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The effect of plasticity on the ability of the deep hole drilling technique to measure axisymmetric residual stress

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ABSTRACT

Mechanical strain relief covers a class of techniques for measuring residual stress in engineering components. These techniques work by measuring strains or displacements when part of the component is machined away. The assumption is that such strain or displacement changes result from elastic unloading; however, in components containing high magnitudes of residual stress elastic–plastic unloading may well occur. Such elastic–plastic unloading introduces errors into the measurement of the residual stresses and these errors may be large. This paper addresses the performance of the deep hole drilling technique, a mechanical strain relief technique particularly suitable for large section components. First a plane strain analysis is presented that quantifies the errors associated with plasticity for different magnitudes of residual stress. A three dimensional finite element analysis is then carried out that shows larger errors may be obtained than those suggested by the plane strain analysis. A method for reducing the magnitude of the error is investigated. Finally, the results of an experimental measurement of residual stress are presented where substantial plasticity occurs. The work demonstrates the potential vulnerability of mechanical strain relief methods to plasticity and introduces methods for quantifying the resulting errors. It also provides further evidence that modifications to the standard DHD technique can be made to make the technique less susceptible to error when plasticity occurs.

1. Introduction

Techniques for measuring residual stress involving the removal of material associated with measurement of strain or displacement are termed mechanical strain relaxation (MSR) techniques. There is a wide variety of such techniques, some classed as semi-destructive where material removal is limited and others as wholly destructive. Examples of semi-destructive techniques are centre hole drilling [1], slotting [2,3] and the Sachs method [4] while an example of a wholly destructive technique is block removal, splitting and layering (BRSL) [5].

The deep hole drilling (DHD) technique is a semi-destructive MSR technique where a small hole is drilled through the thickness of a component. Fig. 1 shows the steps involved in the technique. First a small reference hole, typically about 3 mm in diameter, is drilled through the component to be measured (step 1). Next the diameter of this reference hole is measured accurately using an air probe (step 2). These measurements of diameter are made at a number of angular positions and depth intervals. A column of material containing the reference hole is then trepanned from the component using electro-discharge machining (step 3). Finally the diameter of the reference hole is re-measured at the same angular positions and depths as before (step 4). The change in diameter of the reference hole is used to determine the residual stress field. It is assumed that the relaxation of residual stress caused by the introduction of the reference hole is negligible and that the residual stresses are relaxed in a linear elastic manner. Further details of the DHD technique may be found elsewhere [6].

All MSR techniques for measuring residual stress assume that the change in strain occurs elastically for then the residual stresses may be calculated directly from the measured change. If, however, the residual stresses are close to yield, plasticity may occur when material is removed and there will be no straightforward relationship between the measured strain change and the residual stress. Indeed, it may not have been evident that plasticity has occurred and that the assumptions inherent in the measurement are no longer true. There have only been a limited number of investigations on the influence of plasticity on mechanical strain relaxation techniques. Lin and Chou [7] reported errors of nearly 50% in measurement of residual stresses in the centre hole drilling technique due to local yielding. There are other reports on the effect of plasticity on the centre hole drilling technique [8–10] and

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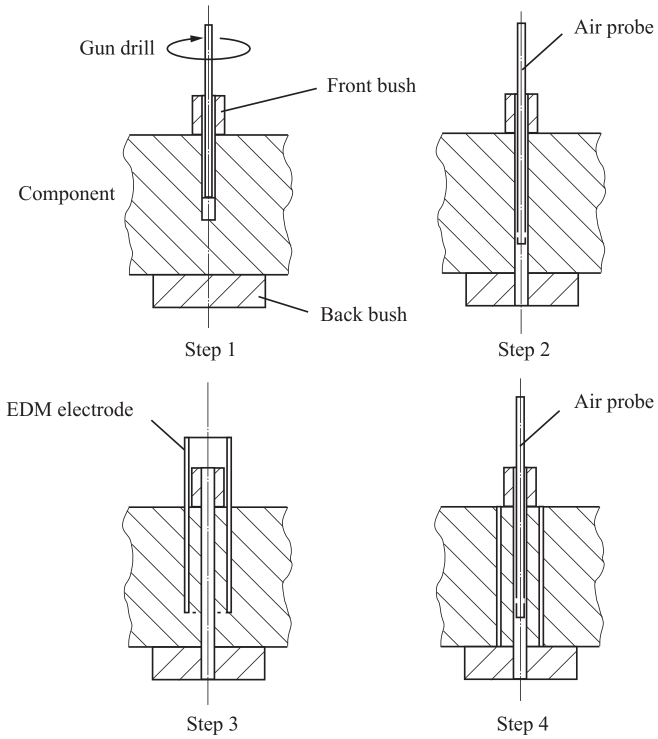

Fig. 1. Steps in the deep hole drilling technique: step 1—drilling of reference hole, step 2—measurement of reference hole diameter, step 3—trepanning of core and step 4—re-measurement of reference hole.

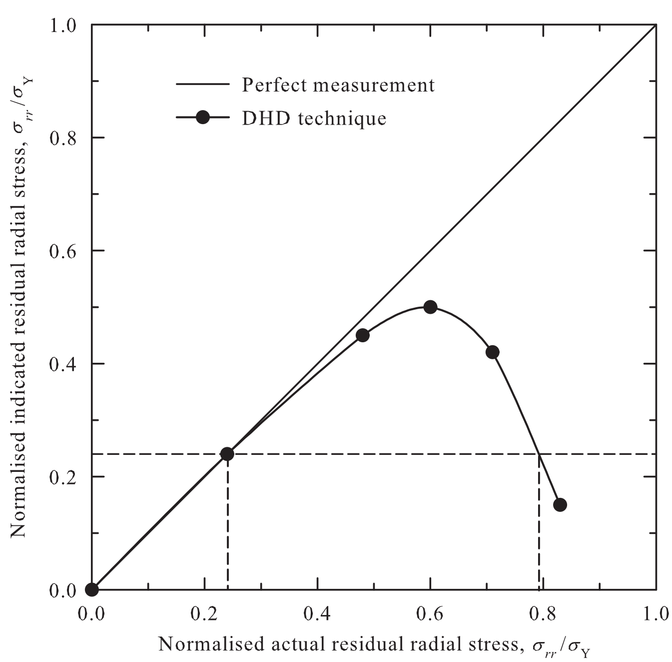

Fig. 2. Normalised measured stress versus normalised actual stress to show there are two actual stress magnitudes giving the same measured stress.

several that suggest methods for correcting for errors associated with plasticity [11–16]. Apart from the centre hole technique, other techniques that have been investigated in relation to plasticity are ring-coring [17], the contour method [18,19] and slitting [20].

Like other mechanical strain relief techniques, the DHD technique also suffers from the effect of plasticity in its ability to measure residual stresses accurately [21]. Fig. 2 shows the results of an axisymmetric finite element simulation of the DHD technique as carried out later in the paper [22]. The figure shows the residual stress as indicated by the technique, normalised with respect to the yield stress, versus the normalised actual residual stress. For the measurement to work perfectly the indicated and actual stresses would be the same. As can be seen, as the magnitude of the stress becomes larger the measurement becomes increasingly inaccurate. There are in general two magnitudes of actual stress that give the same indicated residual stress. For example Fig. 2 shows two normalised actual stresses equal to 0.24 and 0.79 that give the same indicated residual stress. Surprisingly, errors begin to occur at stress levels well below yield. This is because a significant stress concentration exists in the region around the tip of the trepan.

This paper describes analytical and finite element studies to understand the ways in which plasticity effects the measurement of residual stress. The analytic prediction of the performance of the deep hole drilling technique assumes plane strain conditions and a uniform biaxial residual stress field. Although the analysis neglects the three dimensional effects that are addressed by the finite element analysis, it provides an insight into the manner in which plasticity introduces errors in the deep hole drilling measurements of residual stress. This occurs in two ways. The first is because a yielded region forms around the drilled hole, which perturbs the residual stress field. The second is because additional yielding takes place during the trepanning operation, invalidating the assumption of purely elastic unloading.

The finite element analysis used in this paper applies an axisymmetric analysis where the axis coincides with the drilled hole. It allows the progressive material removal of the trepanned core to be analysed. This shows that substantial yielding occurs around the tip of the trepanning tool leading to much greater errors than that suggested by the plane strain analytical approach. Following previous work [22], a method of improving the accuracy of the DHD technique is described and is shown to give substantial improvements when significant plasticity occurs. Finally, an example of an experimental measurement of residual stress is presented for an axisymmetric shrink fitted assembly where substantial yielding occurs during the application of the DHD technique. All the work reported in this paper assumes axisymmetry and has been carried out for elastic–perfectly plastic materials. The generalisation of the work to biaxial residual stress distributions and hardening materials is the subject of ongoing research.

2. Analysis

In this section an analytic prediction of the performance of the deep hole drilling technique is presented for plane strain conditions and a uniform biaxial residual stress field. Three dimensional effects resulting from the progressive trepanning operation are neglected.

We consider a large disc of material containing a central reference hole of radius a with a stress σ_0 applied to the periphery of the disc, as shown in Fig. 3 (radii c and c' are described later). This is equivalent to a residual stress field, which is uniform over an area large enough compared to the size of the drilled hole. The analysis assumes axisymmetry and plane strain conditions. To begin, we revise the elastic case.

The components of stress in the disc are

$$\sigma_r = \sigma_0\left[1-\frac{a^2}{r^2}\right],\ \ \sigma_\theta = \sigma_0\left[1+\frac{a^2}{r^2}\right]\ \text{ and }\ \sigma_z = 2\nu\sigma_0 \tag{1}$$

The tangential strain ε_θ is calculated from the stress by

$$\varepsilon_\theta = \frac{1}{E}(\sigma_\theta - \nu\sigma_r - \nu\sigma_z) \tag{2}$$