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Effects of surface finish and treatment on the fatigue behaviour of vibrating cylinder block using frequency response approach

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Abstract: This paper presents the effects of surface finish and treatment on the high cycle fatigue behaviour of vibrating cylinder block of a new two-stroke free piston engine at complex variable amplitude loading conditions using frequency response approach. Finite element modelling and frequency response analysis was conducted using finite element analysis software Package MSC.PATRAN/MSC.NASTRAN and fatigue life prediction was carried out using MSC.FATIGUE software. Based on the finite element results, different frequency response approach was applied to predict the cylinder block fatigue life. Results for different load histories and material combinations are also discussed. Results indicated great effects for all surface finish and treatment. It is concluded that polished and cast surface finish conditions give the highest and lowest cylinder block lives, respectively; and that Nitrided treatment leads to longest cylinder block life. The results were used to draw contour plots of fatigue life and damage in the worst or most damaging case.

Key words: Finite element method, Fatigue life, Surface finish, Surface treatment, Frequency response approach
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INTRODUCTION

Due to market pressures for improvements in productivity, reliability, ductility, wear resistance and 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 a component's surface properties, such as polished, ground, machined, hot rolled, forged, cast, etc. Some of these techniques produce an improved surface by plastic deformation of surface irregularities (Hassan and Momani, 2000). Various methods have so far been used to enhance fatigue strength, including optimization of geometric design, use of stronger materials and surface processing such as nitriding, cold rolling, shot peening, etc. Among them shot peening has long been widely used as a low cost and simple method for increasing the fatigue strength of the component.

Engineering components and structures are regularly subjected to cyclic loading and consequently are prone to suffer fatigue damage, which in most cases start at the surface due to localized stress concentrations caused by machining marks, exposed inclusions or even the contrasting movement of dislocations. Evidently, control over the start and early propagation of surface cracks is paramount for prolonging the fatigue life of components (Rodopoulos *et al*., 2004). Costly shot peening is used for the above purpose as it produces near surface plastic deformation leading to the development of work hardening and high magnitude compressive residual stresses. Work hardening is expected to increase the flow re-

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sistance of the material and thus reduce crack tip plasticity.

Fatigue is an important parameter to be considered in the behaviour of components subjected to constant and variable amplitude loading (Torres and Voorwald, 2002). Fatigue is a big problem of components subjected 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 start from free surfaces and that performance is therefore dependent on the surface topology/integrity produced by surface finishing. Koster and Field (1973) suggested that the main mechanical property adversely affected by machining is high cycle fatigue strength, the actual endurance limit being dependent on the particular process used and the severity of operation. While 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 (Novovic *et al*., 2004).

Mechanical surface treatments such as nitriding, shot peening, cold and hot rolling are often used on high strength aluminum and titanium alloys to improve fatigue performance (Novovic *et al*., 2004; Bell *et al*., 1998). 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. 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 (Sidhom *et al*., 2005; Harada and Mori, 2005).

Surface finish is measured by surface roughness (groove valley to crest valley). The less the roughness, the smaller the microscopic grooves and the larger the valley radius becomes in proportion to the height of the groove. Larger radii decrease the effect of the stress producer and increase the fatigue stress at which a component fails. Beneficial effects of mechanical surface treatments are mostly compressive stress profiles and strain hardening in near surface regions of the components, yielding higher resistance against fatigue loading. They are most important in the case of high strength materials, if residual stresses remain stable (Altenberger *et al*., 1999). The surface finish and treatments have been the most effective and widely used method of introducing compressive residual stresses into the surface of metals to improve fatigue performance. The significance of polishing, machining, peening, rolling as outstanding surface finishing methods and nitriding, cold rolling and shot peening as surface treatments have risen to even greater importance with the advance of new analysis methods in metal physics and materials science over the past decades. 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 cause of inhibited crack initiation and propagation in components which are cyclically loaded (Martin *et al*., 1998).

This paper was aimed at studying the influence of surface finish and treatments on the high cycle fatigue of aluminum alloys vibrating cylinder block of a two-stroke free piston engine. Numerical investigations were conducted to characterize completely the different induced effects before and after surface treatments. The numerical results are discussed below.

THEORETICAL BASIS OF VIBRATION FATIGUE

Vibration analysis (Rahman *et al*., 2005) is usually carried out to ensure that potentially catastrophic structural natural frequencies or resonance modes are not excited by the frequencies present in the applied load. Sometimes this is not possible and designers then have to estimate the maximum response at resonance caused by the loading. These are best performed in the frequency domain using the power spectral density (PSD) functions of input loading and stress response. The input and output are connected via transfer function, which is a linear frequency dependant function. To get the stress response at a point on the structure which results from an input loading at another point one simply multiplies the input loading by the relevant transfer function.

The stress power spectra density represents the frequency domain approach input into the fatigue. This is a scalar function describing how the power of the time signal is distributed among frequencies (Bendat, 1964). Mathematically this function can be obtained by using a Fourier transform of the stress time history's auto-correlation function, and its area represents the signal's standard deviation. It is clear that PSD is the most complete and concise representation of a random process. There are many important correlations between the time domain and frequency domain representations (Rahman *et al.*, 2005) of a random process. These are highlighted by the spectral moments that are particular PSD functions. In fact there is a mathematical link or transformation which can be used move from time domain to frequency domain as shown in Fig.1. The information extracted from the frequency domain directly and used to compute fatigue damage, are the PSD moments used to compute all of the information required to estimate fatigue damage, in particular the probability density function (pdf) of stress ranges and the expected numbers of zero crossings and peaks per second. The *n*th moment of PSD area is computed by Eq.(1).

$$M_n = \int_0^\infty f^n G(f)\,\mathrm{d}f, \tag{1}$$

where f is the frequency and $G(f)$ is the single sided PSD at frequency f.

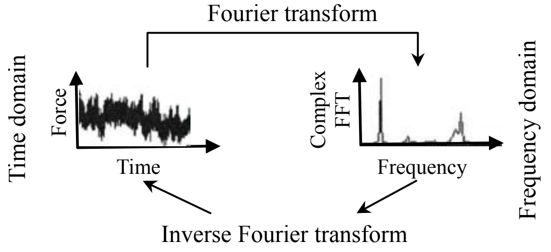


Fig.1 Transformation between time and frequency domains

A method for computing these moments is shown in Fig.2. Some very important statistical parameters can be computed from these moments. These parameters are root mean square (*rms*), number of zero crossing with positive slope ($E[0]$), number of peaks per second ($E[P]$), irregularity factor γ. The formulas in Eq.(2) highlight these properties of the spectral moments.

$$rms=\sqrt{m_0}\,;\ E[0]=\sqrt{m_2/m_0}\,;\ E[P]=\sqrt{m_4/m_2}\,;$$
$$\gamma= E[0]/E[P]=m_2/\sqrt{m_0 m_4}\,, \tag{2}$$

where m_0, m_1, m_2, and m_4 are the zero, 1st, 2nd and 4th order moment of PSD area respectively.

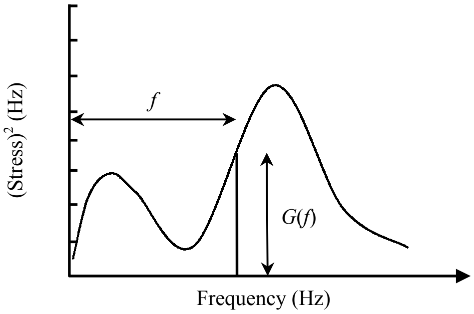


Fig.2 Moments from a PSD

The irregularity factor γ is an important parameter that can be used to evaluate how concentrated near a central frequency the process is. So it can be used to determine whether or not the process is narrow band or wide band. γ varies between 1.0 and 0.0. A narrow band process ($\gamma\rightarrow 1$) is characterized by only one predominant central frequency meaning that the number of peaks per second is very similar to the number of zero crossings of the signal.

FATIGUE ANALYSIS METHODS IN THE FREQUENCY RESPONSE

This section describes various approaches for computing fatigue life or damage directly from the stress PSD as opposed to a time history approach. Bendat (1964) proposed the first significant step towards a method for determining fatigue life from PSDs and he showed that the probability density function of peaks of a narrow band signal tended towards Rayleigh distribution as the bandwidth reduced. To complete his solution method, he used a series of equations derived by Rice (1954) to estimate the expected number of peaks using moments of area under the PSD. His narrow band solution for the mean stress range histogram is therefore expressed in Eq.(3).

Narrow band solution (Bishop and Sherratt, 1989; 2000):

$$E[D]=\sum_i \frac{n_i}{N(S_i)}=\frac{S_t}{k}\int S^b p(S)\,\mathrm{d}S$$
$$=\frac{E[P]\,T}{k}\int S^b\left[\frac{S}{4\,m_0}\mathrm{e}^{\frac{S^2}{8m_0}}\right]\mathrm{d}S=E[P]\,T\left\{\frac{S}{4\,m_0}\mathrm{e}^{\frac{S^2}{8m_0}}\right\}, \tag{3}$$

where $N(S_i)$ is the number of cycles of stress range S occurring in T seconds, n_i is the actual counted number of cycle, S_t is the total number of cycles equal to $E[P]T$. In order to compute fatigue damage over the lifetime of the structure in seconds the form of materials S-N data must be defined using the parameters k and b. The typical S-N curve is shown in Fig.3, simply showing that under constant amplitude cyclic loading, a linear relationship exists between cycles to failure (N) and applied stress range (S) when plotted on log-log paper. There are two alternative ways of defining this relationship, as given in Eq.(4).

$$N=kS^{-b}, \tag{4}$$

where $b=-1/b1$, and $k=(SRI1)^b$.

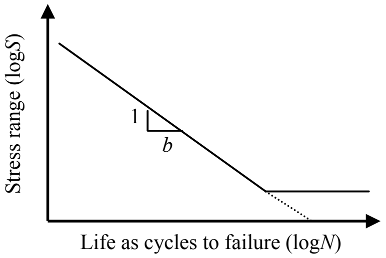


Fig.3 A typical *S-N* curve

Many expressions have been proposed to correct the conservatism associated with this solution. The solutions of Wirsching and Light (1980), Tunna (1986), Chaudhury and Dover (1985), Bishop and Hu (1991), and Kam and Dover (1988) were all derived using this approach. They are all expressed in terms of the spectral moments up to m_4.

Tunna solution:

$$p(S)_{\mathrm{T}}=\left[\frac{S}{4\gamma^2 m_0}\mathrm{e}^{-\frac{S}{8\gamma^2 m_0}}\right]. \tag{5}$$

Wirsching solution:

$$E[D]_{\mathrm{Wirsching}}=E[D]_{NB}[a+[1-a](1-\varepsilon)^c], \tag{6}$$

where $a=0.926-0.033b$; $c=1.587b-2.323$; $\varepsilon=\sqrt{1-\gamma^2}$.

This solution is given in the form of an equivalent stress range parameter S_{eq}, where

$$S_{\mathrm{eq}}=\left[\int_0^\infty S^b p(S)\mathrm{d}S\right]^{1/b}, \tag{7}$$

Hancock's equivalent stress:

$$(S_{\mathrm{eq}})_{\mathrm{Hancock}}=(2\sqrt{2\,m_0})\left[\gamma\,\Gamma(b/2+1)\right]^{1/b}, \tag{8}$$

Chaudhury and Dover equivalent stress:

$$(S_{\mathrm{eq}})_{\mathrm{C\&D}}=(2\sqrt{2\,m_0})\left[\frac{\varepsilon^{b+2}}{2\sqrt{\pi}}\Gamma\left(\frac{b+1}{2}\right)+\frac{\gamma}{2}\Gamma\left(\frac{b+2}{2}\right)\right.$$
$$\left.+\operatorname{erf}^*(\gamma)\frac{\gamma}{2}\Gamma\left(\frac{b+2}{2}\right)\right]^{1/b}, \tag{9}$$

where, $\operatorname{erf}^*(\gamma)=0.3012\gamma+0.4916\gamma^2+0.9181\gamma^3-2.354\gamma^4-3.3307\gamma^5-15.6524\gamma^6-10.7846\gamma^7$

Steinberg solution:

$$(S_{\mathrm{eq}})_{\mathrm{Steinberg}}=[0.683\,(2\sqrt{m_0})^b+0.271(4\sqrt{m_0})^b$$
$$-0.043(6\sqrt{m_0})^b]^{1/b}. \tag{10}$$

The fatigue damage can then be easily obtained by substituting this into the general damage equation used when deriving the narrow band solution.

$$E[D]=\frac{E[P]\,T}{k}S_{\mathrm{eq}}. \tag{11}$$

Dirlik (1985) has produced an empirical closed form expression for the pdf of rainflow ranges, which was obtained using Monte Carlo technique. The Bishop formula (Bishop, 1988; Bishop and Sherratt, 2000) is given below

$$N(S)=E[P]\,Tp(S), \tag{12}$$

where $N(S)$ is the number of stress cycles of range S (N/mm^2) expected in T seconds, $E[P]$ is the expected number of peaks and $p(S)$ is the probability density function.

$$p(S)=\frac{\dfrac{D_1}{Q}\,\mathrm{e}^{\frac{-Z}{Q}}+\dfrac{D_2 Z}{R^2}\,\mathrm{e}^{\frac{-Z^2}{2R^2}}+D_3 Z\,\mathrm{e}^{\frac{-Z^2}{2}}}{2\sqrt{m_0}}, \tag{13}$$

where, $D_1=\dfrac{2(x_m-\gamma^2)}{1+\gamma^2}$; $R=\dfrac{\gamma-x_m-D_1^2}{1-\gamma-D_1+D_1^2}$; $Z=\dfrac{S}{2\sqrt{m_0}}$;

$D_2=\dfrac{1-\gamma-D_1-D_1^2}{1-R}$; $D_3=1-D_1-D_2$;

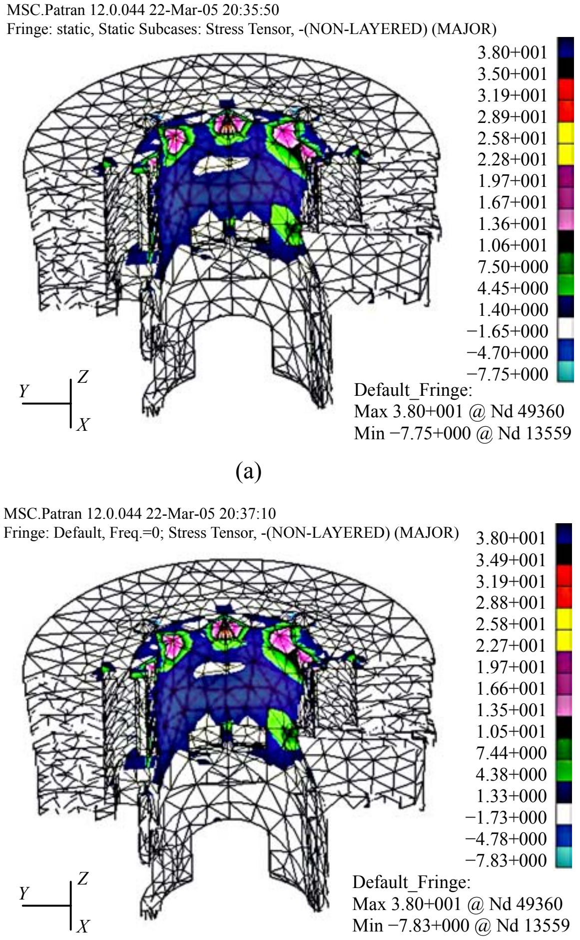
$Q=\dfrac{1.25(\gamma-D_3-D_2R)}{D_1}$; $x_m=\dfrac{m_1}{m_0}\sqrt{\dfrac{m_2}{m_4}}$; $\gamma=\dfrac{m_2}{\sqrt{m_0 m_4}}$.

Where x_m, D_1, D_2, D_3, Q and R are all functions of m_0, m_1, m_2 and m_4, Z is a normalized variable.

All of above discussed methods are determiners of fatigue life resulting from PSDs stress.

RESULTS AND DISCUSSIONS

A geometric model of free piston engine cylinder block is considered in this study. Application of finite element software on the model created a fine mesh by using a total of 10 elements. Finite element analysis of the time domain histories was performed with finite element software using the linear static analysis method (Schaeffer, 2001). The finite element results of the time domain (i.e. the maximum principal stresses distribution) are presented in Fig.4a. The fatigue life in time domain histories was determined using the total life approach (stress-life method) and rainflow cycle counting technique (Bannantine *et al.*, 1990; Stephens *et al.*, 2001; Anthes, 1997; Khosrovanen and Downing, 1990). The time domain fatigue approach consists of a number of steps. The first is to count the number of stress cycles in the response time history. This is performed through a process of rainflow cycle counting. Damage from each cycle is determined, typically from an *S*-*N* curve. The damage is then summed over all cycles using linear damage summation techniques to determine the total life. Fre-



(a)

(b)

Fig.4 Maximum principal stresses distribution (a) using linear static analysis; (b) using frequency response analysis for 0 Hz

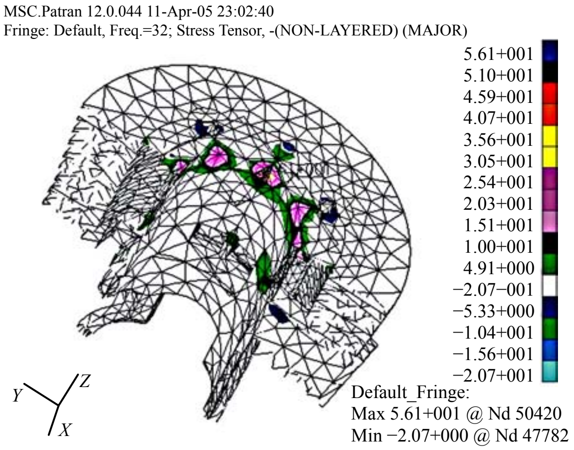


Fig.5 Maximum principal stresses for frequency response analysis at 32 Hz

quency response analysis with damping ratio of 5% of critical location performed using MSC.NASTRAN finite element software. The result of frequency response finite element analysis at zero Hz (i.e. the maximum principal stresses distribution of cylinder block) is presented in Fig.4b. Figs.4a and 4b are almost identical. The higher frequencies plot showing small divergence from the time domain cases is due to the dynamic influence of the first mode shape. This divergence is shown in Fig.6 as a function of frequency at high stress of interest for node 49360. The transfer function contains frequencies from 0 Hz to 50 Hz and is very important for obtaining accurate fatigue results. The maximum principal stress of frequency response analysis at 32 Hz is presented in Fig.5, which is different from Fig.4b. From the results, maximum principal stresses of 56.1 MPa were obtained at 32 Hz node 50420.

Fig.7 shows the time-load histories of 1 peak, 2 peaks and 3 peaks loading histories (Rahman *et al*., 2005; MSC, 2004). Figs.8a and 8b show the power spectral density function and corresponding probability density function of 3 peaks wide band signal respectively. The fatigue life contour result for the most critical locations are shown in Figs.9a and 9b for pseudo-static approach, and for 32 Hz using the 3 peak loading histories respectively. From these contours, the minimum life prediction, were obtained at $10^{6.10}$ s and $10^{6.09}$ s respectively.

Table 1 shows comparison between 1 peak, 2 peaks and 3 peaks loading history with the time domain from all the frequency domain approach methods. The results showed that the Dirlik method yields the best results for all three loading conditions. The narrow band gives good results from the narrow band signal (1 peak), but becomes too conservative when the signal is wide band (2 peaks and 3 peaks). Tunna method breaks down completely for a wide band signal. Wirsching method is unconservative and then too conservative as is the method of Steinberg and of Hancock; the method of Chaudhury & Dover does reasonably well but not as well as that of Dirlik. When the signal is wide band, the narrow band tends to turn any signal into a narrow band signal making the resulting prediction of fatigue life very conservative and sometimes overly conservative. The Dirlik method has been found to give the best results when compared with the corresponding time domain result and those of other methods.

Now we investigated the effect of surface finish and treatments on the fatigue life of component sub-

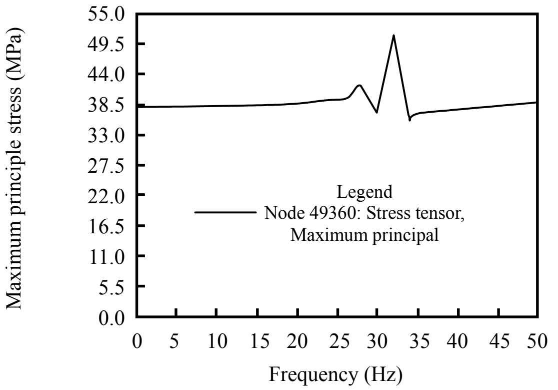


Fig.6 Variation of maximum principal stresses with frequency

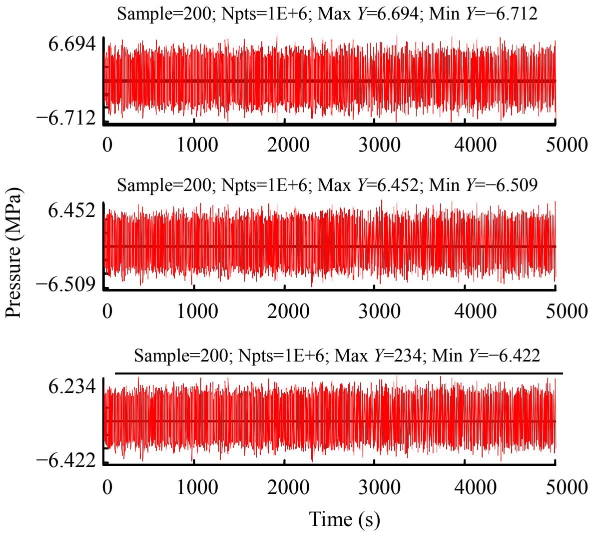
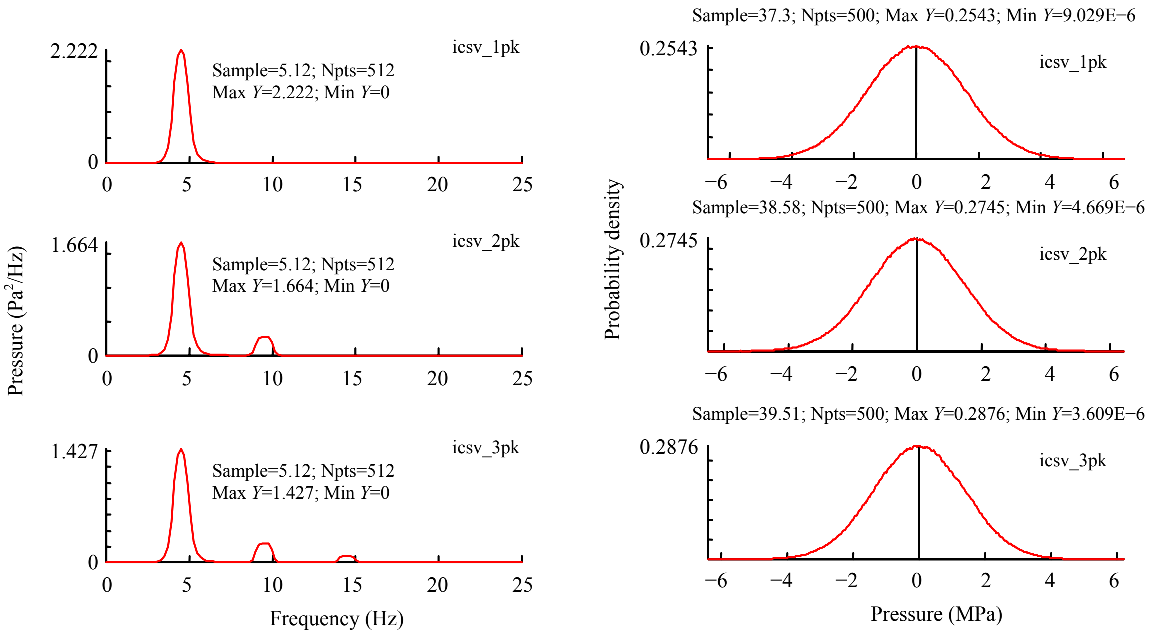


Fig.7 Time-loading histories

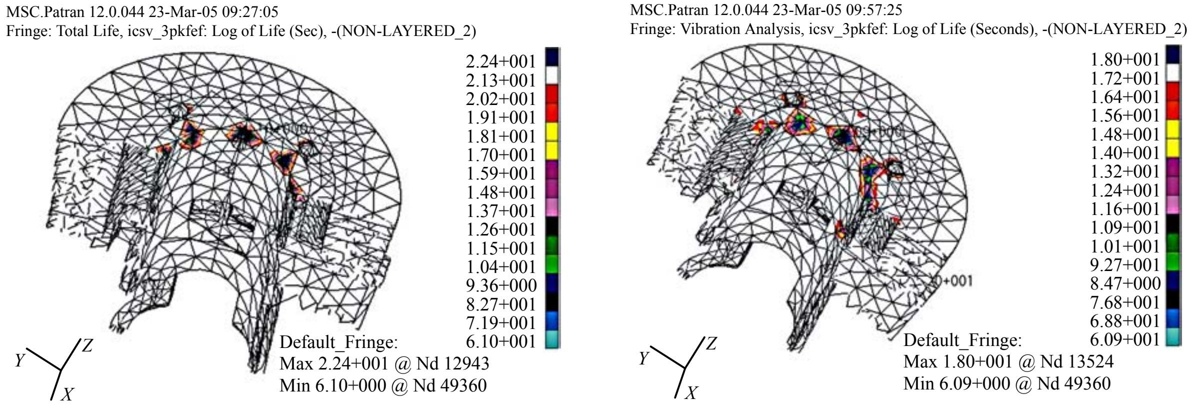
Table 1 Predicted fatigue life at most damaged location (Node 49360)

Peak	Predicted fatigue life at critical location in seconds ($\times10^6$)							
	Time domain	Narrow band	Dirlik	Tunna	Wirsching	Hancock	Chaudhury & Dover	Steinberg
1	2.66	2.61	2.65	5.83	3.83	2.47	2.46	3.18
2	4.48	2.49	4.30	1.11	4.23	3.81	4.53	3.51
3	6.16	2.55	6.38	3.79	4.32	5.19	7.46	3.67



(a) (b)

Fig.8 (a) Power spectral density function and (b) probability density function of narrow band and wide band signal



(a) (b)

Fig.9 (a) Log of life contours using pseudo-static approach; (b) Log of life contours at 32 Hz

jected to variable amplitude loading conditions. The material used in this study was AA6061-T6. A very high proportion of all fatigue failures start at the component surface and so surface conditions become an extremely important factor influencing fatigue strength. Differences in surface effects are due to differences in surface roughness, microstructure, chemical composition, and residual stress (Stephens *et al.*, 2001). The correction factor for surface finish is sometimes used as a qualitative description of surface finish such as polished or machined (Bannantine *et al.*, 1990; Stephens *et al.*, 2001). The surface factors as functions of ultimate tensile strength involving different surface finish conditions such as grinding, machining, hot rolling, and forging (Juvinall and Marshek, 1991). The correction factors for surface treatment and finish are obtained from the empirical data in (Lipton and Juvinall, 1963; Juvinall and Marshek, 1991; Reemsnyder, 1985) and are related to the ultimate strength of the material. The contributions of surface finish and treatments on the fatigue lives at 3 peaks loading conditions using Dirlik frequency response method at critical location are summarized in Table 2. Surface treatments (nitriding, cold rolling, shot peening) that produce compressive residual surface stresses are useful. These treatments cause the maximum tensile stress to occur below the surface. Surface treatments also increase the endurance limit. Nitriding 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. Forging can cause surface decarburization with the loss of carbon atoms from the surface material causing it to have lower strength, and may also produce residual tensile stresses. Both of these factors are very detrimental to fatigue strength. There are several methods used to cold work the surface of a component to produce residual compressive stress. The two most important methods are cold rolling 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 being hit by 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. The effect of nitriding on vibrating cylinder block made of aluminum alloy for wide band 3 peaks loading condition can be seen in Table 2. It can be seen that the fatigue life due to nitriding surface treatments is surprisingly much longer than that due to other surface treatment processes. Fig.10's comparison of treatment methods showed that cold rolled surface treatment had better effect than surface polishing, grinding, and machining treatments on prolonging fatigue life, and that the effect of cold rolling and shot preening surface treatment on prolonging fatigue life are the same, and that cold rolling had better effect than that of shot preening.

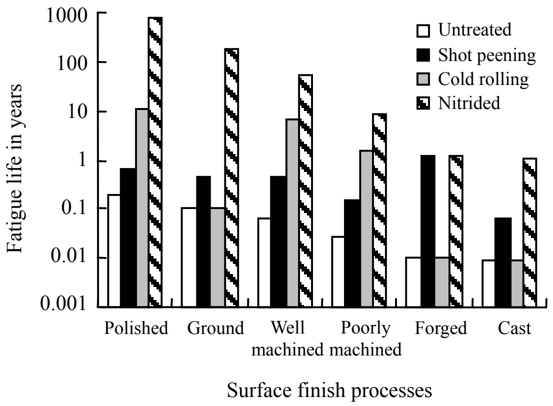


Fig.10 Effect of surface treatments and different surface finishing processes on fatigue life

CONCLUSION

Frequency domain fatigue analysis has been applied to a typical cylinder block of two-stroke free piston engine. All the current methods are discussed and conclusions are drawn showing that Dirlik method is best for the general use. The effect of surface finish and treatments on fatigue life of 6061-T6 aluminum alloys were studied under various amplitude loading conditions at most critical locations. The results showed that 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 can be concluded that polished, ground and machined surface finishes are best, but that forged and cast parts are worst due to the surface finishes. The polished and nitriding combinations have been found to lead to longest lives of the cylinder block.

Table 2 The effect of surface finish and treatments on fatigue life at critical location (Node 49360) for 3 peaks conditions

Surface finish processes	Predicted vibration fatigue life in years			
	Untreated	Shot peened	Cold rolled	Nitrided
Polished	0.202	0.644	10.430	808.600
Ground	0.104	0.425	0.104	170.600
Good machined	0.063	0.450	6.532	54.540
Poor machined	0.026	0.149	1.475	8.689
Forged	0.010	1.265	0.010	1.265
Cast	0.009	0.064	0.009	1.091

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