# Numerical analysis of shot peening effects on the fatigue life of a titanium alloy

H.Bae[1], M. Ramulu[1,] , B Flinn[2] and H. Diep[3]

1 Department of Mechanical Engineering, University of Washington, Seattle WA
2 Department of Materials Science and Engineering, University of Washington, Seattle WA.
3 The Boeing Company, Seattle WA

## ABSTRACT

The fatigue life of a mechanical component depends strongly on its surface layer conditions since crack initiation begins at or near the surface. Shot peening process enhances the fatigue life by increasing surface hardening and inducing compressive surface residual stress but with increasing surface roughness. The effects of surface roughness and surface hardening on the fatigue life of shot peened Ti 6Al-4V (Ti 64) were investigated. Stress concentration factor was calculated by using 2D and 3D Finite element analysis of measured surface roughness induced by shot peening. Stress concentration factor (SCF) calculation was compared with two analytical stress concentration calculation models. Using surface roughness parameters, this paper estimates fatigue life of Ti 64 specimens by using SCF in a fatigue life prediction model including surface roughness and micro-hardness effects.

## INTRODUCTION

Many studies have investigated the effects of dents or micro-notches caused by shot peening and the effect of surface roughness induced by shot peening is represented by the stress concentration factor ($K_t$). The stress concentration factor increases the local surface stress due to induced surface roughness by shot peening and affects the materials fatigue life. Therefore, in most of the recent published reports [1-4], the stress concentration factor $K_t$ was calculated either from averaged geometrical parameters of the surface [5,6] and or by finite element analysis [2-4]. As et al [1,2] found $K_t$ by finite element analysis of the measured surface topography. Machined surface roughness 2D profiles were recorded with a sampling rate of 1 μm/point. From the 17000 points that were recorded, only 800 points were regularly extracted and interpolated with a spline function and used in the finite element modeling for calculating $K_t$. Thompson [4] presented four methods of generating normally distributed rough surfaces using the ANSYS Parametric Design Language (APDL). The resulting geometry, meshes, and solutions were then compared to demonstrate the strengths and weaknesses of the various methods [4].

Several researches have been conducted to calculate the stress concentration factor from surface roughness. The analytical model to estimate the effective surface stress concentration factor, $\overline{K}_t$ using standard surface roughness parameter [5]:

$$\overline{K}_t = 1 + n\left(\frac{\overline{R_a}}{\rho_n}\right)\left(\frac{R_t}{R_z}\right) \tag{1}$$

$R_a$, $R_t$ and $R_z$ are the average roughness, peak-to-valley height, 10-point roughness and $\rho_n$ is the notch radius. Li et al. [7] on the other hand proposed a $K_t$ model using finite element analysis for the shot peened surface in terms of surface profile parameters as

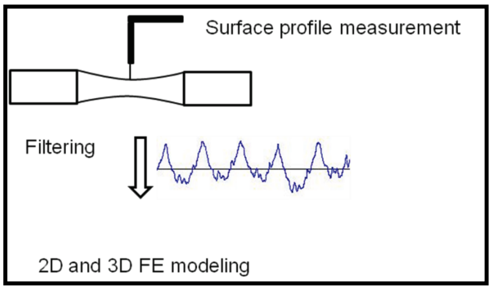
$$K_t = 1 + 4\left(\frac{R_{t_m}}{S}\right)^{1.3} \tag{2}$$

where $R_{t_m}$ is the mean peak-to-valley height of the micro-notches and S is the distance between two micro-notch peaks. Although both of these models provided information into the maximum stress and crack initiation from the surface micro-irregularities of shot peened material, but they failed to provide information on the effect of surface layer hardening and $K_t$ on fatigue life. In this study, stress concentration factor was calculated by using 2D and 3D finite element analysis of shot peening induced surface topography and compared with available stress concentration estimation models [5,6]. This paper also estimates fatigue life of Ti 64 specimens by proposing a simple approach of using both surface roughness and micro-hardness effects in conjunction with endurance strength.

## NUMERICAL METHODS

### FEA Estimation of Stress Concentration Factors

In this study, 2D and 3D finite element analysis were performed to calculate stress concentration factor induced by the machining and shot peening of Ti 6Al-4V. Surface profile measurements were made by contact surface profilometer using a probe of 2.5micron in diameter on the test specimen shown in Figure 1, along with average surface roughness parameter definitions. First, surface profiles were recorded experimentally from the specimen of machined and shot peened Ti 6Al-4V specimens. Surface profile length was 700 μm and recorded 1400 data points with an interval of 0.5μm. Second, by using MATLAB, a filter was developed for eliminating the linear trend and second order roughness from measured surface profile because stress concentration generated by second order roughness is less significant. Approximately, 100 points were extracted by using the filter and interpolated with spline curves that were used as 2D as-machined and shot peened models and as-machined 3D model to generate the finite element geometry. For shot peened 3D model, a 3D model was created by using normally distributed rough surfaces. Normal Gaussian distrubution with a mean ($R_a$) and a standard deviation ($R_t$) was used for generating random surface keypoints and then these key points were connected by lines. These lines generated surface areas and whole areas created a volume in ANSYS.



$$R_a = \frac{1}{L}\int_0^L |z|\,dx$$

$$R_y = |z_{\max} - z_{\min}| = R_{t_m}$$

$$R_z = \frac{1}{5}\left[\sum_{i=1}^{5}(z_i)_{\max} - \sum_{j=1}^{5}(z_j)_{\min}\right]$$

**Figure 1 Procedures of finite element calculation to determine stress concentration factor**

An elastic linear finite element analysis was performed by the commercial software package ANSYS version 11. Material behavior was linear elastic and followed the properties of Ti64. For 2D model, plane strain hypothesis, and triangular elements with quadratic interpolation were used for the meshing. For 3D model, an 8 node element, solid 185 was used and the trianglar elements were used for the meshing. Element size was about 30μm. Applied load was 1 Pa for 2D and 3D models. For 2D model, the displacement about Y-axis was constrained and for 3D model, the displacement about Y-axis and Z-axis was constrained. Stress concentration factor, $K_t$ was calculated by using:

$$K_t = \frac{\sigma_{\max} Area\_net}{load} \tag{3}$$

where, $\sigma_{\max}$ is the maximum von Mises stress from Finite Element Analysis and load is 1Pa. Area_net is the net cross sectional area.

## Estimation of Stress Concentration Factors on shot peened surface

Shot peening process increases material’s surface roughness and the surface micro-hardness and also induces compressive surface residual stress. The effect of surface roughness induced by shot peening is represented by the stress concentration factor (Kt). The stress concentration factor increases the local surface stress at the bottom of indentations and therefore decreases fatigue life of the shot peened materials. However, shot peening also increases surface micro-hardness and compressive residual stress and it negates with maximum local stress from the stress concentration. Therefore the positive effect of surface hardening must be included in calculating the effective stress concentration factor.

Using a rule of thumb, relating hardness and ultimate strength, the following relationship between endurance limit, $S_e$, and hardness, $H_v$ of metallic material is given:

$$S_e = C_v H_v \tag{4}$$

where $C_v$ is the hardness coefficient of the material. For smooth and or as-machined specimen, the fatigue endurance limit is

$$S_{e_{base}} = C_v H_{v_{base}} = \frac{\Delta K_{th}}{F K_{t_{base}} \sqrt{\pi a}} \tag{5}$$

where $a$ is the crack length, $\beta$ is a geometric correction factor, $\Delta K_{th}$ is the threshold stress intensity factor, $H_{v_{base}}$ is the hardness of the base material and $K_{t_{base}}$ is the stress concentration factor of the smooth /as-machined surface. For shot peened specimen, the fatigue endurance limit is

$$S_{e_{peened}} = C_v H_{v_{peened}} = \frac{\Delta K_{th}}{F K_{t_{peened}} \sqrt{\pi a}} \tag{6}$$

where $H_{v_{peened}}$ is the surface hardness of the shot peened material and $K_{t_{peened}}$ is the stress concentration factor of the shot peened surface. By combining and manipulating Eq. 5 and Eq. 6 the shot peened stress concentration factor equation is described in terms of $H_{v_{base}}$, $H_{v_{peened}}$ and $K_{t_{base}}$ :

$$K_{t_{peened}} = \frac{H_{v_{base}}}{H_{v_{peened}}} K_{t_{base}} \tag{7}$$

Here $K_{t_{base}}$ is given by Eq.1 and Eq.7 yields the stress concentration factor equation for the shot peened specimen as:

$$K_{t_{peened}} = \frac{H_{v_{base}}}{H_{v_{peened}}} \left[ 1 + n \left( \frac{R_a}{\rho_n} \right) \left( \frac{R_y}{R_z} \right) \right] \tag{8}$$

Fatigue endurance strength estimation can be made by using fracture mechanics approach by modifying Eq.5 as

$$S_e = \frac{\Delta K_{th}}{C_s \beta K_t \sqrt{\pi a}} \tag{9}$$

where $C_s$ is the parameter that depends on the crack size, $a$ is the smallest grain size that induces the highest value of $C_s$, $\Delta K_{th}$ is fatigue threshold stress intensity factor and $\beta$ is taken as 1.12.

## Numerical Results

Cross sectional areas with as machined and shot peened surface profiles were created for 2D model and shown in Figure 2. One quarter of volume of the circular specimen was analyzed for 3D models. As-machined 3D model created the surface with machining grooves and shot peened 3D model created the surface with the dimples induced by shot peening as shown in Figure 3 along with scanning electron micrographs (SEM) of as machined and peened surface topography of the specimen. From the comparison of FEM generated machined surface with SEM micrograph, it was confirmed that the 3D model created the machined marks well (Figure 3a). Figure 3 also shows a SEM picture of shot peened surface and a 3D model of shot peened specimen in Figure 3b. The SEM picture shows the actual dimples on the surface induced by shot peening and the 3D model also shows the dimples on the model surface. A comparison between the SEM picture and the 3D model shows that the 3D model represented the actual shot peened surface well.

Maximum stress was found by von Mises equivalent stress. Maximum stresses were found at the valleys of the surface profile. $K_t$ values were calculated by using Eq. 3, with resulting maximum stresses. For as-machined model, Stress concentration factor values of 2D and 3D model were 1.13 and 1.11 respectively. It was shown that the results were same in as-machined surface models. However, for shot peened surface models, stress concentration factor values of 2D and 3D models were 1.15 and 1.35 respectively. The stress concentration factor of 3D model was higher than one of 2D model.

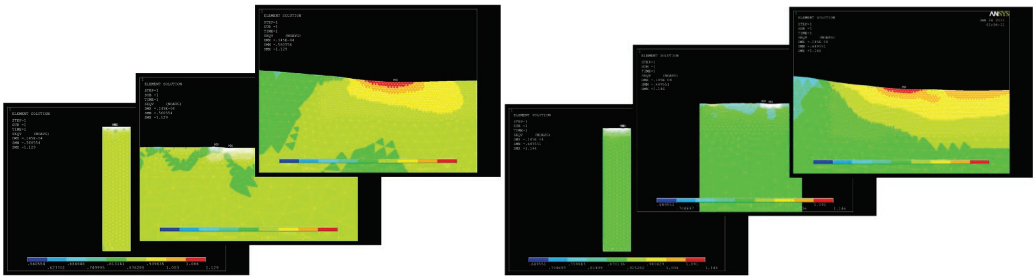


**Figure 2 Analysis results of 2D models of Ti 6Al-4V surface**

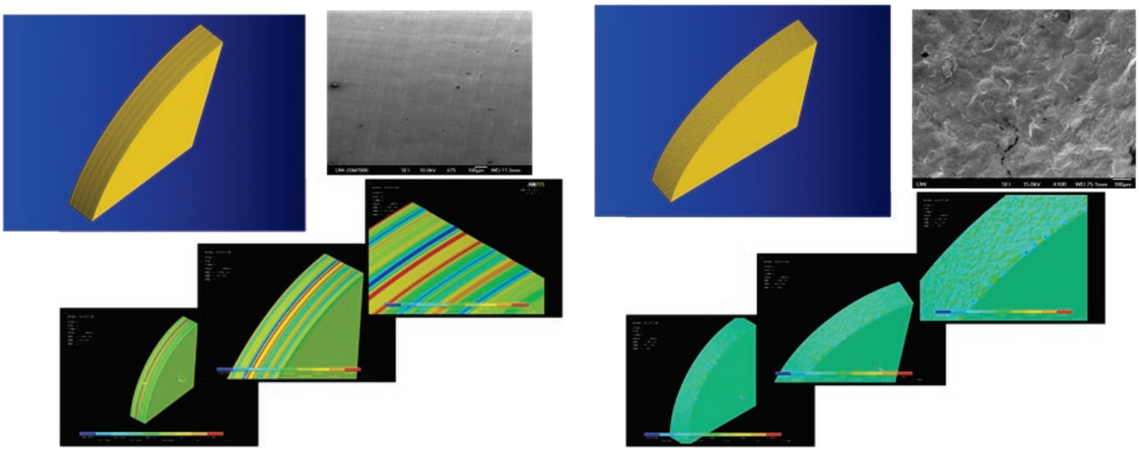


**Figure 3 Analysis of 3D models and results of Ti 6Al-4V surface**

## Experimental Verification

The average surface roughness parameters extracted from the surface roughness profiles of as machined and shot peened Ti 6Al-4V specimens were used for $K_t$ calculation using Eq. 1

and Eq. 2. A typical profile from a specimen with 1.7 μm average roughness and the notch radii or profile valley radii, $\rho_n$ for the surface was estimated graphically as shown in Figure 4 and used in the Arola-Ramulu model for $\overline{K}_t$. Average spacing between the features were calculated and average for the Li's model.

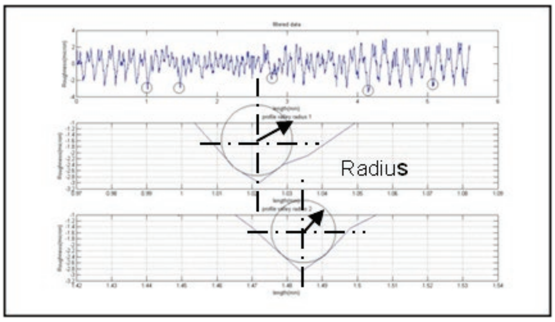


**Figure 4 Surface texture and profile valley radii of the shot peened surface**

The effective stress concentration factors for the shot peened surfaces were also calculated using Li's model and modified Arola-Ramulu model according to Eq. 2 and Eq.1, respectively. Modified Arola-Ramulu model (Eq. 8) required the ratio of the micro-hardness of the base material to the micro-hardness of the shot peened material. This ratio was found to be

$$\frac{H_{v_{base}}}{H_{v_{peened}}} = 0.87 \quad for \quad Ti \ \ 6Al-4V$$

Stress concentration factor from FEA was modified by using Eq. 7 and 8. Stress concentration factor from FEA( $K_{t_{FEA}}$ ) replaced $K_{t_{base}}$ in Eq.7 as $K_{t_{peened}} = \frac{H_{v_{base}}}{H_{v_{peened}}} K_{t_{FEA}}$

By using Eq. 8, the effective $K_t$ for the shot peened surfaces were estimated and given in Table1. Stress concentration factors from the FEA results were also included in Table 1 for comparison.

**Table 1 Stress concentration factors of As machined and Shot peened Ti 6Al-4V surfaces**

| | ρ-avg | Ra(μm) | Rt(μm) | Rz(μm) | S(μm) | Arola-Ramulu $K_t$ Eq 1 | Li Kt Eq.2 | Kt FEA | Arola-Ramulu ModiEq.8 | Modified Kt FEA |
|---|---|---|---|---|---|---|---|---|---|---|
| As machined (Ti 64) | 48.7 | 0.8 | 4.6 | 4.2 | - | 1.02 | - | 1.11 | - | - |
| Shot peened (Ti 64) | 24.8 | 1.7 | 12.3 | 9.6 | 277.3 | - | 1.07 | - | 0.88 | 1.004(2D)<br>1.17 (3D) |

In this study, endurance limit was the stress corresponding to $10^6$ fatigue life and found from MIL handbook[8]. It was assumed that the crack size was five grain diameters in length or 40μm for Ti 6Al-4V. Fatigue threshold stress intensity factor ($\Delta K_{th}$) was 4.6 MPa$\sqrt{m}$ and fatigue endurance limit constant ($C_s$) was calculated. Stress concentration factor for the unnotched specimen was 1 and the maximum stress corresponding to $10^6$ fatigue life cycles found 690MPa (100Ksi). The calculation is shown below.

$$S_e = \frac{\Delta K_{th}}{C_s \beta K_t \sqrt{\pi a}} = \frac{4.6 MPa\sqrt{m}}{C_s \times 1.12 \times 1 \times \sqrt{\pi \times 4 \times 10^{-5}}} = \frac{366}{C_s} = 690$$

$$\text{and yields, } C_s = 0.53$$

The prediction of the fatigue endurance limits at various stress concentration factors is shown in Figure 5. Stress concentration factors calculated from the modified Arola-Ramulu model and Li model are 0.88 and 1.07, respectively for the shot peened specimen and the corresponding fatigue endurance limits are 785MPa and 646MPa. In other words, 22% of the fatigue endurance limits are decreased when stress concentration factors are changed from 0.88 to 1.07. Endurance limit estimation result from Modified Arola-Ramulu model is closer to experimental result than the estimation from Li's model. The fatigue endurance limits are inversely proportional to the stress concentration factors.

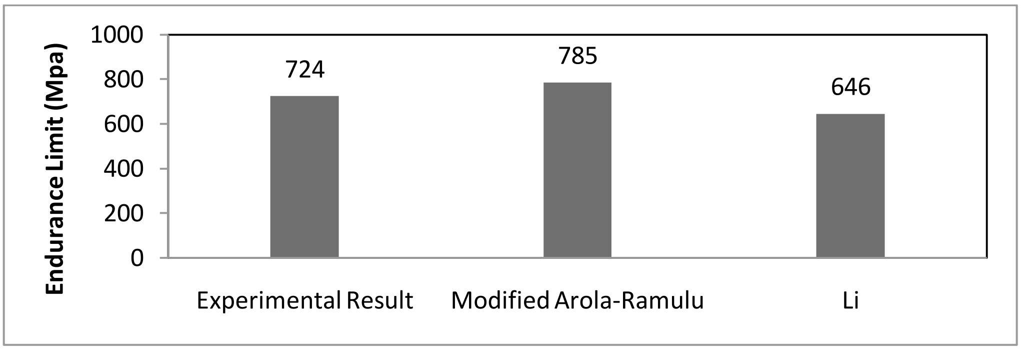


**Figure 5 Fatigue endurance limit prediction of shot peened Ti 6Al-4V**

## SUMMARY AND CONCLUSION

2D and 3D numerical models were developed to describe real surfaces of as machined and shot peened titanium alloy specimens. These models were built by using experimentally obtained surface profiles. The maximum stresses were found at valleys of as machined and shot peened surfaces. Stress concentration factors were calculated by using the resulting maximum stresses. The results of the work show that 2D plain strain model for as machined surface can be used instead of 3D model for as machined surface because of symmetric shape of as machined surface. However, shot peened surface needs to use 3D model due to non-symmetric shape. The numerical models successfully described the real surfaces of as machined and shot peened surfaces and predicted stress concentration factor for both surfaces of the specimens. Modified Arola-Ramulu model was developed to calculate the stress concentration factor for shot peened specimen. To include shot peening effect, modified Arola-Ramulu model included the change of microhardness. Empirical prediction with modified Arola-Ramulu model was performed. It is shown that the prediction is agreed well with the experimental findings.

## REFERENCES

1. As, SK, Skallerud B, Tveiten, BW, Holme B. "Fatigue life prediction of machined components using finite element analysis of surface topography", *Int J Fatigue* 2005; 27: 1590–6.
2. As, SK, Skallerud B, Tveiten, BW, "Surface roughess characterization for fatigue life predictions using finite element analysis", *Int J Fatigue* 2008; 30: pp2200–9.
3. Suraratchai, M, Limido, J., Mabru, C., Chieragatti, R., "Modelling the influence of machined surface roughness on the fatigue life of aluminium alloy", *Int J Fatigue*, 2008;30;2119-26
4. M. K. Thompson, "Methods for Generating Rough Surfaces in ANSYS*", Proceedings of the 2006 International ANSYS Users Conference & Exhibition*, Pittsburgh, PA. pg16
5. Arola, D. and Ramulu, M., “An examination of the effects from surface texture on the strength of fiber-reinforced plastics”, *J Compos Mater*, 1999;33(2);101-86
6. Arola D, Williams CL. “Estimating the fatigue stress concentration factor of machined surfaces”, Int J Fatigue, 2002, 24, 923–30
7. J. K. Li,Yao Mei, Wang Duo and Wang Renzhi , “An analysis of stress concentrations caused by shot peening and its application in predicting fatigue strength, *Fatigue Fract Engng. Mater. Struct.,* 1992, pp 1271-1279
8. Military handbook: metallic materials and elements for aerospace vehicle structures, vol. 1. USA: Department of Defense; 1994