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Design and Analysis of a Residual Stresses from Shot Peening and Its Analytical and Fem Method

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***Abstract*: Shot peening is a cold working process in which millions of peening media are shot onto a substrate surface. The impacts of these media produce a layer of compressive stress over the target component. This residual compressive layer has been proven to significantly improve fatigue life by reducing the magnitude of alternating stress applied to the part over a typical life cycle. Several methods have been developed to predict shot peened residual stresses. They have been shown to accurately represent measured residual data using x-ray diffraction. Numerical methods which utilize finite element solvers simulate shot peening media impacting a substrate surface and the resulting plastic deformation. Analytical methods utilize Hertzian theory to calculate the deformation of the substrate surface after a single shot impact, which is then expanded to predict a fully developed residual profile. However, the integration of these methods into analytical systems predicting the actual benefit of shot peening is limited. The new analytical methods, techniques and algorithms developed in this study aim to address the issue of limited integration of shot peening residual stress into structural applications. In this assessment, an APDL algorithm compatible with the ANSYS finite element solver is developed that enables a user to apply these analytical methods and subsequently predict the benefit of shot peening to static structures under varying load conditions. The methodologies and algorithms developed in this assessment successfully predict shot peening profiles and integrate them with finite element static structural solvers. They can be utilized for real industrial applications and solutions can be quickly computed with reasonably sized models.**

***Keywords:* Design and analysis of residual stresses.**

1. INTRODUCTION

The objective of this study is to implement shot peened surface theory and analytical methods to a finite element surface in the ANSYS advanced analytical interface. This method will involve a user interface through which he or she can select surfaces upon which he or she wishes to apply shot peened boundary conditions.

The ANSYS graphical user interface (GUI) will be utilized to select shot types, coverage areas and prediction methods. This method will employ boundary conditions from theoretical models developed from prior investigations based on Hertzian contact theory. These boundary conditions will also be applied to shot peened surfaces if prior finite element assessments predicting these conditions do not exist. The primary deliverable of this thesis is a working method and system with which an analyst can estimate the preliminary stress state exhibited in shot peened structures. This is an advantage to those materials for which fatigue and other data have not been gathered with respect to shot peened and pre-stressed structures.

The rapid prediction of initial stress states due to shot peening is highly advantageous over other detailed dynamic assessments made in the past using codes such as LS-DYNA. The method described in this thesis has the potential to make quick and accurate predictions giving designers a powerful tool with which his or her designs can be optimized and further improved.

The results obtained from this proposed method will be ultimately calibrated with an Almen strip specimen to ensure these methods accurately predict shot peened residual stresses. Furthermore, the predicted increase in material capability can be compared to actual measured data.

2. LITERATURE

Many studies of shot peening have been conducted over the years. (Meguid S. S., 1999) modeled co-indenting using rigid shot impacting a substrate with two symmetry boundary conditions. This study showed that the proximity of simultaneous impacts had a significant influence on the stresses induced. (Klemenz, 2009) simulated multiple ordered impacts using an isotropic-kinematic hardening law to model the behavior of AISI 4140 steel. Their constitutive law took into account both strain history and strain rate. Good correlation was observed between experimental data and simulation results for surface deformation and residual stresses. (Guagliano, 2001) used fatigue properties and work hardening to model multiple load cycles during multiple impacts on a SAE 1070 steel target. Schwarzer et al. (2002) suggested a 3D geometry to study the effect of multiple steel shots impacting an AISI 4140 steel target. This study modeled the shot with rigid surfaces and mass and rotary inertia elements. They also used infinite element models to reduce stress wave energy reflection into the mesh and residual stress profiles were averaged over an area covering multiple impacts. They also evaluated differences between successive and simultaneous adjacent impacts. Meguid et al. (2002) introduced a symmetry cell representing successive rows of steel shot impacting a large AISI 4340 surface. Mass and stiffness damping were used. Shot deformation was studied and rigid elements were chosen to represent the shot. The effect of friction on the plastic strain induced was determined negligible for coefficients of friction between 0.25 and 0.5. Wang et al. (2002) proposed using random impacts to simulate the shot peening process. Miao et al. (2009) suggested a random finite element model and showed that this type of model could be used to study the influence of peening parameters on residual stresses, saturation, coverage, and surface roughness. Zimmermann et al. (2010) compared deterministic and random finite element simulations regarding the development of coverage, residual stresses and surface topography. Using a strain rate sensitive isotropic-kinematic hardening law for Inconel 718, decent predictions of residual stress profiles were developed. Using a symmetry cell, Kim et al. (2010) showed that averaging calculated stresses over an impacted area provides results closer to experimental x-ray diffraction measurements of residual stresses than a 4-node average. Kang et al. (2010) modeled single and multiple predefined impacts of steel shots on a square 2024-T351 target. A spring back static analysis was used to stabilize the model. The authors showed that multiple impacts tend to create a uniform state in the peened material and that multiple impact modeling is more appropriate than single-impact models to represent shot peening and peen forming. Numerical tools have also been developed for forming simulation. These tools use equivalent loading methods to determine deformed shapes of large parts without simulating millions of impacts. Grasty and Andrew (1996) introduced a ‘‘squeezed-layer’’ model: by applying a squeezing pressure causing yielding of surface elements, permanent deformations and a stress distribution were obtained. Successive loading cycles were applied to determine a stabilized deflection. Calibration was however required to find the appropriate squeezing pressure. Levers and Prior (1998) suggested a thermal loading method to simulate peen forming processes. Their method consisted of introducing stress distributions in shell elements by creating thermal strains. Wang et al. (2006) suggested a thermally-applied loading unit to create a plastic layer in shell elements. The case of unconstrained peening, in which the sample is free to bend and elongate, was studied. A numerical arc height vs. peening time curve was obtained by applying multiple loading cycles and, with proper calibration, accurate predictions were obtained. It should be noted that in the models of Levers and Prior (1998) and Wang et al. (2006), temperature was used as a numerical tool and was not related to the actual process. Han et al. (2002) proposed an equivalent loading scheme that used induced stresses in a solid model to simulate peen forming. Experimental research on shot peening and peen forming has also been performed. Cao et al. (1995) studied the progressive deformation of an Almen strip in an Almen holder during peening in multiple passes. They observed non-uniform curvatures in the constrained and free Almen strip. The authors proposed an analytical model to explain this behavior. X-ray diffraction was used to profile residual stresses after various numbers of passes. Miao et al. (2010) performed a detailed study on the peening of aluminum strips and plates. They studied the effects of shot velocity on saturation, roughness, and coverage and obtained residual stress profiles in thin and thick peened samples. The authors also measured monotonic mechanical properties of 2024 and studied the effect of material anisotropy on the development of arc heights. (Gariepy, Larose, Perron, & Levesque, 2011) proposed the use of a shell element model using stresses determined using dynamic FEA models. As a result of this literary review, it seems there has not been a study that uses the most reliable method of measuring residual stresses beyond the surface of a substrate (Vishay, 2010), the hole drill method. It also seems the use of shell elements to represent different layers of stresses throughout a shot peened sheet has yet to be implemented as a practical and easy way to correlate shot peen intensity to arc height/distortion.

3. MATERIALS

Introduction:

Several common shot peened substrates exist. In aerospace applications these include Titanium alloys and Steel which are examined in this investigation. Some aerospace materials not considered in this study include Aluminum alloys. It is assumed that if data correlate well with the two substrate materials aforementioned, then extrapolation of this method to other materials is warranted, provided that the appropriate material properties are assumed for that material.

Titanium:

Multiple substrate materials are examined within the scope of this thesis. Several industries value titanium above all other available materials used today. It is a light weight, high strength, and retains these properties at relatively high temperatures. It is a naturally occurring element within mineral deposits found throughout the earth. It has been alloyed with multiple different elements such as molybdenum, iron, aluminum and vanadium to enhance and desirable properties of a specific alloy. It is considered to have the strength of steel but at about half the density. It is, however, more dense than aluminum but about twice as strong.

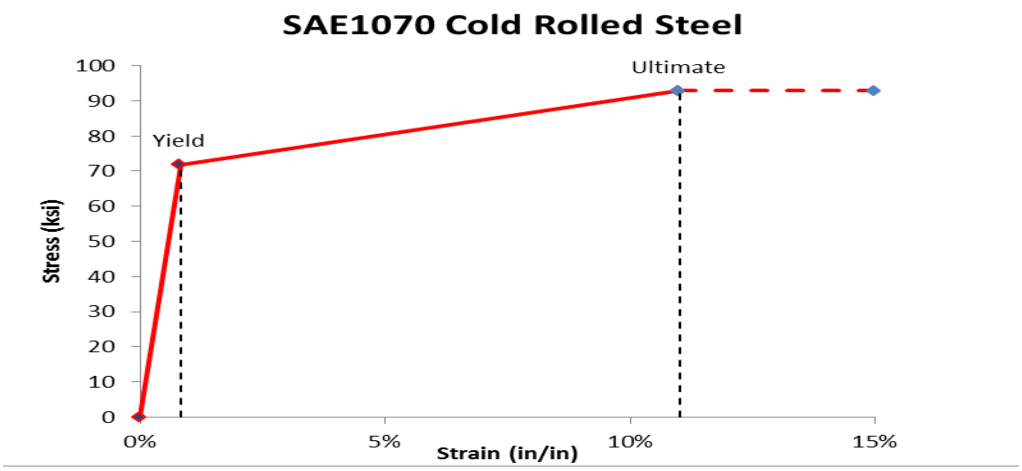

Figure: An example of a Bilinear Material Model of Cold Rolled Steel. This Simple Model can be Easily Used in a Variety of Engineering Application and Still Yield Reasonable Results.

Table The Shot Peening Parameters Used in the 2D Almen Strip FEA [10]

Parameter	**Description**	**Value**
	Shot Material	Steel
R	Shot Radius	0.01378in (0.7mm)
V	Shot Velocity	1575in/s (40m/s)
Coverage	Percent Shot Peening Coverage	20% - 100%

4. INCORPORATION OF ANALYTICAL METHODS INTO FINITE ELEMENT MODELS

Introduction:

A complete analytical model has been developed that predicts both compressive and tensile residual stresses as a result of a fully or partially completed shot peening operation. This analytical model is based on the approximations discussed. Which state that a 2D model sufficiently predicts 3D residual strains and that a residuals stresses developed under a single impact point can be extrapolated to all impact points on a substrate surface.

Two Dimensional Almen Strip:

The two dimensional model of an Almen strip is configured to accomplish two different tasks: the verification of the APDL code and the verification of the analytical methods by comparing finite element deflections to measured Almen strip data. Brigg‟s et al. developed a saturation curve of Almen intensity by testing seven typical Almen strips [10]. The Almen strip and FEM parameters are modeled in accordance with the reference from which the FEM results are compared. The dimensions of the strip are 3in x 0.0512in (1.3mm) and the geometry is modeled as a simple 2D area as shown in Figure 5.5.

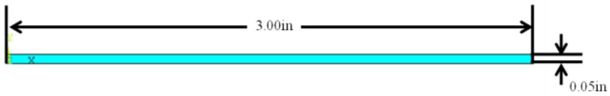

Figure: Almen Strip Finite Element Geometry Used to Calibrate Analytical Methods and APDL Code.

The model utilizes the plane 183 element type. The Plane 183 ANSYS FEA element is a second order 2-D next generation modeling element utilized for solid structures and defined by 8 nodes. Since this is a next generation element, the „inistate‟ command can be used by specifying nodal initial states. The element can support thickness for plane stress options; however, this is not utilized for this specific assessment. Surface loads can be input on these elements using surface effect (surf154) elements or by applying them directly to a line. Key options control element behavior (plane stress, plane strain, etc.) and element formulation (pure displacement or mixed u-P). Average and un-average stresses and displacements are stored as plate 183 results data [21].

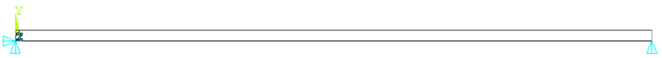

Figure: The Boundary Conditions Applied to the Almen Strip FEM

Three Dimensional Finite Element Plate:

The two dimensional Almen strip is used to verify the APDL code and test its accuracy against measured Almen strip data within a saturation curve. One can envision expanding the capability of these methodologies to a 3D model. To sufficiently examine these capabilities; a 3D flat plate with a central through hole is modeled. This deviates from the typical flat plate used in a number of other studies. This analysis will explore the capability of the APDL code to induce calculated shot peening stresses onto a 3D finite element model and the capability to predict benefits to part durability under subsequent loading.

The induced compressive stress from shot peening should mitigate or reduce any tensile stress put into the component during subsequent load cases. To explore this theory, the flat plate is subjected to a previously calculated residual stress profile developed using some of the peening parameters extrapolated from the data cited in a paper written by Namjoshi, Jain and Mall [22].

The plate is subjected to a fully developed shot peen cycle and then a constant surface pressure will be applied to the part putting the surface layer in tension. The reduction in tensile stress will be calculated and compared to the improvement seen in [22]. In this manner, a comparison of calculated and measured improvement to durability can be made.

The three dimensional plate is modeled to represent real geometry which may be used in industry. The dimensions of the plate are 1in x 1in x 0.1in thick as shown in Figure 6.8. The diameter of the central hole is 0.4in. The model utilizes Solid 186 elements which are higher order brick elements defined by 20 nodes and are compatible with the „inistate‟ command.

5. RESULTS AND DISCUSSIONS

Two Dimensional Almen Strip FEM:

Two models now exist which explore the feasibility of integrating the pre-developed analytical methods and APDL algorithms into ANSYS to predict reactions to residual preloads developed during the shot peening process. The 2D Almen strip model is used to determine the correlation between predicted and measured Almen strip deflection after shot peening. The boundary conditions used for this assessment are derived from both the study conducted by Guagliano [11], to determine Almen intensity based on shot velocity and size, and a paper written by Briggs et al. [10] which depicts a saturation curve of SAE1070 cold rolled steel subject to shot peening conditions at gradually increasing converted feed rates.

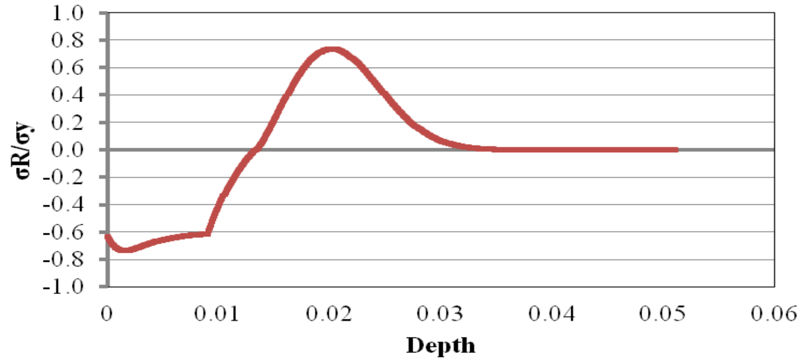

Figure 1: Fully Developed Residual Stress Profile Applied to the Almen Strip FEA as an Initial State of Stress. The Depicted Profile is a Result of 0.01378in Radius Steel Media Impacting a SAE1070 Steel Substrate Surface at 1575in/s

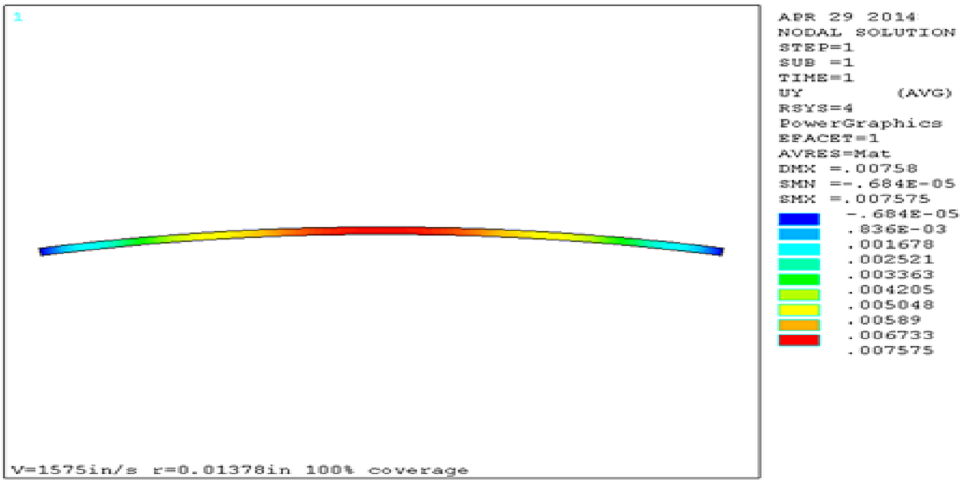

Figure2: Deflected Shape Plot of the Almen Strip FEA in Inches. The Strip is Subject to Shot Peening Media at 0.01378in Radius and 1575in/s Velocity at 100% Peening Coverage

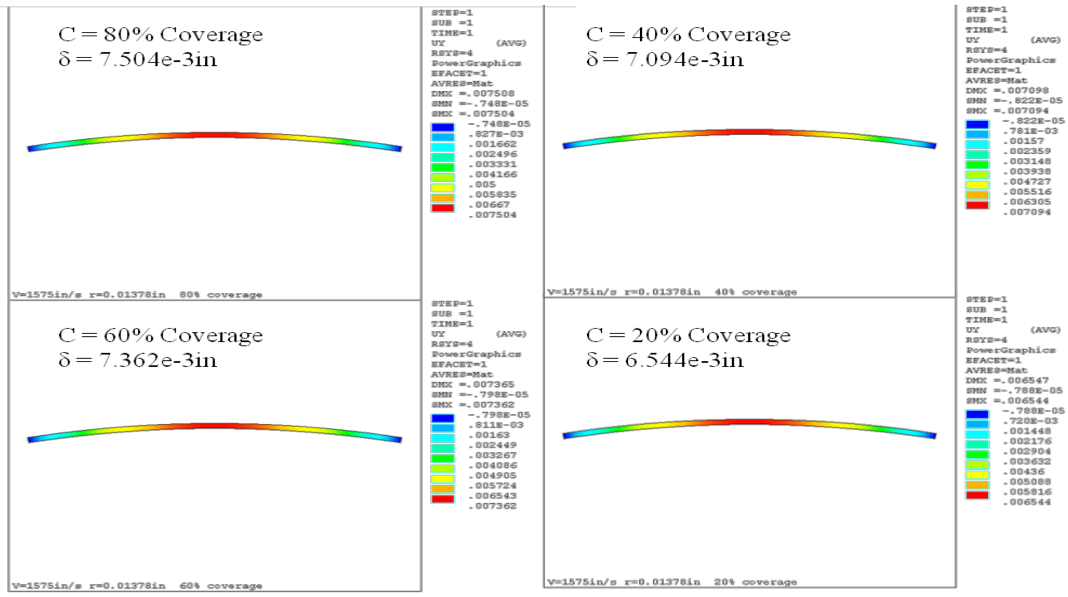

Figure 3: Varying Almen Strip FEA Stress Profiles Resulting from Decreasing Shot Peening Coverage Percentages

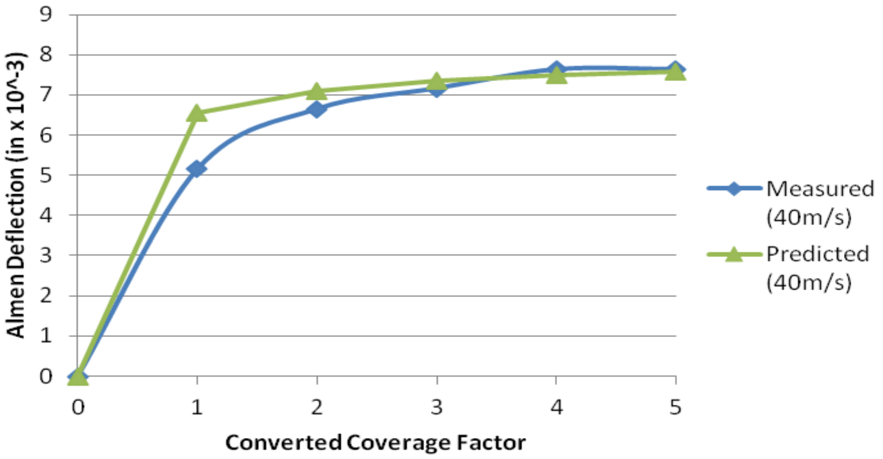

Figure 4: Measured And Predicted Almen Strip Deflection for Varying Converted Coverage Factors or Varying Coverage Percentages. The Curves Indicate that Predicted Deflections Show Good Correlation With Referenced Measured Data

Three Dimensional Plate FEM:

The 3D plate model is developed in order to validate that the APDL algorithm is compatible with general three dimensional finite element models of arbitrary shapes. In addition, multiple load steps are applied to the FEM in order to simulate subsequent loading of a shot peened component. The comparison of a shot peened component under a specific load conditions to an un-peened component under the same load conditions should yield a reduction in surface stresses.This reduction in surface stress can be compared to the benefits of shot peening measured [22].

Shot peening initial conditions are applied to the finite element model. The computed shot peened profile applied to the FEM can be seen by the curve shown in Figure 6.5. The displacement and surface stress profiles developed due to these initial conditions are shown in Figure 6.6 and Figure 6.7 respectively.

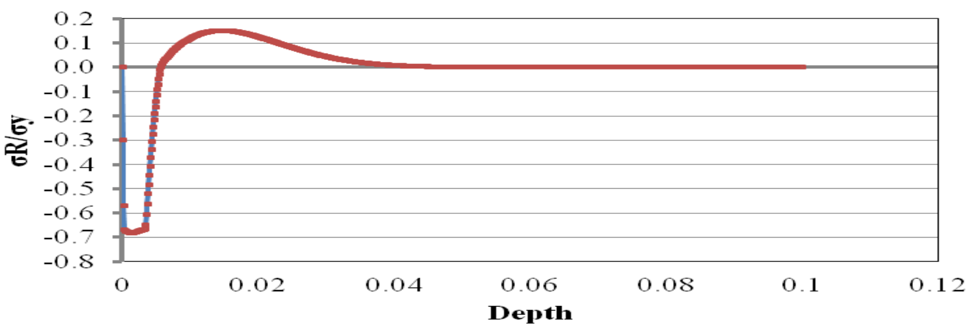

Figure 5: The Fully Developed Residual Stress Profile Applied to the 3D Plate FEA as an Initial State of Stress.

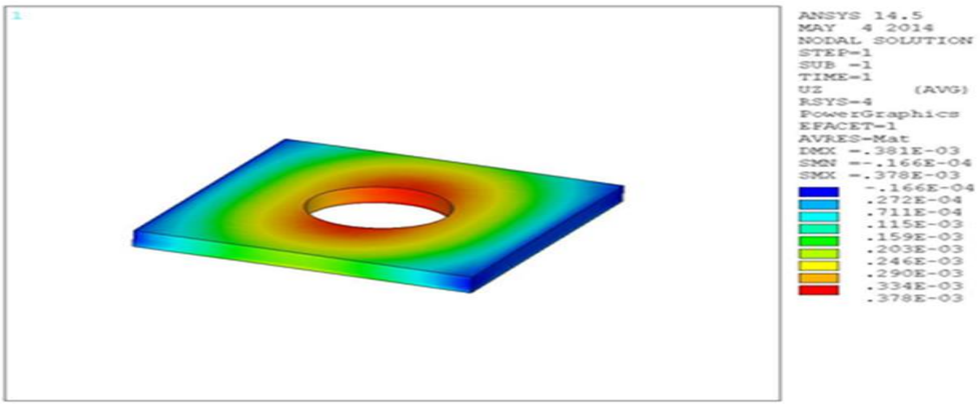

Figure 6: Displacements Developed in the 3D Plate Model After Shot Peening. Inputs for Shot Peening Calculations are those used in [22].

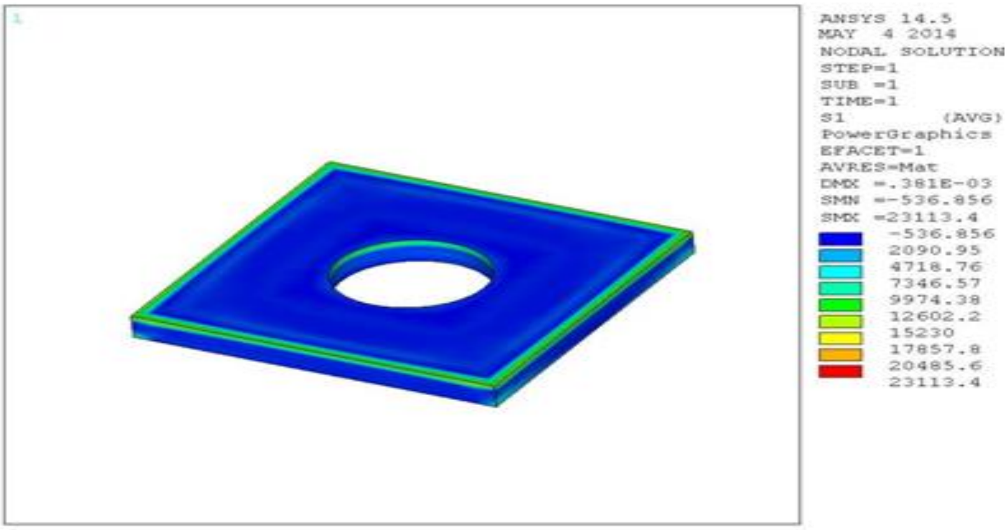

Figure 7: The Max Principal Stress Developed in The 3D Plate FEM after Shot Peening Initial Conditions are Applied. The Max Principal Stress in These Examples is Equal to the Surface Stress in all Planar Directions. Principal Stress Is Shown as a Generalization

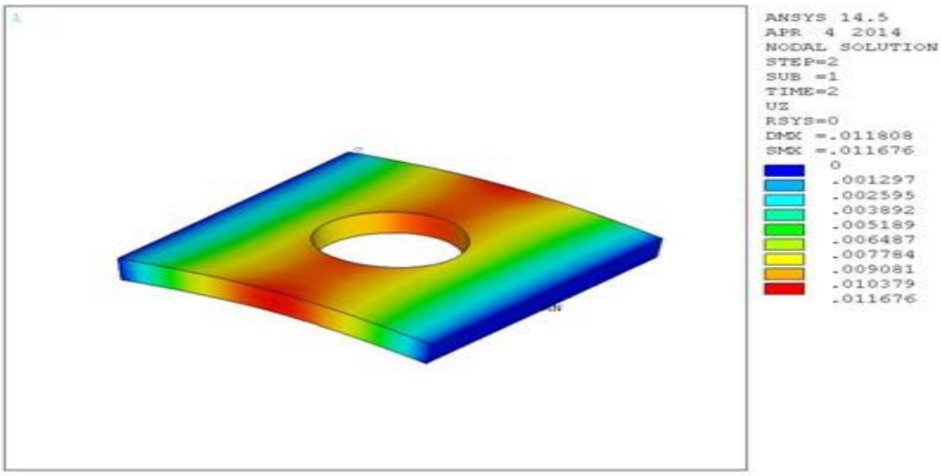

Figure 8: The Displacements Developed in the Shot Peened 3D Plate Model after the Subsequent Application of 1000lbf/in2 away from the shot peened surface.

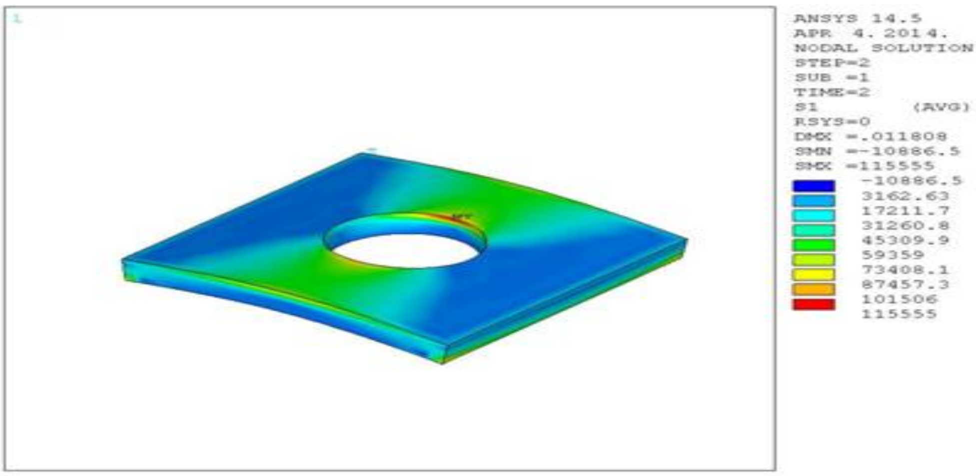

Figure 9: The Max Principal Stress Developed in The Shot Peened 3D Plate FEM after the Subsequent Application of 1000lbf/in2 away from the shot peened surface.

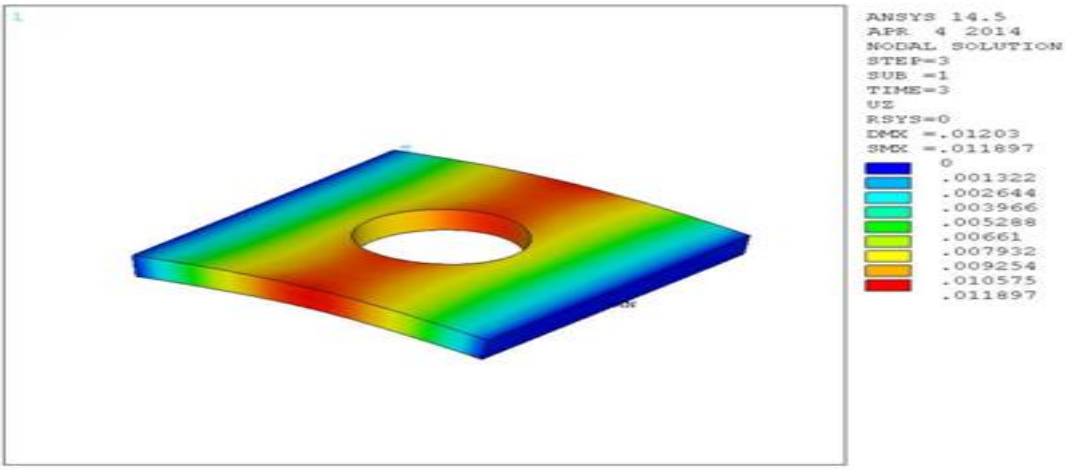

Figure 10: The Displacements Developed Application of 1000lbf/in2 normal to the Conditions Are Applied to the Model.in the 3D Plate Model after the surface. No Shot Peening Initial

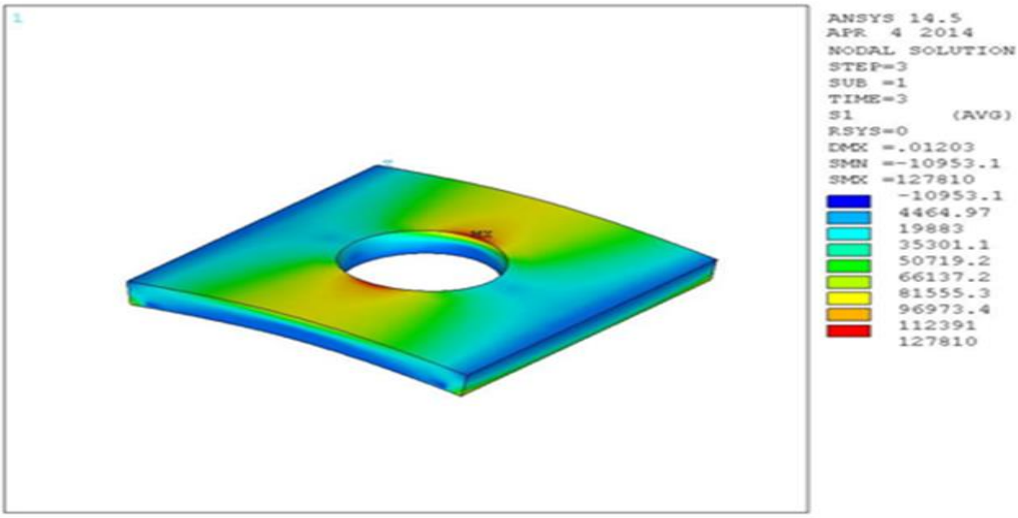

Figure 11: The Max Principal Developed in the 3D Plate Model after the Application of 1000lbf/in2 normal to the surface. No Shot Peening Initial Conditions Are Applied to the Model.

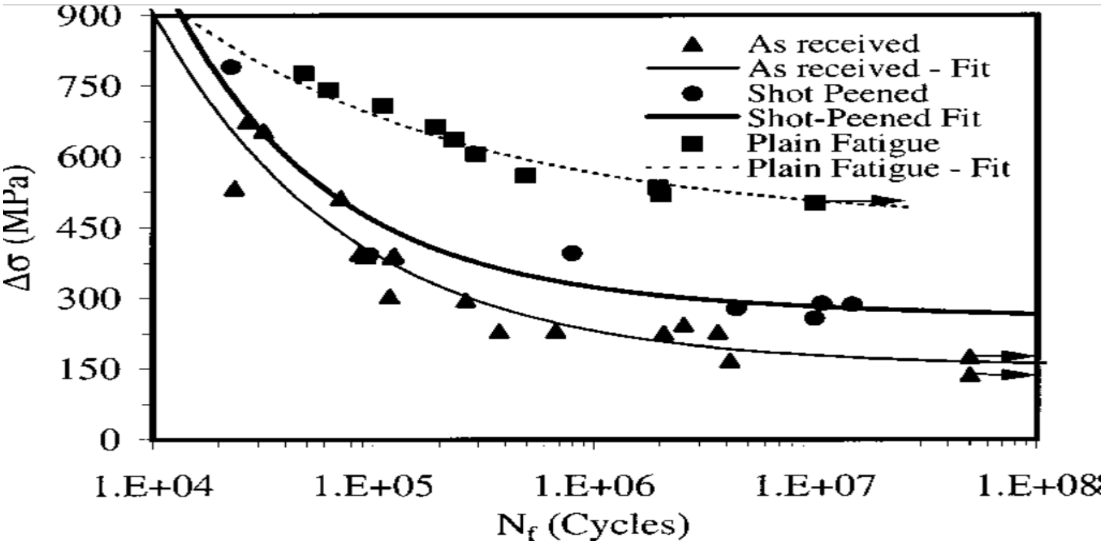

Figure 12: The Data Measured by Namjoshi et al. which Indicate an Improvement in Fatigue Life of a Shot Peened Component Subject to the Same Boundary Conditions Used for the 3D Plate FEA [22].

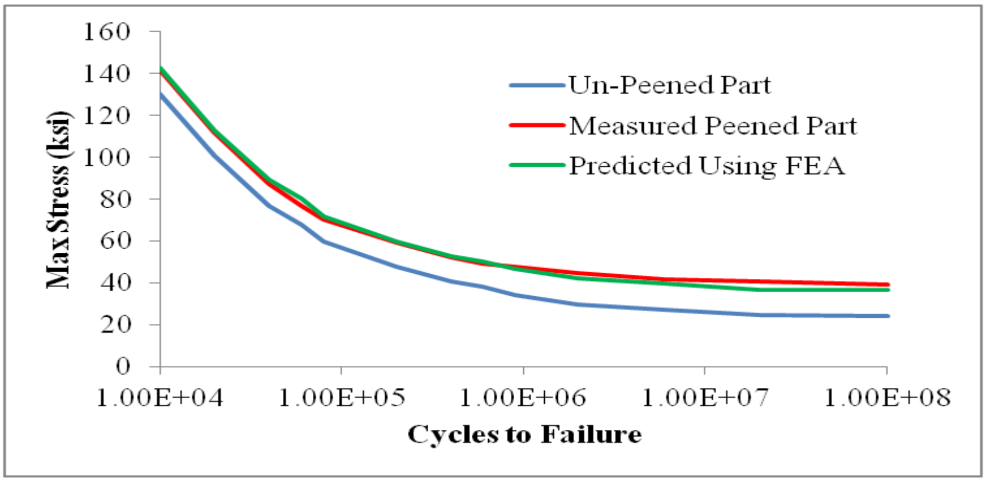

Figure 13: A Plot Depicting Measured Improvement to Fatigue Capability versus Predicted Improvement to Fatigue Capability of a Shot Peened Part Under the Same Peening Conditions. Note that the SI Units Shown in Figure 12 are Converted into English Units

Several conclusions are developed in this paper that proved the subsequent concepts and assumptions are valid. It is shown that a 3D shot peening profile can be accurately predicted with a 2D analysis. In addition, it is considered reasonable to extrapolate the stress developed from a single impact point during a peening operation to the entire peened surface. These two points show that an analytical prediction of the residual stresses formed during shot peening is considered reasonable.

The close agreement between measured and predicted data demonstrated in this thesis indicates that the application of shot peening analytical prediction methods to finite element analysis is successful. However, only two examples are explored in the development of these methods. A limitless number of important exampled could be explored using the APDL algorithms developed in this paper.

This investigation of the implementation of shot peening residual conditions into finite element analysis yield a relatively user friendly graphical user interface that allows an analyst or engineer to interactively define shot peening parameters and run subsequent analyses of the shot peened component. The predictions made by the finite element analysis are considered reliable based on the comparisons made in this paper.

This now opens the realm of implementing commercial codes that give engineers the ability to demonstrate how shot peening will or will not aid in the fatigue capability of a specific component. Potential for further studies include:

1. Physics based prediction of tensile residual stresses developed during the shot peening operation.

2. Physics based prediction of partially covered peened surfaces and the resulting residual stress profile

3. Incorporation of the APDL algorithm into graphical user interface menus. 4. Cleaning up of the APDL code and optimization for speed and performance

5. Application of shot peening residual APDL algorithms to a wider variety of geometries.

6. Incorporation of the APDL algorithm in new finite element interfaces such as ANSYS Workbench, ABAQUS or NX Advanced Simulation.

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