EFFECT OF THE HOLE-BOTTOM FILLET RADIUS ON THE RESIDUAL STRESS ANALYSIS BY THE HOLE DRILLING METHOD

M. Scafidia, E. Valentini, B. Zuccarello

scafid@dima.unipa.it, emilio.valentini@sintechnology.com, zuccarello@dima.unipa.it

aDipartimento di Meccanica, Università degli Studi di Palermo – Italy; www.dima.unipa.it
bSINT Technology S.r.l. – Calenzano, Fi – ITALIA; www.sintechnology.com

ABSTRACT

The hole drilling method is based on the measuring of the surface relaxed strains when a small hole is drilled on the examined component. From the relaxed strains, measured generally by using special strain gage rosette, the residual stresses is computed by using proper influence coefficients, provided also by the ASTM E837-08 standard. Such influence coefficients are obtained by numerical simulations carried out by considering a centered hole with an “ideal” flat bottom. Unfortunately, in all the drilling techniques used in the practical application of the method the hole bottom is never flat and a significant fillet radius that influence the relaxed strains and then the computed residual stress, is observed. In order to detect the effect of such drawback on the computed residual stress as well to implement an accurate correction procedure, in the present work after a systematic numerical analysis performed by using the boundary element method, closed form expressions between the hole bottom filled radius and the measured strain are obtained.

INTRODUCTION

Thanks to its simplicity and low cost, the hole drilling method is one of the used technique for the experimental residual stresses (RS) analysis in mechanical components. For through-thickness uniform RS, the ASTM E837-08 standard [1] describe the practical application procedure that allows the user to obtain in general sufficient accurate results. It provides also the influence coefficients involved in the calculation of the RS from the measured surface relaxed strains. Such influence coefficients are computed by numerical simulations performed by considering a perfect cylindrical hole with “ideal” flat bottom. In the practical application of the method, the hole is commonly drilled by an high speed automatic system (around 400,000 rpm) with an inverted cone tungsten carbide end mill, that allows the user to obtain a cylinder hole with low induced residual stress [2]. In presence of very hard materials, the hole can be drilled by a special diamond covered end mill [3], by the Air Abrasive technique [3,4] or by the Electric Discharge Machining (EDM) technique [4,5]. For any drilling procedure, various errors can affect the geometry and the position of the hole, as:

1. diameter error [4,6];
2. depth error [4];
3. hole-rosette eccentricity error [7,8];
4. misalignment between the hole axis and the normal to the surface component [9];
5. a non-flat bottom due to a unavoidable hole-bottom fillet radius [2-5,10,11].

Excluding the ref.[11], in which the authors propose to limit the hole bottom fillet effect by reducing the hole dimension, accurate study on the effect of the hole bottom fillet radius on the
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measured relaxed strains and on the computed RS, are not published in technical literature.

**THE HOLE DRILLING METHOD**

In presence of through-thickness uniform RS, the surface relaxed strains measured after the hole is drilled, allows the user to calculate the unknown RS components ($P$, $Q$ and $T$) by using the following equations [1]:

$$P = -\frac{E}{1 + \nu} \sum a \cdot p, \quad Q = -E \sum b \cdot q, \quad T = -E \sum b \cdot t,$$  

where $E$ is the Young modulus, $\nu$ is the Poisson ratio, $a$ and $b$ are the influence coefficients reported in [1], that depend to the hole diameter $D_0$ as well as to the average rosette diameter $D$; $p$, $q$ and $t$ are the strain components obtained from the three measured strain $\varepsilon_i$ ($i=1-3$) by the following formulas:

$$p = \frac{\varepsilon_3 + \varepsilon_1}{2}, \quad q = \frac{\varepsilon_3 - \varepsilon_1}{2}, \quad t = \frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{2}.$$  

(4,5,6)

Fig. 1 shows the typical strain gage rosette used for the practical application of the method.

![Figure 1 – ASTM “type A” strain gage rosette](image)

After the stress component evaluation, the RS are computed by the using following relationships:

$$\sigma_{\text{max,min}} = P \pm \sqrt{Q^2 + T^2}, \quad \beta = \frac{1}{2} \arctan \left( -\frac{T}{Q} \right).$$  

(7,8)

In order to verify that the actual residual stress state is uniform through the component thickness, the non-uniformity test reported in [1] has to be carried out by involving the measured strain components. As it is well known, this test compare the measured strain components curves with the theoretical ones: differences higher than 3% indicate a presence of a non-uniform stress distribution.
HOLE-BOTTOM FILLET RADIUS: EXPERIMENTAL ANALYSIS

In the hole drilling method, the hole is commonly carried out by the so-called “high speed drilling” systems (about 400,000 rpm – see also Fig.2) that allow to obtain a cylindrical hole with low induced residual stresses [2]. The classical “low speed” drilling procedure is unadvised and in practice no more used. In special cases, other particular drilling techniques, such as the EDM and the air abrasive technique, are used.

Figure 2 – Example of high-speed drilling automatic system (used in the experimental analysis)

With any drilling technique, the hole bottom is never flat, and a hole-bottom fillet radius \( r \) can be observed. As an example Fig.3 shows the diametrical sections of three different holes, obtained by using two different hole drilling techniques and several end mills.

Figure 3 – (a,b) holes drilled by 2 different TiAlN inverted cone tungsten carbide end mill and (c) by EDM technique (from ref. [5])

From Figs.3a,b it is possible to observe that the high-speed drilling can lead to different hole bottom fillet radius, depending on the particular geometry of the end mill used. In all the cases, the experimental detection has shown that the fillet radius value does not vary with the hole depth. Calling \( D_0 \) the hole diameter, the average values of the hole bottom fillet radius are \( r=0.04D_0 \) for the mill type used in fig.3a and \( r=0.10D_0 \) for the mill type used in fig.3b.

Higher values of the hole bottom fillet radius occur when the EDM technique is used (Fig.3c); in this case value of about \( r=0.30D_0 \) are typically observed. High values are also observed if the air abrasive technique is used.
NUMERICAL ANALYSIS

In order to evaluate the effect of the hole bottom fillet radius on the relaxed strains, several numerical simulations have been carried out by using the Boundary Element Method (BEM, Beasy® code). To this end different numerical simulations has been performed by considering holes without fillet radius (ideal condition) and with different fillet radius $r$. From the corresponding strains relaxed on surface (mean strain in the area of the strain gage) the percentage strain deviation $s_{d\%}$ has been computed by the following simple relationship:

$$s_{d\%} = \frac{\epsilon_r - \epsilon_0}{\epsilon_0} \times 100,$$  \hspace{1cm} (8)

where $\epsilon_r$ and $\epsilon_0$ are the strain with and without fillet radius respectively. In details, two different numerical model have been used: a 2D model (symmetrical respect to the z axis) to evaluate the effect of an equi-biaxial (hydrostatic) stress field (see Fig.4a) and a 3D model to evaluate the effect of pure shear stress field (see Fig.4b).

![Figure 4 – BEM models used: (a) 2D axialsymmetrical model and (b) 3D model](image)

In more details, the 2D BEM model have thickness $H=25D_0$ radius $L=75D_0$; the zone near the strain gages has been modeled by 50 quadratic elements, whereas 500 elements has been used for the entire model. The 3D model has the same characteristic than the 2D model.

The analysis of the 2D and 3D results in terms of relaxed strains, have shown that the influence of the bottom fillet radius does not depend on the particular stress field (the results provided by the 2D model coincides with that of the 3D model) and to the strain gage orientation (for the 3D model all the three gages provides the same results). Therefore all the results are shown synthetically in Fig.5 that represent the strain deviation $s_{d\%}$ versus the non-dimensional hole depth $z/D$, for an ASTM Type A rosette with $D_0/D=0.4$.

From figure 5 it is seen that the percentage strain deviations are always negative, i.e. the hole bottom fillet radius leads to a decreasing of the relaxed strains; also, the strain deviations are not negligible, i.e. for $r=0.1D_0$ and $z/D<0.2$, the strain deviations are $-25%<s_{d\%}<10%$. The magnitude of the strain deviations increase with $r$ and decrease with $z$. 
The percentage strain deviations are well fitted by the following polynomial functions obtained from the numerical results by least square technique (LST):

\[
\sigma_{sd\%} = \sum_{k=0}^{2} \sum_{l=0}^{5} \left( c_{klm} + \frac{D_0}{D} + c_{2lm} \left( \frac{D_0}{D} \right)^2 \left( \frac{r}{D_0} \right)^m \log \left( \frac{2 z}{D} \right) \right), \quad (9)
\]

where the coefficients \( c_{klm} \) (\( k=0-2 \)) depend only on the rosette geometry. Equation (9) provided an accurate evaluation of the percentage deviation in the ranges \( 0.3 \leq D_0/D \leq 0.5 \), \( 0.0 \leq r/D_0 \leq 0.5 \) and \( 0.0175 \leq z/D \leq 0.5 \).

As it is showed in Fig.6, in this ranges the error \( e_{sd\%} \) introduced by the use of Eq.9 for the calculation of the strain deviation, is less about than 2\%.

Figure 5 – Strain deviation \( \sigma_{sd\%} \) vs. the non-dimensional hole depth \( z/D \) (for ASTM Type A rosette with \( D_0/D=0.4 \))

Figure 6 – Strain deviation errors \( e_{sd\%} \) vs. the non-dimensional hole depth \( z/D \), for ASTM Type A rosette with \( D_0/D=0.4 \)
As an example, table 1 shows the value of the $c_{klm}$ coefficients for an ASTM Type A rosette.

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**EFFECTS ON THE RS COMPUTED ACCORDING ASTM STANDARD**

Following the ASTM E837 standard, for uniform RS, in order to test the uniformity of the RS through the thickness of the examined component, a non-uniformity test have to be performed preliminary. In this test the measured strain components $p,q,t$ are compared with the corresponding theoretical ones. If the maximum difference between experimental relieved and theoretical values is higher than 3% the RS distribution can not be considered uniform along the thickness of the component and, consequently, the analysis of the RS can be performed only by using other calculation procedures properly developed for non-uniform RS.

Obviously, since the reference (theoretical) strain components $p,q,t$ have been determined by numerical simulations by considering a perfect flat bottom [12], the effect of the hole-bottom fillet radius can influences significantly also the ASTM non-uniformity test.

As an example, Fig.7 shows the comparison between the reference $p$ component (no fillet radius) and the corresponding component relative to a value of the hole-bottom fillet radius $r = 0.1D_0$; it is seen how the deviation reach values of about 5%, i.e. superior to the limit value of 3%. Consequently, it is possible to state that the hole bottom fillet radius can influence significantly the non-uniformity test, also for limited value of the fillet radius ($r\approx0.1D_0$). In other words, due to the hole bottom fillet radius a uniform residual stress distribution can be erroneously interpreted as a non-uniform residual stress distribution.
In the case \( r=0.1D_0 \), computing the RS by using eqs.(1-8), i.e. without considering the influence of the hole bottom fillet radius, it is possible to note that they are affected by an error of about -3\% (computed values less than the actual one). Considering instead an hole with \( r=0.3D_0 \) (typical values obtained by using the EDM technique), the maximum deviation in the non-uniformity test is higher than 20\% and the evaluated stress is affected by absolute errors higher than 10\%.

**CONCLUSIONS**

In this work the effect of the hole-bottom fillet radius on the residual stresses computed by using the hole drilling method has been studied. Experimental analysis of the diametral sections of the holes obtained by using various drilling procedures has shown that in the practical application of the method non negligible hole bottom fillet radius occurs. In details, values ranging from 0.04\( D_0 \) to 0.10\( D_0 \) are obtained by using the common high-speed drilling technique with TiAlN inverted cone tungsten carbide end mill, whereas values of about 0.30\( D_0 \) are obtained by using the EDM technique.

The study of the effect of the hole bottom fillet radius on the relaxed strains, carried out by several numerical simulation performed by using BEM, has shown that it can not be neglected, especially at the low hole depths.

The hole bottom fillet radius can influence significantly the ASTM E837-08 non-uniformity test: for a hole with a fillet radius of about 0.10\( D_0 \), a uniform strain distribution lead erroneously to deviations of about 5\%, i.e. higher than the 3\% limit advised by the same ASTM standard. Obviously, higher fillet radius, as those related to the EDM procedure, leads to higher deviations (also higher than 20\%).

The effect on the residual stresses are in general less significant. As an example for a hole with a fillet radius of about 0.10\( D_0 \) the percentage error on the RS reach values of about 3\%, whereas can reach values of about 10\% for hole bottom fillet radius of about 0.30\( D_0 \).
BIBLIOGRAFY


