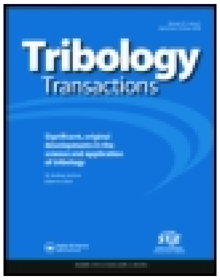

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Material Characterisation and Real Time Wear Evaluation of Pistons and Cylinder-liners of the Tiger 131 Military Tank

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Abstract

Material characterisation and wear evaluation of the original and replacement pistons and cylinder-liners of Tiger 131 is reported. Original piston and cylinder-liner were operative in the Tigers' engine during WWII. The replacement piston and cylinder-liner were used as substitutes and were obtained after failure in two hours of operation in the actual engine. Material characterisation revealed that the original piston was aluminium silicon hyper-eutectic alloy approximately matching specification of RSA - 419 AE, with silicon content (19.92 wt %).

Whereas the replacement piston was aluminium copper alloy with very low silicon content (0.73 wt %), approximately satisfying specifications of Al 2031 and Al 2618 - T6. Scuffing, material removal and ploughing were observed in the replacement piston and cylinder liner. These failures are attributed to inadequate piston material and design. Replacement piston average surface roughness was found to be 9.09 μm while for replacement cylinder-liner it was 5.78 μm. Characterisation results showed that both original and replacement cylinder-liners consisted of mostly iron which is indicative of cast iron, a common material for this application.

Key words

Tiger 1 Tank, Materials' Characterisation, Wear, Scuffing, Ploughing

1. Introduction

The fleet of around 300 military tanks makes The Tank Museum Bovington, United Kingdom, one of the largest tank museums in the world. This large collection of military tanks includes one of the last remaining and running Tiger 131 (Panzerkampfwagen Tiger Ausf. E), also known as Tiger 1.

The Tiger 1 was designed by Henschel and Sons in 1941-1943 during the 2nd World War. The engine fitted was a Maybach HL 210P45. The Tiger 1 was a formidable design which fought against former USSR and Allied Forces (Jackson *(1)* , Chamberlain *(2)*, Bidwell *(3)*). An example of this iconic military tank, which had huge impact on the opponents during the 2nd World War, is now kept in The Tank Museum Bovington. The fact that it was manufactured around 70 years ago participated in the 2nd World War in an extreme operating environment and is still being demonstrated, many of its components including pistons and cylinder-liners endure tribological failures in various forms. Being the last running of its kind; Tiger 1 has enormous

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societal interest in terms of conservation, deterioration through use and aging. In common with other tanks of the collection, it is necessary to protect the Tiger 1 against different tribological malfunctions that could risk its structural integrity and its ability to be demonstrated.

Aging through wear of the military tanks in The Tank Museum is a major issue and therefore reduction in wear can strongly influence material wastage and costs associated with the replacement of components (Scott *(4)*).Though component replacement is not favoured as it compromises the cultural biography and heritage value of the tanks, many tanks in the collection are demonstrated, and accordingly develop tribological related failures from time to time. This leads to higher maintenance costs, risks to the structural integrity, parts replacement and most importantly a tank loses its originality when a part is replaced.

In automotive engines wear plays a vital role in the degradation of the components such as piston-liner assembly (Kori *(5)*, Taylor *(6)*). Pistons and liners are one of the most important assemblies for engine and the engine performance is attributed to them. Tribological behaviour of pistons and cylinder-liners is hugely affected by internal thermo-mechanical loses, wear and consumption of the lubricating oil (Michalski *(7)*,Tung and Huang *(8)*).

Wear evaluation of the piston and cylinder-liner assembly is crucial in the Tiger 1 engine because it operates occasionally after being kept stationary in The Tank Museum. Extended pauses followed by start-stops are adversely affecting the durability of the engine. When engine is stationary corrosion accumulates, after some time when engine starts to function higher rate of wear occurs. Besides when engine operate either cold or extremely hot combined damage through corrosion and wear will be significant (Tung and Huang *(8)*).

This research presents material characterisation and real time wear evaluation for both original and replacement pistons and cylinder-liners. Comparative study reflects actual tribological wear which had taken place in the Tiger 1 engine. This is a novel approach and is the first of its kind in terms of the fundamental study to investigate the critical effects of wear mechanisms on the Tiger 1 engine during operation and the aftermath when the Tiger 1 is not running.

This paper is also part of the research conducted to analyse structural aging in historic military tanks in The Tank Museum Bovington (Saeed et al *(9, 10)*).

2. Experimental Methodology

2.1 Sample Collection

Original piston and cylinder liner were collected from Maybach HL 210 P45 engine. This was the original engine which was operating in the Tiger 1 during the WW2. This engine was disassembled in The Tank Museum to analyse various types of tribological failures. Replacement pistons and cylinder-liners suffered significant failure just after two hours in operation.

The Tank Museum procured replacement pistons from external supplier who provided modified designs. It has been very difficult to obtain materials specifications. Therefore investigations were performed and materials discrepancy in terms of Si was identified.

It is also worth mentioning that sample collection from the tanks of historical importance was a huge challenge, especially for other than non-destructive experimental research. In this project every effort has been made to follow museum ethics and guidelines in handling these artefacts.

2.2 Sample Preparation and Material Characterisation

A piece measuring approximately 1 cm^2 of interest was taken from each component. The purpose of the characterisation was to understand the material which was utilised during 2nd

World War and the material of the replacement components in Tiger 1 for a comparative study in terms of material analysis.

Materials' characterisations were obtained using PANalytical Axios wavelength dispersive x-ray fluorescence spectrometer (WDXRF). The measurements were processed using PANalytical's Omnian standardless software. Figure 1 shows spectra results of Si detection in original piston, cylinder-liner and replacement piston.

Wavelength dispersive x-ray fluorescence spectrometry is an elemental analysis technique capable of determining the elemental content of various materials including metals, oils, plastics and a variety of powder materials.

2.3 Optical Microscopy and White Light Interferometry

Optical microscopy was conducted for surface analysis. Surface roughness profile and three dimensional defect measurements were conducted through white light interferometry. Results from these analyses are provided with the images and are also discussed in the discussion section.

3. Results and Discussion

3.1 Pistons Design

The original piston (130P15) is shown in Figure 2. The original design for the piston was completely circular with two compression rings and two secondary compression/oil scraper rings. There were also two additional scraper rings at the bottom of the piston.

The design of the replacement piston has been modified as shown in Figure 3. First the fourth compression/scraper ring was omitted. Secondly, an additional rectangular profile was included at both ends of the piston-pin, and lastly, the bottom oil scraper rings were excluded. The modifications in design and the material's chemical characteristics of the replacement piston resulted in catastrophic failures within the piston-liner interface after only two hours of operation.

3.2 Characterisation of pistons

Original piston characterisation results are shown in Table 1 and approximately match specifications of RSA-419 AE aluminium super alloy (Table 2) also comparable to AA 4019 and AA 4048 aluminium alloy. Si percentage is 19.92 and results indicate that the original piston is hyper-eutectic Al-Si alloy. The classification of Al-Si alloy in three categories (a) hypoeutectic less than 11% Si (b) eutectic 11-13% Si and (c) hyper-eutectic with more than 13% Si has been well reported (Tutunchilar (11), Mondolfo *(12)*). Al-Si pistons provide low density, high wear resistance, good strength-to-weight ratio, good thermal conductivity and resistance to corrosion and wear in petrol engines of industrial, aerospace and military applications (Wang *(13)*,Yasmin *(14)*). Petrol engines operate under severe conditions of high temperatures and gas pressure and therefore for piston material it is necessary to have excellent temperature and mechanical properties in-order to resist changes influenced by elevated temperatures. Other elements such as Ni, Fe, Ti and Mn detected in the characterisation are added for the purpose of improving the tensile properties and strengthening of α-Al matrix (Wang *(13)*, Li *(15)*, Du *(16)*, Manasijevic *(17)*).

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The exact duration of the operation of the Tiger 1 engine is unknown. However the signs of wear in both piston and liner are negligible compared to the aggressive environment in which they were operated. The performance of the original piston and cylinder-liner can be attributed to the better material compositions which resulted in better mechanical properties and therefore marginal wear was noticed.

Replacement piston shown in Figure 3 and liner which were installed in the engine and operated only for two hours suffered severe failures. Table 1 illustrates the characterisation results of the replacement piston which approximately satisfy the specification of Al 2031 and Al 2618-T6 series. According to the results the replacement piston can be classified as hypo-eutectic piston. Eutectic and hyper-eutectic versions possess better materials' properties and perform better than hypo-eutectic pistons (Tutunchilar *(11)*, Mondolfo *(12)*).

The percentage of Si is significantly low at only 0.73 %. Silicon is a very important part of Al-Si piston alloys and hard Si precipitants within the aluminium matrix are directly related to greater strength, scuff, seizure resistance and provide better resistance to sudden temperature fluctuations (Corniani *(18)*, Dienwiebel *(19)*). The major cause of the failure of the replacement piston was thermal expansion causing less/no clearance. Figure 4 illustrates wear both at the replacement piston and cylinder-liner.

3.3 Characterisation of cylinder-liners

Material characterisation of both original and replacement cylinder liners were conducted and results are provided in Table 3. Results of the original cylinder-liner approximately meet the specifications of UNS F33100 (Table 4) and is comparable to SAE J431, BS 220 and UNS F34100. Fe is the main element present, so indicating that the liner is of cast iron. The source of elements such as Zn, Ca and S is likely to be a residue of lubricating oil. Characterisations of the replacement cylinder-liner revealed Fe and Si as the main elements.

Phosphorus (P) was detected in the original-liner but not in the replacement liner. P content generates better properties for wear and scuffing resistance. In addition alloying elements such as chromium (Cr), copper (Cu), molybdenum (Mo), nickel (Ni), titanium (Ti) and vanadium (V) enhances wear resistance when added (Taylor and Eyre (6)).

3.4 Wear Analysis

The replacement pistons' design was modified as shown in Figure 3. The replacement pistons did not consist of lower oil scraper rings. In addition at the pin bore ends a rectangular profile was built into them as opposed to the original design illustrated in Figure 2. The replacement piston has a very low Si (0.73 wt %) content. Si produces good thermal and wear characteristics. One of the major reasons of the replacement piston failure was its susceptibility to thermal expansion under the influence of temperature which resulted small/no piston-to-wall clearance. Piston expansion has lead to a direct contact between piston-skirt and cylinder-liner resulting in loss of surface integrity of the piston-skirt- thrust face. Material has been removed from both piston-skirt and cylinder-liner surfaces shown in Figures 3 and 4 respectively.

Friction in rolling and sliding contact can arise from asperity interlock, adhesion or abrasion by debris trapped between the contacting surface and viscous drag of the lubricant. When surfaces come into contact under loads welding occurs at the contacting asperities and during the relative motion shear develops due to high localised friction. The presence of any contaminants during the relative motion between the surfaces can strongly influence the shear strength. The resultant shear in one of the surfaces will cause transfer of material from one surface to the other (Scott *(4)*, Bisson *(20)*). Due to high localised friction fragmentation and tearing occur. This phenomenon of materials' removal from the surfaces was observed in the replacement piston and cylinder-liner.

The transfer of material between the surfaces has acted as an abrasive media further facilitating wear due to which scratches on the piston skirt and wear grooves in the cylinder-liner are visible in Figures 3 and 4 respectively. Furthermore the presence of the material particles between the sliding surfaces lead to severe roughing or scuffing wear.

Scuffing is a complex tribological failure mechanism which is the result of severe surface damage when surfaces are in sliding contact, extreme surface roughening with or without materials transfer, solid-phase welding damage occurrence in sliding surfaces, breakdown of the lubricant film, materials properties and operating conditions (Lee *(21)*, Reddy *(22)*, Rohatgi *(23)*, Ye *(24)*, Menezes *(25)*). Severe roughening of the piston-skirt is shown in Figure 4 (a) and (b). Scuffing in this scenario is a result of thermo-elastic instability of the piston material, sudden rise in friction, contact temperature and vibration. This has lead to extreme roughening of piston-skirt-thrust-face and caused the entire piston-liner assembly to fail (Ajayi *(26)*, Zheng *(27)*).

In Figure 4 (c) and (d) of the replacement cylinder-liner formation of ploughing is visible due to plastically displaced material. Repeated unidirectional sliding contact between surfaces and the hard asperities plastically displaces material sideways; material displacement in this way is known as ploughing. The displaced material in this case is subjected to strain during sliding contact and when the strain exceeds a critical value material ruptures and formation of the debris

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starts (Xie *(28)*, Johnson *(29)*, Kato *(30)*). Debris build-up at the cylinder-liner surface can be observed in Figure 6 (a).The deposited wear particles between sliding contact of piston and cylinder-liner has lead to scuffing. Furthermore high tendency of adhesion was observed on the piston-skirt as illustrated in Figure 4 (a) (Wang *(31)*).

Figure 5 (a) shows the appearance of localised junctions/ micro-welds. The formed junctions were strong and therefore significant wear took place between piston and liner leading to a substantial amount of debris particles formation. During contact between piston-skirt and cylinder-liner the accumulated debris have indented the surfaces causing accelerated wear (Gang Xu (32)). Figure 5 (b) shows average surface roughness of 9.09 µm on an area of length 0.58 mm and width 0.43 mm respectively. This is significantly higher when considering friction co-efficient and its implication on frictional heat and wear.

Figure 6 (a) is the optical micrograph of the cylinder-liner surface which shows formation of wear particles and grooves. White light interferometry was conducted to obtain the surface prolife of the cylinder-liner in Figure 6 (b) groove formed because of ploughing is shown with a width of 0.23 mm. The depth of the groove shown in Figure 6 (c) was 21.76 µm whereas in Figure 6 (d) a 3D surface profile of the groove is shown. Average roughness recorded at the groove Figure 6 (d) was 5.78 µm at an area of length 0.58 mm and width 0.43 mm. the formation of debris illustrated in Figure 6 (a) and high surface roughness will further induces stresses. The build-up of residual stresses in/or near the vicinity or in the shallow depth shown in Figure 6 (d) will significantly amplify tribological failures (Warhadpande et al *(33)*).

4. Conclusions

This research work has successfully analysed the material characterisation and wear mechanisms in the piston and cylinder-liner operated in an original Tiger 1 engine through state-of-the-art techniques. Original piston which was designed before/during 2nd World War had enhanced tribological properties. Original piston operated for longer hours under extreme working conditions in the WW2 and has shown excellent resistance towards tribological failures. Nonetheless the replacement piston which was manufactured recently and operated just for two hours under normal working conditions failed catastrophically. Material composition of the new piston was the major reason because of its inability to thermal expansion and did not show good potential for tribological applications. Pistons performance in both cases is attributed to the materials composition Therefore components of a better suited material, based on its composition, will be exploited in order to reduce maintenance costs associated with tribological wear. The Tank Museum has been advised to consider superior quality materials for replacement components.

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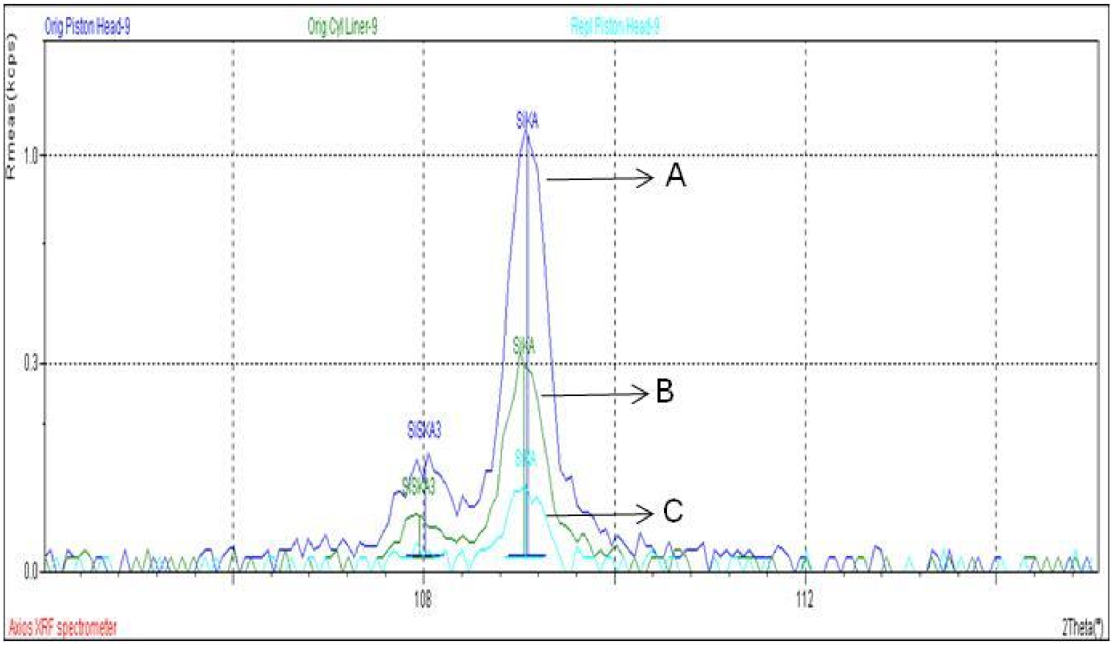

Figure 1 Tiger 1 Spectra results of Si in original piston-liner (A), original cylinder-liner (B) and replacement piston (C)

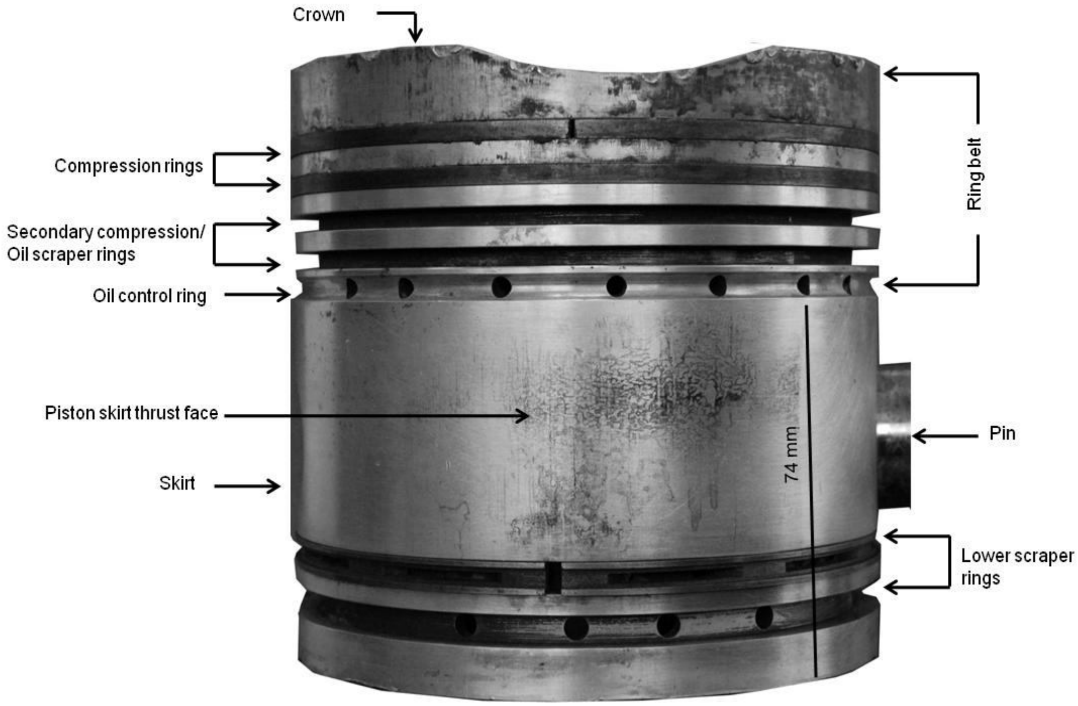

Figure 2 Tiger 1 original pistons (130P15) – Marginal wear

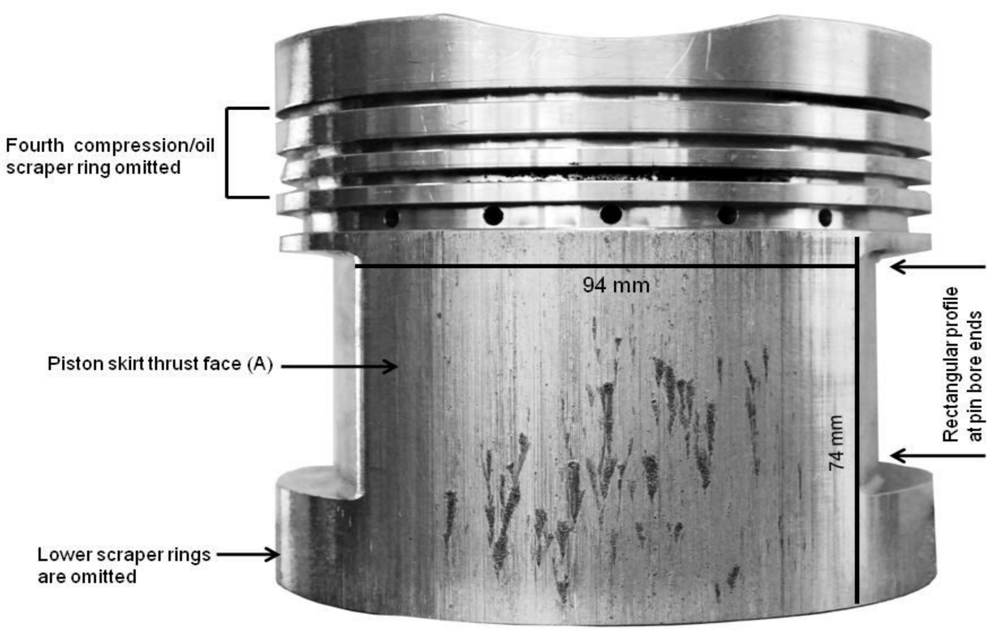

Figure 3 Tiger 1 replacement piston severe scuffing after 2 hours of operation

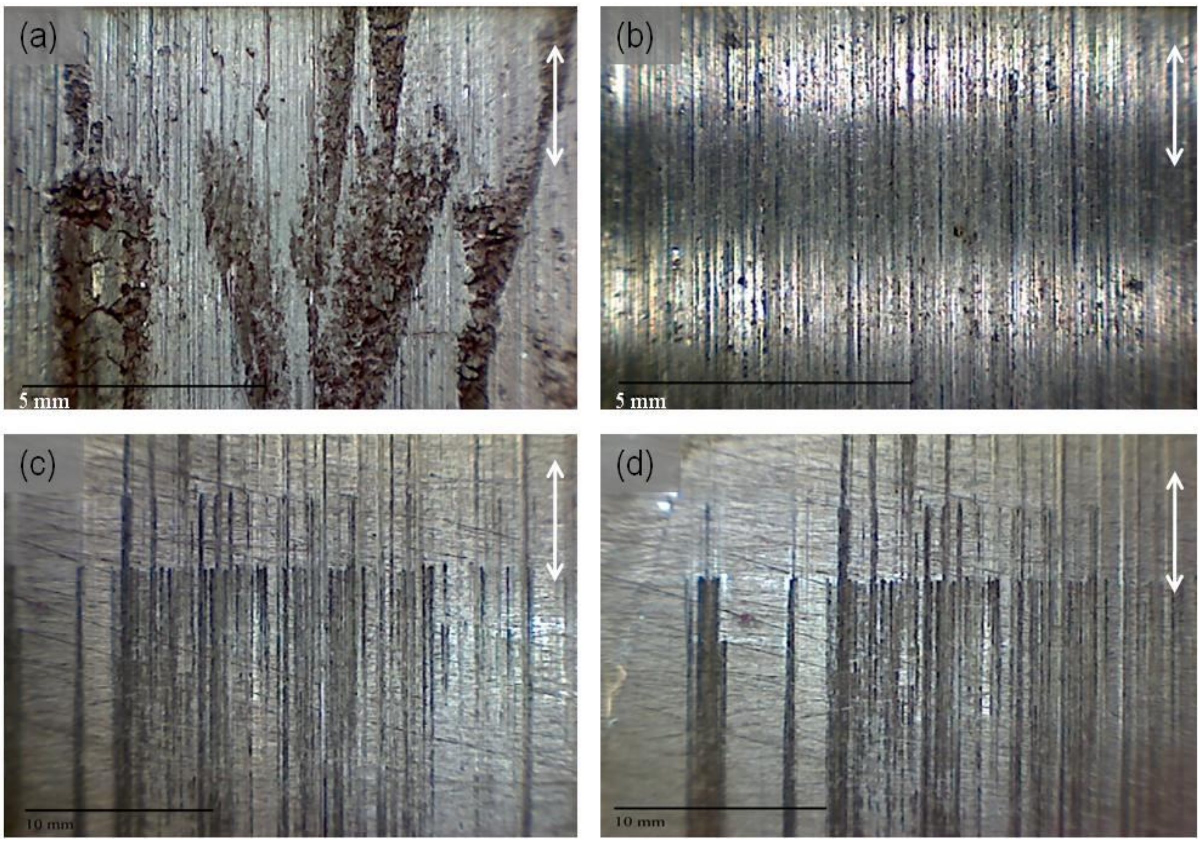

Figure 4 Tiger 1 Arrows indicate the direction of the reciprocating motion (a) replacement piston skirt thrust face - A showing adhesion (b) replacement piston thrust face - B initiation of wear (c) & (d) replacement cylinder-liner wear by ploughing

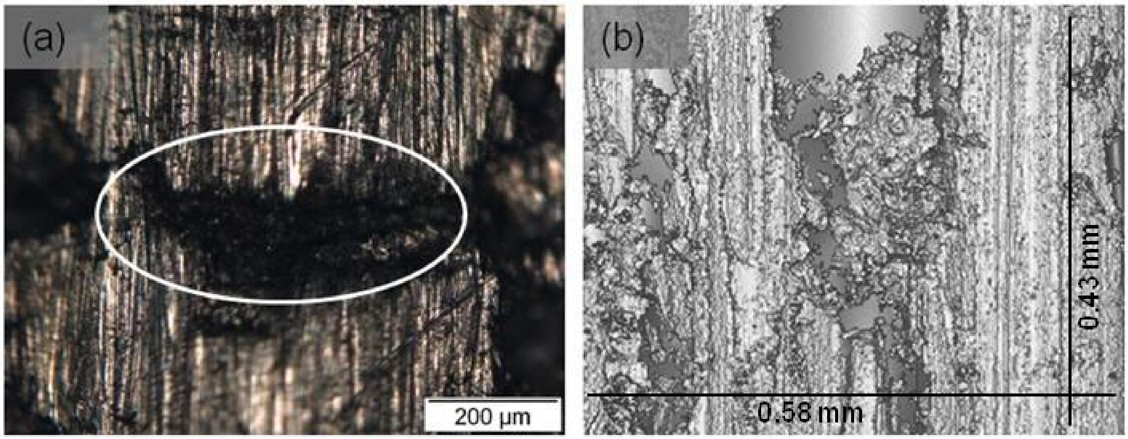

Figure 5 Tiger 1 Replacement piston (a) Surface topography (b) white light interferometry showing surface roughness profile

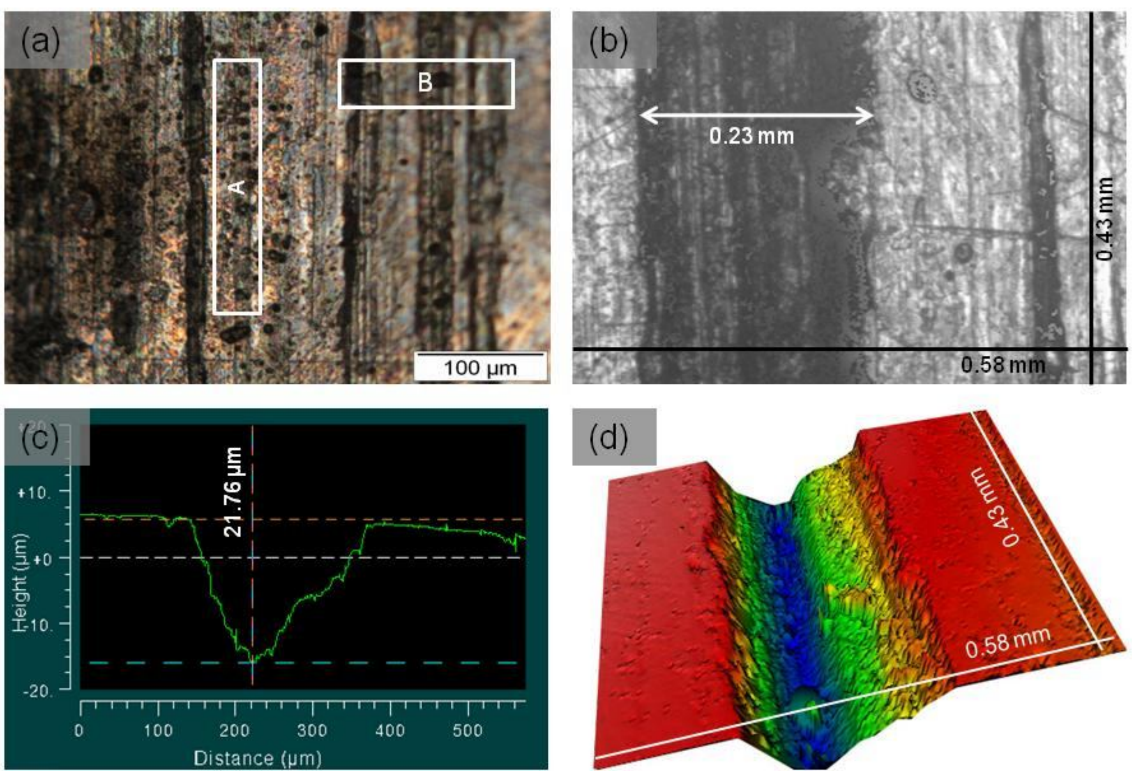

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Figure 6 Tiger 1 Replacement cylinder-liner (a) Surface topography (A) illustrates debris formation (B) shows formation of grooves (b) Groove width (0.23 mm) (c) Groove Depth (21.76 µm) (d) 3D view of the same groove

Table 1 Tiger 1 Original and replacement pistons characterisation (results in wt %)

Elements	Original Piston	Replacement piston
Al	72.81	92.39
Si	19.92	0.73
Cu	1.76	2.52
Fe	1.69	1.24
Ni	1.52	1.13
Mg	0.64	1.66
Cl	0.41	0.00
S	0.35	0.04
Na	0.20	0.00
K	0.18	0.00
Mn	0.08	0.06
Ti	0.09	0.05
Zn	0.06	0.04

Table 2 RSA-419 AE Aluminium Super Alloy [courtesy RSP Technology]

Physical Properties	**Metric**	**English**
Density	**2.75 g/cc**	**0.0994 lb/in³**
Mechanical Properties	**Metric**	**English**
Hardness, Brinell	140	140
Tensile Strength, Ultimate	420 MPa	60900 psi
Tensile Strength, Yield	320 MPa	46400 psi
Elongation at Yield	0.02	0.02
Tensile Modulus	90.2 GPa	13100 ksi
Thermal Properties	**Metric**	**English**
CTE, linear	16.8 µm/m-°C	9.33 µin/in-°F

Thermal Conductivity	120 W/m-K	833 BTU-in/hr-ft²-°F
Component Elements Properties	Metric	English
Aluminium, Al	0.73	0.73
Iron, Fe	0.05	0.05
Nickel, Ni	0.02	0.02
Silicon, Si	20.00%	20.00%
Descriptive Properties		
Specific Stiffness	33	

Table 3 Tiger 1 Material characterisation of original and replacement liners (results in wt %)

Elements	Original liner	Replacement liner
Fe	92.22	95.61
Si	2.75	2.30
Mn	0.47	0.58
Al	0.42	0.00
Mg	0.17	0.00

Mo	0.00	0.47
Cr	0.18	0.10
Cu	0.28	0.00
Ni	0.23	0.91
Ti	0.07	0.00
V	0.05	0.00
Ca	0.37	0.00
P	0.42	0.00
Cl	0.08	0.00
S	0.18	0.00
Zn	2.00	0.00
Pb	0.04	0.00

Table 4 UNS F33100 Cast Iron [courtesy RSP Technology]

Mechanical Properties	**Metric**	**English**
Hardness, Brinell	156 - 217	156 - 217
Tensile Strength, Ultimate	448 MPa	65000 psi
Tensile Strength, Yield	310 MPa	45000 psi
Elongation at Break	12%	12%
Component Elements Properties	**Metric**	**English**
Carbon, C	3.20 - 4.10 %	3.20 - 4.10 %
Iron, Fe	>= 91.765 %	>= 91.765 %
Manganese, Mn	0.10 - 1.0 %	0.10 - 1.0 %
Phosphorous, P	0.015 - 0.10 %	0.015 - 0.10 %
Silicon, Si	1.80 - 3.0 %	1.80 - 3.0 %
Sulfur, S	0.0050 - 0.035 %	0.0050 - 0.035 %