# Effects of Residual Compressive Stresses in the Shot Peening Process

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***ABSTRACT*-This work presents the favorable effects of residual compressive stresses during shot peening process by varying different parameters such as shot velocity, shot angle, shot diameters. The shot peening process is largely used for the surface treatment of metallic components with the aim of increasing surface toughness and extending fatigue life. A secondary consequence of the process is that the residual stress distribution developed within the material may induce distortion of the component. This effect may therefore be used constructively in the straightening and forming of thin flexible metallic structures. The various techniques available for modeling the effect of peening with finite elements are discussed. In particular, a method of simulating the effect of peening on large flexible panels is presented. Analyses are shown in which a novel loading is applied to finite element meshes in order to produce the desired residual stress distribution. Results from tests are compared to finite element analyses with DOE and preliminary results of large scale analyses are presented.**

***Keywords: Shot Peening, DOE, FEM, Residual Compressive Stresses.***

## 1. INTRODUCTION

### *1.1 Shot peening*

Shot peening is viewed as a process involving multiple and progressively repeated impact. In this process, the result is accomplished by bombarding relatively hard particles, usually spherical chilled shots made from cast iron, steel or glass, having impact velocities. Fig 1.1 shows schematic diagram of shot peening. They are projected against the surface being peened with sufficient velocities to indent the surface. The indentation at each point of impact is the result of local plastic deformation. As the deformed regions tend to expand, they are restrained by adjacent, deeper metal that was not plastically deformed by the shot impact. Since the plastically deformed surface layer seeks to occupy more space it is compressively strained, i.e. it is residually stressed in compression. [2]

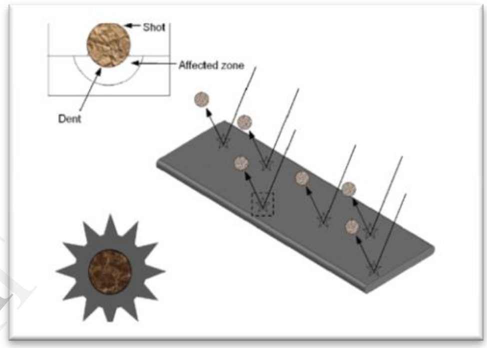


Fig.1.1- Schematic Diagram of Shot Peening

In principle when on rebound of the shot, the balanced system of residual stresses are trapped in the target, the plastically deformed zone recovers only some part of the elastic portion of its total strain. The resulting trapped compressive stresses assume their positions in a thin subsurface layer with tensile residual stresses distributed throughout the lower region. If a peening of a specimen is continued too far, the stress intensity developed may exceed a certain optimum value, thus causing increasing thickness of a compressive layer and extending a tensile region of greater magnitude, ultimately causing fatigue failure. [1,2] Fig 1.2 shows effect of shot peening and stress layers. In other words the Fig 1.2 can be described as, the immediate effect of bombarding high velocity shots onto a metallic target is the creation of a thin layer of high magnitude compressive residual stress at or near the metal surface, which is balanced by a small tensile stress in the deeper core. The magnitude of this compressive residual stress is a function of the mechanical properties of the target material and may reach values as high as 50 to 60 % of the material's ultimate tensile strength.

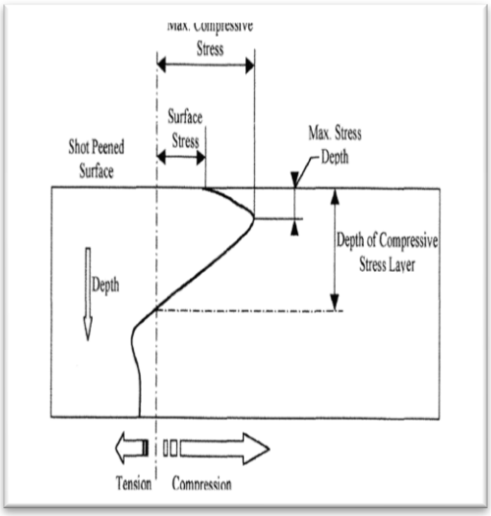


Fig 1.2- Effect of Shot Peening

## 2. FE MODELING

Many researchers showed that FEM can be used for prediction of the residual stresses in the process. [3,4,5,6,7,8]

The model used for shot peening simulation is generated in LS Dyna, consist of three dimensional circular body of Aluminum (LM 13) material having following geometrical properties and act as target in impact analysis. Target have radius R = 8dshot, height H = 3dshot where d shot is the shot diameter. The target has following dimensions and properties shown in table 1 and table 2 show shot properties.

Table 1 Target properties

| Material | Tensile strength | Young's modulus | Poisson's ratio | Density |
|---|---|---|---|---|
| Aluminum LM 13 | 180 Mpa | 73.1 Gpa | 0.35 | 2070 Gm/ $Cm^3$ |

Table 2 Shot Properties

| Shot Type | Young's modulus | Poisson's ratio | Density | Hardness HRC | Shot size (Diameter) |
|---|---|---|---|---|---|
| S 320 (Steel) | 2.1*10E5 Mpa | 0.265 | 7200 Kg / $M^3$ | 45 | 1mm |

### *2.1 Boundary condition*

Piston = Fixed in circular region in all direction as shown.

Shot = free to impact on Piston

Material

Piston = Al (mat 24 – elastic plastic card)

Shot = Rigid (mat 20 – Rigid mat)

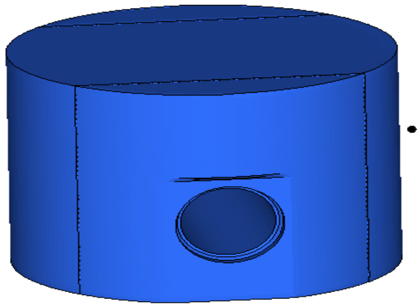

Fig. 2.1 Boundary conditions

Fig. 3.1 shows boundary condition and shot – Target position. Under these boundary conditions shot hits target normal to surface under initial velocity. Also outer sides of target are constrained in all direction considering target is fixed along the periphery.



### *2.2 Mesh Model*

The three-dimensional FE model was developed using the commercial finite element code Ls Dyna. Fig. 2.2 and Fig. 2.3 show the FE mesh that was used to investigate single shot impact on a component in the present paper.

Target mesh model developed in this study global element length 0.2 mm and min 0.1 mm.

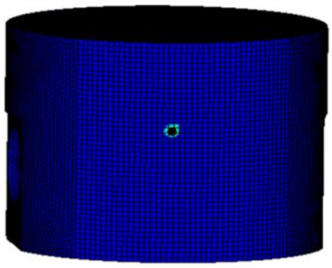

Fig. 2.2 Target mesh model

In LS Dyna, rigid bodies can be defined with an analytical rigid surface. So, a fully spherical surface with a mass positioned at its centre was used to model a shot as shown in Fig. 2.3 Convergence tests were conducted using different meshes and element types to ensure the numerical results presented in this paper were not affected by the choice of mesh or element types.

Shot mesh model developed in this study as rigid element having material type mat 20 and mass applied at all nodes equally.

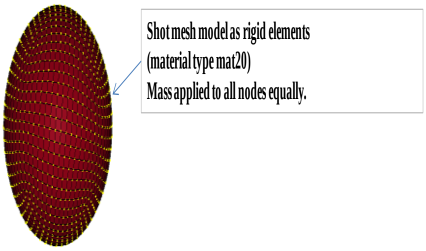


Fig. 2.3 Shot mesh model

*2.3 Parametric study of single shot impact model*

Experimental measurement of single shot impact was very rare. No experimental data is found in the literature for comparison with this study. Fig 2.4 shows impact zone of metallic shot on aluminum LM13 target with a velocity and at perfectly at normal to the surface of circular target.

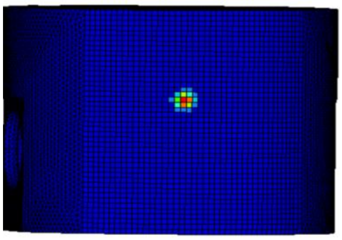

Fig. 2.4 Shot impact zone

Following are the results of shot peening simulation which are obtained by varying process parameters of shot peening process. In this parametric study four parameters are varied. While varying any parameter rest all parameters are maintained constant. In this study process parameter like shot size maintained as 1mm dia., shot velocity 60m/s, distance between nozzle and target is 1m and angle of impact taken as 90°.Parameterwise parametric analysis is mentioned below.

*2.4 Finite element modeling at different speeds.*

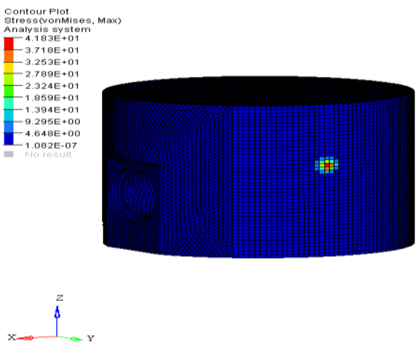


Fig. 2.5 Stress contour at shot speed 30 m/s

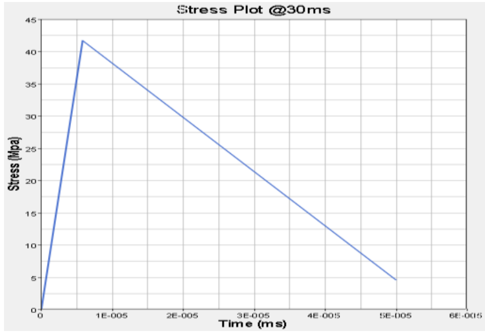


Fig.2.6 Stress plot at shot speed 30m/s

Fig. 2.5 and 2.6 shows stress contour and stress plot at a shot speed of 30 m/s. Stress plot shows stresses developed in piston. Stress plot should be drawn for time interval from point of contact of shot up to rebounding of shot. Stress plot shows maximum stress developed at the time of contact is 42 Mpa. After rebounding of shot due to stress relaxation some part of stress is released. After 0.00005 second 4 Mpa residual compressive stresses retained in material. This residual stress forms compressive stress layer on material surface.

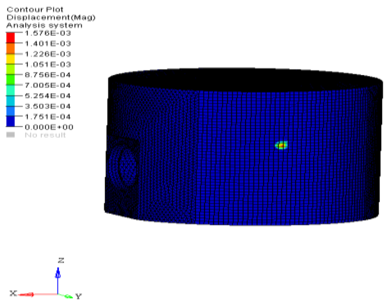


Fig. 2.7 Displacement contour at shot speed 30m/s

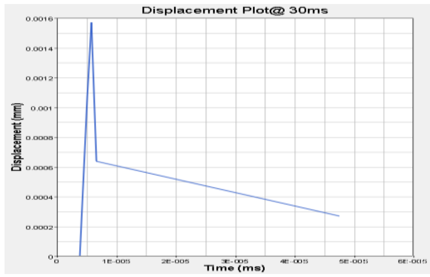


Fig. 2.8 Displacement plot at shot speed 30m/s

From Fig. 2.7and 2.8 it is clear that at the time of contact material deform 0.0016 mm and due to elastic recovery, material contracts and final displacement is 0.0003 mm. Following are the result of second iteration which is carried out at a shot speed of 60 m/s. Von mises diagram shown below is at 60 m/s.

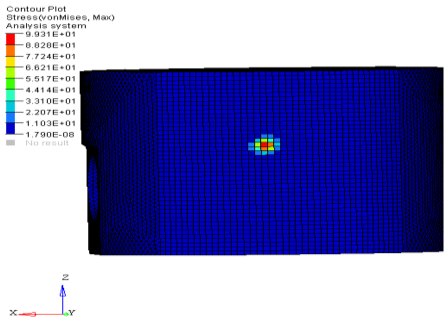


Fig. 2.9 Stress contour at shot speed 60 m/s

Fig. 2.9 and Fig. 2.10 shows stress contour and stress plot at a shot speed of 60 m/s. Stress plot shows stresses developed in piston. Stress plot shows maximum stress developed at the time of contact is 100 Mpa. After rebounding of shot due to stress relaxation some part of stress is released. After 0.00005 second 13Mpa residual compressive stress is retained in material. This residual stress forms compressive stress layer on material surface.

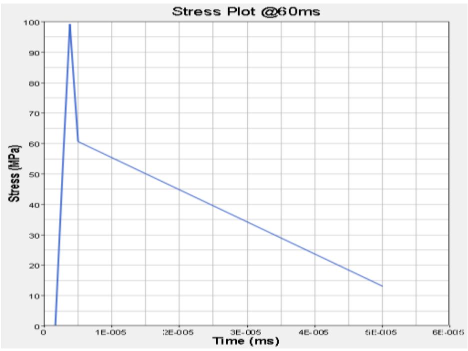


Fig. 2.10Stress plot at shot speed 60m/s

Following Fig.2.11 and Fig. 2.12 shows displacement plot of impact analysis at shot speed of 60 m/s. From the displacement plot it is clear that plate deformation is about 0.002mm which is negligible. In this way we can find out stress retained in material after relaxation of stress.

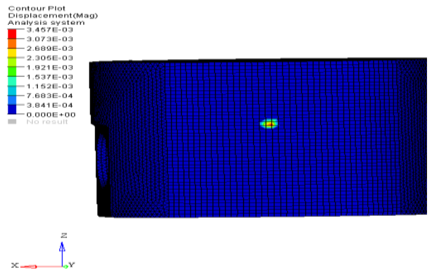


Fig. 2.11 Displacement contour at shot speed 60 m/s

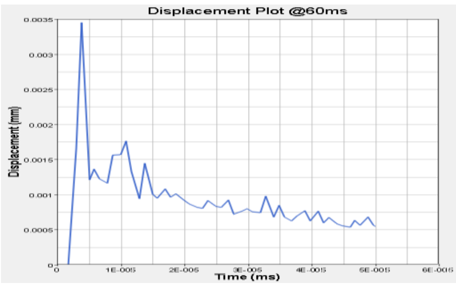


Fig. 2.12 Displacement plot at shot speed 60 m/s

Stress plot and displacement plot shows result of analysis at different speed of shot. Consolidate graph of residual stress at different speed is shown below. Fig. 2.13 shows residual stress obtained in material at different speed. From graph it is clear that at speed 65 m/s residual stress is 15 MPa which exceed yield limit of material. Graph clearly shows as speed increases residual stress value also increases.

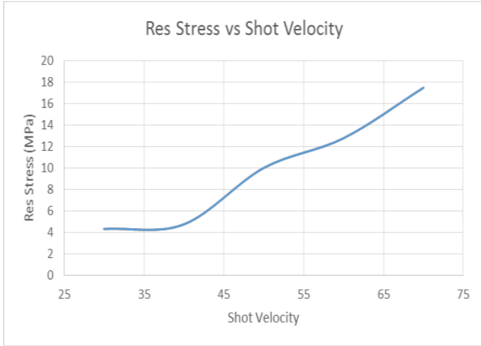


Fig. 2.13 Residual stress distribution at different velocities

Deflection plot shows that for all these speeds maximum deflection in material is 0.022 mm which is negligible. From above study it is clear that there may be chances of getting good fatigue life after shot peening for speed of shot in between 45m/s to 60 m/s.

*2.5 Finite element modeling for different shot sizes.*

Stress contour and stress plot shows result of FE analysis for different shot sizes.

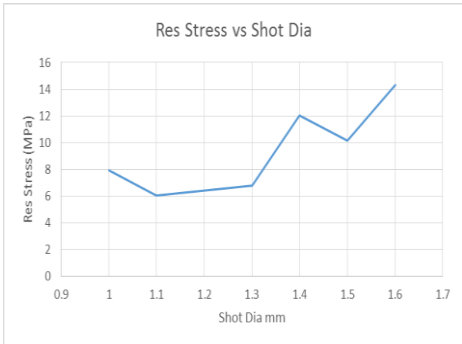


Fig 2.14 Residual stress distribution at different shot size

Fig. 2.14 shows graph of residual stress obtained for different shot sizes. From graph we seen that for shot size 1mm dia. we get residual stress 8 MPa and for shot size 1.1 mm we get 6 MPa residual stresses which is too much below of material strength limit. Also deflection plot shows maximum deflection in material is 0.001 mm which is negligible. So we can preferable choose 1mm dia. shot for experimental study.

*2.6 Finite element modeling by varying impact angle.*

Stress contour and stress plot shows result of FE analysis of shot peening by varying impact angle of shot.

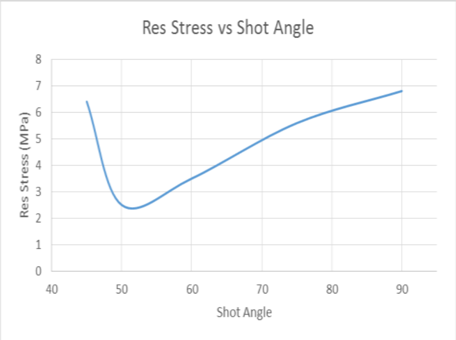


Fig. 2.17 Residual stress distribution at different shot angle

Fig. 2.17 shows residual stresses retained after stress relaxation. These stresses vary from 0 MPa to 7 MPa. At angle of impact 70 deg. and 90 deg. residual stresses obtained round about same i.e. 5 MPa and 6.8 MPa respectively. Residual stress obtained at 90 deg. impact angle is more as compared 70 deg. shot impact. Still we will choose 90 deg. shot impact angle for experimental purpose because it will create less interference between impacting shot and rebounding shot.

*2.7 Summary*

Analysis is carried out at different shot speed, shot impingement angle, shot size and shot impact distance. At different shot speed it is observed that as shot speed increases residual stresss value increase. It is also clear that as shot size and shot impingement angle increases also stress level increases. The relation between residual stress and shot impact distance is reverse proportional. From FE analysis it is found that 60m/sec shot speed, 1mm dia. shot size, 90° shot impingement angle and 1m impact distance is found as optimized process parameter.

## 3. DESIGN OF EXPERIMENTS (DOE)

3.1 Design of Experiments (DOE) By Taguchi Method

Design of Experiments (DOE) is a powerful statistical technique to study the effect of multiple variables simultaneously. Dr. Taguchi's standardized version of DOE, popularly known as the Taguchi method or Taguchi approach, was introduced in the USA in the early 1980's. Today it is one of the most effective quality building tools used by engineers in all types of manufacturing activities. The DOE using Taguchi approach can economically satisfy the needs of problem solving and product/process design optimization projects. By learning and applying this technique, engineers, scientists, and researchers can significantly reduce the time required for experimental investigations.

- Overall advantage

DOE using Taguchi approach attempts to improve quality which is defined as the consistency of performance. Consistency is achieved when variation is reduced. This can be done by moving the mean performance to the target as well as by reducing variations around the target. The prime motivation behind the Taguchi experiment design technique is to achieve reduced variation (also known as ROBUST DESIGN). This technique, therefore, is focused to attain the desired quality objectives in all steps. The classical DOE does not specifically address quality. "The primary problem addressed in classical statistical experiment design is to model the response of a product or process as a function of many factors called model factors. Factors, called nuisance factors, which are not included in the model, can also influence the response... The primary problem addressed in Robust Design is how to reduce the variance of a product's function in the customer's environment." The Taguchi method is used to improve the quality of products and processes.

- Common areas of application of the technique are

- Optimize Designs using analytical simulation studies
- Select better alternative in Development and Testing
- Optimize manufacturing Process Designs
- Determine the best Assembly Method
- Solve manufacturing and production Problems

- PARAMETER DESIGN

Taguchi approach generally refers to the parameter design phase of the three quality engineering activities (SYSTEM DESIGN, PARAMETER DESIGN and TOLERANCE DESIGN) proposed by Taguchi.

- Off-line Quality Control
- Quality Loss Function
- Signal to Noise Ratio(s/n) For Analysis

- Analysis of Results

Calculate factor averages and determine

* Optimum Condition
* Nature of Influence of Factors
* Expected Result at Optimum Condition.

*3.2 Run summary (DOE)*

DOE is carried out in the alter hyperwork software by Taguchi Method. The following results were obtained.

Table 3 DOE run summery

| Sr. no. | Shot Diameter mm | Shot Velocity m/s | Shot Angle deg | Pset | Res. Stresses mpa |
|---|---|---|---|---|---|
| 01 | 1.00 | 40 | 45.00 | 4.02 e-04 | 3.953 20 |
| 02 | 1.00 | 40 | 52.50 | 4.75 e-04 | 15.46 90 |
| 03 | 1.00 | 40 | 60.00 | 5.23 e-04 | 10.60 90 |
| 04 | 1.00 | 50 | 45.00 | 5.32 e-04 | 9.186 50 |
| 05 | 1.00 | 50 | 52.50 | 5.76 | 9.409 |

| | | | | | |
|---|---|---|---|---|---|
| | | | | e-04 | 40 |
| 06 | 1.00 | 50 | 60.00 | 5.76e-04 | 18.0020 |
| 07 | 1.00 | 60 | 45.00 | 5.82e-04 | 16.3420 |
| 08 | 1.00 | 60 | 52.50 | 5.59e-04 | 18.1510 |
| 09 | 1.00 | 60 | 60.00 | 5.23e-04 | 9.61440 |
| 10 | 1.05 | 40 | 45.00 | 4.02e-04 | 3.95320 |
| 11 | 1.05 | 40 | 52.50 | 4.75e-04 | 15.4690 |
| 12 | 1.05 | 40 | 60.00 | 5.23e-04 | 10.6090 |
| 13 | 1.05 | 50 | 45.00 | 5.32e-04 | 9.18650 |
| 14 | 1.05 | 50 | 52.50 | 5.76e-04 | 9.40940 |
| 15 | 1.05 | 50 | 60.00 | 5.76e-04 | 18.0020 |
| 16 | 1.05 | 60 | 45.00 | 5.82e-04 | 16.3420 |
| 17 | 1.05 | 60 | 52.50 | 5.59e-04 | 18.1510 |
| 18 | 1.05 | 60 | 60.00 | 5.23e-04 | 9.61440 |
| 19 | 1.10 | 40 | 45.00 | 5.57e-04 | 14.4340 |
| 20 | 1.10 | 40 | 52.50 | 6.39e-04 | 6.76160 |
| 21 | 1.10 | 40 | 60.00 | 6.71e-04 | 6.40050 |
| 22 | 1.10 | 50 | 45.00 | 6.77e-04 | 7.99130 |
| 23 | 1.10 | 50 | 52.50 | 6.79e-04 | 18.6180 |
| 24 | 1.10 | 50 | 60.00 | 6.56e-04 | 17.3740 |
| 25 | 1.10 | 60 | 45.00 | 6.68e-04 | 18.6630 |
| 26 | 1.10 | 60 | 52.50 | 6.31e-04 | 8.98820 |
| 27 | 1.10 | 60 | 60.00 | 6.14e-04 | 4.34410 |
| 28 | 1.20 | 40 | 45.00 | 6.92e-04 | 3.95100 |
| 29 | 1.20 | 40 | 52.50 | 7.31e-04 | 10.6650 |
| 30 | 1.20 | 40 | 60.00 | 7.32e-04 | 15.7010 |
| 31 | 1.20 | 50 | 45.00 | 7.32e-04 | 16.1650 |
| 32 | 1.20 | 50 | 52.50 | 7.10e-04 | 12.9470 |
| 33 | 1.20 | 50 | 60.00 | 6.92e-04 | 5.22070 |
| 34 | 1.20 | 60 | 45.00 | 6.96e-04 | 7.62160 |
| 35 | 1.20 | 60 | 52.50 | 6.79e-04 | 6.36020 |
| 36 | 1.20 | 60 | 60.00 | 6.48e-04 | 22.7010 |

From above summery it is clear that the results of favorable residual stress value found out 22.701 Mpa.

## 4. EXPERIMENTAL WORK

Previous section presented simulation of shot peening process using analysis software and DOE. From these analyses following parameter for shot peening process are finalized from the analysis carried out and described in previous chapter.

Shot velocity 60 m/s,

Shot size 1 mm dia.

Shot impact distance 1 m

Shot impact angle 90 deg. with target.

The exposure time is set constant, equal to 120 sec for all specimens. Though it is found that 60 m/s as optimized velocity still the shot peening is carried out with three different velocities for study purpose.



### *4.1 Specimen details.*

Aim of this study is to find out Residual Stresses on piston material due to shot peening process. So we use LM 13 Material which is mostly used for piston. Material composition is mentioned in table 4.

Table 4 Material composition of LM 13

| **Name of material** | **Concentration** |
|---|---|
| Copper | 9.0-11.0 % max, |
| Magnesium | 0.2-0.4 % max, |
| Silicon | 10.0-13.0 % max, |
| Iron | 1.0 % max. |
| Manganese | 0.5 % max. |
| Nickel | 1.5 % max. |
| Zinc | 0.1 % max. |
| Lead | 0.1 % max. |
| Tin | 0.1 % max. |
| Titanium | 0.2 % max. |
| Aluminium | Remainder % |
| Others: each | 0.05 % |
| Others: total | 0.15% |

*4.2 Shot peening procedure*

- Feed the shots through hopper.
- Adjust magna valve for desirable flow rate.
- Load the standard test specimen in fixture (It will expose half part of specimen) and close the door.
- Set the speed for desirable shot speed.
- Set the cycle time.
- Start the cycle.
- Open the door after cycle completion and run same cycle for remaining half portion of specimen.
- Repeat the procedure for another specimen.
- Set the new shot speed and repeat the procedure.

## RESULTS

- Shot peening is carry out on specimen with optimized parameters selected from finite element analysis. Shot peening is done on specimen with shot velocity 60m/sec, 1mm dia. shot size, 1 m impact distance and 90° shot impact angle.
- Residual stress found on the test specimen to have a value equal to or greater than permissible (13.0 Mpa average). The residual stresses are found to be in the acceptable range, with reference to FEA acceptable range is 11 to 18 Mpa. Residual stresses test is carried out by Hole drilling method.

## 5. CONCLUSIONS

1 This study is particularly carried out for piston material (LM 13). In this study standard specimen of LM 13 material is prepared and shot peening is carry out on the actual piston which is made by LM13 material. From finite element analysis and experimental work following conclusions are drawn.

- From the FE Analysis it is clear that 60 m/s is optimum speed for shot peening for LM 13.
- For LM 13, 1 mm dia. shot size introduces the residual stress 8 MPa which is maximum, as compared to the stresses developed by other shots and considerably below the yield stress limit of LM 13.
- From FE analysis for LM 13 at variable impact distance residual stress level is constant up to 1 m and at distance 2 m this value falls to 6 MPa. So 1m impact distance is preferable for shot peening on LM 13.
- 90 deg. shot impact angle is best for shot peening on LM13 because it will create less interference between shots.

2 From DOE it is obtained 22.7 Mpa residual stress value with optimized parameters such as shot velocity is 60 m/s.

3 Residual stress value found out by experimentally on the test specimen to have a value equal to or greater than permissible (13.0 Mpa average).



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