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AN APPROACH TO RELATE THE SHOT PEENING PARAMETERS TO THE INDUCED RESIDUAL STRESSES

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ABSTRACT

The prediction of the residual stress field induced by shot peening and the influence of the chracterising peening parameters dealt with. A finite element procedure for the simulation of one multiple impact of a shot against a plastically deformable material is developed being the aim to relate the shot size, material and velocity to the residual stress field induced. Different target materials are considered. By means of these calculations it is found a relation between the Almen intensity and the residual stress field. An approach based on the definition of dimensionless parameters was developed able to collect the results on non-dimensional curves applicable to general materials. The procedure was implemented on a software that allows the estimation of the residual stress field by knowing the Almen intensity and the type of shot utilised. Experimental measurements validate the proposed approach.

KEY WORDS

residual stress prediction, peening index, fatigue strength estimation

INTRODUCTION

From many decades shot peening is widely used to alleviate fatigue in notched elements. which are characterised by an high stress concentration factor [1].

It is well known that the gain in fatigue resistance induced by shot peening is mainly due to the residual stress field caused by plastic deformation following the multiple impacts of the shots. The hardening plays also a role in the increment of fatigue strength of the peened materials but is less important than the residual stresses.The fatigue behaviour of the peened elements is then affected by the peening parameters (shot size, material, velocity, coverage, etc).

In view of optimising the treatment results during the design stage it is necessary to know the relationship between the peening parameters and the residual stress profile.

Most of the methods developed till now with this aim are based on the assumption that the effect of a single impact of a rigid shot against an elasto-plastic material well describe the real event and find a correlation between the type and the velocity of the shot and the residual stress field.

Indeed recent experiments evidenced the importance of considering different impacts in a limited zone to evaluate the residual stress field induced by shot peening [2].

In addition the correlation of the residual stresses with the velocity is of limited practical importance because the speed of the shot flow is not accurately known and its measurement difficult. Bearing in mind that the peening intensity is usually defined in terms of Almen grades [3], it would be more interesting defining a relation between the Almen scale, the type of shot and the consequent residual stress field.

In [4] and [5] an approximate approach of this type is described and the comparison with some experimental presented. However the predictions are based on the results obtained from a single impact analysis.

Due to the ever increasing power and low costs of modern computer, the FE method is becoming more and more diffuse for solving this type of problem [6].

In this paper a research is described being its aim the definition of a procedure able to predict the residual stress field induced in a component by shot peening, once the Almen intensity and the type of shot are defined.

The approach is based on finite element calculation of multiple impacts residual stresses of rigid spheres on a plastic plate. The simulation allows to evaluate the effect of different impacts on the residual stress state and to estimate the depth of the resultant indentations.

The residual stress profiles obtained by considering different materials were made non-dimensional by dividing the stress values by a mechanical characteristic of the material. In addition, by defining a dimensionless parameter, called "peening index" and analogous to the damage number reported in [7, 8] it is possible to make equivalent the peening effects on different materials under different peening conditions.

The calculations are performed by imposing a velocity value as initial condition to the shot. To relate this one to the Almen intensity FEM analyses were performed on a strip with thickness equal to the one of the Almen strip. A procedure was then defined to relate the stresses deriving from the impacts to the ones present in the Almen strip once it is removed from the fixing screws (that is to say that the effect of the residual curvature of the strip is considered).

A software was developed based on the FE results and the non-dimensional parameters able to predict the residuals tress trend in a peened material without performing other FE analyses. The software also include a procedure for predicting fatigue strength of peened components and can be used as a useful tool during the treatment design stage.

FINITE ELEMENT ANALYSES

The numerical simulation of shot peening was carried out by means of the finite element method. The problem is numerically complex because of the non-linearity due to the material behaviour and to the contact between two deformable bodies.

The analyses carried out considers the dynamic impact of one or more shots against a plate. This suggests the application of an explicit integration code; the explicit version of ABAQUS was used; this latter makes possible also to consider the contact between two bodies by using special contact elements.

The shot was considered rigid, while the elasto-plastic constitutive law of the material was utilised in the calculations.

Different models were developed; the first ones were axi-symmetric and enable the analysis of the impact of one sphere. They are all built with first order finite elements.

If the effect of more impacts, in the same contact zone or around a determined zone is considered it is necessary to develop three-dimensional models, with a remarkable increment of modelling and calculation time.

In all the cases analysed a plane body was considered: this approximation of the real geometry of the peened component seems acceptable due the large difference of the curvatures of the shots with respect of the impacted body.

Due to the complexity of the case, many verifications (both considering an elastic and an elasto-plastic material) and many models with different number of element were made to test the accuracy of the results. In Fig. 1 the final 3D FE model utilised for the subsequent analyses is shown: the total number of nodes is 22379. It can be noted that due to the symmetry of the case, only   of the impact zone was modelled, imposing appropriate boundary conditions to the nodes lying on the symmetry plane.

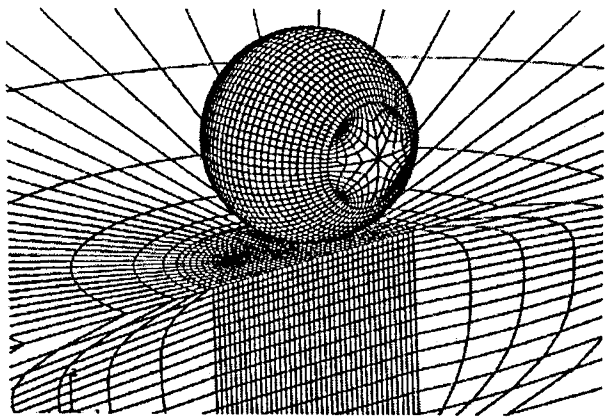


Fig. 1 FE mesh used for the impact analyses.

The preliminary calculations made with a linear elastic constitutive law showed a difference of the maximum contact pressure with respect of the Hertzian value limited to 1%.

The elasto-plastic analyses considered also the kinematic hardening rule. Three steels with different mechanical behaviour were considered; in Table 1 their mechanical properties are reported together with their designation according to the Italian code.

Bearing in mind [7] and due to the lacking of data referring to the mechanical behaviour at high strain-rate, this latter effect was neglected.

TABLE 1. Mechanical characteristic of the steels considered in the FE analyses.

Material	UTS [MPa]	Yield stress [MPa]
Fe510	510	315
35CrMo4	1050	930
C70	1300	1120

The analyses enabled the evaluation of the different relevant peening parameters, such as shot velocity, diameter, material and angle and number of impacts on the residual stress field induced. In particular, the variability of the surface residual stress, the value of the maximum compressive stress and its depth, the depth where the residual stresses change sign were analysed.

The results showed that the effect of angle of impact on the residual stress state is limited if the shot speed is higher than 60 m/s. In addition it was noted that the surface stress is the one that is more influenced by the numerical model and parameters, probably due to the high surface distortion of the elements.

By analysing the calculation results it was possible also to affirm that the residual stress field is mainly influenced by the first impact and the differences due to the following one are limited in a range of about 15%. This enables the use of single impact analyses, at least for first approximation evaluations.

In Fig. 2 the deformed shape of the plate is shown after two impacts.

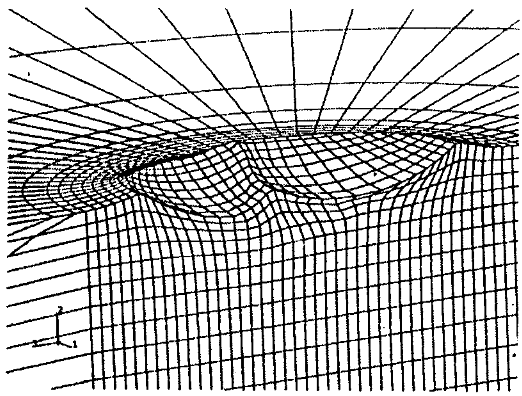


Fig. 2 Deformed shape of the plate after two impacts.

NON-DIMENSIONAL PEENING INDEX DEFINITON

The numerical simulation of shot peening was repeated by changing a peening factor a time, being the aim to study their effect on the residual stress field.

The results were plotted by defining interpolation curves putting into relations the factors defining the residual stress field and the main peening parameters. In particular the shot diameter varied from 0.2 mm to 1 mm, the impact velocity varied from 40 m/s to 120 m/s, the material density of the shot was the one of steel and of glass.

As regards the quantities defining the in-depth residual stress field, they are: surface residual stress maximum compressive residual stress and its distance from the surface, maximum tensile residual stress and its distance from the surface, depth at which the residual stresses change sign, indentation extension.

Th resume the results of all the analyses some non-dimensional parameters were defined relating the peening effects to the treatment parameters. In particular "peening index" *N* was defined, similar to the "damage number" defined in [7]:

$$N = V\sqrt{\frac{\rho_s}{R_m}}$$

where V is the impact velocity, ρ is the shot density and R_m is the ultimate tensile strength of the material.

TABLE 2. Analytical non-dimensional functions defining the residual stress field

Peening index:	$N = V \cdot \sqrt{\frac{\rho_s}{R_m}}$
$\frac{R_i}{R_s} = 1.0749 \cdot N^{0.4999} \quad (R^2 = 0.9854)$	$\frac{P_i}{R_s} = 0.4417 \cdot N^{1.027} \quad (R^2 = 0.9994)$
$\frac{\sigma_{max-}}{R_m} \cdot \sqrt{\frac{R_s}{P_i}} = -2.1.222196 \ \ln(N) + 0.3232 \ (R^2 = 0.9136)$	$\frac{P_{inv}}{P_i} = -65851 \cdot \ln(N) - 0.7417 \quad (R^2 = 0.9673)$
$\frac{P_{max-}}{P_i} = -2.1693 \cdot \ln(N) - 0.0244 \quad (R^2 = 0.7505)$	$\frac{\sigma_{max+}}{R_m} \sqrt{\frac{R_s}{P_i}} = -0.3182 \cdot \ln(N) - 0.1781 \quad (R^2 = 0.8554)$

In this way it is possible to reduce the dependency of the residual stress field (and the quantities defining it) from the peening parameters to the dependency only from N. In Tab.2 the analytical function of the dimensionless variables defining the residual stress field ((R_i is the radius of the indentation, R_s is the shot radius, V is the impact velocity, ρ_s is the shot density, R_m is the ultimate tensile stress of the peened, P_i is the indentation depth, P_{inv} is the depth at which the residual stresses change sign, σ_{max-} and P_{max} are, respectively, the maximum compressive residual stress and the corresponding depth, σ_{max+} and P_{max+} are the maximum tensile residual stress and the corresponding distance from the surface, σ_{sup} is the surface residual stress).

In Fig. 3 the curves of $\frac{\sigma_{sup}}{R_m} \cdot \sqrt{\frac{R_s}{P_i}}$, $\frac{P_{max-}}{P_i}$, $\frac{\sigma_{max-}}{R_m} \cdot \sqrt{\frac{R_s}{P_i}}$, $\frac{P_{inv}}{P_i}$ with respect of N are drawn.

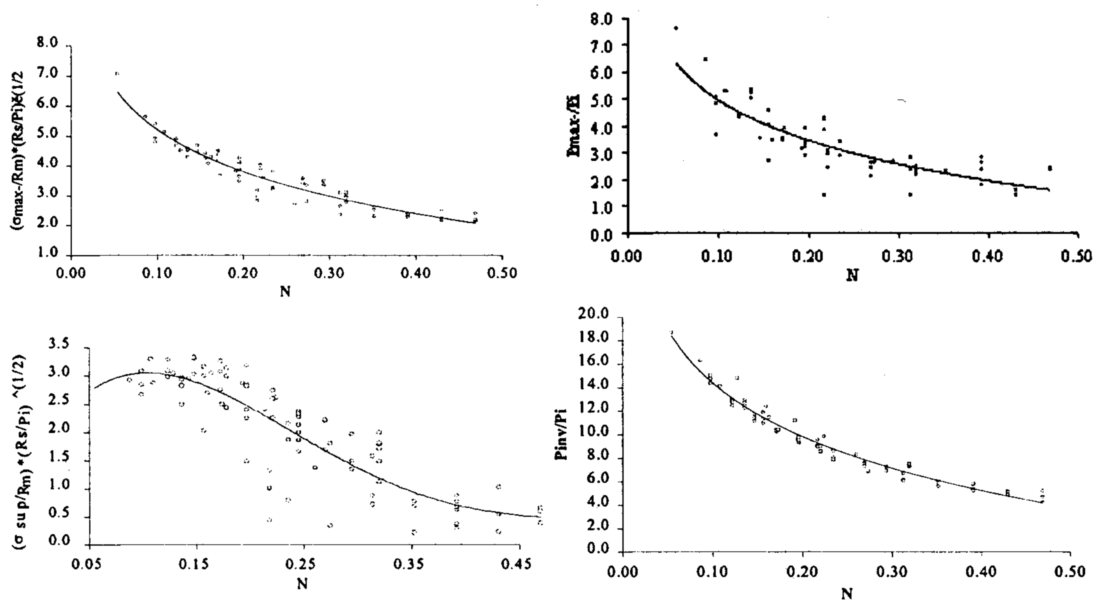


Fig. 3 Interpolation curves of the dimensionless residual stress profile with respect of N.

THE RELATION BETWEEN THE SHOT VELOCITY AND THE ALMEN INTENSITY

The proposed approach would be of limited practical interest because the shot velocity is usually unknown during the treatment execution. With the aim to circumvent this limitation it was investigated the possibility of defining a relation between these two quantities based on the numerical results.

The approach is based on the numerical analyses of the impact of the shot against a plane element with the thickness equal to the one of the Almen strip. Also the material consitutive law is the one of the material of the Almen strip.

After the impact analyses are ended the resultant residual stresses are applied uniformly to the entire Almen strip, whose boundary conditions are the ones experimentally imposed during the intensity measurement. The residual stress field due to the impact is not self-equilibrated; so, after the boundary conditions are removed the strip deflect and assumes a curved configuration. The arc height of the deformed strip is the Almen intensity.

By following the present procedure it is possible to relate the velocity of the shot flow to the resulting Almen grade.

In Fig. 4 the results are shown for steel and glass shots.

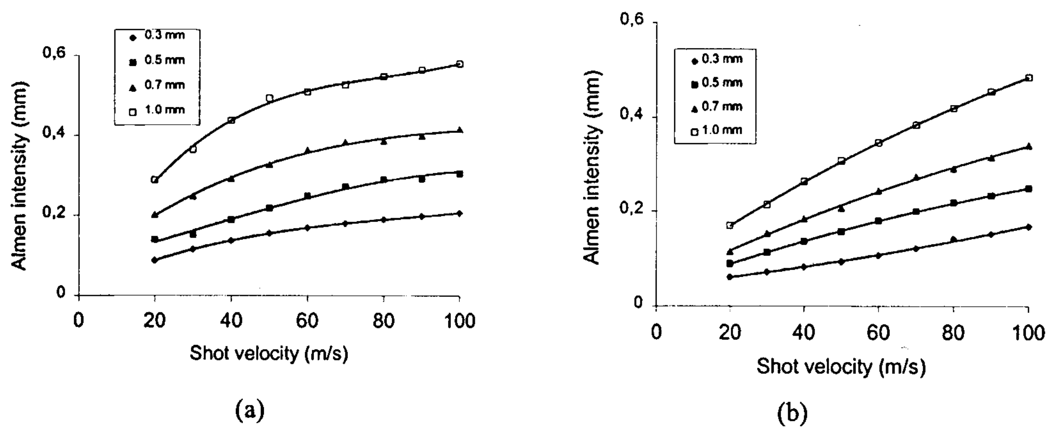


Fig . 4 Interpolation curves defining the relation between the Almen intensity and the shot velocity: (a) steel shot, (b) glass shot.

All the curves have a correlation coefficient R^2 equal or higher than 0.98. In Fig. 5 the comparison of the results with some experimental data found in [4, 9] is shown: the agreement seems satisfactory.

EXPERIMENTAL MEASUREMENTS

To validate the proposed approach some experimental measurements of the residual stresses were carried out. The X-Ray diffraction technique was used ((Ital Structures diffractometer, $\sin^2\psi$ method, proportional detector, Cr radiation, Vn filter, $2\Theta \approx 156°$).

The measurements were carried out on two Almen strips peened with the same intensity (12A) but different shot diameter (0.3 and 0.6 mm). The material of the shots was steel.

In Fig. 6 the comparison between the experimental points and the numerical results is illustrated. The agreement is good in the sub-surface layer of material.

When the residual stresses become tensile the experimental measurements are sensibly from the numerical ones.

This can be interpreted bearing in mind that the internal stresses measurements are performed by removing the material with a electro-chemical device. Due to the very thin thickness of the strip, the removal of some fraction of mm implies the complete rearrangement of the residual stresses that relax and become almost null.

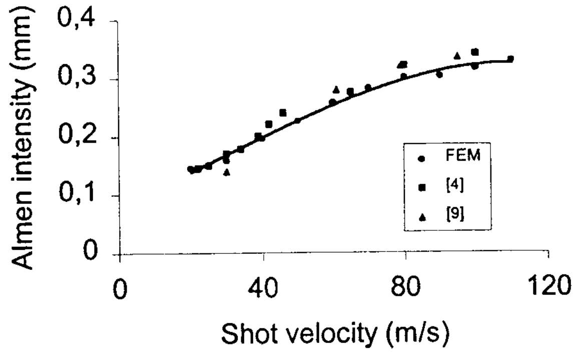
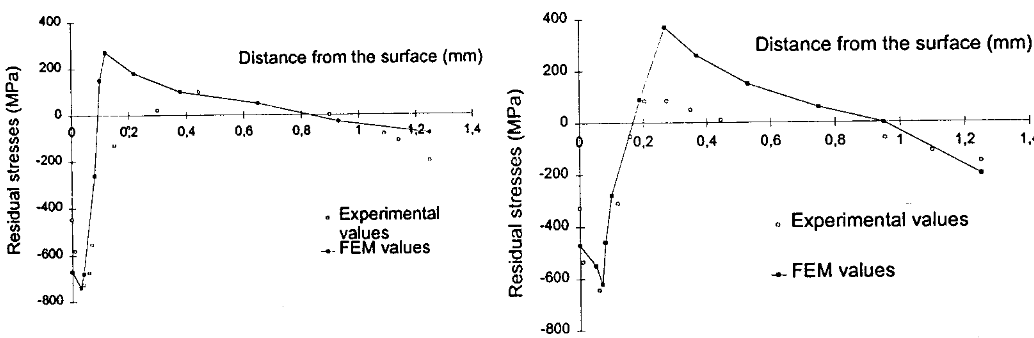


Fig. 5 Comparison between the numerical Almen intensity-shot velocity relation and some experimental data (shot diameter=0.5 mm, shot material: steel).

Further measurements are in course on other geometry and materials and confirm the described trend. Other details on the measurements can be found in [10].



(a) (b)

Fig. 6 FE and experimental trends of the residual stresses in an Almen strip: (a) 12A, shot diameter=0.3mm, (b) 12A shot diameter=0.6 mm.

THE SOFTWARE FOR THE RESIDUAL STRESS PREDICTION

The proposed approach for the prediction of the residual stresses due to shot peening was implemented in a software allowing automatic calculation once the peening conditions are defined.

The software is written in Visual Basic® language and utilises the non-dimensional curves previously defined to relate the peening parameters to the residual stress field. Thanks to the relationship between the Almen intensity and the shot flow velocity the user have only to define the type of shot and the required intensity. The peened material mechanical characteristic must be known, of course.

Another option is to plan a residual stress profile; the software will calculate the type of shot and the required Almen intensity that results in the most similar profile to the one planned.

In Fig. 7 the input data panel and the results panel of the software are shown.

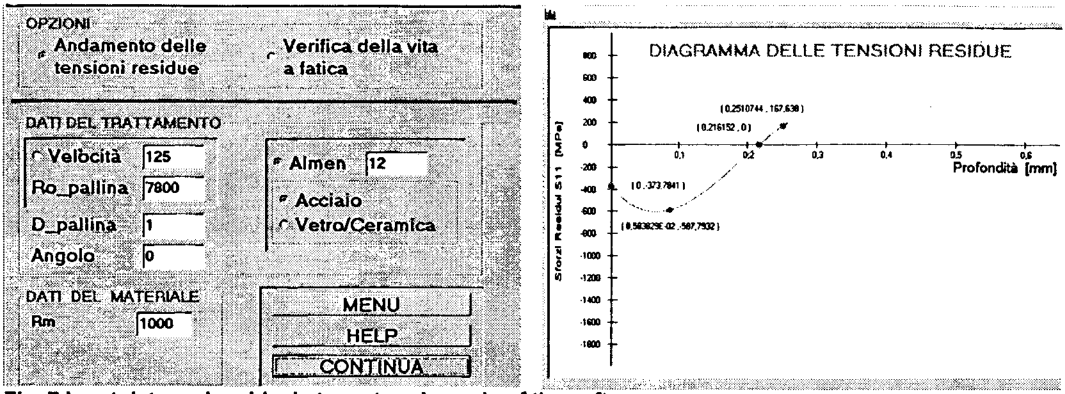


Fig. 7 Input data and residual stress trend panels of the software.

The software has also an option for fatigue strength evaluation of peened components, taking into account the residual stress field previously calculated.

The utilised approach is the classical one based on the Haigh diagram of the component analysed. The software needs the fatigue properties of the material (fatigue limit, yield stress, ultimate tensile strength), the notch characteristics (theoretical stress concentration factor, notch sensitivity, dimension and surface roughness coefficients) and the stress cycle to be known. The approach was verified by means of rotating bending fatigue tests on cylindrical specimens with a stress concentration factor equal to 1.47 peened with an intensity of 12 A with two types steel shot: the first with a diameter of 0.3mm and the second with a diameter equal to 0.6 mm. In the two cases the fatigue limit was, respectively of 410 MPa and 390 MPa. The predicted values are 397MPa and 390MPa. The agreement is good even if further verification are needed to generalise the approach validity. Further details on the fatigue tests can be found in [11].

CONCLUSIONS

A computational approach for the prediction of the residual stresses induced by shot peening was developed: it is based on FE calculations and on the definition of non-dimensional relations between the residual stress field and the peening parameters by means of the "peening index". The approach is suitable for easy implementation on an automatic computational routine and a software for automatic calculation of the residual stress profile and fatigue strength evaluation was developed. The experimental residual stress measurements and the fatigue test results gives positive indications about the accuracy of the proposed approach even if further analyses are necessary to completely validate the approach.

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