SHOT PEENING MODELING BY COMBINING DEM AND FEM

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ABSTRACT

Shot-peening process modeling has been a challenging task because of the complexity of the process. It is extremely time consuming to model individual shots in FE model in presence of contact and subsequently keep track of such shots. Discrete element method has evolved over the years and now commercially available software can be used to model individual shots and overall shot-peening process. However, major limitation of the current DEM based approach is that the method considers work piece material to be elastic only and thus is not able to explicitly model plastic deformation and residual stresses induced by shot-peening. A novel approach is proposed where; one can take spatial information of force vs. time from DEM solution and solve a transient problem with traction boundary conditions in either implicit solver like Ansys or explicit solver like Abaqus or LS-Dyna. The paper would present preliminary results and findings of this approach and discuss next limitations and advantages of such an approach.

KEYWORDS: Shot Peening, Finite Element Method, Discrete Element Method

INTRODUCTION

Shot peening is widely used to enhance the fatigue strength of metals and alloys. Peening is also used for other applications such as peen-forming. It is a cold working process and involves a large number of shots projected against the metallic target surface. It is a complex process as it involves many variables such as shot velocity, size, hardness, angle of impact, friction, target material hardness etc. that influence the material response. There have been significant efforts to quantify the effects of shot peening in order to utilize the benefits of fatigue strength improvement during component design.

MECHANICS OF SHOT PEENING

The shots during impacts stretch the surface layer plastically. Once they leave the surface, the adjoining material with elastic stresses tries to bring the expanded surface back to its normal size. However, the permanent deformation does not allow full recovery of the surface layer thus creating the residual compressive stresses. In addition the Hertzian effect due to static compression produces maximum shear stress below the surface. Thus the net effect of shot peening is due to both the impact and Hertzian effects. The residual stresses, surface roughness and the cold work play important roles in improving the fatigue life, these factors depend on the intensity and the coverage of shot peening.

SHOT PEENING SIMULATION: CURRENT STATUS

To understand the mechanics of shot peening, one needs to understand impact dynamics, strain-rate dependent metal plasticity in three-dimensional environment. Though some key researchers for example Al-Obaid(Al-Obaid 1995), Al-Hassani(Al-Hassani 1981) have attempted analytical solutions to the shot peening, they have limited scope in explaining the complex shot peening process.

Finite Element Method

Numerical methods, specially, Finite Element Method (FEM) offer the best promise to simulate the peening process due its versatility. Quasi-static simulations using 2D and then 3D models have been the first efforts to understand the process. Using ADINA, two-dimensional axis-symmetric analysis has been performed with dynamic effects (Schiffner and Droste Gen. Helling 1999). Guagliano et al have combined FEM and a set of non-dimensional parameters to relate the peeing parameters and the stresses(Guagliano et al. 1999). Using LS/DYNA Meguid et al (Meguid, Shagal, and Stranart 2002) have analyzed the effect of peening on AISI 4340 steel and have concluded that strain-rate is a key parameter that affects plastic strain and residual stresses along with shot velocity and hardness. Hassani has used ABAQUS to calculate stresses with strain-rate non-linear work hardening effects to compare with his theoretical results(Al-Hassani, Kormi, and Webb 1999). Multiple shot impacts have been simulated using LS/DYNA for different velocities (Majzoobi, Azizi, and Alavi Nia 2005) to have good correlation with tests conducted by Torres & Voodwald. A 3D analysis is performed for simulating multiple shots using ABAQUS-explicit tool that uses infinite boundaries used to quieten the stress oscillations(Schwarzer, Schulze, and Vöhringer 2002).

These analyses improved the understanding of the physics of shot peening process. But these simulations have used mostly unit-cell or RVE approach, as the real-life parts are quite large for meaningful simulations. In reality, the process involves random variation of several variables while the FEM based simulations restrict the process to certain deterministic combinations. This method suffers from the following limitations:

- The simulation using FEM cannot be extended for simulation of very large number of impacts.
- The current level of FEM technology needs definition of contact surfaces and continuous tracking of the shots.
- The randomness of shot locations along with different orientation of contact vectors in a real-life part is difficult to simulate.

Discrete Element Method

Discrete element method (DEM) is method used in particle simulation and has been developed by Cundall(Cundall, P.A. and Strack, O.D.L. 1979) et al. Over the years, DEM has evolved in the areas such as rock mechanics, pharmaceuticals etc where particle interactions need to be studied. As this method can be used to calculate the contact forces due to particle-structure interaction, it can be applied for shot peening process simulation. The main advantages of DEM are:

- The shots can be generated into the domain and eliminated automatically from the domain
- The contacts between the shots and between shot and structure are detected easily

Han et al (Han et al. 2000) have used Discrete Element Method (DEM) along with FEM for shot peening process simulation with shot being modeled as a 2D disk. They have identified four different contact models such as, Later Han et al.(Han and Peric 2000) have extended the method to simulate shot peening in 3D environment. These two papers use different contact models. Hong et al. (T. Hong et al. 2005)have used EDEM^{TM} (called EDEM), a software developed by DEM solutions, to determine the effect of mass flow rate, shot initial velocity and angle of incidence on the energy loss on the target surface. They have calculated the necessary Coefficient of Restitution (COR) from shot-shot and shot-plate interactions using ABAQUS Explicit software.

SHOT PEENING SIMULATIONS: PROPOSED METHODOLOGY

The current method is an improvement over the work done by Hong et al. In this method, we attempt to transfer the contact forces back to the FE model to calculate the actual stresses and strains than using energy loss as a metric of residual stresses. Thus the first step is to establish a one way coupling between DEM and FEM software. Fig.1 shows the overall process flow of the proposed model. The geometry is created in any CAD model and transferred to EDEM in the form of STL format (Stereo-lithography-a rapid prototype format), The EDEM software is used to simulate the shot peening process. The contact forces and other key information are transferred to ANSYS program. In ANSYS, the FE analysis is performed to calculate residual compressive stresses. Stresses due to service loads are super-imposed on the residual stresses to evaluate the fatigue strength improvement.

First we simulated single-shot peening to establish the process map. The detailed process map is depicted in Fig.2. Then we attempted to simulate the peening of actual parts. Fig.3 shows the schematic peening simulation of a hole using deflector that deflects the shots onto the hole.

Step-1: FEM Analysis
The FE software ABAQUS/Explicit is used to calculate the response of the material due to the impact of a single shot. The shot is assumed to be spherical and rigid. The density of the shot is assumed to be that of steel. The target material is chosen to be nickel-based superalloy, INCO718. As the impact occurs for a very short duration, strain-rate dependent properties are more appropriate to use. The coefficient of Restitution (COR) is calculated from the ABAQUS analysis from the velocities of the shot before and after the impact.

The COR is a function of shot velocity, shot material, angle of impact, target material hardness etc. Fig.4 .shows the variation of COR with respect to shot velocity. For a given set of shot, target material, velocity and nozzle orientation the COR as calculated from FE software is assumed to be a constant. To calculate the COR accurately, single shot impact is used on the target whose material properties are modeled with strain-rate dependency. This enables the COR to be higher due to the higher dynamic yield strength of the target material. After the impact, the indentation dimensions, namely, diameter and depth are also measured.

Step-2 Discrete Element Analysis
As mentioned before, the surface details are captured by tessellation through Stereo lithography (STL) format and can be imported into EDEM. Alternately, a finite element mesh can also be imported into EDEM. The mesh needs to be at optimum size in order to correctly capture the contact forces. The COR is applied from the ABAQUS results. The elastic material properties are input for both shot and the work-piece. Currently EDEM can handle only elastic material models. The COR indirectly simulates the elastic-plastic collision and thus the energy transfer between the shot and the work-piece.

In order to validate the EDEM results with FEM, a single-shot impact is first simulated in EDEM as well. The contact time, the contact force and the energy transfer between shot and the target are compared between FEM and EDEM simulations and found to be in good correlation. The kinetic energy loss of the shot is mainly used to deform the work piece plastically. Thus this energy transferred can be related as a measure of residual stresses. Fig.5 shows the variation of velocity in single shot simulations in ABAQUS-explicit and EDEM.

The next step is to simulate multi-ball simulation in EDEM. The factory that represents the nozzle is designed to generate the shots normal to the target plate with a specified velocity. The mass flow rate and the duration of simulation is adjusted to be in line with the actual process. The gravity effects can be added if required.

The EDEM program calculates the forces due to the shot impacts and the location of such collisions. These forces are transferred in suitable format to ANSYS using suitable translators. The forces can be transformed into pressures and the application areas of these pressures can be captured through simple mathematical calculations.

Step 3- FEM Analysis
The work-piece is modeled in FE software with fine mesh that can capture the pressure variations as the contact occurs. The analysis is done as a transient analysis to predict the stresses accurately. Fig.6 shows a qualitative comparison of in-plane stresses due to single shot impact obtained in ABAQUS as well as in EDEM-ANSYS coupled analyses.

ADVANTAGES

The proposed DEM-FEM method is capable of shot peening simulation. The key advantages are:

- It can include the effects of variation in shot sizes and velocities.
- The motion of both nozzle and the target object can be simulated.

- Multiple nozzles can be used
- Peening the holes using deflectors can be performed

LIMITATIONS

However, we have the following limitations in the proposed methodology:

- In reality, the energy transfer, represented by COR, between the shot and the target material varies depending on the parameters such as strain hardening effect. This needs to be effectively captured.
- The number of elements required to predict the stresses accurately remains very high, as we want to include the Hertzian effects during impact. This necessitates very high computer memory and disk space.
- The duration of realistic peening process makes the EDEM and FEM simulation time significantly long.

Efforts are underway to simplify the process to reduce the CPU time, memory and hard disk requirements by employing different techniques.

CONCLUSIONS

A method of using the contact forces obtained from EDEM on the finite element model has been carried out. This is calibrated with the results from FEM analysis using ABAQUS-explicit and found to be accurate enough to be used in the design of components. The proposed method significantly reduces the computing time as contact detection and elimination of shots outside the domain are automatically and efficiently done. At the same time, the accuracy of results by using appropriate material models in FEM is maintained. As a future extension, the deformed model can be captured through the tessellation mesh and fed back into EDEM to simulate coverage beyond 100% thus providing 2-way DEM-FEM coupling.

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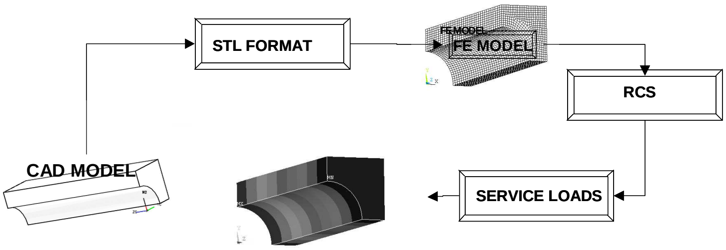


Fig.1 Overall Process Flow in DEM-FEM Simulation

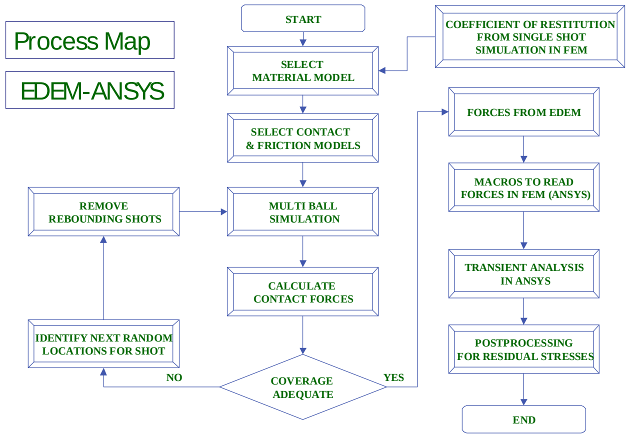


Fig.2 Detailed Process Flow

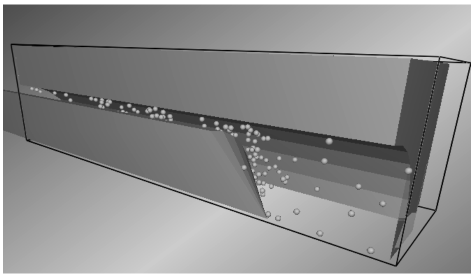


Fig.3 Hole Peening Simulation

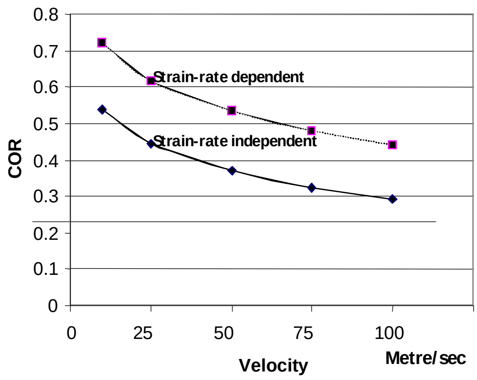
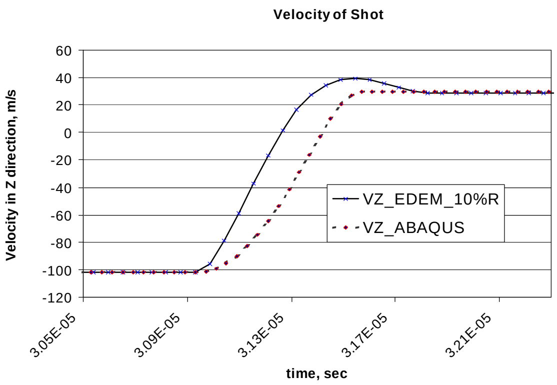


Fig.4 Variation of COR with Shot Velocity



Fig,5 Velocity Comparison in EDEM and ABAQUS

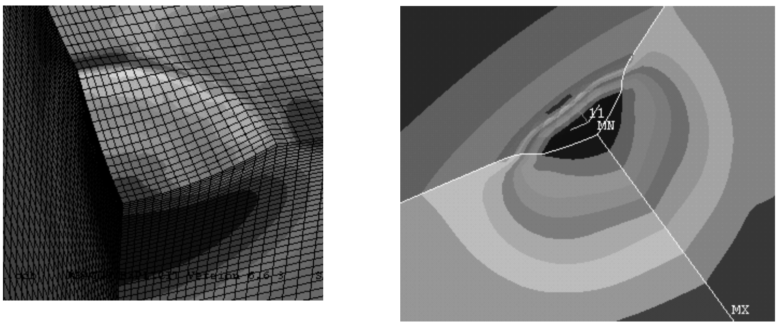


Fig. 6. Comparison in ABAQUS-explicit and ANSYS