A Fatigue Approach to Design Shot-Peened Components Containing Surface Defect

E. Pessard [a], B. Gerin [a,b], F. Morel [a], C. Verdu [b]
[a] LAMPA, Arts et Métiers ParisTech Angers, France, etienne.pessard@ensam.eu, benjamin.gerin@ensam.eu, franck.morel@ensam.eu; [b] MATEIS, INSA de Lyon, France, catherine.verdu@insa-lyon.fr

Keywords: High Cycle Fatigue, residual stresses, large defects, roughness, microstructure

Introduction

Because fatigue crack initiation is usually located at the free surface of loaded component or specimen, a large number of articles in the literature focus on how surface integrity affects fatigue behavior. The term "surface integrity" includes both surface topography (i.e. roughness and local defects) and gradients in terms of residual stresses, hardening, microstructure, hardness, etc. which are often related. Surface integrity is very dependent on the manufacturing process being used, so studies on this subject usually focus on a specific process, such as machining [1-3], shot-peening [4, 5], stamping [6] and punching [7].

The component studied in this paper is a hot-forged C70 steel connecting rod, which is shot-blasted after forging to clean off the forging scale, (shot-blasting is a process akin to shot-peening). During forging, scale can stick to the die surfaces which in turn introduces defects on the surface of forged components. Even if shot peening (or shot blasting) modifies the surface topography, it cannot remove the largest forging defects which can be up to several hundred micrometers in length (Figure 1). The connecting rods therefore exhibit a particular surface integrity characterized by local surface defects, together with hardening and residual stress gradients generated by the shot-blasting process.

Before shot peening After shot-peening (800 μm shot)

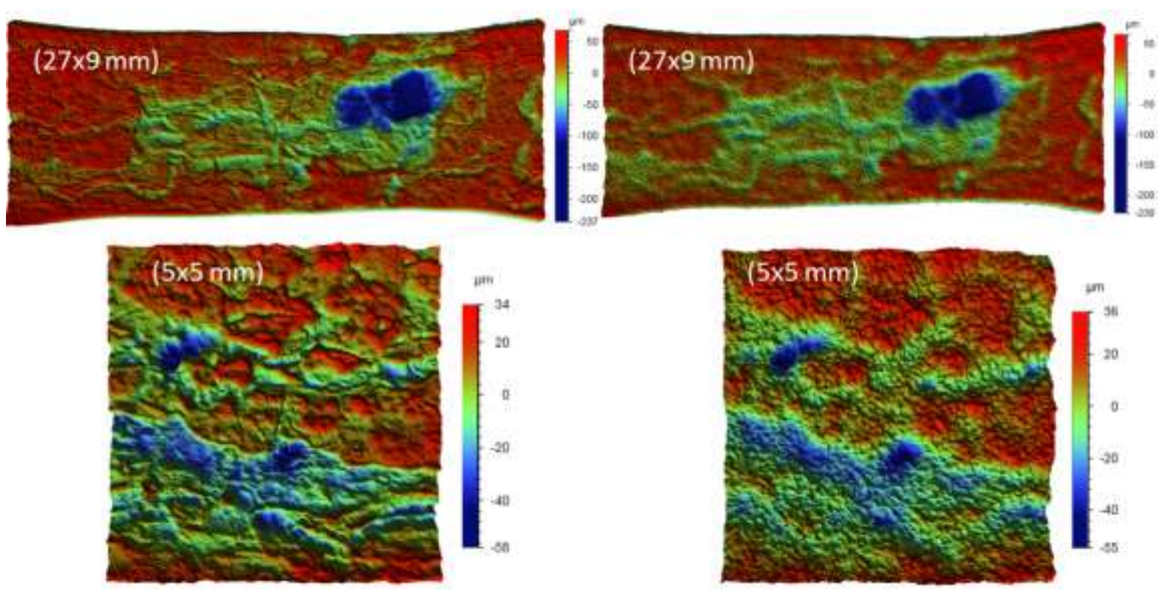

Figure 1. *Surface scan of an as-forged specimen, before and after shot-peening*

Objectives
The first goal of this paper is to analyse the fatigue strength and the crack initiation mechanisms for specifically chosen surface integrity conditions. The various aspects of the surface integrity will be thoroughly characterised, then fatigue tests will be conducted in order to quantify their effects on the fatigue behaviour. The fatigue results will serve to decouple the various surface integrity factors affecting fatigue behaviour. The second goal is to develop a fatigue approach which can take into account the specific surface integrity associated with hot-forged and shot-peened components. The final goal of our industrial partners (Atelier des Janves -ADJ and Renault) is to define new acceptability criteria for surface defect in real forged components.

Methodology
To distinguish the influence of the different effects of shot-blasting, fatigue tests and microstructural characterizations were done for different surface conditions. The first batch has been polished and will be used as a reference. The second batch has been obtained from forged connected rods without shot peening. This batch contains surface defects without microstructural and residual stress gradients. The third batch has been shot blasted after the forging step in the usual industrial conditions. To study in details the shot peening effect, two additional batches, shot peened in carefully controlled conditions have been added. The shot-blasting and peening batches contained similar residual stress levels (-500 MPa) in a depth of approximately 100µm. Shot-blasting and peening also increases the hardness to 60 HV at a depth of 250 µm but does not suppress the large or macro-defects introduced during the forging operation.
The industrial Partner Atelier des Janves (ADJ) delivered more than one thousand connecting rods taken directly from their production line before the final surface control. The fatigue specimens are machined out of industrial connecting rods so that natural defects are present on the gauge length. In-plane bending fatigue tests are performed with a stress ratio of R = -1 to quantify the fatigue strength at $2x10^6$ cycles. The “Locati” step method was used in order to determine a fatigue strength value for each specimen. This method was previously used in a similar study concerning cold-forged components [8]. Each specimen was scanned prior to fatigue testing to identify the critical defect at the origin of the fatigue crack.

Results and analysis
Residual stresses evolution during cycling
Residual stresses potentially have a large impact on the fatigue behavior, which is why it is important to know if stress-relief occurs during fatigue cycling. Kang et al. [9] have shown that for high-cycle fatigue of a carbon steel the surface residual stresses have only minimal stress-relief. In order to quantify stress-relief, a shot-blasted specimen with a large surface defect was chosen; surface residual stresses were analyzed in the center of the specimen and in the defect. The specimen was then loaded in fatigue at a high stress value of 475 MPa, and the test was periodically stopped to measure the residual stresses. The specimen failed at 139400 cycles, with crack initiation located at the defect. For the first 100000 cycles, the surface residual stresses show almost no change in value, both at the center of the specimen and in the defect. In can therefore be concluded that no stress relief occurs during fatigue cycling.

Fatigue results, Impact of surface defect and shot peening on the fatigue strength
For the as-forged, shot blasted and shot peened surface, initiation is always located on the forging defect (Figure 2).

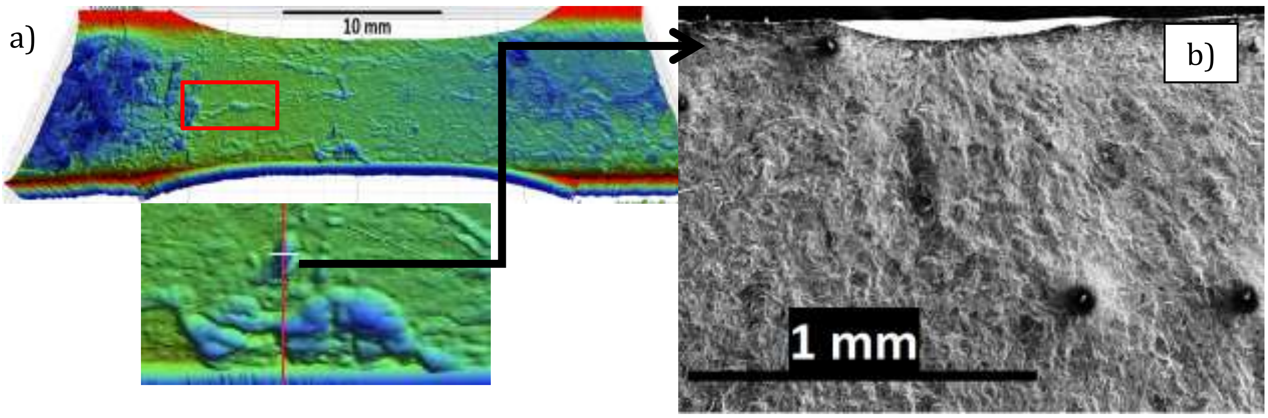

***Figure 2**: a) Surface scan of an as-forged specimen showing the crack initiation site and propagation, b) Fatigue failure surface of the same specimen showing the large defect in which the crack initiated*

Locati fatigue tests combined with surface scans allow the critical defects to be identified and the associated fatigue strength of each specimen. The defect size is represented using the square root of the area, projected along the loading direction as proposed by Murakami [10]. Plotting all experimental results in a Kitagawa-Takahashi diagram [11] shows that the defect size and the residual stresses are the two main controlling parameters of the fatigue strength (Figure 3).
Comparing the polished surface with the as-forged surface shows that the forging defects have a detrimental effect on the fatigue strength (-22%). Shot-blasting and shot peening increase the fatigue strength by +50% compared to the as-forged case. The shot-blasting and shot peening batches with Ø400 µm shot, show very similar fatigue strengths. The shot peening batch with Ø400µm shot has the better fatigue strength (see Figure 3)
The as-forged batch is characterized by high dispersion in fatigue. The fatigue strength is always lower than the polished batch and is 34% lower for the biggest defect. The fatigue strength seems to follow a line with a slope of 1/6 as proposed by Murakami approach. The critical defect size is around 40µm. However, directly using the Murakami criterion based on the material hardness (Hv=292) and the defect size gives conservative prediction (i.e. the dotted curve on Figure 3):

$$\sigma_D = \frac{1.43(H_v + 120)}{\left(\sqrt{area}\right)^{1/6}} \quad (1)$$

Finite element simulations of the critical defects

A numerical approach has been developed to take into account the real defect geometries and the residual stresses. Because of the large number of defects, the simulations are restricted to only the critical defects. As the previous analysis of the residual stresses during fatigue cycling showed that there is no residual stress relaxation, an isotropic linear elastic behavior is used in the finite element models. The process used to perform the FE simulations of the critical defects is presented in Figure 4.
First of all, the bending load creates an essentially uniaxial stress field at the critical point (where the stress is maximal) (see Table1). This is due to the flat geometry of the defects:
To predict the fatigue strength, a non-local initiation criterion based on the calculation of the stress at a critical distance from the hot-spot or averaging on a certain volume is applied [12]. Using this kind of non-local approach avoids meshing errors and makes it possible to take into account not only the maximum stress value at the defect but also indirectly the highly stressed volume (Figure 5

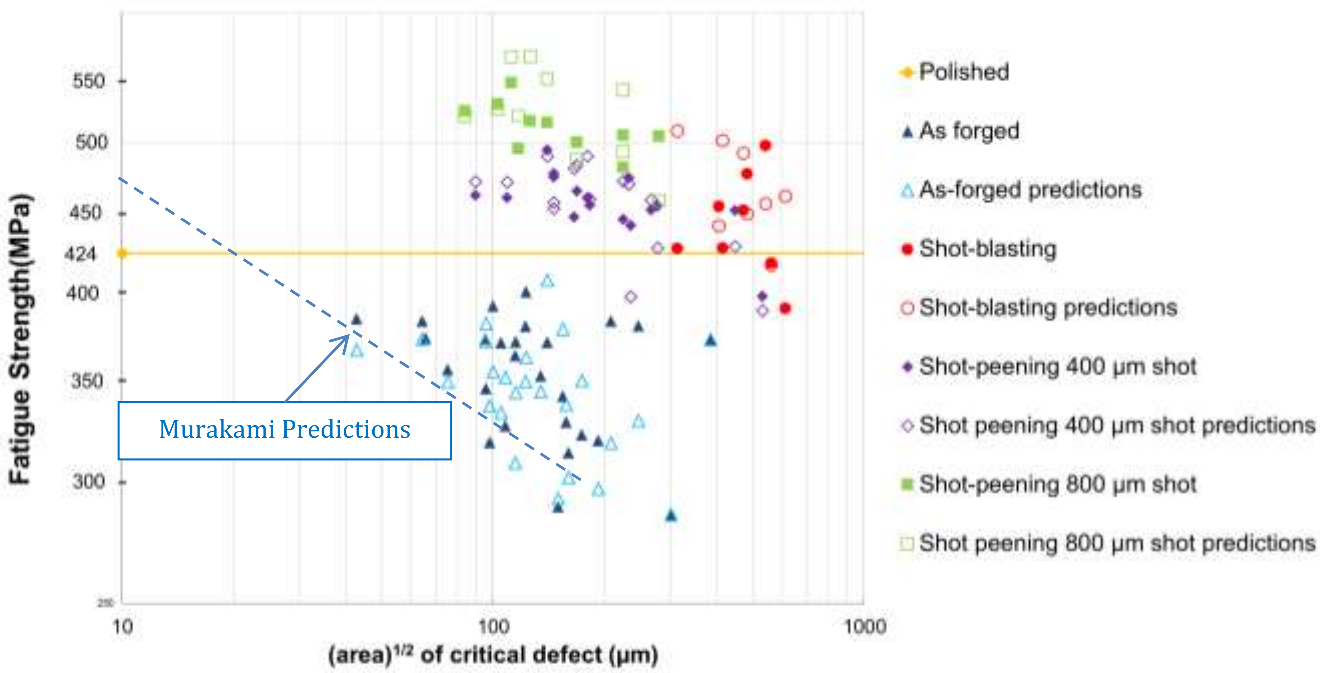

***Figure 3**. Kitagawa diagram of the fatigue tests, with fatigue strength and critical defect size*

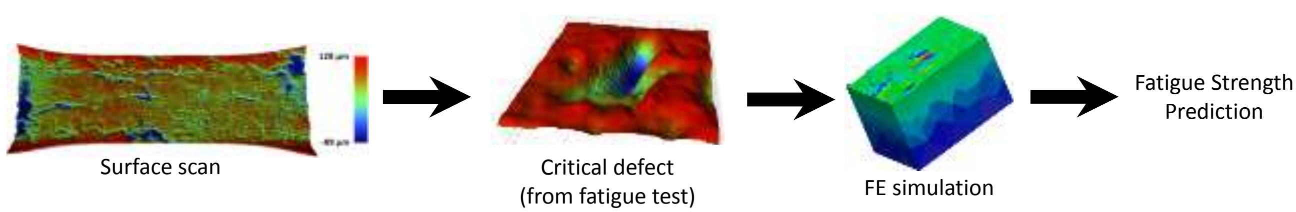

***Figure 4**. Process for performing the FE simulations of the critical defects.*

Position	Σ_{11}/Σ_0	Σ_{22}/Σ_0	Σ_{33}/Σ_0
On the surface defect	2.17	0.36	0.26
At 40μm in depth	1.22	0.06	0.12

***Table 1.** Stress field at the surface defect and at 40μm in depth after applying an amplitude loading Σ_0*

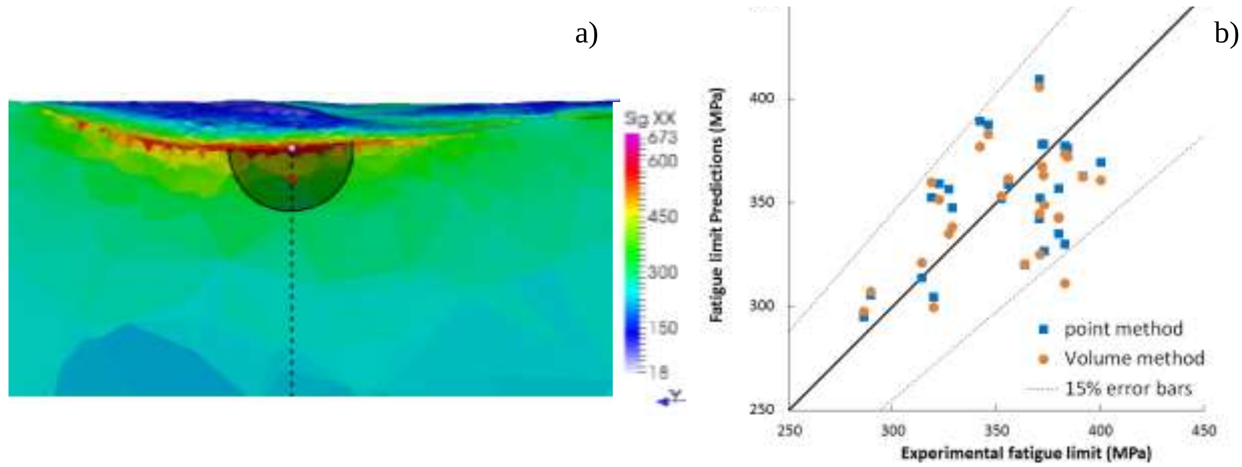

Figure 5*. a) Cross-section of the FE simulation of the critical defect in figure 2. Stress values are in MPa, the white dot locates the maximum stress. The point method (red dot) and volume method (sphere centered on the white dot) are indicated, b) Predictions for each method*

a). The distance (40μm) or the volume size (80μm radius for a semi-spherical volume) are identified applying an inverse methodology that minimize the fatigue prediction errors for all as-forged specimens. The predictions obtained with the two methods are very similar with an error lower than 15% (Figure 5 b).
To take into account the residual stress gradient the Dang Van multiaxial fatigue criterion is used [13]. In the Dang Van criterion the residual stresses are integrated via the hydrostatic stress, for proportional uniaxial loading, it can be written as:

$$\tau_a + \alpha\sigma_{H,\max} \leq \beta \quad (2)$$

where τ_a is the shear amplitude, $\sigma_{H,\max}$ is the maximum hydrostatic stress and α , β are material parameters. Based on experimental results the residual stresses are considered to remain constant during cycling.
The experimental results and predictions are compared in Figure 4 and shows that the error is inferior to 15%. This graph also shows that the strain hardening effect induced by shot peening appears to be negligible compared to the effect of residual stresses.
Even if the two shot-peened batches have very similar residual stress levels on surface they do not show exactly the same fatigue strength. The 400 μm shot batch is around 50 MPa lower for the same defect size. Taking the real defect geometry into account and using the proposed approach allows to correctly predict the differences observed between the two batches. It can be concluded that for the same defect size, the local surface defect topography for the 400 μm shot batch is more critical in fatigue compared to the 800 μm shot batch.

Conclusions
A large experimental campaign conducted on specimen extracted from real component has been conducted. In spite of being shot peened, natural defects introduced during the forging process control the fatigue behaviour of the connecting rod studied in this work. The numerical approach developed, that takes into account the actual defect geometry and the residual stresses is found to

adequately predict all the experimental results. This shows that the strain hardening effect induced by shot peening seems to be less influent compared to the effect of residual stresses.
Recent developments concerning the simulation of the shot peening process show that is now possible to correctly predict the residual stress field [15] and even the roughness [16]. The approach present here could now be merged with shot peened simulations to develop a global simulation chain. This would be a very useful tool to define the shot peened parameters that optimize the fatigue strength of components submitted to shot peening treatment and containing defects

References

[1] Shahzad, M., Chaussumier, M., Chieragatti, R., Mabru, C., Rezai Aria, F., 2010, Influence of anodizing process on fatigue life of machined aluminium alloy, Procedia Engineering, 2: 1015–1024

[2] Chomienne, V. (2014). Étude de l'influence de l'intégrité de surface en tournage de l'acier 15-5PH sur la tenue en fatigue en flexion rotative. PhD thesis, INSA, Lyon

[3] Souto-Lebel, A., Guillemot, N., Lartigue, C., Billardon, R. Characterization and influence of defect size distribution induced by ball-end finishing milling on fatigue life, Procedia Engineering, V19, 2011.

[4] Fathallah, R., Laamouri, A., Sidhom, H., & Braham, C. (2004). High cycle fatigue behavior prediction of shot-peened parts. Int. J. of Fatigue, 26(10), 1053 – 1067

[5] Kim, J. C., Cheong, S. K., & Noguchi, H. (2013). Residual stress relaxation and low- and high-cycle fatigue behavior of shot-peened medium-carbon steel. Int. J. of Fatigue, 114 – 122

[6] D. Shang, X. Liu, Y. Shan, E. Jiang,(2016) Research on the stamping residual stress of steel wheel disc and its effect on the fatigue life of wheel, Int. J. of Fatigue, 93, 173–183

[7] Dehmani, H., Brugger, C., Palin-Luc, T., Mareau, C., Koechlin, S. 2016 Experimental study of the impact of punching operations on the high cycle fatigue strength of Fe-Si thin sheets, IJF 82, 721-729

[8] B. Gerin, E. Pessard, F. Morel, C. Verdu, A. Mary, Beneficial effect of prestrain due to cold extrusion on the multiaxial fatigue strength of a 27MnCr5 steel, Int. J. Fatigue 92 (2016) 345–359.

[9] M. Kang, Y. Aono, H. Noguchi, Effect of prestrain on and prediction of fatigue limit in carbon steel, Int. J. Fat., 29(911), 1855–1862. Fatigue Damage of Structural Materials VI in: Proceedings of the Sixth International Conference on Fatigue, Damage of Structural Materials, 2007.

[10] Murakami Y. Metal fatigue: effects of small defects and non-metallics inclusion. London: Elsevier; 2002.

[11] H. Kitagawa, S. Takahashi, Applicability of fracture mechanics to very small cracks or cracks in the early stage, in: Proceedings of the second international conference on the mechanical behaviour of materials. ASM, 1976, pp. 627–631.

[12]Taylor D. (2011). Applications of the theory of critical distances in failure analysis. Engineering Failure Analysis, 18, 543–549.

[13] Dang Van, K. (1993). Macro-micro approach in high-cycle multiaxial fatigue. In D. McDowell & J. Ellis (Eds.), Advances in Multiaxial Fatigue (pp. 120 – 130). ASTM STP1191.

[14] Gerin B., Pessard E., Morel F., Verdu C. (2017). Influence of surface integrity on the fatigue behaviour of a hot-forged and shot-peened C70 steel component, Materials Science & Engineering A, 686, 121–133.

[15] Pedro Sanjurjo Cristina Rodríguez, Inés Peñuelas, Tomás Eduardo García, Francisco Javier Belzunce, (2014) Influence of the target material constitutive model on the numerical simulation of a shot peening process, Surface & Coatings Technology 258 822–831

[16] G.I. Mylonas, G. Labeas (2011) Numerical modelling of shot peening process and corresponding products: Residual stress, surface roughness and cold work prediction, Surface & Coatings Technology 205 4480–449