

## EFFECTS OF SURFACE TREATMENT ON THE FATIGUE BEHAVIOUR OF CYLINDER BLOCK FOR A NEW TWO-STROKE FREE PISTON ENGINE

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### ABSTRACT

In the present investigation, the effects of surface treatments on the high cycle fatigue behaviour of cylinder block for a two-stroke free piston engine are presented. This paper has been investigated surface finish effects fatigue damage accumulation in the cylinder block at different complex variable amplitude loading conditions. Rainflow cycle counting procedures are used in this study. The finite element modeling and analysis have been performed using finite element analysis software Package MSC.PATRAN/ MSC.NASTRAN and the fatigue life prediction was carried out using a MSC.FATIGUE software. Based on the finite element results, a crack initiation method was applied to predict the fatigue life of cylinder block. Results for different load histories and material combination are also discussed. Results indicate a great effect for all surface finish parameters. It is concluded that polished and seawater corroded conditions have been found to give the highest and lowest lives, respectively. The results are also expected to show contour plots of fatigue life and fatigue damage at the worst or most damaging case.

**Keywords:** Finite element, Fatigue life, Surface finish, Crack initiation approach, Free piston engine

### 1. INTRODUCTION

Due to market pressures for improvements in productivity, reliability, ductility, wear resistance as well as the profitability of mechanical systems, manufacturers are placing increasing demands on available materials. Economic constraints require that these materials are inexpensive and easily available. In order to enhance the surface properties of today's materials, producers of components are turning to different surface finish and treatments. There are several techniques available for mechanically improving the surface properties of the components, such as polished, ground, machined, hot rolled, forged, cast, etc. Some of these techniques produce an improve surface by plastic deformation of surface irregularities [1, 2].

The surfaces used in lubrication, friction and wear components vary in initial surface topology, depending on the particular used involved. For most parts, these surfaces play a useful role in the service life of these components. It is well established practically that the fatigue process is very sensitive to surface state. Fatigue life is strongly influenced by the surface finish and treatments. The reason why fatigue is a surface –sensitive process lies in the fact that fatigue cracks always nucleate from free surfaces of cyclically loaded

metals. The nucleation as well as the whole fatigue process is controlled by the cyclic plastic deformation. Therefore, it can be expected that cracks nucleate at positions where the cyclic plastic deformations are higher than average, in other words, in places of plastic-strain concentration, such as stress concentration.

Mechanical surface treatments such as nitriding, shot peening, cold and hot rolling are often performed on high strength aluminum, titanium alloys to improve fatigue performance [3]. All mechanical surfaces treatments lead to a characteristic surface roughness, increased near surface dislocation density (cold work) and development of microscopic residual stresses. Nitriding is now widely used in manufacturing for surface hardening of ferrous and non-ferrous materials. Typical characteristics of Nitrided and shot peened surfaces are compressive residual stresses and extremely high dislocation densities in near surface layers resulting from inhomogeneous plastic deformations. In some cases phase transformations occur, leading to additional surface hardening. These microstructural features are generally considered as the reason for inhibited crack initiation and propagation in components which are cyclically loaded [4].

Fatigue is an important parameter to be considered in the behaviour of components subjected to constant and variable amplitude loading [5]. Fatigue is of great concern for components subject to cyclic stresses, particularly where safety is paramount, for examples free piston linear generator engine components. It has long been recognized that fatigue cracks generally initiate from free surfaces and that performance is therefore reliant on the surface topology/integrity produced by surface finishing [2]. Whilst it is known that fatigue life is heavily influenced by residual stresses, the metallurgical condition of the materials and the presence of notch-like surface irregularities induced by machining play a key role [3]. Surface treatments such as nitriding, shot peening, cold rolling are often performed on high strength aluminum, titanium alloys to improve fatigue performance [3]. All Surfaces treatments lead to a characteristic surface roughness, increased near surface dislocation density (cold work) and development of microscopic residual stresses. Nitriding is now widely used in manufacturing for surface hardening of ferrous and non-ferrous materials. Shot peening is a well-established cold working process, widely used by the automotive and aircraft industries, as compressive residual stresses induced by the process have been found to profoundly affect the fatigue fracture behaviour of metallic components [6]-[7].

Beneficial effects of mechanical surface treatments are mostly compressive stress profiles and strain hardening in near surface regions of components, yielding higher resistance against fatigue loading. They are most important in the case of high strength materials, if residual stress remain stable [8]. Rios et al. [9] investigated the crack growth behaviour in shot peened AISI 316 steel and reported slower fatigue crack initiation as well as propagation in shot peened compared to non-peened specimens. The effect of prior cold work on the low cycle fatigue behaviour of AISI 304 LN was studied in [10]. These experiments revealed that predeformation is beneficial for lifetime as long as the strain amplitude does not exceed 0.5% under total strain control conditions.

The objectives of this paper is to predict the fatigue life of cylinder block of the free piston engine using crack initiation approach and also investigated the effect of mean stress and material optimization on fatigue life via the design criterion. Mechanical surface treatments are also performed to further improve the fatigue life of the component of free piston engine. However, these investigations are essential in order to understand the involved microstructural mechanisms of hardening or softening in the wake of service load. The influence of surface finish and treatments are also critical.

## 2. CRACK INITIATION APPROACH

The structural analysis calculating strains and stresses at each time increment of the service load history using the finite element structural model. This enables the stress-strain field at critical areas within the model to be found. Stress/strain calculations for fatigue life estimation can be performed in the time domains. The standard time domain approach involves the application

of quasi-static stress analysis method. The quasi-static method is a linear elastic analysis that is associated with external load variations. The main idea of this method is that each external load history acting on the structure is replaced by static unit load acting at the same location in the same direction as the history. A static stress analysis is then performed for each individual unit load. The principle of superposition is used to calculate the total stress histories within the structure. Eq. (1) represents the mathematical form of this method at a specific finite element node assuming plane stress conditions [11].

$$\begin{aligned}\sigma_x(t) &= \sum_{i=1}^n \sigma_{xi} F_i(t); \\ \sigma_y(t) &= \sum_{i=1}^n \sigma_{yi} F_i(t); \\ \tau_{xy}(t) &= \sum_{i=1}^n \tau_{xyi} F_i(t)\end{aligned}\quad (1)$$

In these equations,  $n$  is the number of the applied load histories and  $\sigma_{xi}$ ,  $\sigma_{yi}$ ,  $\tau_{xyi}$  are the stress influence coefficients. A stress influence coefficient is defined as the stress field due to a unit load applied to the component at the identical location and in the same direction as the load history  $F_i(t)$ .

The fatigue crack initiation (FCI) approach involves the following techniques for converting load history, geometry, and material properties (monotonic and cyclic) input into a fatigue life prediction. First, the stress and strain at the critical site are estimated, and "Rainflow" cycle counting is then used to reduce the load-time history. The next step is used the finite element method to convert a reduced load-time history into a strain-time history and calculate the stress and strain in the highly stressed area. Then the strain-life methods are employed for predicting fatigue life. Following this, the simple linear damage hypothesis proposed by Palmgren and Miner [12]-[13] is used to accumulate the fatigue damage. Finally, the damage values are summed until a critical damage sum (failure criteria) is reached. The point at which the failure criteria are met is the predicted life.

The fatigue resistance of metals can be characterized by a strain-life curve. These curves are derived from the polished laboratory specimens tested under completely reversed strain control. The relationship between the total strain amplitude,  $\frac{\Delta\varepsilon}{2}$ , and reversals to failure,  $2N_f$ , can be expressed in the following form[14]-[17]

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad (2)$$

Where,  $N_f$  is the fatigue crack initiation life;  $\sigma'_f$  is the fatigue strength coefficient;  $b$  is the fatigue strength exponent;  $\varepsilon'_f$  is the fatigue ductility coefficient; and  $c$  is the fatigue ductility exponent.

Morrow [18] suggested that mean stress effects could be considered by modifying the elastic term in the strain-life equation by mean stress,  $\sigma_0$ .

$$\frac{\Delta \varepsilon}{2} = \frac{\sigma'_f - \sigma_0}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad (3)$$

Manson and Halford [19] modified both the elastic and plastic terms of the strain-life equation to maintain the independence of the elastic-plastic strain ratio mean stress.

$$\frac{\Delta \varepsilon}{2} = \frac{\sigma'_f - \sigma_0}{E} (2N_f)^b + \varepsilon'_f \left( \frac{\sigma'_f - \sigma_0}{\sigma'_f} \right)^{\frac{c}{b}} (2N_f)^c \quad (4)$$

Meanwhile, in the strain-life approach, the local values of stress and strain at the critical location were used to find fatigue life, according to the Smith-Watson-Topper (SWT) [20] parameter that considers the mean stress effect:

$$\sigma_{\max} \varepsilon_a E = (\sigma'_f)^2 (2N_f)^{2b} + \sigma'_f \varepsilon'_f E (2N_f)^{b+c} \quad (5)$$

where,  $\sigma_{\max} = \frac{\Delta \sigma}{2} + \sigma_0$  is the maximum stress and  $\varepsilon_a$  is the strain amplitude

### 3. LOADING HISTORIES

There are several types of variable amplitude loading histories were selected for the simulation from the SAE and ASTM profiles. The detailed information about these histories was contained in the literature [21]. Raw histories are shown in Fig 1.

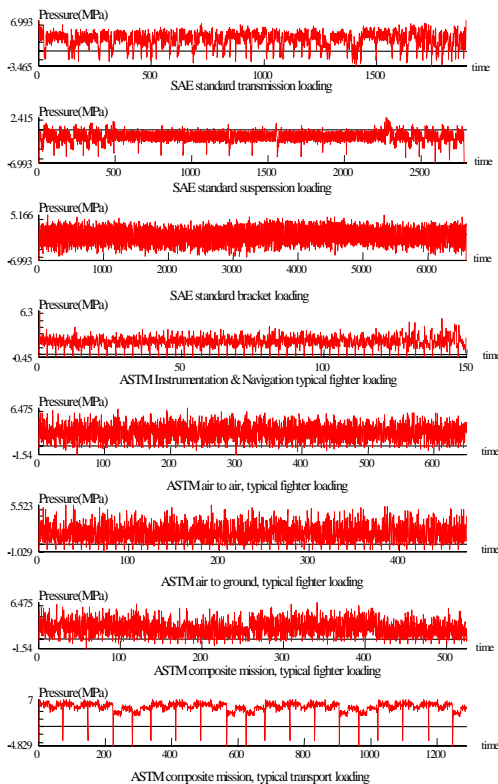


Fig 1. Variable Amplitude load-time histories information

The SAETRN, SAESUS, and SAEBKT in the figure represent the SAE's load-time history obtained from the transmission, suspension, and bracket respectively. I-N, A-A, A-G and TRANSP are the ASTM instrumentation & navigation typical fighter, ASTM air to air typical fighter, ASTM air to ground typical fighter and ASTM composite mission typical transport loading history, respectively [2].

### 4. FINITE ELEMENT MODELING AND ANALYSIS

In linear static analysis [22] by the displacement method, stiffness and mass properties are input either as properties of elements or as properties of grid points. In the finite element model of the cylinder block of linear generator engine, there are several contact areas (for example: cylinder head, gasket, hole for bolt, etc) concerning multi-point constraints (MPC). Therefore constraints are employed for the following purposes: (1) to specify the prescribed enforce displacements, (2) to simulate the continuous behavior of displacement in the interface area, (3) to enforce rest condition in the specified directions at grid points of reaction. Because of the complexity of geometrical design and load path of cylinder block of linear generator engine, it is not easy to model the complicated stiffness distribution of cylinder structure. Therefore, a 3D FE model as shown in Fig 2(a) is considered for free piston linear generator engine cylinder block in order to predict the stress and strain response in detail.

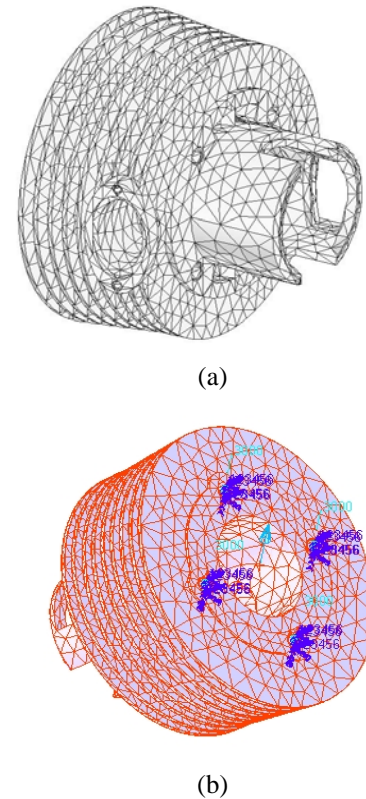


Fig 2. (a) 3D FE Model; (b) Loading and Constraints.

Three-dimensional model geometry was developed in CATIA software. A parabolic tetrahedron element was used for the solid mesh. Sensitivity analysis was

performed to obtain the optimum element size. These analyses were performed iteratively at different element lengths until the solution obtained appropriate accuracy. Convergence of stresses was observed, as the mesh size was successively refined. The element size of 0.20 mm was finally considered. A total of 35415 elements and 66209 nodes were generated at 0.20 mm element length. The constraints were applied on the bolt-hole for all six degree of freedom. The objective of FEM was to investigate stresses of cylinder block of free piston linear generator engine. In this particular cylinder structure, there will be loading configurations in normal mode analysis, it's free-free situation. Multi-point constraints [22] were used to connect the parts thru the interface nodes. These MPCs were acting as an artificial bolt and nut that connect each parts of the structure. Each MPCs will be connected using Rigid Body Element (RBE) that allow users to indicate the independent and dependent nodes. From the viewpoint of machine engine, the bolts were constrained to the head, at their top end, and to the block, at their bottom end. In this situation with no loading configuration, at the bottom end of the bolt head hole, RBE element with six-degrees of freedom were assigned with the independent node was created from cylinder block properties. Fig 2(b) shows loading, constraints and finite element mesh used for the FEA is of cylinder block of free piston engine.

### 5. RESULTS AND DISCUSSION

The linear static finite element was performed using MSC.NASTRAN finite element software. The equivalent von Mises stress contours is presented in Fig 3. From the resulting stress contours, the state of stress can be obtained and consequently used for life predictions. Linear elastic analysis was used, since the cylinder block is designed for long life. Where stresses are mainly elastic. The maximum von Mises stresses of 36.0 MPa at node 49360 was obtained. All the results presented in this paper are based on the fine mesh model. The fatigue life of the cylinder head of the free piston engine is obtained using time domain methods.

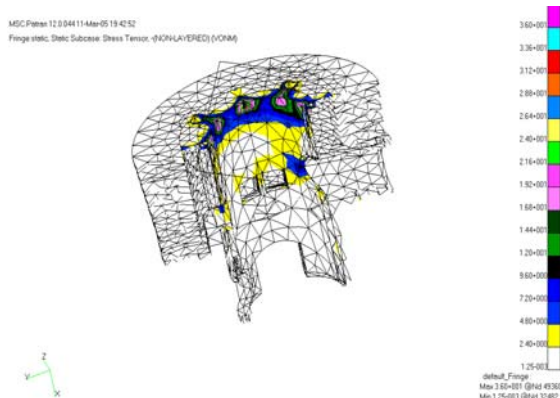


Fig 3. The von Mises stresses distribution

Fig 4 shows the fatigue log life plot and critical location at ASTM composite mission typical transport loading condition arising on the cylinder block of linear

generator engine using crack initiation method. The critical fatigue life using different loading histories and materials combination is tabulated in Table 1. There are considered two mean stress correction methods i.e. Smith-Watson-Topper and Morrow methods. It can be seen that SWT correction has been found to give the most conservative results except SAESUS and SAEBKT loading conditions. For SAESUS and SAEBKT conditions, no mean stress correction methods have been given the most conservative results. It can be also seen that 2014-T6-125-HF is consistently higher life than 6061-T6-80-HF aluminum alloy for all loading conditions. The minimum fatigue life prediction result of cylinder block corresponding to 99.5% reliability value is  $10^{9.83}$  or  $4.41 \times 10^7$  seconds at most critical location (node 50420) for SAETRN loading condition. The fatigue life is in terms of seconds of the variable amplitude-loading condition. It is found that cylinder block edge is the most critical positions among the component.

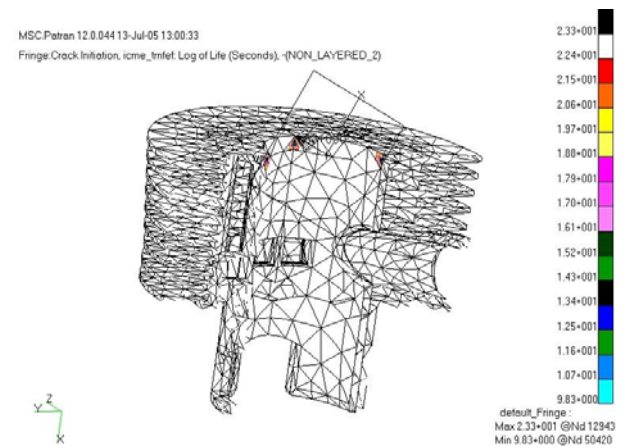


Fig 4. Fatigue life contour plot of log life.

Table 1: Predicted fatigue life in seconds.

Loading Conditions	Predicted life in seconds					
	2014-T6-125-HF			6061-T6-80-HF		
	SWT	Morrow	No correction	SWT	Morrow	No Correction
SAETRN	8.35E7	2.21E8	3.63E8	4.41E7	1.05E8	2.50E8
SAESUS	*BCO	3.13E10	1.65E10	BCO	4.79E10	1.41E10
SAEBKT	5.17E8	3.14E8	2.57E8	3.44E8	2.45E8	1.77E8
ASTM I-N	3.34E4	2.24E5	5.97E5	2.05E4	9.77E4	5.82E5
ASTM A-A	6.26E7	4.76E8	1.40E8	4.66E7	2.62E8	1.38E9
ASTM A-G	1.67E7	9.18E7	2.20E8	9.87E6	4.20E7	2.07E8
ASTM R-C	1.32E5	9.33E5	2.68E6	9.63E4	5.11E5	2.78E6
ASTM TRANSP	2.31E7	3.87E7	5.45E7	9.56E6	1.66E7	2.87E7

\* BCO- Beyond Cut-off (endurance limit).

Mechanical surface treatments are often utilized after surface finishing in order to enhance fatigue performance. The material used in this study is AA6061-T6. Polished surface finish condition are also used in this study. The contributions of surface treatments on the fatigue lives at different loading conditions using crack initiation method at critical location are summarized in Table 2.

Table 2: The effect of surface treatments at different loading conditions for polished component

Loading Conditions	Predicted life in seconds			
	Untreated	Nitrided	Cold Rolled	Shot Peened
SAETRN	4.41E7	1.60E11	1.90E9	1.29E8
SAESUS	1.41E10	BCO	BCO	6.73E10
SAEBKT	2.57E8	5.16E11	1.29E10	7.83E8
ASTM I-N	2.05E4	BCO	1.31E6	6.89E4
ASTM A-A	4.66E7	BCO	9.55E9	1.81E8
ASTM A-G	9.87E6	BCO	6.98E8	3.22E7
ASTM R-C	9.63E4	BCO	1.77E7	3.74E5
ASTM TRANSP	9.56E6	1.67E10	2.23E8	2.33E7

Surface treatments (nitriding, cold rolled, shot peening) that produce compressive residual surface stresses are useful. These treatments cause the maximum tensile stress to occur below the surface. The reverse is also true and tensile residual surface stresses are very detrimental and promotes corrosion fatigue. Surface treatments are also increase the endurance limit. Diffusion process such as nitriding is very beneficial for fatigue strength. This process has the combined effect of producing a higher strength material on the surface as well as causing volumetric changes which produce residual compressive surface stresses. There are several methods used to cold work the surface of a component to produce a residual compressive stress. The two most important are cold rolled and shot peening. Along with producing compressive residual stresses, these methods also work-harden the surface material. The great improvement in fatigue life is due primarily to the residual compressive stresses. In shot peening process, the surface of the component undergoes plastic deformation due to the hit of many hard shots. The fatigue life of the component is improved due to the development of compressive residual stresses and the increase of hardness near the surface.

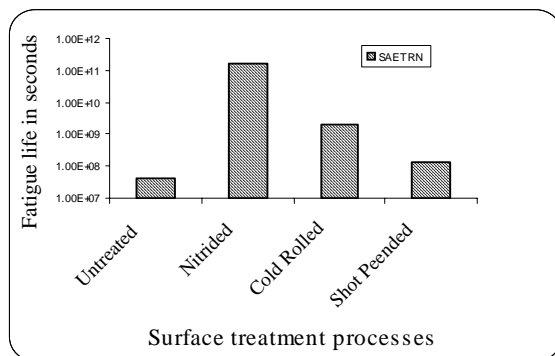


Fig 5. Effect of surface treatment processes for SAETRN loading conditions

The effect of surface treatment at different loading conditions for polished vibrating cylinder block is summarized in Table 2. It can be seen that the fatigue life for nitriding surface treatments is surprisingly increases than those other surface treatment processes. Fig. 5

shows that the effect of different surface treatment processes for SAETRN loading conditions and polished specimen. It is clearly shown that nitrided processes are surprisingly increases the fatigue life at critical location than other processes.

## 6. CONCLUSIONS

Through the study of aluminum alloys specimens, several conclusions can be drawn with regard to the fatigue damage and fatigue life of a component when subjected to complex loading conditions. From the all results, it can be concluded that SWT correction has been found to give the most conservative results except SAESUS and SAEBKT loading conditions. For SAESUS and SAEBKT conditions, no mean stress correction methods have been given the most conservative results. It can be also concluded that 2014-T6-125-HF is consistently higher life than 6061-T6-80-HF aluminum alloy for all loading conditions.

The effect of surface finish and treatments on fatigue life of the 6061-T6 aluminum alloys were studied under variable amplitude loading conditions at most critical location. According to the results, all surface treatment processes can be applied to increase the fatigue life of the aluminum alloys component. The surface residual compressive stress has the greatest effect on the fatigue life. It is concluded that the polished and nitriding combinations have been found the highest lives of the cylinder block. Surface treatment to produce compressive forces in the outer layers of the component will be cyclically loaded at stress raising locations. Mechanical and thermal surface treatments can be beneficial in improving components fatigue performance, although the effect largely depends on components material properties. Therefore it can be used an efficient and reliable means for the sign-off of durability of a prototype engine with actual service environments in the early-developing stage.

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