

Study of the Fatigue Failure of Engine Valve Springs Due to Non-Metallic Inclusions

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ABSTRACT

The engine valve spring is a very important component in automotive engine systems. The non-metallic inclusions in an engine valve spring will significantly reduce its reliability. In this study, an attempt was made to establish a correlation between fatigue failures and non-metallic inclusions by applying statistical methods. Fatigue tests with BZ and OTEVA-90 materials are performed with two different types of experiments, which are rotating bending fatigue test (Nakamura test) and spring fatigue test. By using RELIASOFT, the data of these two tests are analyzed with the Weibull distribution in order to statistically estimate BZ and OTEVA-90's fatigue lives at 90% low confidence under different stresses. On the other hand, fatigue strength of these materials can be estimated by Murakami and Endo's model with maximum inclusion size predicted from the Gumbel distribution.

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INTRODUCTION

Engine valve springs, spiral springs that push back to close the intake and exhaust valves during combustion cycles, are crucial for any engine's performance. The working environment of a typical valve spring in diesel engine is shown in Fig. 1 [1]. The performance of engine valve springs plays an important role in the reliability of engine, and they are usually designed to survive an infinite life under high cyclic stress. Therefore, failure possibilities of the valve springs should be taken into account in design process, because in terms of system reliability, a single valve spring failure corresponds to engine failure [2].

Fatigue fracture is one of the most important failure modes of engine valve springs. Deadly fatigue failures can be caused by the wearing of contacting surfaces of adjacent coil pairs, which is called "bright band" [3]. However, the non-metallic inclusions in the steel springs are usually the main reason causing failure (Some typical alloy materials used to produce springs and their chemical compositions are listed in Table 1). The presence of inclusions decreases the ability of a metal to withstand high static loads, impact forces and fatigue loading. Non-metallic inclusions can easily become stress concentrators because of their discontinuous nature and incompatibility with the surrounding composition [7]. An image of a non-metallic inclusion near the fracture surface is

shown in Fig. 2 [7]. It is possible to correlate fatigue strength of the spring with size and chemical composition of the inclusions, since the weakness of alloy material is usually originated from its chemical inhomogeneity.

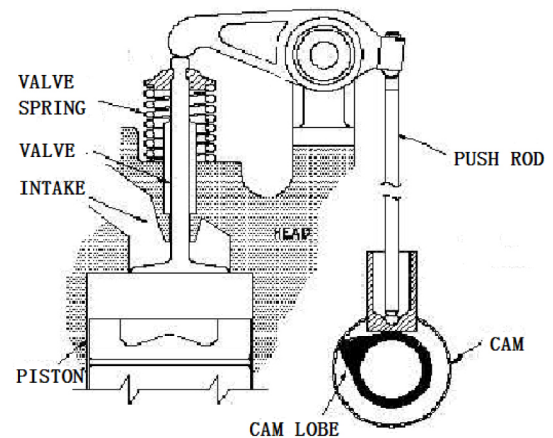
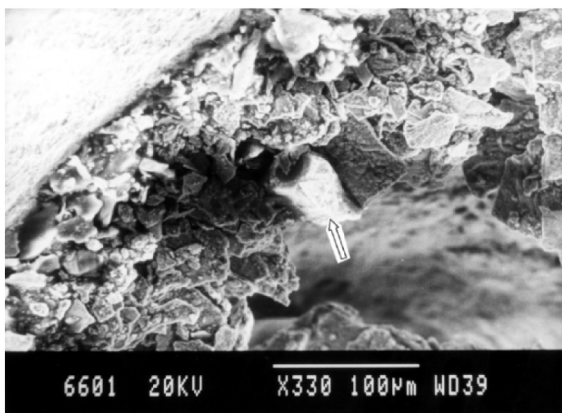


Fig. 1. Engine valve spring working environment [1]

Table 1. Chemical composition of several spring materials

	Chemical composition (Weight %)										
	C	Si	Mn	Cr	V	Mo	Ni	W	S	Cu	P
BZ ^[4]	0.50- 0.70	1.80- 2.20	0.70- 1.00	0.85- 1.05	0.05- 0.15		0.20- 0.40				
OTEVA 90 ^[4]	0.61- 0.65	1.80- 2.20	0.30- 0.60	0.80- 1.00	0.05- 0.15	0.05- 0.15					
SAE 9254 ^[5]	0.55	1.46	0.69	0.73							
Cr-Si-V ^[5]	0.63	1.45	0.64	0.65	0.185						
Mo-W ^[5]	0.61	1.43	0.51	0.51	0.180	0.096		0.096			
55CrSi ^[3]	0.50- 0.60	1.20- 1.60	0.50- 0.80	0.50- 0.80					≤0.03	≤0.02	≤0.03
OTEVA 60 ^[6]	0.60- 0.75	0.15- 0.30	0.50- 0.90	0.30- 0.50	0.05- 0.15				<0.025		<0.03

**Fig. 2. Non-metallic inclusion particle near the surface (bright looking area shown by an arrow mark) [1]**

Fatigue strength refers to the amplitude of cyclic stress that can be applied to a material without causing fatigue failure. If the working stresses of a spring are under its fatigue strength, the initial cracks will not grow and failure due to fatigue can be largely avoided. There are a number of models proposed to describe the correlation between fatigue strength and influencing factors such as inclusions, notches or cracks. For instance, Frost's model and its modified version by Kobayashi and Nakazawa considered the effect of notches or cracks on fatigue strength rather than that of non-metallic inclusions [8]. Mitchell and Nordberg proposed a model that is suitable for analyzing the effect of non-metallic inclusions [8], but Mitchell and Nordberg assumed all defects to be hemispherical pits with constant geometry, which made them neglect the randomness of defect shape - an important factor in practice. El Haddad proposed a fatigue strength model based on fracture mechanics approach [9]. Using this model, the fatigue strength of a component containing a short crack can be evaluated from the material constants (threshold stress intensity factor range *etc.*) determined by conventional fracture mechanics fatigue experiments. However, El Haddad's model is only valid over a limited range of crack

length, and is not applicable to three-dimensional cracks. During experiments, it was frequently observed that the crack initiates at the location of inclusion grain with the biggest size. Therefore, Murakami and Endo proposed a model to predict fatigue strength based on the square root of maximum inclusion area, where the inclusion area referred to the area projected by the inclusion particle onto a plane perpendicular to the tensile stress direction [9]. However, due to random distribution of non-metallic inclusions in steel, the maximum inclusion area is usually difficult to be pinpointed in an individual sample.

In the present work, experimental results of rotating bending fatigue tests and spring fatigue tests are reported for two typical materials which are used to manufacture engine valve springs, BZ and OTEVA-90. Weibull distribution is introduced to analyze experimental results and estimate fatigue life. Also, based on the experimental measurements, an extreme value theory (Gumble distribution) is applied to predict the largest inclusion size, which can then be utilized with Murakami and Endo model to predict fatigue strength of the material.

EXPERIMENTAL METHODS

NAKAMURA TEST (ROTATING BENDING FATIGUE)

Two typical materials which are used to manufacture engine valve springs, BZ and OTEVA-90 steel were studied by rotating bending fatigue tests. The experiments were performed at Associated Spring's Product Development Center in Plymouth, Michigan. The equipment (Nakamura rotating bending tester) utilized is shown in Fig. 3 [4]. Wire samples of BZ and OTEVA-90 2 feet in length and 4 mm in diameter were tested. As shown in the schematic, two main bearings were installed to support the test specimen, and two load applied bearings were mounted at the same distance from the supporting points. When specimens were under rotation, every portion of the material was experiencing cyclic stress due to rotation, causing the possibility of fatigue

failure. Cycles-to-failure data were obtained by testing a number of specimens to failure at different stress levels.

SPRING FATIGUE TEST

The fatigue testing on engine valve springs was aimed to determine fatigue life of a spring in working environment under different stress levels. Similarly, two different types of springs made of BZ and OTEVA-90 respectively were tested. As shown in Fig. 4, a rotary cycle tester at 1200 rpm was utilized for cycling the springs. Stress levels were adjusted by changing the operating heights and their corresponding loads. The stress calculation was based on Goodman stress equation:

$$\text{Goodman stress} = \frac{UTS(S2-S1)}{UTS-S1} \quad (1)$$

Where UTS is the ultimate tensile strength, and $S1$ and $S2$ are the minimum stress and maximum stress respectively. Twelve springs were installed for testing at each stress level and cycles-to-failure data of each spring was recorded. The test was stopped after 6 failures were accumulated.



Fig. 3. Nakamura rotating bending tester [4]



Fig. 4. Rotary cycle tester [4]

MAXIMUM INCLUSION SIZE ESTIMATION BASED ON EXTREME VALUE THEORY

In this study, an extreme value theory (Gumbel distribution) was applied to predict the largest inclusion size. The cumulative distribution function (CDF) of Gumbel model can be expressed as:

$$G(x) = \exp \left[-\exp \left(-\frac{x-\alpha}{\eta} \right) \right] \quad (2)$$

where for this specific application $G(x)$ provides the probability of an inclusion size being smaller than x , and α , η are location parameter and scale parameter, respectively. Inclusion size data collected from field failures were fitted into the Gumbel distribution and parameters α and η were determined. After all the parameters were acquired, the maximum inclusion size can be estimated based on Gumbel distribution by specifying a very small exception probability, e.g. $[1 - G(x)] < 3\%$. This maximum inclusion size can be used in Murakami and Endo model to predict the decrease of fatigue strength.

RESULTS AND DISCUSSION

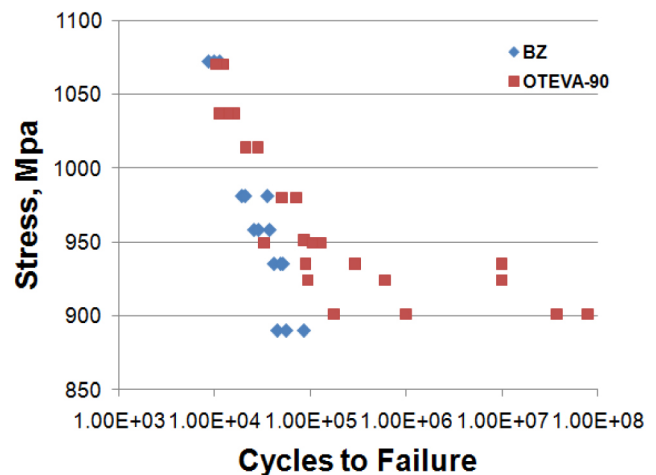


Fig. 5. Rotating bending fatigue test data

The rotating bending fatigue test data for BZ and OTEVA-90 were plotted on a semi-log scale as stress versus cycles-to-failure, as shown in Fig. 5. It can be seen that there are not much difference between BZ and OTEVA-90 when the stress level is high (> 1000 MPa). However, under lower stresses the numbers of cycles to failure for OTEVA-90 are larger than those for BZ, which suggests that OTEVA-90 has a better performance over BZ. The fatigue limits for the BZ and for OTEVA-90 materials are around 700 MPa and 900 MPa respectively. Also, the cycles-to-failure data for OTEVA-90 showed much larger scattering and uncertainties. In the mean time, failure due to inclusion was detected during