Examination of Components from a Failed Marine Engine

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Report by:

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1. Introduction

R-Tech Consultants Ltd received components from a marine engine that had failed catastrophically. XXXX had informed R-Tech that the failure had occurred in an over-speed condition. The components received consisted of a cylinder liner, a piston and conrod. These are shown in figures 1.1 and 1.2 below.

Figure 1.1 Conrod, piston and bolt as received

Figure 1.2 Cylinder as received

The conrod was bent and the piston had fractured into two pieces. More detailed images of these are shown in section 2 below. The incident had occurred whilst the vessel was proceeding on passage and the engine was just re-started following an unscheduled stop to change a damaged / leaking fuel injector pipe. XXXX also informed R-Tech that they had learnt that the engine had also been in an over-speed situation one month prior to this, with no resulting failure. They had also been informed that no inspections of the bolts and fastenings had taken place once the engine had been stopped, and also that no parts were changed after this earlier over-speed incident. This earlier occurrence happened on completion of a major strip-down and overhaul when the engine was being test-run. In neither case did the automatic over-speed protection devices operate. The engine is a six cylinder turbo-charged XXXX medium speed diesel engine developing 2677kW at 600 rpm MCR (maximum continuous rating). The engine had run for a total of 166575 hours, with 559 hours subsequent to the last major overhaul. The failure during the second over-speed resulted in the piston breaking out through the cylinder liner.

R-Tech were requested to examine the items received to determine the mode of failure, and also whether the failure that had occurred during the second over-speed was a result of the first over-speed. The assessment of this failure would entail visual examinations, sectioning, SEM / EDX analysis, hardness testing, chemical analysis and metallography, and the subsequent issue of a full report.

2. Visual Examination

Figures 2.1 to 2.7 show various views of the components received in more detail.

Figure 2.1 Piston working face

Figure 2.2 Top piece of piston, showing the underside fracture face

Figure 2.3 Lower part of piston - fracture face

Figure 2.4 Bent conrod, part of big end, and lower part of piston

Figure 2.5 Fractured end of cylinder liner

Figure 2.6 Cylinder bore

Figure 2.7 Big end bolt fracture face

Figure 2.8 Piston crown studs 1 and 2

Figure 2.9 Piston crown stud 1

Figure 2.10 Piston crown stud 2

The piston working face shown in figure 2.1 has many areas of mechanical damage present on it. The underside of this top piece of the piston shown in figure 2.2 has a granular appearance to the fracture face that is present. This fracture face matches up with that shown in figure 2.3 on the upper end of the lower piece of the piston. It is evident that the fracture of the piston has occurred in a brittle manner with no deformation.

The fracture faces on the piston body were examined at all locations, and appendix 1 shows examples of the appearance at eight different positions. It can be seen that the fracture appearance is similar in them all. There was no evidence of any fracture facets that would suggest that some of the fracture had been present for a longer time than others. There was some rust present at some positions, but on the matching faces of the fracture of the piston body still attached to the piston crown, rust was not present. This rust had therefore formed since the failure.

Figure 2.4 shows that the conrod had been bent by an angle of approximately 30° from being straight. Figure 2.5 shows that the bottom of the cylinder liner had been fractured when the piston broke through it. The bore of the liner shown in figure 2.6 did not reveal any gross scoring, although there was some lighter scoring present.

Figure 2.7 shows the fracture face of the bolt, from the big end of the conrod, to have fractured in a tensile manner, with some bending present. There were other bolts remaining in the lower half of the big end that had also fractured in a tensile manner, one also showing some bending.

Two failed piston crown studs had failed in a purely tensile manner and are shown in figures 2.8 to 2.10. The other two piston crown bolts were still intact and can be seen at the bottom of figure 2.2.

3. Metallographic Examination and Hardness Measurements

As it was believed that the piston crown studs were the first items to fail, (see section 7 - possible scenarios.), it was decided initially to examine these studs and also the piston crown that had failed. Three of the studs were removed from the piston, one being the fractured and bent stud, the other two being the remaining intact studs. These are shown in figure 3.1 below.

Figure 3.1 Piston crown studs after removal

Both of the ‘intact’ studs were slightly bent. A piece was also cut from the piston body itself, and this is shown in figure 3.2 below, where the fracture face is typical of that found at all positions.

Figure 3.2 Piece of piston body

A section was taken from one of the studs and also from the piece of the piston body and prepared for metallographic examination by progressively grinding and polishing to a 1µm finish. These sections were then examined in the polished condition and after etching with a nital solution to reveal the microstructure. Figures 3.3 to 3.7 show the relevant results of these examinations.

Figures 3.3 and 3.4 show the microstructure of a piston crown stud which consists of tempered martensite. The hardness of this microstructure averaged 322HV when measured on a Vickers machine to BS EN ISO 6507-1:2005 with a 10kg load, and is what would be expected in a steel of this type (see chemical analysis in section 6).

Figures 3.5 and 3.6 show the microstructure of the piston body in the etched condition. The microstructure is typical of a grey cast iron, with type A graphite flakes on the ASTM A247 grading system, in a matrix of pearlite. Figure 3.7 shows an example of the section across the fracture face of the piston body. There was nothing amiss with the type of fracture in this material, which is typical of a brittle fracture in cast iron. The hardness measurements averaged 191HV. If the grade of cast iron is similar to G3000 (see later in section 6) then this hardness meets the specification of 187 to 241HV.

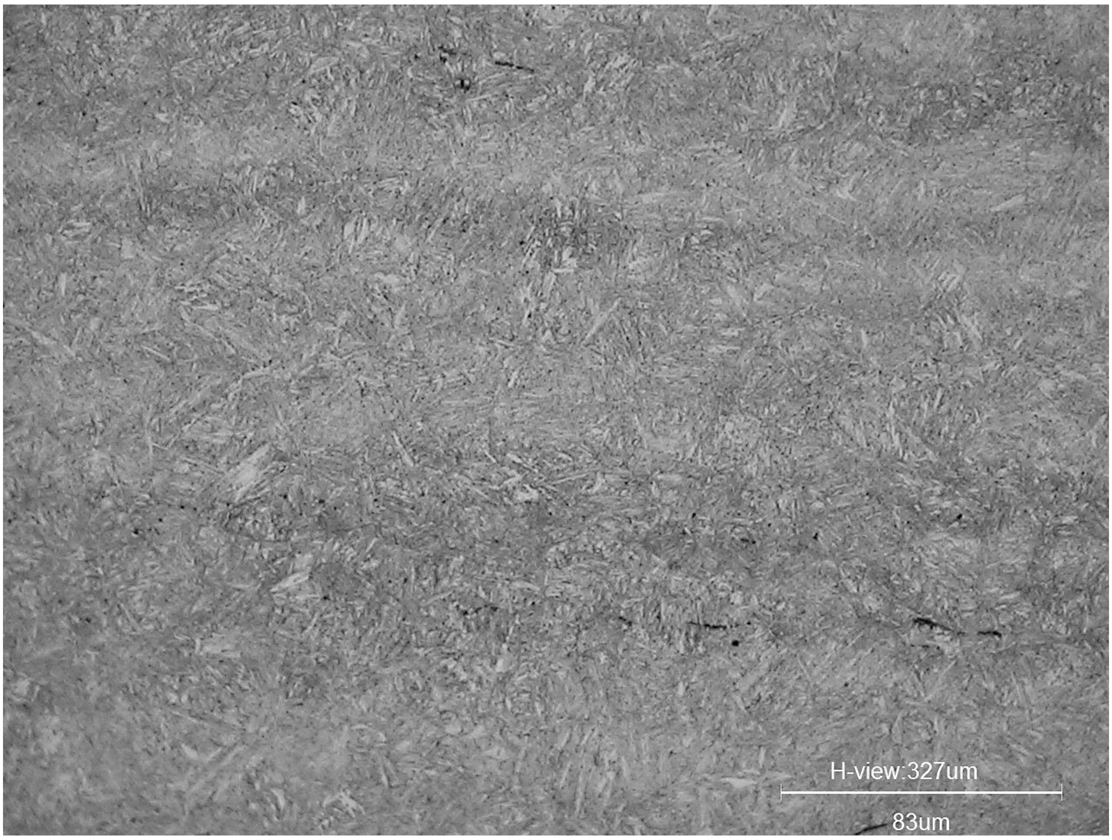

Figure 3.3 Piston crown stud etched

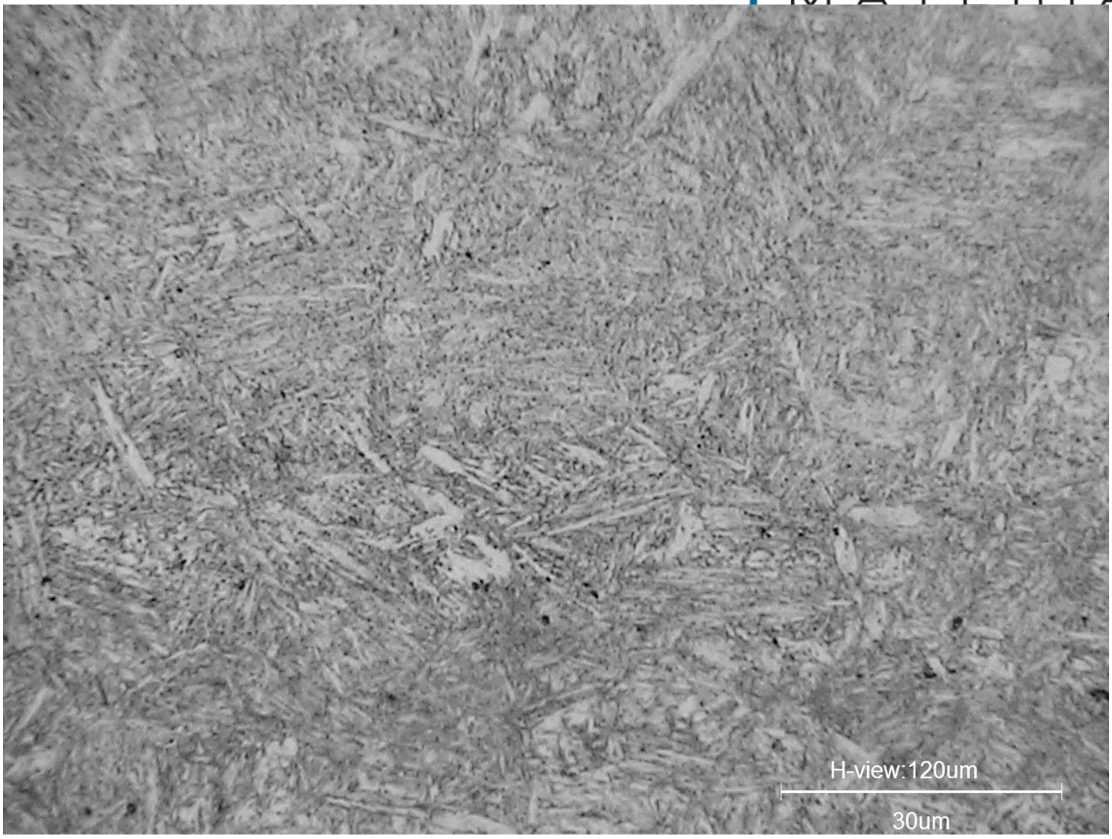

Figure 3.4 Piston crown stud etched

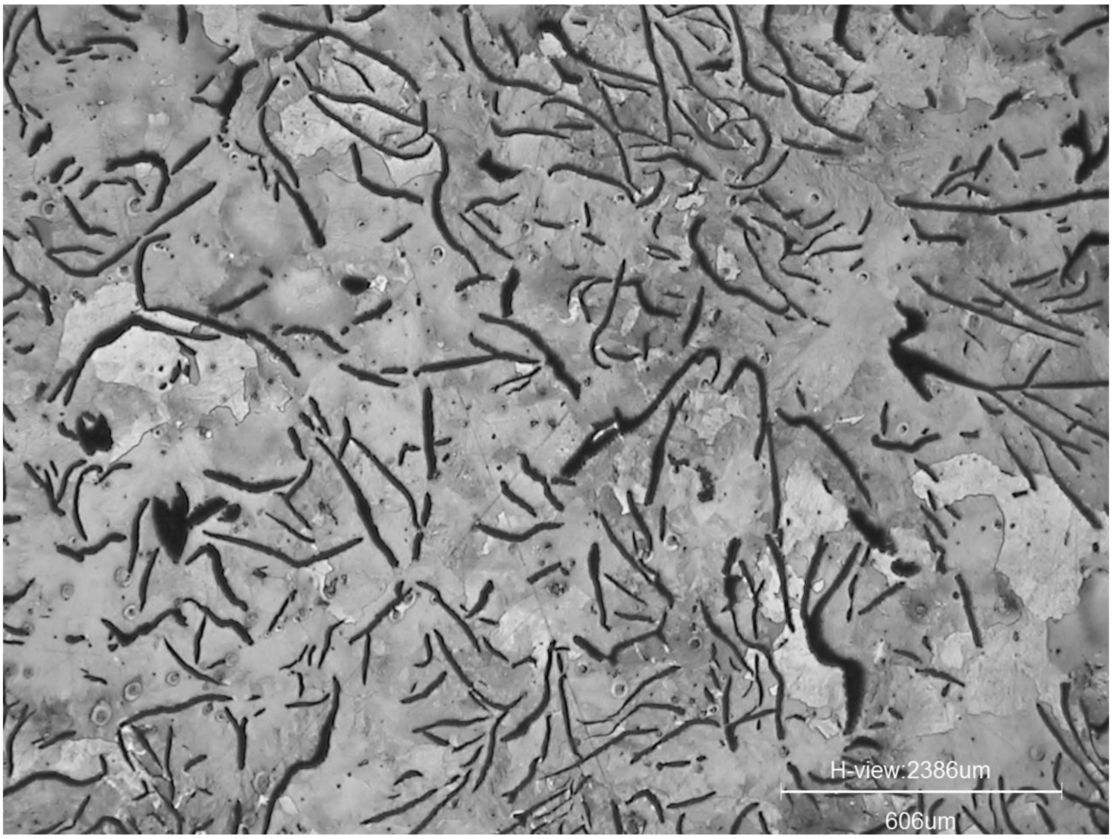

Figure 3.5 Piston body etched

Figure 3.6 Piston body etched

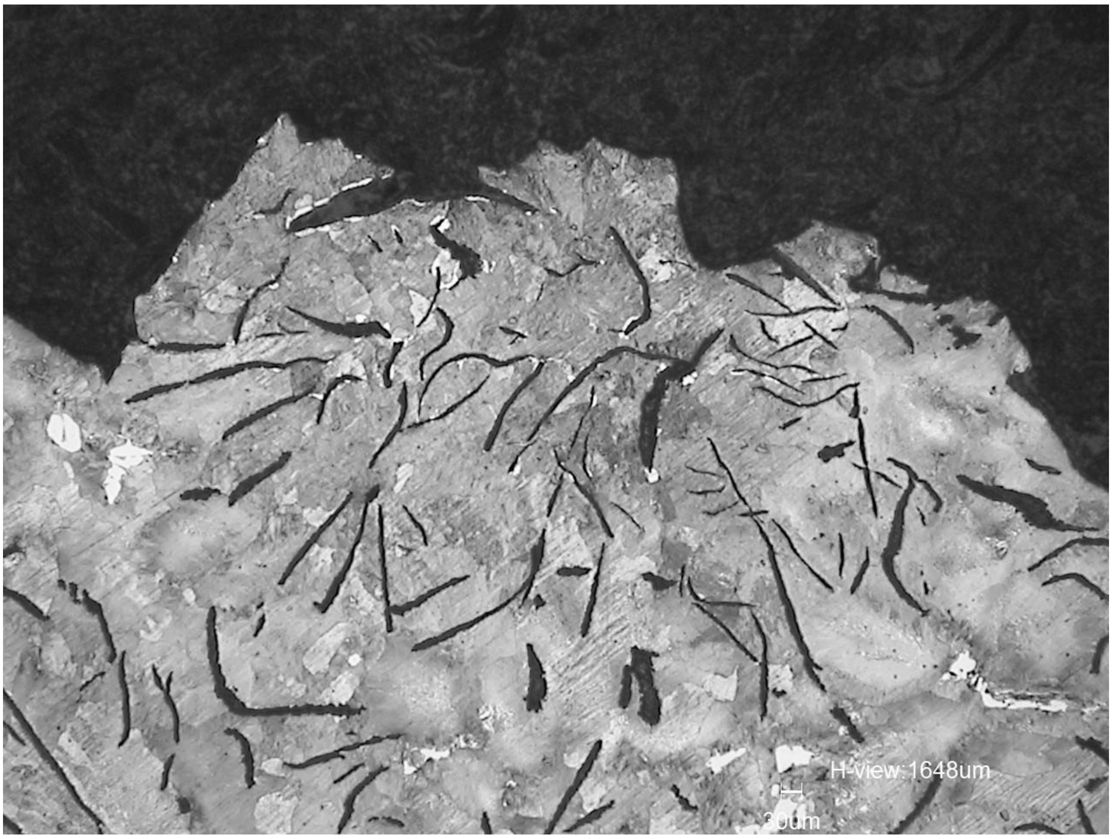

Figure 3.7 Piston body fracture face etched

Figures 3.8 and 3.9 show one of the big end bolts that had failed in a tensile manner. This was sectioned longitudinally and prepared in the same manner as described above.

Figure 3.8 Big end bolt with tensile / bend type failure

Figure 3.9 Big end bolt showing the fracture face

Figures 3.10 and 3.11 show examples of the microstructure of this big end bolt.

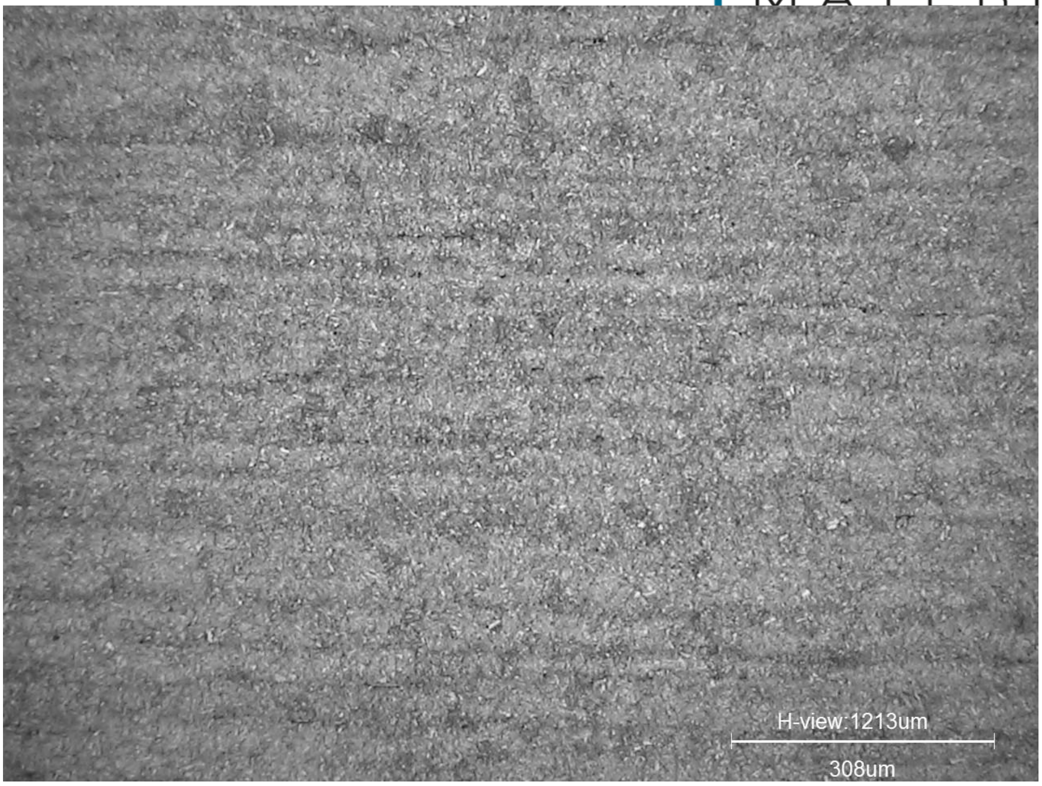

Figure 3.10 Big end bolt microstructure

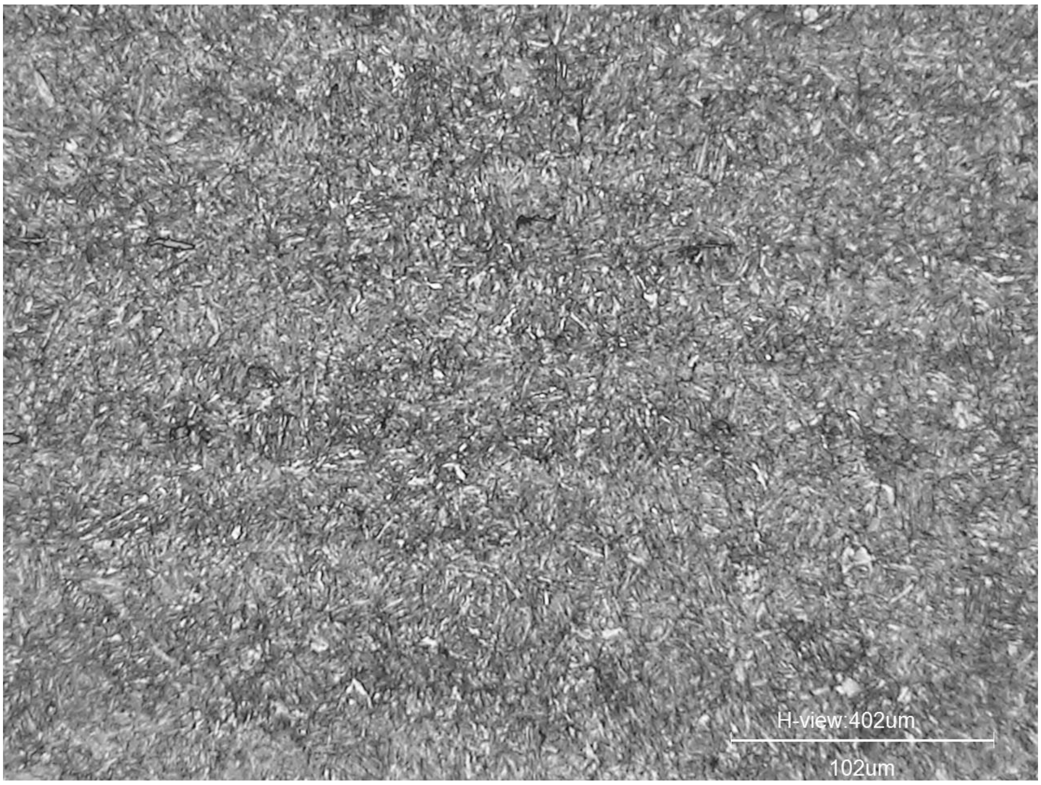

Figure 3.11 Big end bolt microstructure

The microstructure of this big end stud consisted of tempered martensite. Hardness measurements on this gave an average result of 323HV, similar to the piston crown stud.

4. SEM / EDX Analysis

The fracture face on the piston body shown in figure 3.2 was examined using a Zeiss EVO 60 scanning electron microscope with an Oxford INCA EDX microanalysis attachment. Figures 4.1 and 4.2 show examples of the type of fracture face found.

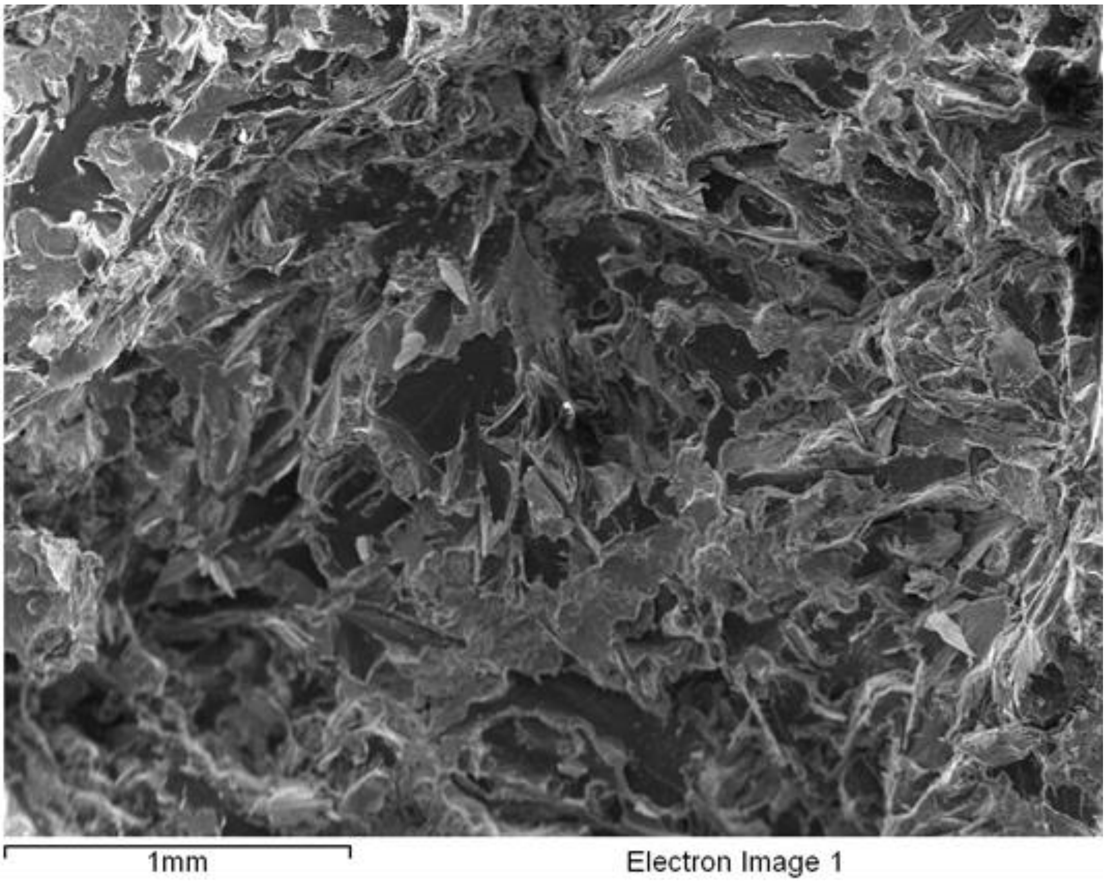

Figure 4.1 Typical fracture face of piston body

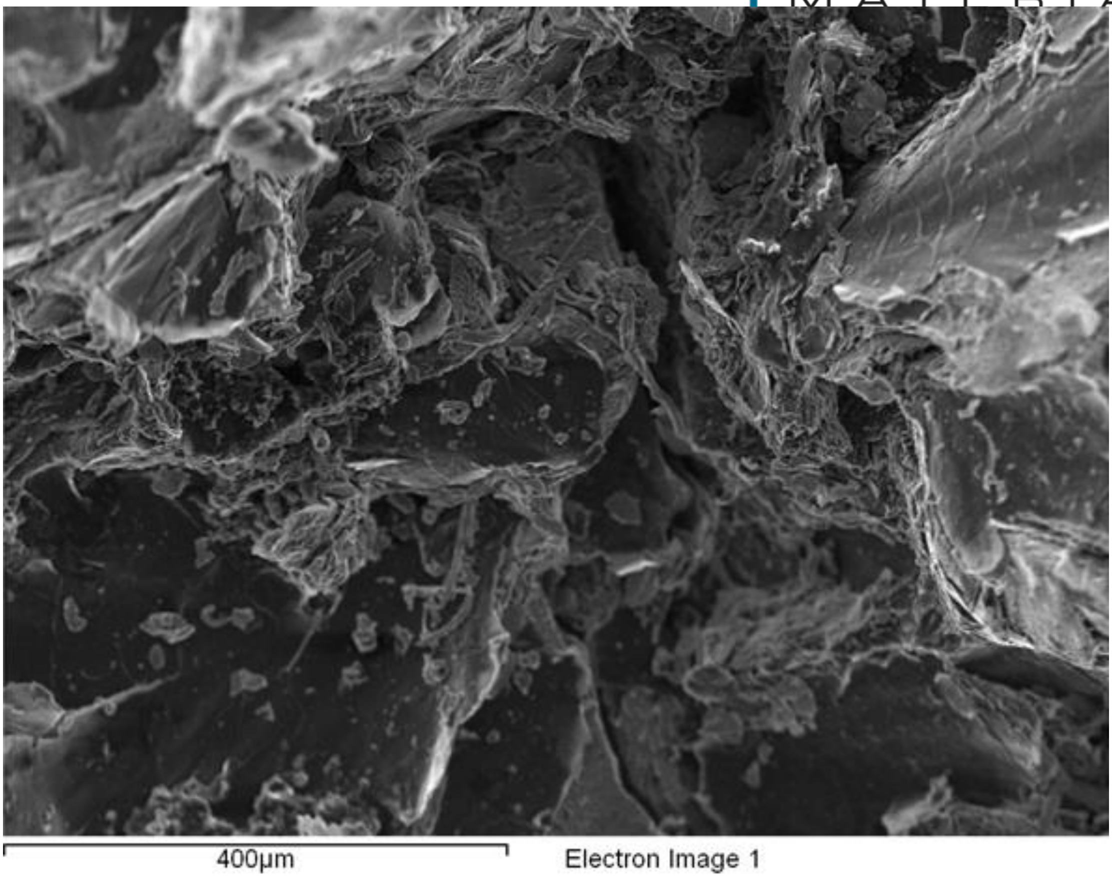

Figure 4.2 Typical fracture face of piston body

These show nothing untoward, appearing to show the flake graphite and pearlite within the microstructure.

5. Piston Crown Stud Tensile Test

A tensile test was undertaken on one of the piston crown studs, and the results are given in table 5.1 below. This is compared to SAE4340 grade of steel which can be used for this type of application.

Table 5.1 Tensile Test on Piston Crown Stud

	Maximum Stress MPa	% Elongation on 50mm gauge length
Piston crown stud	**1076**	**25**
SAE 4340	**1035 minimum**	**13 minimum**

The tensile strength and elongation meet specification. The tensile strength is equivalent to a hardness of 323HV, which ties in well with the hardness measured, i.e. 322HV. A tensile test could not be undertaken on the big-end bolt, but as the hardness and microstructure were almost identical to that on the piston crown stud, the tensile strength would have been similar.

6. Chemical Analysis

Chemical analyses were undertaken by optical emission spectrometry on the piston crown stud, the piston body and also the big end stud. The results are given in table 6.1 below. The carbon analysis on the piston body was undertaken by combustion analysis.

Table 6.1 Chemical Analysis Results

	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	V	N	Nb
Piston crown stud	.42	.31	.53	.008	.007	1.1	.19	1.5	.25	.006	.014	.007
Big end bolt	.40	.29	.62	.006	.022	1.0	.18	1.5	.16		.010	.007
SAE 4340 steel	.37 to .44	.15 to .35	.55 to .90	.04 max	.04 max	.65 to .95	.20 to .40	1.55 to 2.00				
Piston body	2.89	2.05	0.69	.012	.062	.27		.08	.03			
G3000 Cast iron grade	3.10 to 3.40	1.9 to 2.3	0.60 to 0.90	.10 max	.15 max							

Both the big-end bolt and piston crown stud comply approximately to grade SAE4340 that refers to alloy steel forgings that are used in the oil quenched and tempered condition. The cast iron analysis is similar to SAE J431 grade G3000 (commonly used for this type of application), but with a marginally lower carbon content.

7. Possible Scenarios for Failure

The sequence of events that caused this engine failure are not known, but two possible scenarios are postulated below.

7.1 Piston crown studs and piston failed first

If the studs holding the piston crown to the piston body were the first components to fail, there must have been an overload situation on them. Both studs that had failed had what appeared to be purely tensile fractures, with no evidence of bending. One of the failed studs was bent, but it had post failure damage that would have caused this. Possibilities that could have caused the piston crown studs to fail first are:

a. The piston crown became stuck and the studs then failed in a tensile manner.
b. The over-speed rpm of the engine caused an excessive momentum which produced an overload on the piston crown studs at the top of the stroke, causing them to fail in a ductile manner.

There was no substantial evidence of the piston having become jammed within the cylinder as only minor marking was present on the bore.

The momentum of the piston is proportional to its velocity. For example, in an over-speed situation, if the speed doubles then the loading on the piston crown studs doubles.

Two of the piston crown bolts failed in this instance in a tensile possibly due to over-speed causing them to have excessive loads imparted on them, and this could then result in the piston body itself fracturing as a consequence. The lower part of the piston would continue downwards within the cylinder as the engine rotated. When it started to return upwards within the cylinder, it would not have located in the proper manner, and may then have hit the cylinder bore badly, resulting in the piston shattering the cylinder liner. This would also cause the conrod to bend, and would impart excessive loading on the big end bolts, resulting in them failing in a tensile / bending manner. Although there was no evidence of damage to the cylinder liner bore, there would be damage to the pieces of the bottom of the liner that were not received.

7.2 Big-end bolts failed first

Over-speed would increase the centripetal force on the big end of the conrod and the rotating crankshaft bearing position. This could possibly cause the big end bolts to fracture in a tensile manner. If these failed first, then the conrod would become completely or partially detached. This could then result in the conrod pushing the piston back upwards within the cylinder in an incorrect manner. However, in this scenario it is difficult to explain the fact that two of the studs holding the piston crown on to the piston body had failed in a tensile mode by this scenario.

8. Discussion

The microstructures, hardnesses and tensile properties (where these could be measured) of the piston crown studs, piston body and big end bolts were all found to be satisfactory. The chemical analyses results were satisfactory on the piston crown stud and the big end bolt, and analysis on the cast iron piston was similar to SAE J431 grade G3000 with a marginally lower carbon content. This lower carbon content is not believed to be a problem in view of the microstructure and hardness being acceptable.

During normal operation of the engine, the studs holding the piston crown should not have high tensile loads imparted on them. During the compression and combustion stages they are under compressive loads. For them to be under a high tensile load it is possible that the piston crown had become jammed for an unknown reason, or that it was the result of the over-speed situation as explained above. However, as there is no evidence of the piston having been jammed in the cylinder liner, it is more likely that the piston studs failed as a result of over-speed excessive momentum.

All fracture faces on the piston body, which was manufactured from a grey cast iron, appeared to be similar, being granular in appearance. This is normal for a grey cast iron. With a cast iron such as this, it would be highly unusual for a fracture face to exhibit facets that would point to a source of the failure, or even to indicate that there had been a pre-existing crack from the previous occurrence of over-speeding. There was some rust present on one side of portions of this fracture, but it was not present on the mating surfaces on the other side of it. This was therefore not linked to the failure, but had occurred subsequently.

The tensile mode of failure on the piston crown studs does not help in indicating whether they had been partially stretched by the previous over-speed incident.

It therefore would appear that the cause of the failure was that the piston crown studs failed in a tensile manner due to overload imposed on them by the over-speed occurrence. Whether these studs had been stretched during the initial over-speed cannot be determined.

9. Conclusions

9.1 The chemical analyses, hardnesses, and microstructures were all satisfactory on the piston crown stud, big end bolt, with the carbon content of the piston body being slightly lower than a cast iron grade commonly used for this type of application. The tensile strength on a piston crown stud was also satisfactory.

9.2 Two piston crown studs had failed in a purely tensile manner.

9.3 The big end bolts had failed in a tensile / bending manner.

9.4 The cast iron piston body had fracture faces typical of flake graphite cast irons, being granular and brittle in appearance. The fracture appeared similar in all locations, and would have occurred as a one-off event, and therefore would not have occurred during the first over-speed.

9.5 As the bolts and studs had failed in a ductile manner, it was not possible to determine whether they had stretched during the first over-speed.

9.6 It is postulated that the sequence of events in this engine failure was that initially the piston crown studs had failed in a tensile manner due to an overload situation caused by excessive momentum from the over-speeding engine. This then resulted in the conrod becoming bent on the next upward stroke, and the big end bolts failing in a tensile / bending manner.

Appendix 1 Appearance of Piston Fracture Faces at Eight Locations