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Effects of Raw Material Surface Defects on High Strength Cr-Si Engine Valve Grade Spring Performance in Vehicle Operating Condition

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***Abstract-* Engine valve springs are operated by the repetition load and subjected to several thousands of cycles per minute and which requires high fatigue strength. Engine valve springs are required to have extremely high reliability over extended period of times. Raw material used for manufacturing valve spring must be controlled strictly especially for the flaw or any kind of detrimental surface defects like crack, seam,laps, rust /pits, deep line marks, decarburization which could be carried from steel making/ wire/ spring manufacturing processes. These are the principal factors that influences and improves the fatigue strength of engine valve spring. This paper is mainly focused on one of the field failure case study of engine inner valve spring, which was occurred at OEM passenger two wheeler engine. The spring fracture surfaces as well as the surface of the spring close to the fractured surface were examined in a scanning electron microscope at suitable magnifications. Optical microscopy was performed to evaluate the basic microstructure near the fracture face. The analysis reveals that the cause for the premature fatigue failure of the spring is due to the presence of lap / seam crack type surface defect on raw material wire.**

Keywords- Cr-Si engine valve spring; premature fatigue failure;SEM/EDS analysis; Raw material surface defect.

I. INTRODUCTION

There are two major categories of the high-performance wires from which the springs are manufactured: (a) patented and cold-drawn carbon steel (b) carbon and low-alloy steels which have been quenched and tempered subsequent to drawing to size. The second category is usually called as oil hardened and tempered wire (OT wire) and used for manufacturing the engine valve springs. There are different types of OT wires namely Cr-Si (as per JIS standard the grade is referred as SWOSC-V), Cr-Si-V, Cr-Si-V-Mo, and these materials having higher heat-resistance, higher fatigue strength and sag resistance. These materials are considered as super clean inclusion free steel. In the present case study, the raw material used to produce the valve spring is Cr-Si steel wire of wire diameter 2 mm. The typical chemical composition and tensile strength of raw material wire is shown in table 1.

TABLE 1.

% Chemical Composition						UTS (N/mm2)
C	Si	Mn	Cr	S	P	
0.51-0.59	1.20-1.60	0.50-0.80	0.50-0.80	0.025 max.	0.025 max.	1910-2060

Engine valve springs are operated by the repetition load and subjected to several thousands of cycles per minute at elevated temperatures and which requires high fatigue strength. Engine valve springs are required to have extremely high reliability over extended period of times. The engine valve spring should have withstand a running distance of minimum 100,000 KM's or 10 millions cycles without losing properties like sag resistance and fatigue resistance.

Raw material used for manufacturing valve spring must be controlled strictly especially for the flaw or any kind of detrimental surface defects like crack, seam,laps, rust /pits, deep line marks, decarburization which could be carried from steel making/ wire/ spring manufacturing processes. These are the principal factors that influences and improves the fatigue strength of engine valve spring. Raw material maker inspect the material before shipping and marks at the surface defect by paint. Marked portion must be discharged at coiling stage to prevent the release of the defective spring for later stages. The automatic discharge device with color sensor is installed on the coiling machine. The color sensor is used as the detector.

Fig.1 represents the general manufacturing processes of raw material wire and engine valve spring.

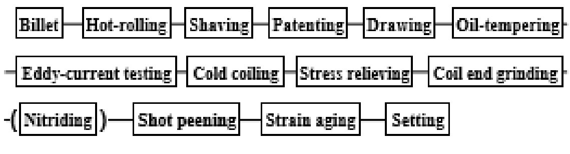

Fig.1 Manufacturing process of valve spring.

Cr-Si steels wires are strengthened as spring wires by repeating a middle heat treatment after wire drawing. A shaving process for the wire rod, which is used for wire drawing, is also a characteristic of this material, which removes the surface flaw, surface decraburization and surface defects carried from steel making and hot rolling. To detect the flaw / defect level on the wire, eddy current test was performed and permissible depth of flaw is maximum 0.01 mm for the present case study raw material wire. If any flaws were found during ECT, these parts would be painted with yellow color for the identification. Similarly decarburized layer also measured and accepted level of partial decarburization is max.0.05 mm or 1 % of wire diameter. No ferritic decarburized layer on raw material wire is acceptable.

The non-metallic inclusions also will have an effect on fatigue, especially the effect to high strengthened Cr-Si wires used for valve springs. Therefore it is required to reduce the quantity and size of non-metallic inclusions and the softening of non-metallic inclusions. To satisfy these requirements special wire rods to be used to manufacture Cr-Si spring steel wire, and hence it is called super clean wire.

II. FATIGUE PROPERTY

As per Yukitaka Murakami, by assuming there is no defect in material used for manufacturing, the fatigue strength is calculated by the equation

$$\sigma_w = 1.6\ HV \qquad (1)$$

Equation (1) represents the relationship between fatigue limit and Vickers hardness. Fig.2 shows the graphical representation for the same.

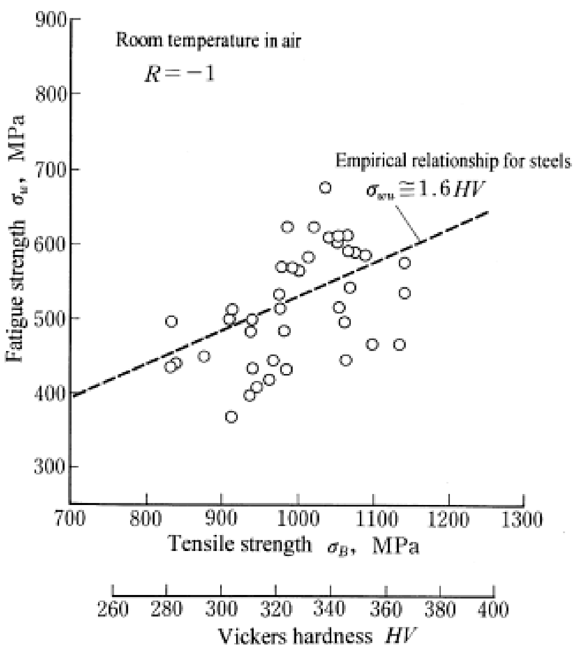

Fig 2 Relationship between fatigue strength and Vickers hardness/UTS

Suppose a defect or inclusions present in the raw material used, which is relatively larger than a phase present in the microstructure, then such defects or inclusions will be acted as fatigue crack initiators and caused fatigue failures.
Murakami estimated that the fatigue strength σ_w in the presence of internal defects to be,

$$\sigma_w=(1.56(HV+120)/\sqrt{area}^{1/6}).((1-R)/2)^{\alpha} \qquad (2)$$

where, $R = (\sigma_m-\sigma_w)/(\sigma_m+\sigma_w)$ and $\alpha=0.226+HV\text{x}10^{-4}$

Area = defect area and σ_m= Average stress.

The formula indicates that an increase in hardness and reduction in defect-size are required to improve fatigue strength.

Since the valve springs are operated by the repetition load and require high fatigue strength. In general, the shot peening process is applied to such a spring. The shot peening process causes the residual strain and hardens the surface of the spring by hitting the small ball with high speed. Also, the small surface defects are reduced by this process. This will increase the fatigue strength. The shot peening process is controlled by the arc height and coverage. Shot-peening, which also increases the compressive residual stress and surface hardness which is effective in improving the fatigue strengths of valve springs.

III. SPRING FAILURE HISTORY

The inner valve spring of passenger two wheeler engine was failed with mileage of 962 KM's of service in the field. The spring was manufactured with oil hardened and tempered Cr-Si raw material wire of diameter 2.00 mm. Tensile strength of the raw material wire used was 2046 N/mm^2 with 53% reduction in area. The spring was manufactured as per the process sequence mentioned in fig. 1 with stress relieving for 30 minutes at 420 Deg C followed by shot peening by using 0.60 mm round shots and low temperature annealing at 220 Deg C for 20 mins.

The as received condition of failed spring is as shown in fig 3. Detailed metallurgical investigations were carried out on the failed spring sample which included visual examination, stereo and metallurgical microscopy, scanning electron microscopy/EDS, and spectro analysis for chemical analysis.

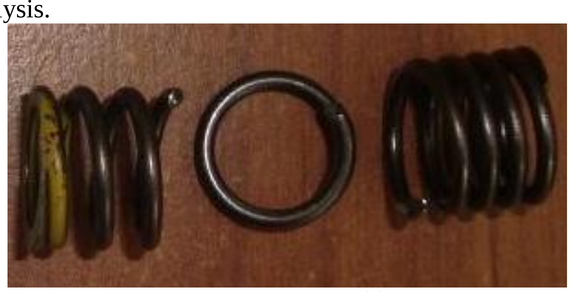

Fig 3 As received photograph of failed spring

IV. EXPERIMENTAL PROCEDURE

A. Visual and Macro Examination

The spring was found to be broken at multiple locations viz. 3.75^{th} and 5^{th} coil from one of the spring as shown in fig 3. The fractures faces was cut from the broken spring and observed under stereo microscope at 10X magnification. The fracture face appears to be fatigue failure and the fatigue crack was found to be initiated from outer surface and further propagated, fig 4-5. At the crack initiation point, seam crack type surface defect was observed, see fig 4. Seam crack continues on the entire length of specimen and which appears to be originated from raw material. The shot peening coverage on the spring surface found to be uniform indicates the shot peening process during spring manufacturing was satisfactory, fig 6.

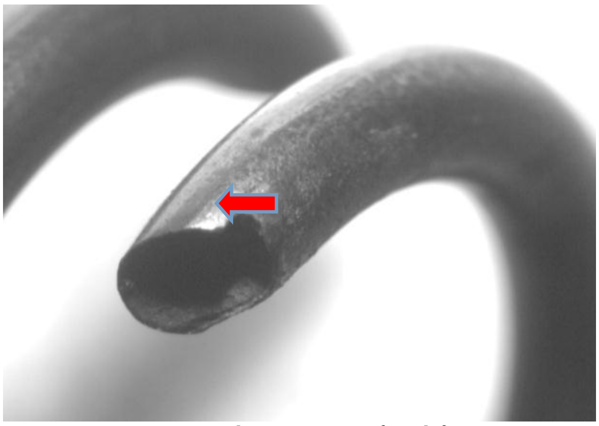

Fig. 4 Seam/lap type type surface defect

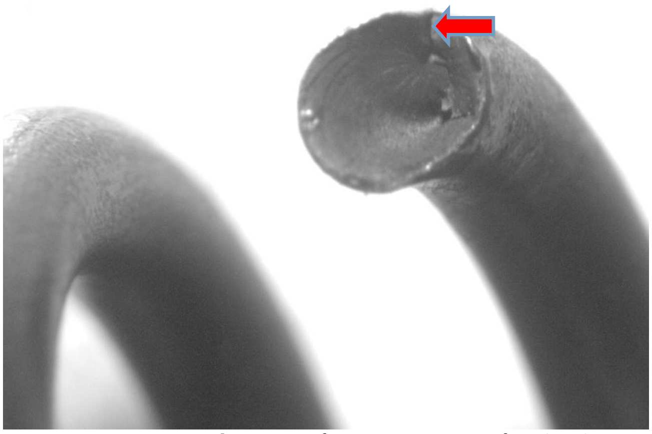

Fig. 5 Fatigue crack initiation from spring outer surface (10X)

Fig 6 Good shot peening coverage on spring surface (10X)

B. Chemical Analysis

Chemical analysis of the failed spring was performed and the results is as shown in table 2. The results are found to be in accordance with the chemical composition mentioned in table 1.

TABLE 2

% Chemical composition observed					
C	Si	Mn	Cr	S	P
0.52	1.40	0.66	0.63	0.009	0.020

C. Micro hardness test

The cross sectional sample was cut near the fracture face of the failed spring, moulded, polished and measured the traverse hardness from surface to core using micro Vickers hardness tester at 300 gms load. Hardness was found to be 550 HV0.3 on the surface and at the core 570 HV, which is satisfactory hardness range for Cr-Si valve spring.

D. Microstructural Examination

The cross sectional sample was cut near the fracture face of the failed spring, moulded, polished, etched and observed under metallurgical microscope at 100X and 500X magnifications. The microstructure reveals that tempered martensite, fig.7 with no significant decarburization, fig.8.

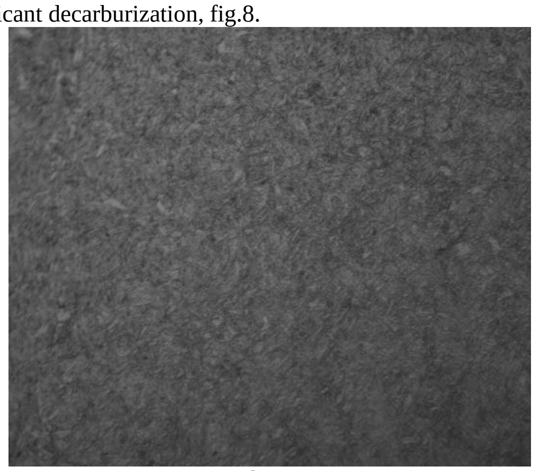

Fig 7 Tempered martensite (500X)

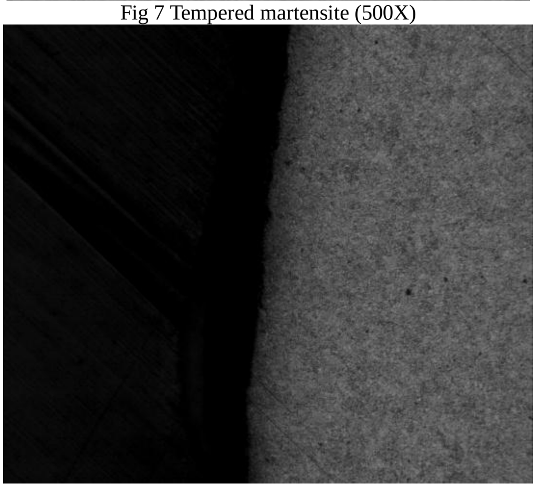

Fig 8 Nil decarburization (100X)

However, the cross sectional microstructure exhibits the presence of seam crack on the raw material used. About 652 microns seam crack depth was measured as shown in fig 9 and decarburization up to 20 microns around the seam crack was observed, which indicates the defect was carried from basic wire rod manufacturing and propagated further processes.

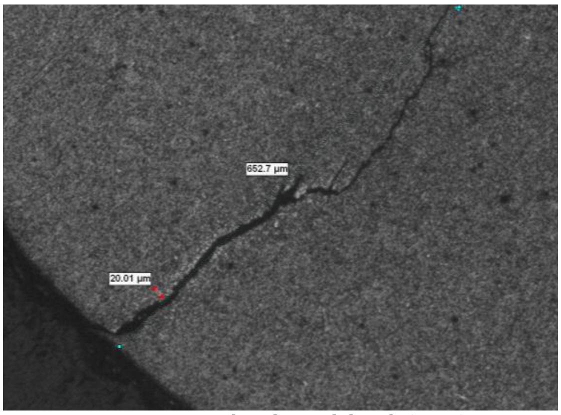

Fig 9 Seam crack and partial decarb (100X)

E. SEM/EDS Examination

SEM images of fractured surface of failed spring are shown in fig. 10-11. Seam crack was observed at the origin of fatigue fracture and on wire surface of failed spring surface. Seam crack continues on the entire length of specimen.

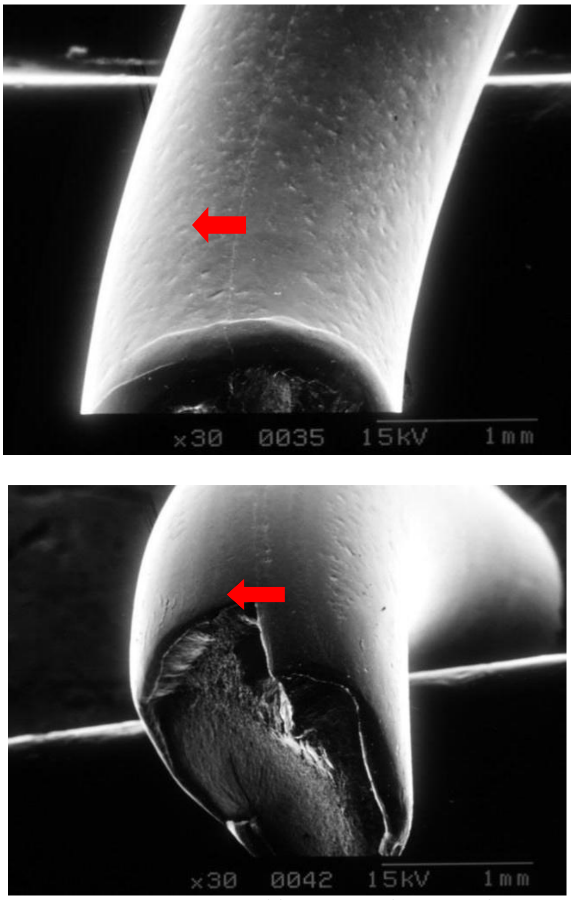

Fig 10-11 SEM images of failed spring fracture surface.

Spring cross section sample was also analyzed with SEM both near the fracture surface and the opposite side end as shown in fig. 12-13. The depth of seam crack was found to be about 650 µm. Decarburization was observed around the seam crack.

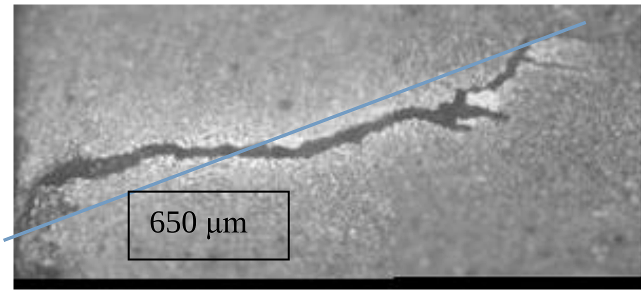

Fig.12 Seam crack and decarburization around crack at the fracture face

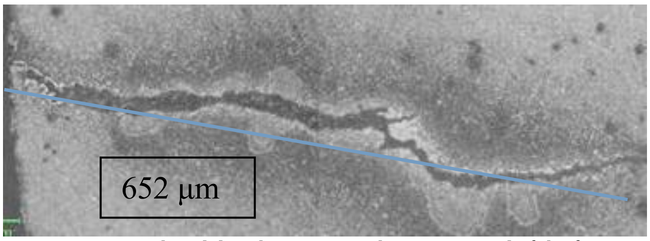

Fig.13 Seam crack and decarburization at the opposite end of the fracture face

EDS analysis was carried out on the seam crack observed locations of failed spring. The result shows that, the presence of Calcium (Ca), Zinc (Zn) and Phosphorus (P) in addition to steel elements and Oxygen (O), fig. 13. The presence of elements like Ca, Zn and P, which could be carried from wire drawing process, where Zinc phosphate and Calcium being used as coating and lubrication purpose.

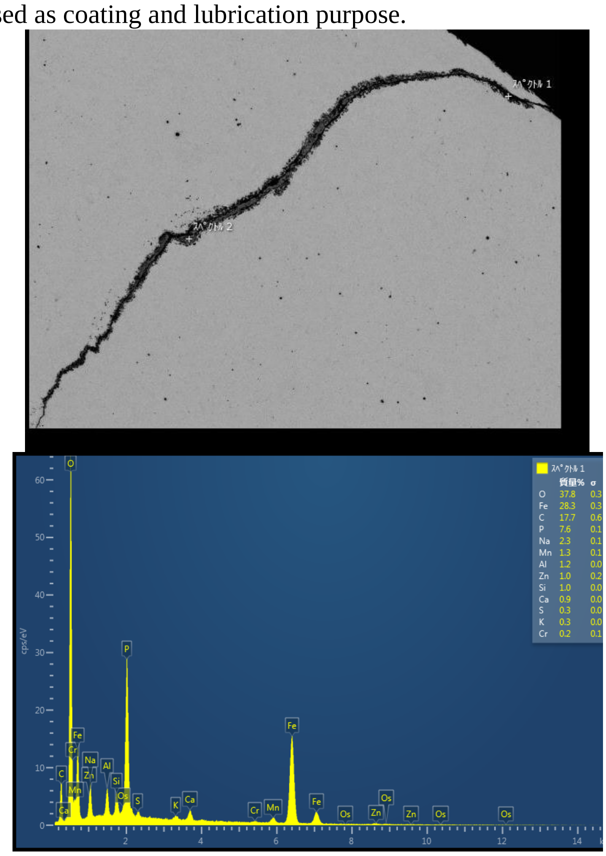

Fig.13 EDS analysis of failed spring near the fracture face.

V. CONCLUSION

The investigation reveals that,
A.The metallurgical properties like material hardness, microstructure, and chemical composition are found to be satisfactory for Cr-Si valve grade spring steel used and this also confirms that spring failure was not due to any violation of heat treatment process.
B. The spring failure was occurred due to premature fatigue failure and the cause for the fatigue is presence of surface defect like seam crack on the surface of raw material used, which has acted stress raiser and fatigue crack has initiator, which was propagated further during heat treatment and cyclic loading condition in the vehicle engine assembly and caused premature fatigue failure.
C.The surface defect like seam crack appears to be carried from basic wire rod manufacturing and which was not removed or missed out in the preceding operations like shaving and not detected or not conducted the eddy current test.
D.As per EDS analysis results, Zinc, Calcium and Phosphorus were present on the seam crack portion, which was carried from wire drawing coating and lubricants used, which indicates that, the defect was preexisting and carried to final spring component. During cyclic loading in the application, the defect was further extended and caused failure.

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