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It is entitled:
Experimental Characterization and Finite Element Simulation of Laser Shock Peening Induced Surface Residual Stresses using Nanoindentation

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Experimental Characterization and Finite Element Simulation of Laser Shock Peening Induced Surface Residual Stresses using Nanoindentation

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ABSTRACT

As a non-destructive technique, nanoindentation has been extensively used in the determination of material properties such as hardness and Young’s modulus at both the macro and micro scale. This thesis explores the use of nanoindentation for measuring the surface residual stress induced by laser shock peening. While the technique has been studied by a number of groups, accurate measurement using nanoindentation is hindered by a good method of estimating the contact area, which is the basis of all the calculations in the literature. Due to the sink-in and pile-up effects, the contact area can be underestimated leading to erroneous values of the residual stresses. The overall objective of the thesis is to improve the existing methodology by incorporating the pile-up effects for the contact area calculation. The accuracy of the residual stresses is further validated with the experimental measurements conducted using X-ray diffraction technique. Along with this experimental development, the thesis also aims at developing a finite element model for simulating the nanoindentation process. A simulation model for nanoindentation in region with and without residual stresses is developed and the results reported are in agreement with the experimental results. A parametric study is performed to understand the effect of stress and strain hardening on the indentation curves for the Nickel based alloy IN718.
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CHAPTER 1
INTRODUCTION

1.1 Background

Measurement of residual stresses in engineering material has been a topic of constant interest. Several methods, such as X-ray diffraction, neutron diffraction, hole drilling, chemical etching have been proposed. Each one has its own strengths and limitations in terms of accuracy, applicability to broad range of geometry and impact of the process to the structural integrity. The method of determining residual stresses using instrumented sharp indentation was developed by a number of groups [1], [2], [3]. Comparing with some of the methods mentioned earlier, the advantages of this method can be summarized as follows:

1) This method can determine the material properties of extremely thin materials which are very difficult to be achieved by other methods like XRD and hole drilling.

2) Nanoindentation method is quick, accurate and can be used for both nanoscale and bulk scale materials.

3) Residual stresses in the material can be measured without prior knowledge of the mechanical properties of the material.

4) X-ray diffraction method depends on the grain-size of the material and fails to give accurate results in case of large grain-size or uneven grain distribution. Nanoindentation, however, does not have such limitations and can be effectively used for any type of grain-size and orientation.
1.2) Objective and Motivation of the Thesis

The main objective of this thesis is to study the application of indentation for residual stress measurement. This study will be performed in the context of surface treatment such as Laser Shock Peening (LSP). LSP process is a relatively new surface peening technique that has been used to induce compressive residual stresses in the materials like nickel alloy (IN718) and titanium alloy (Ti 64). By imparting highly compressive residual stress in the near surface region, higher fatigue strength can be achieved. Estimation of LSP induced residual stresses can be performed using X-ray diffraction. However, this method is time consuming and cannot be used for extremely thin films and thin coats. As an alternative, the instrumented sharp indentation method is used to determine compressive residual stresses and strain fields induced due to LSP. Instrumented sharp indentation can be used as a parallel method along with X-Ray diffraction method to estimate residual stresses in the sample. This method is best suited for surface residual stress estimation.

More specifically, residual stresses in LSP treated IN718 alloy will be calculated by method of nanoindentation using Berkovich indenter. The results will be correlated to the values obtained from the X-ray diffraction. With the use of finite element method, the thesis also aims at analyzing various stress and hardness effect on the IN718 substrate. For the calculation of residual stresses, it has been suggested that the contact area of the indentation should be calculated after the load is removed. Based on this, the average pressure (hardness equivalent) is calculated. Extraction of the residual stress is further based upon the contact area, the hardness and the depth of indentation.

For the calculation of surface residual stresses using the technique of nanoindentation, the method suggested by Suresh et al. [1] is followed as the base method in this thesis. However, in
the method suggested by Suresh [1], the pile-up and sink-in effects exhibited by material are not taken into consideration. As a result, this method does not accurately calculate the contact area which is the basis of all the calculations. Hence different approaches have been developed to calculate the actual contact area of the indenter and to estimate the residual stresses induced. A detailed comparison between various methods is shown in following chapters. Along with different possible methods that can be used to estimate the contact area; the thesis also aims at correlating the load vs. displacement curve obtained experimentally to the one using finite element method. This correlation can be used as the verification tool for estimating the residual stresses obtained by FEM.

Based on the discussions above, there are two specific aims to be achieved in this thesis:

a) Experimentally the thesis aims at solving the issues concerning the evaluation of the contact area, which is the key to the estimation of the residual stresses. Other methods, such as the work of indentation method[2] and the hardness as function of total work and plastic work[3] done during the indentation, explained in later chapter are used to calculate the material properties but have never been extended to estimate the residual stresses to the best of our knowledge. This thesis utilizes the combination of various methods to estimate the correct surface residual stresses.

b) From the modeling point of view, this thesis aims at correlating the load vs. displacement curve obtained experimentally to that obtained by FEM analysis for indentation in virgin area with no residual stresses. Further extension is made to the case in which residual stress is introduced by a process called laser shock peening.
As a brief summary, the overall procedure to be followed to achieve the above aims are as follows:

1) Conducting the experiments on both virgin and laser peened material and extract the load vs. displacement curve using the nanoindentation.

2) Calculating the contact area and hardness using various different approaches and then following the method proposed by Suresh et al. to estimate the residual stresses.

3) Simulating the above experimental setup using FEM for both the virgin and laser shock peening process.

4) Validating the results by co-relating the analytical results obtained by experimentations with the results obtained using the finite element method.

The basic components of the implementation and their relation are shown in figure 1.2.
Extracting the load vs. displacement curves for both virgin and compressive residual stress induced region using sharp indentation instrument.

Calculating the contact area of the indenter using different methods such as image processing, work of indentation method as proposed by Oliver and Pharr [2] and method proposed by Khan [3].

Estimating the mechanical properties such as yield stress, residual stress using the load vs. displacement curve and contact area with help of method proposed by Suresh et al.

Simulating the above procedure in ABAQUS Explicit using axisymmetric model to obtain the load vs. displacement curves for both virgin region and laser shock peened region.

Correlating the experimental and FEM results

Figure 1.2: Flowchart of the process
CHAPTER 2

METHODOLOGY AND LITERATURE REVIEW

2.1 Literature Review

Boussinesq [13] first defined the indentation problem as an elastic problem for the point force acting on the surface of half-space as shown in figure (2.1).

\[ \sigma_{\rho z}(\rho,0) = 0, \quad u_z(\rho,0) = h - f\left(\frac{\rho}{a}\right) \quad 0 \leq \rho \leq a \quad (2.1) \]

And

\[ \sigma_z(\rho,0) = 0, \quad \rho > a \quad (2.2) \]

here, the punch defined in \( z \) and \( \rho \) are co-ordinates, has the equation \( z = f\left(\frac{\rho}{a}\right) \) such that \( f(0) = 0 \), \( a \) is the radius of the contact circle and \( h \) is the depth of penetration.

Based on Boussinesq problem defined in form of boundary conditions and using the Hankel transformation, Sneddon [13] mathematically derived the solution for penetration of
punch in the form of a paraboloid of revolution (Berkovich indenter in this case). The solution is given as follows

\[ P = \frac{4\mu ah}{(1-v)} \]  

(2.3)

where \( P \) is the load of the indenter, \( h \) is the total penetration, \( \mu \) is the rigidity modulus (represented by Lame’s constant), \( v \) is the Poisson’s ratio as shown in the figure (2.1).

Based on Sneddon’s analysis, Suresh et al. [1] proposed a method to estimate residual stresses along with the mechanical properties such as elastic modulus, yield stress and hardness of the material using the method of instrumented sharp indentation. The method is based on determination of material properties using the load vs. displacement curves obtained by nanoindentation of IN718 specimen at fixed load of 500mN in region with and without residual stress using Berkovich indenter of CSM indentation instrument as shown in figure (2.2).

![Force vs Displacement graph](image)

Figure 2.2: Load vs. displacement curve obtained after nanoindentation
The basis of any calculation for residual stress is the contact area of indentation. From the equation (2.3), the Sneddon analysis relation between the load and indentation depth for a punch is given by

\[ P = \frac{4\mu ah}{(1-\nu)} \]  

(2.4)

where \( P \) is the load of the indenter, \( h \) is the total penetration, \( \mu \) is the rigidity modulus (represented by Lame’s constant), \( \nu \) is the Poisson’s ratio. The contact area \( A \) is given in terms of the radius of the cylinder \( a \) as

\[ A = \pi a^2 \]  

(2.5)

Also the shear modulus \( \mu \) can be expressed in terms of elastic modulus \( E \) as follows,

\[ E = 2\mu(1+\nu) \]  

(2.6)

where \( E \) is the elastic modulus of substrate, \( \mu \) is the rigidity modulus and \( \nu \) is the Poisson’s ratio.

Differentiating equation (2.4) with respect to \( h \), leads to

\[ \frac{dP}{dh} = \frac{4\mu a}{(1-\nu)} \]  

(2.7)

Combining equation (2.5) and (2.6) with equation (2.7) leads to

\[ \frac{dP}{dh} = \frac{2}{\sqrt{\pi}} \sqrt{A} \frac{E}{(1-\nu^2)} \]  

(2.8)

Suresh et al. derived and patented [25] the contact area formula based on number of experiments using the indentation curves similar to shown in figure (2.2)
\[ A = \left( \frac{dP}{dh} \cdot \frac{1}{C_u E^*} \right)^2 \]  

(2.9)

with \( A \) being the contact area measured after removal of load, \( \frac{dP}{dh} \) represents the stiffness of the unloading slope, \( C_u \) is the constant for the Berkovich indenter and \( E^* \) is indentation modulus.

The relation between the elastic modulus of the substrate \( E \) and the indentation modulus \( E^* \) is given by equation

\[ \frac{1}{E^*} = \frac{(1-v^2)}{E} + \frac{(1-v_i^2)}{E_i} \]  

(2.10)

here \( v \) and \( v_i \) are the Poisson’s ratio of the substrate and the indenter respectively whereas \( E \) and \( E_i \) are the elastic modulus of the substrate and the indenter respectively.

Further, the method of estimating mechanical properties using instrumented sharp indentation was introduced in 1992 by Oliver and Pharr [2], [4]. The main purpose was to measure the hardness and elastic modulus in materials by instrumented indentation. A schematic representation of the section of through nanoindentation is shown in figure (2.3).
The method suggested by Oliver and Pharr [2] was developed to determine the hardness and the material properties using the load vs. displacement curves generated using Berkovich indenter. Based on the information obtained from the indentation instrument, stiffness of the material can be determined.

Oliver and Pharr [2] empirically derived the contact depth after removal of load ($h_c$). In this case an assumption [26] is made that the pile-up due to indentation was negligible as compared to the sink-in effect. The amount of sink-in is then empirically given by

$$h_s = \varepsilon \frac{P_{\text{max}}}{S}$$  \hspace{1cm} (2.11)

here $h_s$ is the sink-in depth as shown in the figure (2.1), $P_{\text{max}}$ is the maximum load of indentation, $S$ is the stiffness of unloading curve and $\varepsilon$ is the indenter constant. The actual depth along which contact is made between the specimen and the indenter is given by

$$h_c = h_{\text{max}} - h_s$$  \hspace{1cm} (2.12)
where \( h_c \) is the indentation depth after removal of load, \( h_{\text{max}} \) is the maximum depth of indentation and \( h_s \) is the sink-in depth.

Hence from equations (2.1) and (2.2), the indentation depth \( (h_c) \) can be computed by:

\[
h_c = h_{\text{max}} - \varepsilon \frac{P_{\text{max}}}{S}
\]  

(2.13)

where \( h_c \) is the actual indentation depth after removal of the indenter in unloading step and \( h_{\text{max}} \) is the maximum depth that the indenter travels during loading step. \( P_{\text{max}} \) is the maximum load the indenter is subjected to, \( S \) is the contact stiffness calculated by upper portion of the unloading slope [8] and \( \varepsilon \) is a Berkovich constant with value of 0.75.

The contact area of the indentation can be further computed by the empirical equation given by Oliver and Pharr [27]:

\[
A = F(h_c)^2
\]

(2.14)

where \( F \) is the area function. For the diamond tip with included half angle of 70.3 degrees, value of \( F \) is given by 24.505.

Once the contact area is determined, the average pressure i.e. equivalent to hardness can be computed by

\[
p_{\text{ave}} = H = \frac{P_{\text{max}}}{A}
\]

(2.15)

where \( p_{\text{ave}} \) is the hardness of the material, \( P_{\text{max}} \) is the maximum load and \( A \) is the contact area.
Thus the hardness of any material without prior knowledge of material properties can be computed through the reverse analysis method of determining the mechanical properties. With the knowledge of the stiffness and contact area of indentation, the elastic properties such as Young’s Modulus can be determined using the Oliver and Pharr method [2] based on the following formula. As shown in previous chapter, the relation between the stiffness $S$, the contact area $A$ and Young’s modulus of the substrate is given by

$$S = \frac{dP}{dh} = \frac{2}{\sqrt{\pi}} \sqrt{A} \frac{E}{(1-\nu^2)}$$

(2.16)

here $dP/dh$ is the stiffness ($S$) of the unloading curve; $E$ is the Young’s modulus of the substrate, $A$ is the contact area and $\nu$ is the Poisson’s ratio of the substrate on which indentation has to be performed.

This technique was further extended by Suresh and Giannakopoulos [1] to calculate the residual stresses as well as the possible plastic strain induced in the material. The method is based on the calculation of the contact area of the indent after the tool has been completely retracted and the contact ratio which is determined by the maximum distance travelled by the indenter in direction parallel to tool travel. The average pressure equivalent to the hardness can be calculated using

$$P_{ave} = \frac{P_{max}}{A}$$

(2.17)

The contact area of the indentation [25] is determined with the help of slope and indentation Young’s modulus as specified by
in which $C_u$ is a non-dimensional constant based on the type of indenter used for the indentation. For Vickers Pyramid, the value of $C_u$ is 1.142 and 1.167 for trigonal Berkovich Indenter and $E^*$ is the indentation Modulus as given by equation (1.10).

The load vs. displacement curve is obtained for indentation in area without any pre-existing stresses (virgin region) and in area with pre-existing stresses induced by laser shock peening. Using equation (2.6), the contact areas for indentation in both regions are determined. Suresh et al. has assumed that the average contact pressure due to indentation is unaffected by any kind of pre-existing residual stresses [1]. The average contact pressure in both the virgin region and the region with pre-existing residual stresses is given by the following equation.

$$p_{ave} = \frac{P}{A} = \frac{P_o}{A_o}$$  \hspace{1cm} (2.19)

where $p_{ave}$ is the average pressure (hardness equivalent), $P$ and $P_o$ are the indentation loads for the region with residual stresses and without residual stresses respectively, $A$ and $A_o$ are the contact areas obtained after removal of load in region with pre-existing residual stress and virgin region.
2.1.1 Derivation of the equation for determining the compressive residual stress using the nanoindentation technique

Suresh et al. [1] derived the equation for extracting residual stresses based on following assumptions. In case of indentation in region with compressive residual stresses, the stresses are assumed to equibiaxial. Hence the equibiaxial residual stresses acting on the substrate will be equivalent to hydrostatic pressure plus a uniaxial tensile stress component acting in the opposite direction of the load applied. This is a fictitious tensile stress component and may result in loss of contact as it acts in the direction opposite to applied load. The contact between the indenter and the surface is enabled by the residual stress component acting normal to the inclined faces i.e. \( \sigma_{x,0}^R \sin \alpha \). Here \( \alpha \) is the included angle of Berkovich indenter and \( \sigma_{x,0}^R = \sigma_{y,0}^R \) is the equibiaxial stress. Hence a load equivalent to \( \sigma_{x,0}^R \sin \alpha \) \( A \) as seen in the figure (2.4), where \( A \) is the area on which load is acting upon, is utilized in creating a hydrostatic stress.

For further implementation, Suresh et al. considered the indentation curves in region with and without compressive residual stresses as shown in the figure (2.5). The substrate is subjected to indentation at load \( P_1 \) which penetrates up to depth \( h_1 \) which is represented by the point X in...
the graph. In order to change the indentation state from X to Z, the load has to be increased from $P_1$ to $P_2$ and the indentation depth has to change from X to Y.

As seen from the figure (2.5),

$$P_2 = P_1 + \sigma_h \sin \alpha A_i$$  \hspace{1cm} (2.20)

here $\sigma_h$ is the residual stress component and $\alpha$ is the included angle of Berkovich indenter.

Now, under quasi-static conditions in case of sharp indentation, if the load $P$ exerted by the sharp indenter causes an indentation depth of $h$ to occur, then the relation between $P$ and $h$ is parabolic. This is called as Kick’s law [29].

Based on Kick’s law,

$$P_i = Ch_i^2 \text{ and } P_2 = C_0 h_2^2$$  \hspace{1cm} (2.21)

where $P_1$ and $P_2$ are the indenter loads in region with residual stresses and without residual stresses, $h_1$ and $h_2$ are the indentation depth and $C$ and $C_0$ are the curvature constant for indentation in region with and without residual stresses respectively.

And also according to equation (2.14) we have,

$$A_i = Dh_i^2$$  \hspace{1cm} (2.22)

here $A_1$ is the area of the indentation region, $h_1$ is the depth of indentation and $D$ is the indenter constant.

Substituting, equation (2.21) and (2.22) into equation (2.20) we get,

$$C_0 h_2^2 = Ch_i^2 + \sigma_h D h_i^2$$  \hspace{1cm} (2.23)

Dividing the above equation by $Ch_i^2$ we get, 

$$\frac{C_0 h_2^2}{Ch_i^2} = 1 + \frac{\sigma_h D}{C}$$  \hspace{1cm} (2.24)
The basic assumption by Suresh et al. [1] is that the average pressure (hardness equivalent) remains constant irrespective of the region with or without residual stresses. Thus,

\[ p_{ave} = \frac{P_1}{A_1} = \frac{P_2}{A_2} \]  
(2.25)

Thus substituting equation (2.21) and equation (2.22) in equation (2.25) we get,

\[ p_{ave} = \frac{Ch_1^2}{Dh_2^2} = \frac{C}{D} \]  
(2.26)

Thus equation (2.24) becomes,

\[ \frac{h_2^2}{h_1^2} = 1 + \frac{\sigma_h \sin \alpha}{p_{ave}} \]  
(2.27)

Thus using the apparent contact area ratio \( \frac{A_{app}}{A_{0,app}} = \frac{h_1^2}{h_2^2} \), the compressive residual stress can be calculated from:

\[ \frac{A_{app}}{A_{0,app}} = \frac{h_1^2}{h_2^2} = \left\{ 1 + \frac{\sigma_h \sin \alpha}{p_{ave}} \right\}^{-1} = \left\{ 1 + \frac{\sigma_{x,0} \sin \alpha}{p_{ave}} \right\}^{-1} \]  
(2.28)

here \( h_2 \) is the maximum length traveled by the indenter in the region with compressive residual stresses; \( h_1 \) is the maximum length traveled by the indenter in the virgin material and \( \alpha \) is the angle of the indenter tip, which is 24.7 degrees for Berkovich indenter.

As the residual stresses are considered to be equibiaxial in nature, we assume

\[ \sigma_H = \sigma_{x,0}^R = \sigma_{y,0}^R \]  
(2.29)
2.1.2 Issues faced in method suggested by Suresh et al. and alternate methods suggested

Due to the sink-in and pile-up effects, it has been found that the contact area calculated by equation (2.8) is lesser than the actual contact area obtained from the image analysis based on counting the pixels. As a result, it leads to higher hardness value and subsequently an overestimate of the residual stress value. If \( \frac{h_f}{h_{\text{max}}} > 0.7 \), (where \( h_f \) is the depth of the indentation after the retraction of the tool and \( h_{\text{max}} \) is the maximum depth of indentation) and no considerable work hardening has taken place, then the material exhibits pile-up effects [3], [4]. For IN718, experiment indicates that this ratio is greater than 0.7. The AFM images of nanoindentation in IN718 in the following chapters clearly show the pile-up effects. Hence the real contact area under indentation is more than the theoretical formula. As a result of this, the surface residual stress value calculated by using the contact area equation (2.8) differs by large margin compared with the one obtained from X-Ray diffraction method. Such a large discrepancy is not acceptable for routine application of the method. In the preliminary test, the contact area is calculated using the pixel calculations [9] based on image analysis using the Image J software. This method is subjective and can vary with every single calculation. Also this procedure of calculating the pixels can be time consuming for large number of indents. To overcome this drawback, Oliver and Pharr [2] introduced the work of indentation method which facilitates the calculation of hardness without the actual calculation of the contact area. It depends upon the plastic and total work done by the indenter during one loading and unloading cycle. This method, along with the method proposed by Tuck et al. [14], was further used by Khan et al. [3] to determine the elastic properties and hardness of the material with and without prior knowledge about the material characteristics. In the method proposed by Khan, the
hardness of the material is considered to be the function of either the total work done by the indenter or hardness is defined as function of plastic work done as shown in the figure (2.6).

![Load vs. Displacement Curve](image)

Figure 2.6: A schematic load-displacement curve for nanoindentation

The approach where hardness is considered as a function of total work or plastic work done was first used by Stillwell and Tabor [28] to determine the hardness of the material. Here the conventional hardness definition is equated to the ratio of plastic work to plastic volume of the indent as follows

\[
\frac{\text{Load}}{\text{Plastic Area}} = \frac{\text{Plastic Work}}{\text{Plastic Volume}}
\]  

(2.30)

According to the figure (2.5), the total work is represented by the area under the load-displacement curve and is given by,
\[ W_i = \int_{0}^{h_{\text{max}}} P \, dh \]  \hspace{1cm} (2.31)

Here, \( W_i \) is the total work of indentation, \( P \) is the load and \( h_{\text{max}} \) is the maximum depth of indentation.

As per the Kick law of indentation, we know that \( P = Ch^2 \) where \( P \) is the load of the indenter, \( C \) is the curvature constant and \( h \) is the depth of indentation. Therefore, equation (2.31) modifies to

\[ W_i = \int_{0}^{h_{\text{max}}} Ch^2 \, dh = \frac{Ch_{\text{max}}^3}{3} = \frac{P_{\text{max}} h_{\text{max}}^3}{3} \]  \hspace{1cm} (2.32)

According to the empirical equation suggested by Tuck et al. [14], equivalent average pressure (\( H \)) is defined as

\[ H = \frac{kP}{h^2} \]  \hspace{1cm} (2.33)

where \( H \) is the hardness (equivalent to average pressure), \( P \) is the load, \( h \) is the depth of indentation and \( k \) is the constant depending on the type of geometry and its value is 0.0408 for Berkovich indenter. As a result, equation (2.33) leads to depth of indentation in terms of hardness and load,

\[ h = \sqrt[3]{\frac{P}{kH}} \]  \hspace{1cm} (2.34)

Substituting equation (2.34) into equation (2.32) and further solving it, we get hardness in terms of total work done and load of the indentation.

Thus if hardness is considered as function of total work done, then

\[ H = \frac{kP^3}{9W_i^2} \]  \hspace{1cm} (2.35)

If hardness is considered as function of plastic work done, then
\[ H = \frac{kP^3}{9W_p^2} \] (2.36)

Here \( W_t \) and \( W_p \) are total and plastic work done respectively, \( k \) is the constant based on geometry of indenter and value of Berkovich indenter 0.0408. Here \( H \) is the hardness of the material, load of the indentation is given by \( P \).

This thesis explores all of the above methods for estimating the surface residual stress. The thesis also aims at giving overview of comparison of results obtained by various methods as proposed by Suresh et al. [1], work of indentation method as proposed by Oliver and Pharr et al. [2] and Khan et al. [3].

2.2) Laser shock peening process

The method of nanoindentation will be used for measuring the residual stress induced by laser shock peening. Laser shock peening [7] is a material processing technique in which compressive residual stresses are induced by propagation of high intensity pulses for very short duration (typically around 20-30ns). The surface is heated due to the impact and the top layer of the material is vaporized and plasma is formed due to very high temperature of around 10000°C. The rapid expansion of plasma causes very high pressure shock wave (GigaPascals) which is generated in the surrounding medium and material. The LSP process is illustrated in the figure (2.7).
In practice the material surface to be treated is coated with an opaque material or black tape and transparent dielectric material like water is present on top of it. The main purpose of the opaque material is to avoid surface damage due to high temperature of plasma. The function of the transparent overlay is to act as a confining medium. It helps in confining the plasma against the surface of the material and this enables in high shock wave pressures as compared to the direct ablation mode. This method is called a confined ablation mode.

2.2.1) Application of LSP process

Many components used in aerospace industry are subjected to cyclic stresses and fatigue failure is the pre-dominant failure mode. One way to improve fatigue life is to introduce additional compressive stresses to negate the tensile components. Surface peening technique is one of the many ways in which compressive residual stresses can be incorporated. For the proper process control, understanding the relation between the processing parameter and the generated residual stress is important. As such, there is a critical need for accurate measurement of the residual stresses, both before and after the peening process is applied.
With the understanding of importance of characterization of residual stresses in alloy using nanoindentation technique, various methodologies have been proposed in the literature. Some of the methods which will be used in this study are listed in following sections along with their limitations.

2.3) Methodology proposed by Suresh and Giannakopoulos [1] - Method 1 (Base Method)

The method proposed by Suresh et al. focuses on determination of contact area using equation (2.8). The step-wise procedure as described by Suresh et al. for determining the compressive residual stresses are as follows:

1) Obtain the $P_o-h_o$ (load displacement curve for virgin material) and $P-h$ curve for indentation in area with previously induced stresses. The load ($P$) and the displacement ($h$) follow Kicks law of equation $P = Ch^2$.

2) Determine the contact areas after indentation for both the virgin and previously stressed area i.e. $A_0$ and $A$ respectively using equation

$$A = \left( \frac{dP}{dh} \cdot \frac{1}{C_uE^2} \right)^2$$  \hfill (2.37)

3) Calculate the average pressure (equivalent hardness) using equation

$$p_{ave} = \frac{p_{max}}{A}$$  \hfill (2.38)

4) Laser shock peening process induces compressive stresses in the material. According to theory postulated by Suresh et al. for material with compressive residual stresses, the ratio of apparent areas is given as a function of residual stress as stated in equation

$$\frac{A_{app}}{A_{o,app}} = \frac{h^2}{h_0^2} = \left( 1 + \frac{\sigma_{s,0} \sin \alpha}{p_{ave}} \right)^{-1} = \left( 1 + \frac{\sigma_{s,0}^R \sin \alpha}{p_{ave}} \right)^{-1}$$  \hfill (2.39)
Where the induced residual stress is considered to be biaxial [1],

\[
\sigma_H = \sigma^R_{x,0} = \sigma^R_{y,0}
\]  

(2.40)

With this assumption, the residual stress value can be determined from eq. (2.41)

\[
\sigma_H = \sigma^R_{x,0} = \sigma^R_{y,0} = \frac{P_{\text{ave}}}{\sin \alpha} \left[ 1 - \left( \frac{h^2}{h_0^2} \right)^{-1} \right]
\]  

(2.41)

2.4) Method used to measure contact area using pixels method [2], [9]: Method 2

As an alternate to the above method, the area of indent is calculated using the pixels method based on the Atomic Force Microscopy (AFM) image obtained from nanoindentation experiment. The ImageJ software was developed by National Institute of Health (NIH) for the purpose of image processing. It is used to calculate the indentation area in the unit of microns. Once the indentation area is calculated and averaged for multiple readings, method proposed by Suresh et al. [1] is followed to get the final estimate of residual stresses due to laser shock peening process. The exact images of the indent at 25x and 100x are shown in figure (2.8) and figure (2.9).

Fig 2.8: Image of Indentation in virgin material used in area calculation in Image J software at 100x zoom
The steps to compute the residual stresses are

1) Calculate the $P-h$ and $P_o-h_o$ curves for indentation in virgin region and LSP region (i.e. region with surface residual stresses).

2) Calculate the contact areas for both regions using image analysis method.

3) Calculate the contact ratio and compute the equibiaxial residual stress using equation (2.41).

2.5) Method proposed by Oliver and Pharr [2]: Method 3

Cheng and Cheng [15] developed a methodology for computing the hardness and Young’s modulus while considering the pile-up effect. Cheng and Cheng [11], [15] derived the equation which relates the irreversible work done with the hardness and the effective Young’s modulus. This formula was empirically derived based upon experimental data obtained by indentation in fused silica. Cheng and Cheng [11] based upon dimensional analysis of indentation of fused silica postulated a relation between the indenter force ($F$), Young’s modulus ($E$), Poisson’s ratio ($\nu$), work hardening exponent ($n$) and indenter half angle ($\theta$) as follows:
\[ F = Eh^2 \pi_{x}(Y, E, \nu, n, \theta) \]  

(2.42)

here \( \pi_{x} \) is a dimensionless quantity. The total work done by the indenter to perform elastic and plastic deformation when the indenter reaches a maximum depth of \( h_{\text{max}} \) is given by

\[ W_{\text{tot}} = \int_{0}^{h_{\text{max}}} Fdh = \frac{Eh_{\text{max}}^3}{3} \pi_{x}(Y, E, \nu, n, \theta) \]  

(2.43)

The elastic work, i.e., unloading work is defined as the area under the unloading curve. As shown in the figure (2.6) the unloading curve extends from \( h_{f} \) (i.e. final depth of indentation after retraction of the tool) to \( h_{\text{max}} \) (i.e. maximum depth of indentation during loading step of indentation). At the final depth \( h_{f} \), the force of indenter is zero as the tool is completely retracted from the substrate at this stage. Thus Cheng and Cheng [11] defined the force at this point as the following:

\[ F = Eh_{\text{max}}^2 \pi_{y} \left( \frac{Y}{E}, \frac{h_{f}}{h_{\text{max}}}, \nu, n, \theta \right) = 0 \]  

(2.44)

The elastic work (area under unloading curve) is given by,

\[ W_{u} = \int_{h_{f}}^{h_{\text{max}}} Fdh = Eh_{\text{max}}^3 \int_{h_{f}/h_{\text{max}}}^{1} x^2 \pi_{x} \left( \frac{Y}{E}, x, \nu, n, \theta \right) \]  

(2.45)

Here, the integral term \( \int_{h_{f}/h_{\text{max}}}^{1} x^2 \pi_{x} \left( \frac{Y}{E}, x, \nu, n, \theta \right) \) is a dimensionless quantity and is expressed by \( \pi_{u} \).

Thus equation (2.43) becomes

\[ W_{u} = Eh_{\text{max}}^3 \pi_{u} \left( \frac{Y}{E}, \nu, n, \theta \right) \]  

(2.46)
Thus from equation (2.43) and (2.46), the ratio of plastic work done to total work done is expressed as

$$\frac{W_{tot} - W_u}{W_{tot}} = 1 - 3 \pi_{\alpha} \left( \frac{Y}{E}, \nu, n, \theta \right) = 1 - 3 \pi_{\alpha} \left( \frac{Y}{E}, \nu, n, \theta \right)$$

(2.47)

Based on the finite element calculation performed and also on the basis of the experimental data analysis, Cheng and Cheng [11] had empirically established a relation between effective Young’s modulus and hardness of the substrate as follows

$$\frac{H}{E_{eff}} \approx \pi_{b} \left( \frac{Y}{E}, \nu, n, \theta \right)$$

(2.48)

where $\pi_{b}$ is the dimensionless quantity which is function of the yield stress $Y$, Young’s modulus of the substrate $E$, Poisson’s ratio $\nu$, strain hardening exponent $n$ and included Berkovich angle $\theta$.

Thus from equation (2.47) and (2.48), Cheng and Cheng [11] defined a relationship between the hardness ($H$), the effective Young’s modulus ($E_{eff}$), the total work done by the indenter ($W_{tot}$) and the work done during unloading i.e. elastic work done ($W_u$). This relation is shown in equation (2.49)

$$\frac{W_{tot} - W_u}{W_{tot}} \approx 1 - 3 \frac{H}{E_{eff}}$$

(2.49)

With further analysis and finite element simulations, this equation was modified and with introduction of correction factor, this method of work of indentation was further used by Oliver and Pharr [2]. The relation between the hardness and work of indentation used by Oliver and Pharr [3], [4] is given as
\[
\frac{W_{\text{tot}} - W_u}{W_{\text{tot}}} = 1 - 5 \frac{H}{E_{\text{eff}}}
\]  \hspace{1cm} (2.50)

in which \( W_{\text{tot}} \) is the total work done by the indenter and \( W_u \) is the curve done during unloading and \( E_{\text{eff}} \) is indentation modulus given by equation (2.5).

Some of the advantages of this method are:

a) There is no need for approximating the area using image analysis.

b) The pile-up and sink-in effects are taken into consideration, as Oliver and Pharr [4] used a correction factor in work of indentation method to get better results.

This method however was not experimentally verified by Oliver and Pharr. Oliver and Pharr introduced a correction factor 5 based upon the experiments performed by Cheng [15]. However this method does not consider work hardening mechanism in the material. In addition, it has been pointed out [2] that it is difficult to extract the work hardening behavior from load vs. displacement curves alone.

2.6) Method based on hardness as function of total work done or hardness as function of plastic work proposed by Khan et al. [3] - Method 4

Hardness as function of plastic and total work was proposed by Tuck et.al. [14]. This method was further used by Khan et al. [3]. The hardness is calculated based on the method of work of indentation using equation (2.19).

Khan et al. [3] proposed a method in which hardness was considered as function of work (total work done or plastic work done). A schematic diagram of the components associated with work of indentation is shown in the figure (2.6).
In this method, the following steps are followed to calculate the residual stresses

1) Extract the P-h and $P_o$-h$_o$ curves for indentation in virgin region and LSP region (i.e. region with compressive residual stresses).

2) Calculate the hardness for both the regions using equations (2.19) and (2.20) based on the work of indentation technique.

3) Using the apparent area ratio equation (2.25), the residual stress can be found.

The results and direct comparison between various methods are explained in detail in the following chapters.

2.7) Finite Element Method for Nanoindentation Simulation

Two finite element models are created to simulate the nanoindentation experiment: one without pre-existing residual stresses field (virgin area) and one with initial compressive residual stress. In the second case, the pre-existing residual stresses are induced by laser shock peening process.

For finite element implementation, general purpose finite element software, ABAQUS EXPLICIT 6.11, is used for the simulation purpose. The experiment was modeled as a 2D axi-symmetric case with extremely fine mesh in the indentation region. The boundary conditions and material properties are specified according to the experiment. The experiment is load controlled and the displacement output is measured by load cell placed on the indenter. The reaction force vs. displacement of the indenter inside the material is measured. The displacement of the indenter with respect to the time is measured by the load cell mounted on the indenter. This displacement vs. time curve obtained from the experiment was then used as an input for defining the indenter travel in finite element model.
The aim of the finite element model is to validate the residual stress measurement made from the experiment. In this case, the nickel alloy IN718 is the material of interest. The material properties of IN718 alloy are characterized using the Johnson-Cook material model. Major research has been done using JC model for laser shock peening process of IN718 alloy [6]. In order to maintain the consistency in material modeling, the model parameters used are the same as those for simulating the residual stress in laser shock peening, which was performed in LS-DYNA.

The results of the finite element model and its correlation with experimental results are shown in the following chapters.
CHAPTER 3

EXPERIMENTATION AND FINITE ELEMENT MODELING

3.1 Experimentation

Nanoindentation experiment is conducted using the Berkovich Indenter from CSM instrument. With the load vs. displacement data extracted from the experiment, various parameters such as hardness of the material, Young’s Modulus of the material are predicted based on the method formulated by Oliver and Pharr. The application of this method is for bulk as well as thin film structures. The step-wise procedure for the Nanoindentation experiment is as follows:

1. The dimension of the IN718 specimen used for the experiment is 37x37mm as shown in the figure (3.1). The chemical composition for IN718 [6] are shown in table (3.1).

2. The specimen is polished to get a mirror-like surface so as to facilitate nanoindentation without any foreign particles, substrates or scratches on the surface. Extreme care has to be taken as imperfections on the surface such as scratch or foreign particle can affect the results or displacement of the indenter.
3. The specimen is then subjected to laser shock peening process. The process is applied on two single spots of 2mm diameter, the laser energy values are 4J and 8J, respectively and the corresponding laser power intensities are 5.3876GW/cm² and 9.0169 GW/cm² respectively.

4. After laser shock peening, the specimen is subjected to indentation at maximum load of 500mN (the maximum capacity of CSM instrument using Berkovich Indenter). Indentation is performed at fixed load of 500mN at three different regions: virgin region, 8J spot and 4J spot.

5. Total nine indentations in area of 300µm x 300µm are performed in the form of simple 3x3 matrix. The indents are made at a distance of 100µm each in both x and y direction as shown in the figure (3.1).

6. Load vs. displacement graphs and other statistical data are extracted from the experiment.

<table>
<thead>
<tr>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>No</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Co</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>B</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>17</td>
<td>Balance</td>
<td>4.75</td>
<td>2.80</td>
<td>0.65</td>
<td>0.2</td>
<td>1.0</td>
<td>0.08</td>
<td>0.35</td>
<td>0.35</td>
<td>0.015</td>
<td>0.015</td>
<td>0.006</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 3.1: Chemical Composition for IN718 in %

With the acquired load vs. displacement curves, various methods are used to calculate the contact area of the indenter and a direct comparison is made on the various estimates of the surface residual stress.
3.2) Verification of the Estimated Residual Stresses

X-ray diffraction (XRD) method is used for verification of the surface residual stresses. XRD is a non-destructive technique which aims at estimating the residual stresses. In measuring the residual stress using XRD, the elastic strain in the crystal lattice is measured and the associated residual stress is determined from the elastic constants. As the X-rays are incident on the material, many grains contribute towards the measurement of the stresses. The measurement of residual stress by X-ray diffraction method is based on the interaction between the wave front of the X-ray beam and the crystal lattice of the material. This method is also known as \( \sin^2 \Phi \) method as the position of a diffraction peak will shift as the sample is rotated by an angle \( \Phi \).

This technique was used to measure the residual stresses that are introduced after the shock peening process. The XRD parameters used for measurement of residual stresses are shown in the table (3.2).

<table>
<thead>
<tr>
<th>Sample Material</th>
<th>IN718</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray Tube</td>
<td>Manganese Tube (MnTube)</td>
</tr>
<tr>
<td>Bragg Angle of the material</td>
<td>156 degrees</td>
</tr>
<tr>
<td>Filters used</td>
<td>N/A</td>
</tr>
<tr>
<td>Aperture</td>
<td>1mm</td>
</tr>
<tr>
<td>Exposure Time</td>
<td>5 secs</td>
</tr>
<tr>
<td>No. of Exposure profiles</td>
<td>10</td>
</tr>
<tr>
<td>Beta Angles</td>
<td>11 degrees (both directions)</td>
</tr>
<tr>
<td>hkl plane</td>
<td>311</td>
</tr>
<tr>
<td>Material used for Gain</td>
<td>Glass</td>
</tr>
</tbody>
</table>

Table 3.2: XRD parameters for IN718 material
The laser shock peening parameters and the surface residual stresses are presented in table (3.3) and table (3.4).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Spot 1</th>
<th>Spot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spot Size(dia)</td>
<td>2 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>Energy of the pulse</td>
<td>4J</td>
<td>8J</td>
</tr>
<tr>
<td>Pulse width(ns)</td>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>Intensity(GW/cm²)</td>
<td>5.3876</td>
<td>9.0169</td>
</tr>
</tbody>
</table>

Table 3.3: LSP parameters for single shots on IN718

XRD measurement results:

<table>
<thead>
<tr>
<th>Stresses (MPa)</th>
<th>Spot 1 -4J</th>
<th>Spot 2-8J</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_x$</td>
<td>-343.25±17.49</td>
<td>-428.48±14.45</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>-328.34±20.44</td>
<td>-375.59±21.23</td>
</tr>
</tbody>
</table>

Table 3.4: Experimental surface residual stress

3.3) Finite Element Model

3.3.1) Model Setup

Nanoindentation simulation is performed using ABAQUS (version 6.11), a commercially available finite element software. The indentation experiment is modeled as an axisymmetric model as shown in the figure (3.2).
The model consists of an axisymmetric deformable substrate (IN718 material properties) and the Berkovich indenter is modeled as a rigid indenter with an angle of 70.3 degrees as shown in the figure (3.2).

3.3.2) FE Discretization of model

A 0.5x0.5 mm deformable part is nonuniformly meshed. The mesh sizes are extremely small in the area of indentation. A total of 6983 elements with 7091 nodes are included in the model. The model contains 6795 CAX4R elements i.e. axisymmetric 4-noded linear quadratic elements with reduced integration and also 188 CAX3 i.e. axisymmetric 3 noded linear triangular elements. CAX4R elements dominate the mesh structure due to its computational efficiency. The smallest element size used in the model is 250e-6 mm. This ensures the exact modeling of the nanoindentation process with maximum displacement of 2000nm. The Berkovich indenter, normally made up of rigid diamond tip is modeled as a perfectly rigid indenter cone.
3.3.3) Material properties used in the model

The Johnson-Cook material model was used for specifying the material properties to the deformable IN718 substrate. Johnson-Cook material model is used for simulating the behavior of material when subjected to high strain rate, shock treatment processes like LSP. The effective stress in the material is given by JC model as:

\[
\sigma = \left[ A + B \varepsilon^n \right] \left[ 1 + C \ln \dot{\varepsilon} \right] \left[ 1 - T^m \right]
\]  

(3.1)

Here, \( A, B, C, n, m \) is the constants, \( \varepsilon \) is plastic strain, \( \sigma \) is the effective stress, \( \dot{\varepsilon} \) is the plastic strain rate and \( T \) is the temperature. The first term represents the classical power law hardening behavior through the effective plastic strain. The second term accounts for the strain rate dependence of flow stress. The third term accounts for decrease in flow stress due to thermal softening. The material properties [10] incorporated into the alloy is listed in table (3.5) and table (3.6).

Table 3.5: Material properties of IN718 substrate

<table>
<thead>
<tr>
<th>Mass Density (kg/m(^3))</th>
<th>Elastic Modulus - E (MPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>8220</td>
<td>211000</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 3.6: Johnson Cook plasticity model parameters for IN718 SPF

<table>
<thead>
<tr>
<th>( A ) (MPa)</th>
<th>( B ) (MPa)</th>
<th>( C )</th>
<th>( m )</th>
<th>( n )</th>
<th>( \theta_{temp} ) (K)</th>
<th>( \theta_{room} ) (K)</th>
<th>( \dot{\varepsilon} ) (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>1200</td>
<td>0.035</td>
<td>0.19</td>
<td>0.5</td>
<td>1573</td>
<td>300</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3.4) Boundary Conditions

Experimentally, the substrate is confined at the bottom surface and the rigid indenter can displace only in the y-direction. Accordingly in the FEM model, the bottom nodes are
constrained in all degrees of freedom to restrict any movement of the substrate. In addition, the rigid analytical indenter is allowed to move only in the y-direction in which indentation is performed. The x and rotational degree of freedom for the indenter is constrained in both the loading and unloading steps.

3.3.5) Loading conditions

The loading and unloading steps are specified using the tabular step option in ABAQUS. By specifying the reference point on the indenter, the motion of the indentation is prescribed. Figure (3.3) shows the displacement vs. time graph for the virgin regions, region with laser shock peening at 4J energy and region with laser shock peening single dimple at 8J energy.

![Figure 3.3: Comparison of displacement vs. time graph for three regions of indentation](image)

3.3.6) Contact definition

A surface to surface contact definition has been specified in the 2D axisymmetric model. The rigid analytical indenter is modeled as master surface whereas the IN718 substrate is modeled as the slave surface. The contact condition is specified such that only the master surface is allowed
to penetrate into the slave surface. Frictionless contact has been specified to reflect the fact that the contact between the mirror-like finish and the indenter experiences negligible frictional force.

3.3.7) Mass scaling

Mass scaling is a technique where nonphysical mass is introduced in a structure in order to achieve larger explicit time steps. The total time required for both loading and unloading step is 62 seconds (average). In the explicit analysis the automatic time step increment considered by ABAQUS is extremely small. If no adjustment is made, it will take long time for a complete simulation. Mass scaling factor is introduced in order to reduce the computational time required for this quasi-static problem without losing accuracy. In this model a variable mass scaling scheme is applied to all the elements of the substrate. The total time required for complete analysis is 30 minutes after the introduction of mass scaling factor.

3.3.8) Initial stress condition

Two different types of models are developed in ABAQUS Explicit, one representing the indentation in the region without pre-existing residual stresses and the other representing indentation in the region with pre-existing compressive residual stresses. In the first model no stresses are induced and indentation is directly performed in the nonuniform mesh generated.

In modeling the indentation response with pre-existing elastic residual stresses, laser shock peening process is first simulated using an axisymmetric 3D model in LS-DYNA. The laser parameters are specified according to table (3.3). The stresses and strains obtained after the LS-DYNA analysis are then introduced into ABAQUS as initial conditions. A flowchart of this finite element procedure is shown in the figure (3.4).
FEM model setup with mesh and BCs in ABAQUS Explicit 6.11

Pre-existing stresses

YES

Laser shock axisymmetric 3D impact analysis in LS-DYNA

Extracting the elastic stresses (x and z direction) and plastic strain in spot region

Introduce the stresses and equivalent plastic strain as pre-defined field in initial configuration of ABAQUS 2D model

NO

Indentation using ABAQUS Explicit analysis

Output - Load (Reaction forces) vs. Displacement curve

Figure 3.4: Flow chart of the finite element process
CHAPTER 4

RESULTS AND DISCUSSIONS

4.1) Comparison of experimental results

As mentioned earlier, four methods have been applied in extracting the residual stress from the indentation experiment. These are

Method 1 – Method proposed by Suresh et al.

Method 2 – Contact area is calculated by image analysis

Method 3 – Work of indentation method as proposed by Oliver and Pharr et al.

Method 4 – Extracting residual stresses using hardness calculation as function of plastic work as proposed by Khan et al.

In addition, XRD measurements are also performed to measure the residual stress in the x and y direction and these values are listed with the others derived using the methods above.

Table 4.1: Experimental comparison between different methods

<table>
<thead>
<tr>
<th>LSP Spot</th>
<th>Method 1 (MPa)</th>
<th>Method 2 (MPa)</th>
<th>Method 3 (MPa)</th>
<th>Method 4 (MPa)</th>
<th>XRD measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hardness as function of total work</td>
<td>Hardness as function of plastic work</td>
</tr>
<tr>
<td>Spot1 - 4J</td>
<td>-1015.84</td>
<td>-400.56</td>
<td>-1670.45</td>
<td>-467.75</td>
<td>-467.75</td>
</tr>
</tbody>
</table>

The values in the table clearly shows that the surface residual stresses estimates obtained using Method 2 (where contact area is calculated by image J method) and Method 4 (where hardness is
considered as function of plastic work) are more accurate if one uses the values from the X-Ray diffraction method as a reference.

### 4.1.1) Method 1

The residual stresses estimated by Method 1 i.e. method in which the stiffness of the unloading curve is determined, varies by a large margin as compared to X-ray diffraction method. The possible reason for this is that the method does not take into account the pile-up and sink-in effects of the material due to indentation. In this method, the contact area of the indentation is calculated using equation (4.1).

\[
A = \left( \frac{dP}{dh} \cdot \frac{1}{C_s E} \right)^2
\] (4.1)

In this equation, the slope \( \frac{dP}{dh} \) is the slope of the upper 10% of the unloading curve \([8]\) and is derived by following formulae. The unloading curve is governed by equation \([3],[4]\)

\[
P = B(h_{\text{max}} - h_f)^m
\] (4.2)

where \(B\) and \(m\) parameters are found out by curve fitting and \(P\) is the load that the indenter is subjected to. The slope of the curve can be calculated by differentiating equation (4.2) with respect to \(h\), which gives

\[
\frac{dP}{dh} = mB(h_{\text{max}} - h_f)^{m-1}
\] (4.3)

A curve fitting is performed to extract the unknown parameters \(m\) and \(B\) which further enables the calculation of the slope. Figure (4.1) shows the curve fitting result which illustrates that curve fitting is accurate with a residue error of 2.74e-05.
Based on the curve fitting results the parameters of the equation (4.2) are as follows: $m = 1.4524$ (which is in agreement with the literature value for spherical indenter [2]) and $B = 42.296 \times 10^3$.

With the help of these parameters and the acquired data of load vs. displacement curve, the contact area of the indentation profile is underestimated. It has been observed and also supported by literature review [2], [3], [6] that, softer materials exhibits pile-up effects due to indentation whereas harder materials exhibits sink-in effects. Method 1 however does not take into account these features. IN718 material is a relatively soft material and hence as seen in figure (4.2) there is a significant pile-up area around the indentation. This pile-up area also adds to the contact area which is required in calculation of the residual stress. Figure (4.3) gives a graphical representation of contact area with respect to the $\frac{h_i}{h_{\text{max}}}$ ratio for indentation in the region with 8J energy single laser shot.
4.1.2) Method 2

Method 2 overcomes the drawback of method 1 as it gives a clear picture of calculating the pile-up area by method of image processing. This method provides a better estimate of the residual stresses; however it is subjective and hence can vary depending upon the method adopted while calculating the pixels. Figure (4.2) gives us an insight about the area calculation using ImageJ software.

The ratio $\frac{h_f}{h_{max}} > 0.7$ indicates the pile-up nature of material subjected to nanoindentation by Berkovich indenter. Figure (4.3) illustrates a comparison between the contact area calculated by method 1 i.e. by calculating slope and method 2 i.e. by image processing. It can be clearly seen that the contact area is underestimated in method 1 and is much less than the actual contact calculated taking pile-up in to consideration in method 2.

Figure 4.2: Area calculation using ImageJ method
4.1.3) Method 3

Method 3 overcomes the subjectivity of the method 2. The results estimated by Method 3 are also higher than the estimated XRD measurements. This method [2] has not been experimentally verified. It has been proposed that even though this method can be used for high $rac{h_f}{h_{\text{max}}}$ and $\frac{E}{\sigma_y}$ ratio it is not independent of work hardening behavior.

4.1.4) Method 4

Method 4 gives a better estimation in comparison to X-Ray diffraction measurements and also overcomes the subjectivity issue. This method accurately measures the hardness without the need of calculating the contact area. The hardness calculated using suggested formula is further used to estimate the surface residual stress. Figure (4.4) gives a direct comparison between hardness values calculated by all the described methods. It can be verified from this graph that the hardness value obtained using the image processing method is the lowest due to the accurate measurement of pile-up contact area. Next to this result is the hardness value obtained by method...
4 with the inclusion of the work of indentation factor. The hardness value obtained is in agreement with the values obtained from CSM indentation instrument which is based on Oliver and Pharr method experimentally.

![Comparison of Hardness calculated by Method 1 and Method 2](image)

Figure 4.4: Comparison of hardness calculated by different methods with experimental O&P hardness obtained by CSM instrument

### 4.2) Finite Element Method Results

Finite element method is employed to model the nanoindentation procedure. The aim for FEM results is to correlate the experimental and FEM curves so as to estimate the surface residual stresses by simulating the nanoindentation process in ABAQUS Explicit. Finite element analysis study is performed to find out the effect of residual stresses on the hardness value and the Young’s Modulus ($E$) of the IN718 SPF material.

Figure (4.5) shows an experimental comparison between the curves generated due to indentation in virgin region, in LSP spot with 4J energy and in LSP spot with 8J energy.
Figure 4.5: Experimental comparison of indentation curves in different regions

Experiments are performed using Berkovich indenter subjected to the maximum load of 500mN and are performed at different regions as stated.

4.2.1) Correlation with experimental data in virgin region

A good correlation fit is observed for indentation in region without any prior residual stresses. As per the literature, the upper most part of unloading curve is of utmost importance as the slope is determined using that region. As seen from the figure (4.6), there is a slight deviation from experimental curve but final displacement value ($h_f$) coincides with the experimental value. The value of $h_f$ is another important parameter while calculating the analytical results.

Figure 4.6: FEM and experimental comparison for indentation in virgin region
4.2.2) Correlation between FEM and experimental region for laser shock peened region

The stresses and strains from LSP are averaged over small areas of 0.1mm to 0.3mm in both x and z direction as shown in figure (4.8) and are correspondingly introduced into ABAQUS model in the initial configuration using the 'Predefined Field' option in ABAQUS. The area right under the indentation is of concern and the stresses are introduced into the sets of elements in that area. Schematic representation of localized stresses introduced for spot1 and spot2 are shown in figure (4.8) and the corresponding values of the stresses and strains are summarized in table (4.2).
The dimension of the IN718 substrate modeled in ABAQUS is 0.5x0.5mm. The LS-DYNA explicit simulation model is carried out on IN718 substrate with the same material properties as used in ABAQUS explicit. For LSP simulation, a 5x5mm substrate is meshed in HYPERMESH 10.0 with 26,724 elements and 30,006 nodes in the model. The output elemental results are averaged over the area as shown in figure (4.8).

Table 4.2: Stresses and strain from 3D LS-DYNA model to 2D axisymmetric ABAQUS model

<table>
<thead>
<tr>
<th>Region Dimensions</th>
<th>Spot1 - 4J</th>
<th>Spot2 - 8J</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stress introduced (MPa)</td>
<td>Strain introduced</td>
</tr>
<tr>
<td>0.1x0.1</td>
<td>-250</td>
<td>0.03</td>
</tr>
<tr>
<td>0.2x0.2</td>
<td>-175</td>
<td>0.01</td>
</tr>
<tr>
<td>0.3x 0.3</td>
<td>-150</td>
<td>0.01</td>
</tr>
<tr>
<td>Remaining</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4.8: Schematic representation of LS-DYNA stress contour to ABAQUS stress and strain distribution
Figure (4.9) and figure (4.10) shows a correlation between FEM and experimental model of nanoindentation for region with LSP spot of 4J and with region with LSP spot of 8J.

![Figure 4.9: 4J spot experimental and FEM comparison](image1)

![Figure 4.10: 8J spot experimental and FEM comparison](image2)

From the above two figures, it can be seen that a good agreement between the simulation and experimental is accomplished. Figure (4.11) and figure (4.12) show a direct comparison of the model with pre-defined residual stresses and without residual stresses.
Figure (4.11) and figure (4.14) depict a direct comparison between indentation in various regions for both experimental and finite element curves. 

Figure (4.11): Comparison virgin region and 4J spot

Figure (4.12): Comparison virgin region and 8J spot

Figure 4.13: Experimental comparison between load vs. displacement curves of indentation at different regions
4.3) Analysis of effect of stress and strain on the hardness and the Young’s modulus of IN718 material

Extensive computational studies are conducted to analyze the effect of stress and strain on hardening in IN718 material. No literature has been found which encompasses the information on significant hardening of this material due to mechanical treatment such as the LSP process. Series of analysis are performed to relate hardening to the change in the load vs. displacement curves. It is important to identify whether the different curves generated can be correlated to the residual stresses. The ABAQUS finite element model developed for purpose of nanoindentation is used to analyze the effect of stress and strain on the indentation curves.

4.3.1) Effect of different stress values on load vs. displacement curves.

In the FEM modeling, the experimental displacement vs. time curve generated for nanoindentation is used as the input for controlling the displacement of rigid indenter. The input data for controlling the displacement of the indenter is the same for the all 6 simulation
experiments in this case. The substrate is subjected to different pre-existing compressive stresses ranging from -200 MPa to -600 MPa. No plastic strain is introduced in the elements, because the aim is to understand the effect of stress alone on the indentation curve.

Figure 4.15: Effect of residual compressive stress on indentation curve

It is clearly seen from figure (4.15) that with the increase in residual stress in the substrate, the load required to achieve required indentation depth increases. In the case of pre-existing compressive residual stress, in order to maintain the constant average pressure, Suresh et.al [1] postulated that due to the equibiaxial residual stresses, there exists a differential tensile force which acts in direction opposite to application of the indenter load. As a result the load required is higher for indentation in region with higher residual stresses.

4.3.2) Effect of various values of equivalent plastic strain on indentation curves

In order to study the effect of equivalent plastic strain on the load vs. displacement curve, simulation experiments similar to experiments explained in section 4.3.1 are conducted. In these finite element models, the elements lying right under the indentation area are assigned different strain values as obtained from laser shock peening models. A similar load control scheme as in the last section is applied. No stress component was directly introduced so as to study the effect
of strain alone on the curves when the indenter is allowed up to fixed indentation depth. The results obtained are shown in figure (4.16).

Figure 4.16: Effect of different values of strain on indentation curves

The above graph clearly depicts the change in the curvature of loading curve owing to the change in the plastic strain near the indentation area. Model with lower strain values require lower loads for fixed indentation depth. With increase in strain value, the load required to achieve the displacement for 0.002mm increases. The change in the loading part of the curve clearly indicates the significant effect of strain on the load vs. displacement curves obtained during indentation. Figure (4.15) and figure (4.16) can be used to understand whether the change in the load vs. displacement curves are due to the residual stress or strain hardening effect associated with plasticity.

4.3.3) Effect of both stress and strain hardening effects

LSP process introduces both plastic strain and compressive elastic residual stresses in the model. In order to understand the indentation behavior of IN718 material with pre-existing residual stresses and plastic strains due to LSP process, analysis is performed considering both the factors. The aim of this study is to understand the predominating factor behind the change in load
vs. displacement curve when indented in different regions with pre-existing stresses and without any stresses. It is of great interest to understand the contribution of hardening effect in nanoindentation of post IN718 substrate. In order to distinguish between the effects of stress and strain component, the finite element model used is divided into two main categories.

a) Understanding the effect of strain while keeping the stress value constant

b) Understanding the effect of stress while keeping the strain value constant

4.3.3.1) Effect of different values of plastic strain for constant stress value

Three simulation models are developed with different strain conditions and constant stress. The plastic strain introduced in the model ranged from 0.04, 0.07 and 0.1 with constant compressive residual stress of -450MPa.

Figure (4.17) shows similar trend of the indenter behavior as seen in figure (4.15) in IN718 material. With constant stress and variable strain values, the change in the load vs. displacement curve follows a similar pattern. As the plastic strain varies substantially from 0.04 to 0.1, there is subsequent rise in the load imposed by the indenter.

Figure 4.17: Effect of different strain values for constant stress value
4.3.3.2) Effect of different values of stress for constant strain value

Simulations similar to those explained in section 4.3.3.1 are performed for variable compressive stress values with constant plastic strain in the elements. Figure (4.18) shows slight variation curves due to change in the residual stress. This variation is not as high as figure (4.17).

![Comparison between indentation for plastic strain at 0.04 and variable Residual stress](image)

Figure 4.18: Effect of different stress values for constant plastic strain value

4.3.4) Effect on hardness and Young's Modulus

In order to determine the influence of the applied stress on the hardness and Young's modulus of the material, different sets of models are run subjected to different stress components. The stress introduced ranged from tensile to compressive. A change in the hardness value is expected from tensile stresses to compressive stresses (600 MPa to -600MPa). The experimental displacement vs. time data for indentation in the region without any residual stresses (virgin region) is used as an input for the indenter. The FEM obtained load vs. displacement for various stress components is shown in figure (4.19).
Figure (4.19) illustrates that load required for purpose of nanoindentation increases from the tensile to compressive zone. Figure (4.21) and figure (4.22) show the values hardness and Young’s modulus as a function of the stress.
The hardness value does not vary appreciably with the change in the loading condition of the substrate. The hardness value was calculated using the traditional way suggested by Oliver and Pharr [2]. The hardness value obtained from the finite element calculations are in agreement with the hardness value obtained by CMS instrument during nanoindentation in virgin region area. The hardness value increases to 5.5GPa for compressive stress region from 4.7GPa for tensile region. As there is no appreciable change in hardness of IN718 material, it can be inferred that change in residual stress value does not significantly affect the hardening of the material.
These results support the literature [23], [24] that no specific work hardening has occurred in IN718 material.

4.4) Study of stress and plastic strain effect on indentation curves in 4J and 8J LSP spot

A simulation study is performed to verify whether the change in the indentation curves between the 4J and 8J energy spot was due to the strain hardening or the stress effect. Finite element simulations are carried out for following different conditions:

4.4.1) Case 1:- Indentation in area with 4J single shot LSP

1) Indentation in region with corresponding stress of -250 MPa only
2) Indentation in region with corresponding strain of 0.02 only
3) Indentation in region with both stresses of -250 MPa and plastic strain of 0.02 which matches the actual experimental results.

The FEM results for all the above conditions are shown in figure (4.23) with a closer view in figure (4.24).

![Figure 4.23: Comparison for indentation in 4J single LSP spot with three different conditions](image-url)
4.4.2) Case 2:- Indentation in area with 8J single shot LSP

1) Indentation in region with corresponding stress of -300 MPa only

2) Indentation in region with corresponding strain of 0.04 only

3) Indentation in region with both stresses of -300MPa and plastic strain of 0.04 which matches the actual experimental results.

Figure 4.25: Comparison for indentation in 4J single LSP spot with three different conditions
As shown in earlier figures (4.11) and (4.12), the experimental curve matches exactly with the finite element result for indentation. From the results of both case 1 and case 2, it can be inferred that to obtain the exact correlation with the experimental load vs. displacement curve, both strain and stress components are responsible. With the strain component alone, it can be seen for both the cases that the load required was less than actual experimental load of 0.5N and also the curve did not match the experimental results. Similar trend was observed in indentation with substrate with stress component alone.

Hence from the entire finite element study, it can be very well inferred that the change in indentation curves are due to both stress and strain effect. These changes are due to both the strain hardening effects and also the residual stresses.

4.5) Discussion
The previous sections give an outlook on the various techniques to be used to estimate the surface residual stresses of the LSP treated specimen. From the table (4.1), it can be clearly
interpreted that the residual stresses obtained from method 2 are in closest match with the validation X-ray diffraction results. The O&P method [2] and Khan et al. method [3] used to calculate hardness values are extended to extract the residual stresses. Method 2 gives residual stress values in accordance with the XRD measurement. Method 4 gives values higher than method 2 but overcomes the subjectivity issue.

From finite element results, it can be concluded that the ABAQUS model was successfully developed to get exact correlation between the FEM and experimental load vs. displacement curves. Series of simulations were performed to analyze the actual reason for the change in indentation curves. Though the exact correlation factor was not derived but from the results showed in section 4.2-4.4, it can be inferred that the change in the indentation curves is due to contribution of the both the stresses and strain present in the model. Also it can be concluded that the change in the indentation curve was not due to strain hardening effect alone. It was also seen in the FEM analysis that there was no drastic change in hardness and Young’s modulus of IN718 material value when the material was subjected to various stresses from tensile to compressive region.

The conclusion obtained from both the experimental and finite element calculations are discussed in detail in the next chapter.
CHAPTER 5

CONCLUSION AND FUTURE WORK

A comprehensive study on method of nanoindentation was performed both experimentally and using finite element method. In summary the following has been accomplished in this thesis:

- The technique of estimating the residual stresses from load vs. displacement curves obtained by nanoindentation using Berkovich indenter as proposed by Suresh et al. [1] was modified for estimation of stresses in IN718 material which exhibits pile-up effects.
- A comprehensive experimental study was performed by comparing various analytical methods to estimate the residual stresses. Except for method 1 proposed by Suresh [1] all the other methods are originally used for hardness and Young’s modulus calculation. Coupling with the Suresh et al. method, the other methods are extended for estimation of residual stresses.
- The method of calculation of area using pixels from AFM image had closest match with the experimental X-ray diffraction validation. However this method suffered a disadvantage of subjectivity.
- In method 4, hardness can be calculated as function of total work or plastic work. This method was extended to estimate the residual stresses and had the next closest match with the experimental validation.
- A 2D FEM model has been successfully developed to replicate the exact experimental conditions. Indentation in region with laser shock peening (i.e. pre-existing residual stresses) was successfully performed in ABAQUS explicit software. The correlation between FEM and experimental load vs. displacement curve has ensured the accuracy of the model.
• Extensive FEM study was performed and it is observed that the change in the indentation curve was not only due to strain effect alone but also due to the residual stresses. The finite element produced curves can be used for validating the method of nanoindentation.

• The method of nanoindentation can be extensively used for residual stress estimation for material exhibiting less pile-up effects and less work hardening.

• Nanoindentation can be used as a tool for estimation of residual stresses and a new procedure which overcomes the subjectivity and pile-up effect has been proposed.

On the basis of this work, future extensions can be made on following lines

• Aiming towards extraction of exact residual stresses without strain effects based on the load vs. displacement curve alone. Deriving the exact correction factor due to strain effect which contributes towards some change in the indentation curves.

• An experimental study of nanoindentation on other materials with laser shock peening and implementation of proposed method can help in verifying this method for broader spectrum of materials.
References


APPENDIX

This section of the thesis aims at providing an overview of setting up simulation in ABAQUS Explicit software. This section aims at setting up a quasi-static indentation model and hence STANDARD ABAQUS CAE module is used. To go to the standard ABAQUS CAE, we have to use the following path.

Start→All Programs→ ABAQUS 11.0→ABAQUS CAE→ Create model database with Standard/Explicit model.

This tutorial shows how the 2D indentation model was set-up in ABAQUS in setup-wise manner.

The model which is set-up in ABAQUS is saved as a ‘.cae’ file and it contains all the data saved in the model. The ‘.cae’ file is saved in working directory and C:/Temp is the default working directory for ABAQUS CAE.

**Aim of the simulation:** To set-up 2D axi-symmetric indentation model in ABAQUS and to correlate the FEM results to the experimental results.

**Parts required in the model:** Indentation is done using the rigid indenter inside a deformable substrate. Hence there two major components in the model.

a) Indenter (Rigid)  
b) IN718 substrate (deformable body)

Setup in ABAQUS is mainly categorized into 12 major modules. The major modules used for any model setup, along with their functions are explained below.
1) Part

This is module is the basic module used to initiate any set-up in ABAQUS. The parts to be included in the setup are created/modified in this tab. So in this setup we have two parts: - a) The rigid indenter and b) the deformable substrate.

a) Creating the parts: To create the substrate part, first go to part module and say create. Once clicked on the create tab, a small dialogue box will pop-up as shown in figure which will ask for the type of the part to be made. As we want the substrate to be axi-symmetric deformable substrate with mesh, we will select the options as shown in figure (1).

![Figure 1: Creating the part in ABAQUS](image)

Then after clicked “Continue”, a wire frame background will appear which will allow the part to be sketched and modified. So here, we draw a square box of 0.5x0.5 mm using the “Rectangular” box tab as shown in figure (2).
Once clicked “Done “at the bottom of the window, we get a grey 2D square. Next part is a rigid indenter with an angle of 70.3 degrees. So use the following path.

Part  Create  Axisymmetric  Analytical rigid  Shell.

This will get us to grid background as before. Here we can sketch the indenter using the “Line” option. A line is drawn at inclined angle of 70.3 degrees as shown in figure (3). Also a reference point is allotted to indenter so to give displacement on that point.
After creation of parts, we need to mesh the part. As the indenter is an “ANALYTICAL RIGID”, it cannot be meshed. For meshing a part,

Go to mesh module → Assign global seeds (nodes) → Click on mesh

For biased meshing, choose the edges where biased meshing has to be performed and assign the number of seeds (or nodes) manually.

To change the type of element:

Go to “MESH” module → Mesh control → Select the types of element required (say trias, quads, reduced integration/full integration etc.)

Once both the parts are created, we need to assign material and properties.

2) Materials: The Elastic-plastic material model with Johnson-Cook hardening is used to model the material properties of IN718 substrate. The indenter is modeled as “Analytical rigid” in part module and hence it does not need any material assignment as it is modeled as rigid.

So to assign material properties, go to “Material” module and follow these steps

1) Double click on Material module → General Tab → Density (enter the value for IN718 substrate)

2) Go to Mechanical tab → Elasticity → Elastic and then enter the elastic properties of Isotropic elastic properties for IN718 material.
3) Go to Mechanical tab → Plasticity → Plastic and enter the plastic properties like yield stress and plastic strain. Then go to the “Suboptions” and chose the “Rate-dependent” → Power Law → Johnson-Cook. Here enter all the parameters required for JC model.

The overall material tab is shown in figure (4).

![Material Tab](image)

**Figure 4: Assigning material properties to the substrate**

3) **Sections**: Once the materials and parts are defined, “Sections” module allows us to link them together i.e. we can assign the Elastic-plastic material to the substrate made in the part module here. In order to assign the sections, click on “Section” → Name the section → Homogenous → Click the material card and the grey square substrate will turn into green after assigning the section.

4) **Assembly**: The parts that are created are not always placed in required position of the setup. The assembly module allows aligning the parts as required in actual simulation. The parts required in simulation have to be defined as instances first. It can be summarized that only “instances” can take part in actual simulation.
So in this case, we need to create two separate instances for the indenter and the substrate. In order to do so, click on Instances→Select the part whose instance has to be made→Continue. Repeat this procedure for remaining parts required in the simulation.

In ABAQUS, only the instances are allowed to translate, rotate, or moved from their original position. Thus in this case, translate the indenter to the left-upper corner of the substrate, as the model is being modeled as 2D axi-symmetric model. The final positions of the model are shown in figure (5).

![Figure 5: Positioning the INSTANCES](image)

5) **Step:** Once all the parts are set-up in required position, then we are ready to incorporate, the steps or loading conditions in the model. ABAQUS by default has “INITIAL” step in it. Initial step represents the initial state of the simulation or rather how we want our model just before the simulation begins with all the boundary conditions (if any). In the step module, we can set-up all the required loading conditions and boundary conditions. We can define the displacement to the part which has to be traveled during simulation and also request for the output variables which we would like to view in the results.
The “Initial” step has only two main sub divisions: - a) Interactions and b) Boundary Conditions. The steps other than “INITIAL” which are manually created, contains following sub-categories.

1) **Interactions:** This option allows to set-up interaction between the instances. There are different interaction and its properties depending upon the type of analysis to be done.

![Image](image.png)

**Figure 6: Defining the interactions between master and slave**

In this case, a surface to surface interaction is established between the indenter and the substrate. The rigid indenter is chosen to be “MASTER” surface and substrate is chosen to be a “SLAVE” surface. Generally, a MASTER surface is specified on to the instance which will be displaced during the simulation and “SLAVE” surface is the deformable part. Figure (6) shows interaction between the master and the slave surface. To choose the interactions follow:

INTERACTION module→Surface to surface (Explicit)→ Select the master surface first (will appear red in color)→ then select the slave surface (pink color)→ Continue.

2) **Interaction properties:** This suboption is critical while defining the interaction between two surfaces. ABAQUS should be specified with interaction properties which will enable it to understand the movement of the master surface with respect to the slave surface.
Also if any kind of friction is persisting in the model, then it can be defined through this tab.

3) **BCs (boundary conditions):** If there are boundary conditions right from the INITIAL step of model, then those BCs can be provided in INITIAL step. BCs defined in the INITIAL step are propagated to all preceding steps by default.

In this case, the bottom face of the substrate is constrained in all the degrees of freedom. Hence this BC is specified in INITIAL step. To specify boundary condition in particular step: 

- **BCs** → Select the type of BC → Pick the region to which BC has to be assigned (surface/nodes/elements) → select the degrees of freedom to be constrained from the dialogue box.

![Figure 7: Defining the boundary conditions on bottom surface](image)

Figure (7) shows the BCs assigned to bottom edge of the substrate in initial condition. Similar steps have to be followed for specifying BCs in any other step for any other region or surface.

4) **Field Output requests:** This tab allows selecting the output desired in the results i.e. it allows us to pick what kind of output we like to view in our results.
Go to “Field Output request”→ Select the instance/ area where the results are to be viewed→ Select the output variables such as (Stresses/Strains/Displacements/ Forces etc). It also gives the option of requesting the output after desired number of timeframes. Figure (8) shows the overview of the “Field output requests”.

![Figure 8: Defining the field requests output variables](image)

If not specified, ABAQUS by default extracts all the output variables for entire model.

6) Submitting the analysis: After the entire setup, the job can be submitted by

Go to JOB→ Select the model→ Submit

Once the job is created in job module, an “.inp” is automatically created in the working directory. “.inp” file contains all the commands used throughout the creation of job and can be edited if required.

7) Post-processing: After successful completion of the analysis, the results are stored in “.odb” file. By opening the “.odb” file in ABAQUS “Results” tab, we can view the animation and also
the plot the graphs. Here the “Field output variables” come into picture and the output variables can be plotted at desired position.

Results can be viewed as animation from animation tab. Animation can be viewed as “scaled factor” or according to the “time history”.

For plotting the graph, Tools→XY data→ Create→ODB field output → Select the output variable→ In this case, plot the reaction force at the reference point specified on indenter.

Figure 9: Plotting graph in ABAQUS

Thus using the above guidelines any analysis module can be set-up and run in ABAQUS 11.0.