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Surface Morphology and Wear Investigation of Valves used in LPG- fueled Passenger Car Engines

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ABSTRACT

Liquefied petroleum gas (hereafter LPG), with an Octane Number of ~105, was looked upon and used as a viable vehicle - fuel option as early as 1912. However, its usage gained significant momentum with the advent of dual – fuel technology in the mid 1950s. This technology made it possible for LPG to be used in parallel with another fuel – Gasoline or Diesel. Though the LPG fuel system has become far more sophisticated while moving from 1st generation of technology development to the 5th one, most passenger car engines running on LPG are still not specially designed to operate on LPG. It is a very common practice in many developing countries, including India, to use retrofitted gasoline engines that operate on a dual – fuel mode: LPG and petrol. The extreme temperature conditions in LPG - run retrofitted gasoline engines result in considerable changes in the microstructure and wear growth patterns for both inlet and exhaust valves. This investigation focused on analysis of valve wear using a Pin – on – Disc (POD) wear tester. The characterization of wear was done by wear rate, analyses of worn surfaces, wear debris structure and sub – surfaces. The precipitation characteristics and behavior of secondary particles like carbides, oxides, silicates, etc., was also studied. The microstructure analysis and quantitative metallography of inlet and exhaust valve specimens was carried out by employing Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) techniques. The images thus obtained were utilized for microstructural characterization of the valve specimens. The surface morphology of the valve material was studied and AFM measurements were used for quantitative characterization of the structure as also to gain useful information about crystallographic orientation of individual grains, the formation of cracks, identification of potential crack initiation and fracture sites, etc. A comparative evaluation of microstructure of worn - out valves with new valves was also carried out.

Keywords: LPG, retrofitting, poppet valve, wear, microstructure

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INTRODUCTION

LPG or Autogas, primarily consists of Propane and Butane, with traces of Propylene and other light hydrocarbons. Propane was found to be the most suitable fuel for internal combustion engines after petrol and diesel (Mistry, 2005). Increased emphasis on clean, green and cost – effective transportation modes has encouraged the usage of LPG as a commercially viable and eco – friendly fuel across the world. The usage of LPG, however, requires elaborate investigation of its characteristics and thorough understanding of the associated technical problems, such as power losses, adjustment of the composition of exhaust gases, etc. (Bayraktar & Durgun, 2005; Campbell et al., 2004; Erkus et al., 2013; Li et al., 2002 and Mistry, 2005). Since most car engines fueled by LPG have been designed to run on petrol, they encounter operational problems. No gas equipment systems are available that can suitably fit in every gasoline engine as each one of them has its specific characteristics.

Valves, used in LPG - fueled retrofitted passenger car engines, are constantly exposed to high temperatures and pressures. Since pressures and temperatures affecting the valves vary with the type of fuel used and its combustion characteristics, valves are subjected to different dynamic and thermal stresses (Karamangil et al., 2008). The exhaust valve, in particular, operates in extreme service conditions and subjected to longitudinal cyclic stresses, thermal stresses, creep deformation and chemical corrosion. Exhaust valves of heavy - duty engines have been found to fail by a combination of oxidation and adhesive wear mechanisms (Forsberg et al., 2011). The stem failure is due to overheating which results in significant hardness reduction, surface oxidation and fretting / galling (Zhao & Yan, 2005). The middle portion of the stem exhibits longitudinal fretting damage. High temperatures cause the hardness of the valve material to go down and affect its fatigue properties adversely (Stanzl - Tschegg, 2014). The failure of the contact conical surface of valves is mainly due to elastic and plastic deformation, the fatigue micro-crack, and spalling (Vardar & Ekerim, 2010).

The inlet valves are not subjected to extreme thermal loading. Besides, they are cooled by incoming gases, thermal transmission at the seat, and by other means. The difference in operating temperatures necessitates the use of an advanced material for exhaust valves in comparison to inlet valves. The inlet valves are made up of martensitic steel while the exhaust valves are made up of austenitic steel. These two steels differ significantly in their microstructure and the mode of interaction of various ingredients in the alloy when molten steel is cast and cooled. Engine valves are extremely vulnerable to wear and consequent failure. Wear failure of valves is aided by fatigue crack growth. Valve guttering is also a recognized failure mode in internal combustion engines (Scott et al., 1995). All these failure contributing mechanisms alter the microstructure of valves, and metallographic images of these variations can be stitched together to provide an insight into valve behavior and its failure.

EXPERIMENTAL DETAILS

Technical Specifications

The valves chosen for this experimental investigation were standard, mechanically operated poppet valves used in LPG – run, retrofitted passenger car engines in India. The valve specifications are L/TH/D/1, α 45° (inlet valve) and S/TF/D/1, α 45° (exhaust valve).The inlet valve dimensions are 31.6 mm (D) × 7.0 mm (d) × 110 mm (l) whereas the exhaust valve dimensions are 27.0 mm (D) × 7.0 mm (d) × 119.5 mm (l).

Sample Preparation

Wear tests were performed on specimens made from heads and stems of inlet and exhaust valves, both worn out and new. A Metacut DCM machine was employed for preparing samples of adequate sizes. The dimensions of the testing elements were - head (10 mm diameter) and stem (25 mm length and 5 mm diameter). The faces of these specimens were polished by diamond paste, cleaned in acetone and dried prior to wear tests on the POD wear tester.

For microstructure characterization, specimens of standard dimensions were prepared using - failed and new - exhaust and inlet valves. The operations involved cutting, surface finishing with different grades of emery papers, clothing, and finally etching by an etching solution with 2% HNO_3 and 98% methanol / acetone solution. Each specimen was etched for 3 to 5 minutes and then dried completely in an oven prior to its microstructure analysis through a Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM) (Pandey & Mandloi, 2014).

METHODOLOGY

The wear analysis of prepared valve specimens was carried out by using a Pin – on - Disc wear tester. The pin – on - disc testing consists of a rotating disc in contact with a fixed pin with a spherical top (ASTM G99 - 04). The specimen was located in a holder in such a way so as to bring it in contact with the plate (19 cm diameter, 9 mm thickness) to ensure rubbing between contact surfaces. During the wear testing, the parameter values were: a constant load of 20 N, testing time duration of 15 – 60 minutes, rotational speed of Pin - on - Disc as 200 RPM, and the wear track radius as 40 mm. The variation patterns of wear with time were obtained. The wear patterns thus obtained for worn - out and new specimens were studied and analyzed to understand the building up and growth of wear. The worn out valve head samples were benchmarked against corresponding new specimen samples.

The JEOL JSM – 6390A Analytical Scanning Electron Microscope was used for micro - image generation on standardized settings of 10 kV / 15 kV accelerating voltage for optimized edge resolution, 5 µm working distance for optimized resolution, and a magnification of X5000. The nature of particle shape and surface texture was detected on the surface profile. Careful processing and analysis of the digitized image enabled determination of the presence of micro-projections and their relative sizes. Processing of the images generated considerable bit of useful information about surface topography.

Atomic Force Microscopy was introduced by Binning and Rohrer in 1986 (Binning et al., 1986). It uses a microscopic probe mounted on a cantilever having a low force – constant. The sample surface is scanned by the probe. Short range atomic forces like van der Waals force are used to detect the surface morphology (Hosemann et al., 2008).The atomic force microscope (AFM) is a scanning probe microscope (SPM). SPMs are designed to measure local properties, such as height, friction, magnetism, etc., with a probe. To acquire an image, a small area of the sample is scanned with simultaneous measurement of the local property. AFMs operate by measuring the force between the probe and the sample (Mann et al., 2014). Normally, the probe is a sharp tip, which is a 3-6 µm tall pyramid with 15-40 nm end radius. The lateral resolution of AFM is quite low (~30 nm) but its vertical resolution can be as good as 0.1 nm. The testing of samples in the current work was done on an NT - MDT scanning device. The scanning areas chosen were 10 µm × 10 µm and 5 µm × 5 µm. Images obtained were analyzed for evaluation and understanding of various parameters, as also for the purpose of relative comparison between new and worn – out valves.

Observations and Results

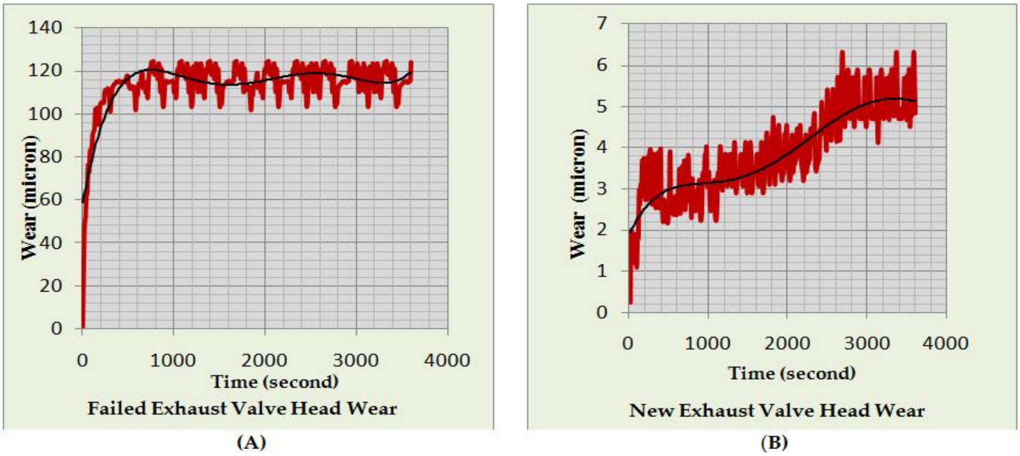


Figure 1: Wear variation curves for failed and new exhaust valve heads

The growth of wear with respect to time for a Failed Exhaust Valve Head (FEVH) is represented by (A) of figure (1). The FEVH curve exhibits a definite similarity with oxidative wear mechanism. Corresponding to a particular load, the surface oxidation phenomenon is beneficial as it reduces the depletion of material at high sliding speeds. The softened oxide film acts typically like a lubricant layer that protects the metallic substrate. The oxide films formed prevent direct metal - to - metal contact and also result in a reduction in the coefficient of friction on contact surfaces, thereby reducing adhesive and deformation - controlled wear. The oxidation of material is closely linked to the existing operating temperatures and is on expected lines as the exhaust valve in an LPG - run retrofitted gasoline engine usually encounters high temperatures to the tune of 900°C - 950°C. However, the oxide layers formed on the material surface start wearing off with the passage of time. The wear magnitude varies from a pretty low value of 0.39 microns to 124.41 microns as shown.

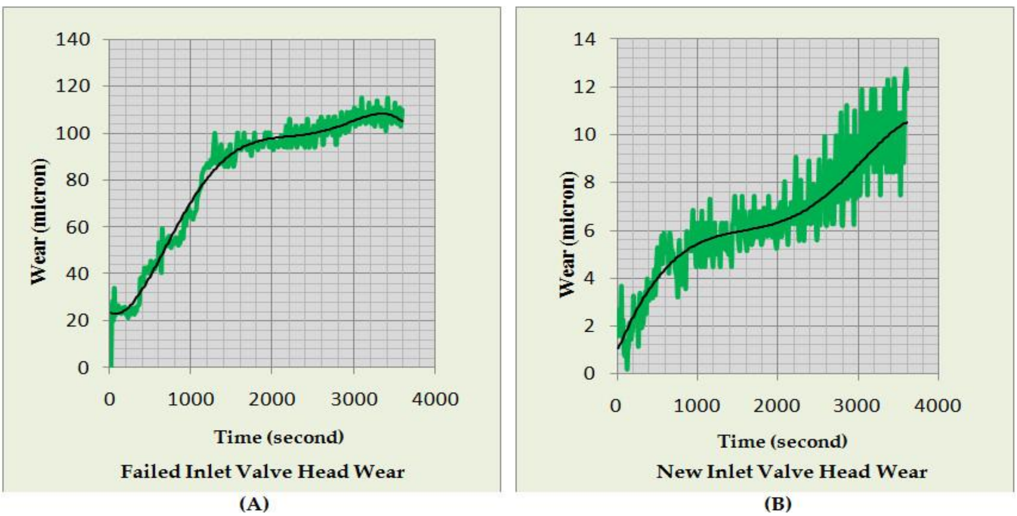


Figure 2: Wear variation curves for failed and new inlet valve heads

The nature of the curve for a New Exhaust Valve Head (NEVH) is represented by (B) in figure (1). The NEVH curve shows steady state wear after the initial zone of instability. The crests and troughs observed on this curve may be attributable to the presence and sudden appearing of highly abrasive particles that raise or lift the pin on the POD tester, thereby creating sharp changes in wear values. The magnitude of wear varies from a minimum value of 0.24 microns to a maximum value of 6.31 microns as is evident.

The variation of wear with respect to time for a Failed Inlet Valve Head (FIVH) is shown in (A) of figure (2). The variation reflects an almost steady wear condition with no noticeable abnormal behavior across any zone. The corresponding curve for a New Inlet Valve Head (NIVH) is shown in (B) of figure (2). It exhibits a wear pattern that is quite akin to adhesive wear.

The initial portion of wear V/s time curves exhibits some instability and randomness. However, beyond this region, the nature of the curves becomes more predictable and uniform.

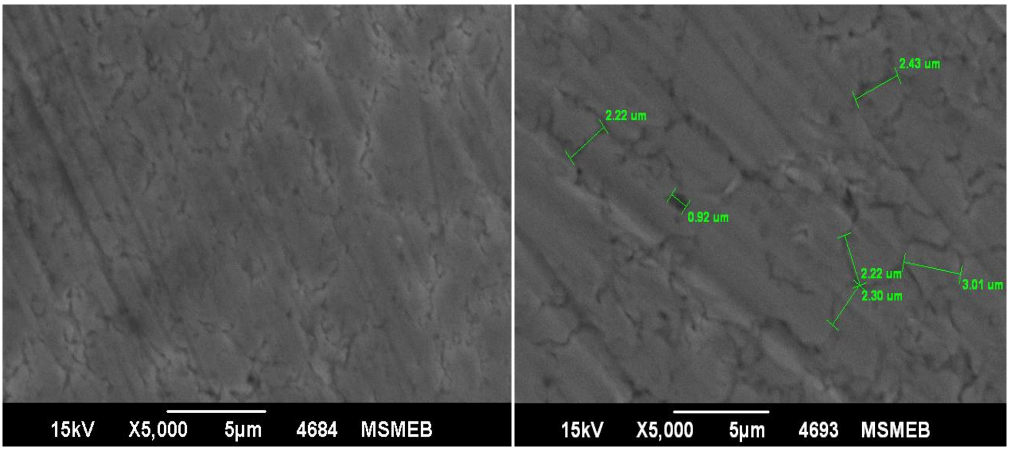


Figure 3: SEM images depicting microstructure of failed and new exhaust valve heads

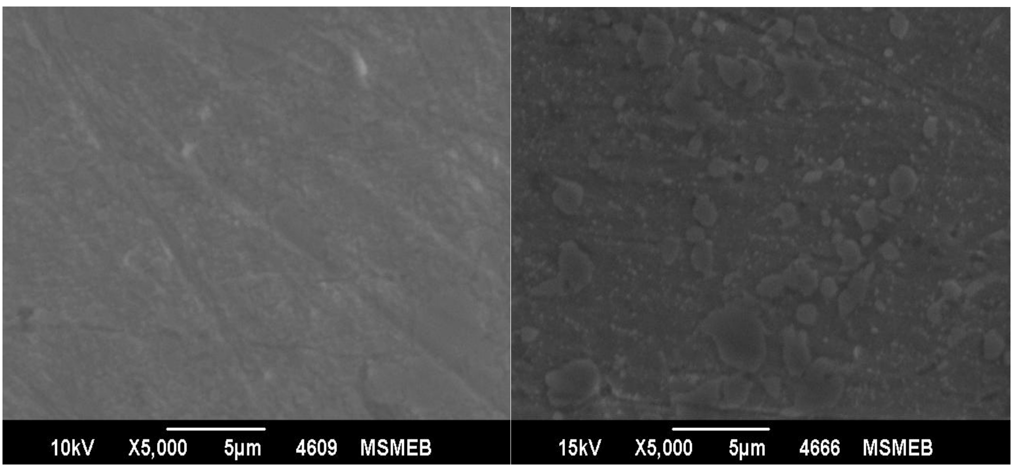


Figure 4: SEM images depicting microstructure of failed and new inlet valve heads

SEM images indicating the microstructure of new & failed intake & exhaust valves at X5000 resolution are shown in figures (3) & (4). These images show the range of particle sizes that occurred in the experimental samples.The white colour spots in the images are a clear indication of the presence of oxides. The blackish grey patches, on the other hand, reflect the existence of carbides in the valve material and the effect of corrosion that becomes more pronounced at high temperatures. A definite coarse distribution of carbide particles is observed in the SEM image of failed exhaust valve head. In the case of failed inlet valve head, the carbide particles do have a coarse distribution but to a lesser extent.

A fine distribution of carbides represents increased material hardness whereas a coarse distribution of carbides is an indication of material - shift towards the grain boundaries with an accompanying reduction in the hardness and weakening of the material. The SEM images indicate that grains are broken and are not uniformly distributed. The size of grains, which is an indication of material strength, increases after working at high temperatures. Large grains result in lower strength whereas the presence of small - sized grains leads to higher material strength. Elongated grains visible in SEM images of failed valves indicate that the valve material strength comes down significantly because of high temperatures.

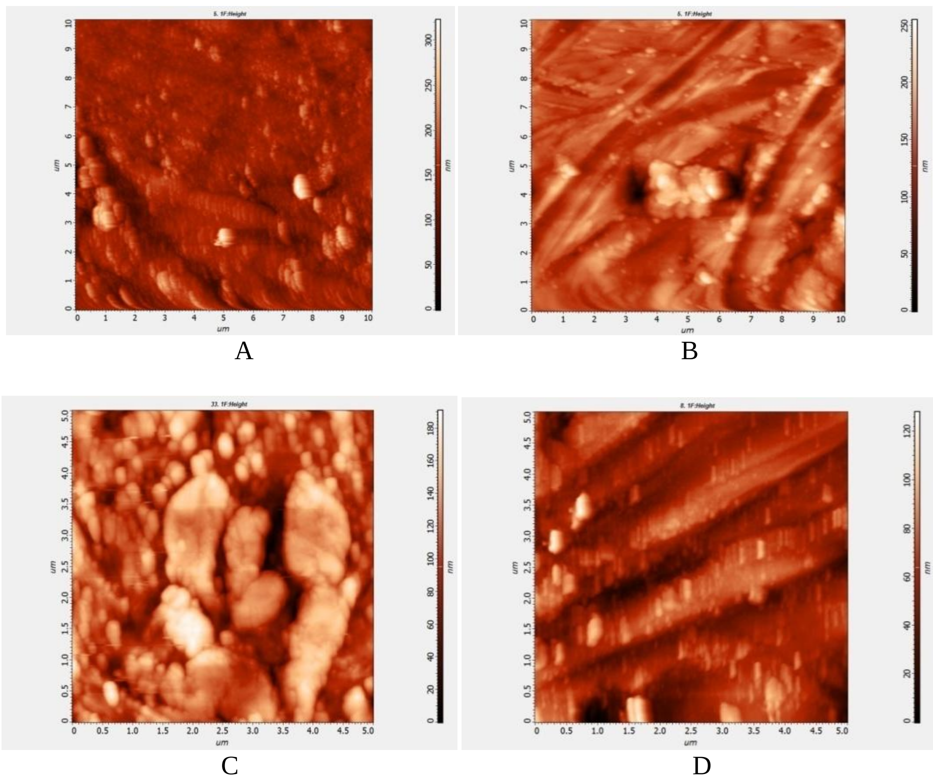


Figure 5: 2D AFM images of failed and new exhaust valve head (A&B), and failed and new inlet valve head (C&D)

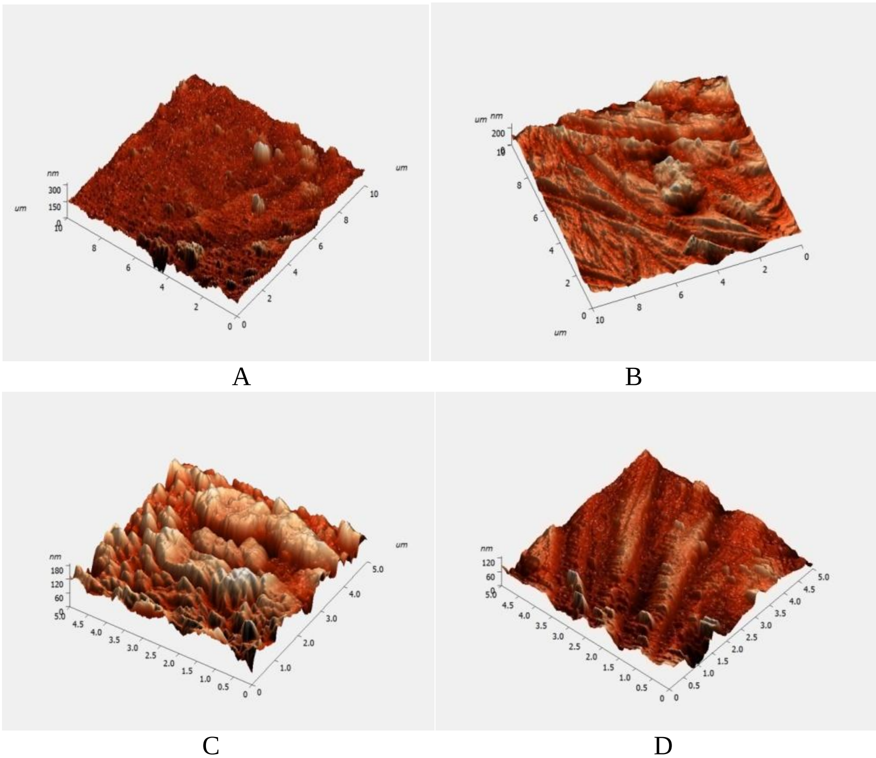
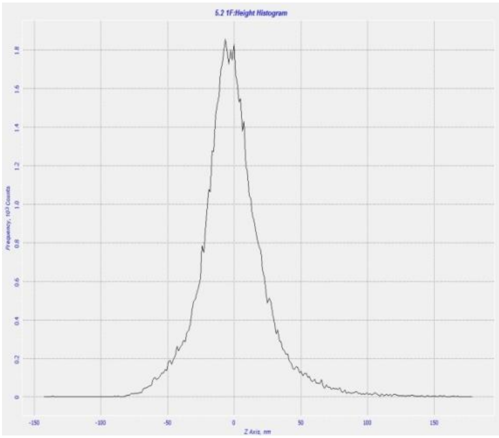


Figure 6: 3D AFM images of failed and new exhaust valve head (A&B), and failed and new inlet valve head (C&D)

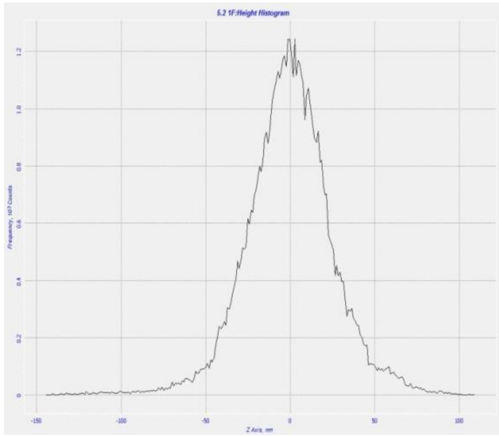
The 2D and 3D AFM images for the failed exhaust valve head in (A) of figure (5 & 6) clearly indicate the presence of a significantly large number of secondary particles like silicates, oxides and / or carbides. The crack initiation sites are likely to surface across all projections. The effect of thermal stresses and mechanical failure causing agents is visible through material deformation and material drifting. The images for a new exhaust valve (B) of figure (5 & 6) show the inclusion of an abrasive particle. Some finishing patterns that are so typical of the manufacturing operations employed are also visible.

The 2D and 3D images for the failed inlet valve shown in (C) of figure (5 & 6) exhibit pronounced effect of high chemical abrasion. A number of voids scattered across the section are an indication of a thermal shock wave and accompanying thermal stresses. The changes in the surface and its structure are an indication of the effect of temperature and chemical agents. The cracks at some locations may also be attributable to the escaping out of entrapped gases that result in appearance of secondary structures. The images for a new inlet valve (D) in figure (5 & 6) are quite similar to those for an exhaust valve with a number of minute granules distributed in a more or less uniform manner.

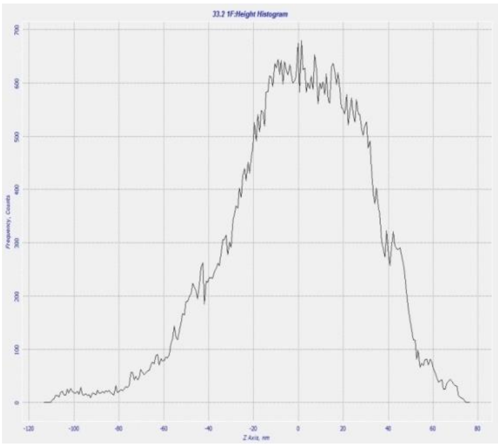
The images obtained through atomic force microscopy can be better illustrated and understood with the help of statistical parameters and their graphical representation. The height histogram of a topographical image, which is amongst the most commonly used descriptors, provides statistical distribution of z- values (heights) within the contours of the image. It can be used for quantification of gross volume of voids and protrusions of the surface under the consideration. It also helps in ascertaining the homogeneity of the surface by checking the translational invariance of statistical descriptors of the sample surface. The random surface height distribution is usually represented by a Gaussian function whose skewness is zero as it represents equal distribution of peaks and valleys.



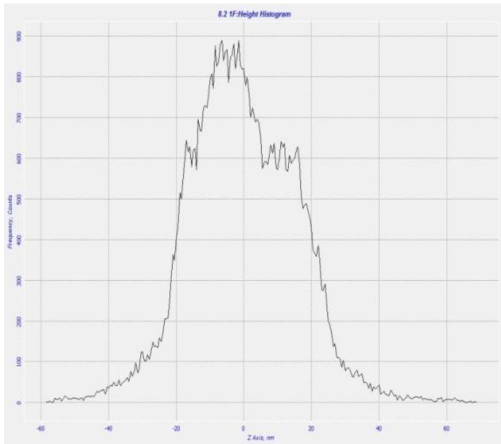
A



B



C



D

Figure 7: Height histograms for failed and new exhaust valve head (A&B), and failed and new inlet valve head (C&D)

The height histograms shown here are a representation of the height distribution for surfaces covered with bumps and pits. The height histograms for the failed and new exhaust valve head (A & B) in figure (7) are quite close to Gaussian distribution whereas those for failed and new inlet valve heads (C & D) in figure (7) show considerable deviation which can be attributed to large lateral correlation length and inadequacy of the scanning area (5 µm × 5 µm) to provide sufficient statistical averaging. The height distribution with negative skewness shown in Table (I) owes its origin to a significant number of valleys whereas positive skewness indicates presence of large number of peaks. The skewness parameter provides a clear indication of the existence of deep valleys or sharp peaks.

Table I: Statistical descriptors for failed and new valve samples

Statistical Descriptors	Failed Exhaust Valve Head	New Exhaust Valve Head	Failed Inlet Valve Head	New Inlet Valve Head
Amount of Sampling	65536	65536	65536	65536
Sampling Area (μm^2)	100	100	25	25
Mean (10^{-17} nm)	-185	-123	-411	625
Minimum (nm)	-142.661	-144.391	-113.382	-58.418
Maximum (nm)	179.959	110.025	77.227	69.409
Peak to Peak (nm)	322.621	254.416	190.61	127.828
Root Mean Square Value (nm)	25.929	25.995	30.145	15.775
Roughness Average (nm)	18.425	19.457	24.073	12.552
Skewness (Ssk)	0.937	-0.252	-0.429	0.147
Kurtosis (Ska)	7.048	4.934	3.172	3.48

CONCLUSION

The wear of valves in LPG - run retrofitted gasoline engines used in passenger cars is a complex phenomenon as a number of failure modes like oxidative wear, adhesive wear / material transfer, abrasive wear and plastic deformation, erosion and corrosion interact with each other and contribute collectively to the failure of the valve. Surface oxidation or parting agents are also found to play a significant role in the wear of valves. Localized surface contact results in surface irregularities (projections or asperities) on the mating surfaces to go through plastic deformation. The gouging and scoring on the contact surfaces are a reflection of abrasive wear whereas abrasion and radial flow serve as clear indicators of plastic deformation. The presence of hard carbides and trapped wear debris ultimately results in clear detachment of particles from the valve surface. Corrosive wear is observed in failed exhaust valve and is attributable to the presence of a harsh chemical environment and high temperature. A comparison of the microstructure of failed valves and new valves reveals that high - temperature operating conditions affect grain size, grain boundaries, and distribution of carbide particles. Such conditions severely impact the useful life of valves by promoting crack initiation, its propagation and by influencing the growth of wear. At high temperatures encountered by the exhaust valve used in an LPG - fueled retrofitted Gasoline engines the grain size of austenitic steel changes and grains undergo a significant bit of damage, distortion and redistribution. The 2D images, corresponding 3D images and magnitudes of statistical descriptors for inlet and exhaust valves (failed and new) provide useful information about the existence of surface asperities, grain sizes and crack propagation. The peak – to - peak value is the maximum for the failed exhaust valve which indicates that this valve has suffered a significant bit of mechanical damage which, to a large extent, is attributable to the high temperature the valve encounters in an LPG engine. The peak – to - peak values are less for inlet valves as they are subjected to lesser thermal gradient and lower highest temperature. The average roughness values exhibit exactly the opposite patterns for exhaust and inlet valves. For failed inlet valve, the average roughness value is almost double the value for the new inlet valve which is an indication of bulk surface deformation under thermal and cyclic stresses.

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