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Residual stresses reconstruction in shot peened specimens containing sharp and blunt notches by experimental measurements and finite element analysis

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ABSTRACT

The knowledge of the residual stress (RS) field in the vicinity of a notch is of paramount importance to understand the fatigue resistance of shot peened components containing such stress raisers. In the first part of this work (Winiarski et al. 2016, Exp. Mech.), RS were measured along the notch bisector using non-destructive and destructive techniques, namely micro-XRD and FIB-SEM DIC micro-slot cutting (μSC) and micro-hole drilling (μHD). These indicate an increasing concentration of the longitudinal residual stress component with increasing sharpness of the notch. In this paper, these linescan measurements are used to reconstruct the complete RS field through finite element (FE) analyses. Specifically, RSs are introduced into the FE model using thermal misfit strains (eigenstrains), whose intensity and spatial distribution are deduced by fitting the experimental data. Since the eigenstrains depend on the actual notch geometry, their distribution cannot be estimated from residual stress distributions measured on plain or notched specimens of different geometry. The proposed approach can be very useful to estimate the notch fatigue resistance of shot peened components on the basis of local stress and fracture mechanics approaches.

1. Introduction

Shot peening (SP) is a surface treatment where the surface to be treated is bombarded with a large number of hard, small spherical shots under controlled conditions. This treatment introduces plastic deformation in a shallow surface region of the treated part leading to a compressive in-plane surface residual stress (RS) state [1]. Shot peening is widely applied to improve the fatigue resistance of mechanical components carrying stress raisers or notches, for example shouldered shafts, riveted aeronautical panels, gears, etc., because it can treat, with near-full coverage, geometrical details that are inaccessible to other surface treatments, such as hammer or ultrasonic peening or ball burnishing. The benefit conferred by the SP in terms of the increment in fatigue strength and reduction in notch fatigue sensitivity is strongly correlated to the RS produced by the treatment [2]. Hence, the knowledge of the RS field near the notch is essential in understanding the fatigue behavior of notched components. In recent years, there has been increasing interest in explicitly including the effects of shot peening process into life assessment models rather than considering shot peening simply as an additional safety factor [1,2]. Specifically, RS produced by shot peening are incorporated into multiaxial fatigue criteria, sometimes in combination with critical distance approaches [3–5], or into damage tolerant approaches [6–8]. In the former, the RS are treated as mean biaxial stresses superimposed on the stress field produced by external loading, in the latter case, the RS are included as *R*-ratio and crack closure effects.

Despite the importance of this topic for the structural integrity assessment of shot peened components, very few papers in the literature dealt with the determination of the RS distribution near notches. Explicit dynamic finite element (FE) simulation of the shot peening process proved to be an effective way of estimating RS [9,10], but, to the best of our knowledge, simulations have only considered flat target surfaces and no one attempted to simulate the multiple shot impacts onto complex geometrical details. The German guideline FKM [11] for fatigue strength assessment proposes an empirical correction factor to account for the surface

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treatment effects; FKM prescribes a range for this coefficient, which is [1.1,1.2] for un-notched and [1.1,1.5] for notched steel components and the actual value must be selected by the user as suggested by the practice. Olmi et al. [12] included RS measured at the root of teeth in shot peened gears in the calculation of the relative stress gradient proposed by Eichlseder [13] for the fatigue verification of notched components. Bagherifard et al. [5] incorporated an equi-biaxial RS state measured far from the notch into a multiaxial fatigue criterion combined with a critical distance approach to predict the fatigue strength of shot peened notched components, thus neglecting the perturbation exerted by the notch on the RS field in terms of intensity and mono- or multi-axiality. Bertini and Fontanari [14] estimated the RS field in induction hardened notched components on the basis of FE analyses and far-field XRD RS measurements. Unfortunately, no experimental RS data was available to validate their numerical estimation. Benedetti et al. [3] adopted a similar approach for evaluating RS in shot peened notched samples. Specifically, eigenstrains were determined from in-depth RS measurements undertaken on plain specimens and then transferred to the surface of notched samples, neglecting the contribution of the peening treatment on the lateral surface at the notch root. Once more it was not possible to validate the models with RS measurements. Achintha et al. [15] used an eigenstrain approach to reconstruct the RS field in open hole fatigue specimens subjected to laser shock peening, but no experimental verification of the estimated RS state was provided.

Some attempts have been made in the past to make measurements of the RS field at the tip of a notch [16–22], but considerable experimental challenges were encountered. In fact, the shallow treatment depth (some hundreds of microns) and the high lateral RS gradients (on the order of MPa/μm) render conventional far-field experimental techniques unsuitable. For instance, blind-hole-drilling [23], contour method [24] and slitting technique [25] can only be applied to macroscopic through-thickness RS fields in work-pieces of simple geometry while conventional X-ray and neutron diffraction used in [16–22] probe regions of millimetre dimensions, which are too large to resolve steep RS gradients [26].

In Ref. [27,28] we have used novel micro-slot cutting (μSC), and micro-hole drilling (μHD) techniques with micron-sized gauge volumes to resolve the high RS gradients local to a notch validated by micro-XRD measurements sampling tens of micron areas. In this paper, we apply an eigenstrain approach to reconstruct the RS field along the notch bisector on the basis of the collected RS measurements. The term eigenstrain indicates any permanent non-reversible strain arising in the material due to some inelastic processes such as plastic deformation, visco-elasticity and -plasticity, and thermal expansion. Eshelby was one of the first to use eigenstrains to represent residual stress fields [29]. This approach has been adapted to the finite element method having been used by Ueda et al. [30,31], Fujimoto [32], Beghini and Bertini [33] to investigate RSs in welded structures. Jun and Korsunsky [34] further developed and formalized the method and applied it to a variety of situations, such as shot peening [35], laser shock peening [36], autofrettaged tubes [37]. You et al. [22] used this method to model the RS in-depth distribution in notched samples subjected to shot peening. In all these situations, the RS field is reconstructed on the basis of an inverse eigenstrain problem, viz. the unknown eigenstrain distribution is determined by fitting RSs measured at a finite number of experimental points. Usually, eigenstrains are introduced into FE models by using a temperature distribution and setting appropriate coefficients of thermal expansion [2]. Often, the eigenstrain distribution is assumed to be geometry independent, so that the eigenstrain profile determined on a simple geometry is then applied to components of any geometry to evaluate their RS state [38].

The present paper is aimed at applying the eigenstrain reconstruction method to the measurements undertaken in [27] in shot peened prismatic Al-7075-T651 specimens carrying two edge V-notches. In this way, the full knowledge of the RS field on the notch bisector plane is possible. Eigenstrains are introduced into the FE model of the notched samples through suitable temperature distributions that are functions of the coordinates of a local reference frame centred on the notch tip. The intensity of the temperature fields is determined with a fitting procedure based on the minimization of the square residuals. Special emphasis is placed on the estimation of the fit robustness on the basis of the statistical variability of the experimental measurements.

2. Experimental data

The experimentation has been performed on the aluminium 7075-T651 alloy supplied in the form of 4 mm thick rolled plate. The bulk material properties have been determined in [3] and are summarized in Table 1. The geometry of the prismatic specimens carrying two edge V-notches is illustrated in Fig. 1. The notch root fillet radius *R* was set to 2 mm ("blunt" notched samples), 0.5 mm ("sharp" notched samples) and 0.15 mm ("very sharp" notched samples).

The central part of both lateral and frontal surfaces of the specimens were shot-peened to an Almen intensity of 4.5 N using a 90° impingement angle with ceramic (ZrO_2 and SiO_2) beads of 60–120 μm diameter; details about the shot peening process are given in [27].

Fig. 2a and b shows SEM micrographs of the frontal and lateral surfaces, respectively, taken close to the notch tip of the very sharp-notched sample. It can be observed that the shot peening treatment was able to cover the root zone of the sharpest notch owing to the fine size of the ceramic beads employed. Moreover, the shot peening smoothed off the sharp edges produced by the EDM cut resulting in material flow toward both the frontal and lateral notch bisector (as indicated by arrows in Fig. 2). This could be explained by shot impacts occurring onto the specimen edge at different angles with respect to the surface normal while the nozzle of the air-blast machine rotates about the specimen longitudinal axis to treat both frontal and lateral surfaces of the notch.

In [27], the RS field in the notched samples was characterized by measuring the longitudinal RSs along the notch bisector through two complementary experimental techniques. (i) μXRD measurements were made on opposite frontal faces of the samples using Cu Kα radiation with high penetration depth (≈40 μm) to capture information about RSs averaged throughout the surface layer modified by the peening treatment, in contrast to Cr Kα radiation that gives information more localized on the specimen surface [27]. (ii) μHD and μSC measurements were made on specimens that had been previously polished to remove the outer 30 μm thick surface layer. In this way, information was obtained in a region of high compressive RS, but the local point to point variations arising from the individual impact dimples and surface damage had been eliminated, as discussed in [27].

Fig. 3a shows the average of the two μXRD measurements as a function of the *y* coordinate (as defined in Fig. 1) aligned with the notch bisector and centred on the notch apex. Due to the high

Table 1
Monotonic tensile properties of the Al-7075-T651 alloy.

E (GPa)	$\sigma_{Y0.2}$ (MPa)	σ_{UTS} (MPa)	σ_F (MPa)	T.E. (%)	R.A. (%)
73 (±1)	515 (±5)	565 (±5)	760 (±10)	18 (±2)	24 (±2)

E: elastic modulus; $\sigma_{Y0.2}$: 0.2% yield strength; σ_{UTS}: ultimate tensile strength; σ_F: true fracture stress; *T.E.*: total elongation; *R.A.*: reduction in area.