

Effect of Thermal Impact Failure on Aluminum Alloy Piston Crown

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Abstract—An analytical study of the thermal impact failure on a diesel engine piston has been performed in order to determine and analyze the possible causes of the failure. The piston is subjected to preliminary inspection, microstructure analysis and then hardness testing. Visual examination revealed the impact made by piston with valve head and the subsequent welding of the broken valve portion with the piston crown. It is observed to be caused by improper operating conditions. SEM and EDS analysis performed on the piston specimen revealed the presence of high alloy content and various intermetallics that precipitated in the Al-Si alloy material during combustion process. These particles are attributed for the high hardness and brittleness of the piston surface which thereby resulted in its fracture upon the impact. The weak boundaries between the intermetallics easily enable fatigue crack growth up to failure. Results from the microhardness test performed on the specimens validate the increase in hardness on the crown than on skirt. The analysis of obtained data and observations suggests that piston would have failed by fatigue even if the valve operated properly.

Keywords—Piston, failure, aluminum alloy, thermal, microstructure.

I. INTRODUCTION

Piston failure is an essential part that should be considered while analyzing total engine failure. Being the power developing component of engine, it is essential to provide necessary and thorough maintenance for pistons. Otherwise, even a minute fault will cause the piston failure. Damages to engine piston are one of the most expensive failures regarding final consequences and possibilities of engine repair [1].

Once the piston has failed, there arises the necessity for a proper and detailed failure investigation. Such a procedure requires the information regarding various factors that contributes to piston performance. These factors includes fuel formulation, lubricating oil, design and material of piston, ring and pin, coating materials, operational parameters, installation procedure, personnel

errors etc. Deviations in such performance factors are responsible for the failure [1].

By performing a detailed and accurate investigation process of failure, the primary cause will be identified and thus rectified.

A piston is subjected to continuous thermal loading during its entire operation. It first gets heated to a temperature of about 400⁰C on the crown portion due to the burned gases which reaches a peak temperature of about 2500⁰C. Also, heat fluxes of maximum 10 MW/m² are produced in the combustion chamber [[2]]. The red hot piston is further cooled by heat transfer by rings, lubricating oil etc. Such heat exchanges when proceeds, results in unsteady cyclic loading on the piston. This is mainly caused by the thermal gradients that distributed vertically in the piston and on the piston crown.

Combined with mechanical loading, this could develop large thermal stresses on the material, which in turn reduces the material strength. Also, an inefficient heat removal from the piston crown can intensifies the effect of thermal gradients on the piston strength. The cracks thus formed grow further under the fatigue conditions thereby weakening the material further to final fracture of the piston [3].

Here, an aluminum alloy diesel engine piston with damaged crown portion, as shown in Fig.1, has been undergone failure investigation by performing proper tests and subsequent analysis of results.



Fig.1: Piston with damaged crown portion.

II. EXPERIMENTAL SETUP

The specimens for analysis purpose were the cut sections of the piston and are subjected to microstructure analysis and hardness testing.

2.1 Microstructure Analysis

The microstructure of the specimen is analyzed by means of High Resolution Field Emission Scanning Electron Microscope (HR FESEM). It has a theoretical resolution of 1nm at 15kV. It is equipped with Energy Dispersive X-ray Spectrometer that can detect various elements at a resolution of 127eV. SEM utilizes a focused electron beam to scan across the specimen and obtains the microstructure information through the secondary electron beam and signals received from the specimen. The results are displayed directly on the screen.

The specimen surface to be analyzed is polished well to obtain a fine surface finish by using emery papers and by cloth polishing in polishing machine. After polishing, specimen is etched using a suitable etchant solution so as to reveal the microstructure and grain boundaries clearly. Here, Weck's reagent which is used for the etching of aluminum alloy samples. It contains a solution of 100ml distilled water, 4g potassium permanganate and 1g sodium hydroxide [7]. The etched specimen is then analyzed in SEM for microstructural analysis. Using EDS Spectroscopy method, the elemental composition of the specimen is determined.

2.2 Hardness Testing

The specimen is undergone Vickers microhardness testing procedure. A microhardness test is performed by measuring static indentations made by loads not exceeding 1 kgf. The test procedure is similar to that of a standard Vickers hardness test, except that high precision microscopes are used for measurement. The Vickers hardness test consists of indenting the test material by applying load with a diamond indenter (in the form of an inverted right pyramid with square base and vertex angle of 136 degrees) for 10-15 seconds. The two diagonals of the indentation left in the material surface, as shown in Fig.2, after load removal are measured using microscope and its mean value is used to calculate the indentation area [8].

The Vickers hardness is then calculated by the formula:

$$HV = \frac{2FS \sin\left(\frac{136}{2}\right)}{d^2} \approx 1.854 \frac{F}{d^2}$$

F = Load in kgf; d = Arithmetic mean of the two diagonals d1 and d2, in mm

For the work, specimens are cut from the damaged crown part and from the bottom skirt portion so as to compare the hardness value on these portions. The specimens are polished well by using emery paper or polishing machine or both so that a smooth surface finish is obtained. Now, the specimen is fixed in the holder and placed in the Digital Micro Hardness Testing Machine, where a load of

100g is applied by the indenter for 10 seconds. Once the process is completed, the hardness value is directly displayed on the screen.

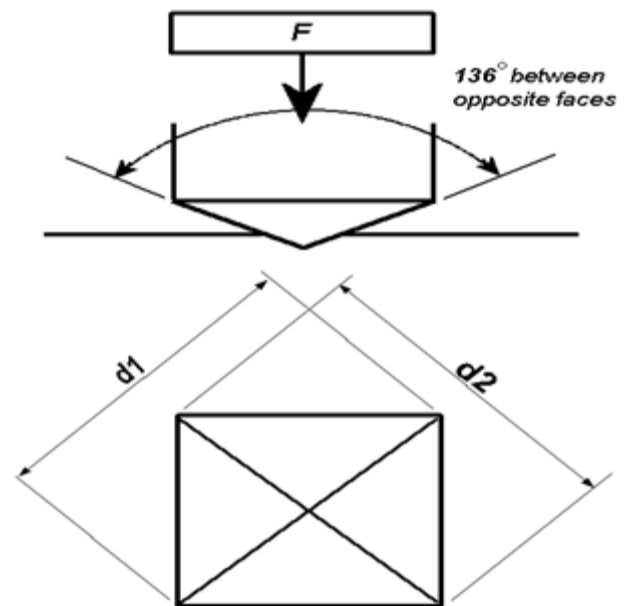


Fig. 2 Vickers hardness testing [8]

III. RESULTS AND DISCUSSION

3.1 Visual Observation

The damaged piston contains a piece of valve being welded to the crown. The fractured crown portion indicates the severity of impact it had with the valve. During engine running, a piston is always at a red hot condition due to the peak combustion temperature (about 2000°C) at which the piston material could deform plastically [2]. Meanwhile, the valve is also experiencing high temperature (about 200-700 °C) and fatigue loading from combustion process which thereby weakens the material [4]. Under such conditions and because of the incorrect valve timing, piston makes impact with the valve at high velocity. Here, the valve is at a weaker state than the much harder piston material and the high pressure developed in this impact causes the valve head to break away from the valve body and get inserted into the red hot piston crown.

Indentations caused by the collision of piston with broken valve body and the fractured valve fragments trapped in the combustion chamber are also visible.

The conditions at which the piston makes impact with valve during engine running are as follows:

1. Valve body slips from the locking seat or valve guide due to incorrect fitting during engine assembly.
2. When the valve spring fails during closing stage, it would not compress back which causes the valve to remain open.
3. Valve get seized or stuck during operation due to improper lubrication of the valve and /or camshaft.

4. The timing belt/chain could get ruptured due to unsteady loads during high speed operation. This would stop the running of camshaft and hence the valve working.
5. Slippage of timing belt/chain during running. This could happen due to uneven tension in the belt caused by the weakening of belt material after long run service. For chain drive, gears/sprockets with worn out tooth creates slippage of the chain. Such condition affects the camshaft rotation which in turn results in incorrect valve timing.

These conditions could results in noisy operation of the piston due to improper compression and combustion which in turn leads to engine failure. By proper follow-up of necessary precautions and maintenance functions, the operation of valve and camshaft systems could be ensured and thus the failure would not occur.

3.2 Microstructure Analysis

Table.1: Elemental composition of piston specimen

Element	Mg	Si	Mn	Cu	Al
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Weight %	0.63	25.61	3.69	3.44	66.63
	0.73	27.11	4.16	3.20	64.81
	1.08	22.32	4.04	3.75	68.82
Standard wt %	0.05-2	9-11	0.05-0.10	0.25-0.30	remainder

The elemental compositions of the specimen as measured on three portions of the specimen surface by EDS are as given in Table 1.

The data from composition measurement shows that the silicon content in the specimen lies between 22-27 wt %, which indicates that the alloy is having hyper-eutectic composition (the eutectic composition being at 12-13 wt %) [9]. Along with copper and manganese (at 3-4 wt %), there is an increase in the strength and hardness of the material by precipitation hardening heat treatment.

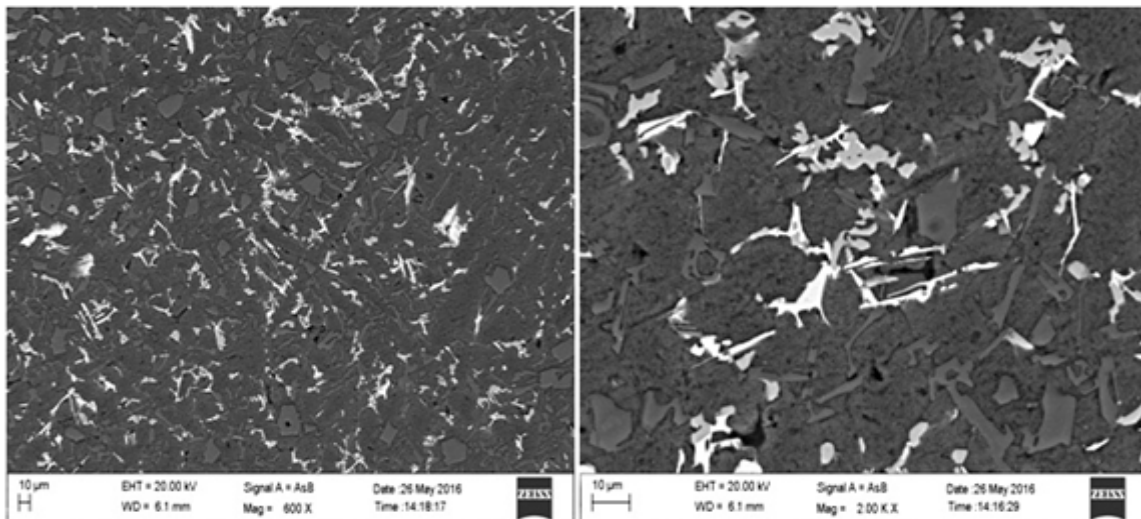


Fig. 3: SEM microstructure of Al-Si alloy

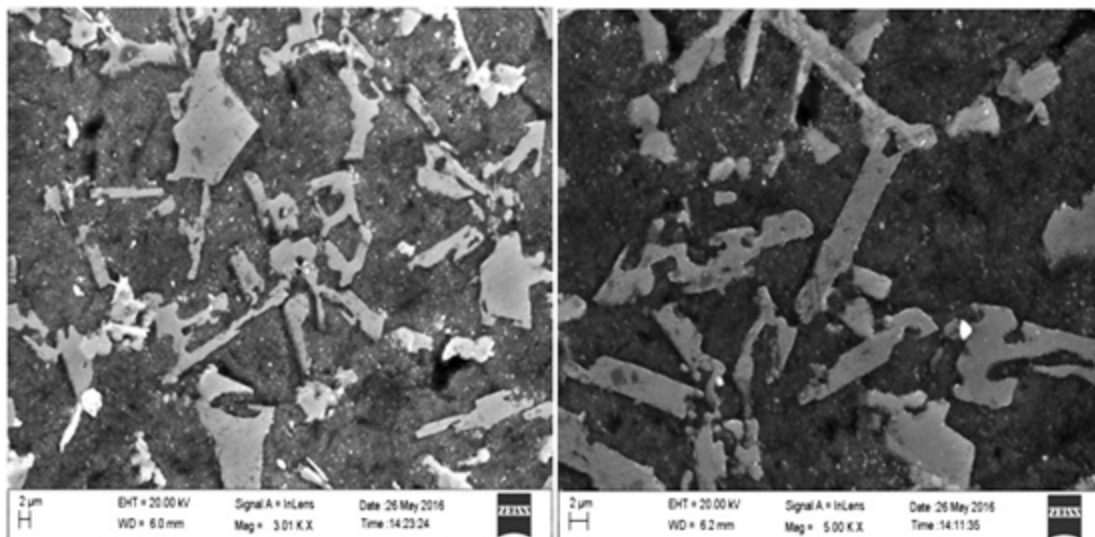


Fig. 4: SEM image of eutectic Si particles and intermetallics in different orientations

Table.2: Hardness testing results

Test area	d1(μm)	d2(μm)	D(μm)	Depth(μm)	HV
Crown	25.4750	25.4625	25.4687	3.63	285.8
	25.3125	25.3250	25.3187	3.61	289.2
Skirt	34.8000	32.7625	33.7812	4.82	162.4
	36.3250	32.7875	34.5562	4.93	155.2

Alloying elements at such high levels of composition could reduce the melting point of the piston material largely which would have helped the piston to reach the molten plastic state.

From the SEM images shown in Fig.3 and Fig.4, it can be seen that many intermetallics have been precipitated from the alloying elements in the piston during running at high temperature. The most common intermetallics include $\text{Al}_3(\text{CuNi})_2$, Al_5FeSi , Al_9FeNi , $\text{Al}_5\text{Cu}_2\text{Mg}_8\text{Si}_6$, $\text{Al}_8\text{FeMg}_3\text{Si}_5$ etc [5] [6]. These intermetallics are stiff and hard enough to deform in an inconsistent manner compared to Al matrix. The resulting stresses develop cracks that propagate further to form voids or pores as shown in figure. These pores could weaken the grain boundaries and interfaces between the intermetallics which enables the cracks to pass through them, thereby accelerating crack growth. The weakening of interfaces is attributed to the debonding or fracture of intermetallics and brittle Si particles that are in different orientations in the Al matrix [5] [6].

Such vastly distributed intermetallics precipitated out in the Al matrix makes the piston hard and brittle by reducing ductility. The increased brittleness beyond the limit could facilitate easy crack propagation and erosive fracture of particles from the surface upon the impact with valve head.

Thus, it is observed that the piston would have failed by fatigue cracking and fracture if the impact with valve has not occurred. In order to avoid the fatigue failure, the alloying element content in the material needs be reduced to the standard values as given in Table 1.

3.3 Hardness Testing

The Vickers hardness testing performed on the piston specimens provided results as shown in Table 2.

The results shows the anisotropic nature of the piston material which is indicated by the higher hardness on the crown portion than the bottom skirt portion. It is clear that the crown portion was subjected to a smaller indentation area and depth as compared to skirt portion. This could be explained by the high hardness imparted by the stiff intermetallics precipitated on the crown part during

service at high temperature and the considerable resistance to deformation caused by the same.

Another possible reason for the high hardness at the crown could be the quenching by lubricating oil. Once the valve has been fractured and engine stops, the lubrication oil leaks out into the combustion chamber which is still at a high temperature. The interaction of hot piston with oil would be that of a quenching process which results in the increased hardness at the crown portion.

IV. CONCLUSIONS

The damaged piston has been tested for failure cause by performing visual inspection, microstructural analysis and hardness testing and the results are analyzed.

The high speed impact made by the red hot piston fractured the valve and got it welded to crown, which was in a near to plastic state. The impact was caused by the incorrect valve timing which is attributed to the factors such as incorrect valve fitting, spring failure, improper lubrication of valve and camshaft, slippage and rupture of timing belt/chain etc.

The SEM and EDS results showed the high content of alloying elements in the Al-Si alloy piston material (which is found to be hypereutectic with Si at 22-27 wt%, Cu and Mn at 3-4 wt%) which caused the high hardness and brittleness by the precipitation of intermetallics at high combustion temperature. The stiff intermetallics results in the formation of cracks which develop further due to the weak interfaces between the intermetallics.

The microhardness test results depicted the large difference in hardness between crown and skirt portions with values obtained as 287 HV and 158 HV respectively. This was observed as due to the precipitation hardening, as explained by microstructural analysis and also due to quenching of piston crown by the leaked lubricating oil.

It is suggested that the piston failure by impact with valve could be prevented by ensuring the proper working of valve and camshaft systems. Also, failure by fatigue that would have occurred otherwise could be prevented by limiting the alloy content in the material.

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