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Effects of High Temperature on the Microstructure of Automotive Engine Valves

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ABSTRACT
In this paper, failures of automobile valves are considered and discussed. The changes in microstructures of valves were studied and analyzed with the aid of a Scanning Electron Microscope (SEM). Specimens were prepared out of failed engine valves whereas new valves were also analyzed for the sake of comparison. This was done by image analysis of specimens of failed and new valves at adequate magnification. The benchmarking of microstructures of failed valves v/s new valves revealed that the size of grains, grain boundaries, and distribution of carbide particles across the material matrix is affected by high temperature conditions and the effects are more severe for exhaust valves. The microstructure of valve material shows discernible changes after operating at high temperatures. The grain size of the material also changes at high temperature, thus resulting in a reduction in the hardness of the valve material which, in turn, causes more wear.
Key Words: Exhaust Valves, Intake Valves, Hardness, Erosion, Corrosion, Wear, Fatigue, Microstructure.

I. INTRODUCTION

Valves of automobile engines are subjected to significantly high temperatures and pressures, impact loading, thermal stresses, and exhibit a pronounced effect of fatigue loading too, when analyzed for failure. There are four distinct types of failure mechanisms for a valve or valve component: brittle failure, ductile failure, wear, and corrosion [1]. Wear failure of valves is a commonly encountered phenomenon and the fatigue crack growth has its own role to play in contributing to the failure. The wear mechanism in exhaust valves of heavy duty engines has been found to be a combination of oxidation and adhesive wear [2]. Valves also fail due to surface erosion and corrosion. The erosion - corrosion of exhaust valves (“valve guttering”) is a recognized failure mode in internal combustion engines [3]. Valve failure may occur due to valve recession caused by loss of material from the seat of the valve and increases with increasing engine load [4] .Valve recession occurs when wear of the valve or seat inserts in an automotive engine cause the valve to sink or recede into the seat insert. Excessive recession leads to valves not seating correctly and cylinder pressure loss. Leaking hot combustion gases can also cause valve guttering or torching which accelerates valve failure [5]. Available research literature pertaining to valve failures indicates that valve design is a truly complicated task because the valve is subjected to multiple loads at any point of time that are characteristically different. Some factors that are important and worth considering are - reverse loading at a high temperature, stress concentration at the keeper groove area, and under carbon deposits at exhaust valves. Otto and Diesel engines, when in operation, result in generation of temperatures that are 600ºC (or there about) inside the intake valve; the corresponding value for the exhaust valves being 700°C to 800°C, respectively. However, the exhaust valve temperatures can shoot up to 950°C. Since the exhaust valves operate at relatively higher 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.

This analysis had its focus on investigation of valve failures by observing and analyzing the changes in microstructure of valves as reflected by images taken through a Scanning Electron Microscope (SEM). For this purpose, a number of specimens were prepared out of engine valves that failed in service and the changes were benchmarked against the new valves.

1.1 INTERNAL COMBUSTION ENGINE VALVES

Internal combustion engine valves are precision engine components. They are located at the cylinder head of the motor and control the flow of the air–fuel mixture (intake valves) and the burned gases (exhaust valves) during the Otto or Diesel cycle [6]. Fresh charge (air - fuel mixture in Spark Ignition Engines, and air alone in Compression Ignition Engines) is induced through the intake (inlet) valves whereas the products of combustion are emitted to the atmosphere through exhaust valves. Valves are used to seal the working space of the combustion chamber, they are opened and closed by means of what is known as a valve train mechanism, and are subjected to high pressure and thermal loading due to high temperature. Material change of valve train parts can change the dynamic behavior of the valve and cause deformation [7]. Poppet Valves (Figure - 1) are the most frequently used valves because of their efficient design and ease of operation.

1.2 INTAKE AND EXHAUST VALVES

Valves working under different loads and temperatures are the most forced engine elements. This is because they are tensile and work under quick variations of temperature and load, and different accelerations, which vary suddenly and periodically during engine operation. In an internal combustion engine, pressures and temperatures affecting the valves vary with fuel type and the combustion characteristics of the fuel. Consequently, valves are exposed to different dynamic and thermal stress [8]. Being in the combustion chamber, valves are constantly exposed to hot gases. Due to inadequate cooling, they attain higher temperatures. The exhaust valves are subject to a much higher temperature than the intake valves. The exhaust valve opens and permits the hot gases to go out between the valve head and engine head, at high velocity. During the exhaust process, the exhaust valve comes in direct contact with the hot gases. The exhaust valves are exposed to thermal overstress more than the intake valves because the incoming fresh charge / air at atmospheric temperature cools the intake valves [9]. When the engine works on higher loads, the exhaust valve may become red hot and this is primarily the reason why it is made up of a heat resistant material. Some common situations that contribute to valve failure are - valve seat / face being too narrow, worn valve guide and / or valve stem, weak valve spring, sticking valve stem, incorrect tappet clearance, loose valve seat insert, valve guide being / becoming loose in the block, valve head / stem breakage, valve head burning, deposits on the valve, etc.

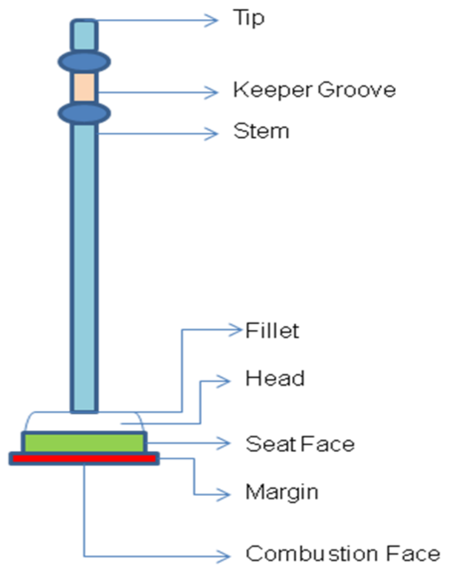

Figure – 1: Poppet Valve

1.3 EFFECT OF TEMPERATURE

Valves operate at very high temperatures and are subjected to cyclic loading. The failure of the contact conical surface is mainly caused due to elastic and plastic deformation, the fatigue micro-crack, and spalling [10]. Exhaust valve stem generally fails by overheating which manifests itself in terms of significant hardness loss and extensive surface oxidation and fretting / galling on the valve stem [11]. The temperature the exhaust valve is subjected to is about 750ºC to 950ºC. The fractured surface of the valves is covered with a black oxide scale formation whereas the fractured surface in the fatigue area is smooth and is covered with thick oxide or deposits that cannot be removed easily. On the other hand, the middle portion of the stem exhibits a longitudinal fretting damage. High temperatures result in reducing the hardness of the valve material and also affect its fatigue properties. Some small cracks get initiated and propagated across the section. With high loading, multiple cracks are initiated as the valves are subjected to high temperatures. Overheating is largely responsible for surface oxidation and fretting / galling on the valve stem.

II. EXPERIMENTAL METHODOLOGY

Specimens of standard dimensions for microstructure analysis on Scanning Electron microscope (SEM) are prepared using used and new exhaust and inlet valves. The preparation involves cutting and surface finishing with different grades of emery papers, clothing, and finally etching by an etching solution with 2% HNO_3 and 98% methanol. Each specimen is etched for 3 to 5 minutes and then dried completely in oven. Each specimen now passes through a scanning electron microscope (SEM) which is an electronic microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample and generate various signals that can be detected. These signals contain decipherable information about the sample's surface topography and composition. The electron beam is generally scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image. The images, taken at adequate resolution, provide the desired information about microstructure of the specimen.

III. Observations and Related Discussion

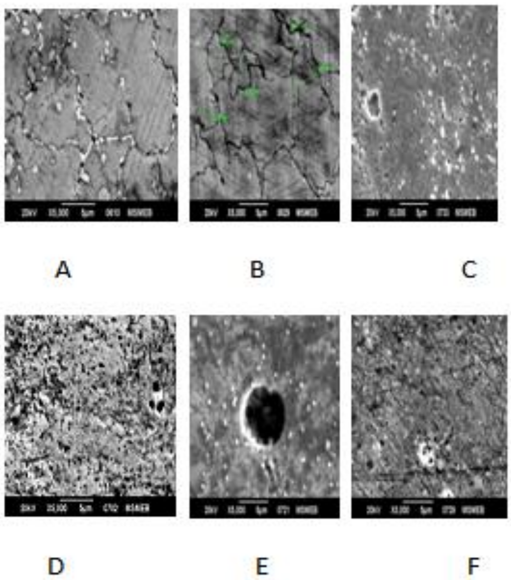

Figure-2: Failed valve images at X5000 magnification through SEM.
(A, B) Microstructure of failed exhaust valves,
(C) Microstructure of new exhaust valve
(D, E) Microstructure of failed intake valves,
(F) Microstructure of new intake valve

Images depicting the microstructure of failed exhaust valves are shown in Figure - 2 at X5000 magnification. The white colour spots in the images indicate the presence of carbides in the valve material. If the distribution of the carbide is fine, it increases the hardness of the material but a coarse distribution of the carbides makes them shift towards the grain boundaries with an accompanying reduction in the hardness and weakening of the material. The grain boundaries shown in the SEM image shows that they are broken and grains are not uniformly distributed. The size of grains increases after working at high temperatures. The size of grains indicates the strength of the material; big size grains indicate lower strength whereas small size of grains (or finer grain sizes) indicates higher material strength. This means that an increase in the size of the grains, or elongated grains, in SEM images of failed exhaust valves material indicates that the valve material strength has come down after being subjected to high temperatures for considerable periods. The microstructure of steel used for manufacturing the internal combustion engine valves is a combination of ferrite matrix and carbide distributed all through. The process heading towards the equilibrium state continues and the microstructure changes to a ferrite - carbide mixture. Selective electron microscope diffraction identifies the complex and larger carbide particles in the matrix; the first identification happening at grain boundaries. Inside the grains and in the grain boundaries, carbide particles precipitate. At many locations, they form a network or grid like shape at the grain boundaries.

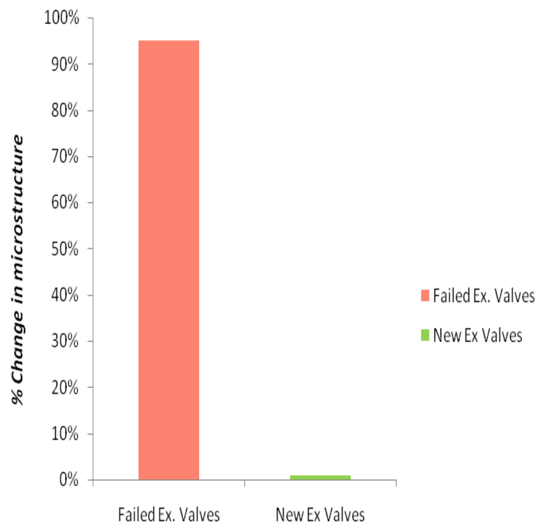

Figure-3 Failed Exhust Valves v/s New Exhaust Valves

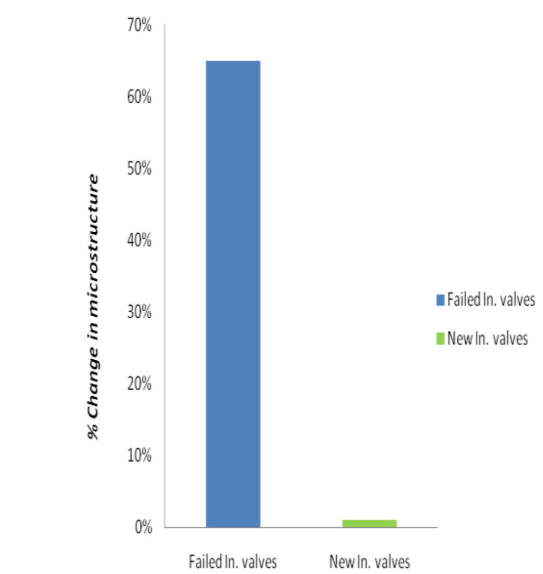

Figure - 4 Failed Inlet Valves v/s New Inlet Valves

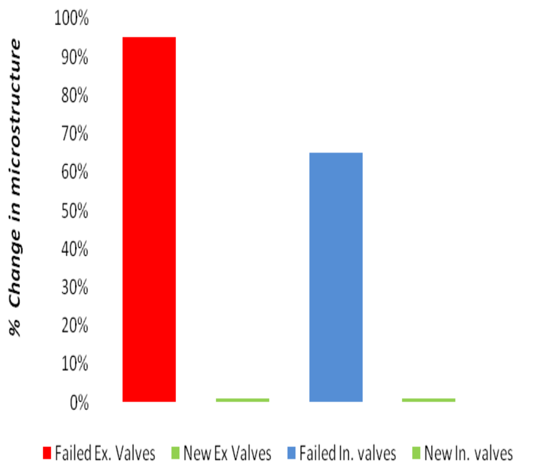

Figure 5 Comparison between Failed Exhaust Valves, Failed Inlet Valves and New Valves

IV. CONCLUSION

SEM images, taken at adequate resolution, are compared with the corresponding ones for new valves. The carbide distribution is expectedly regular with no observed shift towards grain boundaries, small sized grains are observed and no black holes are seen for the new valves. The images obtained for used valves indicate that the carbides present in the material get shifted to grain boundaries and distributed there, whereas the grain boundaries are also distorted and broken. Distorted / broken grain boundaries are also observed in the failed exhaust valves at X5000 resolution but carbides are absent here. The grain sizes as shown in the SEM images indicate that grain sizes vary from very small to very big, and are distorted too. This means that at high temperature the grain sizes of austenitic steel are changed with an accompanying distortion that is usually present. The study of microstructures of failed valves and its comparison with the new valves clearly indicates that the size of grains, grain boundaries and distribution of carbide particles is affected by high temperature.

Some of the results that were observed in the SEM images of failed engine valves and new engine valves are as following:

1. A definite coarse distribution of carbide particles was observed in the SEM images of all failed exhaust valves.
2. In case of failed inlet valves, coarse distribution of carbide particles was observed in some whereas fine distribution of carbide particles was observed in few others.
3. New valves were always characterised by fine distribution of carbide particles.
4. In both failed exhaust and inlet valves, a clear shift of carbide particles was observed towards the grain boudaries.
5. Broken and distorted grain boundaries were also observed in failed valves.

A comparison of the microstructure of failed valves and new valves reveals that the size of grains, grain boundaries, and distribution of carbide particles is affected by high temperature operating conditions and has a serious impact on the useful life of the valves by not only adding to crack initiation and its propagation but by influencing the wear pattern also.

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