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SHOT PEENING PROCESS MODELLING ON GAS TURBINE APPLICATIONS

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Abstract
The application of surface treatments to finished parts in gas turbine aero-engines such as shot peening is one of the most common procedures to prevent early fatigue crack initiation and propagation to enhance the resistance against environmental induced corrosion fatigue, stress corrosion, wear generation, and fretting. Whilst much was done in recent years to develop numerical approaches which could reproduce the effects of the shot peening process [Ref. 1], a historical and mainly empirical approach, based on generated knowledge and experience to define the parameters for the same process applicability, is still widely used in the industry.
Objective of the current work is to introduce, define and develop a numerical approach which would allow to replicate the real process and to predict the effects of shot peening. A set of numerical tools, for given shot peening input parameters and nozzle geometry, is here developed and the gained knowledge is then applied to representative 3D features on gas turbine components.
Firstly is introduced the usage of equivalences between the experimental based and the numerical work for the shot peening process, focusing on the definition of conventional fundamental parameters such as intensity and coverage, which are then used in the numerical Finite Element (FE) simulations. Details are given to demonstrate the method has a validation basis to be trusted for a simple but representative geometry, i.e. a flat specimen. The definition introduced is validated over a simplified but still numerically representative form, the so called symmetry cell. The numerical tools applied are time-dependent numerical FE methods, with a selection of adequate material models. The methods developed are then selectively applied to representative geometry 3D features, with a selective example reproduced in details.

Keywords
Shot Peening, Numerical Simulation, Residual Stress; 3D Feature

1. Introduction

Shot peening is a manufacturing operation carried out by firing small spherical shots against a target surface with a typical initial velocity which, depending on the application, can vary between 20m/s up to approx. 120m/s. The application of surface treatment via shot peening induces a protection with an outer and uniform compressively stressed surface layer and surface work hardening, from which the following benefits may be derived:

- An improvement in fatigue strength;
- An improvement in frettage fatigue characteristics;
- An improvement in stress corrosion resistance;
- The inducement of certain grain size requirements.

It is a common manufacturing and design practice to define the shot peening specification based on empirical rules. However, with the variety of processing parameters involved in the shot peening application, the selection of the most suitable and adapt ones to achieve the given and desired degree of improvement is a matter of answering questions with multiple outcome, not always straightforward. Challenges are especially arising when the process is applied outside known

previous experience, for example in terms of geometrical features or material behaviour, to name two of the main ones. The current approach is based upon numerical analysis of the shot peening process effects with the intentional help to make the right decisions once the process needs to be replicated or the application deviates from the known previous experience.
It is particularly useful to have a validated and solid numerical method to apply in cases where the measurements of residual stresses are not existing, or not easily possible. Here the main intention of the current numerical analysis is the application looking at unknown behaviour of the shot peening process over 3D features as well as to the generation of profiles which are going to be used as input for life calculation and other subsequent numerical applications.

2. Objectives & Methodology

The numerical applications of shot peening are reported in many open literature references, as for example in [Ref.2, Ref.3, Ref.4, Ref.5]. While different authors are giving importance to different aspects of the process, it is here also recognised that two are being identified as the most important parameters to be accepted and adopted for engineering analysis as:
- the intensity and
- the coverage.

Intensity is an index of transferred energy from the flow of shots to the target component, while coverage indicates the amount of target surface that is treated by the shots.
The numerical simulations which are reported in literature are often concentrating mainly on the investigation of the effects of the shot into a target surface and neglect for simplicity the shot to shot interaction. To analyse shot to shot and shot to surfaces interactions, an approach based on discrete element models has been proposed by several authors, as reported by [Ref.6] assuming both shot and target surface being rigid bodies. However, here an approach based on the application of FE analysis has been applied without any shot to shot interaction. The usage of equivalences between the experimental based and the numerical work for intensity and coverage is developed as follows.

2.1 Intensity

The intensity is the one of the important parameters here used to characterise the shot peening process. It is a necessary piece of information also to be used for comparison purpose. The calibration and the definition of the intensity is usually carried out by an Almen strip on an experimental base. A procedure to correlate the values of the Almen-scale to residual stresses in the component has been established by Avrami and it has been also here adopted [Ref.7]. The residual stress distribution calculated in the FE analysis of an equivalent model in the centreline of the impact zone is assumed to be uniformly distributed over the whole Almen strip, fixed to the Almen block.
The Almen strip, which was originally straight, after the fixing bolts are released becomes curved and modifies the residual stress field. Since the residual stresses originating from the impact are not being equilibrated, the thin plate will bend and elongate as a consequence. As long as the fixtures are in place, these effects are not allowed. The effects of those fixtures can be replicated by an equivalent force F and a bending moment M, applied to keep the strip straight. Therefore it is possible to calculate elastically the residual stresses as:

$$F = \int_A \sigma_{res,imp}(y)\, dA \; ; \quad M = \int_A \sigma_{res,imp}(y)\, y\, dA$$

Where $\sigma_{res,imp}$ are the residual stresses due to the shot impacts, A is the cross section of the strip and y the distance from the strip neutral axis. The intensity can also be analytically calculated by referring to the beam theory. The removal of the bolts can be seen as equivalent to the application of a moment and a force of same values but with the opposite sign. The stresses, stains and deflections are determined once the residual stresses due to the impact are known, by applying the theory of elasticity.

2.2 Coverage

The coverage is the second most important parameter to define within the basic definition of the shot peening process modelling. The coverage is defined as the ratio of area of the material, which is subject to impact, to all the surface area of the component. In Fig.1 the progression of the coverage is illustrated from isolated impressions (Fig1.a) to a situation of partially overlapping impressions (Fig.1.b). It is usual to refer to the application of the Avrami equation [Ref.3] to define the achievement of a full coverage (or a 98% equivalent) as illustrated in Fig.2.

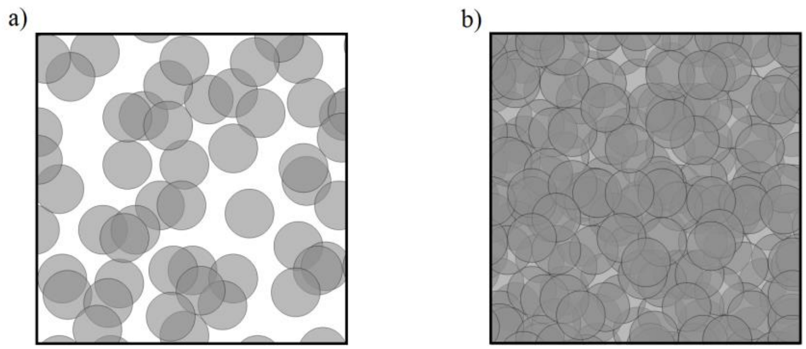

Fig.1. Progression of coverage of shot peening.

Based on the knowledge generated for one single shot indentation area, it is possible to derive the minimum number of shots which are necessary to generate the relevant numerical coverage for a given geometry. Having assumed a regular square form for the target area, a relation between the impression area generated by one single shot and the impression generated by a number of multiple shots is then proposed.

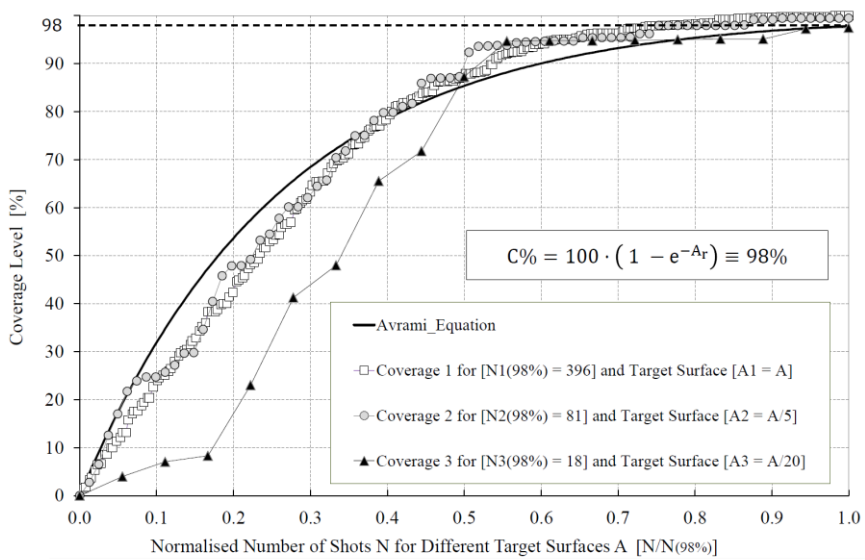

Fig.2. Coverage of shot peening following Avrami definition for three different analyses.

A discrepancy between the Avrami equation solution and the achieved Finite Element coverage exists, as demonstrated in [Ref.4], which become only partially reduced increasing the number of shots for the same geometrical parameters. In the current example, three different numerical applications of coverage level are reproduced, varying from a number of shots of 18 to 81 to 396 (Fig.2). It has to be noted that also the target surface is respectively adapted (increased) following the number of shots, however a smaller number of shots are limiting the residual stress distribution as well as a realistic and cumulative work hardening and surface roughness definition. Therefore it was considered a minimum number of impact representatives when this was in excess of 81 shots.

2.3 Material model and calibration

Different types of materials can be used for the shot peening process simulation, such as steel shot peening; glass bead peening; ceramic shot peening. The material models which apply have to be selected in accordance with the manufacturing process. Although the principles here described are generic and no main differences should arise from the application of different materials, the current work focuses on the steel shot peening as reported in the manufacturing related work [Ref 1]. Between the existing numerical material models available also with rate dependency property, the Johnson Cook (JC) plasticity model was here successfully implemented to simulate the shot peening process with Abaqus/Explicit. A set of parameters has been evaluated based on calibration curves which have been used to approximate the fitting parameters with relevant strain rates curves data.

3. Numerical analysis results

3.1. Basic implementation (single shot)

The starting implementation of a shot peening simulation is based on a single shot model. The necessity to have such a model, which obviously does not want to represent a real peening process, is fundamental to define the initial model settings, including shot velocity and size effects as well as the material model basic characteristics and the influence of the developing plastic zone.

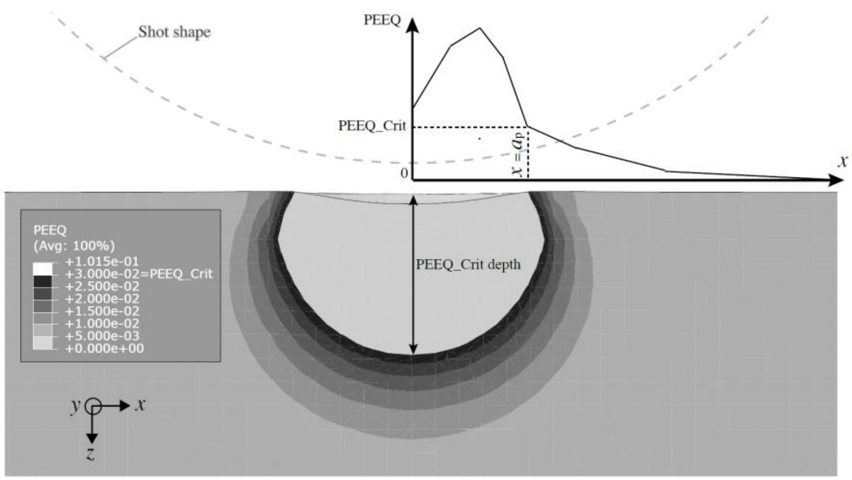

Fig.3. PEEQ under a single shot model.

As illustrated in Fig.3, a critical value for the accumulated plastic equivalent strain (PEEQ) is introduced at the boundary (a_p) of the circular indentation resulting from the impact. This quantity is defined as a critical value or PEEQ_Crit, here equal to 0.03. Further it can be found that a specific depth corresponds to PEEQ_Crit. Therefore, any point at the most outer surface can be defined as impacted if the accumulated plastic strain overcomes this critical threshold either at the surface or at the critical depth underneath. Using this approach, the development of coverage for a multi shot simulation is obtained as the combination of points at the surface layer and points at the critical depth layer satisfying the defined requirement.

3.2. Advanced implementation (symmetry cell)

Based on the knowledge gained from a single shot model, an advanced multi shot simulation is defined. In accordance with the Avrami equation, the necessary number of shots for 98% coverage depends on the size of the representative target surface. As observable in Fig.2, variation of the target surface size leads to different progressions in the evolution of coverage. It was found that a target surface side length of $8a_p$ is the most appropriate compromise between an accurate depiction of coverage and reasonable simulation effort. The shots are randomly distributed above the target surface and hit the surface one after another. Fig.4.a shows the surface deformation after ten random impingements. The indentation area left behind is traceable for each impingement due to the PEEQ_Crit approach. Fig.4.b shows all 81 shots having interacted with the surface. It can be observed that all near-surface points, i.e. all points above the critical depth, have accumulated plastic equivalent strain identical or greater than PEEQ_Crit, thus full coverage is achieved.

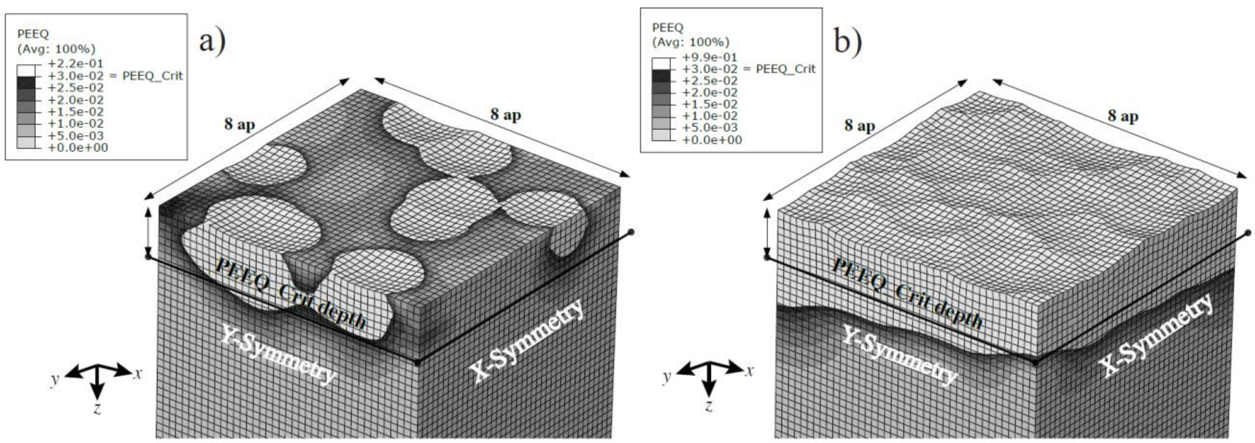

Fig.4. PEEQ evolution for a symmetry cell model.

3.3. Gas turbine applications

When a real shot peening application is sought, for instance to a gas turbine component, it is by far more complicated than looking at investigating flat and symmetric surface bodies. A necessary initial step here is to define what happens if the peening is applied to a real 90° sharp edge component, which can be considered the basis for any complex 3D feature without a radius or chamfer. Many questions are arising, what would be the best sequence of process to be used and which process parameters should be applied, if different from the standard ones. Since no reference could be found in literature, it was decided to create a model which would represent a real edge component and to have a series of impact parameters as already applied for a flat body. The results are shown in Fig.5 where the edge is shown after the application of the peening process. Fig.5.a shows the PEEQ resulting from the full coverage when this is applied to the edge feature, respectively. to the vertical and the horizontal surfaces, both at 98% coverage. In Fig5.b the distribution of the residual stresses at different slices of the same edge, taken at 0.2R, 0.6R and R distance from the initial edge location is displayed. As a qualitative illustrative information, a complementary colour picture of the Von-Mises residual stresses induced from the impact is shown in Fig.5.b. The results of the shot peening on the edge leave a component with a highly damaged corner to a depth (quantified by PEEQ) affected which extends far deeper than what originally would have been expected by an equivalent flat surface treatment or by simply linear assumptions.

4. Conclusions

The approach here taken has been developing a numerical method which can numerically reproduce the process of shot peening with Abaqus/Explicit. Identifying two main shot peening

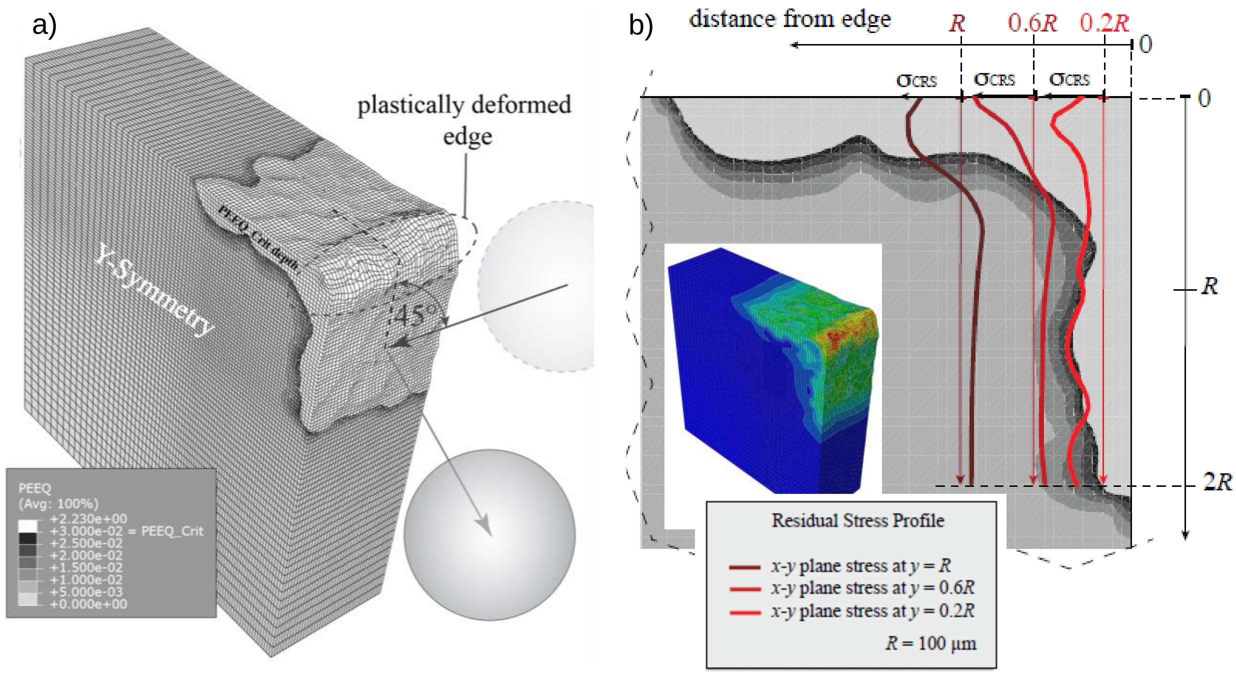

Fig.5. PEEQ, damage induced and residual stresses over a representative 3D edge feature.

parameters such as intensity and coverage, here in combination with steel shot peening and defined nozzle parameters, have been demonstrated to be necessary to carry out realistic simulations. The material model and basic parameter calibration was carried out on a single shot model. A further model was built to enhance the simulation and introduce a correct validated plastic equivalence zone for multiple shots. The application into a component representative 3D model without full symmetry but with a 90° edge was providing fundamental evidence about the quantification of damage and of the amount of plasticity induced, which was demonstrated to have a strong non-linear effect.

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