverage. This shot-peening was performed on as-forged specimens and was chosen so as to be as close as possible to the shot-blasted surface.
- Shot-peening with shot diameter 400 μm, Almen intensity 20–30 A with 200% coverage. This shot-peening was performed on as-forged specimens and was chosen so as to have a lower roughness and a shallower residual stress profile.
- Polished, used as the reference in fatigue

The surface of the specimens was scanned using a profilometer prior to fatigue testing. This allowed the identification of the critical defect (the defect where crack initiation occurred) for each specimen. Fig. 1b shows the crack path and the critical defect for an as-forged specimen.

In addition to the surface topography, the hardness, residual stresses and microstructure gradients were analysed. Fig. 2 shows the residual stress profiles of all batches. Additional information on the preparation and the analysis of the specimens can be found in the article [43].

Fatigue test were performed in plane bending with a load ratio $R = -1$. Some specimens were stress-relieved in tension prior to fatigue testing, in order to quantify the influence of the residual stresses. Fatigue tests were also performed in tension $R = -1$. However, not all specimens were valid as crack initiation sometimes occurred in the corner. Only one of the tension tests was valid, performed on a stress-relieved shot-peened Ø800 μm shot, all the others had a corner crack initiation.

Table 1 details the number of valid specimens for each batch, with their respective fatigue strength range. The average value from the staircase method on the polished specimens is the reference fatigue strength of the material: $\sigma_0^D = 424$ MPa.

Crack initiation for valid specimens was always located on a large forging defect. The fatigue results for all specimens are represented in a Kitagawa diagram (Fig. 3). Defect size is represented using the square root of their surface area, projected along the loading direction [6]. The fracture surfaces can be used to calculate the projected surface area of each critical defect, which is generally used to represent defect size. All the defects have a projected area of similar shape, with the width much bigger than the depth (defects are typically 500–2000 μm wide and 50–200 μm deep). Calculating the projected area is done using the SEM fracture surface images: the total width and maximum depth of the defects are measured and their projected surface area is calculated by supposing that they have a semi-elliptical shape. As suggested by Murakami, the defect width is limited by a threshold of 10 times the depth when calculating the projected area.

The fatigue results show that:

- **Forging defects play a significant role in fatigue.** Crack initiation was always located on a forging defect. The as-forged specimens all have a lower fatigue strength than the reference