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Fatigue reliability prediction of metallic shot peened-parts based on Wöhler curve

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ABSTRACT

The fatigue behaviour of shot-peened mechanical components is characterized by high uncertainty, where deterministic approaches fail to exactly estimate the structural service life. The aim of this paper is to evaluate the fatigue behaviour reliability of shot-peened metallic parts through a probabilistic approach based on the scattered S-N curves' experimental results. The dispersions of: (i) the Wöhler material coefficients, (ii) the applied loading and (iii) the shot-peened surface conditions are considered in the proposed model. The “strength-load” method using the Monte Carlo simulation technique is utilized to compute fatigue strength reliability. This approach can be regarded as a helpful method to analyse and discuss the influence of the shot-peening operating parameters on the fatigue behaviour reliability of metallic parts. Moreover, the suggested approach leads to predict iso-probabilistic S-N curves (P-S-N) for different shot-peening conditions.

1. Introduction

The fatigue phenomenon is generally considered as the origin of most mechanical structure failures [1]. It is a decisive constraint that must be considered in the service behaviour of mechanical components subject to cyclic loadings. Accordingly, the fatigue resistance improvement of mechanical components is a challenging point for engineers. In this context, several techniques are used to improve the fatigue behaviour, such as: (i) mechanical surface treatments (ii) thermal treatments, (iii) and surface coating.

The mechanical surface treatment processes are already well-known as the main process used for improving the fatigue life behaviour of aircrafts and marine and automotive structures [1]. In this field, shot peening is one of the most effective surface pre-stressing treatments used to enhance the fatigue strength of mechanical components [2–4]. The benefits obtained by this process are attributed to: (i) Compressive Residual Stress (CRS) fields, (ii) and surface work hardening. However, in the cases where the shot peening parameters are not well-optimized, two unfavourable effects can be observed, which are: (i) the micro-geometrical surface imperfections, and (ii) the superficial defects [4]. Therefore, the shot-peened components' fatigue performance is very linked to the balance between benefits and detrimental shot-peening effects. As a consequence, many studies have taken interest in the prediction of the fatigue behaviour of shot-peened mechanical components. An earlier method was proposed by Fuchs [5] to predict the High Cycle Fatigue (HCF) limit of shot-peened parts. It was based on Haigh diagram, which would be valid only for the case of uni-axial loading. This method enabled analyzing and visualizing the effect of the CRS fields on the fatigue behaviour. Deperrois [6] put forward a model for predicting the HCF limit of shot-peened parts. This method took into account only the two favourable effects of the shot peening. Fathallah [7] developed a model to predict the HCF behaviour of shot-peened parts, taking into account favourable and unfavourable effects of the shot-peened surface properties. It was based on the HCF criteria of Crossland and Dang Van. The obtained results were in good agreement with the experimental investigations. In the majority of cases, these approaches remain deterministic. However, it is well-established that the shot-peening surface conditions are characterized by large scatterings in nature. These dispersions are related to: (i) material parameters (ii) measurement techniques, (iii) and shot-peening operating parameters such as velocity, shot size, exposure time, etc. To consider these probabilistic effects on the fatigue behaviour of shot-peened structures, several works have been proposed. The majority of these studies have been used in the case of one-dimensional loading [8–9]. Other studies have developed utilizing the weakest-link theory in order to explain the statistical distribution on the fatigue resistance of mechanical components [10–13]. More lately, F. Morel used a combination of the concept of the weakest-link theory and the critical plane damage model to describe the scatterings of the fatigue limit and the fatigue life under cyclic loadings [14]. It is based on a micro plasticity analysis. More recently, a probabilistic approach has been developed to predict the HCF reliability of metallic structures by Ben Sghaier [15]. This approach was based on multi-axial HCF criterion of

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Crossland by taking into account the dispersions of: (i) the HCF Crossland material's characteristic parameters and (ii) the applied loading [15]. The reliability has been computed using the “strength-load” with the first-order reliability method. However, the latter approach did not consider the influence of surface conditions on the fatigue behaviour of mechanical components. In the same framework, an engineering predictive design approach of the HCF behaviour of shot-peened metallic parts was proposed by Bouraoui [16]. The multiaxial HCF criterion of Crossland was used. The reliability was determined by the “strength-load” method and computed by the numerical “Monte Carlo simulation” (MCS). The proposed model's performance was verified by comparing the obtained results with the experimental observations [4]. In the same context, Castillo and Canteli developed an interesting probabilistic model which allows the fully description of the complete S-N field [17]. The model's constants can be identified using the software ProFatigue [18].

Despite the diversity of the proposed methodologies, the fatigue failure remains a major issue for the reliability analysis and mechanical component design. The stress-life approach is the main tool used for assessing the fatigue behaviour of mechanical components and structure subjected to cyclic loadings. However, in order to predict as correctly as possible the fatigue behaviour of the shot-peened mechanical components, uncertainty sources, such as surface conditions, loading and material parameters, should be taken into account.

The aim of the present work is to develop a probabilistic approach for evaluating the fatigue reliability of shot-peened metallic parts, based on the S-N curve, for both low and high cycle fatigue life regions. The stress-life (S-N) approach has been used by taking into account the dispersions of fatigue results characterized by: (i) the variation of the slope and the intercept of the S-N curve for the low fatigue life region and (ii) the variation of the fatigue limit for the HCF region. The reliability has been computed using the “strength-load” approach and the MCS method. The P-S-N curves have been obtained for different specimen surface conditions. The proposed approach leads to improve the deterministic prediction analysis, using the 50%-deterministic S-N curve, by taking into account the various dispersions which are very significant and rarely considered. It can be used by design engineers to quantify the fatigue reliability influence of the surface treatment conditions and to predict reliable safe design of treated and untreated components. This approach presents the advantage to avoid the indiscriminate use of security coefficients. An application of the proposed approach has been carried out on shot-peened AISI4340 steel. The obtained results are qualitatively coherent with the experimental ones.

2. Monte Carlo method review

To compute the fatigue reliability, several numerical methods can be used [19–20], to wit: (i) the analytical resolution, (ii) the approximate computational methods and (iii) the Monte Carlo Simulation. In the present work, the fatigue reliability is computed using the MCS method. This technique is usually used in the case of a high number of random variables as well as when the evaluations of the limit state function is complicated [19–20].

Assuming that X is a set of random variables, representing the scattering of experimental results, the performance function$G$ separating the safe and unsafe regions is given by:

$$G(x_i) = S(x_i) - L(x_i) \tag{1}$$

where S is the resistance function and $L$is the load function.

The probability of the failure P_f is expressed as follows:

$$P_f = \Pr(G(x_i) \le 0) = \int_{G(x_i \le 0)} f_{\{X\}}(x_i) dx_1 \ldots\ldots dx_n \tag{2}$$

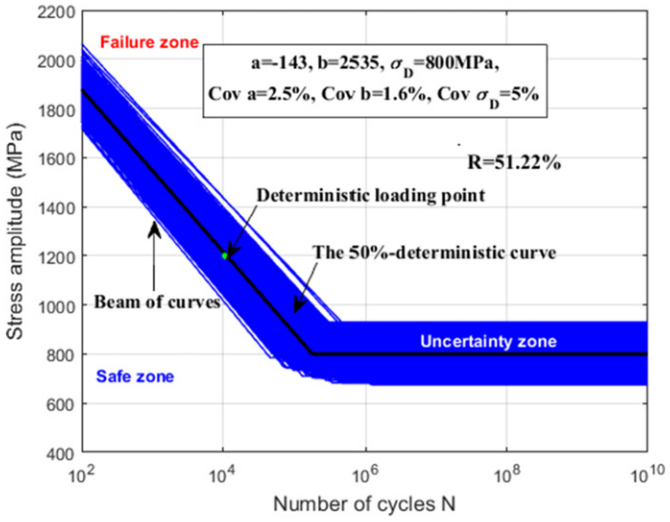

Fig. 1. The material dispersion surface in the probabilistic S-N curve.

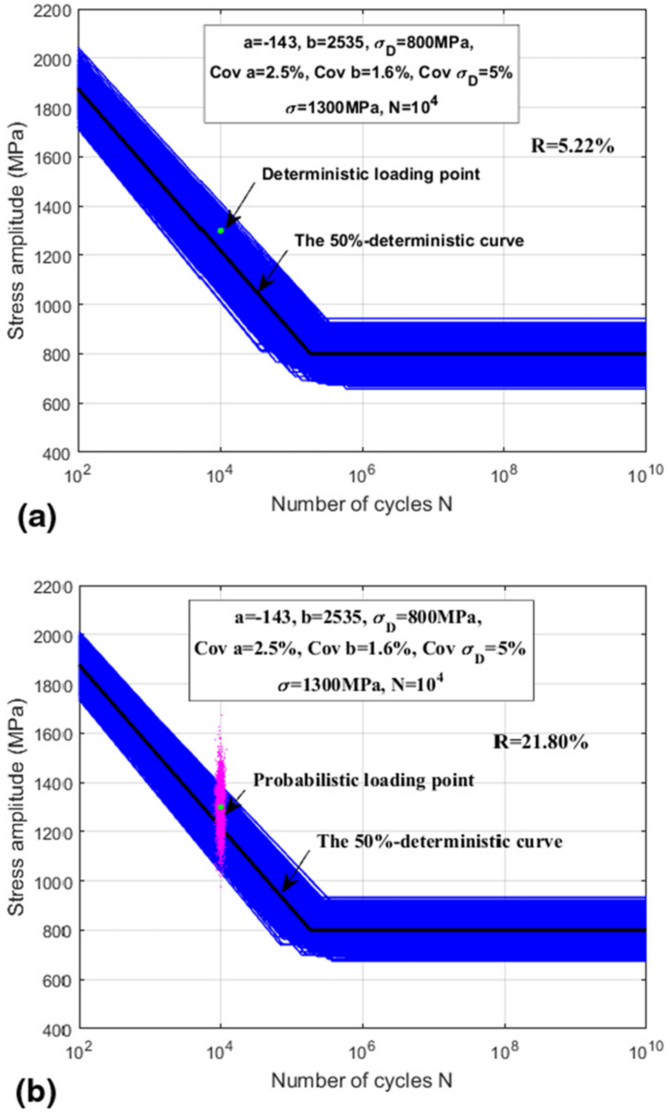

Fig. 2. The material dispersion surface in the probabilistic S-N curve: (a) deterministic loading point; (b) random loading point.