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Failure Analysis of an Exhaust Valve Spring Failed in Automotive Diesel Engine

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***Abstract*:- This paper presents a failure analysis on a failed exhaust valve spring in an automotive diesel engine. The spring was failed in the service after working for 930 hours. Metallurgical examinations (by a metallurgical microscope and a scanning electron microscope) are conducted on the fracture surface of the spring. The results confirmed that, the spring has failed due to typical fatigue failure caused due to the presence of suspected Silicate type non-metallic inclusion, which assumes to be carried from the basic steel manufacturing. The basic spring steel wire is oval in shape and material grade is Chrome-Silicon-Vanadium (Cr-Si-V), which was cold drawn and followed by oil hardened and tempered. The fracture face confirms the fatigue initiation, where non-metallic inclusion was present and further propagation took place. Presence of beach marks are also confirms the fatigue propagation.**

Keywords:- Engine valve spring, Fatigue failure, Non-metallic inclusion, Compressive residual stress

1.INTRODUCTION

The valve springs are a central part of the valve train, whose main functions are to lift the mass of each valve during the closing operation, and to produce just the right amount of friction between the cam follower and the camshaft. This is important, as these parts should be in contact during the valve operations, so that the cam follower accurately follows the cam profile [1,5]. High performance valve spring wires are manufactured from special, high-tensile-strength alloys of very high purity, and later subjected to oil hardening and tempering process and followed by eddy current test for confirming the presence of any surface defects. The valve springs manufactured using these wires undergoes various surface treatments like shot peening in order to have the improved fatigue properties, which is quantitatively measured by measuring the compressive residual stresses using X-ray diffraction method.

In the present case, the failed spring was failed in the field, which was assembled in a diesel engine of heavy commercial heavy vehicle. The engine has operated for 930 working hours when the spring failure occurs. The breakages occurred at multiple locations of the spring as shown in Figure 1 and 2. The oil hardened and tempered wire used for manufacturing the particular failed spring having the tensile strength of 2050 N/mm^2 with percentage reduction in area of 46%. The material grade of high performance spring steel wire used to manufacture the spring is Cr-Si-V with oval cross section, which measures 4.36X3.35 mm.

Fig. 1 and 2. The broken exhaust valve spring in the diesel engine and multiple fracture faces

2. INVESTIGATION METHODS

To carry out failure analysis of exhaust valve spring, three types of possible root causes are considered which include mechanical properties, metallurgical and material properties and surface treatment specifically shot peening effectiveness [2].

2.1. Possible mechanical properties or phenomena that can cause fatigue failures are,

- Mechanical damages on spring surface, which could be carry from manufacturing process, tools, assembly, wear, alignment or handling.

2.2 Possible Metallurgical and material properties that can cause fatigue failures are,

- Poor Microstructure due to improper phase transformation during the oil hardening and tempering process.
- Decarburization that could be carry from basic raw material wire or heat treatment process.
- Poor Pre-Austenite Grain Size could be carry from basic raw material wire heat treatment.
- Steel cleanliness that is presence of non-metallic inclusions.
- Chemical composition of steel is out of specification limit.
- Abnormal variation in hardness across the cross section.

- Surface defects like surface crack, laps, seam that could be carry from basic raw material wire manufacturing.

2.3 Possible surface treatment properties that can cause fatigue failure are,

- Poor or insufficient shot peening coverage or distribution on spring surface.
- Poor shot peening resulting poor compressive residual stress on spring surface.

3. EXPERIMENTAL PROCEDURES

3.1 Visual and Macroscopic Observations

As shown in figure 1-2, the exhaust valve spring has failed at multiple locations, specifically at 2.5th coil from both the end of the spring. The fracture faces are cut from the failed portion of the spring as shown in figure 3,cleaned and observed under optical microscope. The failure mode clearly indicates typical fatigue in nature and which has initiated from the surface in between the spring inner diameter and outer diameter and further propagated towards core, figure 4-5. Closer look at the fracture surface reveals the presence of some foreign particle at fatigue origin point and radiating ridges emanating from this point suggest fatigue failure caused by cyclic loading during the service [7]. At the fatigue origin, spring surface found to be free from any of the possible mechanical damages, tool marks or any material surface defects like crack or laps as mentioned in 2.1 and 2.2 above.

Fig.3. Fracture faces removed from the failed spring

Fig. 4.Fracture face A at 10X

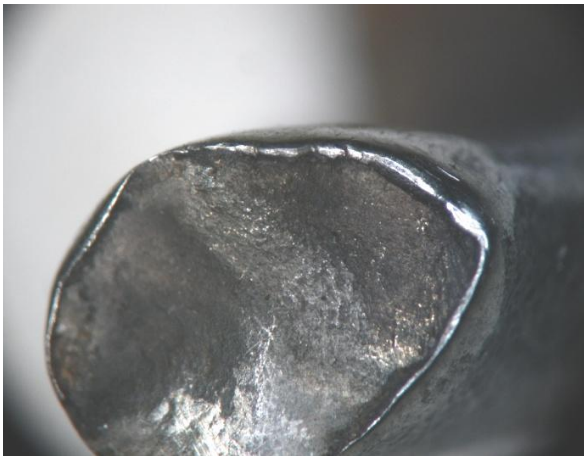

Fig. 5.Fracture face B at 10X

3.2 Scanning Electron Microscopy

The fracture specimens are cleaned ultrasonically to remove the contaminations, there after scanning electron microscope (SEM) was used to examine the detailed features of the fracture surface [8]. Refer figure 6, a crescent shaped region on the fracture face where fracture originated and clear beach marks and further crack propagation are visible, which are typical fatigue failure characteristics. About 117 µm beneath from the spring surface, non-metallic inclusion, which carried from basic steel was observed. The non-metallic inclusion measured with size of 26.1 µm x 3.58 µm and EDAX analysis confirms the presence of Silicate type non-metallic inclusion, Refer figure 7-9.

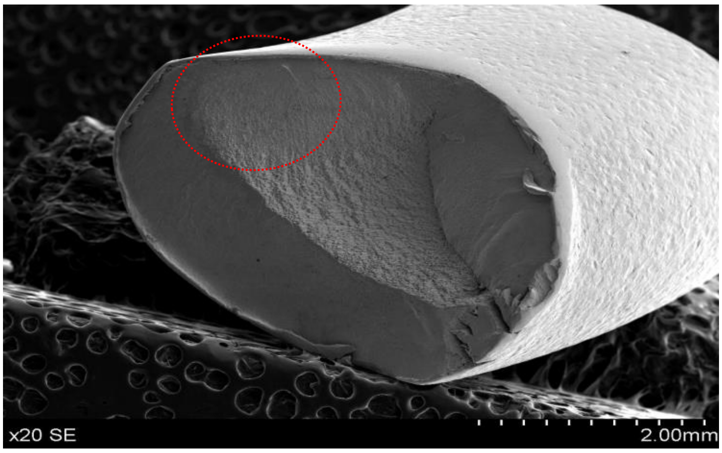

Fig.6.Fracture face with crescent shaped region at fatigue origin

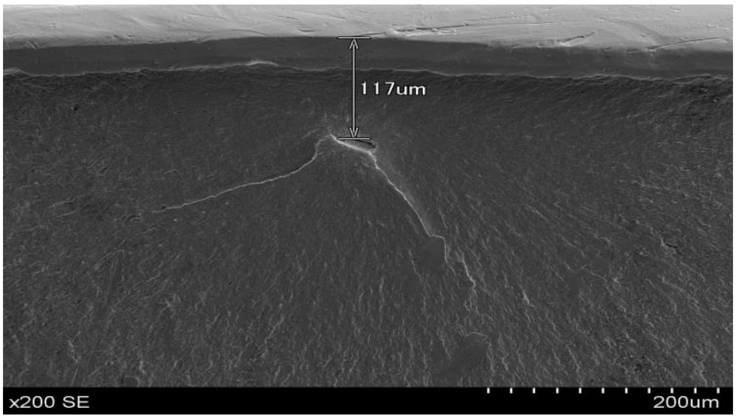

Fig.7.Presence of non-metallic inclusion at fatigue origin

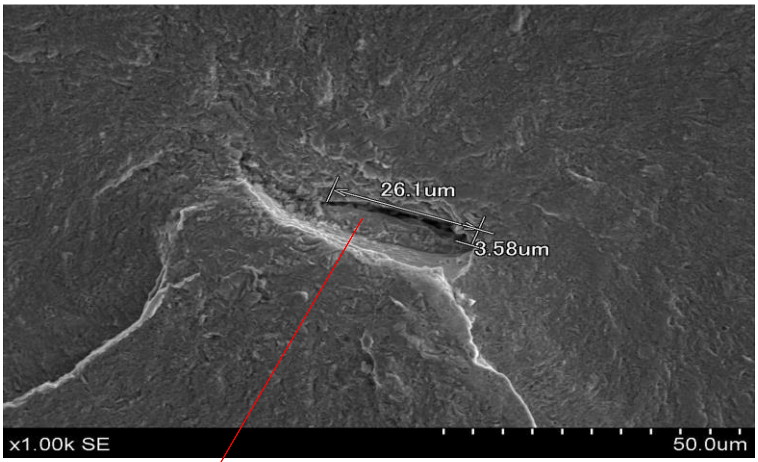

Fig.8, Inclusion size measures as 26.1 µm x3.58 µm

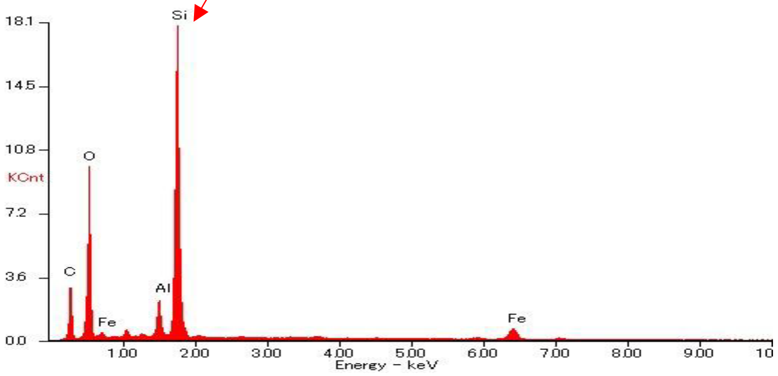

Fig.9.EDAX analysis confirms the Silicate type inclusion

3.3 Microscopic Analysis:

A specimen was cut from the failed spring (near the fracture surface), polished and etched using 4% Nital as standard metallography techniques to reveal microstructures. The microstructure revealed as fine tempered martensite and there is no decarburization, see figure 10-11.

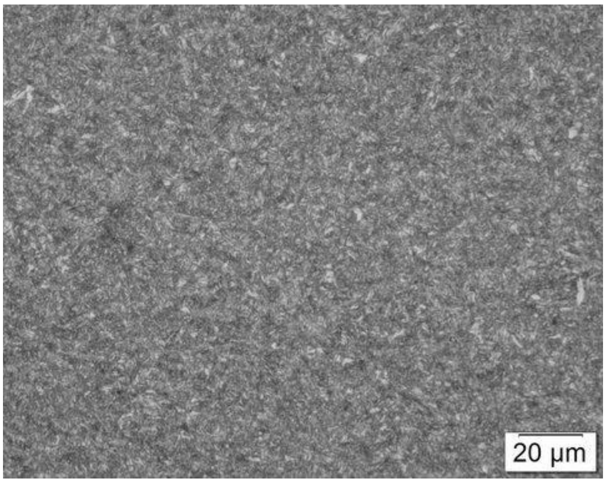

Fig.10.Fine Tempered Martensite (X500)

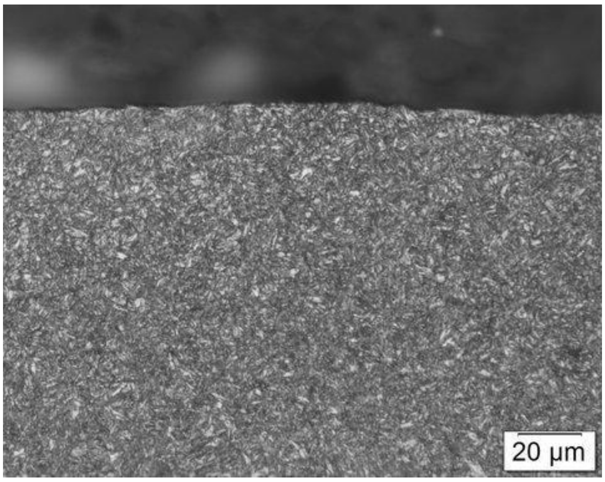

Fig.11.No decarburized layer on the surface

Prior Austenite grain size also analyzed near the fracture face of the spring and it measures as 7.9, see figure 12. The test method followed for measuring the grain size is IS 4748:2009, ISO 643.
There is no abnormalities found with respect to microstructure in failed spring.

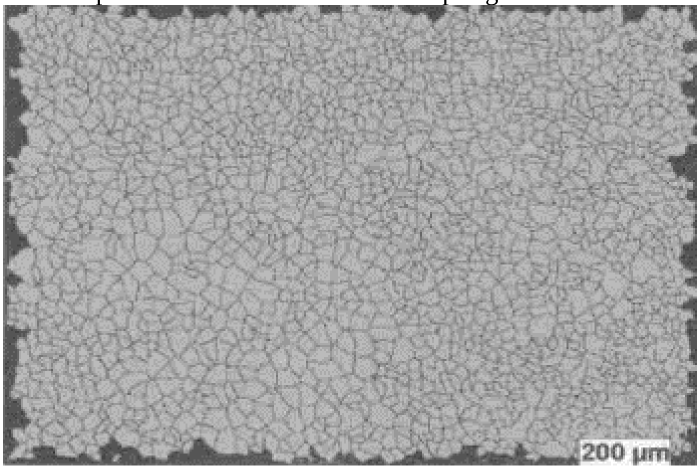

Fig.11.Prior Austenite grain size measures as 7.9

3.4 Hardness Measurement

A hardness survey was made across the cross section of the metallographically prepared sample of the failed spring. The sample showed average hardness value of 582 HV, which is the acceptable criterion for the spring steel. Figure 12-13 shows the graphical representation of cross sectional hardness survey.

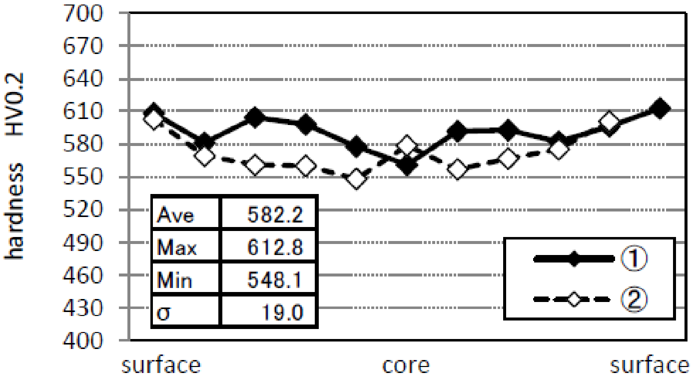

Fig.12.Cross sectional hardness survey

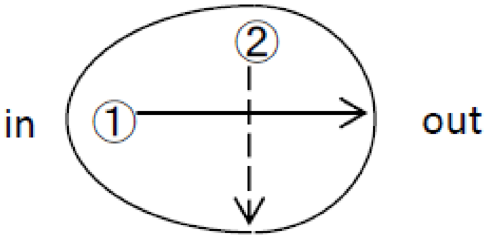

Fig.13.Schematic image of wire

3.5 Chemical Composition Analysis

An examination of material composition was analyzed using Spectrometer, and showed that the compositions of failed spring were within the specification limits of Cr-Si-V spring steel grade. Table 1 shows the actual chemical composition of failed spring as against material specification.

Table 1 Chemical composition of Cr-Si-V steel in /wt%.

	Chemical Composition							
	C	Si	Mn	Cr	V	P	S	Cu
Cr-Si-V steel spec.	0.63-0.68	1.20-1.60	0.50-0.80	0.50-0.80	0.10-0.15	0.025 max.	0.025 max.	0.20 max.
Failed spring chemistry	0.65	1.47	0.72	0.67	0.11	0.008	0.005	0.01

3.6 Shot peening and Residual stress analysis

Shot peening coverage on failed spring was observed under optical microscope at 10x magnification. Figure 14 shows the uniformly distributed shot peening coverage on spring surface.

Quantitatively to confirm the effect of shot peening on failed spring, compressive residual stress was analyzed using X-ray diffraction method. Surface compressive residual stress was measured as -800 M Pa on the surface and maximum compressive residual stress was measured as -935 M Pa at 50 µm depth from the surface. Figure 15 shows the graphical representation of compressive residual stress profile in failed spring. There is no abnormality observed with respect to residual stress profile.

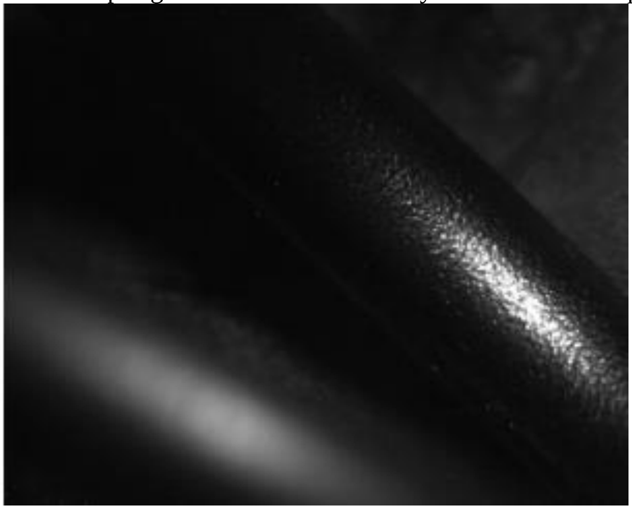

Fig.14.Good shot peening coverage on failed spring

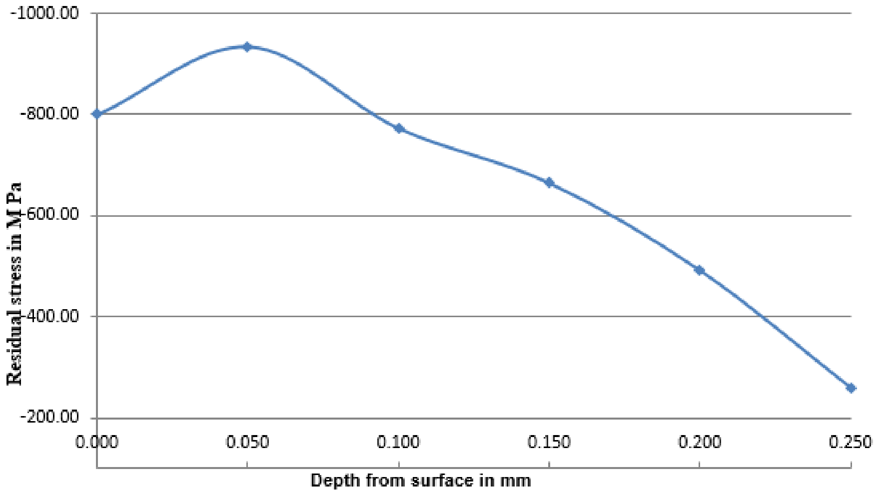

Fig. 15. Compressive residual stress profile in failed spring

4.RESULTS AND DISCUSSION

Visual and macroscopic examination of fractured valve spring revealed that the failure is typical fatigue in nature, which has initiated from the surface. A crescent shaped region on the fracture face where fracture originated and clear beach marks and further crack propagation are visible, which are typical fatigue failure characteristics [7]. The macroscopic examination also reveals that, the spring surface found to be free from any harmful mechanical damages, tool marks, surface crack or any other mechanical or material defects, which could be carried from manufacturing, assembly or any external impacts and these factors are not contributed spring failure.

Scanning electron microscope analysis reveals the presence of a non-metallic inclusion about 117 µm beneath the surface and fatigue has initiated from the same location and further propagated towards core. The non-metallic inclusion measures 26.1 µmX3.58 µm in size. Energy dispersion analysis (EDAX) analysis reveals that the composition of non-metallic inclusion is of Silicate type. Silicate type non-metallic inclusion assumed residues of Silicon, carried from steel making process, where Silicon being used as alloying element and as a deoxidizer [3].

Metallographic examination reveals that, the microstructure of failed spring is fine tempered martensite and free from any surface decarburization. Prior austenite grain size also found to be finer. Hence, any of the metallographic properties are not contributed to spring failure.
Cross sectional micro-hardness analysis confirms that, average hardness of failed spring is 582 HV and data reveals that spring failure is not associated with violation of heat treatment process.

X-ray diffraction analysis reveals that, shot peening distribution is adequate and induced compressive residual stress on the spring surface is adequate and normal. Hence, poor shot peening or residual stresses has not contributed fatigue failure of the spring.

Spectroscopic chemical analysis reveals that, the chemical composition of failed spring confirms to the specification of Cr-Si-V spring steel and this has not contributed to spring failure.

5.CONCLUSION

The failure analysis presented in this paper was concentrated mainly on possible root causes for fatigue failure of automotive engine valve springs manufactured using high strength spring steel wire. Fracture faces of the failed spring was examined using different experimental methods to confirm the root cause for failure. Findings reveals that presence of Silicate type non-metallic inclusion, which is assumed to be, residues of Silicon, which is used as alloying element and also deoxidation process during steel making. The non-metallic inclusion acted as a stress raiser during the service due to cyclic loading, resulted in fatigue initiation and caused fatigue failure.

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