# Experimental verification of the hole drilling plasticity effect correction

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**Abstract.** The Hole Drilling Method introduces a hole in a (residual) stressed volume of material, typically a metal, then a stress concentration follows. A portion of the volume near the hole can experience an equivalent stress higher than the material yield stress. The relaxed strains measured by the rosette strain gage grids are then affected by the plasticity, in particular if the residual stress is quite large with respect to the material yield stress. This is the so called Hole Drilling Plasticity Effect. The authors recently proposed a numerical procedure to correct this perturbation effect and retrieve a more accurate residual stress components values. A way to validate this correction procedure is proposed in the paper.

## Introduction

The Hole Drilling Method is a well known and common technique to evaluate residual stresses at any position of the surface of a piece of metal (also other materials) and below the surface up to a depth of 1.0–1.5 mm. A small hole, typical diameter 1.8–2.0 mm, is manufactured on the surface, concentric with a rosette strain gage. As residual stressed material is removed, the strain gage grids measure strains, that are the so called “relaxed” (or “relieved”) strains [1,2,3]. The relaxed strain values, measured by the rosette strain gage grids at different depths, are recorded and then elaborated in order to find the residual stress distribution. Initially, the residual stress distribution had to be assumed as uniform from the surface throughout the entire hole depth. This limitation was overcome as the Finite Element (FE) simulations offered an accurate tool to predict the relaxed strains as the result of a known stress distribution and by applying the superimposition principle, that can be used under the strain to stress linearity relationship [1,2,4,5,6]. However, the geometry of the hole itself is reason of stress concentration, so a certain amount of material at the hole edge can experience plasticity when the equivalent stress exceeds the material yield stress. The relaxed strain measured by the rosette gage grids are somewhat perturbed by the plasticity at the hole edge. By assuming the material as linear elastic, the residual stress obtained from the measured relaxed strain is different to the actual residual stress. This is the so called “plasticity effect” [7,8,9]. The authors recently proposed a plasticity effect correction procedure [10]. The first step of the procedure is to calculate the residual stress from the relaxed strain, just assuming the material as linear elastic everywhere, next find a correction intensity factor, finally modify the “as elastic” residual stress previously found, on the basis of to the correction intensity factor. The limitations of the proposed correction procedure are here investigated and, finally, an experimental activity to validate the procedure itself is here proposed.

## Plasticity effect

The plasticity effect is a possible source of error for the Hole Drilling Method (HDM) when a ductile material (such as any metal) is investigated. The introduction of the hole, in a stressed region is reason of stress concentration, same as applying an external load on a hole notched geometry.  Theoretically, the HDM measure is affected by the plasticity effect starting when there is plasticity onset at the most stresses point. According to this limitation, the maximum residual stress that can be measured with the HDM, without the plasticity effect, is quite low for any biaxiality ratio, Fig. 1.

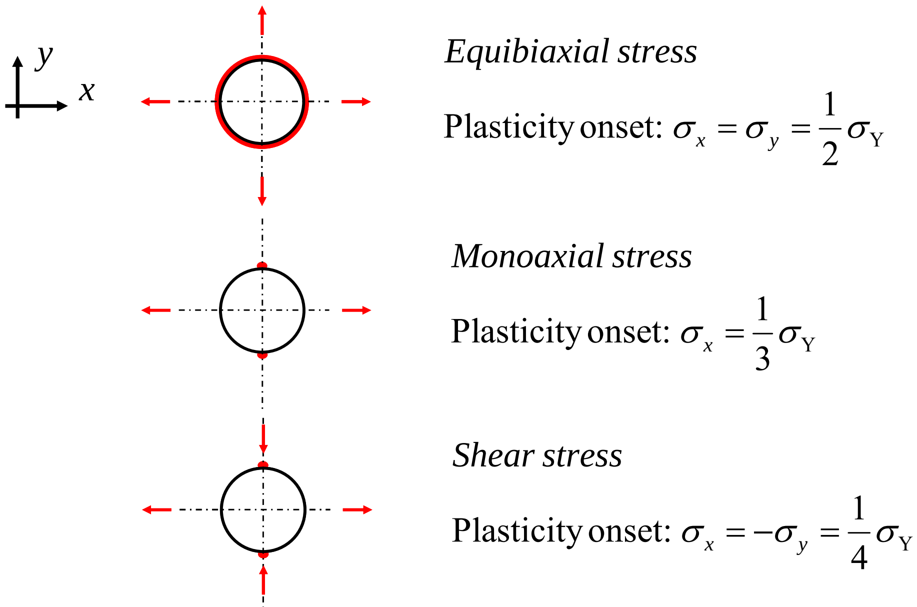


**Figure 1**. Plasticity onset limits, according to the plane stress Kirsch solution.

However, it is worth noting that the strain gage grids are not very close to the hole edge. So, the plasticity onset does not really perturb the strain measures. A significant effect is evident only when the plasticity volume at the edge of the hole is large. The plasticity effect is, therefore, a real problem only for very high residual stresses with respect to the material yield stress, Fig. 2 [10]. The plasticity effect is not a real source of error unless the (equivalent) residual stress is higher than 70–90% (depending on the depth of the hole and on the biaxiality ratio) of the material yield stress.

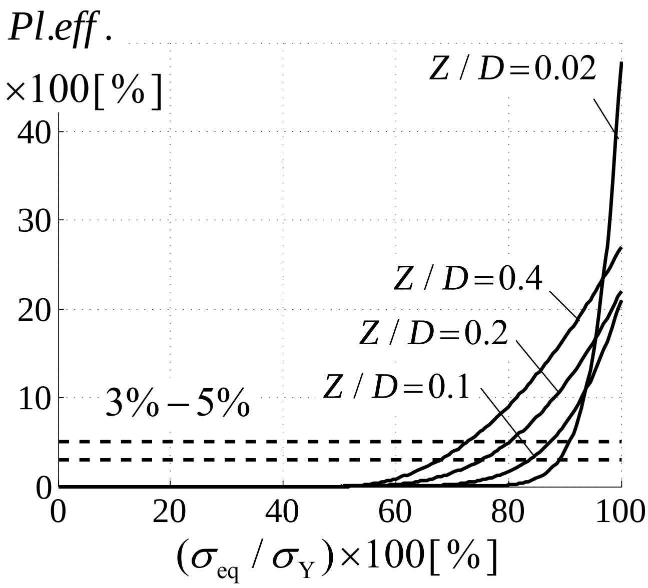


**Figure 2**. Plasticity effect intensity as function of the equivalent residual stress to material yield stress ratio.

### Plasticity effect correction procedure

The steps of the plasticity effect correction procedure are:

- evaluate the residual stress, just by assuming the material as linear elastic ("as elastic" residual stress);

- calculate a (properly defined) plasticity effect intensity parameter;
- re-evaluate the residual stress components from the as elastic stress initially found and the plasticity effect intensity.

The as elastic residual stress components are calculated according to the Eq. 1, where $\varepsilon_x, \varepsilon_y$ are the relaxed strain as measured by the strain gage rosette grids

$$\sigma_{x,\mathrm{el}} = -\frac{E(\varepsilon_x+\varepsilon_y)}{2a(1+\nu)} - \frac{E(\varepsilon_x+\varepsilon_y)}{2b}$$
$$\sigma_{y,\mathrm{el}} = -\frac{E(\varepsilon_x+\varepsilon_y)}{2a(1+\nu)} + \frac{E(\varepsilon_x+\varepsilon_y)}{2b} \tag{1}$$

The as elastic stress components overestimate the actual stress components because the strains are higher when affected by plasticity. The plasticity effect intensity parameter, or simply "plasticity factor" $f$, is defined as follows, Eq. 2:

$$f = \frac{\sigma_{\mathrm{eq}} - \sigma_{\mathrm{eq,i}}}{\sigma_{\mathrm{Y}} - \sigma_{\mathrm{eq,i}}},\ \sigma_{\mathrm{eq}} = \sqrt{\sigma_x{}^2 + \sigma_y{}^2 - \sigma_x\sigma_y},\ \sigma_{\mathrm{eq,i}} = \sigma_{\mathrm{Y}}\frac{\sqrt{1-\Omega+\Omega^2}}{3-\Omega}\ \ \text{(Kirsch)} \tag{2}$$
$$\sigma_{\mathrm{Y}}:\text{material Yield stress}$$

The plasticity factor is negative if there is not plasticity, at any point of the holed surface, while it ranges between 0 and 1 when there is some plasticity effect. The plasticity factor describes the intensity of the plasticity effect. The maximum plasticity effect is when $f = 1$.

After having found the as elastic stress components the value of $f$ can be evaluated. The "as elastic" plasticity factor $f_{\mathrm{el}}$ has to be introduced as:

$$f_{\mathrm{el}} = \frac{\sigma_{\mathrm{eq,el}} - \sigma_{\mathrm{eq,i}}}{\sigma_{\mathrm{Y}} - \sigma_{\mathrm{eq,i}}},\ \sigma_{\mathrm{eq,el}} = \sqrt{\sigma_{x,\mathrm{el}}{}^2 + \sigma_{y,\mathrm{el}}{}^2 - \sigma_{x,\mathrm{el}}\sigma_{y,\mathrm{el}}} \tag{3}$$

The (actual) plasticity factor $f$ can be obtained from the as elastic plasticity factor $f_{\mathrm{el}}$ by means of a numerically found relationship (fitting a large database of FE results), Fig. 3.

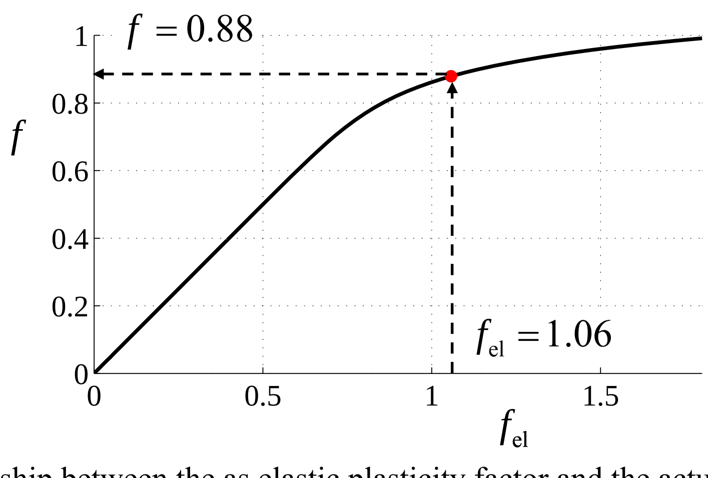


**Figure 3**. Relationship between the as elastic plasticity factor and the actual plasticity factor.

The numerical relationship, expressed by the graph of the Fig. 3, is reported in Eq. 4:

$$f_{\mathrm{el}} = f + W f^{\mu}$$

$$\begin{aligned} W &= w_1\Omega^3\delta^2 + w_2\Omega^2\delta^2 + w_3\Omega\delta^2 + w_4\delta^2 + w_5\Omega^3\delta + w_6\Omega^2\delta \\ &\quad + w_7\Omega\delta + w_8\delta + w_9\Omega^3 + w_{10}\Omega^2 + w_{11}\Omega + w_{12} \\ \mu &= m_1\Omega^3\delta^2 + m_2\Omega^2\delta^2 + m_3\Omega\delta^2 + m_4\delta^2 + m_5\Omega^3\delta + m_6\Omega^2\delta \\ &\quad + m_7\Omega\delta + m_8\delta + m_9\Omega^3 + m_{10}\Omega^2 + m_{11}\Omega + m_{12} \end{aligned} \tag{4}$$

The parameters in the Eq. 4 are reported in the paper by Beghini et al. [10]. The Eq. 4 actually reports $f_{\mathrm{el}}$ as a function of $f$, while during the application of the procedure, $f_{\mathrm{el}}$ is available and $f$ is to be found. So, the procedure requires the Eq. 4 to be inverted.
Finally, the residual stress components can be obtained from the plasticity factor $f$, by inverting the Eq. 2:

$$\begin{aligned} \sigma_{\mathrm{eq}} &= \sigma_{\mathrm{eq,i}} + f(\sigma_{\mathrm{Y}} - \sigma_{\mathrm{eq,i}}) \\ \sigma_x &= \frac{\sigma_{\mathrm{eq}}}{\sqrt{1-\Omega+\Omega^2}}, \ \sigma_y = \Omega\sigma_x \end{aligned} \tag{5}$$

**Plasticity effect correction procedure limitations.** The proposed correction procedure has two limitations:

- Uniform stress has to be assumed from the surface up to the maximum depth of the hole, because the superimposition principle can not be applied due to the plasticity;
- The principal directions have to be known in advance, because the procedure requires $\varepsilon_x, \varepsilon_y$ and returns $\sigma_x, \sigma_y$, where $x, y$ are the residual stress principal directions.

The uniform stress limitation can be (partially) overcome by proposing the procedure coefficients for many depths the residual stress has to be assumed uniform up to. Beghini et al. [10] proposed four depths: $Z = 0.02D = 0.1\,\mathrm{mm}\,(D = 5.1\,\mathrm{mm}); Z = 0.1D; Z = 0.2D; Z = 0.4D$. It is advisable to perform fine increments hole drilling, recording all the relaxed strains at different depths, and then apply the procedure assuming uniform stress up to each of the proposed four depths, along with the standard non uniform, elastic, residual stress evaluation. Then, all these pieces of information can be put together to figure out the residual stress distribution.
The standard three grids rosette (0°/45°/90°) is enough to describe the relaxed strain angular relationship, when there is not any plasticity effect, because it follows the tensorial angular dependency: $\varepsilon(\vartheta) = \bar{\varepsilon}_0 + \bar{\varepsilon}_2\cos[2(\vartheta+\varphi)]$, where $\bar{\varepsilon}_0, \bar{\varepsilon}_2$ are the strain parameters of the relationship and $\varphi$ is the residual stress principal directions angle. On the contrary, the relaxed strain relationship is more complex, where there is a significant plasticity effect. A Fourier expansion requires more than just two terms:

$$\varepsilon(\vartheta) = \bar{\varepsilon}_0 + \bar{\varepsilon}_2\cos[2(\vartheta+\varphi)] + \bar{\varepsilon}_4\cos[4(\vartheta+\varphi)] + \bar{\varepsilon}_6\cos[6(\vartheta+\varphi)] + \ldots + \bar{\varepsilon}_{2n}\cos[2n(\vartheta+\varphi)] + \ldots \tag{6}$$

However, a good approximation can be obtained up to the 4th harmonic only, Eq. 7:

$$\varepsilon(\vartheta) = \bar{\varepsilon}_0 + \bar{\varepsilon}_2\cos[2(\vartheta+\varphi)] + \bar{\varepsilon}_4\cos[4(\vartheta+\varphi)] \tag{7}$$

Now, there are four parameters: the strains $\bar{\varepsilon}_0, \bar{\varepsilon}_2, \bar{\varepsilon}_4$ and again the residual stress principal directions angle $\varphi$.

A four grids rosette could, therefore, be used to get enough information to deduce these four parameters. The residual stress principal directions relaxed strain components $\varepsilon_x, \varepsilon_y$ can then be obtained from the Eq. 7 model after the four grids readings $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$, Fig. 4.

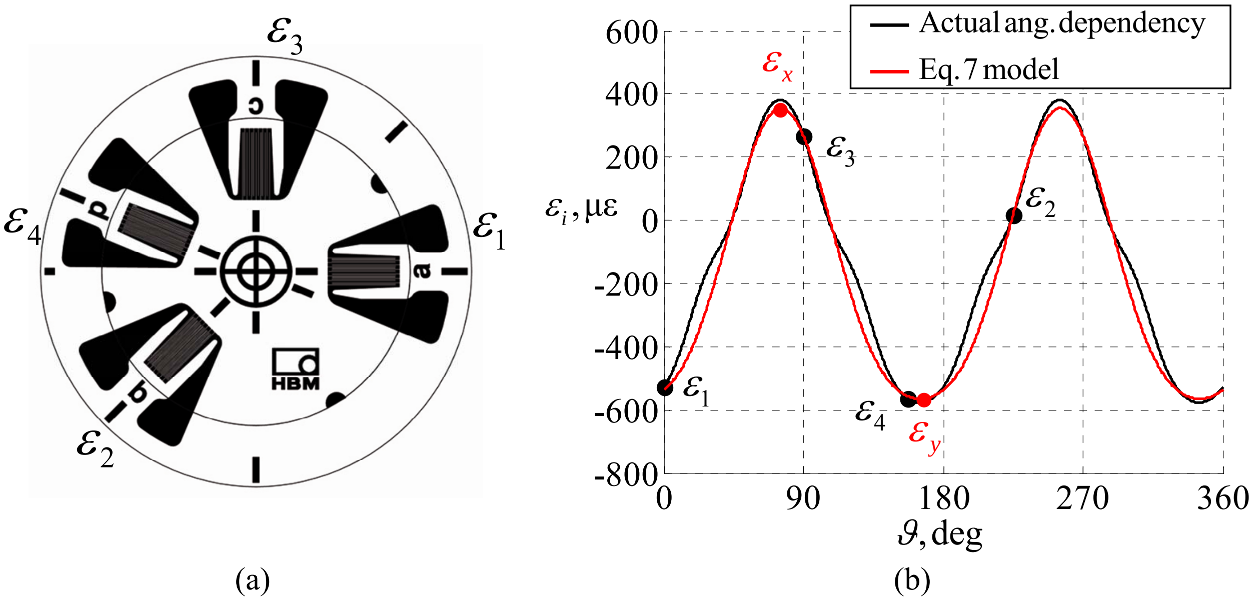


**Figure 4**. (a) Four grids rosette scheme. (b) Actual angular dependency and Eq. 7 model, determination of the residual stress principal directions relaxed strain components, from the model, after the four grids readings.

## Experimental validation of the plasticity procedure

The proposed correction procedure was formulated just by means of FE simulations and analytical tools. An experimental validation is, therefore, required. In order to have a reference residual stress, near the material yield stress, an external load can be used. The main issue is that the *external* stress (obtained with the external load) is not a *residual* stress. The procedure to simulate a known residual stress is: anneal the bar and attach the rosette strain gage; drill the concentric hole; set strains to zero; apply the tensile load and record the strains; calculate the strains if the load were applied without the hole (this can be even performed before manufacturing the hole, also to verify the strain gage). The relaxed strains are to be obtained as difference between the strains with the load and with the hole and the strains with the load but *without* the hole. Finally, the correction procedure can be performed and the stress obtained is to be compared to the known reference value.

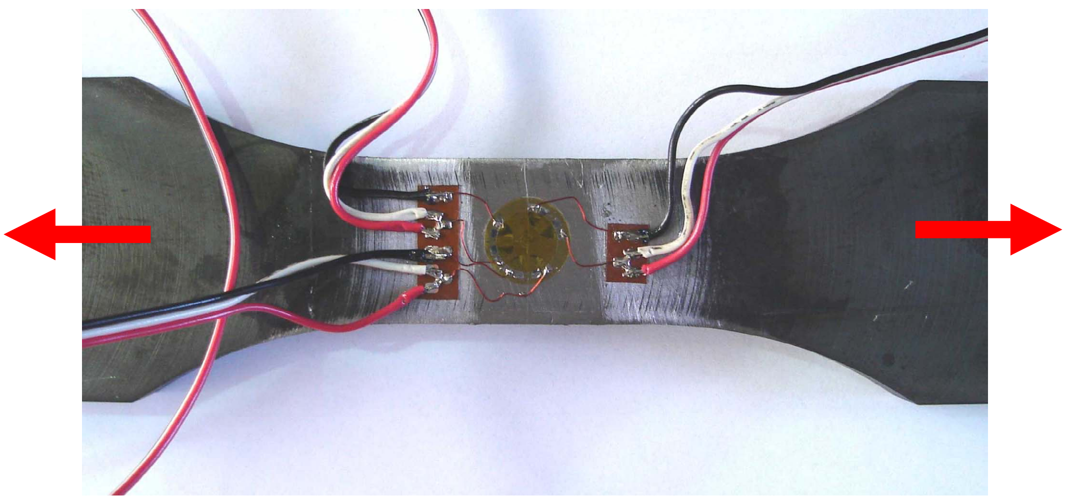

**Figure 5**. Experimental set up to simulate a residual stress by means of an external load.

## Conclusions

- The strain gage Hole Drilling plasticity effect is caused by the stress concentration produced by the hole itself in a residual stress field.
- The residual stress that causes plasticity onset is quite low if compared to the material Yield stress (depending both on the hole depth and on the stress biaxiality ratio), however, a significant plasticity effect is obtained only for a residual stress near the material yield stress (70–90% of the material yield stress).
- A numerically obtained correction procedure can be used to correct the residual stress plasticity affected measures. This corrections has two limitations: the residual stress has to be assumed as uniform; the residual stress principal directions orientation has to be known.
- A four grids rosette, designed on purpose, can retrieve the relaxed strains along the residual stress principal directions with a good approximation.
- The correction procedure can be experimentally validated by means of an external load to simulate a known residual stress to be assumed as reference.

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