Investigation of fatigue strength of aluminium 2024-T3 subjected to shot peening process by Ni shots

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Abstract
Aluminium alloys are most suitable for light weight applications. This research paper investigates the fatigue strength of Aluminium alloy 2024-T3 after shot peening process using nickel shots. Nickel shots are used in this research to investigate the influence of nickel on the fatigue strength of aluminum 2024-T3 alloy. Compressed air is used for shot peening process. Shot peening process parameter values are chosen based on response surface method (RSM) to conduct the experiments. Desirability approach is used to get the optimized values of process parameters. High cycle fatigue testing is performed to find the fatigue strength of specimens before and after shot peening process. An increase in the fatigue strength up to 34% is observed after peening using the nickel shots. FESEM and EDS tests revealed the presence of nickel on the surface of aluminium 2024-T3 specimen after shot penning with nickel shots.

1. Introduction

Shot peening imparts residual compressive stresses on the material surface and alters the surface property of base material. Plastic deformation is possible by altering surface layer of materials when shots strike the material surface using compressed air. This results in improvement of fatigue strength of the base material. Severe shot peening enhances hardness and wear resistance [1]. Recent research works also proved that intensity of shot peening process increases the fatigue strength [2]. Fatigue life depends on various factors like relaxation level of the stress layer, surface modification created by peening process and the compressive residual field induced [3]. From experimental investigations, it was observed that enhancement of fatigue life was influenced by arresting crack formation. Many failures occur because of the imperfections on surface.

A research work showed improvement in fatigue life of AA7075-T7451 when electroplated and shot peened using ceramic and glass beads [4]. The effect of surface damage on the fatigue life of nickel super alloys is evaluated by Fleury et al [5] and it was found that residual compressive stresses around the damage significantly improved the fatigue life. Comparative study between shot peened and unpeened specimen were done by focusing on the microstructure and strain developed. Fatigue life and hardness enhanced when shot peened using laser source on Ti834 [6] and Ti6Al4V alloys [7].

It is also evident that the material used for shot peening also has a great influence on the outcome of results. Wide range of materials like ceramic shots, glass beads are used for peening. Proper selection of peening material will result in surface alloying. A study showed that zinc was surface alloyed with AA2024 at certain peening conditions and this led to enhancement in hardness and anti-corrosion properties of AA2024 material [8]. Efforts are continuously taken to improve the shot peening process each day and alternatively fine particles ranging from 5–100 microns in diameter were used for shot peening. This process named as Fine particle shot peening (FPSP) improves the fatigue life was one order magnitude higher than the one peened using normal peening particles [9]. It is also found that superior material properties are obtained when severe shot peening was carried out on steel samples. This was due to the result of nanostructured surface layer of material that was formed during the peening process [10].
Almen strip intensity verification, coverage and trajectory of peening are all influencing factors. Therefore, effects of trajectory were also studied and reported by Gariepy et al [11]. Hence optimization on peening parameters to control the fatigue life were also carried out for controlled shot peening process [12]. Mechanical incompatibility between different layers on the peened surface to the un-deformed layers on the specimen interior introduces enhanced mechanical properties [13]. Shot peening techniques are now being used as correction techniques apart from enhancing mechanical properties. Shot peening was carried out to restore the specimen to its shape because of buckling, while welding. As shot peening also enhances the hardness and modifies surface roughness, peening was carried out using ultrasonic methods after welding 5A06 Aluminium alloy in order to restore the buckling effect [14]. The shot-peening pretreatment yielded a significant increase in the Ti2Ni content and the nano-hardness of the layer, resulting in grain size refinement of the formation phase [15]. The nano-hardness of the Ni implantation layer increased with the shot-peening pretreatment. At an implantation energy of 40 keV, the nano-hardness of the shot-peened layer was 50.8% higher than that of the non-peened layer. The shot-peened samples resisted fatigue delamination of the Ti6Al4V alloy [16].

The recent advances in shot peening process demands the necessity to analyze the influence of process parameters on the mechanical and metallurgical properties of materials. From the literature study, it is found that Nickel shots were not used for shot peening on AA2024-T3. For a metal to be tough, it must display both strength and ductility [17]. Nickel has higher tensile strength and higher yield strength than aluminium. Hence an experimental study using Nickel as shot material in peening process on Aluminium 2024-T3 specimen is carried out and the effect of shot peening using Nickel shots on the fatigue strength are measured. Optimization of peening parameters for desired fatigue properties are done using design expert software. Comparison of fatigue strength before and after shot peening process is done for better understanding of the improvement in mechanical property of AA2024-T3.

### 2. Material selection

AA2024-T3 is chosen as target material of interest. Nickel spherical balls having diameter ranging from 0.5 to 1 mm is chosen as shot material. The chemical composition of AA2024-T3 and Ni balls are indicated in table 1.

### 3. Experimental procedure

#### 3.1. Shot peening process

A tailor made shot peening machine manufactured by MEC SHOT with a pressure range of 0 to 12 bar is used for shot peening. Shot peening process is done using pressurized air. Shot material is loaded in the bottom hopper. The pressure and distance are taken as the two parameters for study purpose which is shown in table 2.

Shot peening pressure and peening distance can be adjusted as per the experimental requirement. To perform shot peening process, each specimen is cleaned with acetone and kept on the machine table inside the peening chamber. The peening pressure and peening distance is adjusted for various combinations as obtained from response surface method (RSM) as shown in table 2. During peening process, the nickel shots along with the compressed air are made to bombard on the specimens. Specimens are shot peened for 13 combinations. Shot peening is done on both the sides of specimen.

### Table 1: Chemical composition of AA2024 T3 and Nickel shots.

| Specimen       | Mg | Cu | Mn | Si  | Cr | Ni | Zn | Fe | l  |
|----------------|----|----|----|-----|----|----|----|----|----|
| Target-AA2024-T3 | 1.83 | 4.98 | 0.52 | 0.13 | 0.03 | 0.01 | 0.06 | 0.33 | 92.09 |
| Shot-Nickel     | --- | --- | --- | --- | --- | 99.99 | --- | 0.01 | --- |

### Table 2: Input parameters for investigation.

| S. No | Parameters | Remarks |
|-------|------------|---------|
| 1     | Pressure   | Refers air pressure used during shot peening process. Nickel shots go along with air during peening process. (4 MPa to 6 MPa). |
| 2     | Distance   | Refers perpendicular distance between the surface of target specimen and the nozzle from which the shot materials come out (30 mm–60 mm). |

The chemical composition of AA2024-T3 and Nickel shots are shown in table 1.
3.2. Specimen preparation
AA2024 sheet pretreated for T3 condition, i.e. solution treated at the temperature of 550 °C, cold rolled and aged at room temperature. Thickness of the sheet is 3 mm. AA2024 -T3 sheet is cut into required size as per ASTM E466 standard using water jet cutting with dimensions shown in figure 1. All the dimensions shown below are in millimeters. Water cutting is chosen to avoid the influence of cutting temperature which can create thermal stress around the cutting edges that affects the material properties.

3.3. Almen strip test
Almen strip test is essential to decide the shot peening time. Before shot peening the AA 2024-T3 specimens, Almen strips are shot peened. 'A' type Almen strips are used for measuring the Almen arc height. After shot peening process, the straight Almen strip bends due to induced compressive residual stress. Sample Almen strips after shot peening process are shown in figures 2(a)–(c). Arc height is measured for different timings and the same is plotted as a graph shown in figure 3. The Almen arc height is measured as 4 mm for 130 s and the height remains same after peening it for more than 130 s. Saturation of Almen arc height is identified as 4 mm at 130 s. Shot peening time for reaching maximum Almen height is adopted for shot peening the AA2024-T3 specimens. This Almen height is identified for a particular peening condition to control the peening intensity.

3.4. Fatigue test
The uni axial fatigue testing machine with a maximum load capacity of 1000 kg and a frequency of 4 cycles per second is used for fatigue testing. Specimen is fixed vertically in the uni axial fatigue testing machine as shown in figure 4. High cycle fatigue testing is adopted for determining fatigue strength with tensile-tensile axial loading cycle. The Stress Ratio is taken as \( R = 1 \). Each specimen is tested for a minimum of \( 10^5 \) cycles. Initially higher load is applied to specimen. If the test specimen fails before \( 10^5 \) cycles, then the applied load is reduced and test is repeated until the maximum load for which the specimen with stands \( 10^5 \) cycles and the fatigue strength is calculated.
3.5. Design matrix

Design expert software is used for experimental design of RSM based on central composite design as well as statistical analysis [18]. In the present work, peening pressure and peening distance from specimen to nozzle are the two factors considered for analysis. Fatigue strength of AA2024 T3 is the response chosen for studying the influence of shot peening process. Trial experiments are conducted to decide the feasible and suitable range of values for the considered factors. The first factor distance between peening nozzle and target specimen is varied from 30 mm to 60 mm. Second factor shot peening pressure is varied from 4 MPa to 6 MPa. Thirteen combinations of pressure and distance are obtained from Central composite design of RSM and the design matrix obtained is shown in table 3.

4. Results and discussion

4.1. Fatigue strength

Fatigue strength value is tested for the specimen before and after shot peening process. Initially higher load value of 350 kg is given in the uniaxial fatigue testing machine and the total number of cycles completed before failure
is noted. If the cycles are less than $10^5$, new specimen is shot peened with same parameter combination and tested for a lesser load, say, 300 kg. This testing procedure is repeated until the specimen shot peened for a particular combination completes $10^5$ cycles. Corresponding load is noted for calculation of fatigue strength obtained for a particular combination of factors. Similar procedure is adopted for testing all the specimens shot peened with 13 combinations obtained from design matrix. Test is performed for three unpeened specimens and average value of fatigue strength before shot peening process is found to be 116 MPa. The fatigue strength values obtained for all 13 combinations after shot peening process are shown in table 4.

The total number of cycles completed by specimens that are tested for finding fatigue strength before and after shot peening under various loading conditions are graphically represented in figure 5. Thirteen specimens are tested for fatigue strength and they are indicated as ASP01 to ASP13 in the graph shown in figure 5. They represent the number of cycles completed for different loads by the specimens after shot peening (ASP) process for the applied tensile-tensile loading cycles. BSP1 curve represents number of cycles completed by specimens before shot peening (BSP) process for different loading conditions. In the graph, ASP07 curve shows the response of the specimen shot peened with 5.99 MPa peening pressure with a peening distance of 45 mm. This specimen has taken a maximum cyclic load of 334 kg for $10^5$ cycles without failure. Corresponding fatigue strength of this specimen is calculated and mentioned in table 3.

### 4.2. Residual stress calculation using XRD test

X-Ray diffraction method is used for calculation of residual stress induced in AA2024 T3 after shot peening process. Panalytical x-ray Diffraction machine is used to find diffraction angle and lattice spacing of crystal planes for the specimens before and after shot peening process. Changes in the lattice spacing results in the

| Table 3. Experimental design. |
|-------------------------------|
| Coded value | Actual value |
| Std. | Run | Pressure (MPa) | Distance (mm) | Pressure MPa ($X_1$) | Distance mm ($X_2$) |
|-------|-----|----------------|---------------|------------------|------------------|
| 10    | 1   | 0.000          | 0.000         | 4.9945           | 45               |
| 3     | 2   | −1.000         | 1.000         | 4.28987          | 55.6066          |
| 4     | 3   | 1.000          | 1.000         | 5.69913          | 55.6066          |
| 11    | 4   | 0.000          | −1.414        | 4.9945           | 30               |
| 2     | 6   | 1.000          | −1.000        | 5.69913          | 34.3934          |
| 6     | 7   | 1.414          | 0.000         | 5.991            | 45               |
| 5     | 8   | −1.414         | 0.000         | 3.998            | 45               |
| 9     | 9   | 0.000          | 0.000         | 4.9945           | 45               |
| 12    | 10  | 0.000          | 0.000         | 4.9945           | 60               |
| 1     | 12  | −1.000         | −1.000        | 4.28987          | 34.3934          |
| 13    | 13  | 0.000          | 0.000         | 4.9945           | 45               |

| Table 4. Experimental design and results. |
|-----------------------------------------|
| Coded value | Actual value |
| Std. | Run | Pressure (MPa) | Distance (mm) | Pressure MPa ($X_1$) | Distance mm ($X_2$) | Response fatigue strength (Y) MPa |
|-------|-----|----------------|---------------|------------------|------------------|-------------------------------|
| 10    | 1   | 0.000          | 0.000         | 4.9945           | 45               | 148                           |
| 3     | 2   | −1.000         | 1.000         | 4.28987          | 55.6066          | 143                           |
| 4     | 3   | 1.000          | 1.000         | 5.69913          | 55.6066          | 153                           |
| 11    | 4   | 0.000          | −1.414        | 4.9945           | 45               | 148                           |
| 7     | 5   | 0.000          | −1.414        | 4.9945           | 30               | 151                           |
| 2     | 6   | 1.000          | −1.000        | 5.69913          | 34.3934          | 155                           |
| 6     | 7   | 1.414          | 0.000         | 5.991            | 45               | 156                           |
| 5     | 8   | −1.414         | 0.000         | 3.998            | 45               | 142                           |
| 9     | 9   | 0.000          | 0.000         | 4.9945           | 45               | 148                           |
| 12    | 10  | 0.000          | 0.000         | 4.9945           | 45               | 148                           |
| 8     | 11  | 0.000          | 1.414         | 4.9945           | 60               | 146                           |
| 1     | 12  | −1.000         | −1.000        | 4.28987          | 34.3934          | 145                           |
| 13    | 13  | 0.000          | 0.000         | 4.9945           | 45               | 148                           |

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corresponding shift in the diffraction angle. Residual stress is calculated from the values of lattice spacing and diffraction angle. Figure 6 shows the graphical plot for diffraction of x-rays obtained from the surfaces of specimens before and after shot peening process. The plots shown in figure 6 indicate the results obtained from Panalytical XRD machine with Copper x-ray tube. From the XRD results the residual stress is obtained and shown in table 5.

From the XRD analysis, observations show that there is a small increase in the residual compressive stress on the surface of AA2024 T3 specimen after shot peening process. This increase in residual compressive stress is expected to influence the mechanical properties of the specimen [19].

### 4.3. Optimizing fatigue strength

After obtaining the test result values, design expert software is used to predict the optimum combination of shot peening pressure and peening distance for getting maximum fatigue strength. Regression equation is obtained for fatigue strength in terms of actual factors based on the experiments conducted using central composite design of design expert software. This regression equation is used to predict the values of response for given levels of each factor.

| Table 5. Residual stress values before and after shot peening process. |
|---------------------------------------------------------------|
| Residual stress before shot peening process | Residual stress after shot peening process |
| −12 MPa | −18 MPa |
The regression equation for fatigue strength is shown below

\[ Y = 170.42269 - 10.15511X_1 - 0.52353X_1 - 1.4844E15X_1X_2 + 1.70531X_2^2 + 4.4119E003X_2^2 \]

In the above regression equation, \(X_1\) and \(X_2\) represents the two factors, peening pressure and peening distance. \(Y\) represents the response fatigue strength.

Optimum combination of peening pressure and distance are predicted as 5.699 MPa and 30 mm respectively. Maximum fatigue strength is predicted as 156 MPa. Three specimens are used for confirmation test. Shot peening is done on both the sides of specimens with the optimum pressure and distance. Then tests are performed on the specimens.

Actual fatigue strength is measured from confirmation tests for three specimens as 154 MPa, 156 MPa and 155 MPa. The average of the actual fatigue strength is measured as 155 MPa. The predicted value and average value of three trials are shown below in table 6. Desirability value for prediction of the optimum fatigue strength is obtained as 1.00 in the design expert software. In the present work the fatigue strength of AA2024-T3 before shot peening process is measured as 116 MPa and the fatigue strength after shot peening with Nickel shots is measured as 155 MPa (average). An increase in fatigue strength of 34% is observed. Rajesh and Ashoka [20] reported 17% increase in fatigue strength when AA2024 T3 specimen is shot peened using glass bead shots. Hence, shot peening using Nickel balls has resulted in significant improvement in fatigue strength when compared to glass bead shots.

Contour plot shown in figure 7(a) represents the influence of factors, peening pressure and peening distance on the response. From the graph, it is clearly evident that peening pressure (factor \(X_1\)) is influencing the response fatigue strength more when compared to factor \(X_2\), peening distance. During shot peening process, impingement rate of shots will increase with the peening pressure. When the peening pressure increases from 4.2 MPa to 5.6 MPa, the graph shows an increasing trend in the fatigue strength. Fatigue strength is high when pressure is increased by keeping the peening distance at 45 mm. Figure 7(b) shows the comparison of actual and predicted values of fatigue strength.figure 7(c) shows the 3D representation of the factors that influence the response. Similarly, 3D contour plot also shows an increase in fatigue strength when peening pressure increases from 4.2 MPa to 5.7 MPa. From the observations it is understood that the peening pressure has more influence on fatigue strength.

### Table 6. Maximum Fatigue strength after shot peening.

| Pressure\((X_1)\) in MPa | Distance\((X_2)\) in mm | Predicted value | Actual value |
|--------------------------|--------------------------|----------------|-------------|
| 5.699                    | 30                       | 156            | 155         |

The regression equation for fatigue strength is shown below

\[ Y = 170.42269 - 10.15511X_1 - 0.52353X_1 - 1.4844E15X_1X_2 + 1.70531X_2^2 + 4.4119E003X_2^2 \] (1)

4.4. ANOVA test results

Design expert software is used for analysis of variance for response surface quadratic model and it is shown in table 7. The model is found significant and the corresponding details are given in the below table. 'Predicted R-Squared' value is 0.8879 and the 'Adjusted R-Squared' value is 0.9730, the difference is less than 0.2 between predicted and adjusted R-square values. So predicted R-square has a reasonable agreement with adjusted R-square. 'Adequate Precision' measures the signal to noise ratio as 29.230. A ratio greater than 4 is desirable. It indicates an adequate signal to noise ratio.

4.5. Metallographic investigations

4.5.1. Field emission scanning electron microscope

Field emission scanning electron microscope (FESEM) is widely used to analyze the changes in the microstructural behavior of materials [21–23]. Microstructural and micro chemical analysis is performed on AA2024-T3 specimens before and after shot peening with nickel balls. Both specimens are analyzed by Field emission scanning electron microscope (FESEM) with a magnification of 500 X. Figures 8 and 9 show the images obtained from FESEM test. It shows the surface of AA2024 T3 specimens before and after shot peening process. The impact of shots on the surface is visible in the scanned images. Before shot peening the specimen surface is flat and after shot peening the surface has mountain type curved peaks and valleys. When the shots impinge the surface it has a bombarding effect on the surface and small dents are created as shown in figure 9, which in turn results in the induction of residual compressive stresses.
Figure 7. (a) Contour plot for actual factors and response. (b) Plot for predicted and actual responses. (c) 3D plot for influence of factors on response.
4.5.2. Energy dispersive x-ray spectrometer (EDS).

The results of the energy dispersive x-ray spectrometer (EDS) is used for micro chemical analysis which shows the presence of different metals in the specimen before and after shot peening. Color mapping of different elements present on the surface specimens before and after shot peening is done. Test results of FESEM and EDS of specimen before and after peening process are shown in figures 10(a) and 10(b) and 11(a) and (b).

Color mapping image in figure 10(a) shows different metals present in the AA2024-T3 specimen before shot peening process that are mapped to different colors. Zinc, silicon, magnesium, ferrous, copper and aluminium (except nickel) are present in figure 10(a). The color mapping image results of specimens after shot peening process using nickel shots are shown in figure 11(a). It shows the existence of nickel which is mapped to red color. EDS results shown in 10(b) is not having the presence of nickel whereas results shown in 11(b) has 3.78 percentage normalized weight of nickel on the surface of shot peened AA2024-T3 specimen. The analysis done for specimens before and after shot peening process is evident that shot peening (SP) process results in surface level penetration of shot material with the base material.

### Table 7. ANOVA for response surface quadratic model.

| Source          | Sum of Squares | df | Mean Square | F Value | p-value | Prob > F |
|-----------------|----------------|----|-------------|---------|---------|----------|
| Model           | 208.41         | 5  | 41.68       | 87.44   | <0.0001 | Significant |
| A-Pressure      | 187.97         | 1  | 187.97      | 394.32  | <0.0001 |
| B-Distance      | 14.39          | 1  | 14.39       | 30.19   | 0.0009  |
| AB              | 0.000          | 1  | 0.000       | 0.0000  | 1.0000  |
| A²              | 4.99           | 1  | 4.99        | 10.46   | 0.0144  |
| B²              | 1.71           | 1  | 1.71        | 3.60    | 0.0998  |
| Residual        | 3.34           | 7  | 0.48        |         |         |
| Lack of Fit     | 3.34           | 3  | 1.11        |         |         |
| Pure Error      | 0.000          | 4  | 0.000       |         |         |
| Cor Total       | 211.74         | 12 |             |         |         |
| Std. Dev.       | 0.69           |    | R-Squared   | 0.9842  |         |
| Mean            | 148.44         |    | Adj R-Squared | 0.9730 |         |
| C.V.%           | 0.47           |    | Pred R-Squared | 0.8879 |         |
| PRESS           | 23.73          |    | Adeq Precision | 29.230 |         |
| −2 Log Likelihood | 19.21        |    | BIC | 34.60 |         |
|                 |                |    |             | AICc    | 45.21   |
Figure 9. Photography of FESEM image after shot peening.

Figure 10. (a) And (b) results of FESEM and EDS test before shot peening.

Figure 11. (a) And (b) results of FESEM and EDS test after shot peening.
5. Conclusion

Aluminium 2024-T3 specimens are shot peened on both front and rear surfaces using nickel shots to investigate the influence of shot peening on fatigue strength. Following are the findings from the investigation

(i) Shot peening process using nickel shots on the surface of AA2024-T3 increases its fatigue strength by 34 percentage.

(ii) The best parameters for obtaining maximum fatigue strength for AA2024-T3 using nickel shots are 5.699 MPa peening pressure and 30 mm peening distance. For the above parameters, fatigue strength of 156 MPa is obtained.

(iii) From FESEM test, the presence of nickel on the surface of AA2024-T3 was found and it has confirmed the penetration of nickel at surface level due to shot peening process.

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