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Failure Analysis of Internal Combustion Engine Valves: A Review

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Abstract: Intake and exhaust valves are very important engine components that are used to control the flow and exchange of gases in internal combustion engines. They are used to seal the working space inside the cylinder against the manifolds; and are opened and closed by means of what is known as the valve train mechanism. Such valves are loaded by spring forces and subjected to thermal loading due to high temperature and pressure inside the cylinder. The present study focuses on different failure modes of internal combustion engine valves, failures due to fatigue at high temperature, high temperature effects on mechanical properties of materials, like hardness and yield strength; wear failure which is due to impact loading, and wear rate that depends on load and time. For the study of fatigue life, a combined S-N (max. stress v/s number of cycles) curve is prepared. Such a curve helps in comparing the fatigue failure for different materials at different high temperatures and may also assist the researchers in developing the valve materials with a prolonged life.

Keywords: Failure, Internal Combustion Engine Valves, High Temperature, Fatigue, Wear.

I. INTRODUCTION

Internal combustion engine valves are precision engine components. They open and close as and when needed. The fresh charge (air - fuel mixture in Spark Ignition Engines and air alone in Compression Ignition Engines) is induced through inlet valves and the products of combustion get discharged to atmosphere through exhaust valves. They are also used to seal the working space inside the cylinder against the manifolds [1].

There are different types of valves used by the manufactures; some common types of valves being poppet valves, slide valves, rotary valves and sleeve valve. The basic nomenclature used for valves is as shown in Figure 1.

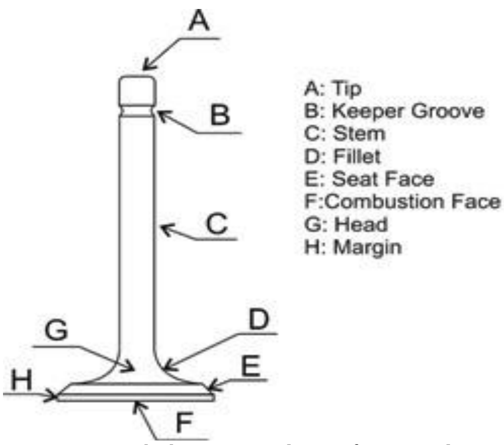

Fig. 1 The basic nomenclature of engine valve.
Source: H.J.C. Voorwalda *et al.* (2011) [2]

Any type of valve failure affects the engine performance thus making it mandatory to give due importance to failure analysis of internal combustion engine valves. Possible modes of valves failure are wear failure, valve face recession, fatigue failure, thermal fatigue, erosion / corrosion of valves, overheating of valves, carbon deposits on valves etc.

Available research literature about valve failures indicates that valve design is a complicated task because the valve is subjected to various loads at any point of time, such as reverse loading at a high temperature, stress concentration at the keeper groove area and under carbon deposits at exhaust valves. The valves generally fail by fatigue [1], [2].

A closed valve is loaded by spring force and pressure inside the cylinder, which varies periodically during engine operation and reaches a peak value of the order of 15 MPa. Such high pressures inside the cylinder cause bending of the valve cone, which results in a sliding motion and improper contact between valve face and seat insert thus eventually leading to wear failure. The Otto and Diesel engines operate at temperatures of 550ºC inside the intake valve; the corresponding values inside the exhaust valve being 700°C and 800°C, respectively. The exhaust valve temperature can shoot up to 900°C. Since the exhaust valves operate at high temperatures, they are exposed to thermal load and chemical corrosion. The intake valves, which are not subjected to such extreme thermal loading, are cooled by incoming gases, thermal transmission at the seat, and by other means [1], [2], [3].

Valves are subjected to cyclic loading due to valve train dynamics. The stem of the valve is under axial repeated loading, it can fail by axial Fatigue. The keeper groove area is subjected to tensile stresses and becomes a critical section due to geometric stress concentrations. In this paper all possible failures of valves are considered and discussed [2].

II. **METHODOLOGY**

There are Different methodologies used by researchers to obtain a good design and economic performance of the valves by considering different valves failure criteria. Different types of failure and their causes are discussed in the following articles**.**

A. Failure due to fatigue

The word *fatigue* is derived from the Latin *fatigare* which means "to tire". In engineering terminology *fatigue* is a progressive structural damage of materials under cyclic loads. Important categories of *fatigue* include: *Mechanical fatigue* due to fluctuating stresses *Creep fatigue* due to cyclic loads at high temperatures; *Thermal fatigue* due to cyclic changes in material's temperature; *Thermo-mechanical fatigue* due to a combination of mechanical and thermal fatigue; *corrosion fatigue* due to cyclic loads applied on corroded materials, *Fretting fatigue* due to cyclic stresses together with the oscillation motion and frictional sliding between surfaces, etc.. Fatigue failure occurs at stresses that are well below the yield point of the material [3].

I.C. Engine valves are subjected to repeated cyclic loading due to valve train dynamics. Repeated loading results in materials failing well below the yield strength. When the material is subjected to fatigue, one or more tiny cracks usually start developing in the material, and these grow until complete failure occurs.

There are different types of fatigue mechanisms: thermal fatigue, high-cycle fatigue, low-cycle fatigue, surface fatigue, bending fatigue, corrosion fatigue, torsional fatigue, and fretting fatigue. In valves, some of the more common failures are due to thermal fatigue, corrosion fatigue, and low and high-cycle fatigue.

When it comes to fatigue, the S–N curves are often used to represent fatigue behavior. Because fatigue testing is time and energy consuming, predictive methods are often used [4], [5], [6].

In many industries, the number of stress cycles for lifetime services are above 10^7 cycles, The fatigue fracture is basically observed under low cycle fatigue, normally less than 10^5 cycles. The fatigue life varies usually from 10^5 cycles to 10^7 cycles [6].

Researchers have come up with a number of results for fatigue testing, one of them being discussed in this paper for material X45CrSi93 stainless steel for engine valves. The X45CrSi93 stainless steel is prepared from hot rolled bars that are machined, quenched and tempered. After heat treatment the materials are divided into two groups - nitride and chrome plated. These two

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Vol. 1, Issue 2, December 2012

groups are compared with the material without surface treatment. By comparison it is found that the fatigue limit is directly proportional to the mechanical strength. The hardness profile analysis of nitride material is prepared so as to determine the actual nitrogen diffusion depth. To start with, the hardness value is high but becomes constant as one goes deeper. Fig.2 shows the nitride layer hardness profile. Fig.3 S-N depicts axial fatigue curves for X45CrSi93 stainless steel [2]. These curves (fig.2 & 3) show that the fatigue limit is well below the yield limit of the material.

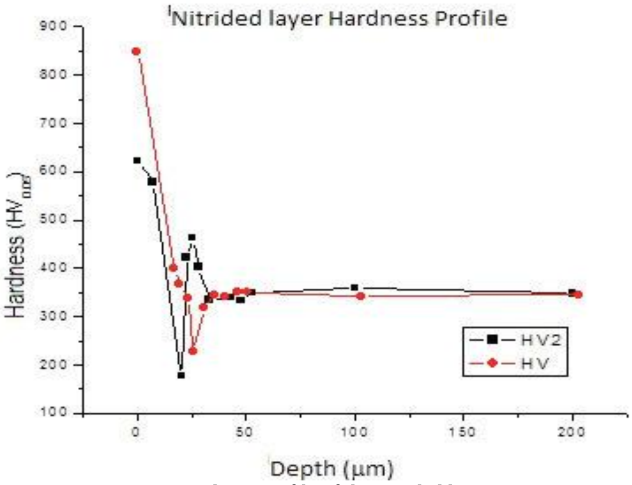

Fig. 2 Hardness profile of the nitrided layer

Source: H.J.C. Voolwalda *et al.* (2011)[2]

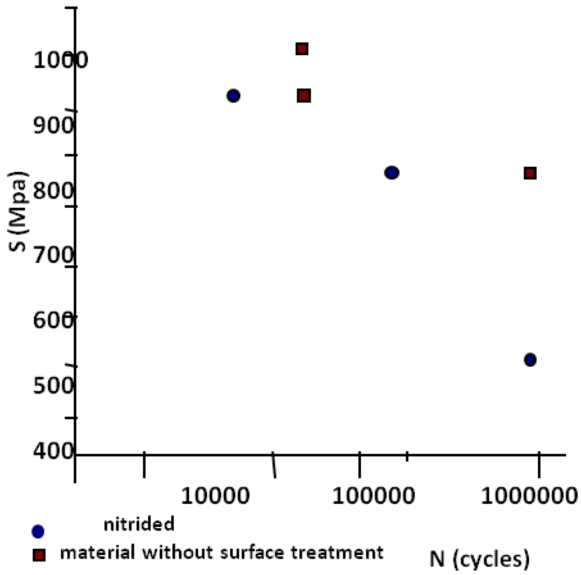

Fig.3 Axial fatigue curve for nitrided X45CrSi93 Steel

The fatigue cracks are found in the nitride layer stainless steel in fig.4. At the diffusion layer the fracture propagation starts and leads up to the final rupture [2]. The different fracture propagation between the regions with higher and lower nitrogen contents are shown in fig.4.

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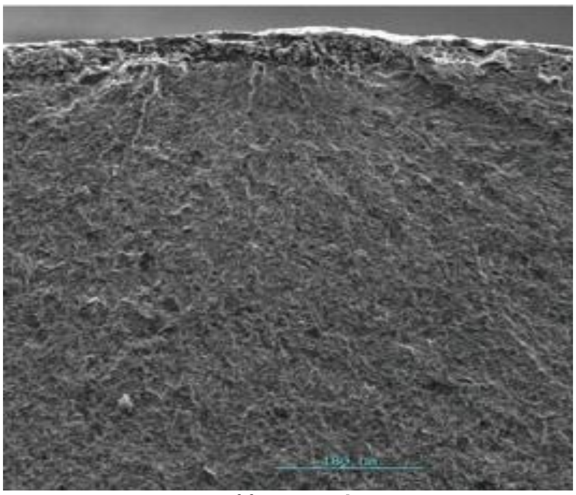
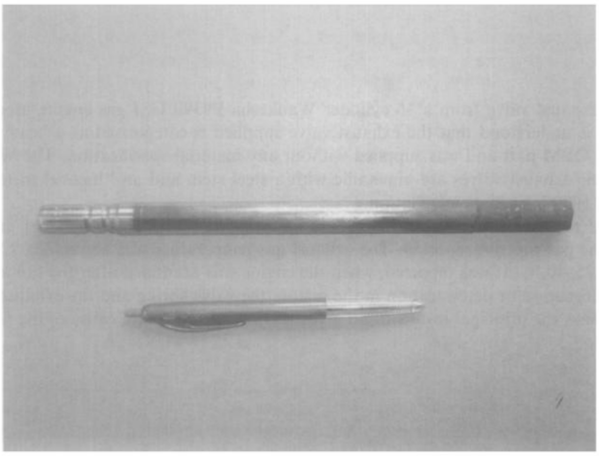


Fig. 4 Start of fatigue crack propagation
Source: H.J.C. Voolwalda *et al*. (2011)[2]

B. Failures due to high temperature

Exhaust valves operate at very high temperatures and subjected to cyclic loading, The failure of the conical surface of valve is mainly caused by the elastic and plastic deformation, and fatigue. Exhaust valve stem generally fail by overheating because the temperature of the exhaust valve is about 720 ºC. The fracture surface of the valve stem is covered with a black oxide scale formation; fracture surface in the fatigue area is smooth and is covered with thick oxide or deposits that cannot be removed satisfactory. In the middle portion of the stem a longitudinal fretting damage is occurred. Some small cracks are initiated and propagated across the section. With high loading, multiple cracks are initiated if the valves are subjected to high temperatures and, under such operating conditions, it would be logical to expect that failure would occur within a few million cycles. A fractured valve stem is shown in fig.5 (a) & (b) [7].

The significant hardness is loused and the surface oxidation and fretting/galling on the valve stem occur due to overheating. The fatigue properties of the alloy suffer due to high temperature. This is the cause of multiple fatigue crack initiation. The failed exhaust valves are shown in Fig. 6, valve no. 4 is a new exhaust valve that is compared with the failed valve No. 1, No. 2 and No. 3. The failure had taken place at the plates of the exhaust valves as seen in fig.6 [8].



(a)

ISSN: 2319 – 8753

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Vol. 1, Issue 2, December 2012

(b)
Fig. 5 (a) The failed exhaust valve stem & (b) Edge of the fracture surface of valve stem .
Source: Oh Geon Kwon and Moon Silk Han(2004) [7]

Fig. 6 Photograph of failed exhaust valves
Source: Z.W. Yu and X.L. Xu (2006) [8]

In Valve No. 1 and No. 2, the cracks initiated from the tapered plane of the plate and propagated toward the bottom plane along a 45º direction to the bottom plane. In case of Valve No. 3, serious loss occurred at one side of the plate (fig.7). There are two main radial splits in the plate, having both edges burnt. There are some small circumferential cracks on the tapered plane of both sides of the splits. It was found that a lot of carbon deposition appears on the plate surface [8].

ISSN: 2319 – 8753

International Journal of Innovative Research in Science, Engineering and Technology
Vol. 1, Issue 2, December 2012

Fig. 7 Fractured plate of Valve No. 3
Source: Z.W. Yu and X.L. Xu (2006) [8]

C. Failure of valve due to erosion-corrosion

As discussed above, the exhaust valves operate at high temperature**.** The resulting scale formation on the valves corrodes the surface of valve due to exhaust flue gases. Structural metals have always had surface material removed in service as the result of erosion by small, solid, impacting particles. In most elevated - temperature erosion environments, the eroding surface is undergoing corrosion as well as erosion. In one test series, a nickel oxide scale was formed up to 100 µm thick at 1000ºC on commercially pure nickel [9].

The erosion-corrosion of exhaust valves (valve guttering) is an important cause of failure of internal combustion engines valves. Valve guttering generally occurs due to exhaust gas flowing across the valve face surface, resulting in the formation of a radial channel or gutter. Typical causes of leakage include valve distortion, face peening and degradation of face deposits. The accumulation of combustion - derived deposits on valve surfaces interferes with proper seating of the valve and promotes leakage. In studies of the effects of burning heavy fuels on the degradation of diesel exhaust valve seats, the role of "scales" deposited on seating surfaces are reduced the heat flow through the contact. Lubricants containing high sulfated ash levels (over 1.0 weight %) have been identified as potential contributors to heavy deposit formation and valve guttering in these engines [10].

D. Failure of valve due to wear

Wear Failure occurs generally at the seating face of valves and stem at which portion that slide on valve stem guide. Wear mainly occurs due to two major factors, he first one is the impact force between seating face of valve and seat insert, whereas the second one is due to sliding of the valve on the seat insert during the action of combustion pressure. The rubbing action and impacting action wear out the valve face. Typical mechanisms of wear include adhesive, abrasive, fretting, erosion, cavitation, and contact rolling fatigue.

The gas engine valves are more wear - prone. Fig.8. shows the relationship between wear mass loss and time. It is seen that at 1.0 KN loading wear mass loss larger than at 0.7 KN loading [5], [11], [12].

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Vol. 1, Issue 2, December 2012

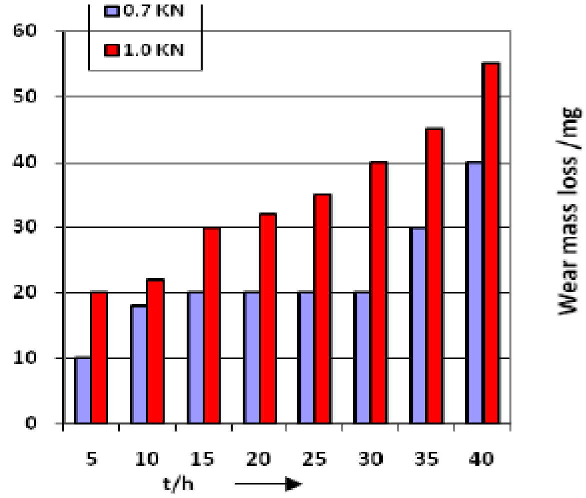

Fig. 8 Relationship between wear mass loss and time.

Wear is divided into three stages: running - in wear stage, stable wear stage, and sharp wear stage. In running - in wear stage, the temperature is high. Under the action of high impact varying load, the strength and hardness of surface material of gas - valve is decreased because of high temperature, the plastic deformation initiates so the seat face of valves are worn out and the wear mass loss sharply speed - up with the passage of time. With the increment of expulsion quantity, surface roughness drops and practical contact area of gas - valve increases. R_{max} data shows the wear at seat face of valve which is the difference between maximum and minimum values of measurement length. A bar graph shows the R_{max} v/s number of cycles in fig.9. From the graph it is clear that more wear occurs with increasing number of cycles [11], [13].

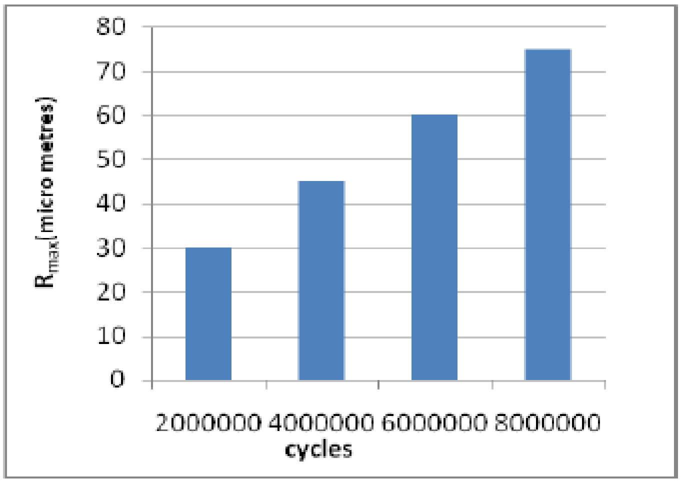

Fig. 9 Average R $_{max}$ at 10 Hz For seat face of Valve

III. ANALYSIS

From the above study, it is found that the predominant cause of failure of valves of internal combustion engine is fatigue. The valves are subjected to high temperature, cyclic loading, impact loading, erosion-corrosion and high pressure inside the cylinder, thus making it critically important to know about fatigue under these conditions. Researchers have been seeking to know the fatigue failure mechanism, because the fatigue failure under actual loading conditions is different from simple mechanical fatigue failure. In fatigue failure the material fails well - below the yield strength of that material. In this study a combined S-N (max. stress V/s number of cycles to failure) curve is prepared for different materials.

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Vol. 1, Issue 2, December 2012

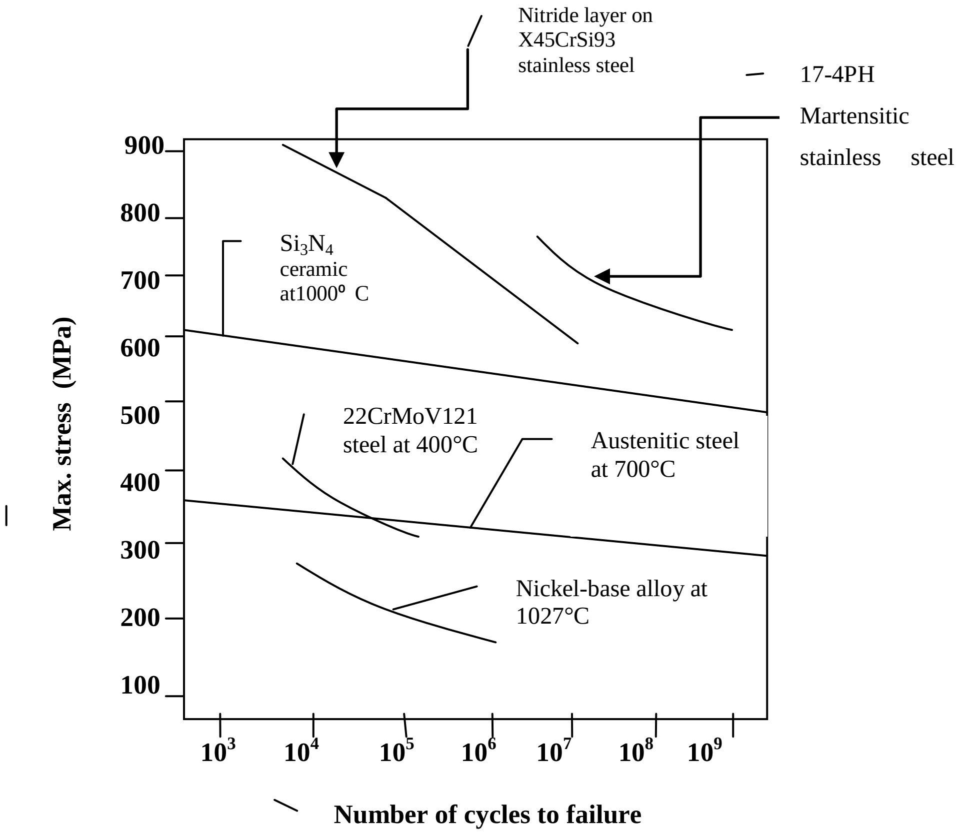

Fig. 10 S-N curve for different materials engine valve at high temperature.

Fig.10. shows the S-N curves for different materials, nitride layer on X45CrSi93 stainless steel fail at 900 MPa max. stress after 10^4 cycles and at 600 MPa stress after 10^6 cycles. Similarly, other materials like austenitic steel at 700°C fail at 380 MPa stress after 10^3 cycles and at 300 MPa stress after 10^9 cycles. The curve is very flat which indicates that the it can be used only at high cycle applications.

Internal combustion engine valves are generally designed up to 10^6 stress cycles to prevent the failure of valves but at present there are different materials available which do not fail even after 10^7 or 10^8 cycles. At high temperature, the fatigue strength decreases considerably but the ceramic materials have a good fatigue strength even at high temperatures and can operate without failure up to 10^9 cycles but it can be used only for high cycle applications. Nickel - base alloys have low fatigue strength but can operate at very high temperature of about 1027°C.

IV. CONCLUSION

From the above study of I.C. Engine valve failures, it is quite evident that a common cause of valve fracture is fatigue. Valves fail due to cyclic loading at high temperatures. High temperature is also responsible for decrease in hardness and yield strength of valve material, and also causes corrosion of exhaust valves. The surface oxidation and fretting / galling on the valve stem occur due to overheating and fatigue strength is decreased due to overheating. The impact loading of the valve face on the valve seat results in removal of material from that portion, which is known as valve recession. Wear failure occurs generally at the seat face of valve and at the stem due to sliding inside the stem guide. The wear rate increases with increase the number of cycles. Failure due to erosion-corrosion of exhaust valves is also a recognized failure mode in internal combustion engine valves.

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International Journal of Innovative Research in Science, Engineering and Technology

Vol. 1, Issue 2, December 2012

Fatigue failure is the main cause of valve failure. The fatigue strength is significantly decreased with increase of temperature. The combined S-N curve shown in Fig.10 is useful for comparing fatigue failure of the material, corresponding stresses cycles; and for developing a high fatigue strength material even at high temperature. The current focus is on light weight engine valves made up of ceramic materials which can operate without failure at high temperatures and can sustain stress cycles up to 10^9.

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