General paper

Residual Stress Determination by the Hole Drilling Method in the Case of Highly Stressed Surface Layers

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Abstract: For different rotationally symmetrical compressive residual stress distributions, typically found for shot peened steel surfaces, the reliability of the incremental hole drilling method is investigated by using the finite element code ABAQUS. Simulations of the hole drilling procedure were carried out in order to calculate strain relaxations at the surface due to the material removal with respect to the actual drilling depth. These calculated strain relaxation curves were evaluated by two different hole drilling evaluation methods, the integral method (IM) and the differential method (DM). The errors of the so called plasticity effect were determined by comparing the results of purely elastic simulations with those determined by elasto-plastic calculations. Obviously, the DM has principal difficulties in determining a residual stress gradient properly. The plasticity effect results for both methods in overestimated residual stress values in the surface near region.

Key words: Incremental hole drilling method, Residual stress gradient, Shot peening, Plastic deformation

1. INTRODUCTION

Incremental hole drilling (IHD) is a well established method in the field of residual stress analysis. The method, first proposed by Mathar in 1933 [1], is based on the interference of the residual stress equilibrium by incremental hole drilling. As a reaction the strain relaxations in the vicinity of the hole are measured for each drilling increment at the surface usually by specially designed strain gage rosettes. The commonly applied evaluation procedures are based on the analytical solution of Kirsch for the linear-elastic stress distribution around a through hole of an infinite plate subjected to an external load [2]. For the given geometry of the hole the method has to be uniquely calibrated, considering that in general a blind hole is machined.

For uniform residual stress distributions the technique gives reliable results unless the geometrical restrictions are kept (e.g. distance from the hole to free edges, distance between adjacent holes, curvature of the surface, etc.) [3]. Regardless of the applied evaluation method, this is particularly true until the magnitude of the residual stresses does not exceed about 60-70% of the materials yield strength σ_y [4]. However, due to stress concentrations caused by the blind hole, plastic deformations in the immediate vicinity of the hole will affect the strain relaxations recorded at the surface just as the magnitude of the local residual stress state exceeds the above given limit. The so called plasticity effect results in an overestimation of the local residual stresses during application of the incremental hole drilling method and was already mentioned by Meßmer in 1936 [5]. Since then several publications dealt with the effect of plastic deformations on the determination of residual stresses by the incremental hole drilling method (e.g. [6-10]). The recom-

mendations for the amount of residual stresses since when remarkable effect of plastic deformations during drilling has to be taken into account vary between 50% (e.g. [8]) and 70% (e.g. [9]) of the materials yield strength. Furthermore corrections of the plasticity effect were proposed (e.g. [3], [6]). However, due to the strong

Fig.1. Residual stress and microhardness depth profiles for a shot peened steel X42Cr13.

restrictions and assumptions considered in these procedures no universally valid corrections are available for application.

Beyond that the application of the incremental hole drilling to in-depth residual stress gradients uncovers its limitations. In e.g. [11] and [12] it is reported about the inability of the hole drilling method to determine a residual stress distribution introduced by deep-rolling or shot peening, properly. A characteristic result is presented in Fig 1. The diagram shows the residual stress depth profiles for the shot peened cold work tool steel X42Cr13 determined by X-ray diffraction (XRD) as well as by incremental hole drilling, by the integral method (IM) and the differential method (DM), respectively. In addition a depth profile of the Vickers microhardness is shown, indicating a distinct work hardening in the near surface layers. At least for the first 300 μm below the surface an effect of plastic deformation in the vicinity of the hole can be expected, since the residual stresses clearly exceed 60% of the initial materials yield strength. In the surface near region the DM shows an excellent agreement with the X-ray diffraction results. In larger distances to the surface the DM obviously overestimates the compressive residual stresses clearly. The IM shows a totally different characteristic. Near the surface the residual stresses determined by X-ray diffraction are obviously overestimated whereas in larger distances from the surface an excellent agreement of the stress values with the X-ray diffraction results can be observed.

This example describes in a typical way the limitations of the incremental hole drilling when being applied to residual stress distributions showing an in-depth gradient in the surface near region. Such results presented for a shot peened steel X42Cr13 (see also [12]) deliver a motivation for carrying out extensive finite element simulations.

Fig.2. Different shapes of the residual stress gradients considered here as an input for the finite element simulations.

tions.

Complementary to a recent survey on the residual stress determination by incremental hole drilling in highly stressed shot-peened surfaces [13] the indicated shortcomings of the IHD were systematically investigated using the finite element method (FEM). The main objective of this project was to separate the errors caused by the plasticity effect from the errors caused by the limitations of two commercially used incremental hole drilling evaluation methods to follow a shot-peening residual stress gradient correctly.

Fig.3. Residual stress depth distributions calculated for strain relaxations determined in elasto-plastic finite element simulations.

2. HOLE DRILLING EVALUATION PROCEDURES

In this work it is distinguished between two different well accepted evaluation methods, the integral method (IM) and the differential method (DM). According to [14] these methods are the most suitable ones for the analysis of complex residual stress states, particularly for in-depth non-uniform stress distributions. For a comprehensive description about the differences between the various hole drilling evaluation methods it is referred to [15] and [16]. The main difference between the DM and the IM is that for the DM it is assumed that only the residual stresses being present in the actual drilling increment do affect the strain relaxation at the immediate surface. In comparison, for the IM it is supposed that also the residual stresses above the actual drilling increment cause additional deformations at the surface.

The differential method used in this work is proposed by Kockelmann et. al. [14] and is offered commercially under the designation MPA II. Bijak-Zochowski [17] proposed the integral method (IM), further developed by, e.g., Schajer [18, 19] and Lu [20]. The IM - software used in this work is the program H-drill developed by Schajer.

3. FINITE ELEMENT SIMULATION

For the simulations a rotationally symmetrical model was designed using the finite element code ABAQUS implicit considering an elasto-plastic materials behavior with multilinear isotropic hardening. The drilling increments were introduced by using the so called birth and death option [21]. Strain relaxations in the region of the strain gauges were calculated as a function of the drilling depth. Here the strain field at the surface was integrated over the gauge area. Residual stresses were introduced by using prestressed elements. Uniform as well as non-uniform residual stress distributions were considered. Here the focus will be on the non-uniform stress distributions with different shapes of the in-depth gradients near the surface.

Figure 2 illustrates the stress gradients used, showing different slopes and different interceptions with the zero stress level, which were considered here as input for the simulations. They have all in common that the maximum residual stress amount was – regardless of the shape of the presented curves – close to 95% of the materials yield strength, which was assumed in this first approach to be constant with depth, so that in all cases an effect of plastic deformation on the results could be assumed. Finally the calculated strain relaxations were evaluated with the DM and the IM.

4. RESULTS AND DISCUSSION

The diagrams in Fig. 3 show the residual stress depth profiles determined by the two evaluation methods distinguished here, when using the calculated strain relaxations in comparison to the nominal stress distribution used as input for the finite element simulations. For all

Fig.4. Strain relaxations occurring due to the plasticity effect and corresponding stress error distributions.

shapes of the residual stress distributions to some extent large divergences to the nominal residual stress distribution can be noticed for both evaluation methods. Both have characteristic difficulties in determining the residual stress gradient properly. Obviously the IM overestimates the residual stresses in the surface near region whereas the DM determines residual stress values that are too low. For the residual stress depth distribution showing a maximum residual stress value below the surface (shape 2), near the surface the DM is in good agreement with the nominal residual stress distribution. At larger distances to the surface the residual stress values determined by the IM agree well with the nominal distributions. Here the depth profiles determined by the DM strongly diverge from the nominal distributions.

The divergences to the nominal residual stress distributions shown here are based on two main error sources. First, the problems of the evaluation methods for determining the residual stress gradient properly and second, the plasticity effect. As an example, for the residual stress gradient shape 1, in Fig. 4 the effect of local plastic deformation is demonstrated by plotting the percentage strain relaxations as a function of depth. The percentage divergence $(\epsilon_{pl} - \epsilon_{el}) / \epsilon_{el}$ for the strain relaxations calculated by purely elastic simulations ϵ_{el} and elasto-plastic calcu-

Fig.5. Stress errors caused by the given residual stress gradients (solid line) when evaluating the results of the elastic calculations by the integral method (IM) and the differential method (DM).

lations ε_{pl} is presented with respect to the drilling depths.

Of course, these percentage strain relaxations are independent on the evaluation methods. In general the strain relaxation, which can be attributed to plastic deformation is higher when the residual stresses in greater depths have a high level, but the percentage value is generally less than 12% in the cases investigated here. The highest absolute strain relaxations occur for the highest residual stress-yield stress ratio (σ^{RS}/σ_y). Conspicuously the strain relaxation curves show a minimum when the residual stresses drop down to $\sigma^{RS}/\sigma_y \approx 0.7 \dots 0.8$. For higher drilling depths ($\sigma^{RS}/\sigma_y < 0.7$) the value for the

strain relaxations calculated by elasto-plastic simulations increases again slightly, which is caused by the high residual stress values in the surface near region leading to further deformations at the surface and to an increase of the plastic zone in the surface near region (see also Fig. 6). This additional deformation is not considered by the mathematical formulation of the differential method. These strain relaxations are converted in a next step to stress errors caused by this plasticity effect (see lower part of Fig. 4). Generally the IM determines higher errors for the residual stresses as the DM. The DM shows a lower sensitivity to plastic deformations occurring in the

Fig.6. Contour plot of equivalent plastic strain as an indicator of the extension of the plastic zone in the vicinity of the hole for a residual stress gradient in the surface near region (shape 3).

vicinity of the hole. This might be due to the smoothing characteristic of the DM. The stress errors are following at least qualitatively the corresponding strain distributions. Figure 5 illustrates the difficulties the two evaluation methods do have when dealing with residual stress gradients. For that purpose strain relaxations of purely elastic simulations are evaluated by the two methods and the resulting residual stress distributions are compared to the nominal ones. In this way, consequences of possible plastic deformations were avoided. It can be noticed that in all cases the IM overestimates the nominal compressive residual stress distribution in the first 200 μm below the surface, regardless of the shape of the residual stress gradient. This can be attributed to the strain sensitivity of the IM if small amounts of strain relaxation occur like e.g. in the first drilling steps. For the further drilling increments the IM shows an excellent agreement with the nominal values. A different behavior can be noticed for the results of the DM. Regardless of the shape of the gradient the DM generally determines underestimated residual stress distributions in the surface near region. For drilling depths larger than 200 μm the DM determines residual stress values strongly diverging from the correct ones. Here the character of the method shows its impact on the results, since the DM does not take into account further deformations, which are caused by the residual stresses being present in the already drilled depth increments.

To visualize the deformation processes during application of the incremental hole drilling contour plots were produced, which present the extension of the plastic zone in the vicinity of the hole. The equivalent plastic strain is plotted in Fig. 6 for the residual stress gradient shape 3 as an example for the drilling depths 0.2 and 1 mm. The plots clearly show that in the surface near region plastic deformation starts during the first drilling steps at the bottom of the hole (in the notch) as it is the case for uniform residual stress distributions [1]. But in contrast to the case of a uniform residual stress distribution, no further plastic deformation occurs in the depth of the drill-hole for larger drilling depths. However, the highly stressed surface layers cause additional deformations at the surface and increase the plastic zone.

5. CONCLUSIONS

The finite element simulations of the hole drilling followed by a subsequent evaluation of the calculated strain relaxations with the integral and the differential method have shown that two effects have to be distin-

guished during incremental hole drilling in highly stressed surface layers: the residual stress gradient itself and the effect caused by plastic deformations in the immediate vicinity of the hole. Both hole drilling evaluation methods considered here have characteristic difficulties in determining a residual stress gradient properly. Furthermore the results have shown that in the surface near region the divergences are enforced by the plasticity effect. Regardless of the shape of the residual stress gradient the plasticity effect becomes apparent for a $\sigma^{\text{RS}}/\sigma_y$ - ratio of approximately 70%. In addition the DM shows a lower sensitivity to the occurrence of plastic deformations, whereas the IM is very sensitive to small amounts of strain relaxation, in particular during the first drilling steps.

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