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# Plasticity Effects in the Hole-Drilling Residual Stress Measurement in Peened Surfaces

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**Abstract** The incremental hole-drilling technique (IHD) is a widely established and accepted technique to determine residual stresses in peened surfaces. However, high residual stresses can lead to local yielding, due to the stress concentration around the drilled hole, affecting the standard residual stress evaluation, which is based on linear elastic equations. This so-called plasticity effect can be quantified by means of a plasticity factor, which measures the residual stress magnitude with respect to the approximate onset of plasticity. The observed resultant overestimation of IHD residual stresses depends on various factors, such as the residual stress state, the stress gradients and the material's strain hardening. In peened surfaces, equibiaxial stresses are often found. For this case, the combined effect of the local yielding and stress gradients is numerically and experimentally analyzed in detail in this work. In addition, a new plasticity factor is proposed for the evaluation of the onset of yielding around drilled holes in peened surface layers. This new factor is able to explain the agreement and disagreement found between the IHD residual stresses and those determined by X-ray diffraction in shot-peened steel surfaces.

**Keywords** Residual stress · Hole-drilling method · Plasticity effect · Laser peening · Shot peening

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## Introduction

The incremental hole-drilling technique (IHD) is a widely established technique for measuring residual stresses induced by mechanical surface treatments, such as laser peening, shot peening, stress peening, warm peening, or a combination of these processes [1]. Laser peening, for example, due to the development of laser technology, imparting deeper layer with beneficial residual compressive stress and decreasing surface roughness, improving fatigue and corrosion resistance, has received particular attention of the aeronautical and aerospace industries in recent years [2]. In this context, the IHD technique has been extensively used to determine the induced residual stresses [3], crucial, for instance, for the optimization of the laser shock peening parameters [4]. Therefore, this paper critically analyses the IHD residual stress results obtained and provides information how to assess the possible influence of plastic deformation during the hole drilling process.

According to the American standard ASTM E837 [5], the incremental hole-drilling technique involves the drilling of a small shallow hole in a number of depth increments, while a standard strain gage rosette measures changes in strain at the surface, due to the corresponding stress relaxation. In depth non uniform stress profiles can then be determined relating the strain relaxation, measured at the surface, with the previously existing stresses in each depth increment, throughout the total hole depth. The American standard preconizes the use of the integral method for this determination [5], which has been proved to be the theoretically more correct method, among the several proposed methods. Since the strains measured at the surface cannot directly be related with the stress existing at a given depth, the integral method needs specific calibration coefficients, previously determined by the finite element method. For this numerical calculation the material is considered to behave linear elastically.

However, in practice, the existence of higher residual stresses can lead to local plastic deformations, due to the stress concentration around the drilled hole, and, therefore, affect the residual stress evaluation, which is based on linear elastic equations. The resultant overestimation of residual stresses is directly dependent on the ratio between the residual stress magnitude and the material's yield strength. This ratio can accurately be evaluated by the plasticity factor, as defined by Beghini et al. [6, 7].

Several authors [6, 8–11] have referred that residual stresses can be accurately determined by IHD, if the residual stress magnitude does not exceed 60% of the material's yield strength. Considering more recent studies, on in-depth uniform residual stress evaluation [7], the American Standard ASTM E837 [5] has recently fixed this limit in 80% for the case of "thick" specimens and in 50% for the case of "thin" specimens. However, this limit cannot be considered without a definition of a parameter which takes into account the existing stress state in the tested part, such as the plasticity factor defined in section "Plasticity Factor Definition" in the following.

The so-called plasticity effect on the IHD residual stress results was quantified mostly by means of numerical calculations by several authors. According to Beaney and Procter [8], for example, an error of +15% can be expected in stress calculation for residual stress magnitudes of 70% of the yield strength. An overestimation of 20%, for residual stresses reaching 90% of the yield strength, was reported by Beghini et al. [6]. Gibmeier et al. [10] reports an error of 35% for a stress magnitude of 95% of the yield strength. Such error estimations, however, require the exact knowledge of the respective yield strength, which may differ considerably from the bulk material's value after mechanical surface treatments [11]. Numerical studies on this issue are generally performed considering in depth uniform stresses. The combined influence of stress gradients and the plasticity effect needs additional studies, following the pioneering work of Kornmeier et al. [12]. More recently, some methods to correct the plasticity effect have been proposed. A special reference should be made to the work of Beghini et al. [7, 13]. Their method is based on finite element analyses, considering different materials, testing parameters and standard strain-gage rosettes. However, due to the inherent non-linearity between relaxed strains and residual stresses when local yielding occurs, this correction method is almost limited to in depth uniform residual stresses. Moreover, the knowledge of the local material's yield strength, which is unknown and difficult to quantify in surface-treated layers, is necessary.

Despite the importance to propose a reliable method to correct the IHD residual stress results, when local yielding arises around the hole, for the case of in-depth non-uniform stress fields, a problem which remains unsolved so far, the knowledge of the local yield stress seems to be crucial in this context. This work clearly shows the importance of this knowledge to predict the effects of local yielding on the IHD results, when this technique is used to determine residual stresses induced by peening treatments, proposing a new plasticity factor which is able to predict such effects.

## Plasticity Factor Definition

To quantify the plasticity effect on IHD residual stress results, Beghini et al. [7] have proposed a dimensionless plasticity factor, which can be appropriately called "Beghini's factor", as follows:

$$f = \frac{\sigma_{eq} - \sigma_{eq,i}}{S_Y - \sigma_{eq,i}} \quad (1)$$

$\sigma_{eq}$ is the von Mises stress (for plane stress states), which takes into account the effect of biaxiality, $\sigma_{eq,i}$ is the equivalent residual stress producing the onset of plasticity in the 2D case and $S_Y$ is the material's yield stress. This factor, $f$, evaluates the residual stress magnitude with respect to the approximate onset of plasticity given by the plane Kirsch's solution [14]. This solution is only valid for a plane stress state, e.g., a through hole made in a very thin plate. However, Beghini et al. [13] showed that similar elastic limits can also be assumed for a deep blind hole performed on a thick plate, under uniform through-thickness biaxial residual stress. According to the ASTM E837 standard [5], a deep hole has a minimum depth of 0.4D and a plate is considered thick when its thickness is at least 1.2D, where D is the rosette mean diameter. Defining a biaxiality ratio, $\Omega$, by:

$$\Omega = \frac{\sigma_y}{\sigma_x} \quad (2)$$

$\sigma_{eq,i}$ can be expressed as a function of this ratio:

$$\sigma_{eq,i} = S_Y \frac{\sqrt{1 - \Omega + \Omega^2}}{3 - \Omega} \quad (3)$$

Thus, the plasticity effect can be quantified from $f = 0$, no plasticity, to $f = 1$, full plasticity, i.e., for residual stress producing general yielding around the hole. This factor theoretically predicts the onset of yielding considering the existence of a plane stress state around the hole. It is well-known that, for isotropic materials and biaxial stress states ($\sigma_z = 0$), the stress concentration factor around a through hole attains a minimum value of 2 for equibiaxial stresses ($\sigma_y = \sigma_x$), being equal to 3 for uniaxial stresses ($\sigma_y = 0$) and attains a maximum value of 4 for pure shear stresses ($\sigma_y = -\sigma_x$). For example, for an equibiaxial stress state, $\sigma = \sigma_x = \sigma_y$, $\Omega = 1$, $\sigma_{eq,i} = 0.5S_Y$, $\sigma_{eq} = \sigma$ and Eq. (1) reduces to:

$$f = 2\left(\frac{\sigma}{S_Y}\right) - 1 \tag{4}$$

Therefore, for an equibiaxial stress state, the onset of plasticity begins when $\sigma = 0.5S_Y$ for which $f = 0$. For a uniaxial stress state, considering the same magnitude, i.e., $\sigma_x = 0.5S_Y$, the plasticity factor will be $f = 0.25$ and, for a pure shear stress state, $\sigma_y = -\sigma_x = 0.5S_Y$, the plasticity factor will be $f = 0.76$.

A finite element study conducted by Beghini et al. [7] showed that the ratio between the measured relieved strains along the principal directions $\varepsilon_x$ and $\varepsilon_y$ depends on the biaxiality ratio $\Omega$ but it is almost unaffected by the plasticity factor, $f$. As a consequence, the biaxiality ratio $\Omega$ can be approximated by the ratio between the elastically calculated residual stress components.

In work-hardened surface layers, due to laser shock or shot peening, for example, equibiaxial stress states are often found. In addition, the numerical simulation of the incremental hole-drilling in materials subjected to these stress states can be performed using 2D axisymmetric models, relatively easier to implement, since there is no influence of the orientation of the strain gage rosette in respect of the principal stress axes. Therefore, in this study only equibiaxial stress states will be considered. In all other situations, the three-grid strain gage rosette, typically used for hole-drilling measurements, does not provide sufficient information. The use of a four-grid strain gage rosette has been suggested by Beghini et al. [15] to evaluate the principal directions misalignment angle. In these situations the problem can be analyzed in a similar way, since the plasticity factor could be determined. However, in all situations, the quantification of the plasticity factor, $f$, remains dependent of the exact knowledge of the material's yield stress of the surface treated-layers, $\sigma_Y$, as shown in the following.

## Proposed Plasticity Factor

Any attempt for judging, and posteriorly correcting, the plasticity effect requires the knowledge of the local yield stress in the treated layers. This is difficult to achieve and several attempts have been made in the last decades, with varying degrees of success [16, 17]. All of them, however, imply laborious experimental and numerical work. Nobre et al. [17] proposed the normalized hardness variation method (NHVM), relatively easy to apply, based on microhardness readings carried out over the cross-section of the surface-treated specimens, to estimate the local yield stress throughout the treated layers. This method considers that the relative variation of hardness, due to the increase of plastic deformation, quantifies the material's strain hardening. For normalization purposes, this method uses bulk material reference values. Nobre et al. [16, 17] found the following incremental relation for the case of several shot-peened steels, which relates the relative increments of hardness and yield stress. The equation enables the yield stress to be estimated, for each level of plastic deformation, in terms of the normalized hardness variation, as follows [16]:

$$\sigma_Y(z) = S_Y\left(1 + \gamma\frac{\Delta HV(z)}{HV_Y}\right) \tag{5}$$

Where $\Delta HV(z)$ is the Vickers hardness variation ($HV(z)$-$HV_Y$) at each depth, $z$, with respect of the bulk material; $S_Y$ and $HV_Y$ correspond to the yield stress and hardness of the bulk material, respectively, and $\gamma$ is a constant (scale factor). In five different steels, $\gamma$ seems to be material independent and a value close to 2.8 was obtained [16]. This method was validated for shot-peened surface layers using another method based on X-ray diffraction [17]. Therefore considering Eqs. (1) and (5), the plasticity factor can be rewritten as a function of the hole depth, $z$, as:

$$f(z) = \frac{\sigma_{eq}(z) - \sigma_{eq,i}(z)}{S_Y\left[1 + \gamma\frac{\Delta HV(z)}{HV_Y}\right] - \sigma_{eq,i}(z)} \tag{6}$$

For equibiaxial residual stresses, Eq. (6) reduces to:

$$f(z) = 2\left(\frac{\sigma(z)}{S_Y\left(1 + \gamma\frac{\Delta HV(z)}{HV_Y}\right)}\right) - 1 \tag{7}$$

Thus, in work-hardened surface layers, the onset of plasticity arises at a given depth, z, when $f(z) \geq 0$. However, the plastic strains are localized near the hole borders. Hence, it is necessary to verify and quantify whether or not these strains begin affecting the IHD residual stress results. A small and limited plastic deformation field around the bottom edge of the hole does not necessary mean that a significant error will be induced on the final IHD residual stress calculation, which is based on pure elastic calculations. More precisely, the necessary calibration coefficients used in these calculations are determined by finite element analysis considering a pure elastic material behavior. The appearance of plastic strains modifies the whole strain field around the hole, comparatively to the pure elastic case and, as a consequence, there will be an overestimation on the residual stress value determined by IHD. From the results of the numerical study carried out in the following, it will be shown that the plasticity effect influences the IHD residual stress results, in work-hardened surface layers, if the local plasticity factor attains values greater than 0.2, $f(z) \geq 0.2$. This new criterion upgrades that proposed by Nobre et al. [18].

Considering the case of equibiaxial stress states, the onset of local yielding and, more important, its effect on the IHD residual stress results, will be analyzed in the following. Numerically, induced errors due to local yielding are quantified considering in depth uniform stress states and different stress gradients for equibiaxial non uniform stress distributions. Experimentally, the plasticity effect on the IHD residual stress results is shown for the case of shot-peening residual stresses. Different steels were subjected to shot-peening and the induced residual stresses were determined by IHD and X-ray diffraction (XRD), which is used as reference technique. The discrepancies found on the experimental results, more precisely, to explain the differences between the residual stresses determined by IHD and XRD, the plasticity factor, as a function of the hole depth, is determined according to Eq. (7). Considering the critical value for the plasticity factor, determined during the numerical study, the new definition for the plasticity factor clearly enables to explain the differences found in three selected shot-peened steels.

## Numerical Approach

Using a 2D axisymmetric finite element model (FEM), incremental strain relaxation curves, corresponding to different in depth residual stress profiles, are determined by elastic and elasto-plastic finite element implicit calculations, using ANSYS APDL code. The FEM model is developed using 8-node isoparametric elements. Each hole depth increment is simulated using the "birth and death" ANSYS code features [19]. The surface strain relaxation in the region of the strain gages (an ASTM type B strain gage rosette was assumed [5]), corresponding to each drilling depth, is determined by subtracting the actual strain from the initial one. The dimensions of the strain gages are taken into account by integrating the axisymmetric strain field over the strain gage area.

Three asymptotic curves, relating the variation of the strain relaxation, measured at the surface by the three strain gages of the standard rosette used, as a function of the hole depth, are obtained ($\Delta\varepsilon^{i}(z)$, with $i$ = 1, 2 or 3). For equibiaxial stress states, the three measured curves, $\Delta\varepsilon^{i}(z)$, are coincident and, therefore, do not depend on the direction of measurement. These in depth strain relaxation curves can be determined for different plasticity factors, $f$, i.e., increasing the magnitude of the residual stresses relatively to the material's yield stress. While no yielding arises around the hole, the obtained in depth strain relaxation curves, determined by pure elastic FEM calculations and by elasto-plastic FEM calculations, are coincident and no differences on these curves are observed while the plasticity factor, $f$, is kept lower than zero. Thus, the quantification of the plasticity effect is shown, comparing the in depth strain relaxation curves determined using pure elastic finite element calculations, $\Delta\varepsilon^{el}(z)$ ($f = 0$), with those determined using elasto-plastic finite element calculations, $\Delta\varepsilon^{pl}(z)$, for different plasticity factors, $f > 0$. This way, for each plasticity factor analyzed, $f$, an expected strain error, $\boldsymbol{X}(z)$, can be defined, as a function of the hole depth, $z$, by:

$$\mathrm{X}(z) = \frac{\Delta\varepsilon^{pl}(z) - \Delta\varepsilon^{el}(z)}{\Delta\varepsilon^{el}(z)} \qquad (8)$$

Using the standard residual stress evaluation procedures, prescribed by the ASTM E837 standard [5], for uniform and non-uniform stresses, a corresponding error on the final residual stress evaluation, $\boldsymbol{\Phi}(z)$, can also be defined in a similar way:

$$\Phi(z) = \frac{\sigma^{pl}(z) - \sigma^{el}(z)}{\sigma^{el}(z)} \qquad (9)$$

$\sigma^{el}(z)$, is the in depth residual stress profile corresponding to the in depth strain relaxation curves, determined using pure elastic finite element calculations, $\Delta\varepsilon^{el}(z)$ ($f \leq 0$), and $\sigma^{pl}(z)$, is the in depth residual stress profile corresponding to the in depth strain relaxation curves, determined using elasto-plastic finite element calculations, $\Delta\varepsilon^{pl}(z)$ (with $f > 0$).

Since during hole-drilling simulation there is no reverse loading and the yield surface is very small and localized around the hole walls, the elasto-plastic material behaviour is assumed to be described by a bilinear isotropic hardening law without Bauschinger effect [20]. Typical elastic constants for steel, $E$ = 210 GPa and $\nu$ = 0.29, are used in all numerical calculations. To numerically study the local yielding arising around the drilled holes, the elasto-plastic FEM calculations are first performed considering a constant through the thickness equibiaxial stress of 380 MPa. The material's yield stress, assumed constant through the thickness, is adjusted in each IHD simulation to obtain increased plasticity factors, $f$, varying from 0 (pure elastic case) to 1 (full plasticity). Subsequently, to numerically study the combined influence of the plasticity effect and stress gradients, on the results of the IHD technique, the elasto-plastic FEM calculations are performed considering a constant through-thickness material's yield stress of 400 MPa. In this case, due to the simulated stress gradients, the plasticity factor varies over the hole depth. In both cases, a low material's strain hardening behavior, corresponding to a tangent modulus $E'$ = 2.1 GPa, is considered. This low material's strain hardening behavior is purposeful selected to numerically study the most unfavorable cases and, thus, to determine the maximum errors that can be expected when the IHD technique is applied to measure high residual stresses, such those induced by peening treatments. In addition, in peened layers, the highest residual stresses are found near the surface, where the material is strongly work-hardened, with few capacity for subsequent work-hardening [17]. Elastic and elasto-plastic finite element calculations are performed considering a typical 1.8 mm hole diameter. The surface strain relief is measured in depth increments of 0.02–0.08 mm, up to about 1 mm below the surface.

## Numerical Results and Discussion

### In Depth Uniform and Equibiaxial Stress States

A FEM simulation of incremental hole-drilling (IHD), on an infinite plate subjected to an in depth uniform equibiaxial residual stress field, considering different plasticity factors, *f* (cf. Eq. (1)), was firstly carried out to show how the plastic strains arising around the hole can affect the results of the IHD technique.

Figure 1 shows the plastic deformation field around a simulated 1.8 mm diameter hole with 0.1 mm depth (top) and 0.5 mm depth (bottom), corresponding to two plasticity factors, *f*, equal to 0.6 (left) and 0.9 (right). The size of the yielding region is substantially greater in the second case. In addition a maximum equivalent plastic strain of 0.3% is found for the first case ($f = 0.6$), against 0.4% for the second case ($f = 0.9$), which are relatively small values considering the low material's strain hardening behavior assumed. These maximum plastic strain values appear due to the notch effect caused by the sharp corner at the bottom of the hole, but increased values are observed at surface when the hole depth increases (Fig. 1 (bottom)). This local yielding arising near the hole borders changes the total strain field around the hole, compared to the pure elastic case assumed to numerically determine the calibration coefficients for the integral method [5], resulting in overrated residual stress calculated values.

Comparing the in depth strain relaxation curves obtained by FEM simulation for the case of pure elastic calculations, with those determined by elasto-plastic calculations, for plasticity factors $f > 0$, clear differences are observed and can be quantified by the expected strain error, ***X***, as previously

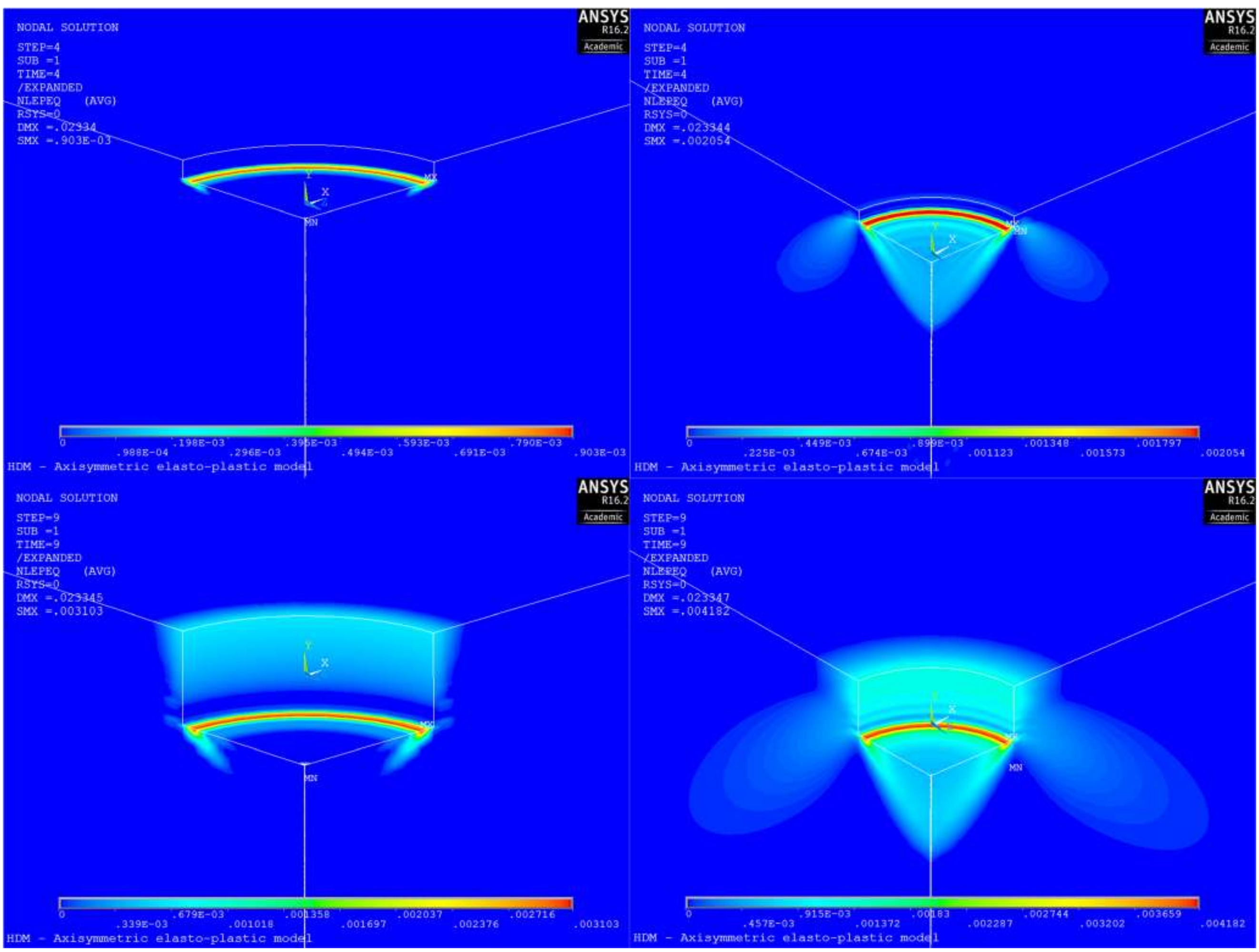


**Fig. 1** Equivalent plastic strain field around a simulated *1.8 mm* diameter hole with 0.1 mm depth (top) and *0.5 mm* depth (bottom). $f = 0.6$ (left) and $f = 0.9$ (right)

defined by Eq. (5). The variation of the expected strain error, $X$, as a function of the hole depth, is shown in Fig. 2 (left). In Fig. 2 (right), the corresponding stress error, $\Phi$, is also shown. For the determination of this error, two calculation methods proposed by ASTM are used [5]: the integral method, generally used for determining in depth non uniform residual stresses and the classic ASTM method, which can only be used for the determination of in depth uniform residual stresses (represented by straight horizontal lines in Fig. 2 (right)).

Both figures show the plasticity effect on the IHD measurements, evaluated through $X$ and $\Phi$ for different stress magnitudes ($f$). For lower stress magnitudes, $f \leq 0.8$, which, for an equibiaxial stress state corresponds to a stress magnitude of 90% of the material's yield stress, the plasticity effect increases with the hole depth, see Fig. 2 (left). For thick specimens with shallow holes, the local stress concentration is lower than the case of deeper holes, since the material adjacent to the bottom of the hole supports the material surrounding the circumference of the hole. However, for high stress magnitudes, $f > 0.8$, the plasticity effect induces greater errors for the case of shallow holes, instead for deeper ones, attaining a maximum effect at ≈0.1 mm hole depth ($Z/D \approx 0.02$, where $D$ is the mean diameter of the standard ASTM strain gauge rosette), decreasing when the depth of the hole increases. According to the numerical study performed, this critical hole depth seems to be related with the depth where the local yielding, arising at the bottom of the shallow hole, spreads all over the hole walls and attains the surface, when the stress magnitude is high enough.

In Fig. 2 (left), it is also possible to observe that a negligible strain error, $X$, is found for $f = 0.2$. In this case, there is almost no plasticity effect on the strain relaxation measured at the surface and then $\Delta\varepsilon^{pl}(z) \approx \Delta\varepsilon^{el}(z)$. These small errors lead to a maximum stress error of $\Phi = 4\%$ at a hole depth of 0.08 mm, with an average error through the depth of ~2%, when the integral method is used for stress calculation, as it can be seen in Fig. 2 (right). For plasticity factors lower than 0.2, $f < 0.2$, the strain error $X$ and the corresponding stress error $\Phi$ are negligible. Therefore, the plasticity effect only becomes relevant for plasticity factors $f \geq 0.2$. This corresponds to a residual stress magnitude of 60% of the material's yield stress. Nevertheless, increasing the plasticity factor, $f > 0.2$, a crescent strain error, $X$, is found with a clear effect on the corresponding stress error, $\Phi$, as it can be observed in Fig. 2. The plastic strains arising around the hole lead now to an increase of the strain relaxation measured at the surface, when compared to the case of the pure elastic case, i.e., $\Delta\varepsilon^{pl}(z) > \Delta\varepsilon^{el}(z)$. For plasticity factors greater than 0.2, the values of the strain relaxation will be overestimated in comparison with those obtained in a pure elastic calculation. For a plasticity factor $f = 0.4$, the relative strain error, $X$, attains 3% at 1 mm hole depth and the corresponding stress error, $\Phi$, is greater than 10%. However, the maximum relative strain error observed, $X$, attains 40% at 0.1 mm hole depth, whereas $\Phi$ attains 85%, which corresponds to a plasticity factor $f = 0.99$, i.e., when the residual stress magnitude approaches the material's yield strength.

In Fig. 2 (right), the corresponding stress error, $\Phi$, related with the classic ASTM method for the determination of in depth uniform residual stresses (represented by straight horizontal lines) is also shown (considering the strain relaxation curves up to $z = 1$ mm ($Z/D \approx 0.2$)). In this case, the effect of the errors on the strain relaxation is less important compared to the use of the integral method. A maximum stress error, $\Phi$, of +23% is found for a plasticity ratio $f = 0.99$, while this error drops to +17% for $f = 0.90$, +4% for $f = 0.4$ and +9% for $f = 0.6$, which corresponds to a stress magnitude of 80% of the material's yield strength. These results agree with ones reported by Beghini et al. [7]. This is the reason why the ASTM E837 standard states that "satisfactory measurement results can be achieved providing the residual stresses do not exceed about 80% of the material yield stress for hole drilling in a "thick" material" [5]. In conclusion, the sensitivity to measurement errors presented by the integral method leads to much greater errors than those found when the classic ASTM method for uniform stress calculation is used. This should be emphasized since the integral method (or any other based on it) is the only one able to accurately determine in depth non uniform stress distributions, such those induced by peening treatments. The underlying nature of the Inverse Problem involved with the integral

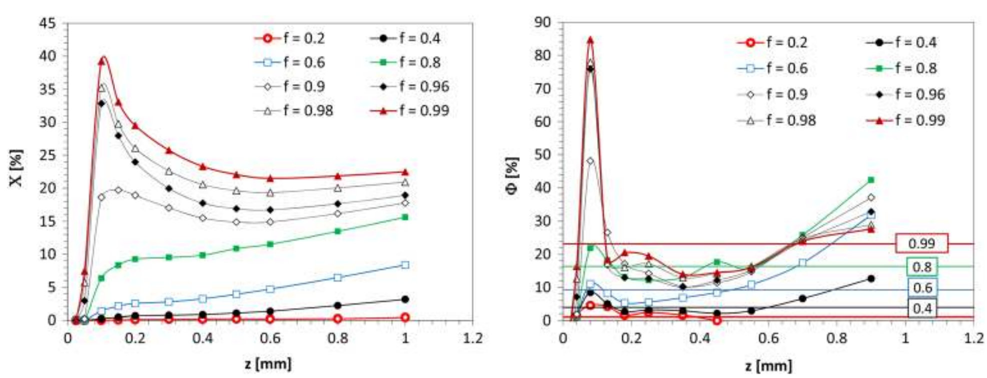


**Fig. 2** Expected errors, X (left) and Φ (right), as a function of the hole-depth, z. Φ is based on the determination of in depth non uniform (integral method (markers)) and uniform stress distributions (horizontal lines with indication of the plasticity factor) according to ASTM E837 [5]

method makes stress calculation very sensitive to measurement errors. Since its numerical solution is ill-conditioned, small errors in the input data cause large errors in the results [21], which is clearly shown in Fig. 2 (right). As the hole depth increases, the amount of relieved stress, which can be sensed at the surface, tends to zero, notwithstanding the magnitude of residual stress in the deepest layers. Therefore, for a depth approximately equal to the hole diameter, a significant strain relaxation cannot be measured anymore. Consequently the stress calculation becomes strongly ill-conditioned for depths greater than half the hole diameter [22]. As consequence of its high sensitivity to measurement errors, in this case due to the plasticity effect, the integral method leads to final stress errors, $\Phi(z)$, of about twice than those observed in the strain values, $\boldsymbol{X}$. As reported by Nobre et al. [23], following the ASTM E837 standard [5], in the absence of measurement errors, the integral method is able to determine in depth uniform stresses within an error of 2%.

**Stress Gradient Effects**

In practice, due to mechanical surface treatments, such as laser-peening or shot-peening, in depth non uniform residual stress distributions are commonly found. The resultant stress gradients are dependent of the surface treatment parameters. To study the plasticity effect in these cases, three stress gradients were simulated by FEM, which are shown in Fig. 3. The resultant in depth strain relaxation curves were then used as input for the integral method, according to the ASTM E837 standard [5].

As before, the comparison between the in depth strain relaxation curves, determined by elastic, $\varepsilon^{el}(z)$, and elasto-plastic, $\varepsilon^{pl}(z)$, FEM calculations, allows analyzing how far local plastic deformations, occurring close to the surface, can affect the entire stress profile. The solid line corresponds to the in depth stress distribution simulated by FEM and the circles correspond to results of the integral method for its determination.

Figure 4 permits to discuss the occurrence of the plasticity effect and its impact on the overestimation of IHD residual stresses, for the three different stress profiles shown in Fig. 3. Figure 4 shows the variation of the plasticity factor, $f(z)$, and the strain relaxation overestimation (error), $\boldsymbol{X}(z)$, with the hole depth. For all cases, the material's yield strength is considered constant through the thickness. Thus, due to the existing stress gradients, the plasticity factor, $f$, varies now over the hole depth. In addition, a maximum plasticity factor, $f$, equal to 0.95 for the first cases is considered, whereas a plasticity factor, $f$, equal to 0.91 is considered for the third case.

Distinct characteristics can be found between the three analyzed cases. In general, comparing with the case of in depth uniform stresses, lower strain errors, $\boldsymbol{X}$, are found. Up to 10% ($\boldsymbol{X} = 0.1$) greater strain relaxations, than the expected for elastic material behavior, are observed in the zones where the residual stress magnitude reaches maximum values (max. $f$).In addition, it seems that the strain overestimation is anticipating the evolution of the residual stress level. Especially for the third case (Fig. 4 (right)), the maximum strain error ($\boldsymbol{X}$) is clearly reached before the stress magnitude achieves its maximum value. This can be understood supposing that the stress field right below the actual drilling depth determines mainly the amount of plastic deformation, caused by the stress concentration around the bottom edge of the hole. This influence of the deeper layers can also explain that, for the considered stress gradients, the strain overestimation remains always lower than for the case of in depth uniform stress (see Fig. 2 (left)), where a strain overestimation of about 18% is determined already at 0.1 mm depth, for a comparable plasticity factor $f = 0.9$, being almost constant over the hole depth. At the hole depths where the plasticity factor drops below 0.4 ($f = 0.4$), the strain overestimation, $\boldsymbol{X}$, reaches minimum values for all cases. The smallest value is obtained for the steepest stress gradient (Fig. 4 (left)). While in this case, the strain overestimation stays on a very small level, it increases again with growing depth for the

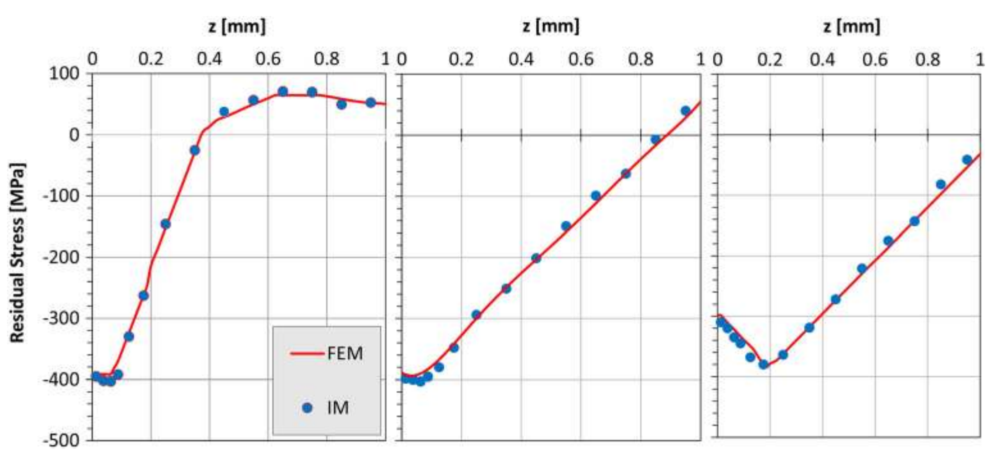


**Fig. 3** Different stress gradients simulated by FEM

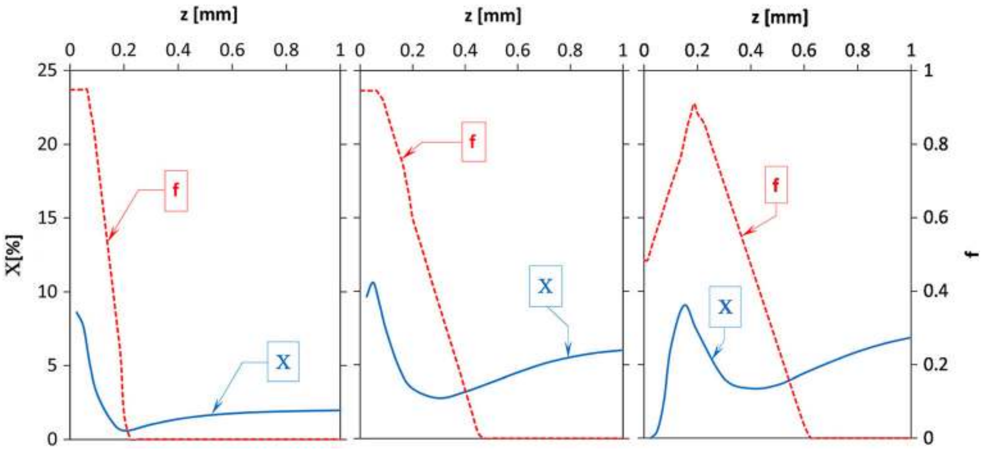


**Fig. 4** Stress gradient influence on the plasticity effect

other cases. Obviously, the much larger depth region where the residual stresses stay on a very high level is now responsible for the strain overestimation far from the surface. At deeper layers, due to the small residual stress level, plastic deformations will not occur directly at the actual drilling depth. Therefore, the strain overestimation must be rather caused by the extension of the plastic zones already existing in the highly stressed layers, initiated indirectly by the mere change of the hole geometry.

This can be better understood by the analysis of Fig. 5, where the plastic strain field around the hole (presented in the bottom of the figure), for three different depths, corresponding to the third case of Fig. 3 (right), can be observed. The third case corresponds to the case of the existence of a maximum compressive residual stress arising below the surface for a maximum plasticity factor equal to 0.91. In Fig. 5 (top), the corresponding von Mises stress field can also be observed. The overestimation of the strain relaxations is directly transferred into overestimated residual stress values. Figure 6 shows the corresponding stress error, ***Φ****(z),* when the integral method is applied. The in depth distribution of the residual stress error follows quite well the strain overrating evolution near the surface, shown in Fig. 4.

Two distinct regions are observed. Near the surface, highest overestimation of the residual stress values is also obtained in the zones where the strain overrating reaches its maximum values. A maximum stress error of about 10% is verified for the first case of Fig. 3, decreasing for the deeper layers. In this

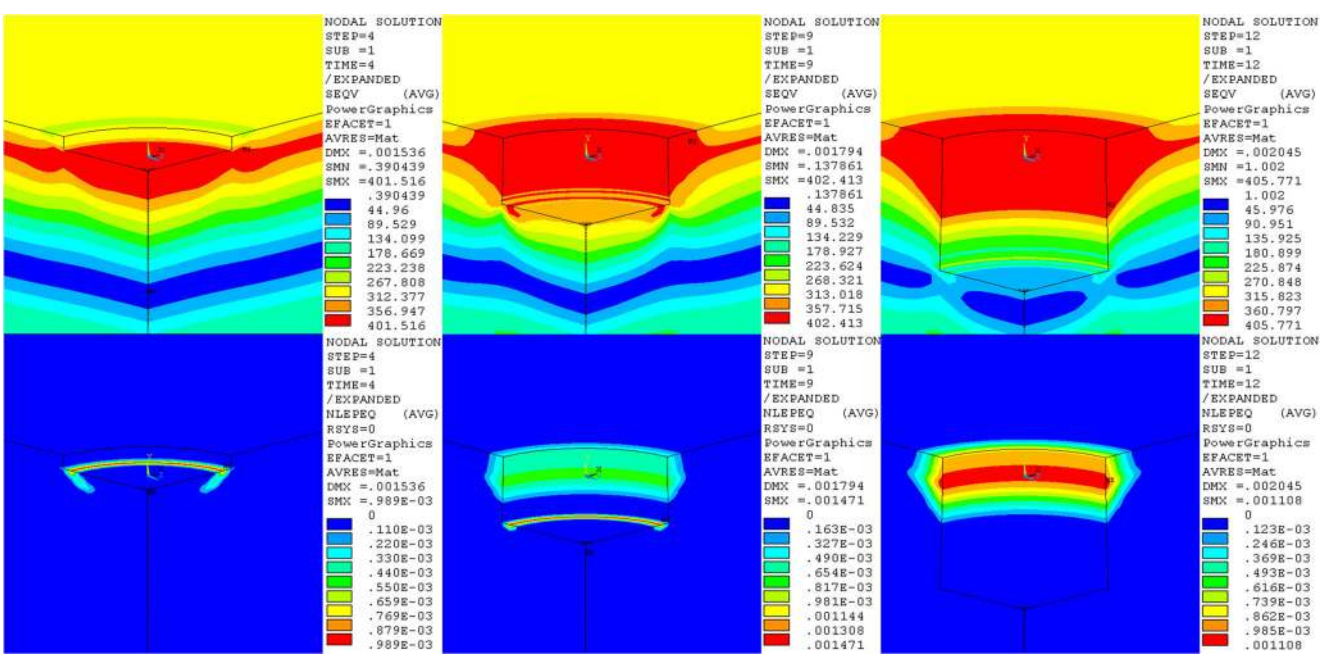


**Fig. 5** Equivalent stress field (top) and plastic strain field (below), corresponding to the third case (Fig. 3) for 0.1 mm hole depth (left), 0.5 mm hole depth (center) and 1.0 mm hole depth (right)

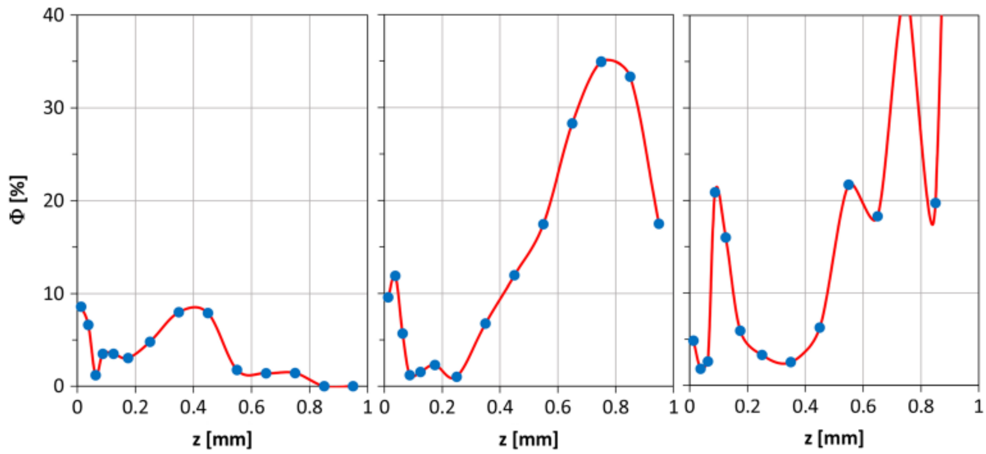


**Fig. 6** Stress error, Φ(z), due to the different stress gradients

case the plasticity factor, *f*, remains below 0.2 in these layers, as shown in Fig. 4. In the other cases, where the highly stressed zones reach farther into the material, stress errors up to 20% (third case) due to local plastic deformations are observed in the near surface layers. In these cases, a distinct residual stress overestimation appears in deeper layers, where the plasticity factor increases and attains values above 0.2. The stress error attains higher values and a large scattering for these layers is observed, even if the plasticity factor is already lower in these layers, especially for the third case. It seems that the higher the errors occurring close to the surface, the higher stress errors and larger scattering will occur in the deeper layers. This is certainly due to the propagation error effect during the residual stress calculation by the integral method. In addition, for deeper layers, considering the studied gradients, the stress magnitude approaches zero and even a small influence of the plasticity effect induces greater final residual stress calculation errors, than for the increments near the surface, where the residual stress presents highest magnitude. Since the absolute amounts of residual stress are small, these high stress errors become less relevant.

## Experimental Evaluation of High Residual Stresses in Peened Surfaces

### Materials and Experimental Procedure

To analyze the plasticity effect in real cases, such as high laser-peening or shot-peening residual stresses, a set of steel alloy specimens, presenting a different strain hardening behavior, were submitted to a shot-peening treatment. Table 1 lists the mechanical properties of each steel alloy used. The specimens were machined in flat plates of 10 mm thickness. The dimensions chosen were sufficiently large to avoid edge effects. After grinding, the specimens were heat treated to relax the residual stresses induced by the machining procedure. The specimens were then subjected to shot-peening (according to the MIL-S-13165 C standard): S170 peening medium, impact angle of ±90°, Almen intensity of 14A and 100% coverage.

The in depth shot-peening residual stresses were determined at the center of each sample by the incremental hole-drilling (IHD) and X-ray diffraction (XRD) techniques. For the IHD technique, high speed drilling equipment was used. The surface strain relaxation was measured by a standard strain gage rosette (ASTM type B rosette [5]). Adopting depth increments of 0.02 to 0.06 mm, the strain relaxation was measured after each drilling increment to about 1 mm depth. The average hole diameter was about 1.8 mm. For the residual stress evaluation, elastic constants of E = 210 GPa and ν = 0.3 were used. The integral method was selected to determine the residual stresses by IHD [5].

XRD residual stress analysis was combined with the electrolytic layer removal technique to determine the shot-peening residual stress profiles. XRD profiles are used as reference values for those determined by IHD. Lattice deformations of the Fe {211} planes were determined on a conventional ψ diffractometer for 15 ψ angles between −40° and +40° using CrKα radiation. Residual stresses were calculated according to the $\sin^2 \Psi$-method [24] for plane stress conditions using X-ray elastic constants of ½ $s_2 = 5.832 \times 10^{-6}$ $MPa^{-1}$ and $s_1 = -1.272 \times 10^{-6}$ $MPa^{-1}$ [25, 26]. In addition, since the layer removal procedure was restricted to a very small area at

**Table 1** Bulk material mechanical properties of the shot-peened steel samples

| AISI | $S_y$ [MPa] | $S_{UT}$ [MPa] | n* | HV** |
|---|---|---|---|---|
| 420 | 350 | 630 | 0.24 | 200 |
| 1045 | 440 | 720 | 0.18 | 220 |
| 3415 | 460 | 590 | 0.14 | 210 |

*Strain hardening exponent evaluated considering the whole plastic region

**$HV_{0.1}$ obtained in the bulk material (after electrolytic polishing of the specimens)

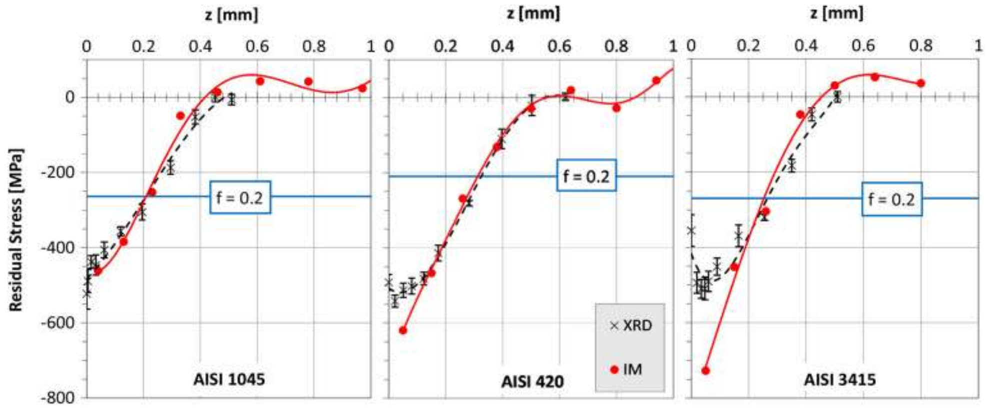


**Fig. 7** In depth shot-peening residual stress profiles determined by XRD and IHD

specimen's surface and the direct effect of the plasticity effect essentially has influence in the near surface layers, despite its indirect effect on the deeper layers, there was no correction on the residual stress values determined by XRD, using, for example, the procedure proposed by Moore and Evans [27].

## Experimental Results

Figure 7 shows the shot-peening residual stresses determined by IHD and XRD ($\sin^2\psi$ method [24]) in shot-peened steel samples. The results shown in Fig. 7 correspond to maximum principal stress values, since the residual stress state, obtained by both techniques, can be considered equibiaxial. In Fig. 7, the magnitude of the residual stresses related with a constant plasticity factor equal to 0.2, defined before as the critical value from which the plasticity effect will lead to overrated residual stress determined by IHD, is also shown. However, for this calculation, the yield stress of the bulk material not affected by the mechanical surface treatment was considered. As it can be observed, in all cases, the residual stresses exceed by far the limit that leads to the plasticity effect in the near-surface regions and, therefore, discrepancies between both techniques are to be expected, especially for AISI 420. For steel AISI 1045, however, a very good agreement between XRD and IHD is observed. In this case, it seems that there is no plasticity effect, although shot-peening residual stress clearly exceeds 60% of the bulk material's yield strength (which corresponds to $f = 0.2$). Apparent plasticity factor reaches 140% ($f = 1.4$). Therefore, the knowledge of the yield stress of the bulk material is useless when the local yielding in its work-hardened surface has to be evaluated. For the correct calculation of the plasticity effect, the strain hardening of treated layers has to be considered, since the possible effect of plastic yielding is prevented. For steels AISI 420 and 3415, however, the observed discrepancies, especially near the surface, should be attributed to the plasticity effect. For steel AISI 3415 discrepancies arise over the whole depth, which might be surprising, if only the yield strength of the bulk material is used to assess the occurrence of the plasticity effect. An apparent plasticity factor greater than 200% ($f \approx 2.1$) is found for AISI 420, while attaining 125% ($f \approx 1.25$) for the case of AISI 3415. However, the plasticity effect seems to have a greater effect on the IHD results in AISI 3415 than for AISI 420. These observations can only be explained if the work-hardening behavior of the shot-peened layers of the two steels differs. In conclusion, the yield stress of the bulk material is completely irrelevant to assess the effective plasticity effect on the residual stresses determined by IHD in work-hardened surfaces.

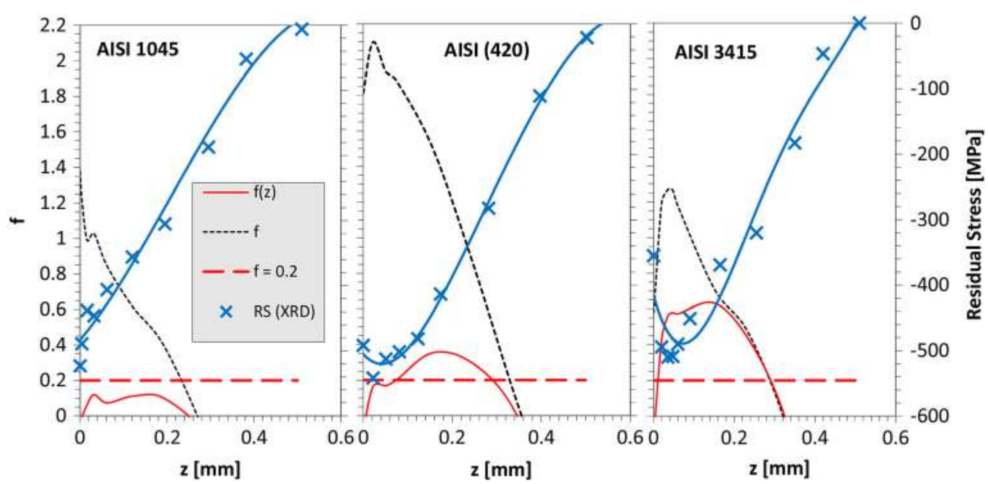


**Fig. 8** Apparent plasticity factor ($f$) vs. local plasticity factor ($f(z)$) determined in three shot-peened alloy steels

**Discussion of the Experimental Results**

The XRD residual stress profiles, the apparent plasticity factors (considering the bulk material's yield stress, $S_Y$), $f$, and the local plasticity factors, $f(z)$ (from Eq. (7)), considering the strain hardening effect corresponding to the shot-peened steels investigated are shown in Fig. 8.

From Fig. 8, effectively, the greatest maximum local plasticity factor is found in AISI 3415, attaining 0.65, $f(z) = 0.65$, while the lowest maximum local plasticity factor is found in AISI 1045, below 0.2, $f(z) < 0.2$. The maximum local plasticity factor reaches 0.35, $f(z) = 0.35$, in AISI 420. Obviously the greater strain hardening of AISI 420 steel prevents the plasticity effect on IHD results, but not in steel AISI 3415, which presents the lowest strain hardening capacity. In conclusion, the proposed local plasticity factor, $f(z)$, is able to explain and predict the appearance, or absence, of local yielding around the drilled holes that lead to overrated IHD residual stress results in the three studied cases.

## Conclusions

The so-called plasticity effect on the residual stresses determined by the incremental hole-drilling technique (IHD) was numerically and experimentally analyzed. The major factor to evaluate its occurrence is the plasticity factor, $f$, which defines the onset of plasticity around a drilled hole for plane stress states. Using the integral method, this plasticity effect leads to IHD residual stress overestimation when the plasticity factor attains a value around 0.2, $f \geq 0.2$, affecting differently the relaxed strain after each depth increment. For $f < 0.8$, the strain relaxation error increases with the hole depth, while for $f > 0.8$ maximum strain errors are found in the first depth increments. A maximum overestimation of 51% for the surface strain relaxation is found at 0.1 mm hole depth, but drops to around 20% for 1 mm hole depth. Due to its high error sensitivity, the integral method can lead to IHD residual stress errors twice as high as observed for the strain relaxation values.

The combined influence of stress gradients and plasticity effect is also shown. In general, the error found decreases compared to that found for in depth uniform stress states. However, greater errors are found for deeper layers where the plasticity factor already attains low values. In these deeper layers, the strain overestimation must be rather caused by the extension of the plastic zones already existing in the highly stressed layers, initiated indirectly by the mere change of the hole geometry. This effect is more evident on the overestimation of the IHD residual stresses determined by the integral method, due to the intrinsic characteristics of this calculation procedure, which takes into account the stresses existing in the previous depth increments for the calculation of the residual stress existing in the current depth increment.

The evaluation of the plasticity effect, or any attempt to correct this effect, requires the exact knowledge of the respective local yield strength, which may differ considerably from the bulk material's value, due to material's local work-hardening induced by any mechanical surface treatment, such as, e.g., laser peening or shot-peening. A method to estimate the local yield strength in the treated layers, based on the relative hardness variation over these layers, enabled to explain the IHD residual stress results found in three shot-peened steels. A new equation for the determination of the local plasticity factor in work-hardened surface layers is, therefore, proposed.

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