

Analyzing Field Failures of Engine Valve Springs in Presence of Non Metallic Inclusions by Applying Statistical and Fracture Mechanics Models

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ABSTRACT

The reliability of engine valve springs is a very important issue from the point of view of warranty. This paper presents a combined experimental and statistical analysis for predicting the fatigue limit of high tensile engine valve spring material in the presence of non-metallic inclusions. Experimentally, Fatigue tests will be performed on valve springs of high strength material at different stress amplitudes. A model developed by Murakami and Endo, which is based on the fracture mechanics approach, Extreme value statistics (GUMBEL Distribution) and Weibull Distribution will be utilized for predicting the fatigue limit and the maximum inclusion size from field failures. The two approaches, experimental and theoretical, will assist in developing the S-N curve for high tensile valve spring material in the presence of non-metallic inclusions.

INTRODUCTION

The quality of steel is strongly influenced by the presence of inclusions which are microscopic particles of irrelevant material within the material matrix. Fatigue strength, in particular, is influenced by the size of the largest inclusions, which can act as a starter for fractures that eventually lead to failures [9]. Inclusions consist of elements like calcium, silicon, aluminum, sulfur, and magnesium. Recent work and research has been focusing on estimating the size of big inclusions and defects that can be found in a component. An engine valve spring, which is made of high strength,

clean steel, is a key component for an engine. It is designed to survive an infinite life under high cyclic stresses. Fatigue life of valve spring material can be described as a relationship between stress amplitude and number of cycles. This relationship is known as S/N curve Fig.1. The stress or the logarithm of the stress is plotted against the logarithm of life. An important characteristic of the S/N curve is the fatigue limit, where the valve springs will never break if the applied stress is below the endurance limit. Fig.1 demonstrates the shift and drop of the fatigue life due to presence of an inclusion. In terms of system reliability, a single valve spring failure corresponds to engine failure. The failure of an engine valve spring is not always caused by the presence of inclusions. Only when the cracks, originated at these inclusions and grow sufficiently, the probability of failure will increase. The above explanations will lead to the definition of "fatigue limit", which is the threshold for the stress under which the initial cracks will not grow. Inclusions are rated qualitatively based on their chemistry and morphology. However, the rating method is not capable of making the correlation between the inclusion size and fatigue strength of the material. Recently, a considerable number of models were developed for predicting the fatigue strength in presence of inclusions. The latest model that can correlate the fatigue strength and inclusion sizes was developed by Murakami. The Murakami model is based on 1) square root of maximum inclusion size, (which can be predicted by applying extreme value statistics) and 2) the hardness of the material.

Murakami and Endo Model

Murakami and Endo developed a fatigue limit model based on experimental results by considering the square root area ($\sqrt{area}$) of a defect (inclusion) or a crack projected onto a plane perpendicular to the maximum tensile stress. This allows the maximum stress intensity factor to be calculated as:

$$\Delta k = 0.65 * \Delta \sigma * \sqrt{\pi * \sqrt{area}}$$

Many experiments carried out by Murakami have shown that a crack will not propagate when its stress intensity factor Δk is lower than the threshold value Δk_{th} . This supports the concept that the fatigue limit of a material containing defects is not the critical stress for crack initiation but the threshold stress for the non-propagation of small cracks emanating from the original cracks or defects. Experiments on 15 different materials with hardness ranges between 70 and 720 H_v performed by Murakami and Endo had shown that Δk_{th} for small cracks correlated well with $\sqrt{area}$ as shown in Fig.2.

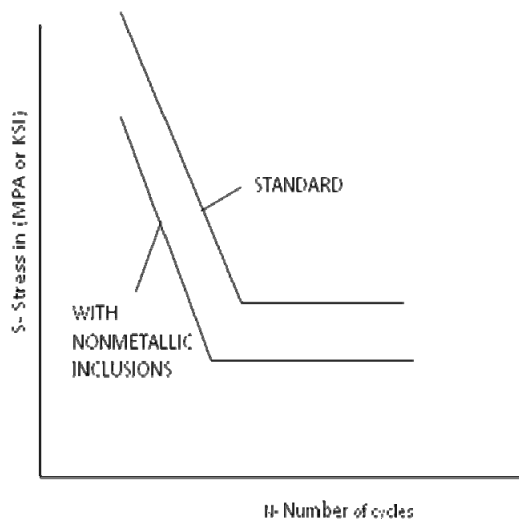


Fig. 1 –S/N Plot Stress (S) vs. Number of Cycles (N) [6]

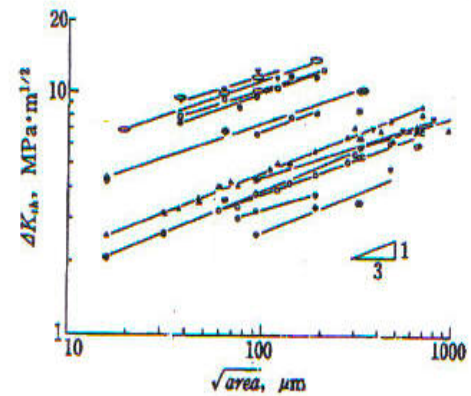


Fig.2 threshold intensity factor vs square root area

The experiment leads to the following relationship:

$$\Delta k_{th} \propto (\sqrt{area})^{1/3}$$

Another relationship developed by Murakami was threshold intensity factor as a function of hardness and square root area.

$$\Delta k_{th} = 3.3 \times 10^{-3} (H_v + 120) (\sqrt{area})^{1/3} \quad (1)$$

This leads to the development of the fatigue limit as:

$$\sigma_w = \frac{1.43 (H_v + 120)}{(\sqrt{area})^{1/6}} \quad (2)$$

Δk_{th} is the threshold stress intensity factor under

stress ratio $R=-1$. $R = \frac{\sigma_{min}}{\sigma_{max}}$

$\sqrt{area}$ Geometric parameter of the defect in μm

H_v Vickers hardness

Equation (2) is applicable for surface defects or inclusion. In case of internal inclusion, the fatigue limit will be modified as:

$$\sigma_w = \frac{1.56 (H_v + 120)}{(\sqrt{area})^{1/6}} \quad (3)$$

Extreme value theory for predicting the maximum inclusion size

Extreme value statistics is an analytical method of observing extremes and predicting further extremes. For example, finding the expected largest inclusion size in a volume of 1000 ton of steel for a volume of steel that only has inclusion data for 10 ton of steel would be an application of extreme value statistics. Historically, this type of analysis was first used to predict the magnitude of river flooding that could be expected to occur in a certain number of years. Major contributions to both the

theory and practical application of extreme value theory were made by Gumbel . More recently, this analysis has been used to predict how large a non-metallic inclusion could be found in a given volume of steel. Murakami and his co-workers were the first to apply extreme value theory to the estimation of inclusion size. The basic concept of extreme value theory is that when a large number of observations follow a basic distribution, such as normal, exponential, log-normal, are collected, the maximum or minimum of these sets also follow a distribution which is different from the basic distribution. In this study, the interest is in drawing inferences about the maximum values of the inclusions. Based on Murakami's work, the distribution of inclusions in metals is expected to be nearly exponential which makes its extreme distribution, doubly exponential.

Details of the application of Murakami's work can be explained as follows:

- 1- A section of steel rod perpendicular to the maximum principal stress is cut from the specimen
- 2- A standard inspection area, $s_0(mm^2)$, is fixed. In the area s_0 the inclusion of maximum size is selected and this operation is repeated n times.
- 3- The values of $\sqrt{area_{max}}$ are classified, starting from the smallest and indexed from $j=1...n$
- 4- The obtained data is plotted on probability paper where the abscissa is $\sqrt{area_{max}}$ and the ordinate is $y_i = -\ln(-\ln(i/(n+1)))$.
- 5- If $-\ln(-\ln(i/(n+1)))$ is plotted against $\sqrt{area_{max}}$, a straight line that represents the linear distribution of the maximum size of inclusion will be formed.
- 6- The slope of the line will give the graphical estimate of slope, σ , and the intercept on the vertical axis is μ .
- 7- The analysis of inclusions is applied by extrapolating measurements obtained on small areas, S_{ref} , to estimate the size of maximum defects in much bigger areas
- 8- The characteristic size of the maximum inclusion or defect which can be found in the prospective area, S_p , can be derived as ,

$$z_{max}(S_p) = \mu - \sigma \cdot \ln(-\ln(1 - 1/T))$$

where $T = V/V_0$

V_0 is the control volume used in defect sampling and V is the volume of the component.

WEIBULL distribution for estimating fatigue life

The Weibull distribution has been extensively used as a probability distribution function for the statistics of life test experiments. It was originally proposed by a Swedish scientist, Weibull, for statistical analysis of material strength and fatigue failure. It will be utilized for analyzing the fatigue data generated from the Nakamura (rotating fatigue test) and valve spring testing. The probability density function, $f(x)$ of the Weibull distribution can be expressed as:

$$f(x, \theta, \beta, \delta) = \frac{\beta}{\theta} (x - \delta)^{\beta-1} \exp \left\{ -\frac{(x - \delta)^\beta}{\theta} \right\} \quad (4)$$

where x is a set of sample observations, β is a shape parameter, θ is a scale parameter and δ is a location parameter. In fatigue life analysis, the location parameter is assumed to be zero. The three-parameter weibull distribution will be reduced to a two parameter weibull distribution as:

$$f(x, \theta, \beta,) = \frac{\beta}{\theta} (x)^{\beta-1} \exp \left\{ -\frac{x^\beta}{\theta} \right\} \quad (5)$$

According to the relations between the probability density function, $f(x)$, and the cumulative distribution function $F(x)$:

$$f(x) = \frac{dF(x)}{dx} \quad \text{and} \quad F(x) = \int_{-\infty}^x f(x) dx ,$$

The cumulative distribution function of the two-parameter Weibull Distribution can be expressed as:

$$F(x) = 1 - \exp \left[-\left(\frac{x}{\theta} \right)^\beta \right] \quad (6)$$

The probability of survival at x is expressed by the Reliability function:

$$R(x) = 1 - F(x) = \exp \left[-\left(\frac{x}{\theta} \right)^\beta \right] \quad (7)$$