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Application of different fatigue strength criteria to shot peened notched components. Part 1: Fracture Mechanics based approaches

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ABSTRACT

Fatigue strength assessment of notched components is an essential step within their design process. It is well known that shot peening strongly increases the fatigue strength of mechanical structures. However, the contribution of shot peening to fatigue strength is generally underestimated by engineering design codes. This is due to the difficulty of defining a general fatigue design approach that is able to correctly and quantitatively consider the effect of shot peening, in terms of residual stresses, surface work hardening and surface roughness alteration.

This work critically evaluates the criteria available in the literature that have been applied to shot peened notched specimens. The entire work is divided in two parts. In the first part, fatigue strength evaluation methods based on fracture mechanics concepts are applied to notched shot peened specimens tested under different fatigue loading conditions. The second part, on the other hand, studies two recognized local stress approaches. Comparison of the results highlights the restrictions of each approach and the field in which it can be successfully applied; where possible, appropriate corrections were introduced in order to obtain a better agreement with the practical condition and the experimental data.

1. Introduction

Shot peening (SP) is a well-known mechanical surface treatment generally applied to improve fatigue behavior of metallic components. During SP process, a large number of hard and almost spherical shots accelerated in peening device impact the surface of a work piece and cause local plasticity. It is known that SP is a considerably useful method to increase the roughness, improve fatigue properties, avoid fretting, wear and stress corrosion cracking. Final aim of the process is to create compressive residual stresses close to the surface and work-harden the same layer of material. These effects are very useful in order to totally prevent or greatly delay the failure of the part [1–3]. The schematic of the air blast shot peening equipment that is the standard apparatus for this treatment is illustrated in Fig. 1. Other types of plants can be used; the final effect on the treated surface is not varying with the technology used to accelerate the media.

Normally SP is reported to be more effective for fatigue strength improvement of components with geometrical discontinuities, with respect to smooth ones, mainly due to presence of high stress gradient [4–6]. This observation can be attributed to the fact that the high gradient just under the notch results in considerable decrease in the stress level, and at the same time the compressive residual stresses induced by SP help stopping and retarding crack propagation.

Fatigue strength assessment of structural components is an essential step within their design process. Application of experimental approaches to determine the S–N diagram of notched components under a wide range of loading conditions and notch effects requires an extremely high effort in terms of time and costs. To limit or eventually avoid the required experimental efforts, fatigue assessment criteria are generally used, even if the application of each criterion is mostly limited to particular loading condition or material range. That is to say a unique criterion able to cover all practical cases is not still available. Application of a criteria to shot peened parts is still more difficult due to the modifications induced by SP in the surface layer of the treated material. SP involves generation of compressive residual stresses, work hardening and surface topography alteration. Due to the complex nature of the phenomenon, it is not easy to find a universally accepted theoretical model for assessing the fatigue strength of shot peened components that can be sufficiently robust to deal with various conditions. Indeed, despite the importance of the stress concentration effect on fatigue strength, still an agreed set of standard methods for evaluating the effect of notches, holes, joints, defects and other stress-raisers is not available and there is not a commonly accepted fatigue assessment criterion in the literature to be applied to shot peened parts. Notwithstanding SP's widely recognized beneficial effects on fatigue strength, its contribution is

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Nomenclature

R	stress ratio
σ_{eff}	effective stress
$\Delta\sigma_0$	plain fatigue strength
L	material characteristic length
ΔK_{th}	range of the threshold value of the stress intensity factor
f_0	pulsating plain fatigue strength
f_{-1}	fully reversed plain fatigue strength
σ^{RS}	residual stress components
σ_m	mean stress component
α	material parameters
β	material parameters
σ_{VM}	Von-Mises stress
p_m	mean hydrostatic pressure
σ_{eq}	equivalent stress b_2 roughness coefficient
$\Delta\sigma_{g,th}$	threshold range of the gross nominal stress
α_γ	non-dimensional coefficient, dependent on component geometry, loading type and notch opening angle
a	reference dimension of a component, for example the notch depth
$\tilde{a}$	degree of singularity of the stress distributions
$\Delta K^V_{i,th}$	threshold range of mode I notch-stress intensity factor
$\Delta\sigma_0$	range of the fatigue limit of the material
a^V_O	characteristic length parameter for a V-notched component
β_{LEFM}	coefficient that depends only on the notch opening angle

generally underestimated by the design codes; mainly due to the difficulties involved in correctly considering the peculiar effects of SP in fatigue strength assessments. For instance AGMA code for gears [7], that to the best knowledge of the authors is the only design code that considers quantitatively the SP contribution, has recognized that SP increases the fatigue strength of gears up to 25%, even if in many cases the actual improvement is more than this.

The present paper is aimed at critically reviewing the application of the most widely used fatigue criteria to shot peened notched specimens. The study is based on the results obtained for specimens with different notch geometries, applied loads and SP parameters. The considered criteria are divided in two major groups that have the potential to provide the design engineer with a practical tool to address the fatigue strength of shot peened material. The criteria considered in this study are mainly based on fracture mechanics and local stress approaches. Other criteria as the De los Rios [8] concepts are also helpful to understand the mechanisms through which SP influences the fatigue strength; however this criteria is not so practical to be used for notched components, since its implementation requires data and parameters that are not easily available for many materials and thus is not considered in the present paper. In this first part the fracture mechanics concept based approaches are discussed.

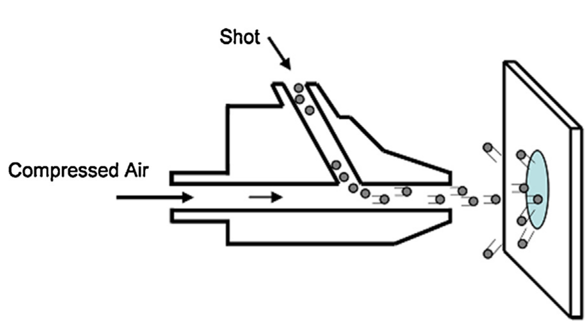

Fig. 1. Schematic illustration showing the equipment of air blast shot peening.

Theory of critical distance (TCD) [9–12], as the first approach, assumes fatigue strength can correctly be estimated only if the entire stress field damaging the fatigue process zone is correctly taken into account, suggesting to average the stress close to the stress concentrator apex over a material unit called as critical distance.

The second criteria is based on the statement that under appropriate conditions, notches can behave as cracks with the same depth and the fatigue limit can be estimated by means of linear elastic fracture mechanics [13]. A unified approach proposed by Atzori et al. [13] which substitutes the notch effect by an equivalent crack and estimates the fatigue limit for different stress raisers (i.e. defects, cracks, crack-like notches and blunt notches) was considered.

These criteria are applied to two different experimental campaigns that are subjected to rotating bending and axial fatigue tests. The comparison highlights the restrictions of each approach and the field in which they can be successfully applied; where possible, appropriate corrections are introduced in order to obtain a better agreement with the experimental results.

2. Fatigue assessment criteria

In this section a brief review of two fracture mechanics based methods applied for calculation of fatigue strength of notched components subjected to SP is provided.

2.1. Theory of critical distance (TCD)

Originally proposed by Neuber [9] and later simplified by Peterson [10], TCD implies that the maximum stress at the notch root is inappropriate for fatigue prediction in situations where the gradient of stress near the notch is high. Here we have considered the revision of Taylor to the TCD that is based on the calculation of the equivalent strength on a line (Line Method (LM)) [11]. LM method assumes that the notch fatigue response is governed by an effective stress, calculated through the material characteristic length, L, as a function of the stress field in the neighborhood of the notch tip.

According to the TCD, notched components are in their fatigue limit condition when the effective stress $\Delta\sigma_{eff}$, calculated by averaging an equivalent stress σ_{eq} along the notch bisector over the material characteristic length L, equals the plain fatigue strength, $\Delta\sigma_0$ (see Fig. 2).

$$S(L) = \frac{1}{2L}\int_0^{2L} \sigma_{eq} dy = \Delta\sigma_0 \tag{1}$$

where y is the local coordinate along the notch bisector with the origin lying on the notch apex. The material characteristic length, L, can be calculated as follows [12,14]:

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_0}\right)^2 \tag{2}$$

where ΔK_{th} is the range of the threshold value of the stress intensity factor and, again, $\Delta\sigma_0$ is the plain fatigue limit of the material (both determined under the same load ratio, R, applied to the specimen).

The TCD approach can be applied to assess fatigue strength of shot peened notched components considering the effective stress $\Delta\sigma_{eff}$ according to the Sines criterion and residual stresses as mean