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Fatigue behaviour of geometric features subjected to laser shock peening: Experiments and modelling

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ABSTRACT

Finite element models, using the eigenstrain approach, are described that predict the residual stress fields associated with laser shock peening (LSP) applied to aerospace grade aluminium alloys. The model was used to explain the results of laboratory fatigue experiments, containing different LSP patch geometries, supplementary stress raising features and different specimen thickness. It is shown that interactions between the LSP process and geometric features are the key to understanding the subsequent fatigue strength. Particularly relevant for engineering application, is the fact that not all instances of LSP application provided an improvement in fatigue performance. Although relatively deep surface compressive residual stresses are generated which can resist fatigue crack initiation in these regions, a balancing tensile stress will always exist and its location must be carefully considered.

1. Introduction

Laser shock peening (LSP) uses high power laser pulses (typical process parameters are power = 1–25 J, pulse duration = 18–30 ns, laser beam size <10 mm) to generate an advantageous residual surface stress distribution in structural components (e.g. for airframe applications) [1]. The technique involves firing laser pulses at the surface of a component to introduce a surface compressive residual stress. Typically, an LSP treatment produces compression to a depth of 1–2 mm, which is about five to ten times deeper than that produced by conventional shot peening [1–4]. A significant advantage is that the laser parameters are more reproducible than their equivalents during shot peening, and this allows the process to be tailored to specific design requirements.

LSP is particularly attractive for application at geometric stress concentrations; by introducing a compressive surface residual stress, fatigue performance can be enhanced through the increased resistance to crack initiation. However, these are precisely the areas where the technique is most difficult to apply in practice, often due to "line of sight" restrictions or simply the difficulty in applying the ablative tape (used to transfer the laser shock to the substrate) around complex geometric features. Further, as will be shown in the paper, the interaction between the process and complex geometries can lead to unexpected results. The current paper examines such interactions in two aerospace grade aluminium alloys (Al 2024 and Al 7010). The analysis presented here shows how the eigenstrain technique may be used as an efficient tool for predicting the associated residual stress. This approach obviates the need for a completely explicit finite element (FE) analysis, which may be impractical, since in practice an array of multiple LSP pulses is generally required to treat the surface area of a component.

Surface treatment by LSP usually involves applying an ablative or sacrificial aluminium tape to the surface of a component. This tape is then vaporised by a laser pulse, producing a rapidly expanding plasma. The plasma is confined by a jet of water simultaneously sprayed on the surface [1,2] and the effect is to generate a high-amplitude, short duration shock (pressure) wave in the work piece [1–4]. As the stress wave propagates, localised plastic deformation occurs and, once the pulse has decayed, misfit between the plastically deformed material and surrounding elastic region generates a residual stress [2,3]. Due to the short duration of the laser pulse (typically <30 ns) no significant heating occurs in the substrate. Hence the generation of residual stress may be regarded as a largely mechanical process, involving the response of the material to a pressure wave [1,2]. An explicit FE analysis is generally required to model the residual stresses caused by LSP. However, in order to obtain the stabilised stress distribution, the FE simulation must be run until the stress waves caused by each laser pulse fully dissipate. Hence modelling the process in this manner is demanding in terms of computational processing times and cost [2,3].

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Although the LSP technique offers significant potential to improve the fatigue resistance of engineering components, instances have been reported [5] where a subsequent fatigue benefit has not been found. Indeed, unless great care is taken, the balancing tensile stresses [1] may actually reduce fatigue life, therefore knowledge of the locations and magnitudes of these tensile stresses is required. For instance, in thin sections, care must be taken in the choice of the laser power to avoid "overpeening", leading to a largely tensile field near the surface.[1] The beneficial effects of LSP on fatigue strength have been widely reported in the literature, for example using dog-bone [6] and open hole specimens [7]. There are also some investigations of the effect of LSP on fretting fatigue [6]. Titanium (Ti–6Al–4V) [6] and aerospace grade aluminium alloys (Al 2024 and Al 7010) [5] have been used in many studies, but limited research has been carried out using other alloys, including Ni-based super alloys [8]. The exact nature of the balancing tensile stress regions can be difficult to determine, because the residual stress arises as the result of the elastic response of the whole component to the localised plastic strain introduced by LSP. A knowledge of the precise interaction between the LSP parameters, the geometric features and the resulting tensile "hot spots" is required in order to model the fatigue strength.

It has been proposed that the improvements in fatigue life generated by LSP are dominated by a significant increase in life during initiation and early stage crack growth [6]. Even so, a comprehensive understanding of the effect of LSP on fatigue strength is still lacking, and the influence of residual stress and surface conditions are very difficult to determine. Development of a comprehensive analytical method to predict the residual stresses generated by LSP and subsequent fatigue performance is difficult because of the complex interaction between the geometry of the component and the residual stress field. The authors have previously developed a hybrid eigenstrain approach (i.e. employing misfit strains, which act as sources of incompatibility of displacement) to determine the residual stresses generated by the LSP [2–4]. The current paper extends the method to model the stress field in open-hole specimens, both after treatment and during subsequent fatigue loads.

The eigenstrain technique is an efficient tool for modelling the residual stress state present in a component and the technique has been successfully used in a number of applications. For example, Korsunsky et al. [9] successfully constructed the residual stress induced by welding; Prime and Hill [10] determined fibre scale residual stress variation in metal-matrix composites; and Korsunsky [11] evaluated residual stresses in auto-frettaged tubes. The knowledge of eigenstrain distribution may be used to determine the residual stress rather than seeking the stress field directly. This has the advantage that the eigenstrain distribution is less sensitive to component geometry than the resulting stress field. Previous analyses [2–4] have shown that the plastic strains are usually stabilised within a short time period and hence the eigenstrain distribution can be conveniently extracted from an explicit FE simulation by the modelling the effect of a LSP pulse as a dynamic pressure load. The residual stress distribution is then determined as the elastic response of the workpiece after incorporating the eigenstrain as an initial misfit strain in a static FE model [2,3]. It should be noted that the plastic flow caused by the shot has been captured in the eigenstrain extracted from the explicit simulation, so that the yield condition is unlikely to be exceeded in the implicit model.

Previous work [2–4] has shown that the eigenstrain caused by the array of shots in a single layer of LSP pulses can be simply modelled as that generated by a single LSP shot but applied over a wider area in an appropriate misfit strain FE model. This allows modelling of the effect of an array of LSP shots, arranged side by side, to peen a desired surface patch of a component. Thus, the residual stress distribution can be determined from a static FE model by incorporating the eigenstrain depth profile obtained from a representative simple array, thereby significantly reducing the computational cost compared to an equivalent wholly explicit FE analysis [3]. Similarly, the residual stress in a range of different geometries and for a range of peened areas (in a given material) can be simply derived using the knowledge of a single eigenstrain depth profile, related to a particular set of peening parameters. This has allowed modelling the effect of LSP treatment adjacent to geometric features (e.g. in the vicinity of a straight or curved edge) [4].

This paper investigates experimentally and numerically the degree to which the fatigue response of complex geometric features can be modelled by using an understanding of simple eigenstrain distributions. Thus, the model will be validated by comparing the predicted stress profiles in a particular specimen geometry with the corresponding experimental fatigue lives. The results suggest that the eigenstrain approach is particularly useful in these cases (e.g. in the hole geometry investigated here). It will be shown that care must be exercised in the application of LSP at stress concentrations. In some cases, no fatigue benefit can result and performance may even be worse than the non-peened condition. Notably, the results show that LSP, when restricted to small patches around geometric stress raising features, may be more effective than LSP applied to larger areas.

2. Experimental methods and data

Fatigue tests were carried out on two aerospace grade aluminium alloys supplied by Airbus, Al 7010 T7451 and Al 2024 T351. The 0.2% proof strength of these two alloys is 340 MPa and 430 MPa respectively. Fig. 1 shows the design of two open hole fatigue specimens, which were tested under cyclic tension. Two thicknesses of specimen were employed, 5 and 15 mm respectively. The specimens were initially machined into rectilinear blanks using CNC milling. LSP was then applied to the shaded regions indicated in Fig. 1 on the front and rear faces only (i.e. no LSP was applied to the side faces). Where LSP was applied across the full width of the test piece this was designated a "full face specimen". Alternatively, LSP was restricted to a central region of

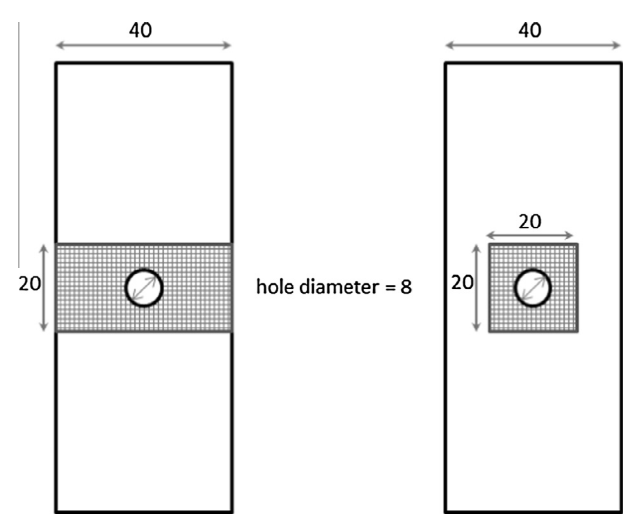

Fig. 1. Mid gauge section details of the full face (left) and patch (right) test specimens (total length of specimens = 330 mm, all dimensions quoted in mm).

[1] For thin sections, it is possible to develop tension close to both the surfaces, if the stress wave reflection from the back surface is high enough to cause reverse plasticity in the initial compressive field underneath the LSP patch.