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Influence of surface integrity on the fatigue behaviour of a hot-forged and shot-peened C70 steel component

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ABSTRACT

Hot-forging is a process commonly used in the manufacturing of automobile parts such as connecting rods. Most hot-forged components are shot-blasted after forging in order to clean off the forging scale. The shot-blasting process is akin to shot-peening and greatly affects the surface integrity of the components by introducing hardening and residual stresses. This study focuses on the influence of the surface integrity on the fatigue behaviour of a hot-forged C70 steel connecting rod. Specimens were machined out of the connecting rods in order to perform fatigue testing on the forged surface. Several surfaces states, including shot-peened surfaces, were studied in order to quantify the influence of the surface integrity.

A thorough characterisation of the surface integrity of the specimens was first performed. The hardness, residual stresses and microstructure gradients were analysed, and the surface of each specimen was scanned using a profilometer. The specimens show complex networks of surface defects introduced during forging, and the shot-blasting process introduces important surface residual stress and microstructure gradients. High cycle fatigue tests in plane bending were then performed on the specimens, with the surface scans helping to identify the critical defect on which crack initiation occurred. The fatigue results, presented in the form of a Kitagawa diagram, are analysed in order to determine which surface integrity parameters are the most influential on fatigue behaviour. The forging defects have an important negative effect on fatigue strength. After shot-blasting, the fatigue strength increases considerably because of the large compressive residual stresses introduced by the shot-blasting process.

1. Introduction

Hot-forging is a process commonly used in the manufacturing of automobile parts. The expensive dies used for this process mean it is mainly used for mass production. Connecting rods for an internal combustion engines are a typical example of components manufactured with this process.

Hot-forging requires heating the material to high temperatures in order to achieve sufficient ductility (typically 1000 °C for steel). The subsequent phase transition during cooling means that the resulting microstructure shows little to none of the hardening or the residual stresses introduced during forming.

However, the high temperature increases oxidation and often a layer of oxides, called forging scale, is formed on the surface of the components. This layer must be removed before the next steps of the manufacturing process can be performed (sizing, machining, etc).

A very common method for cleaning off the scale is the shot-blasting process [1]. Several hundred components are placed in a rotating barrel while steel shot is propelled into the barrel (Fig. 1a). Shot-blasting is therefore similar to shot-peening but does not have the same purpose, as shot-peening is used to introduce compressive residual stresses and also to change surface roughness (Fig. 1b). Both processes (shot-blasting and shot-peening) introduce local plastic strain with each shot impact, resulting in hardening and internal stresses near the surface of the components.

During forging, defects can appear on the surface of the components. Between two strikes, scale can get stuck on the dies' surface, generating surface defects the size of which can reach several millimeters in length and several hundred micrometers in depth. Shot-blasting does not remove the largest of these forging defects. Surface defects are potentially very harmful in fatigue, which is why it is important to study their impact on fatigue behaviour [2].

The oxidation during forging can also lead to decarburisation of the surface: the carbon content decreases which directly impacts the mechanical characteristics, most notably hardness. Gildersleeve [3] studied the influence of surface carbon content on the fatigue strength

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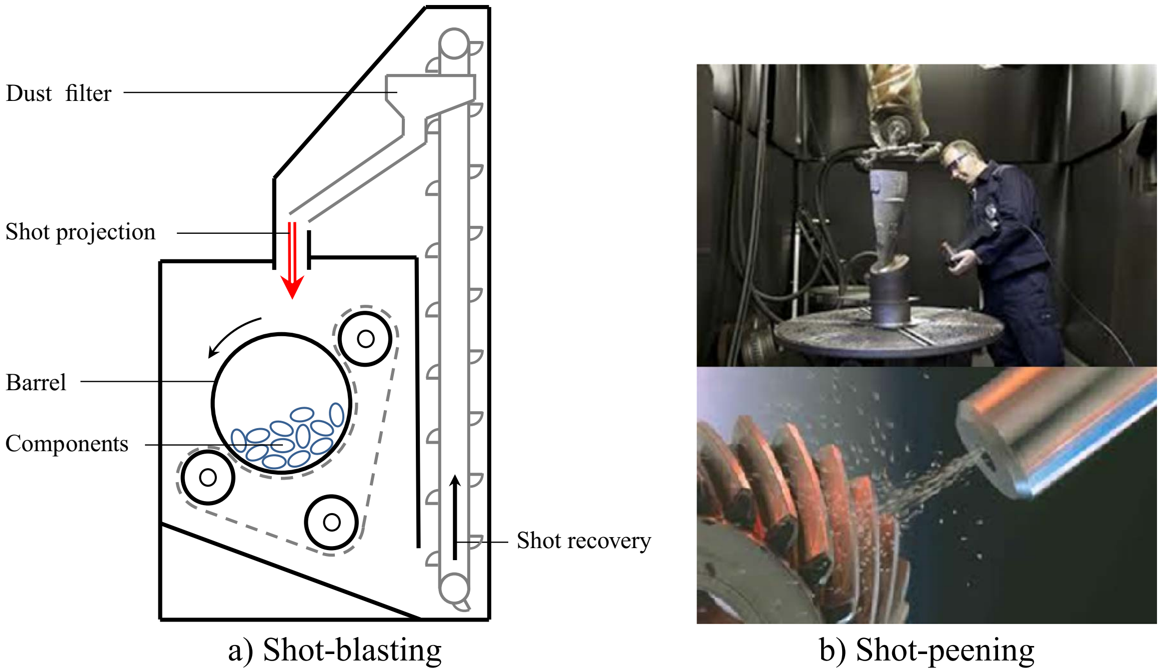

Fig. 1. a) Diagram of the shot-blasting process. b) Photos illustrating the shot-peening process, source: Metal Improvement Company.

of steel specimens. Using controlled decarburisation to modify the carbon content, he found that fatigue strength was proportional to surface hardness and followed the empirical law suggested by Garwood et al. [4]: $\sigma^D = 1.5 \times H_V$.

McKelvey & Fatemi [5] performed fatigue tests on hot-forged specimens, studying the effects on fatigue of decarburisation and shot-cleaning of the surface. They showed that the as-forged surface has a much lower fatigue strength compared to polished specimens (50% to 70% drop) because of the combined effects of surface roughness and decarburisation. The severity of the decarburisation depends on the heating process, with induction heating leading to less decarburisation than gas heating. They also showed that the use of shot-cleaning on the as-forged surface improves fatigue strength, independently of decarburisation.

Numerous studies have been conducted on how shot-peening affects surface integrity. Gariépy et al. [6] conducted a thorough characterisation of the surface of a shot-peened aluminium, measuring the hardness, microstructure and residual stresses gradients generated near the surface. They also showed that shot-peening increases roughness and creates surface micro-defects.

The influence of shot-peening on fatigue behaviour has also been extensively studied. Bhuiyan et al. [7] investigated shot-peened magnesium alloy specimens, some of which were stress-relieved after peening. They showed that the fatigue strength depends on the combined effects of the compressive residual stresses (which improve the fatigue strength), and the roughness (which decreases fatigue strength).

Sakamoto et al. [8,9] performed fatigue tests on steel specimens, polished or shot-peened. Focused ion beam (FIB) was used to introduce small surface notches (50 µm) in some of the specimens. The fatigue results showed that the notches reduced the fatigue limit for the polished specimens, but not the shot-peened ones. The shot-peened specimens had multiple crack initiations, on the notches and on cracks generated by the shot-peening. These results show that surface defects have no effect on the fatigue behaviour of a shot-peened surface if they have the same size as the cracks generated by the shot-peening.

Fathallah et al. [10] studied the effect on fatigue behaviour of shot-peening coverage. They performed characterisations and fatigue tests on steel specimens with 100% or 1000% surface coverage. The found that 1000% coverage had bigger surface defects and lower surface residual stresses than 100% 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. Their model correctly predicted the experimental fatigue limits and showed that ignoring the effects of the defects and the surface damage would lead to predicting crack initiation not on the surface but at the depth where the residual stresses reach zero.

These articles show that the surface integrity of forged components is the combination of different aspects that can all have an effect on fatigue behaviour. These aspects result from the hot-forging or the subsequent shot-blasting.

From forging:

- Large surface defects
- Decarburisation

From shot-blasting:

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

These aspects all influence fatigue behaviour differently, and are not easily studied independently, especially in the case of shot-blasting where all are introduced simultaneously. Very few articles have managed to decouple the various effects of the surface integrity.

The goal of the present study is therefore to analyse the fatigue strength and the crack initiation mechanisms for specifically chosen surface integrity conditions. Fist, the various aspects of the surface integrity will be thoroughly characterised, then fatigue tests will be conducted in order to quantify their effect on fatigue behaviour. The fatigue results will serve to decouple the various surface integrity factors affecting fatigue behaviour.