ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

REMANUFACTURING OF CYLINDER BLOCKS BY PTWA THERMAL SPRAY COATING APPLICATION

M.Sc. THESIS

Osman Arda GÖÇMEN

Department of Mechanical Engineering

Materials and Manufacture Graduate Program

JUNE 2013

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Thesis Advisor: Assoc.Prof. Dr. Turgut GÜLMEZ

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

MOTOR BLOKLARININ PTWA TERMAL KAPLAMA UYGULAMASI İLE REKTİFİYESİ

YÜKSEK LİSANS TEZİ

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HAZİRAN 2013

Osman Arda Göçmen, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID **503091338**, successfully defended the **thesis** entitled "**Remanufacturing of Cylinder Blocks by PTWA Thermal Spray Coating Application**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Assoc.Prof. Dr. Turgut GÜLMEZ** İstanbul Technical University	....
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Date of Submission : 03 May 2013
Date of Defense : 14 June 2013

Dedicated to my beloved wife,

FOREWORD

This thesis is written as completion to materials and manufacture graduate program, at Istanbul Technical University, under the teaching supervision of Dr. Turgut Gülmez.
I owe my deepest gratitude to those who made this thesis possible; their support has brought this work to the appreciable existence. I therefore would like to thank my supervisor and my colleagues in Ford Otosan and Ford Motor Company for their support and cooperation. I would also like to thank my advisor, Dr. Turgut Gülmez, for his valuable insights and directions, Gehring, GTV and Sinerji Metal, of being so supportive with thermal spray coating application and of course to my family who helped and supported me throughout the years. I thank my wife for her big love and invaluable support.

May 2013

Osman Arda GÖÇMEN
(Mechanical Engineer)

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ABBREVIATIONS

Al	**:** Aluminum
AlSi	**:** Aluminum Silicon
APS	**:** Atmospherical Plasma Spray
BDC	**:** Bottom Dead Center
BHN	**:** Brinell Hardness Number
C	**:** Carbon
CGI	**:** Compacted Graphite Iron
CKS	**:** Chrome Ceramic Coating
Cr	**:** Chromium
Cu	**:** Copper
CO2	**:** Carbon dioxide
DC	**:** Direct Current
EGR	**:** Exhaust Gas Recirculation
EPS	**:** Expanded Poly Styrene
FCSD	**:** Ford Customer Service Division
Fe	**:** Iron
FeO	**:** Wuestite
HD	**:** Heavy Duty
HV	**:** Vickers Hardness
HVOF	**:** High Velocity Oxygen Fuel
Mn	**:** Manganese
Mo	**:** Molybdenum
OEM	**:** Original Equipment Manufacturer
Ni	**:** Nickel
PTWA	**:** Plasma Transferred Wire Arc
SEM	**:** Scanning Electron Microscopic
Si	**:** Silicon
TDC	**:** Top Dead Center
TWA	**:** Twin Wire Arc

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REMANUFACTURING OF CYLINDER BLOCKS BY PTWA THERMAL SPRAY COATING APPLICATION

SUMMARY

The scope of this thesis is investigation of Plasma Transferred Wire Arc (PTWA) sprayed coating application on cylinder bore wall for remanufacturing purposes. 0.8% C- steel is used as coating material. According to literature survey, 0.8% C-steel is commonly used for cylinder block remanufacturing . However it hasn’t been used for remanufacturing of heavy duty engine cylinder block before. On the other hand, there is no experiment in local market as well.

During the study, the effects of micro structure and mechanical properties of coating material on wear resistance, thus engine performance parameters are analyzed. The coating quality inclusing coating thickness, bond strength, porosity level and oxide content is investigated.

Thermal spraying is the process of melting or heat softening of a material, fragmenting and propelling the softened material in particulate form against a substrate. During thermal spraying process a feedstock, which can be a wire or powder is continuously fed into a heat source, where the material is being molten, respectively partially molten. The energy to heat the feedstock is supplied by electrical (plasma, arc) or chemical means (combustion flame). The particles are being further atomized and propelled onto a prepared substrate by a stream of compressed air or other gas. Due to the high kinetic energy the particles flatten when they impinge on the surface of the substrate; the heat transfer between the flattened particles and the substrate causes a rapid solidification.

When low carbon steel is used with the PTWA thermal spraying process and compressed air is used for the atomizing gas, the iron in the alloy react with the oxygen of the atomizing gas and forms FeO (Wuestite) a high temperature oxide, which, due to the high cooling rates is frozen at room temperature. Wuestite is a hard, self-lubricating oxide phase that is responsible for the excellent exhibited tribological properties of these Fe/FeO-coatings. These oxides are significantly harder than the iron matrix (430 HV0.3 compared to 260 HV 0.3; 0.1 C-steel as feedstock). Wuestite also works as a self lubricating material, similar to the graphite lamellas in grey cast iron.

Ford Motor Company was one of the early pioneers in the automobile industry implementing a thermal spray process for cylinder block coating. Ford’s patented plasma transferred wire arc (PTWA) process, is similar to the traditional arc spray process but instead of normal gas as the atomizing medium, plasma gas is used.

For remanufacturing the goal is to replace the worn material and have the repaired bore act similarly to the original surface so that the repaired block can be as good as new. Depending on the engine architecture engine blocks can be remanufactured by using oversize pistons or by re-linering. However, modern engines sometimes do not

permit these solutions due to the remaining bore bridge dimensions. Material research has led to lighter and stronger materials being available allowing much thinner wall sections. The overall dimensions of the engine blocks are reduce to such an extent that replaceable liners are not originally designed into the engine and the other standard remanufacturing processes of re-lining or machining the cylinder bore oversized are no longer possible due to the reduced bore bridge. Most of these engines have to be currently scraped and replaced with new engine blocks.On these and other engines it is now possible to salvage the worn engine block with the thermal spray process.

In thesis study, Selection of coating material and the wire material was the most critical item for the 9.0L block cylinder bores coating. The 0.8%C steel seems to be most applicable one since it is approved for Puma blocks and it has been successfully tested with various engines for remanufacturing purpose. On the other hand, it is known that it has cost advantage over other applicable materials. Hence, Ecotorq cylinder block was coated with 0.8% C-steel by using compressed air as atomizing gas to achieve hard oxide content to achieve bore – piston interaction at required tribology.

400 hours High Speed Test test was defined for the engines built coated blocks with 10W40 Castrol Oil. The reasons of selecting this test are ; a)Test data from previous test which had been performed with standard cylinder block was available for comparison, b) It is a recommended test to see wear of cylinder block and power conversion components including piston and rigs.

According to test results, there was no coating delamination observed. The performance parameters of engine in view of power-torque, oil consumption and blow-by were in specification defined for the Ecotorq 9L engine.

In conclusion, the test which has been performed during the thesis work proved that PTWA is a promising option to traditional cylinder block remanufacturing methods which have a lot of disadvantages mentioned in the study.

MOTOR BLOKLARININ PTWA TERMAL KAPLAMA UYGULAMASI İLE REKTİFİYESİ

ÖZET

Plazma iletimli kaplama (PTWA) ile silindir bloklarının rektifiyesi bu tezin konusunu oluşturmaktadır. Tez çalışması kapsamında 9L Ecotorq motor bloğu %0.8 C-çeliği ile kaplanmış ve Ford Otosan bünyesinde tanımlanmış, motor bloğu ve piston – segman sistemindeki aşınmalara karşı motoru inceleyen dinomometre testi ile kaplamanın işlevselliği doğrulanmıştır.

PTWA kaplama ile motor bloklarının rektifiyesi daha önce birçok firma tarafından çalışılmış ve uygulamaya konulmuştur. Ancak daha önce tez konusunu oluşturan yüksek güçteki kamyon motoruna yakın güçe sahip bir motorda uygulama bilinmemektedir. Ayrıca yine Türkiye'de daha önce PTWA'nın motor rektifiyesi üzerine herhangi bir güçteki motorda yapılan bir çalışma bilinmemektedir.

Tez kapsamında daha önce yapılan çalışmalar ışığında PTWA ile motor rektifiyesi amacı ile kullanılabilecek kaplama malzemeleri mikroyapı, mekanik özellikleri ve aşınma direnci bakımından incelenmiştir. Ayrıca PTWA ile uygulanan kaplamanın ana malzeme üzerine yapışma mekanizmaları ve yüzeyde oluşan boşluklar , oksit yapısının motor performansına ve dolayısı ile motorun aşınmasına etkileri incelenmiştir.

Isıl püskürtme, ince öğütülmüş metal, metal oksit veya plastikleri, ergimiş veya yarı ergimiş halde, uygun bir altyapı (esas metal) üzerinde, bir yapışma kaplama teşkil edecek şekilde yada yapısal şekil meydana getirecek biçimde püskürtülmesidir. Bu süreç daha sonra kullanılan enerji kaynağına göre tanımlanır: Yanma alevi, elektrik arkı, plasma veya patlatma; bu, iki temel malzeme şekline göre de katogorilere ayrılır: a) malzemenin başta ince öğütülmüş parçacıklar halinde olduğu toz ve b) tel veya çubuk olarak kullanılması. Toz veya tel şeklinde bulunan kaplama malzemesi çok yüksek bir ısı kaynağının içinden sevk edilirken ergimiş ya da yarı ergimiş hale gelirler; bu haldeki malzemeler bir altyapıya çarptıklarında yassılaşırlar ve ince plaket veya lamel haline gelerek yüzeyin herhangi bir düzensizliğine uyum gösterirler. Yüzey, bu iş için önceden pürüzlendirildiğinden, bu düzensizlikler, püskürtülen parçacıklara takılma yeri olurlar. Bu parçacıklar, bu kez, arkadan gelenlere takılma yeri teşkil ederler ki böylece bir yapışma meydana gelir. Bu mekanik bağlantı boyunca parçacıkların bazı nokta – nokta ergimesi ve bazı oksit – oksit bağlantısı oluşsa da esas bağlantı mekanizması mekaniktir. Yüzeydeki pürüzlülükler, sıvı halde püskürtülen partiküllerin katılaşma sürecinde gerilimlerin yoğunluk kazandıkları bölgelerdir. Bu gerilme noktaları yüzeye çarpan partiküllerin yüzeye tutunmasını sağlar.

Termal püskürtmeyle kaplama işleminin güvenilirliği kaplanacak metalin yüzeyinin iyi hazırlanması ile doğrudan bağlantılıdır. Yüzeyin hazırlanması en az prosesin ve

parametrelerin seçimi kadar önemlidir. Adesyon ve biraraya gelip yapı oluşturma, katılaşmış parçacıkların parça yüzeyine ve mekanik olarak bağlanmalarına bağlıdır.

PTWA kaplama üzerine yapılan önceki çalışmalar da kaplama ile ana metal arasında olması gereken minium 30 MPa bağ dayanımının elde edilmesi için yüzey hazırlama işlemlerinin önemini ortaya koymuştur. Çalışmalar kapsamında yüzey hazırlama metodu olarak; mekanik işleme yardımı ile pürüzlendirme, kumlama, su jeti ile yüzey hazırlama denenmiştir. Kumlama yöntemi motor bloklarında kalabilecek yabancı parçacıkların zararları göz önüne bulundurulduğundan vazgeçilmiştir. Su jeti yönteminden de özel ekipmalara ihtiyaç duyulduğundan ve dolayısı ile maliyeti arttırdığından vazgeçilmiştir. Mekanik işleme ile pürüzlendirme en iyi sonucu veren yöntem olarak öne çıkmaktadır. Ancak geleneksel işleme takımları ile yapılan pürüzlendirme tekrarlanabilirlik açısından yetersiz olduğundan gerekli bağ dayanımının elde edilememe riski barındırdığından seri üretim hatları için bu çözüm de yeterli bulunmamış Braunschweig Üniversitesi Makina Takımları ve İmalat Teknolojileri Enstitüsü bu amaçla "kırlangıç kuyruğu" adı verilen kesme takımlarını geliştirmiştir. Bu yöntem hem seri hatta uygulanabilirliği hem de 50 – 60 MPa civarında bir bağ dayanımı sağladığından kabul edilen bir yöntem haline gelmiştir.

Tez çalışması kapsamında kullanılan motor blokları uygun boyutta kesme takımı bulunmadığından geleneksel – seri hatta bulunan – takımlar ile mekanik olarak pürüzlendirilerek yüzey hazırlama işlemi tamamlanmıştır. Püskürtme gazı olarak hava seçilmiştir. Bunun sebebleri; daha once yapılan çalışmalar ışığında püskürtme gazı olarak hava kullanılması sonucunda kaplama malzemesi ve havanın yüksek sıcaklıkta kimyasal reaksiyon sonucu oluşan oksitlenmenin getirdiği avantajdır. Genel olarak da oksitler ana metalden daha serttirler ki bu da malzemenin aşınma direncini arttırmaktadır.

Motorlar blokları çalışmaya başladıkları ilk andan itibaren aşınmaya maruz kalırlar. Belirli bir sure sonunda motor bloklarındaki aşınmalar öyle bir noktaya ulaşırlar ki motor performansında düşüş, yağ tüketiminin artması gibi sorunlara neden olurlar. Bu nedenle aşınmış motor bloklarının değiştirilmesi veya rektifiye işlemi görmesi gerekmektedir. Yeni blokların kullanılması ekonomik olarak daha pahalı olduğundan çoğunlukla söz konusu motorlarda rektifiye işlemleri gerekmektedir. Diğer yandan yeni bir motorda bile diğer parçalarda gelebilecek bir problem silindirlerin kazınmasına ve motor bloğunun değiştirilmesi veya rektifiye görmesini zorunlu kılabilmektedir.

Geleneksel olarak motor bloklarının rektifiye işlemi, motor bloğunun işlenerek aşınmış yüzeyin ortadan kaldırılması ve bir üst ölçüde piston – segman sisteminin kullanılması olarak veya motor bloğunun işlenerek içerisine gömlek çakılması yöntemleri ile yapılmaktadır. Ancak günümüzde geliştirilen yüksek mukavemetli blok malzemelerinin yardımı ile ve günümüzde her geçen gün daha da önem kazanan motor ağırlığının düşürülmesi amacı ile silindir boşlukları ile su ceketi arasında olan mesafeler öyle bir seviyeye gelmiştir ki geleneksel yöntemler ile rektifiyesi mümkün olmamaktadır. Bu gibi durumlarda motor bloğunun değiştirilmesi gerekmetedir ki bu yöntem rektifiyeden daha maliyetli olmaktadır. Diğer taraftan gömlek çakılması ile yapılan rektifiye çalışmalarında işlem görmüş motorların yaklaşık yüzde kırkı işlemden gelen değişkenler sebebi ile tekrar hasara uğraması söz konusu olduğundan işlem parametrelerinin daha sıkı control edilebildiği ve daha fonksiyonel yöntemlere ihtiyaç duyulmaktadır. PTWA kaplama ile motor rektifiyesi bu soruna bir çözüm olarak görülmüş ve başarılı uygulamalar ile bir çok otomotiv şirketi tarafından kabul görmüştür. PTWA ile motor rektifiyesinin başarısı ardında silindir malzemesinden beklenen tribolojik özellikleri fazlası ile karşılamasından kaynaklanmaktadır.

PTWA kaplama ile motor rektifiyesi garanti kapsamında bulunan araçların hasar görmüş motor bloklarının rektifiyesinde de bir çözüm olarak karşımıza çıkmaktadır. Garanti kapsamında hasar gören motor blokları çoğu zaman yenisi ile değiştirilmektedir. Ancak motor bloğu üzerinde bulunan motor numarasının tekrar işlenmesi durumu da göz önüne alındığında PTWA kaplama ile motor rektifiyesi otomotiv şirketlerinin bu durum için garanti maliyetlerini yarı yarıya azaltacağı düşünülmektedir.

Tez çalışması kapsamında PTWA ile kaplanan bloklar belirlenen dinomometre testine tabi tutulmuş ve sonuçlar daha önce kaplamasız bloklar ile aynı testi koşan motorun sonuçları ile karşılaştırılmıştır. Test sonucunda blokta herhangi bir dökülme gözlenmemiştir. Motor performans parametreleri de kaplamasız blokla aynı testi koşan motor ile uyum göstermektedir. Test sırasında motor güç değerleri belirlenen spesifikasyonlar dahilinde olup önceki motora kıyaslandığında daha fazla güç elde edilmiştir. Yağ tüketimi önceki motora göre biraz artmış olmakla birlikte yine spesifikasyonlar dahilindedir. Yağ tüketiminin bir miktar artması kaplamanın porozlu yapısından kaynaklandığı düşünülmektedir. Silindirden krank yatağına geçen gaz miktarına bakıldığında ise önceki motora göre düşüş gözlenmiş olup, sebebinin daha pürüzsüz bir yüzey elde edilmesi sonucunda segmanların daha efektif çalışmasından kaynaklandığı düşünülmektedir. Test öncesi ve sonrası çap değerleri karşılaştırıldığında ise aşırı bir aşınma gözlemlenmemiştir.

Sonuç olarak bakıldığında PTWA kaplaması ile rektifiye Ecotorq motorları içinde uygulanabilir bir yöntem olma potansiyeli göstermekte olup, uygulamanın tam başarısının kanıtlanması için yol testleri de dahil olmak üzere diğer testlerin tamamlanması gerekmektedir. Türkiye’de bulunan bazı rektifiye firmaları PTWA hattının kurulumu açısından ön çalışmalara başlamış olması gelecekte bu yöntemin rektifiye amacı ile kullanılma ihtimalini arttırmaktadır.

1. INTRODUCTION

1.1 Cylinder Block Design Trends in Automotive Industry

The global market for new vehicles is set to grow from today's level of 71 million vehicles to 103 million by 2020. And according to Bosch market researchers and external experts, around 100 million of these vehicles will be fitted with a combustion engine. As a result, automotive technology that reduces fuel consumption and CO_2 emissions in gasoline and diesel engines is gaining importance [1].

The reduction of fuel consumption and pollution emissions, the improvement of the engine efficiency as well as the cost reduction in manufacturing and assembly are in the focus of actual research activities in the automotive industry. Most of these requirements can be fulfilled by a reduction of the total vehicle weight [2].

One component that has been modified significantly over the last ten years to achieve significant weight savings in a vehicle is the engine block [3]. Nowadays the mass proportion of the engine block on the total vehicle weight is in the range of 10 to 15 %. Therefore light-weight engine design offers a great potential for a successful mass reduction and finally fuel consumption [2].

Two of the most important material characteristics that are needed for the cylinder block surface are wear and scuffing resistance. In order for cylinder block to meet these functional requirements the engineering materials used to manufacture the product must possess high strength, modulus of elasticity, wear resistance, scuffing resistance, and corrosion resistance. The material of the cylinder block must be of a sufficient hardness to resist the wearing of the piston as it slides up and down on the cylinder wall [4].

Although cast iron is heavier than aluminium, it has been used as the material for engine blocks for over 100 years for many reasons. It has excellent tribological properties as well as good machining properties. Cast iron has excellent inherent scuff resistance due to its multiphase constituents consisting of a uniform distribution of iron and iron carbide phases throughout the material. Finally, the presence of graphite flakes provides the necessary scuff resistance during high temperature, high load, and heavy wear conditions when carbon based lubricants often break down [3].

Grey cast iron is now replaced more and more by AlSi-alloys. Crankcases made of those alloys weigh up to 50 percent less compared to those made of grey cast iron. The fact that most AlSi-alloys do not match the tribological requirements, especially in the contact area between the piston ring and the surface of the cylinder bore has to be considered as a disadvantage [5].

Due to the low wear resistance of hypoeutectic AlSi-alloys, the surface in this contact area has to be modified or replaced. Generally the material on the surface is replaced by pressed in or cast in cylinder liners made of grey cast iron. Grey cast iron has a sufficient hardness and the embedded graphite lamellas serve as a solid lubricant, especially in the bottom and top dead center where the piston speed is near zero (mixed friction).

However, these solutions present some problems:

- Cast-in grey cast iron liners show no metallic bonding between the liner material and the surrounding cast aluminium alloy, but only a mechanical contact. The quality of the mechanical bond depends on the casting conditions and the surface topography of the cast-in liner, a mechanical clamping with e.g. a suitably machined surfaces is advantageous.
- The size of the always existing gap between the grey cast iron liner and the surrounding casting alloy may be optimized by a subsequent heat treatment. But the operation of the engine at high temperatures will still lead to a local variation of the heat transfer which is difficult to predict. The smallest gap between the liner and the engine block is achieved in combination with high pressure die casting, but also other casting processes are applicable. Nevertheless substantial development efforts and extensive thermal and stress calculations are necessary in the design phase of the engine block to avoid potential functional problems, in particular in long-term operation [6].
- The different thermal expansion coefficients of grey cast iron and aluminum can cause a deformation of the liner and also local heat transfer problems (heat pockets) if the liner disengages from the crank case. Particularly the deformation

of the liner leads to an increased oil and fuel consumption (blow-by) and increasing emissions [7].

In order to eliminate these kind of problems, there are four most promising alternative approaches for improving the tribological characteristics of aluminum cylinder bores include hypereutectic aluminum silicon alloy cylinder blocks, fiber or particle reinforced aluminum matrix composite cylinder blocks or liners, thermal spray coatings on the cylinder bore, or electrochemical deposited coatings on the cylinder bore [4].

Thermal spray coating is believed to be the best process for high volume production because it does not require the expensive machining associated with blocks made entirely of hypereutectic aluminum silicon alloys, and it does not involve some of the expensive steps associated with chemical plating processes or with the production and insertion of separate liners [8].

The PTWA (Plasma Transferred Wire Arc) process, as a thermal spray coating process, has a proven ability to help meet the goals for the automotive industry over the next years in a reduction in CO_2 emissions [7].

The PTWA (Plasma Transferred Wire Arc) spray technology is used in industrial applications for economical replacement of cast iron liners, which are pressed or casted as cylinder sleeve into aluminum cast engine blocks.

Characteristics of PTWA coatings for engine blocks:

- Weight reduction
- Improved efficiency of engines due to defined porosity coatings that provide an additional retention oil volume, especially in the highly loaded areas of top and bottom dead centers
- Reduced friction power
- Improved heat transfer from the cylinder wall into the cooling water circuit, cylinder surface temperature is reduced by up to 30°C
- Accordingly higher compression ratios can be realized without occurrence of glow ignition [9].

Thermal spray coating applications will be focus of this work and will be explained in details in following sections.

1.2 Potential Of PTWA Coating Application For Cylinder Block Remanufacturing

For remanufacturing the goal is to replace the worn material and have the repaired bore act similarly to the original surface so that the repaired block can be as good as new [7].

Depending on the engine architecture engine blocks can be remanufactured by using oversize pistons or by re-linering. However, modern engines sometimes do not permit these solutions due to the remaining bore bridge dimensions.

Material research has led to lighter and stronger materials being available allowing much thinner wall sections. The overall dimensions of the engine blocks are reduce to such an extent that replaceable liners are not originally designed into the engine and the other standard remanufacturing processes of re-lining or machining the cylinder bore oversized are no longer possible due to the reduced bore bridge. Most of these engines have to be currently scraped and replaced with new engine blocks.

On these and other engines it is now possible to salvage the worn engine block with the thermal spray process. Although the technology was originally developed to apply a wear resistant surface onto the cylinder bores of aluminium engine blocks, the same technology can be used to restore worn engine bores back to original dimensions.

A huge potential for reduction of CO_2 emissions is being offered by the usage of remanufactured spare parts. Previous studies have found that remanufactured components require 50 % to 80 % less energy to produce than their new manufactured equivalents [10].

1.3 Scope Of Thesis Work

With the scope of this thesis work, PTWA application on Ecotorq 9L cylinder block will be studied for remanufacturing purpose. In order to investigate potential of PTWA applications for remanufacturing, two cylinder blocks will be coated by PTWA process and will be tested to see the robustness of coating strength and wear resistance of coating material. Three different coating metarial will be tested.

Details of cylinder block design will be explained including manufacturing prosesses and material properties. Wear mechanism acting on cylinder bore surface and princibles of thermal spray coatings will be explained as well. Addition to these items, traditional cylinder block remanufacturing methods will be explained.

2. CYLINDER BLOCK

2.1 Functions of Cylinder Block

The cylinder block, also know as engine block, is the portion of the engine between the cylinder head and the oil pan and is the supporting structure for the entire engine. All the engine parts are mounted on it or in it and holds the parts in alignment. Large diameter holes in the block-castings form the cylinder bores required to guide the piston. The surface of these bores is commonly referred to as the cylinder walls. The cylinders are provided with a web or bulkhead to support the crankshaft and head attachments. The bulkhead is well ribbed to support the applied loads giving the block structural rigidity and beam stiffness. The cylinder block has separate passages for the flow of coolant and lubricating oil. Common features of a cylinder block are represented in Figure 2.1 below.

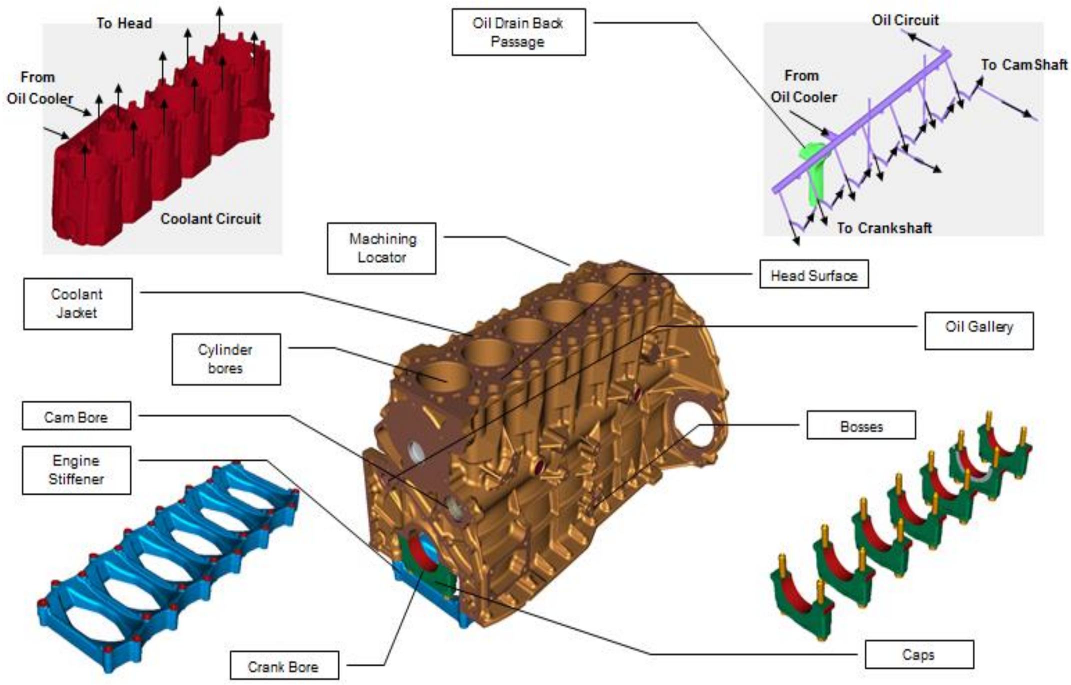


Figure 2.1 : Ecotorq 9L cylinder block features.

Internal combustion engine cylinder blocks must satisfy a number of functional requirements. Within the cylinder, the combustion process produces rapid and periodic rises in temperature and pressure, shear loading, and impingement of hot gases. The extreme pressure from the combustion process induces circumferential and longitudinal tensile stresses. The functional requirements include lasting the entire life of the vehicle, housing internal moving parts and fluids, ease of service and maintenance of internal components, and withstand pressures created by the combustion process. Cylinder block bore surface material must have high wear resistance and capable of withstanding high pressures on the order of 100 to 200 bar in engines with high peak firing pressures [4]. A summary of loads acted on cylinder block is represented in Figure 2.2 below.

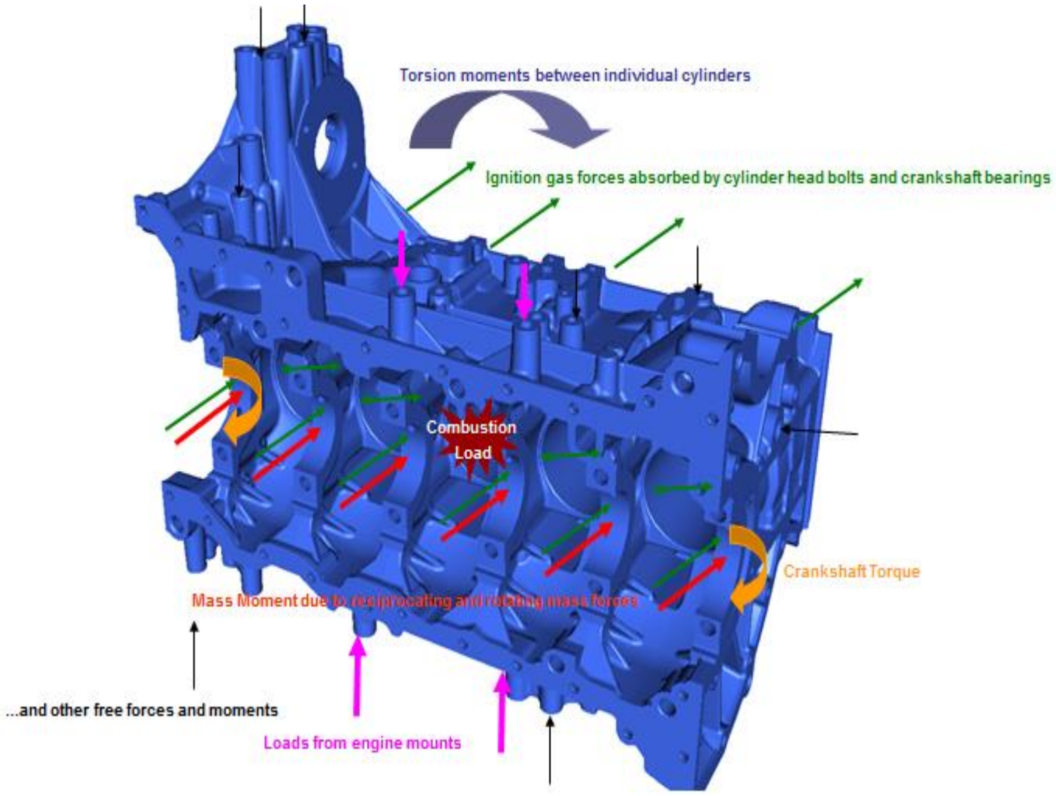


Figure 2.2 : Loads on cylinder block.

The primary functions that the engine block fulfills are;

- Absorbing the gas and mass forces in the crankshaft bearings and at the cylinder head bolts.
- Accepting the energy conversion assembly, comprising the pistons, conrods, crankshaft, and flywheel.
- Accepting and connecting the cylinders or, in the case of multisection engine blocks, connections to the individual cylinders or to the cylinder bank block or blocks.

- Carrying the crankshaft and (only rarely today) the camshaft.
- Accepting channels to convey operating media, primarily lubricants and coolant. Lubricants to supply the crankshaft bearings and conrod bearings, including the oil feeds and drains serving the cylinder head and in some cases serving as the mounting point for the spray nozzles used for oil cooling of the pistons.
- Transporting the coolant through cavities and channels contained in the engine block in liquid-cooled engines. This is also the mounting point for the coolant pump. Feed and drain channels guarantee that coolant reaches the cylinder head.
- Integrating a system for crankcase venting.
- Connecting to the transmission and to the valve actuators (with cover) and carrying and guiding power transmission elements such as chains
- Connecting to and mounting position for various auxiliary assemblies, such as the engine mounts, coolant preheating components, oil-to-water heat exchanger, oil filter, oil separator for crankcase venting, and a variety of sensors for oil pressure and temperature, crankshaft speed, knock detection, etc.
- Isolating the crankcase from the outside world with the oil pan and—by way of radial shaft seals—at the point where the crankshaft passes through the engine block [11].

The cylinder block is a complex part to cast because of the crankshaft/head bulkheads, bulkhead support ribs and the cooling passages. There are several different configurations for cylinder blocks. The two most widely used configurations are inline and v-banked cylinder blocks. A third configuration called horizontal opposed cylinder block is used more sparingly for production cars [4].

2.2 Cylinder Block Design

The types of engine blocks can be classified according to the engineering design in the areas at the;

- Top plate
- Main bearing pedestals
- Cylinders [11].

2.2.1 Top plate

2.2.1.1 Closed-deck designs

In this engine block construction, unlike the open deck construction, the cylinder deck is closed up to the water penetration openings on the side of the cylinder heads as shown in Figure 2.3. This is especially advantageous for the cylinder head sealing [12].

The top of the engine block is largely closed in the area around the cylinders. In the top plate there are always, depending upon the specifics of the design, openings for the cylinders, openings for the tapped holes for the cylinder head bolts, and bores and channels for oil feed and return (for coolant circulation and for crankcase venting) [11].

Figure 2.3 : Mercedes inline 4 cylinders closed-deck design [12].

The top plate is penetrated essentially only by the smaller openings of appropriate cross sections to allow for coolant passage. These openings join the water jacket surrounding the cylinders (with the water jacket inside the cylinder head) through specified channel cross sections in the head gasket and at openings in the cylinder head combustion chamber plate. This design suffers disadvantages regarding cylinder cooling in the TDC area.

Producing the engine block water jacket requires a sand core in the closed-deck version because the water jacket, in the upper area of the engine block, is largely sealed off by the top plate. Consequently, the water jacket cannot be created as a feature of the external casting mold for the engine block upper section; a core has to be inserted inside the casting mold. These bearing points are generally found in the finished engine block as casting "eyes" in the engine block side walls. The openings for the core inserts are closed off with sheet metal plugs. Once the engine is assembled, core insertion points such as this are an indication that it is a closed-deck engine block [11].

Also the use of sand cores makes the maintenance of smaller tolerances in the thickness of the cylinder walls more difficult. Closed deck engine blocks can be produced by gravity as well as low-pressure casting processes [12].

The advantage of the closed-deck design in comparison to the open-deck version is the greater stiffness of the top plate. This has positive effects on top plate deformation, cylinder warping, and acoustic properties [11].

2.2.1.2 Open-deck designs

In the open-deck version, the water jacket surrounding the cylinders is open at the top as shown in Figure 2.4. From the casting technology viewpoint, this means that no sand core and, thus, no core inserts are required to form the water jacket. The casting core for the water jacket requires no undercuts and may be made up as a steel mold.

The water jacket open at the top enables better cooling of the cylinder's hot upper section (compared to the closed-deck version).

There is less stiffness in the top plate of the open-deck design than that of the closed-deck version. A metallic head gasket is used to compensate for the increase in negative influence on the top plate by deformation resistance and cylinder warping. The metallic head gasket permits a lower preload value for the head bolts, thus reducing top plate deformation and cylinder warping.

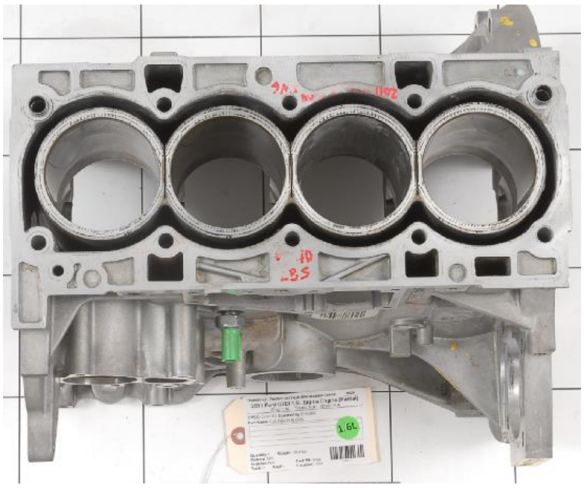


Figure 2.4 : Ford 1.6L sigma 4 cylinder inline open-deck design.

Manufacturing open-deck engine blocks enables the use of essentially all types of casting processes. In rare cases, gray iron cast engine blocks with an open-deck design are manufactured using a sand casting technique.

The open-deck design makes it possible to manufacture engine blocks from an Al-Si alloy using the economical die-casting process. Over and above this, it enables the realization of special techniques for the cylinders and cylinder sleeves [11].

2.2.2 Main bearing pedestal area

The main bearing pedestal area in engine blocks is the area around the crankshaft bearings. The engineering design for this area is of particular importance because the forces acting on the crankshaft bearings have to be taken up here.

The upper section of the crankshaft-bearing surface in the engine block is referred to as the main bearing pedestal as shown in Figure 2.5. Regardless of the engineering design of an engine block in the area around the crankshaft bearings, the main bearing pedestals are always a part of the casting for the engine block or for the upper section of the engine block.

In designing the main bearing caps, one distinguishes between individual main bearing caps, their integration into a longitudinal frame unit, and integration into the engine block lower section [11].

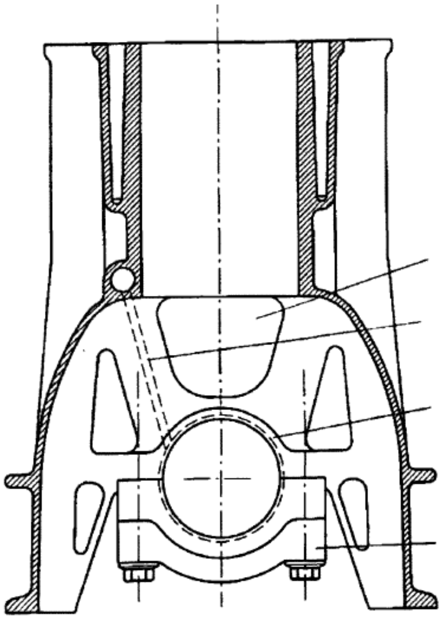
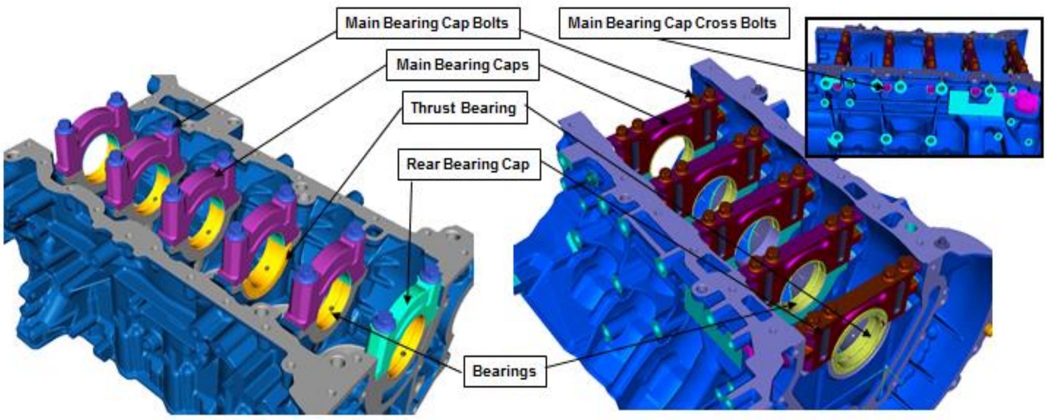


Figure 2.5 : Main bearing pedestal/main bearing cap [11].

2.2.2.1 Main bearing cap

The main bearing caps represent the lower boundary of the main bearing pedestals; the caps are affixed and bolted to the main bearing pedestals as shown in Figure 2.6. The main bearing caps and the main bearing pedestals have essentially the same function, i.e., absorbing the forces and torques imposed upon the crankshaft, accepting the corresponding bearings including the thrust bearing (collar bearing or thrust washers), as well as accepting a radial shaft sealing ring at the transmission output end, at the final main bearing, to seal the rear end of the crankshaft.



Figue 2.6 : Ford cylinder blocks with MBC design.

Main bearing caps are manufactured exclusively as gray castings and are combined with engine blocks made both of gray cast iron and of aluminum alloys. Working the aluminum main bearing pedestal and the gray cast bearing cap simultaneously is not without its difficulties because of the differences in ideal cutting speeds (specific to the materials). This is the procedure used in mass production today. The combination of an aluminum main bearing pedestal and a cast iron main bearing cap has advantages resulting from the gray cast iron: the low coefficient of thermal expansion in the main bearing cap made of gray cast iron limits the amount of play in the crankshaft bearings that develops during operation. This reduces the amount of oil that passes through the main crankshaft bearings. Reduced main bearing play and greater stiffness in the cast iron bearing cap (Young's modulus for gray cast iron is higher than that for aluminum) reduce noise generation and emissions in the area around the main bearing pedestals.

The version most widely used in mass production is the engine block made of gray casting with main bearing caps of the same material. The engine blocks are engineered either with the oil pan flange level with the center of the crankshaft or as an engine block with side walls or skirts that extend downward [11].

2.2.2.2 Bedplate concept

In this type of construction the main bearing cover of the crankshaft is included in a separate bedplate as shown in Figure 2.7. The bedplate is screwed to the cylinder crankcase and has sphero cast reinforcements anchored in the aluminium in order to control the main bearing clearance better or to compensate for the increased, specific thermal expansion of the aluminium. This produced extremely rigid engine block constructions. As with solid blocks, insert can be cast for the cylinder bore area here as well [12].

The split design in the form of a cylinder block top part and a bottom part called the bedplate satisfies higher demands on rigidity. The parting line is arranged at the level of the crankshaft axis. Especially in aluminum cylinder blocks, this design can be found relatively often, and it is frequently referred to as ‘’stiff bottom end’’. In its simplest form, the bedplate consists of a stiffening element similar to a ladder-shaped frame. In the main bearing area it assumes the function of conventional main bearing caps. To compensate for the coefficient of thermal expansion, which is twice as high as that of the crankshaft, reinforcements (inserts) are typically cast into that area, mostly made of spheroidal cast iron.

Figure 2.7 : Ford 1.8L lynx cylinder block with bedplate concept.

If the strength requirements are not extreme, bedplates are typically made by high-pressure die casting from a standard aluminum alloy. If a strength-increasing heat treatment is necessary, sand- or low-pressure die casting methods are applied in conjunction with higher-grade alloys. The latest developments in bedplates indicate that aluminum might be partly replaced by the even lighter magnesium [13].

2.2.3 Cylinder design

Both engineering and materials aspects have to be taken into account when designing the cylinder and the cylinder running surface. Both aspects are linked one with another. Taking the materials as the starting point, the designs for the cylinders and engine block may be subdivided as follows:

- Monolithic design
- Insert technology
- Bonding technology [11].

2.2.3.1 Monolithic design

Typical representatives for a monolithic (monometal) design are engine blocks made of cast iron alloys in which the cylinders are an integral part of the engine block. The required surface quality is achieved by machining in several steps, including preliminary and precision reaming and honing. Monolithic engine blocks made of Al-Si alloys are found in two versions:

a. Manufacturing the engine block casting from a hypereutectic Al-Si alloy. Al-Si alloys are deemed to be hypereutectic if their silicon content exceeds 12%. The primary silicon precipitated out in the cast component, following the machining of the engine block at the cylinder running surfaces, is exposed by a chemical etching process or with special mechanical honing. A hard, wear-resistant cylinder running surface (referred to as non-reinforced) is created; it has to be mated with an iron-plated piston.

b. Manufacturing the engine block from a hypoeutectic Al-Si alloy in combination with a finish for the cylinder running surface. The finish may be applied either by electroplating or with a thermal spatter process. In the meantime cylinder running surfaces that are remelted or plated using lasers are in the development phase [11].

2.2.3.2 Insert technology

Insertion techniques are normally used for cylinder sleeves in automotive engines in conjunction with aluminum engine blocks. Sleeves made of any of a variety of materials are inserted into the engine block in any of a number of ways. Following differentiation by function into wet and dry cylinders, one distinguishes whether the sleeve is cast in place, pressed in place, shrink fit, or slid in place in the engine block. Moreover, one may distinguish according to the material used for the sleeve, possibly cast iron or aluminum [11].

Wet cylinder

Wet cylinders as shown in Figure 2.8 are slid into the engine block, mating with mounting areas machined and prepared accordingly. The water jacket around the cylinder is formed between the engine block and the sleeve.

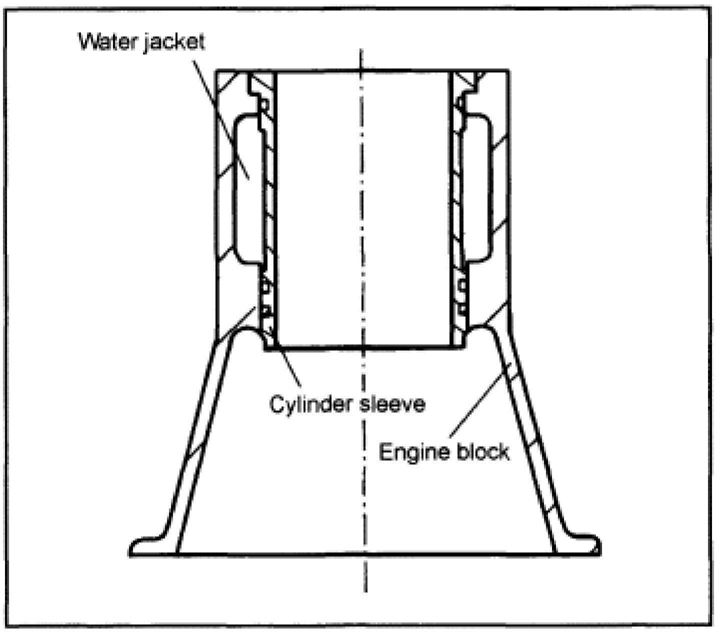


Figure 2.8 : Wet cylinder [11].

The hanging cylinder sleeve features a collar at its upper end; this collar is clamped between the engine block and the head gasket or cylinder head. The sleeve is centered in the engine block at the collar itself or at a diameter below the collar. Using the collar for centering offers the advantage of good cooling for the top end of the cylinder sleeve, which is subjected to severe thermal loading. The disadvantage is the heavy loading at the fillet in the engine block. Centering the sleeve at a point below the collar causes less satisfactory cooling at the upper end of the sleeve but does relieve this fillet. O rings are used at wet sleeves that are suspended from the top to seal against coolant at the top and against oil from the crankcase at the bottom.

In the standing wet cylinder, the support and centering functions are at the lower end of the sleeve. This sleeve concept requires particularly careful engineering to keep down cylinder deformation. Sealing is by the head gasket at the top and a flat gasket at the bottom below the sleeve support surface or by O rings. Misalignment of wet cylinder sleeves at the top plate, resulting in protrusion or depression, can be a problem. This has a negative effect both on the surface pressure applied by the head gasket around the cylinder and on cylinder deformation. Consequently, sleeve protrusion or depression can be reduced to the unavoidable minimum.

Inserting fully machined, wet cylinder sleeves into an engine block after the top plate has been finished is done by imposing extremely close tolerances on the relevant sleeve dimensions. When installing standing sleeves, shimming is a commonly used technique. A further option is final machining of the engine block top plate and the sleeves after the latter have been installed.

Wet sleeves, regardless of their design and material, can be used for both open-deck and closed-deck designs and can be combined with all casting processes that are normally used for engine blocks. They are given preference, for cost reasons, in die-cast engine blocks with open-deck design.

Wet aluminum sleeves are found almost exclusively in lightweight metal engines for sports cars or racing cars, where lower weight and better heat transfer are given preference over cost considerations.

Dry sleeves

Dry sleeves are pressed, shrink fit, or cast in place in the engine block as shown in Figure 2.9. When cast in place, the sleeves are inserted in the engine block mold, and the molten aluminum alloy is cast around them. In contrast to wet sleeves, the water jacket is not between the sleeve material and the engine block casting but, as in the monolithic design, is a component of the engine block casting. Consequently, no sealing is required between the sleeve and the engine block.

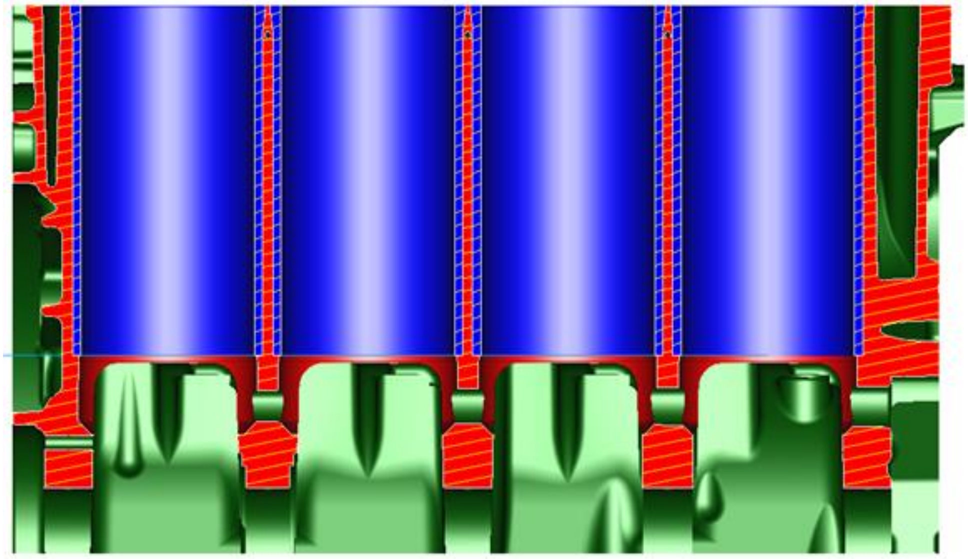


Figure 2.9 : Ford DV 1.6L cylinder block with cast-in liners.

Any protrusion of the dry sleeve—pressed or cast in place—in relation to the top plate level is corrected by machining the deck plate and the inserted sleeve together.

Dry sleeves may be made of either gray cast iron or (hypereutectic) aluminum alloys; sintered sleeves made of powdered metal materials are another option. The running surfaces for dry sleeves made of gray cast iron or aluminum are treated the same way as wet sleeves and, thus, exhibit the properties listed there. Dry sleeves, regardless of the material, may be used for both open-deck and closed-deck designs and can be combined with all the casting processes that are normally used for engine blocks. Aluminum engine blocks are found in mass production and are characterized by the closed-deck design, made in die casting or low-pressure casting, with gray cast iron cylinder sleeves pressed in place; also seen is the open-deck design made with pressure casting where gray cast iron sleeves are cast in place. The advantages of dry cylinder sleeves are freedom in the selection of the materials, the easy repair option (in the case of gray cast sleeves) by reaming out to oversize dimensions, separate manufacture (in aluminum sleeves) of the cylinder running surface, and the option for combining sleeves with an engine block made of a different aluminum alloy [11].

2.3 Casting Processes For Cylinder Blocks

Engine blocks for automotive engines are manufactured from cast iron or aluminum-silicon alloys. The costs, numbers produced, and engineering design are the main criteria applied when selecting the casting process.

2.3.1 Sand casting

Sand casting is the process traditionally used for engine blocks made of gray cast iron in mass production. Models and core boxes made of hardwood, metal, or plastic are used to replicate the later engine block casting inside the sand mold. The casting molds are normally made of quartz sand (either natural or synthetic sand) and binders (synthetic resin, CO_2). The sand is introduced, using "sand shooting machines," to make the cores. Combining individual cores to form a core package and assembling this core package and the outer casting mold is handled mechanically and fully automatically, even when producing only moderate numbers of castings.

Model, core, and mold parting in various planes, and inserting cores in the casting mold make it possible to produce complex cast components with undercut areas. During the casting process, the hollow cavities between the outside mold and the cores are filled with molten metal. Following the casting process and after the metal has solidified, the casting is removed from the sand mold. The mold is destroyed when doing so. The casting is then reworked to remove traces of the gating, sprues, casting skin, and flash.

The sand mold can be used to produce only a single casting [11]. A schematic of sand casting process is given in Figure 2.10.

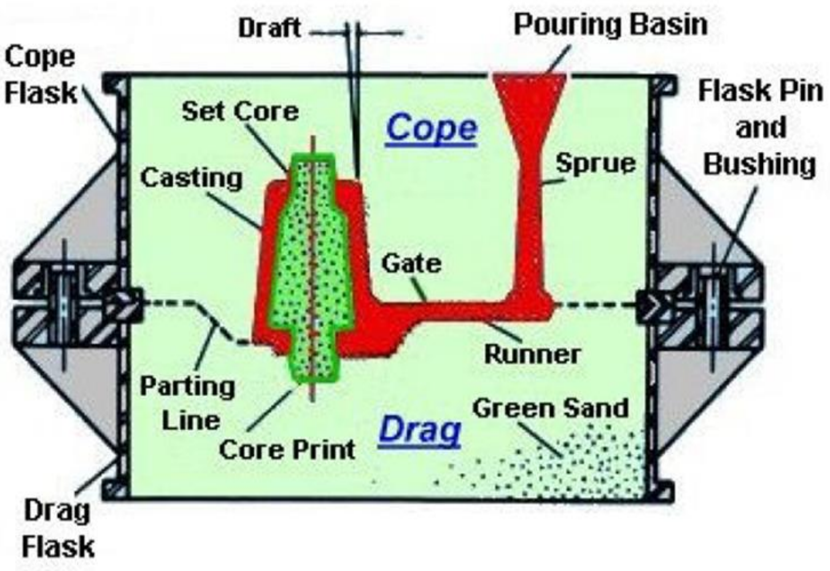


Figure 2.10 : Sand casting mold section [14].

2.3.2 Die casting

Permanent molds made of hardened hot-work steels are used in the pressure die-casting process. The sections of the mold have to be treated with a parting agent before each casting is made.

In contrast to sand casting, no cores can be inserted into the mold since the lightweight metal melt is introduced into the casting form at high pressure and high speed. The pressure level depends on the size of the casting and is between 400 bar and about 1000 bar. The pressure is maintained during solidification. In larger castings the two halves of the form are cooled, allowing a directional solidification of the cast component.

In contrast to sand casting, pressurized die casting provides the most precise reproduction of the hollow cavity in the mold and thus for the greatest precision in the cast component. Thin-walled castings with close dimensional tolerances, great exactness of shape, and superb surface quality can be fabricated. Casting eyes, holes, passages, and lettering to exact dimensions eliminates the need for subsequent machining and casting in place bushings such as the cylinder sleeves made of gray cast iron. Pressure die casting, when compared with sand casting or die casting, offers the highest productivity since almost all the casting and mold movement processes are fully automated.

The drawbacks are the limited engineering freedom for the cast component, since undercuts are not possible. Air or gas bubbles that might be trapped in the casting preclude double heat treatment, as for sand casting and die casting.

Engine blocks made of aluminum-silicon alloys, in particular with special cylinder sleeve technologies, are produced to an even greater extent in pressure die casting [11]. A schematic of die casting is given in Figure 2.11.

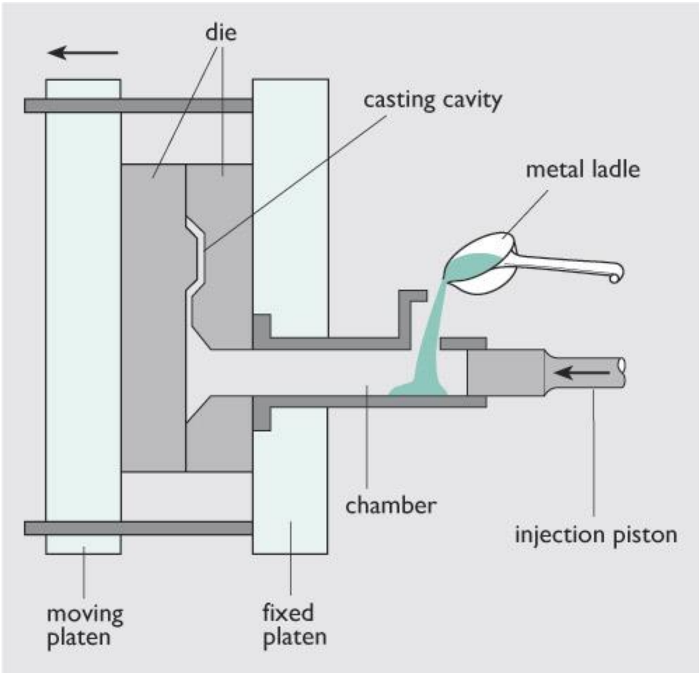


Figure 2.11 : Die casting mold section.

2.3.3 Lost foam casting

This is a special variation of the sand casting process. A plastic model is made of the piece to be cast, using EPS (expanded polystyrene), by foaming in place and, if necessary, by gluing individual segments together. The expanded polystyrene model is coated with a water-based parting agent. The model, coated and dry, is placed in a casting shell in which pure quartz sand (without any binders) is filled using vibratory compaction. In this fast casting procedure (taking 15 to 20 s), the molten metal is directed to the plastic model as a so-called full-mold casting. The heat in the molten metal degrades the plastic model: its liquid and gaseous components are absorbed by the casting sand. Following cooling and deforming a flash-free casting is obtained.

The particular advantages of this process are found in the capabilities for making up plastic models that replicate casting geometries not possible with conventional sand casting processes because of technical limitations on the latitude for mold fabrication.

The lost-foam process is suitable for making up both gray castings and lightweight metal alloy castings [11]. A schematic of lost foam casting is given in Figure 2.12.

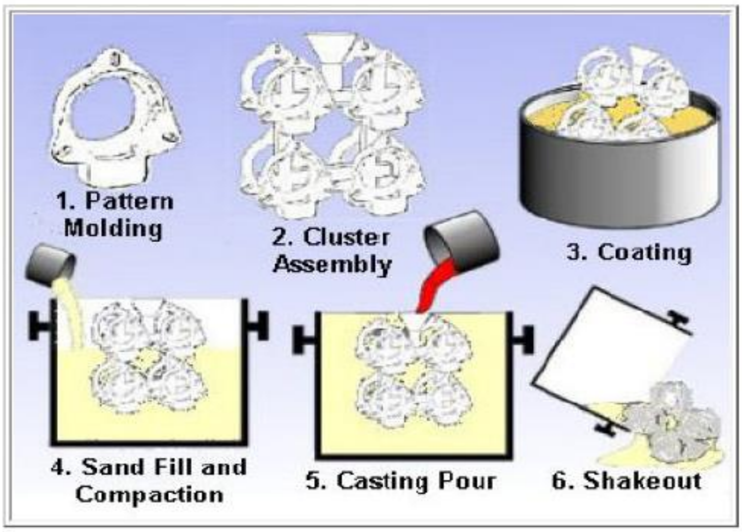


Figure 2.12 : Graphical description of lost foam casting [14].

2.4 Cylinder Block Materials

The primary demands on cylinder blocks for ensuring impeccable engine operation are as follows;

- High global an local rigidity
- Satisfactory strength and stability by proper design
- Cylinder bore surfaces with suitable tribological properties
- Sufficient heat dissipation [13].

In order for an engine block to meet the functional requirements mentioned before, the engineering material(s) used to manufacture the product must possess high strength, modulus of elasticity, abrasion resistance, and corrosion resistance. High strength is a particular concern in diesel engines, since compression ratios are normally 17.0:1 or higher (compared to about 10.0:1 for conventional engines). The material should also have a low density, thermal expansion (to resist expanding under high operating temperatures), and thermal conductivity (to prevent failure under high temperatures).

Good machinability and castability of the metal alloy are also important factors in selecting the proper material, as the harder it is to machine the product, the higher the costs of manufacturing. In addition to the previously mentioned properties, the alloys must possess good vibration damping to absorb the shuddering of the moving parts [14].

The material of the cylinder block must be of a sufficient hardness to resist the wearing of the piston as it slides up and down on the cylinder wall. Two of the most important material characteristics that are needed for the cylinder block surface are wear and scuffing resistance. Wear is erosion or displacement of material from its original position on a solid surface performed by the action of another surface. Scuffing is the phenomenon characterized by mass movement of surface elements to form linear scratches and local welds on surfaces in relative motion. Wear and scuffing occurs on the cylinder bore surface when the lubrication conditions deteriorate [4].

The Table 2.1 below defines key characteristics of cylinder block material must posses.

Table 2.1 : Cylinder block material characteristics [4].

Cylinder Block Material Characteristics	
High strength	Low density
High Modulus of Elasticity	Low thermal expansion
High wear resistance	Good machinability
High scuffing resistance	Good castability
High corrosion resistance	Good vibration dampening
High thermal conductivity	

2.4.1 Aluminium alloys

Aluminum alloy use has gained popularity since the 1960’s as a way to reduce the overall weight of the vehicle. There are two practical implications: improved performance-to-weight ratio and increased fuel efficiency. The drawbacks of using aluminum in engine blocks are that they are more expensive to manufacture than cast iron alloys. However, the strength-to-weight ratio of aluminum alloys is hard to ignore, and manufacturing processes developed throughout the years have minimized the cost disparity between aluminum and cast iron. There are two aluminum alloys that are mainly used in the manufacture of cylinder blocks: 319 and A356.

Aluminum alloy 319 has a composition of 85.8-91.5 wt.% aluminum, 5.5-6.5 wt.% silicon, 3-4 wt.% copper, 0.35 maximum wt.% nickel, maximum 0.25 wt.% titanium, maximum 0.5 wt.% manganese, maximum 1% iron, maximum 0.1 wt.% magnesium, and maximum 1 wt.% zinc. The alloy has good casting characteristics, corrosion resistance, and thermal conductivity. When heat treated with the T5 process, it possesses high strength and rigidity for engine block use.

Aluminum alloy A356 has a composition of 91.1-93.3 wt.% aluminum, 6.5-7.5 wt.%silicon, 0.25-0.45 wt.% magnesium, and maxima of 0.2 wt.% copper, 0.2 wt.% titanium, 0.2wt.% iron, and 0.1 wt.% zinc. Mechanical properties are similar to that of aluminum alloy 319. However, when heat treated with a T6 treatment, it possesses higher strength than 319 [14].

2.4.2 Magnesium alloys

Magnesium alloys have been used in engines before, but not for cylinder blocks. Rather, they were used as valve covers, cylinder head covers, intake manifolds, rocker arm covers, air intake adaptors, induction systems, and accessory drive brackets. The biggest attraction for manufacturers is that the material is much lighter than cast iron and aluminum alloys and has the same strength as cast iron and aluminum alloys. Material scientists and engineers were determined to exploit these characteristics of magnesium alloy and use it to fabricate engine blocks. There were a number of magnesium alloys available that met or exceeded the requirements demanded by manufacturers for an engine block, but insufficient material stability at high temperatures hindered their actual use. However, in 2003 material scientists and engineers from the Cooperative Research Center for Cast Metals Manufacturing and the Australian Magnesium Corporation presented their discovery of sand-cast magnesium alloy. This grade of magnesium alloy contains two rare earth elements, lanthanum and cerium, and was heat-treated with T6. This stabilizes the strength of the alloy at high engine operating temperatures, which is a necessary requirement for a cylinder block material. Other properties of the magnesium alloy include good thermal conductivity, excellent machining and casting qualities, and excellent damping characteristics [14].

2.4.3 Gray cast iron

Gray cast iron alloy have been the dominant metal that was used to manufacture conventional engine blocks. Though extensive use of aluminum alloys has diminished the popularity of this material, it still finds wide use in diesel-fueled blocks, where the internal stresses are much higher. Gray cast iron alloys typically contains 2.5-4 wt.% carbon and 1-3 wt.% silicon, 0.2-1.0 wt.% manganese, 0.02-0.25 wt.% sulfur, and 0.02-1.0 wt.% phosphorus. It has excellent damping capacity, good wear and temperature resistance, is easily machinable, and is inexpensive to produce. However, gray cast irons are relatively weak and are prone to fracture and deformation. Due to these problems, compacted graphite iron has recently begun to compete with gray cast iron as the choice material to produce diesel engine blocks [14].

Grey cast iron has excellent tribological properties due to its microstructure consisting of ferrite and lamellar graphite, the latter being a good dry lubricant. Grey cast iron liner can be pressed-in after pre-machining of the engine block [6].

2.4.4 Compacted graphite cast iron

Compacted graphite cast iron (CGI), which was accidentally discovered while trying to produce ductile cast iron, possesses higher tensile strength and elastic modulus than gray cast iron due to the compacted graphite found on the microstructure of CGI [14].

The material of cylinder block which is scope of this work is compacted graphite iron produced according to Ford internal material specification.

Peak combustion pressures in heavy duty truck applications are already exceeding 200 bar. At these operating levels, the strength, stiffness and fatigue properties of grey cast iron and the common aluminum alloys may not be sufficient to satisfy performance, packaging and durability criteria. Several automotive OEM’s have therefore evaluated Compacted Graphite Iron (CGI) for their petrol and diesel cylinder block and head applications.

As shown in Figure 2.13, the graphite in compacted graphite iron (sometimes referred to as vermicular iron) appears as individual ‘worm-shaped’ or vermicular particles. Although the particles are elongated and randomly oriented as in grey iron, the compacted graphite particles are shorter and thicker, and have rounded edges. While the compacted graphite particle shape may appear worm-like when viewed with a conventional light microscope, deep-etched SEM micrographs. Figure 2.14 shows that the ‘worms’ are connected to their nearest neighbours within the eutectic cell. This complex graphite morphology, together with the rounded edges and irregular bumpy surfaces, results in strong adhesion between the graphite and the iron matrix. Ultimately, the compacted graphite morphology inhibits both crack initiation and propagation and is the source of the improved mechanical properties relative to grey cast iron [15].

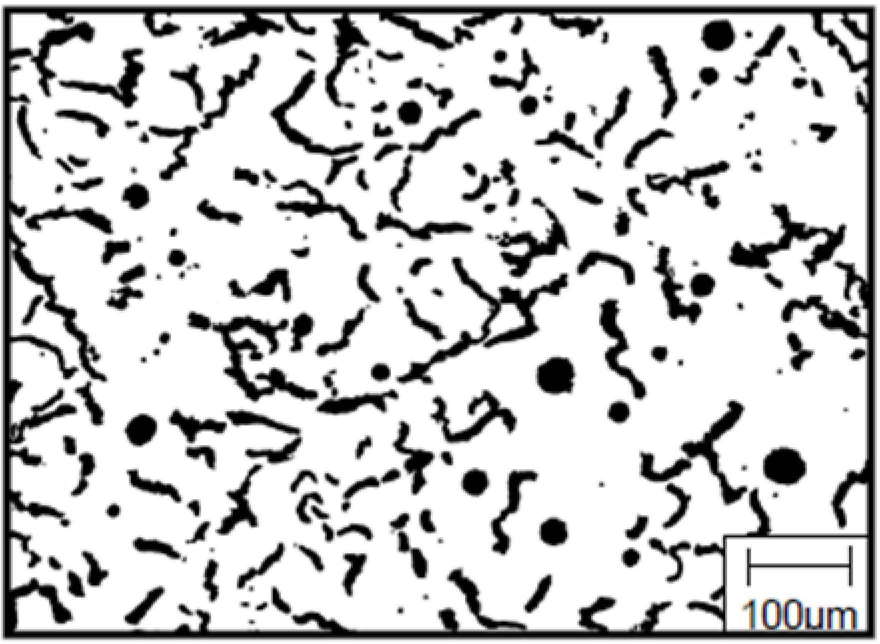


Figure 2.13 : CGI microstructure with 10% nodularity [15].

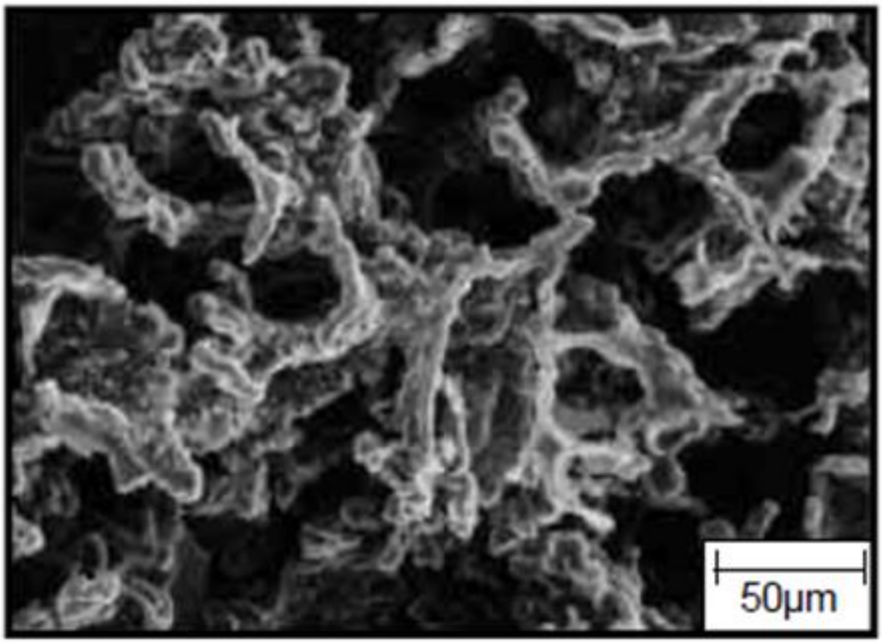


Figure 2.14 : Deep-etched micrograph shows graphite morphology [15].

The graphite shape, carbon content and pearlite content of cast irons each play an important role in determining the mechanical and physical properties of cast irons. While some material properties, such as Poisson's ratio or thermal expansion, are effectively constant over a wide range of microstructure and chemistry, the present study addresses the effect of microstructural changes on the properties of compacted graphite iron [15].

Fewer than 20% of the graphite particles should be in the spheroidal form to ensure optimal vibration damping, thermal conductivity, thin-wall castability and machinability. To ensure optimal mechanical strength, the microstructure must not contain any flake graphite. In comparison to grey iron, the compacted graphite particles are shorter, have rounded edges, and possess aspect ratios less than ten (aspect ratios for grey iron flakes typically range from 50 to 100).

The graphite network in conventional grey cast iron is dominated by randomly oriented and interconnected flakes which possess smooth surfaces and sharply pointed 'knife-edges'. The continuity of graphite provides good thermal conductivity, vibration damping, and machinability, however, the sharp edges of the flakes act as crack initiation sites. Once the cracks are initiated, the smooth flake surfaces provide a series of natural cleavage planes resulting in the low strength and brittle nature of grey cast iron. Similar to grey iron, compacted graphite particles are elongated and interconnected within eutectic cells thus providing similar thermal conductivity, vibration damping and machinability. However, in contrast to grey iron, the 'coral-like' shape of the compacted graphite particles, with rounded edges and roughened surfaces minimize the initiation and propagation of cracks. This unique graphite shape ultimately results in substantially increased tensile strength, fatigue strength and elastic modulus relative to grey cast iron [16].

The change in the ultimate tensile and the 0.2% yield strength of predominantly (85-100%) pearlitic cast irons as a function of nodularity is shown in Figure 2.15. While the strength gradually increases with increasing nodularity, the presence of even a small amount of flake graphite results in a step-reduction of 20-25% tensile strength.

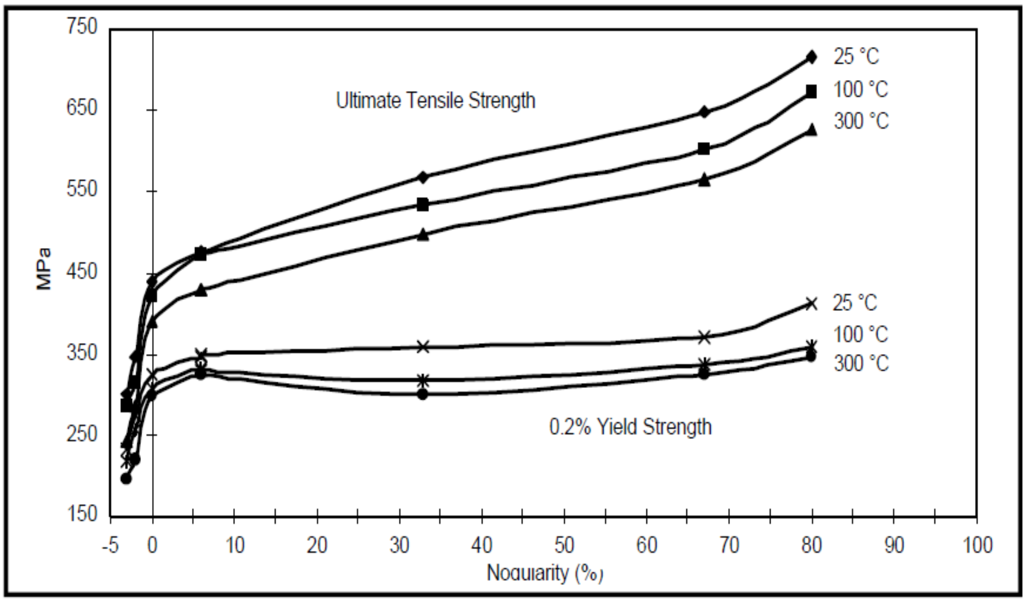


Figure 2.15 : Ultimate tensile strength and 0.2% yield strength of 85-100% pearlitic cast irons as a function of nodularity and temperature [15].

The graphite growth and carbon diffusion behavior during solidification of compacted graphite iron naturally favours the formation of ferritic rather than pearlitic matrices. Therefore, pearlite stabilizers such as copper and tin must be added to the base iron to ensure a predominantly pearlitic matrix. The solidification behavior of compacted graphite iron results in 10 to 15% higher hardness than grey cast iron when compared at equal pearlite contents. While a typical Brinell hardness range for fully pearlitic grey iron cylinder blocks may be BHN 179-223, fully pearlitic CGI cylinder blocks may range from BHN 192-255. Compacted graphite iron cylinder blocks containing approximately 70% pearlite have a similar hardness to fully pearlitic grey iron blocks. As shown in Figure 2.16, the hardness level of CGI increases linearly with increasing pearlite content. While this trend is certainly true, the slope and intercept of the linear correlation depend on the concentration of manganese, chromium, titanium and other trace elements in the raw materials as well as the casting shake-out time [15].

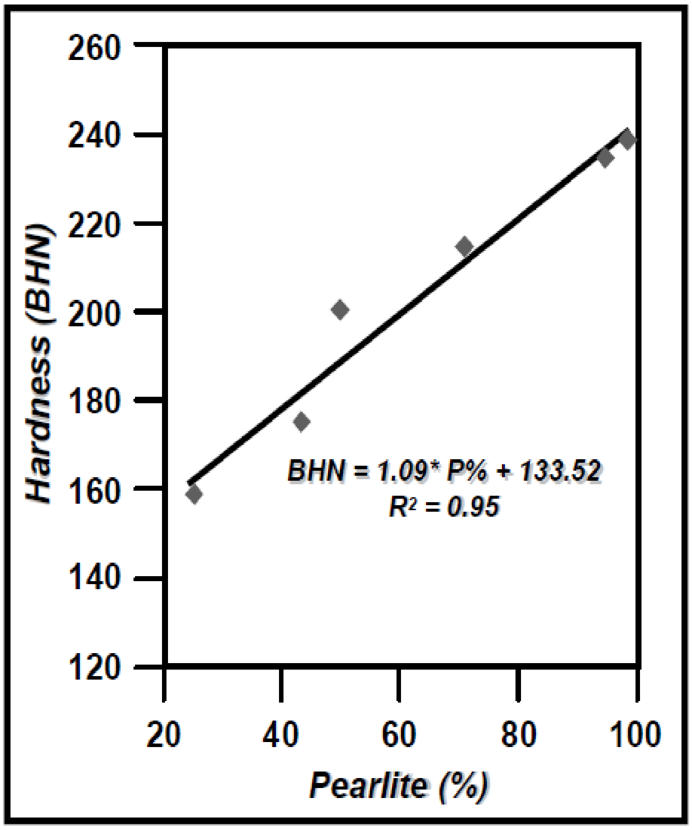


Figure 2.16 : Brinell hardness of unalloyed 0-10% nodularity CGI as a function of pearlite content [15].

3. CYLINDER BORE TRIBOLOGY

In an internal combustion engine, the tribological performance of the piston ring/engine cylinder bore system has long been recognized as important in achieving desired engine efficiency and durability in terms of power loss, fuel consumption, oil consumption, blowby, and even harmful exhaust emissions [17].

The piston ring/bore friction and wear are extremely important in that they seriously affect sealing and as a result affect oil consumption, emissions and fuel economy. The bore wear,in particular, is a primary engine life-limiting factor. Most of severe bore wear occurs at top ring reversal zone due to high ring/bore contact pressures combined with very low- near zero – piston speeds producing boundry friction condition. The cast iron bores are finish honed to produce special, oil retaining (oil – holding) surface texture. This oil retained in the surface texture dissipates frictional heat and prevent excessive wear. However, with accumulating engine operation time, the bore wear at the top rind reversal zone continues to occur and ultimately destroys the oil retaining texture. This further aggravates bore wear and oil consumtion and as a consequence, limits engine life. Incorporating low friction solid film lubricants that promote rapid oil film formation into the bore system and which tenaciously cling to the oil film should reduce the friction and wear significantly [18].

3.1 Tribological Principles

Tribology plays an important role in these processes. According to DIN 50323, "Tribology . . . [is] the science and technology of surfaces influencing one another in relative motion. It covers the total area of friction and wear, including lubrication, and includes appropriate boundary surface reciprocal effects both between solids and between solids and liquids or gases."

Here lubrication permits, improves, and ensures the function, profitability, and service life of the components and functional groups of the engine and the complete powertrain.

In the field of their interactions, tribological systems can be reduced to a basic structure (system elements) (DIN 50320): Basic surface, mating surface, intermediate substance (particles, fluids, gases), and ambient medium [11].

A schematic of tribological system is given in Figure 3.1.

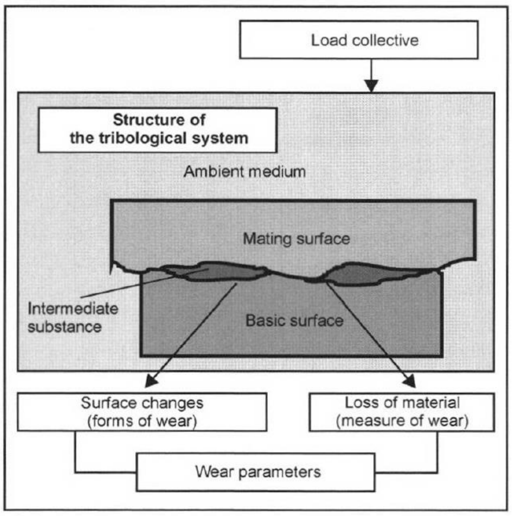


Figure 3.1 : Tribological system.

3.1.1 Friction

Friction is a complex phenomenon that is not easy to understand. It is ambiguous because it prevents movement as well as actually makes movement possible. There is no firm hold without friction—but also no movement away from the hold.

Friction is an interaction between material areas of bodies in mutual contact. It opposes their relative movement. In the case of external friction, the areas of the substance in contact belong to different bodies, in the case of internal friction they belong to one and the same body.

Friction depends both on the state of movement of the friction partners, adhesive friction (static friction, striction) and motional friction (dynamic friction), and on the type of relative movement of the friction partners.

- Sliding friction: Sliding, translation in the contact surface, relative movement of the sliding partners.
- Rolling friction: Rolling, rotation about an instantaneous axis in the contact surface.

- Combined sliding and rolling friction: Rolling with microscopic or macroscopic proportions of sliding.

Friction is also dependent on the condition of the substance areas involved:

- Dry friction.
- Fluid or viscous friction.
- Gas friction.
- Mixed friction.

In the engine, friction is undesirable because part of the mechanical energy already "generated" with poor efficiency is converted again into thermodynamically "lower valency" heat. By reducing the viscosity and load-bearing strength of the lubricant, this heat impairs the function of components. In extreme cases, damage can occur because of the bearings running warm or hot.

Dry friction is a result of several mechanisms:

- Adhesion and shearing: Formation and destruction of adhesive connections in the contact surfaces.
- Plastic deformation: Deformation due to relative tangential movement.
- Scoring: Sliding partners of different hardness, the rough peaks of the hard partner press into the surface of the soft partner and/or a hard particle between the sliding partners is pressed into the surface of one or both.
- Deformation: Elastic hysteresis and damping.
- Energy dissipation: Frictional energy (mechanical energy) is transformed into heat and is lost.

Static friction exists when a body is pressed onto its counterpart under the effect of a resulting force and adheres at rest. Static friction is the basis for the transmission of power between all parts of the engine permanently joined by bolts, clamps, or compression fits, such as crankcase and cylinder head, crankshaft and drive flange, or mounting bore and bearing. The critical coefficient of static friction μ_R for such connections depends on the material pairing, the surface condition, and the tribological conditions (lubrication); it is, therefore, a system property and not a material property.

In the case of sliding friction (friction of movement), fluid friction, in particular, is of the greatest relevance to engine technology; it presupposes lubrication. The relevant friction conditions for machine parts are represented in the Stribeck curve named after Richard Stribeck (1861–1950) as:

- Dry friction with direct metallic contact between the sliding partners.
- Boundary friction when the sliding partners are covered with traces of the lubricant.
- Mixed friction as a combination of dry and fluid friction when the lubricant film between the sliding partners is partially interrupted.
- Elastohydrodynamic lubrication: If high pressures exist between the sliding partners, the pressure in the oil film increases the viscosity of the oil. This is why - despite essentially unfavorable conditions- a sufficient minimum lubricant film thickness is obtained (for example, contraform contacts: gear pairs, cam/cam follower, etc.).
- Hydrodynamic lubrication: Fluid friction with complete separation of the sliding partners from one another by a lubricant film.

Losses because of friction are included in the mechanical efficiency. As the quotient of the effective power and the indicated power, the mechanical efficiency includes all the mechanical losses from the piston to the crankshaft flange. Furthermore, it also takes into account hydraulic losses (splash losses) and the drive powers of the ancillary machines necessary for operation of the engine [11].

The friction between the cylinder block bore material and the piston rings is the single biggest contributor to the loss of power in an internal combustion engine. Limiting this friction goes a long way in increasing the fuel efficiency of an automobile outside of reducing vehicle weight. Friction between the cylinder block surface and the piston rings has a major impact on the efficiency of an automobile’s powertrain. Friction accounts for a loss of over 40% of the total vehicle power. Over half of that power loss can be attributed to the frictional loss between piston rings and cylinder bores as shown in Figure 3.2 below [4].

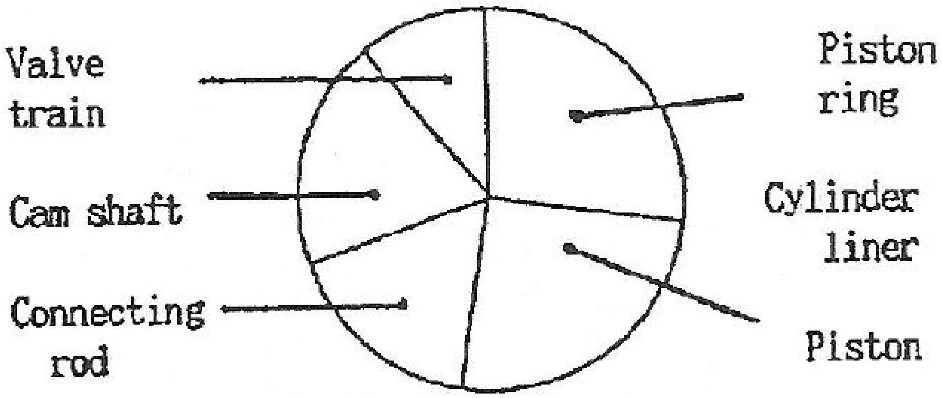


Figure 3.2 : Breakdown of friction loss for engine components [4].

3.1.2 Wear

"Wear is a progressive material loss from the surface of a solid body caused by mechanical effects, i.e. the contact and relative movement against a solid, liquid or gaseous counterpart" (DIN 50320). Wear impedes functions and shortens service lives, but, as part of the gradual use, it is unavoidable in the operation of any machine.

Wear occurs when two friction bodies (basic and mating surfaces) are moved relative to one another under the effect of force continuously, in oscillation, or intermittently. Here structural properties, strengths, hardness form, and surface geometry all have an influence on the wear. The wear process comprises several components that occur individually or in differing combinations with one another: Shearing, elastic and plastic deformations, as well as boundary surface processes. As a result, particles are released from the basic and mating surfaces and, in turn, increase the wear.

Wear mechanisms are represented in Figure 3.3.

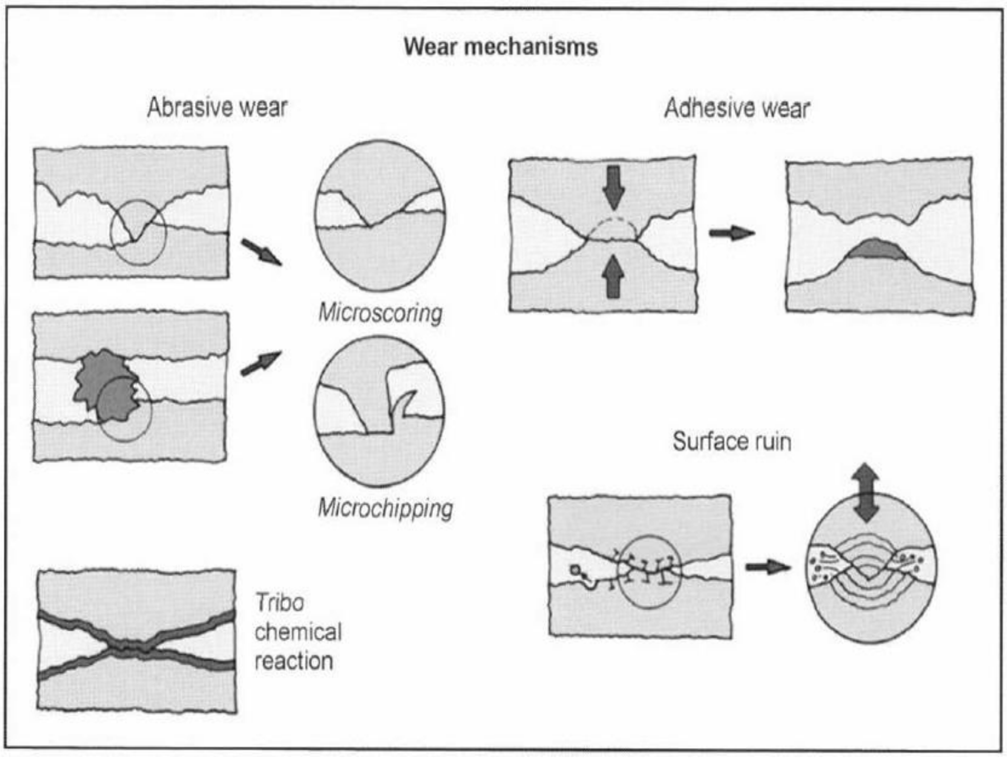


Figure 3.3 : Wear mechanisms [11].

For engine operation, it is the wear rate that is important, i.e., the speed at which the wear develops:

- Degressive: Running-in processes during which roughness unavoidable in production is smoothed out and the bearing surfaces of the partners are increased.
- Linear: Normal operation during which the wear increases steadily, but only slightly.
- Progressive: Self-propagating, the rate of wear accelerates so that functional faults quickly occur and lead to damage.

In engines, wear is predominantly caused by;

- Sliding wear with dry contact and with boundary and mixed friction (incomplete separation of basic and mating surfaces).
- Vibrational wear. Typical: Fretting (rubbing oxidation, fretting corrosion).
- Fluid friction (complete separation of basic and mating surfaces).

- Cavitation: Formation of cavities because of localized low pressure in a fluid with subsequent implosion of the vapor bubbles. This causes damage to the adjoining surfaces; hydrodynamic properties deteriorate.
- Erosion: Exposure of solids to liquids containing particles [e.g., lubricants or fuels with foreign particles or gas streams with particles (exhaust gas with combustion residues)]; parts of the material surface are worn away.
- Wear due to impingement.
- Wear due to corrosion.

In the engine, wear expresses itself as a reduction in cross section, changes in surfaces, functional deterioration because of increased clearances, reduction in overlaps, and impairment of the geometry and kinematics. Consequences can be increased friction, seizing, and overload or vibration fractures. Wear in the engine is generally caused by;

- Overloading.
- Inadequate lubrication as a consequence of lack of lubricant and/or unsuitable or old oils.
- Unfavorable operating conditions.
- Malfunction or failure of engine components.

Wear occurs predominantly in the following function groups:

- Engine: Pistons, piston rings, cylinders, bearings, and shafts.
- Gearing drive: Gear wheels.
- Control system: Cams and cam followers, valves, valve seats and valve guides, beltdrives [11].

3.2 Cylinder Bore Wear

The functions of piston rings are (a) to seal the clearance between the cylinder and the piston in order to retain gas pressure and reduce blowby, (b) to control the lubricant flow on the cylinder surface and reduce oil consumption and (c) to assist in heat transfer from the piston into the cylinder. The tension in the rings helps to achieve these functions. A higher ring tension results in better sealing but increases friction and may also increase wear of rings and cylinder bore. Therefore, optimum ring tension is desired for control of blowby, oil consumption, friction, and wear.

Generally, wear is a complex process influenced by a multitude of factors including (a) metallurgy of contacting materials, (b) surface texture, (c) operating conditions of the components; load, speed, temperature, etc., (d) environment such as presence of blowby, (e) lubricant formulations, etc. A recent survey showed that there are about 182 wear equations in the literature [14].

Practical observations and theoretical analyses correlate well in terms of the strongest wear of the cylinder bores taking place in the vicinity of the top reversal point of the top piston ring, where the thermal, chemical, erosive and abrasive conditions are the severest. A high sulphur content of the fuel can increase the proportion of tribochemical wear of the cylinder bore dramatically, particular at low cylinder surface temperature [20]. It is known that wear on the cylinder bore surface is promoted when acid adheres to the bore surface during engine warm up as a result of sulfur in the fuel Figure 3.4 below is a graph showing the sulfur concentration in gasoline in various parts of the world. Toyota used this information to help guide their cylinder block material selection for use in a sports car application in the late 1990s [4].

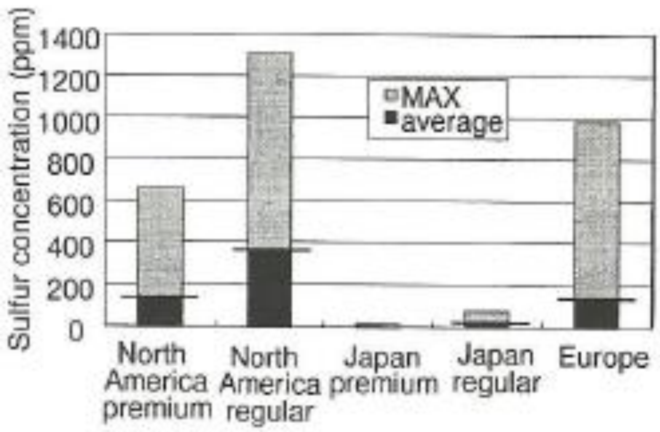


Figure 3.4 : Sulfur concentration in unleaded fuel [4].

High wear of the cylinder bore is furthermore associated with the top reversal point of the second piston ring, and to a less extent with the bottom reversal points of the piston rings. Carbon deposits above the ring pack on the piston may significantly increase the cylinder bore wear in the TDC region.

Cylinder bore polishing, which can be subdivided into light, medium and heavy polishing, is the first occurrence of wear in a cylinder liner. A light degree of bore polishing increases the oil consumption. When the bore polishing has evolved to a stage of heavy polishing, and most of the oil-retaining honing pattern has been erased, the risk of lubrication starvation and scuffing is obvious. The thermal loads cause lubricant degradation by ageing and partial evaporation. The chemical loads comprise dilution by fuel, acidic combustion products and water vapour from the combustion process. The erosive loads comprise the mechanical effect of the flushing by hot gases along the upper parts of the cylinder bore surface, and the removal of oil from the bore surface. The wear of the cylinder bore is additionally accelerated by solid carbon particles from the combustion process, and possibly by dust from the intake air that can contribute by causing abrasive wear. Wear of cylinder bores occurs as well in the mid-stroke region of the piston ring motion. The wear of the cylinder bore is higher on the anti-thrust side than on the thrust side of the bore, owing to the distribution of the thrust forces during the different cycles of the engine [20].

The three important wear mechanisms mentioned over the years are: corrosion, abrasion, and adhesion. Corrosion is the dominant mechanism when the engine runs either very cold or very hot. Abrasion results from the cutting and plowing action of hard particles. Adhesion is usually described as occurring when the oil film between the ring and the bore is so thin that metal-to-metal contact occurs. Other wear mechanisms, such as oxidation and splat delamination have been reported as well [17].

Corrosion is the dominant mechanism when the engine is run either very cold or very hot. In particular, large increase in wear rate is noted when the cylinder wall temperature falls below the dew point of combustion products in the cylinder. Corrosion has been successfully reduced by the use of thermostats and by the addition of corrosion inhibitors to engine oils [21].

When an engine is operated under low-water temperature conditions, the cylinder bore wear increases due to the following mechanism:

- When water temperature is low, bore surface temperature is also low, which means that the vapor in combustion gas condenses into water-drops on the bore surface.
- Combustion products dissolve in water-drops on the bore surface.
- Acids, such as hydrochloric acid, nitric acid and sulfuric acid are produced from these dissolved combustion products, gasoline components etc.
- Oil film disappears [22].

Abrasion results from the cutting and plowing action of hard particles. Two approaches to minimize abrasion are to prevent hards particles (such as dust) from entering the cylinder with air, and removing particles that become entrained in the oil. Periodic oil changes, and the use and regular replacement of oil filters and air filters, have become routine.

Adhesion is usually described as occurring when the oil film between the ring and bore is so thin that metal to metal contact occurs. The difficulties of producing the ideal running surfaces means that metal – to – metal contact will occur early in the life of the engine, and some wear of a ‘not-too-destructive type’ is necessary to produce an acceptable interface for long engine life. Once wear-in is complete, adhesion should only occur where oil film thickness is less than the roughness of the surface. This condition only happens near top dead center (TDC) and bottom dead center (BDC), where ring velocity goes to zero, and on engine start up, after the oil has had time to 'drain' from the walls [21].

The wearing of piston rings and cylinder walls may be divided into three regimes or types.

a) The break-in stage

Material loss is primarily from the upper part of the cylinder and from the top compression ring. It occurs primarily in the cylinder at the top dead center (TDC) of piston ring travel. Excessive surface damage at this stage is often referred to as scuffing but it is not uniquely described by this term.

b) The progressive wear stage

The cylinder may wear more at TDC than elsewhere but there is measurable wear all over. The piston rings rather than the piston are the main cause of cylinder wear. There is higher wear at TDC than elsewhere because it is the location of the highest contact pressure, the location of the greatest concentration of acids and the location of the thinnest lubricant film. On the latter point, there have been several attempts to calculate the lubricant film thickness between piston rings and cylinder wall. The film thickness beneath the top compression ring at TDC was found to be very small, in the range 0 - 3.0 μm, because of the low sliding velocity at that location. The maximum oil film thickness was found near the center of the stroke where the maximum speed is reached. This applies, of course, to the condition of normal running. All engines that stop and start do so with very thin lubricant films at all locations. For perspective on the influence of oil films, 75% of the total wear which took place during a 2 h run occurred in the first 6 min. Cylinder wear in the progressive stage may occur by several mechanisms but mostly by abrasion and corrosion. Some abrasive wear is caused by particles left in the engine during manufacture and assembly. This is correctible by proper cleaning during the various stages of manufacture .

c) A catastrophic mechanism

Catastrophic wear can occur in a well-functioning engine if some unusual events take place. This may be due to high temperature, high loads, interruptions of oil supply or intake of large quantities of contaminants. The result is a type of damage along much of the length of the cylinder and piston, widely referred to as scuffing. The outward signs of severe scuffing in an engine are high oil consumption and blow-by; if the scuffing is allowed to continue, seizure will often result. This is the type of scuffing that is most often reported in the literature. In fact, scuffing is usually defined in terms of the latter stages of damage. In a review of scuffing, subscribes to the Institution of Mechanical Engineers' definition of scuffing as "gross damage characterized by the formation of local welding between the sliding surfaces" [23].

The sequence of events leading to scuffing is thought to be:

- Lack of hydrodynamic lubrication causes micro welding and smoothing of the surface by plastic deformation of the surface layer and deposition of oxides.
- After some time the oil reservoirs are closed off and most asperities have been removed, resulting in a large contact area between piston ring and cylinder liner.
- At a critical level, the amount of available oil drops to a point where the smooth surfaces obtain metallic contact, causing adhesion and thereby severe wear [24].

In conclusion wear increases rapidly with time due to run-in followed by a steady state period. In inadequately lubricated engines the latter period could be followed by a catastrophic failure. An engine spends most of its useful life in the steady state period although during this period wear fluctuations also occur due to transient conditions, i.e., change of load, speed, oil and coolant temperatures, etc. The wear in piston ring/ cylinder bore contact takes place due to abrasion of piston rings against the cylinder bore (mechanical wear) but under some circumstances it could also occur due to corrosion (chemical wear) [19].

3.2.1 Materials for cylinder wear

While the ring – bore interface needs to be considered as a tribological systems, cylinder wear is more important to the engine manufacturer and user than ring wear, because cylinders are more expensive to replace than piston rings [21].

The speed at which the piston and piston rings reciprocate on the cylinder block bore surface requires the material to be extremely hard and wear resistant. Resistance to wear from a sliding surface is one of the key characteristics that a cylinder block material needs to exhibit. The harsh environment of an internal combustion engine can easily damage softer materials. Several researchers have performed extensive wear resistance testing of the alternatives for cast iron for cylinder block bore material. The results show that cast iron’s wear resistance with its tendency to hold lubricating oil because of its porous nature is excellent. Cast iron also showed an ability to resist wear at elevated temperatures better than the alternatives. A cylinder block material’s ability to resist scuffing is another important characteristic [4].

Many automotive components are made from gray cast iron which is known for its excellent properties such as good thermal conductivity, good machinability, vibration damping capacity along with good mechanical strength and wear resistance. Gray cast iron contains ferriticpearlitic or fully pearlitic matrix with graphite flakes randomly dispersed in the matrix. Therefore, it is suitable for components such as piston rings, engine liners, clutch and brake systems.

Alloying elements would tend to strengthen the matrix, refine the microstructure or introduce hard phases in the matrix to impart suitable properties required for specific applications. For example, Si is a strong graphitizer and Mn is a pearlite stabilizer. Ni and Cu add strength to the matrix and Mo and Cr form respective carbides to impart wear resistance.

Dry sliding friction and wear behaviour of hypereutectic and hypoeutectic alloyed gray cast irons in as-cast and austempered conditions have been studied earlier. It is reported that addition of alloying imparts adequate mechanical strength to the matrix while significantly improving their wear properties. Heat treatments such as austempering can bring about much higher improvements in their wear properties compared to pearlitic irons at comparable strength.

Solid lubricants in sufficient thickness can effectively work under extreme conditions of temperature, loads and speeds. Layered solid lubricants (boric acid, molybdenum disulphide and graphite) reduce friction by the mode of easy shear between their layers. Graphite is a well-known solid lubricant with lamellar morphology used in all the industrial lubrication system. It is available in the form of amorphous, natural and synthetic grades. It needs moisture for good lubricity. Graphite blends and pure graphite dry film is widely used for applications such as hot and cold forming, wire drawing and billet coatings, on high-speed cutting tools, as a mold release for die casting process, plastic and rubber mold applications, cylinder head and exhaust bolts, ammunition and armament applications, automotive engine and many common industrial applications [25].

Most engine cylinders in use today are also made of pearlitic gray cast iron. Cylinders as well as rings should contain no more than 5 wt.% free ferrite in the surface, to prevent adhesion to the rings. To limit free ferrite formation, it is possible to use small amounts of tin or chromium, hold the amount of silicon to a minimum and use up to 0.8 wt.% Cu. Many investigators also recommend that some phosphide eutectic should be present in the microstructure to ensure good wear resistance but reasons are usually not given for this recommendation. Type A flake graphite of ASTM size 4 - 7 is often recommended for good wear resistance but again the reasons are not known [23].

3.2.2 Surface topography

Lubrication theory suggests that, for long product life, the surface roughness of sliding elements should be no greater than the thickness of the lubricant film. This would require very smooth cylinder walls because the oil film on the cylinder walls must be rather thin to avoid high oil consumption [23].

The trend in the cylinder bore surface finishing has been directed by demands to reduce oil consumption, increase the durability and increase the resistance against wear and scuffing. To limit hydrocarbon emissions and particles by reducing the oil consumption, the surface roughness of the cylinder liner should have an Ra (mean deviation of the surface roughness) value between 0.25 and 0.4 μm and an Rz (mean surface roughness) value between 3 and 6 μm. This can be achieved with optimally honed bore surfaces. There is a consensus for a surface texture of cleancut surfaces with smooth, flat plateaux and a regular, consistent arrangement of primary oil-retaining valleys. The surface finish of the cylinder liner has an influence on the scuffing resistance. The rise in friction, which leads to the scuffing, is associated with the polishing of the liner.

Honing is applied for finishing the surface of cast-iron cylinder liners. The cutting marks of the honing form a pattern of diagonal valleys on the liner surface. The honing grooves, the volume and the direction of the valleys control the amount of oil available, by keeping the oil on the liner surface and by improving the spreading of the oil. Since the requirements of good sealing properties and optimal lubrication are contrary to each other, the demands on the topography of the cylinder liner are exacting [20]. Although there are several kind of honing operation, most of the cylinder blocks are machined with plateau honing. Surface profile examples obtained from various honing process is shown in Figure 3.5.

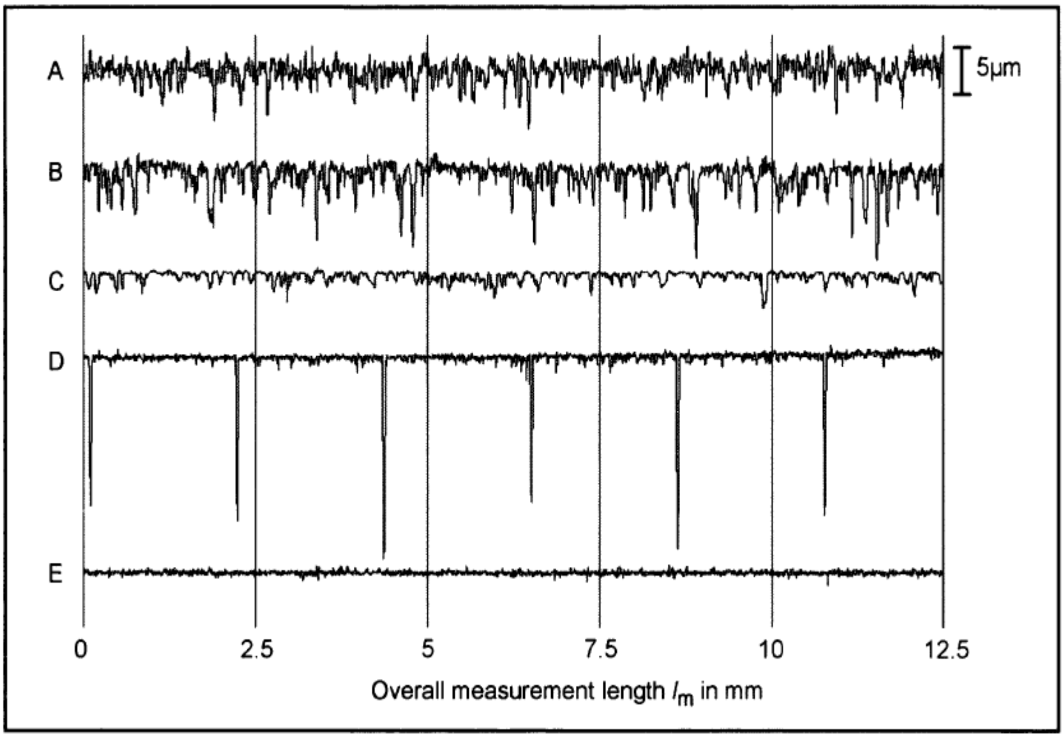


Figure 3.5 : Roughness profile for standard honing (A), plateau honing (B), helical slide honing (C), laser-imparted texture (D), and smooth standard honing (E) [11].

The quality of the honed surface is affected by the bore geometry and diameter tolerances, the surface roughness of the fine bored surface, the machining operations and the number of machining stages, and the material, hardness and type of the honing stones. To obtain the specific surface, the liner is usually machined in four steps:

- Rough boring – for the basic geometry.
- Rough honing – for alignment.
- Fine honing – for desired surface roughness.
- Plateau-honing – for surface smoothing.

Step 3 removes all the traces of the first two steps. Step 4, the plateau-honing, partly replaces the running-in process of the liner surface, which improves the dimensional tolerance of the cylinder, increases the engine efficiency and decreases oil consumption.

Many parameters have been used for characterising the plateau-honed surface:

- 2D-parameters, such as Ra (mean deviation of the surface roughness), Rz (mean surface roughness), and Rmax.
- Parameters describing the shape of the surface, such as skewness (Rsk) and kurtosis (Rku).
- Functionally characterised 2-dimensional Rk and 3-dimensional Sk parameters, such as Rpk and Spk (Reduced peak height, addresses the running-in properties), Rk and Sk (Core roughness depth, addresses the wear and load-carrying capacity), and Rvk and Svk (Reduced valley depth, addresses the oil volume for lubrication).
- On the probability plotting method based parameters for the control of the manufacturing process, such as Rqpc (Rq value of the plateaus giving a surface roughness value of the plateau-honing step), Rqvc (Rq value of the fine-honing step) and Mr2c (intersection of the two lines defined by the angular coefficients Rqpc and Rqvc, define the share of plateau versus valley texture in the topography) [20].

4. THERMAL SPRAY COATINGS

4.1 Nature Of Thermal Spray Coating

Thermal spraying is the process of melting or heat softening of a material, fragmenting and propelling the softened material in particulate form against a substrate [4].

During thermal spraying process a feedstock, which can be a wire or powder is continuously fed into a heat source, where the material is being molten, respectively partially molten. The energy to heat the feedstock is supplied by electrical (plasma, arc) or chemical means (combustion flame). The particles are being further atomized and propelled onto a prepared substrate by a stream of compressed air or other gas. Due to the high kinetic energy the particles flatten when they impinge on the surface of the substrate; the heat transfer between the flattened particles and the substrate causes a rapid solidification. These so-called "splats" build up a lamellar coating [10].

Formation of a 'splat' during thermal spray is represented in Figure 4.1.

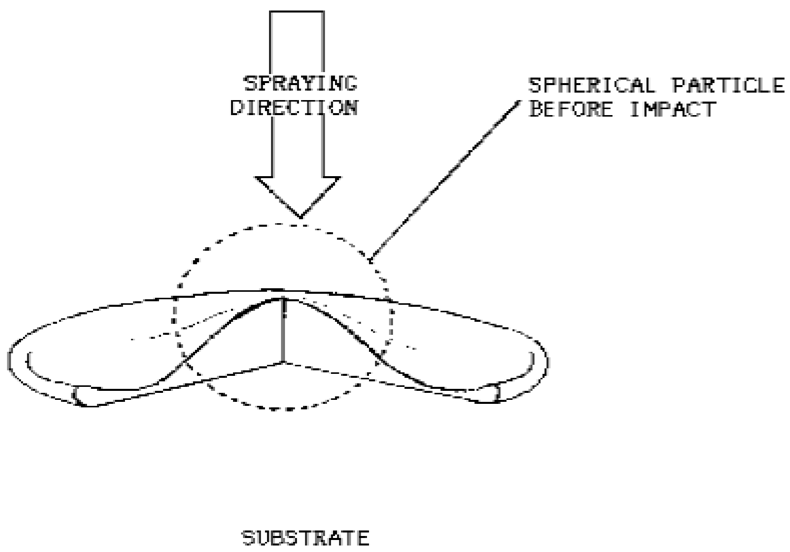


Figure 4.1 : Schematic of thermally sprayed spherical particle impinged onto a flat substrate [26].

These systems are typically characterized by a rotating spindle; the gun head, with the plasma generator or the combustion chamber and the nozzle is mounted to the bottom of thespindle. Due to the axial feed combined with the rotation of the spindle a spiral spray patternis created on the bore wall [10]. Schematic of thermal spraying process is repesented in Figure 4.2.

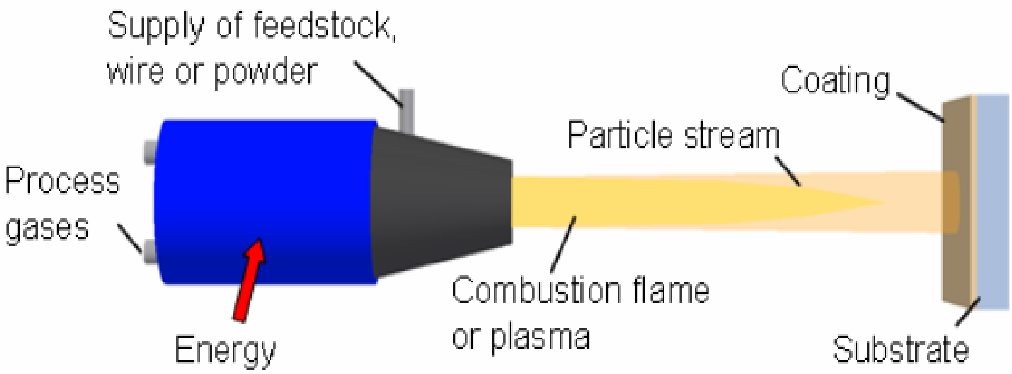


Figure 4.2 : Schematic of thermal spraying process.

Thermal Spray coatings in general are characterized by a certain amount of porosity and oxidized particles [10]. Coating quality is determined by its porosity, oxide content, macro and micro-hardness, bond strength and surface roughness [4]. Schematic of thermal sprayed coating is repesented in Figure 4.3.

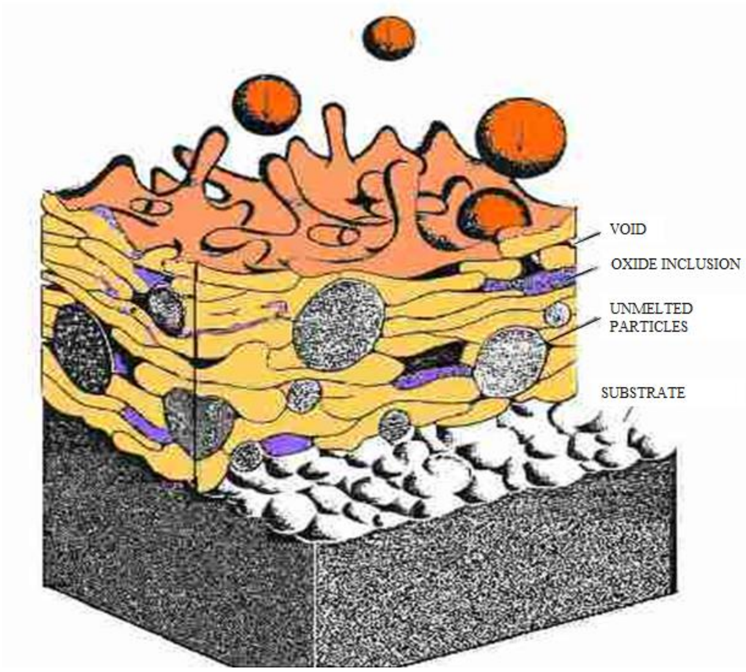


Figure 4.3 : Schematic diagram of thermal spray metal coating [26].

The coatings can have any of the following functions:

- Tribological (wear, resistance).
- Corrosion resistance.
- Heat resistance.
- Thermal barrier.
- Electrical conductivity or resistivity
- Abradable or abrasive.
- Textured surfaces.
- Catalyst and prosthetic properties,
- Restoration of dimension.
- Copying of intricate surfaces [26].

4.1.1 Bonding

The bonding mechanisms at the thermal spray coating/substrate interface and between the particles making up the thermal spray coating is an area which in many cases is still subject to speculation. It generally suffices to state that both mechanical interlocking and diffusion bonding occur. Thermal spray coating bonding mechanisms are as below:

•Mechanical keying or interlocking.

•Diffusion bonding or Metallurgical bonding.

•Other adhesive, chemical and physical bonding mechanisms -oxide films, Van der Waals forces etc..

Factors effecting bonding and subsequent build up of the coating:

- Cleanliness
- Surface area
- Surface topography or profile
- Temperature (thermal energy)
- Time (reaction rates & cooling rates etc..)

- Velocity (kinetic energy)
- Physical & chemical properties
- Physical & chemical reactions

Cleaning and grit pre-treatment are the most two important processes for substrate preparation to achieve active surface needed for good bonding in terms of chemically and physically. As the surface area increases, the bonding strength of coating would increase accordingly. The rough surface profile will promote mechanical keying.

Individual particle cooling rates on impact can be of the order of 1 million º C per second (10^6K/s). Thermal interaction is obviously very limited. Important with regard to diffusion bonding (temperature and time dependent). Due to limited thermal interaction, possibility for diffusion bonding generation is very low.

Increase in thermal and kinetic energy increases chances of metallurgical bonding. (temperature, velocity, enthalpy, mass, density and specific heat content etc..). Thermal spray materials like molybdenum, tungsten, and aluminium/metal composites produce so called "self bonding" coatings. These materials have comparatively high bond strengths due to increased metallurgical or diffusion bonding, and can bond to clean polished substrates. Molybdenum and other refractory metals have very high melting points thus the interaction between substrate and coating particles will be increased due to the higher temperatures involved and longer cooling cycles. Also molybdenum oxide volatilizes and does not get in the way of metallurgical bonding. Aluminium/metal composites produce increased levels of exothermic reaction due to reactions of aluminium with metals like nickel to produce nickel aluminide and with oxygen producing aluminium oxide. The increased thermal action increases degree of diffusion bonding. Higher preheat temperatures for the substrate increase diffusion bonding activities but will also increase oxidation of the substrate which could defeat the objective of higher bond strengths. High kinetic energy thermal spraying using, HVOF and cold spray produce high bond strengths due to the energy liberated from high velocity impacts. The high density tungsten carbide/cobalt and cold spray coatings are good examples. Metallurgical or diffusion bonding occurs on a limited scale and to a very limited thickness (0.5 µm max. with heat effected zone @ 25µm) with the above type coatings [26].

Due to the kinetic energy and the viscosity of the molten particles, they can infiltrate undercuts and flow around the peaks of the roughened prepared surface before they solidify rapidly within about 10^{-8} to 10^{-4} seconds. This form locking mechanism is supported by a force fit mechanism, caused by the contraction strain of the solidifying particles. Thus, a roughened surface, characterized by numerous undercuts is essential to gain sufficient bond strength. A schematic of the build-up of a thermally sprayed coating is given in Figure 4.4 [7].

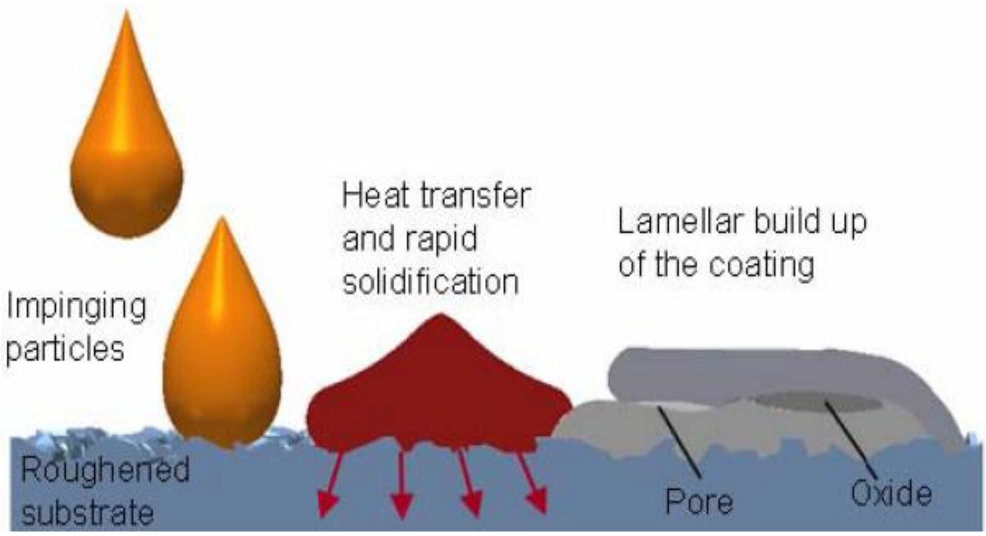


Figure 4.4 : Formation of a thermally sprayed coating [7].

4.1.2 Coating structure

High cooling rates or super cooling (10^6 K/s) of particles can cause the formation of unusual amorphous (glassy metals) microcrystalline and metastable phases not normally found in wrought or cast materials.

A large proportion of thermal spraying is conducted in air or uses air for atomisation. Chemical interactions resulting from high temperature occur during spraying which leads metallic particles to oxidise over their surface forming an oxide shell. This is evident in the coating microstructure as oxide inclusions outlining the grain or particle boundaries. Some materials (such as titanium) interact with or absorb other gases such as hydrogen and nitrogen.

Coatings contain lamellar or flattened grains oriented parallel to the substrate. Thus the structure is not isotropic, which results in physical properties being different parallel to substrate (longitudinal) compared to across the coating thickness (transverse). Strength in the longitudinal direction can be 5 to 10 times that of the transverse direction.

The coating structure is heterogeneous relative to wrought and cast materials. This is due to indivisual particles have variations during origination. It is so hard to ensure that all particles are obtained with the exact same size and by achieve the same temperature and velocity.

All conventionally thermally sprayed coatings contain some porosity which is generally between 0.025% and 50%.The reasons of porosity formation:

- Low impact energy (unmelted particles / low velocity)
- Shadowing effects (unmelted particles / spray angle)
- Shrinkage and stress relieve effects

The above interactions can change the coatings from their starting materials in terms of chemically and physically.

4.1.3 Stress

Cooling and solidification of most materials is accompanied by contraction or shrinkage. When particles strike on substrate, rapid cooling and solidification occur which generates a tensile stress within the particle and a compressive stress within the surface of the substrate. As the coating is built up, so are the tensile stresses in the coating. If coating thickness reaches up to a level where the tensile stresses exceed the bond strength or cohesive strength, coating failure occurs. The stress origination on thermal spray coatings is repesented in Figure 4.5.

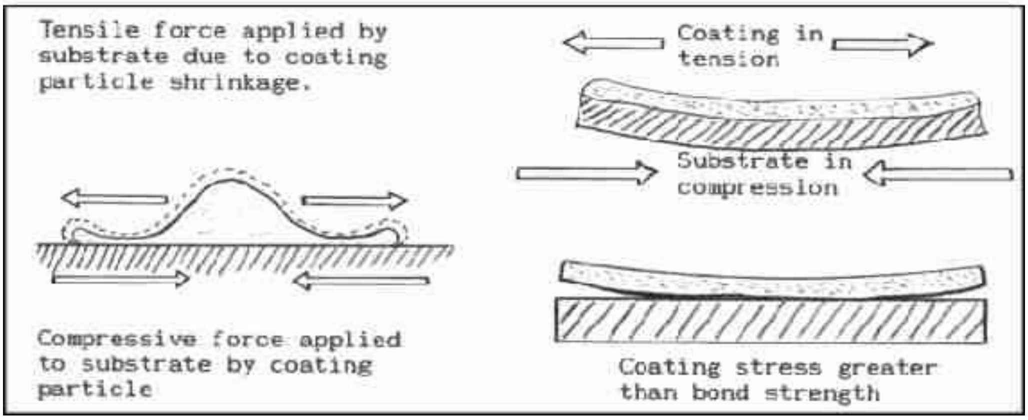


Figure 4.5 : Stress origination on a thermal spray process [26].

High shrink materials like some austenitic stainless steels have a tendency to high levels of stress build up and thus have low thickness limitations. In general, thin coatings are more durable than thick coatings.

Spraying method and coating microstructure affect the level of stress build up in coatings. Dense coatings are generally more stressed than porous coatings. It should be highlighted that combustion powder sprayed coatings generally have greater thickness limitations than plasma coatings.

In contrast to that just mentioned, the systems using very high kinetic energy and low thermal energy like HVOF can produce relatively stress free coatings with extreme density which is believed to be due to compressive stresses formed from mechanical deformation (similar to shot peening) during particle impact counteracting the tensile shrinkage stresses caused by solidification and cooling.

4.1.4 Porosity

Porosity is present in most thermally sprayed coatings . 1 to 25% porosity is normal but can be further manipulated by changes in process and materials.

Porosity can be detrimental in coatings with respect to:

- Corrosion.
- Surface quality after machining.
- Strength, macro hardness and wear characteristics.

Porosity can be important with respect to:

- Lubrication as porosity acts like reservoir for lubricants.
- Increasing thermal barrier properties.
- Reducing stress levels and increasing thickness limitations.
- Increasing shock resisting properties.
- Abradability in clearance control coatings.
- Applications in prosthetic devices and nucleate boiling etc. [26].

4.1.5 Strength

Coatings generally have poor strength, ductility and impact properties. These properties tend to be dictated by the "weakest link in the chain" which in coatings tends to be the particle or grain boundaries and coating/substrate interface. Coatings are limited to the load they can carry, and thus require a substrate for support, even then, coatings are poor when point loaded.

Internal tensile coating stresses generally adversely affect properties. Effective bond strength is reduced and can be destroyed by increasing levels of internal stress. This in turn effects coating thickness limits. Coatings on external diameters can be built up to greater thickness than the ones on internal diameters.

Surface properties such as wear resistance and hardness are usually good, but the properties are highly dependent to the material or materials used in the coating. The properties of a substrate need only to be strength, ease of fabrication and economic (like mild steel). The coating supplies the specific surface properties desired. For example, materials used for applications of thermal barrier and abradable clearance control by nature have poor strength and thus benefit from being applied as a coating onto a substrate which supplies the strength.

4.1.6 Oxide

Most metallic coatings suffer from oxidation during normal thermal spraying in air. The products of oxidation are usually included in the coating. Oxides are generally much harder than the parent metal. Coatings of high oxide content are usually harder and more wear resistant. Oxides in coatings can be detrimental towards corrosion, strength and machinability properties [26].

4.2 Type Of Thermal Spray Coatings For Cylinder Blocks

Up to date at least four thermal spraying systems have been designed for cylinder block applications.These are:

- Rotary atmospherical powder plasma process (APS).
- Rotating twin wire arc system (TWA).
- High velocity oxygen fuel system (HVOF).

• Plasma Transferred Wire Arc system (PTWA) [10].

Although there are much more thermal spray coating methods available for industry, apart from these four methods listed above will be out of scope of this work as they are not used for cylinder block applications.

4.2.1 Rotary atmospherical powder plasma process (APS)

The RotaPlasma process, developed by Sulzer Metco, is a rotating powder fed atmospheric plasma spray torch. Since 2000, Volkswagen has been using this RotaPlasma process in new aluminum block production. The torch is suitable to deposit coatings on the internal surface of cylinder bores uses powder as feedstock material. As coating material in the serial production low alloyed carbon steel is used but a broad variety of other materials can be deposited, including ceramics. With the atmospheric plasma spraying process electrical energy is used to transfer a plasma gas (mixture) into the plasma state which provides the thermal energy needed to heat up the powder feedstock. The plasma generator consists of a tungsten cathode and an annular copper anode. The plasma gas flows around the cathode exiting the anode, which works as a constricting nozzle. The plasma is initiated by an arc which is ignited by a discharge. Electrons, emitted by the cathode, are being accelerated by the electric potential between anode and cathode. The collision of the electrons with the atoms or the molecules of the plasma gas causes them to dissociate (molecular gases) and ionize. As soon as the plasma leaves the nozzle, no more electric energy is applied, the gases recombine. This recombination is responsible for the high temperature, up to 20,000 K, within the plasma. Due to the high temperature the plasma expands and leaves the plasma generator. The powder feedstock is being injected radially into the plasma stream where it is heated up and accelerated towards the bores surface. To avoid overheating of the plasma generator, the system is water cooled [7].

The schematic of rotary atmospherical plasma powder process is represented in Figure 4.6.

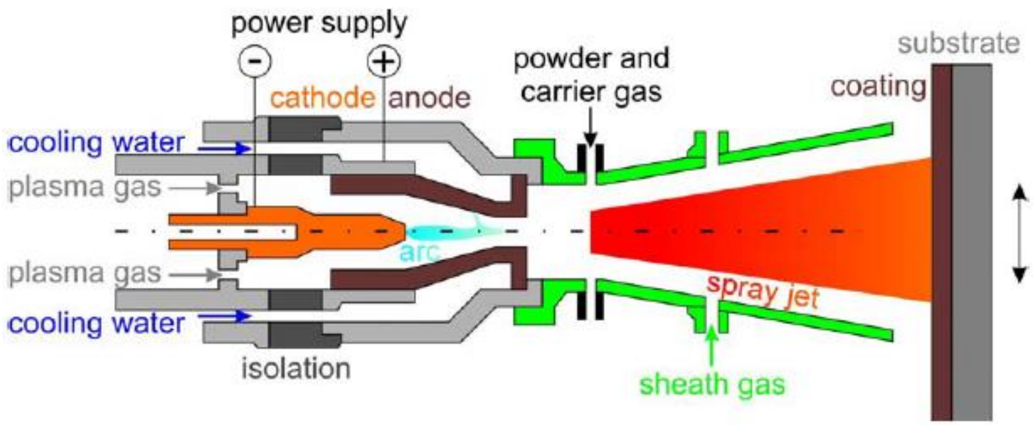


Figure 4.6 : Schematic of rotary atmospherical plasma powder process [27].

4.2.2 Twin wire arc

The rotating Twin Wire Arc System, developed by Daimler Chrysler, is a process in which two electrically conductive wires are continuously fed in one plane. Both wires are connected to a DC-power supply. As soon as the wires contact or approach contact, the constant voltage power supply attempts to maintain voltage by increasing current. The current passes through the contact tips of both wires creating an arc, which causes the wire tips to melt. Compressed air or any non-combustible gas atomizes the molten particles and accelerates them towards the work piece [7].

This arc spray process carried out correctly is called a "cold process" (relative to the substrate material being coated) as the substrate temperature can be kept low during processing avoiding damage, metallurgical changes and distortion to the substrate material.

Electric arc spray coatings are normally denser and stronger than their equivalent combustion spray coatings. Low running costs, high spray rates and efficiency make it a good tool for spraying large areas and high production rates.

Disadvantages of the electric arc spray process are that only electrically conductive wires can be sprayed and if substrate preheating is required, a separate heating source is needed.

The main applications of the arc spray process are anti-corrosion coatings of zinc and aluminium and machine element work on large components [26].

The schematic of twin wire arc process is represented in Figure 4.7.

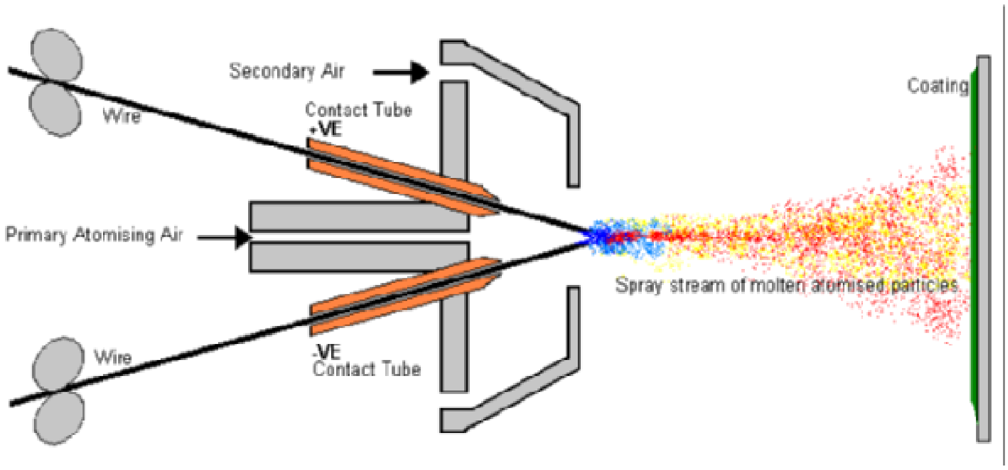


Figure 4.7 : Schematic of twin wire arc process [26].

4.2.3 High velocity oxygen fuel (HVOF)

General Motors has developed a HVOF (High Velocity Oxygen Fuel) system to deposit coatings on the internal surface of cylinder. The energy necessary to melt and propel the wire feedstock in this system is generated by a combustion process of pure oxygen with either a liquid or a gaseous fuel, which occurs in an open combustion chamber mounted to the bottom of a rotating spindle. The wire with a diameter of 4,8 mm is fed down the center of the spindle into the combustion chamber [7].

There are a number of HVOF guns which use different methods to achieve high velocity spraying. One method is basically a high pressure water cooled HVOF combustion chamber and long nozzle. Fuel (kerosene, acetylene, propylene and hydrogen) and oxygen are fed into the chamber, combustion produces a hot high pressure flame which is forced down a nozzle increasing its velocity. Powder may be fed axially into the HVOF combustion chamber under high pressure or fed through the side of laval type nozzle where the pressure is lower. Another method uses a simpler system of a high pressure combustion nozzle and air cap. Fuel gas (propane, propylene or hydrogen) and oxygen are supplied at high pressure, combustion occurs outside the nozzle but within an air cap supplied with compressed air. The compressed air pinches and accelerates the flame and acts as a coolant for the HVOF gun. Powder is fed at high pressure axially from the centre of the nozzle [26].

The choice of the combustible determines the maximum achievable flame temperature which is summarized in figure 4.8 [27].

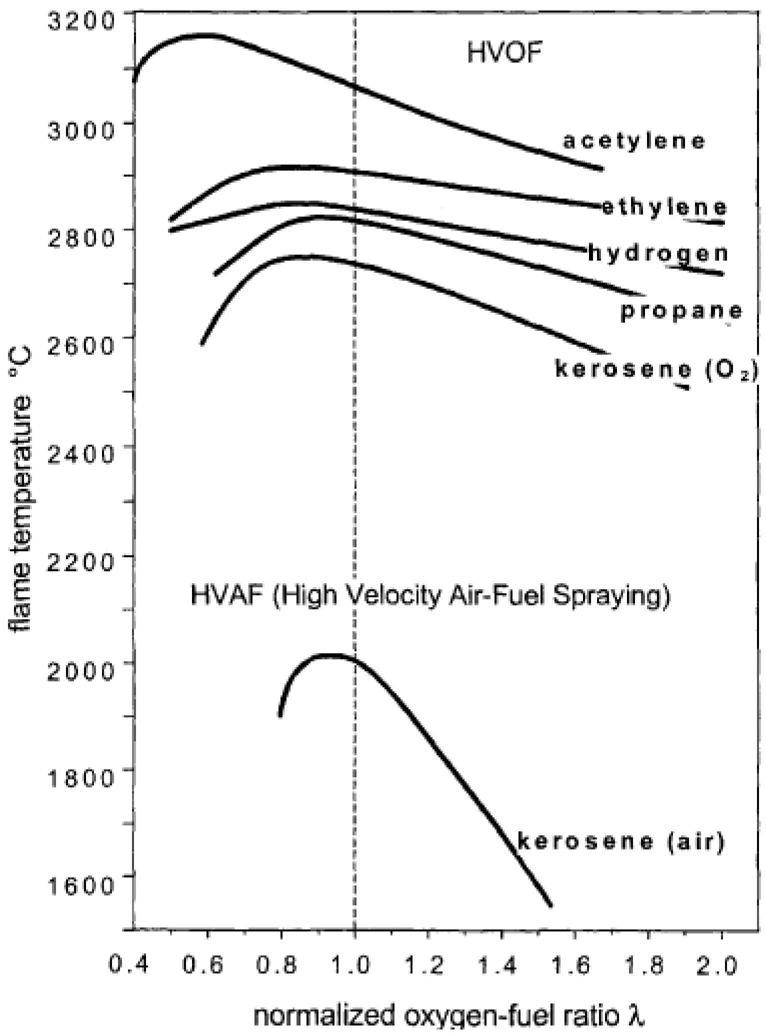


Figure 4.8 : Flame temperature depending on fuel type and oxygen-fuel ratio [27].

The coatings produced by HVOF are similar to those produce by the detonation process. HVOF coatings are very dense, strong and show low residual tensile stress or in some cases compressive stress, which enable very much thicker coatings to be applied than previously possible with the other processes.

The very high kinetic energy of particles striking the substrate surface do not require the particles to be fully molten to form high quality HVOF coatings. This is certainly an advantage for the carbide cermet type coatings and is where this process really excels.

HVOF coatings are used in applications requiring the highest density and strength not found in most other thermal spray processes. New applications, previously not suitable for thermal spray coatings are becoming viable [26].

The schematic of high velocity oxygen fuel process is represented in Figure 4.9.

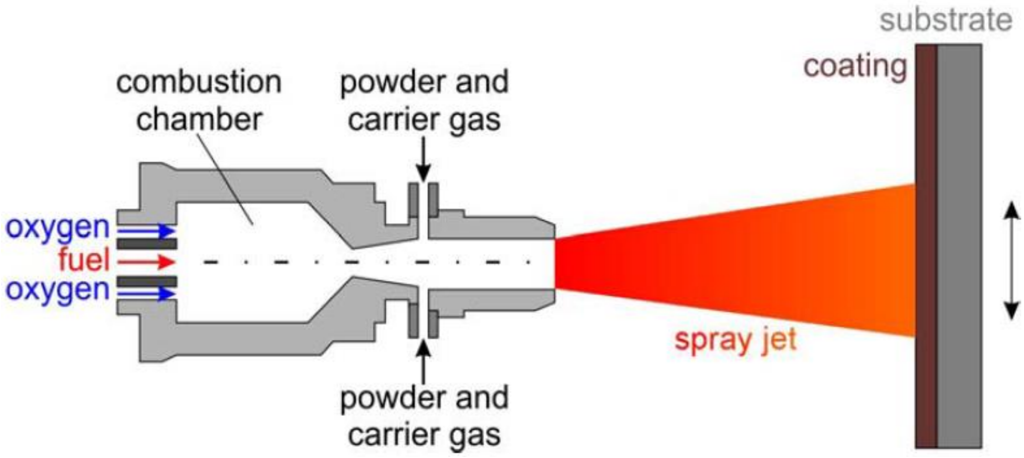


Figure 4.9 : Schematic of high velocity oxygen fuel process [27].

4.2.4 Plasma transfer wire arc (PTWA)

Ford Motor Company was one of the early pioneers in the automobile industry implementing a thermal spray process for cylinder block coating. Ford's patented plasma transferred wire arc (PTWA) process, is similar to the traditional arc spray process but instead of normal gas as the atomizing medium, plasma gas is used.

Ford has used their PWTA process on two US market cars to date. They are the 2011 Ford Mustang Shelby GT500, and the 2009 Nissan GTR. Ford licensed their process to Nissan for the GTR. Both are high performance sports car, the Mustang has a 5.4 liter eight cylinder engine producing 550 horsepower and the 2012 version of the GTR has a 3.7 liter six cylinder engine twin turbocharged engine producing 530 horsepower [4].

The plasma generator or gun head consists of a tungsten cathode, an air-cooled pilot nozzle made of copper and an electrically conductive consumable wire which is the anode. The head is mounted to a rotating spindle, which rotates with up to 600 rpm. The wire is fed perpendicularly to the centre orifice of the nozzle. To start the process, a high voltage discharge is initiated, which ionizes and dissociates the gas mixture between the cathode and the nozzle. Due to a constricting orifice in the pilot nozzle the plasma is forced to exit the nozzle at supersonic velocity. The elongated plasma is transferred to the consumable anode, the wire, completing the electric circuit. A constant current power supply maintains the plasma from the cathode to the wire with an arc voltage of 100 – 120 V and a current of 60 – 100 A. This melts the tip of the wire and then the high-pressure plasma gas together with the atomizing gas strips the molten particles from the end of the wire. Thereby a jet of finely atomized particles is created, which is accelerated towards the substrate at high speed. The atomizing gas can be any non-combustible gas [10].

The schematic of plasma transfer wire arc process is represented in Figure 4.10.

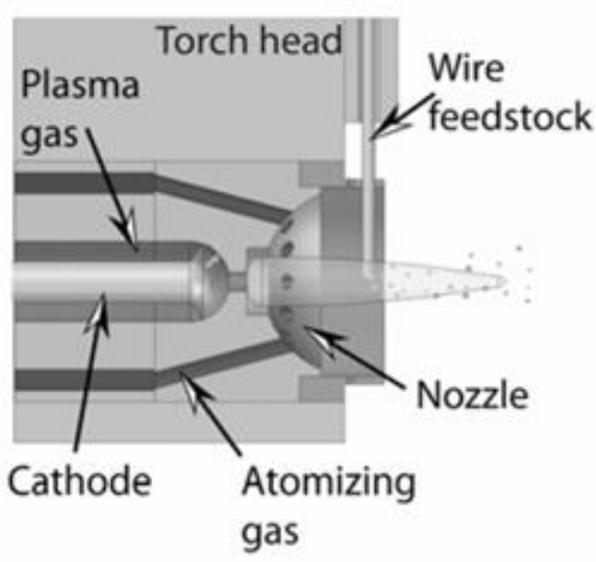


Figure 4.10 : Schematic of plasma transfer wire arc process [10].

A picture of PTWA systems is given in Figure 4.11.

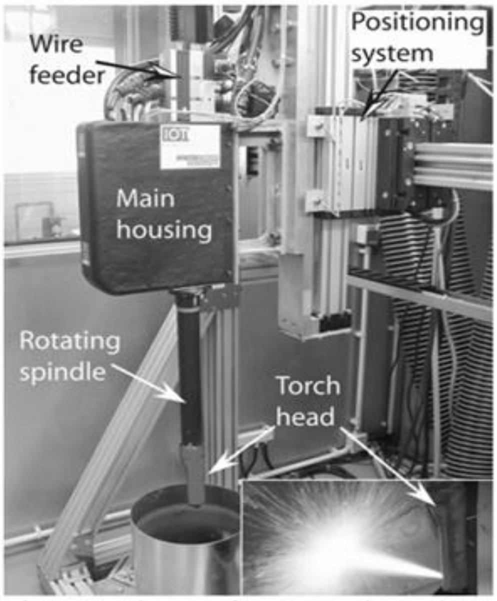


Figure 4.11 : PTWA system [10].

Regarding the scope of this thesis work, PTWA process has been selected as thermal spray process for investigation on reconditioning cylinder bores with thermal sprayed coatings instead of regular remanufacturing methods.

The process chain in the production of coated cylinder bores consists of four steps. The first steps are machining the cylinder bore to a certain diameter, and machining the surface to be pre-treated, so the coating is able to adhere. Next steps are the thermal spraying process and the honing of the coated bore to receive a surface that meets the tribological requirements. The thickness of the coating after the honing operation for most applications is typically 100 - 150 µm. Because of the as-sprayed roughness of the coating, the thickness as deposited is at typically 200 - 250 µm; it depends on the feedstock and also on the thermal spraying process [7].

Summary of process sequence for PTWA application is reprsented in Figure 4.12.

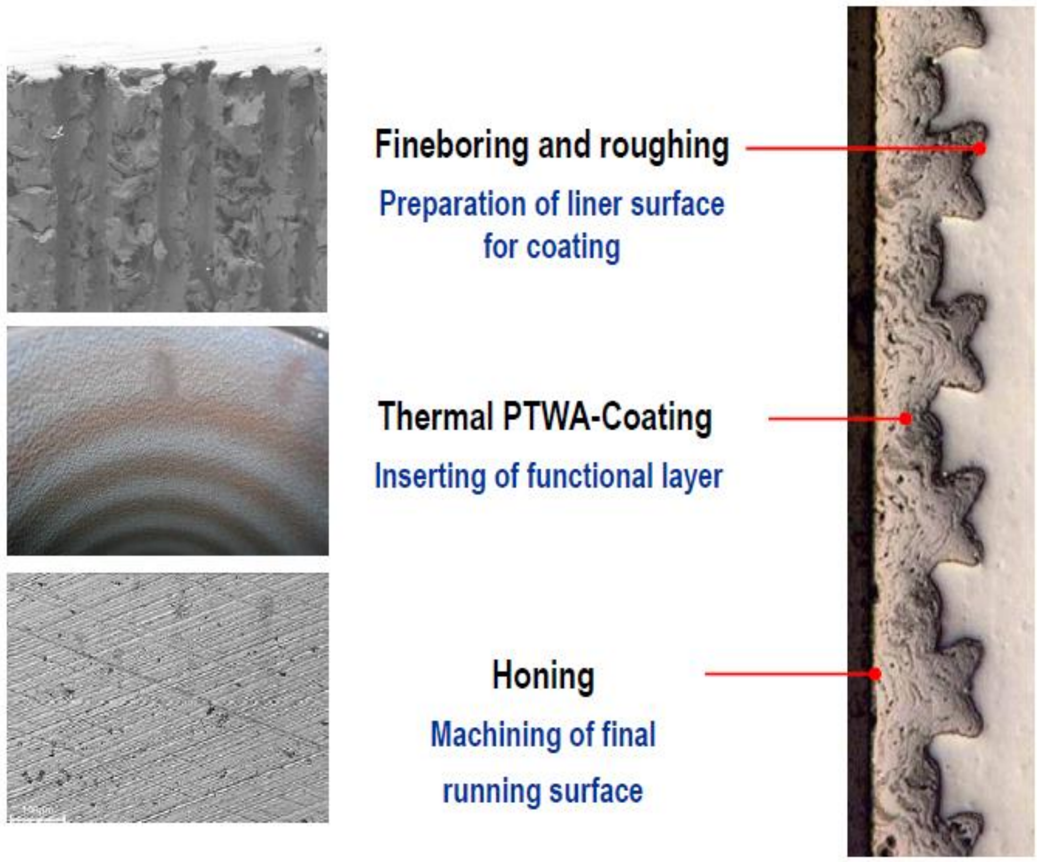


Figure 4.12 : Process sequence for PTWA process [28].

As pre-treatment process plays significant role on bond strength, it will be discussed further in following chapter.

4.2.4.1 Pre-treatment and bond strength

One of the first challenges in developing PTWA thermal spray process was to identify a suitable surface preparation technique capable of preparing millions of cylinder bores on a high rate production line. Ford completed an extensive evaluation of available thermal spray surface preparation techniques including rough machining, grit blasting, and high pressure water jet surface preparation. Based on manufacturing robustness criteria, it was determined that rough machining did not produce a repeatable surface preparation process nor did it provide adequate bond strength for cylinder bore coating application. Grit blasting, although capable of providing adequate bond strength, was not preferred for PTWA engine coating application because of potential problems with containment of the grit in the manufacturing and assembly areas. In addition, any grit remaining in the finished machined cylinder block could potentially destroy bearing surfaces, plug oil passages, and potentially cause significant engine damage after assembly. Water jet surface preparation was also found to produce excellent coating bond strength; however the process is expensive and can often excessively roughen and consequently damage the substrate [3].

Therefore, there is a need for a pre-treatment process that can be easily integrated in the serial production of engine blocks which has led to a different mechanical roughening processes. One process was developed by the Institute of Machine Tools and Production Technology of Braunschweig University within the framework of the “Nano Mobile” project. With this fine machining process a tool with a mechanically defined cutting edge is used to bring different topographies into the substrate. The most successful out of the evaluated profiles is a dove tail like profile as shown in Figure 4.13. The process is not only characterized by good integrability, it also leads to very high bond strength between the coating and the substrate. The bond strength thereby reaches values of up to 60 MPa on liners made from aluminum which is twice as much as the recommended value of 30 Mpa [7].

The obtained bond strengths from various of pre-treatment method is summarized in Figure 4.13.

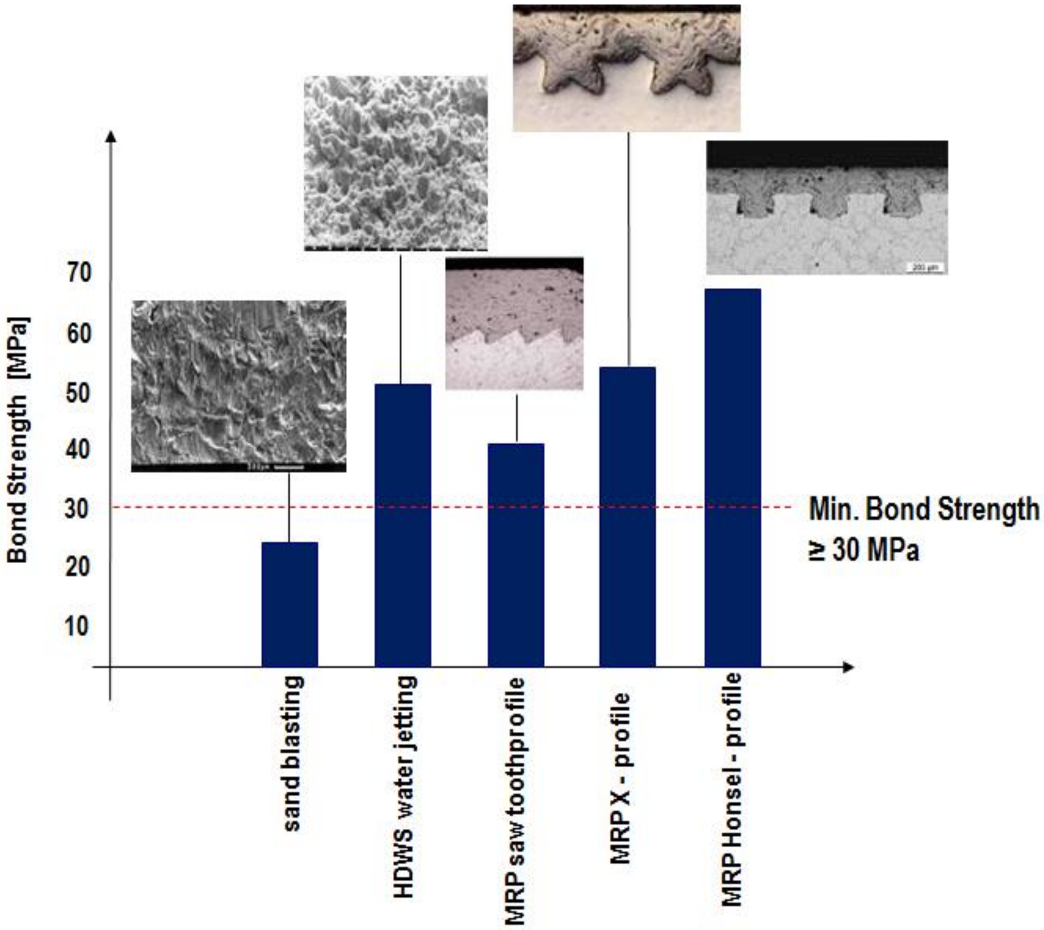


Figure 4.13 : Bond strength obtained from various pre-treatment methods [29].

For the measuring of the bond strength a PAThandy pull off adhesion tester is used. Compared to the established testing method following ASTM-C 633 respectively DIN EN 582 it is possible to measure the bond strength directly on coated parts such as the curved surface of a bore. A suitable test element with the face side machined to the same curvature as the bore wall is glued onto the coating. In a second step all the coating has to be cut from the substrate surrounding the test element to define a specific area for the adhesion test. This can be done by using a hollow drill or by laser cutting. The test element is then connected to the pulling head shown in Figure 4.14. With a small hydraulic pump pressure is applied onto the four jack cylinders which tears the test element and the coating off the substrate. The pressure at which the coating separates from the substrate is measured and converted into the bond strength [30].

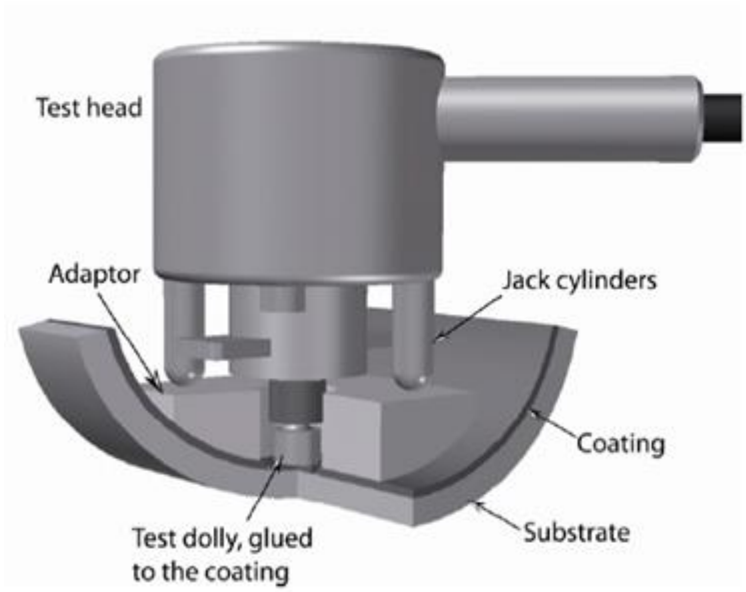


Figure 4.14 : Schematic of PAT pulling head [30].

The machining tool for 'dove tail' machining for pre-treatment is shown in Figure 4.15.

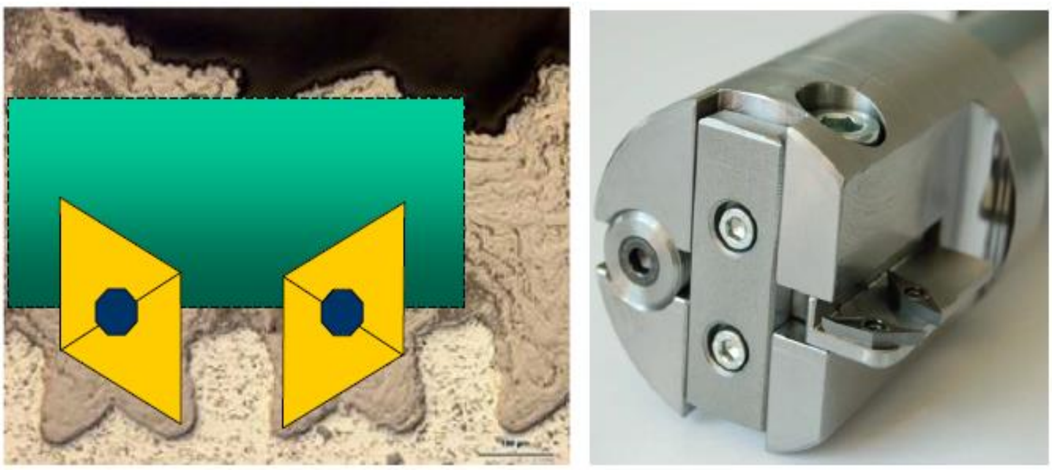


Figure 4.15 : Dove tail machining for pre-treatment [28].

Due to unavailability of dova tail machining tool compatible for Ecotorq 9L cylinder block, rough boring was applied as pre-treatment in this study.

4.2.4.2 Coating material and wear resistance

When low carbon steel is used with the PTWA thermal spraying process and compressed air is used for the atomizing gas, the iron in the alloy react with the oxygen of the atomizing gas and forms FeO (Wuestite) a high temperature oxide, which, due to the high cooling rates is frozen at room temperature.

Wuestite is a hard, self-lubricating oxide phase that is responsible for the excellent exhibited tribological properties of these Fe/FeO-coatings. These oxides are significantly harder than the iron matrix (430 HV0.3 compared to 260 HV 0.3; 0.1 C-steel as feedstock). Wuestite also works as a self lubricating material, similar to the graphite lamellas in grey cast iron. Wuestite has a cubic closed packed structure, due to its crystallographic shearplane it acts as a low shear strength, lubricious oxide [7].

First, the wear is decreased due to the increased hardness of the coating. With the presence of FeO throughout the microstructure, the microhardness of the coating increases from 190 HV to 440 HV. The increase in hardness results in improved wear and friction characteristics, due to the decrease in plastic deformation between contacting surfaces. Second, wuestite has a cubic closepacked structure similar to rock salt and is based on a ccp anion array. Therefore, due to its particular crystallographic shear plane, it acts as a low shear strength, lubricious oxide. In addition, because there is a fine and even distribution of FeO throughout the microstructure, it aids the wear and friction characteristics of the entire coating [8]. Depending on the thermal spraying process, and of course on the parameters chosen, the amount of Wuestite varies.

Thermally sprayed coatings in general contain a certain amount of porosity. For most applications these pores are disadvantageous. For this specific application though, it was found out that the pores can have a positive effect on the frictional behavior of the coating if they are machined open by the following honing process. The open pores at the functional surface of the cylinder bore act as micro cavities, which are able to store a certain amount of oil thereby improving the frictional behavior of the surface as shown in Figure 4.16 . The recommended oil storage capacities are between 0,050 – 0,070 mm3/cm2 for the pores and 0,014 – 0,018 mm3/cm2 for the honing topography.

The surface is similar to cast iron liners in that it is characterized by the honing grooves which store a certain amount of oil to lower the friction between the piston rings and the bore wall. Since thermally sprayed coatings contain some porosity that is machined open by the honing process, the surface provides an additional oil storage capacity.

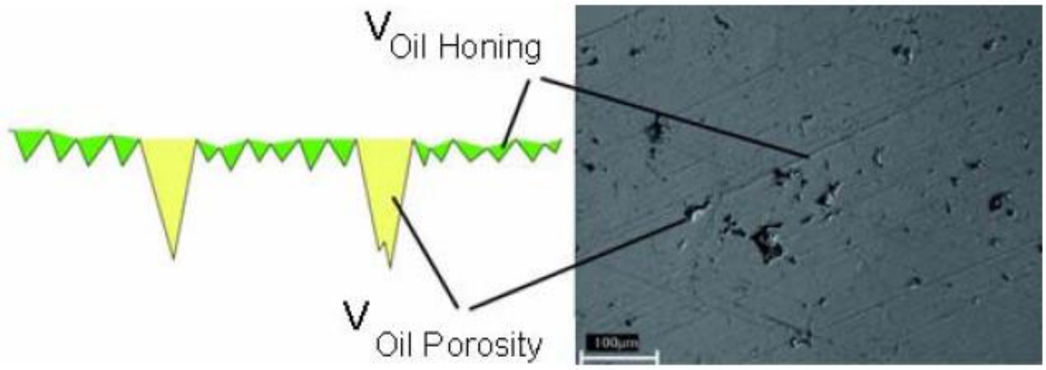


Figure 4.16 : Schematic of the different oil storage capacities of a thermally sprayed and honed coating (left), SEM-picture of a honed surface (right) [7].

Figure 4.17 shows a cross section of a honed PTWA thermal spray coating. The micrograph shows some porosity within the coating, pores which were machined open at the surface and some finely distributed Wuestite particles [7].

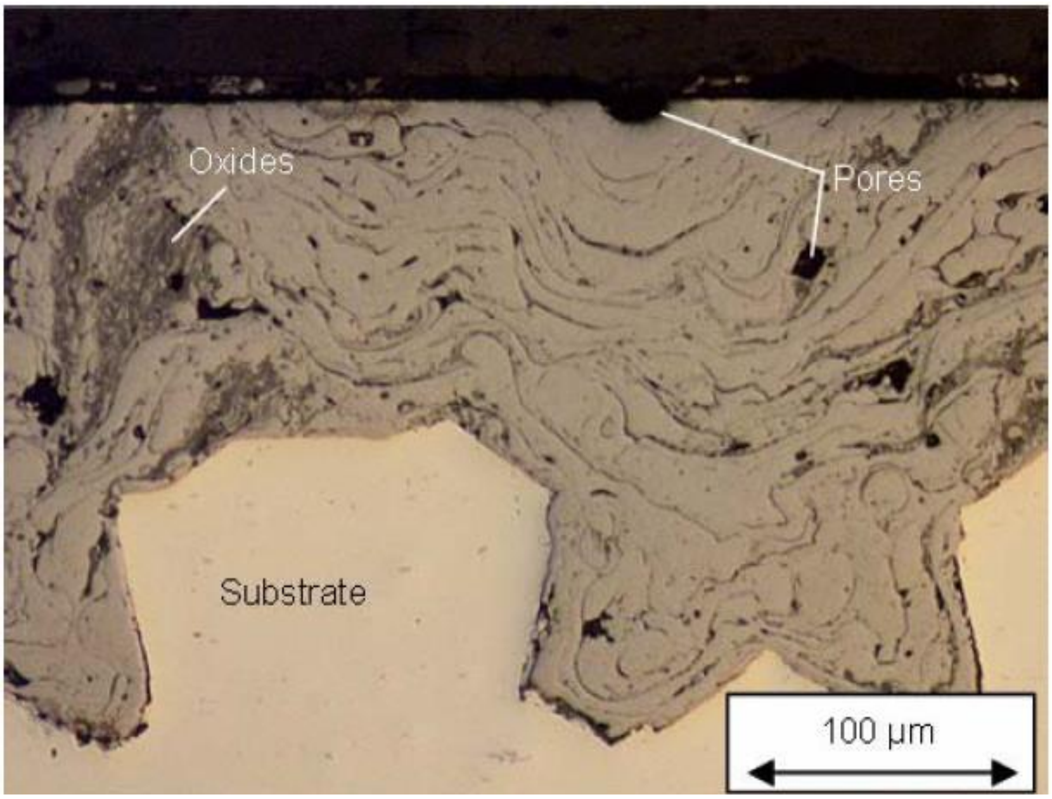


Figure 4.17 : Cross section of a 0.1 % C-steel coating applied with the PTWA system [7].

One of the key advantages to the Fe/FeO coating for wear resistance is obviously the cost of the material. By using the PTWA process it is possible to achieve this excellent wear resistant Fe/FeO coating by spraying low cost, low carbon steel wire with an air atomizing gas. This means that the feedstock cost can be as low as \$0.50 - \$0.75 USD per pound.

The Ford patented Fe/FeO coating system has proven to meet and in many cases exceeds the performance of cast iron, and is finding more utilization in the thermal spray and automotive industry as an alternative wear surface to cast iron [8].

The wear resistance of the plasma sprayed coating is significantly higher in comparison with cast iron. The wear rate in the critical area of the top position of a piston ring is about 5 nm/h of service, also in the case of high loaded diesel engines. These combinations of behavior properties are the result of the obtained topography after finishing by diamond honing. A smooth surface with micro cavities due to the residual porosity of the plasma coating gives excellent conditions for the hydrodynamic lubrication in a large window of pressure and velocity [31].

4.2.4.3 Advantages and drawbacks of PTWA thermal coating application

Advantages of plasma sprayed coatings for cylinder bores include the reduction in the cylinder block bore-to-bore distance, reduction in the friction between the piston rings and the liner surface, increase in fuel efficiency, and reduction in the oil consumption. Additionally the wear resistance of the plasma sprayed coating is higher than cast iron.

The best alternative for reducing friction is the thermally sprayed coating material. The coating is extremely hard and its ability to retain a layer of oil for lubrication during operation is key for reducing the coefficient of friction.

Another advantage of PTWA thermal spray coating is to avoid of using cast iron liners in aluminium cylinder blocks and to increase the fuel economy of a given engine by replacing hte cast iron liners. Typically the aluminum alloys and the coatings can increase the vehicle’s fuel economy on average by 3 to 5% [4].

On the other hand, truck engine manufacturers are under increasing pressure to reduce emissions. Permitted levels of NOx and emitted particles are set to drop by more than 90% in less than a decade from now on . Improved combustion and injection systems, particulate filters, Selective Catalyst Reduction (SCR), Lean NOx Trap (LNT) and Exhaust Gas Recirculation (EGR) are some of the methods applied and under further development to deal with these emissions. The EGR technique, however, increases the amount of particulate matter produced, as a consequence of a lowered air to fuel ratio and a reduced amount of air entering the engine [32]. With high wear resistance property, PTWA coating will probably become most applicable solution with increase of EGR rates in the future.

The most basic of the drawbacks of the thermal spray coatings is the possible weakness of the bond between the coated material and the aluminum. If the coating is not applied properly or pre-treatment is insufficient to achieve required bond strength, over time de-lamination can occur, stripping away the coating and exposing the block material. Once that happens, premature wearing occurs and eventually the engine will lose compression resulting in engine failure.

Another concern with thermal spray coatings is the initial capital investment of the spray equipment. In order to coat cylinder blocks, existing production lines in the plant will need to be either modified or new ones created to allow for the cylinder blocks to be prepped and coated with a thermal spray process. The automaker would then be relying on volume and reduction in cost per unit to ensure a timely buyback period [4].

5. CYLINDER BLOCK REMANUFACTURING

5.1 Case For Remanufacturing

Wear of the cylinder bore results in the increase of clearances between the cylinder and the piston, and clearances in the ring end gaps. This leads to the increase in gas leakage from the combustion chamber to the crankcase (blow-by). The decrease in combustion chamber tightness is disadvantageous for the engine, as it has consequences which include: a) drop in performance, b) increase in fuel consumption and emission of toxic exhaust gasses, c) acceleration of the degradation of engine oil and, consequently, the wear of components, and d) deterioration of the colt start properties of the engine. Excessive increase in the blow-by is identified with the wear of the whole engine. Therefore, the wear of the cylinder, piston and rings often determines engine durability or the necessity for general overhaul [33].

Cylinder blocks with following conditions often require to be reconditioned for proper engine performance.

5.1.1 High-polished running surfaces of the cylinder

Bright, mirror-finish cylinder surfaces without any more honing grooves are either the result of natural wear after a long running time, or caused by dirt and mixed friction after a short running time.

The fact that all honing grooves have been removed due to wear is a sure indication that a cylinder bore is worn. Re-measuring using appropriate measuring equipment is no longer necessary. In any event, such cylinder bores should be replaced (cylinder liners) or newly bored and honed (engine blocks).

Locally restricted bright spots on the cylinder sliding surface after a comparably short running time (the honing pattern in this area is also completely removed) are evidence that the area where the bright spot has been formed has been exposed to mixed friction, resulting in increased wear on the cylinder wall [34].

5.1.2 Locally restricted bright spots due to cylinder distortions

Cylinder distortions caused out-of roundness at certain point inside the cylinder bore. The position of the bright spot, as shown in Figure 5.1, is identical with the point of origin of the distortion. The piston rings pass these constrictions and remove material there. Insufficient lubrication and mixed friction are caused by the constriction whenever the piston ring slides over the raised spot and consequently touches the cylinder wall.

Figure 5.1 : Polishing due to local bore distortion [34].

Causes:

- Thermal distortion due to local overheating which is caused by poor heat transfer (contamination) to the cooling agent.
- Non-observance of specified tightening torques, using wrong O-rings or other distortions as a result of tightening.

Remedies:

- Through cleaning and, if necessary, refinishing of the cylinder counter bore of wet and dry cylinder bores.
- Exact compliance with tightening specifications when installing the cylinder head.

- Regular cleaning of the cooling fins on air-cooled finned cylinders
- Ensuring the specified function of the cooling system (speed, cleanliness).
- Using the prescribed sealing rings (dimensions, material composition) [34].

5.1.3 Bright and polished spots on the upper cylinder section (bore polishing)

There are bright spots in upper section of the running surface of the cylinder liner travelled over by the piston top land as shown in Figure 5.2. These spots are caused by hard deposits on the top land due to irregular combustion, poor oil quality or low combustion temperatures, caused by frequent idling periods or part-load operation. The carbon layer results in abrasive wear on the cylinder wall, an interrupted oil film, mixed friction, increased piston ring wear and consequently in high oil consumption.

Figure 5.2 : Upper bore polishing [34].

Remedies

- Proper engine operation
- Using the specified oil qualities
- Using branded fuels
- Proper maintenance, inspection and adjustment of fuel injection system [34].

5.1.4 Top ring reversal bore wear

Top ring reversal bore wear, as shown in Figure 5.3, appears at the reversal points of the piston rings at the top and bottom dead center after a longer runtime. The piston speed is reduced in this section, and even stops briefly at the reversal point. This reduces the lubricating effect, since the piston ring is no longer floating on the oil film due to the lack of relative speed to the cylinder wall and comes into metal contact with the cylinder wall. The example of water skier makes this clearer. As soon as the speed of the boat is inadequate the water skier sinks into the water.

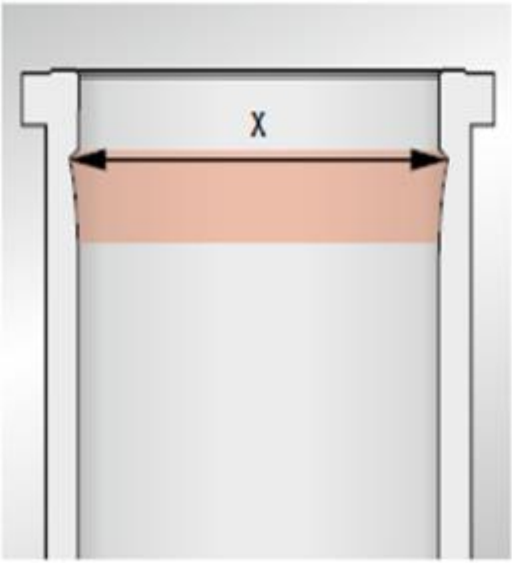


Figure 5.3 : Top reversal bore wear [34].

Due to design, wear on the top ring reversal bore is most pronounced in the piston ring reversal section close to the top piston dead center, because the cylinder surface is exposed to hot combustion at that point which affects lubrication.

The extent of top ring reversal bore wear is decisive on whether the cylinder liner or the engine block may be reused or not. If the top ring reversal bore wear exceeds the values specified in Table 5.1, the engine block re-honed [34].

Table 5.1 : Top reversal bore wear limit [34].

Engine design	Top ring reversal bore wear limit "X"
Petrol engines	≥ 0.1 mm
Diesel engines	≥ 0.15 mm

5.2 Methods Of Cylinder Block Remanufacturing

The remanufacturing of engine blocks with worn cylinder running surfaces depends on the engine block concept as well as on the engine block material. Standard engine remanufacturing processes for monolithic or heterogeneous engine concepts (blocks with cast, pressed or shrunk in cast iron liners) typically involves one of the following solutions [10]:

a. Machine the cylinder bore oversize and use oversize pistons and rings

b. Machine cylinder bores oversize and install thin wall liners and use standard pistons and rings

c. In some engines that were designed with replicable liners, remove and scrap old liners and replace worn liners with new liners [7].

The cylinder bore re-conditioning steps are summarized in Figure 5.4.

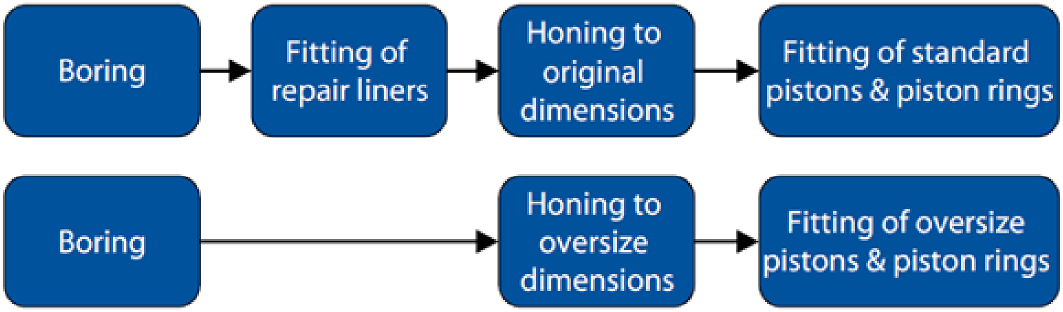


Figure 5.4 : Procedures to remanufacture engine blocks [10].

5.2.1 Remanufacturing by using oversized piston and ring set

To correct bore wear and make the cylinders straight again, the cylinders must be enlarged to the next oversize by honing or boring. Boring is fast, but leaves much too rough a finish for today's rings. Even with a properly sharpened tool, boring tears up the surface as it plows through the metal, leaving behind microscopic furrows, fractures and pits—all of which must be eliminated to produce a compatible surface for the rings to seat against.

Removing the surface rubble means taking the cylinder down to base metal (undisturbed metal) by finish honing after boring. It is suggested leaving 0,075-0,125 mm of material to allow for finish honing after cylinder boring when using 70 grit conventional stones (aluminum-oxide or silicon-carbide).

If the cylinder is being oversized by a rough honing operation, the surface won't be torn up as badly. What's more, the cylinder won't have to be enlarged as much, which means a smaller oversize can be used (which may double or triple the life of the block by allowing future reconditioning).

If honing to oversize, the coarse scratches left by a 70-grit aluminum oxide or 100-grit diamond metal-bond stone will have to be eliminated during finish honing. Not as much metal will have to be removed, but you should still leave about 0,075-0,125 mm for 70-grit aluminum oxide and 0,125-0,175 mm for 100-grit metal-bond diamond stones for finish honing following the rough honing operation.

Regardless of the process that's used to take the cylinder to oversize, process should be checked periodically with a good quality dial bore gage to make sure the bores are within specifications. In general, taper should not exceed 0,025 mm over nominal diameter, and out-of-round should be held to less than 0,13 mm. Measurements in at least places (top, middle and bottom) to check for straightness, and in two directions 90˚ apart to check for size variations [35].

5.2.2 Remanufacturing by liner installation

In case of one cylinder is damaged or passed the wear limit while others are OK, it may be less expensive to have that cylinder sleeved instead of scraping a block. On the other hand It's also possible the block cannot be bored because it's already to maximum oversize or a certain bore size must be retained. This is a situation where it may be desirable to sleeve all cylinders.

There are essentially two types of dry cylinder liners that are used in grey cast iron engine blocks. One version is referred to as a ‘’slip fit’’ liner, and the other a ‘’press fit’’ liner.

The name itself explains the way in which these liners are installed. The construction is the same for both liners. Both versions have an outside diameter that is manufactured to size and often a liner flange in the area of the cylinder head mounting surface. The only difference-without taking into account the dimensions is that with press fit liners the cylinder sliding surfaces must still be finished (honed) after liner fitment, while the slip fit liners are already finished and honed.

The advantage of both types of construction is that engine block can be reconditioned again and again by installing new cylinder liners. The slip fit version can be installed in the workshop by any mechanic even without the support of machines.

a) Slip Fit Liners;

Compared to the cylinder counter bores, these liners have a slightly smaller diameter. Because of the resulting installation clearance of 0.01 to 0.03 mm, the liners can be installed and removed manually without much force. With this type of design the liner flange is absolutely necessary to secure the liner in the intended position inside the engine block during engine operation. The liner flange is clamped down in the engine block and fixed in an axial direction by the surface pressure of the cylinder head gasket. The disadvantages of the slip fit liner are the low clearance between the cylinder liner and the liner counter bore and the resulting, somewhat reduced, thermal transfer between the liner and the engine block.

b) Press Fit Liners;

Compared to the cylinder counter bores, press fit cylinder liner have a slightly larger outside diameter. Because of an overlap of 0.03 to 0.08 mm (depending on the diameter of the liner), the liners have to be pressed cold into the engine block by a press. For this purpose, liners can be cooled by nitrogen. However according to lessons learnt from remanufacturing companies, machining of bores should be performed several hours after cold insertion to have equal temperature for the assembly to achieve good bore distortion. On the other hand, because of the pressure used to force-fit the liners into the engine block, the liners can become slightly oval and uneven during installation. To take this into account, the cylinder liners come with a smaller inside diameter of approximately 1 mm (semi-finished) and must still be adjusted to size by drilling and honing after press fitting. Because this kind of liner has a press fit inside the engine block, a liner flange is not absolutely necessary, or is not provided to fix the liner in the engine block for some engine designs. But in the case of press fit liners with a liner flange it is recommended that it be retained. Especially in critical operating situations, when the piston is seized inside the cylinder, the surface pressure on the outside diameter of the liner is often nor sufficient to hold the liner in position. It is pulled downward by the frictional grip of the piston when it is being seized and crushed properly by the crank web of the crankshaft.

In calculating the exact geometry of the liners to be made, it is recommended that the liner walls be kept as thick as possible before shrink-fit. In other words, the liner walls will be reduced to the desired thickness of 1.5 to 3 mm by drilling and honing after shrinking and finishing. This way the liners will remain as round as possible before and during installation and will be able to be inserted well into the cylinder counter bore. Because of the increased thickness of the material, it will take more time for the liner to be fixed during the shrinking process. When the liner is being made, the measurement of the outside diameter will also be more exact than for a very thin liner, which can be deformed by a few 1/100 mm solely by the pressure of the measuring instrument.

When the cylinder liners inserted for repairing are being drilled, especially those made of grey cast iron, it is important to select a feed and material removal that is not too great. This is to prevent excessive local heating of the liner and the engine block. Excessive heat entering the engine block from the drilling could cause the liner to come loose and turn in the engine block as a result of the different thermal expansion of the engine block and the inserted liner.

For inserted grey cast iron liners, the material removal from drilling must not be more than 0.1 mm. this value applies also to grey cast iron liners pressed into grey cast iron cylinders.

In general, during machining all heat build-up should be avoid or minimized. Adjacent cylinder bores should be drilled only after the engine block has cooled off again. To prevent thermal problems, experienced engine re-conditioners always skip the adjacent cylinder when drilling and first drill the next cylinder after the adjacent one. To avoid thermal problems, it is recommended that the use of cooling lubricant (oil/water emulsion) when drilling. Cooling lubricant is also used in the series production of aluminium engine blocks, which improves the surface quality of the cylinder bores as well as the product life of the cutters [12].

5.2.3 Remanufacturing of originally sleeved cylinder blocks

Some engines are manufactured with replaceable cylinder sleeves. Sleeves can be renewed to restore perfect engine balance, meaning that the compression and displacement will not change.

There are two styles of sleeve assemblies—dry and wet. Dry sleeves are those whose outer surface does not contact the engine coolant. Typically, dry sleeves do not require a seal to keep out coolant liquids. We sleeves are those whose outer surfaces come into contact with the engine coolant. A packing (paper gasket, metal gasket, or ‘’O’’, or quad ring) is used to keep the coolant away from the piston and crankcase [35].

5.2.4 Remanufacturing by PTWA thermal spray application

Service-exposed engine blocks often exhibit unacceptable wear of the cylinder running surfaces. Depending on the engine architecture engine blocks can be remanufactured by using oversize pistons or by re-linering. However, modern engines sometimes do not permit these solutions due to the remaining bore bridge dimensions [10].

The overall dimensions of the engine blocks are reduced to such an extent that replaceable liners are not originally designed into the engine and the other standard remanufacturing processes of re-lining or machining the cylinder bore oversized are no longer possible due to the reduced bore bridge. Most of these engines have to be currently scrapped and replaced with new engine blocks [7].

On the other hand, the different thermal expansion coefficients of grey cast iron and the engine block material can cause a deformation of the liner and also local heat transfer problems (heat pockets) if the liner disengages from the engine block . The deformation of the liner leads to increased oil and fuel consumption (blow-by) and increased emissions [30].

For these modern engines PTWA spray repair process using conventional 0.8 % C-Steel is used for remanufacturing. In addition, this repair process can also result in cost savings as compared to standard remanufacturing process on existing cast iron and aluminium engines [10].

As remufacturing of cylinder blocks by PWTA thermal spray application is main focus of this thesis, details about PTWA remufacturing will be discussed in detail on following chapters including detail of previous works studied on PWTA remanufacturing.

6. THESIS WORK

6.1 Previous Studies

6.1.1 Ford puma engine cylinder block remanufacturing

Ford approved /released PTWA thermal coating for all Puma engine cylinder block manufacturing in 2010.

The study was conducted by Ford of Europe service engineering. According to FCSD (Ford Customer Service Division), they considered tradional remanufacturing methods such as oversizing and liner installation before implementing PTWA process for Puma cylinder block remanufacturing. However, the design of the block and the level of bore distortion limited the possibility of using the overbore approach so they had to dismiss the oversizing option and moved to liner intallation option.

Three engines were linered and were tested on hydropulse rig.All three failed due to cracking.The resulting failures of the block or major degradation of its structural performance meant that this approach would have reduced the second life of the engine to a level where it would not pass the sign-off criteria a service engine is expected to meet. In addition they found that the liner degraded the rate of heat transfer away from the bore, adding to the distortion of the liner, the temperature of the piston and the oil and increased the events of Piston Scuff. Investigation also showed that as the liner distorted, then the contact between the liner and the block reduced and there was some evidence of block fatigue around the remaining material holding the liner. It was considered that over time this area would fail with material going into the engine.

The remaining option PTWA had been available. Using the Plasma process, the cylinder still has to be machined but this is less than the other two methods thereby maintaining a greater level of the blocks structural integrity and reducing the negative effects seen by the other two processes. In addition once wire specification is fixed that was compatible with the ring material, it is possible to create a process that would allow proceeding with the technique. Furthermore, additional benefits were realized when using PTWA, namely reduced friction through better ring lubrication and reduced wear to the piston, rings and bore when compared with a standard engine when both had completed the 1202 hour durability and better and more controlled heat transfer again reducing the risks causing failure. The same was seen during the other tests completed especially the Piston Scuff tests.

For the full validation of PTWA for Puma cylinder block remanufacturing, team performed the following test for final sign off;

- Bore distortion analysis
- Bond strength testing
- Hydrodynamic pulse
- Piston thermocycle scuff
- Deep thermal shock
- General durability
- Fleet testing

After completion of these test without failure related with PTWA thermal coating, Puma Global cylinder block remanufacturing engineering specification was released.

A schematic of the PTWA spray repair process chain is shown in Figure 6.1. First, the complete engine block is washed and the worn bores are machined oversize to remove all the wear. The third step is the activation of the bore wall in order to enable good bonding between the engine block and the coating. The next step is the application of the thermal spray coating with the Ford patented PTWA process. After thermal spray, the coated bore has to be honed to its original dimensions, so that OE pistons and piston rings can be fitted.

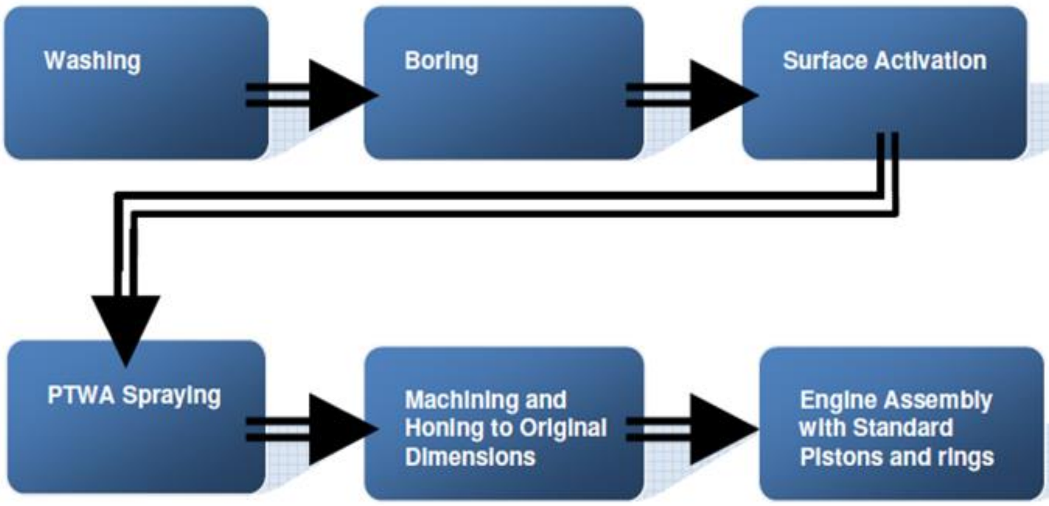


Figure 6.1 : Schematioc of spray repair process.

The wire used is 0.8% C, 0.7% Mn and 0.3% Si with balance Fe. Applied thickness is 0.350mm [36,37].

6.1.2 Other engines

Within the frame of [10] several petrol and diesel engine blocks have been successfully refurbished by PTWA spraying:

a) Land Rover 3.5L and 4.2L V8 petrol engines (AlSi engine blocks with cast in grey castiron liners),

b) Monolithic BMW 4.4L petrol engines (hypereutectic AlSi engine),

c) Ford Puma 2.4L, monolithic 4 cylinder cast iron block.

With all engines, first the bores were bored up to an oversize of 300 µm in diameter since the required minimum coating thickness is 150 µm. Because of the "as sprayed" roughness of the coating and the required machining allowance, the thickness of the "as sprayed" coating(s) is typically around 200 – 300 µm. In the second step the bore walls were slightly roughened with a dry honing process in order to enable bonding between the bond coat and substrate. All top coats were made from 0.8 wt.-% C-Steel (1.0616 in accordance to DIN EN 10016-1) [10].

Study in [7] was also focused on using PTWA coatings for cylinder bore remanufacturing; Actual piston rings from a Caterpillar 3116 engine and the Land Rover TD5 engine were mounted in a wear tester to reciprocate the rings against the thermal spray coated samples. The tests were conducted to measure ring and bore wear on a TE 77 (ISO 12156) High Frequency Reciprocating Rig (HFRR) for wear and scuffing tests as shown in Figure 6.2.

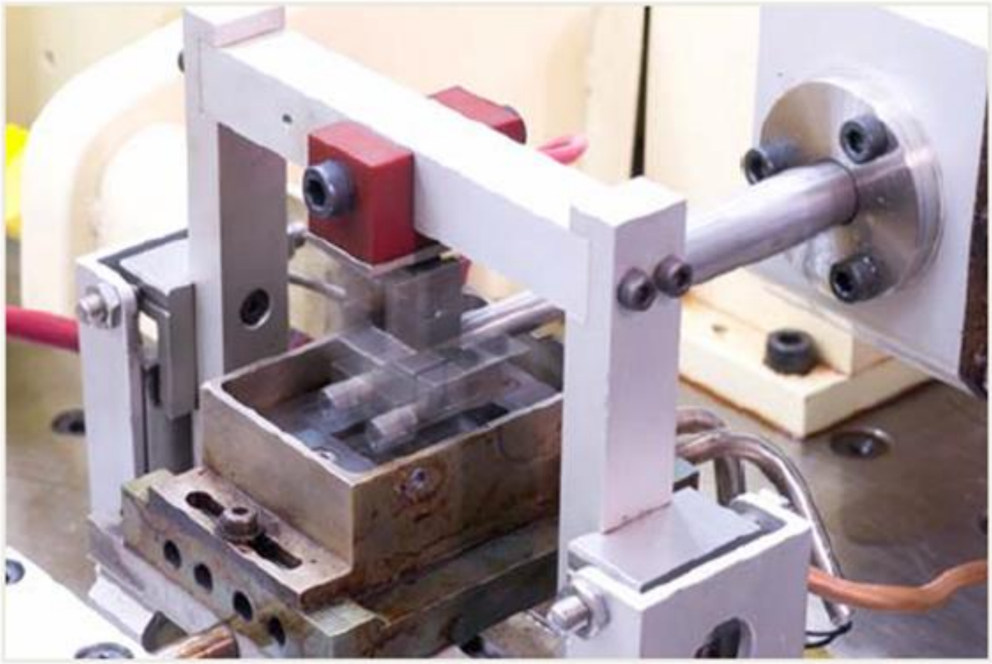


Figure 6.2 : Wear test equipment at the caterpillar research and development center (Peoria, IL) used to test the thermal sprayed low alloyed carbon steels.

Samples were produced with the PTWA thermal spray process using three different spray wires: A low carbon steel, a medium carbon steel and a high carbon steel. The results of these tests shown in Figure 6.3 for the TD5 rings were similar to results seen for the Caterpillar 3116 rings. Results from testing both rings demonstrated that of the low alloyed carbon steels evaluated, the high carbon steel spray material showed the lowest bore wear with ring wear similar to the other samples. The hardness of the high carbon steel coatings reaches values of 650 HV 0.1 to 750 HV 0.1 depending on the coating parameters.

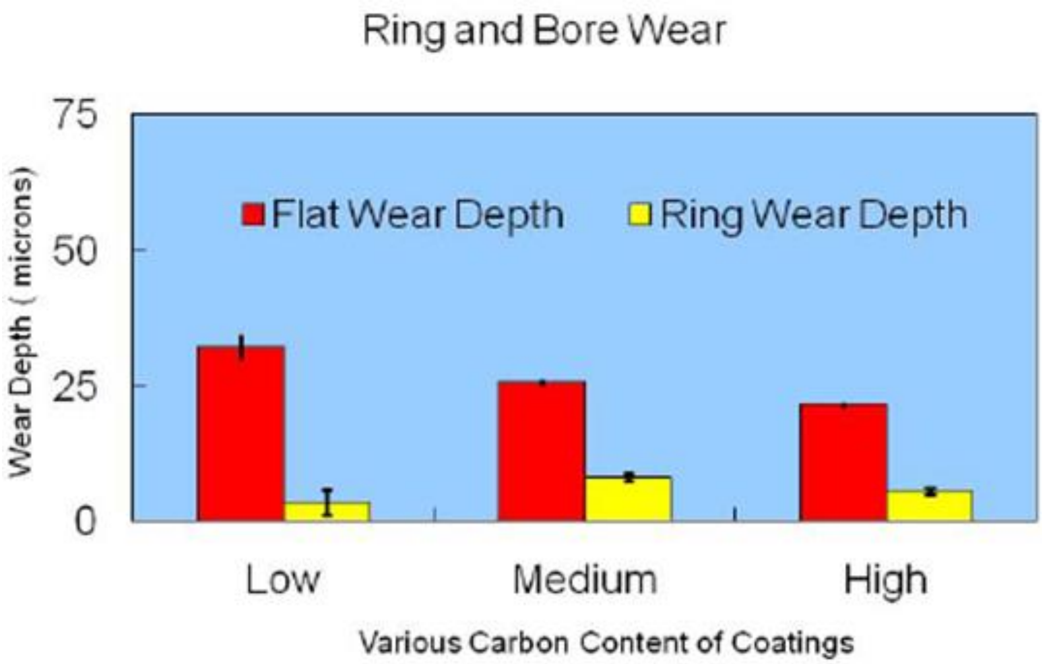


Figure 6.3 : Wear test results from reciprocating testing of TD5 piston rings on PTWA thermal spray coatings.

For confirmation on running engines many different engines including gasoline and diesel engines from several manufacturers have been tested in engine dynamometer and vehicle fleet testing. In addition, spray repair has also been tested on several different engine block materials including grey cast iron, compacted graphite iron, and hyper and hypo eutectic aluminum alloys. Some of PTWA spray repaired and tested engines include the following: Jaguar AJ27, Jaguar AJ33, Land Rover TD5, Ford 2.7L Diesel, Ford Zetec, BMW M62, and Caterpillar 3116. The Caterpillar 3116 is a heavy duty diesel inline 6 cylinder engine that is rated up to 205 kW (275HP). This engine has successfully completed dynamometer and vehicle testing. This engine was torn down after 900 hrs vehicle running and demonstrated no measurable ring or bore wear. Land Rover test facility where the BMW M62 engine was installed in a Range Rover and run for over 120,000 km. Tear down and inspection of the tested PTWA remanufactured engine showed only 3μm of bore wear and no measurable ring wear.

In addition, several Land Rover TD5 engines have been successfully thermal spray repaired using the PTWA process. These engines have been successfully tested in dynamometer and vehicle testing. Land Rover has recently approved the PTWA thermal spray repair for remanufacturing production and a PTWA thermal spray system has been installed at the Caterpillar Remanufacturing facility (Shrewsbury, UK) to support this application [7].

With the study in [8], wear of PTWA thermal spray coated bore was compared with wear of plain bore. the coating was evaluated on a production 4.6L V-8 engine in a series of dynamometer tests. This extensive dynamometer test plan involved over 20 different engine tests included the following:

- 50 hour piston and gasket test
- 100 hour thermal shock test
- 20 hour deep thermal shock test
- 50 hour piston hot scuff test

To compare the performance of the coating to the baseline cast iron liner materials, it was necessary to run two identical series of dynamometer tests. One was performed on an all-aluminum block with the PTWA applied Fe/FeO coating, and one was performed on a standard production engine block. Otherwise, both engines were built with all standard production components including pistons and piston rings. Both engines underwent a 220 hour series of severe engine tests. Bore wear and ring wear of the three rings were measured. Bore wear was measured at the top of the cylinder bore near the ring reversal (the area which would show most significant bore wear), and ring wear was measured by evaluating the gap change in the piston ring after the engine test. The wear performance of the coating compared to the cast iron baseline material was also evaluated. Bore wear and ring wear were measured, and the results are shown in Table 6.1. These results show that thermally sprayed 1010 steel coating performs as well or better then the cast iron baseline material.

Table 6.1 : Wear comparison.

	Engine with Cast Iron Liners	Engine with Thermal Spray Coating
Bore Wear (μm)	2.9	2.0
Top Ring Wear (μm)	117	108
Second Ring Wear (μm)	165	152
Third Ring Wear (μm)	10	10

In addition to the extensive dynamometer testing, a 32 vehicle test program was conducted to verify the function and durability under real world customer conditions. Fleets were run in nine individual North American locations to capture the full range of climatic conditions. The 32 vehicles accumulated over 3.2 million test miles with zero coating failures. Multiple vehicles achieved over 250,000 miles, and all exhibited excellent performance including piston and ring wear, power output, oil consumption, and vehicle emissions. The completed vehicle fleet test demonstrated full compliance with all Ford Product Engineering functional and durability requirements [8].

6.2 Remanufacturing Of Ecotorq Cylinder Block By PTWA Thermal Coating Application

6.2.1 PTWA coating application

6.2.1.1 Activities before coating

When we consider even Ford EU is not very familiar to application of PTWA to a HD engine, PTWA application to Ecotorq 9.0L cylinder block is a challenging topic. The main goal of study is utilization of PTWA coating in view of wear resistance that affects to power, oil consumption and blow by. According to results of the study, remanufacturing of the block bores with PTWA can be considered for future works.

The followed process is the same as described for Puma blocks in Figure 6.1.

The activities before coating are:

- Differently from serial production, Inonu Plant machined only fire deck surface of block and bores.
- 0.5 mm stock was left on fire deck surface of block during machining
- Bores were fine bored and roughened 0.5 mm oversize in diameter (Actual bore diameter: 115 mm, oversize bore diameter: 115.5 mm)
- Honing was not performed, only dry roughing was applied without coolant
- VCI paper (rust proof brown paper) was used for packaging
- All bores were covered with VCI paper attentively
- Final machine in Ford Otosan plant (IEP)

6.2.1.2 Coating Material

Selection of coating material and the wire material was the most critical item for the 9.0L block cylinder bores coating. The 0.8%C steel seems to be most applicable one since it is approved for Puma blocks and it has been successfully tested with various engines for remanufacturing purpose. On the other hand, it is known that it has cost advantage over other applicable materials. However we were not sure about the lubrication effect of 0.8%C steel (or wear resistance) when compared with graphite particles in GJV 450 material.

In order to understand the effect of coating with different materials and prove the effect of 0.8%C steel for Ecotorq engine, two cylinder blocks were coated. One was coated with 0.8%C steel for all 6 bores while the other one was coated with 0.8%C (A), 17% Cr steel(B) and 20%Cr-5%Al(C) per two bores as shown in Figure 6.4.

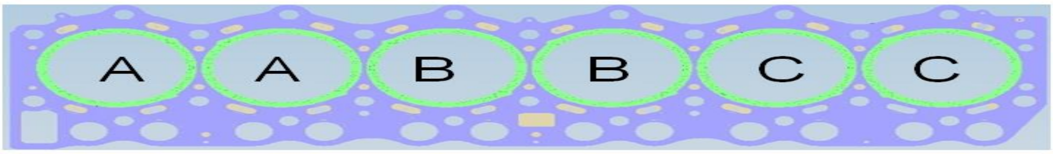


Figure 6.4 : “A” with 0.8%C, “B” with 17%Cr and “C” with 20%Cr-5%Al.

Cost comparison on coating materials showed us that 17% Cr steel was two times higher than 0.8%C steel while 20%Cr-5%Al was three times higher. So 0.8%C steel is thought to be the best option for cylinder block remanufacturing.

6.2.1.3 Honing

Honing operation was conducted by Gehring with D30 honing stones according to honing specification of 9.0L block to allow usage same piston ring pack. The honing specification is represented in Table 6.2.

Table 6.2 : Honing parameters for Ecotorq cylinder block.

Ra	0.3 – 0.7 µm
Rz	3 – 5,7 µm
Rpk	< 0.3 µm
Rk	0.6 – 1.6 µm
Rvk	1.2 – 3.2 µm
Mr1	< 10%
Mr2	70 % – 90 %

The engines were numbered as BB37 and BB49. BB37 was coated with only 0.8%C steel while BB49 was coated with 3 different materials per two bores.

Pre-test measurement results of BB37 cylinder block diameter are summarized in Table 6.3.

Table 6.3 : Deviation from bore specification in BB37 cylinder block.

	BB37											
	1.Cylinder		2.Cylinder		3.Cylinder		4.Cylinder		5.Cylinder		6.Cylinder	
	0°	90°	0°	90°	0°	90°	0°	90°	0°	90°	0°	90°
20mm	-11	-3	-6	-4	-25	-8	-18	-6	-10	-8	-14	-2
60mm	-6	-2	-7	-4	-16	-8	-13	-6	-10	-8	-8	-4
105mm	-4	-3	-7	-3	-12	-7	-10	-5	-10	-6	-6	-7
140mm	-3	-1	-8	-3	-9	-6	-9	-5	-9	-6	-7	-6
195mm	-3	-1	-15	-3	-8	-5	-9	-5	-8	-6	-8	-6
						-8						
Avarage	-3,7		-6		-10,4		-8,6		-8,1		-6,8	

The Table 6.3 shows that diameters are smaller than specification so special rings needed to be ordered for smaller diameter cylinder bores. Diametrical tolerance is 0/+0.022mm.

After honing operation, honing parameters were measured before test for BB37 cylinder block. Honing parameters measurement results is represented in Table 6.4.

Table 6.4 : BB37 Pre-test honing parameter measurement.

					BB37																	
					Cylinder 1			Cylinder 2			Cylinder 3			Cylinder 4			Cylinder 5			Cylinder 6		
					0°	90°	Average	0°	90°	Average	0°	90°	Average	0°	90°	Average	0°	90°	Average	0°	90°	Average
Ra	0,3-0,7	µm	25	mm	0.22	0.35		0.19	0.21		0.2	0.21		0.22	0.17		0.22	0.4		0.21	0.25	
			120	mm	0.21	0.2	**0.24**	0.2	0.16	**0.20**	0.22	0.14	**0.25**	0.22	0.16	**0.20**	0.19	0.18	**0.24**	0.16	0.19	**0.19**
			180	mm	0.26	0.2		0.18	0.24		0.24	0.46		0.27	0.18		0.22	0.24		0.17	0.16	
Rz	3-5,7	µm	25	mm	5.16	9.59		3.45	4.4		6.18	5.03		4.9	2.85		5.44	7.38		4.02	5.87	
			120	mm	5.27	7.3	**6.22**	5.46	3.58	**4.47**	6.03	2.33	**5.71**	5.2	3.89	**4.35**	3.04	3.95	**5.17**	2.28	5.04	**3.91**
			180	mm	6.56	3.42		4.36	5.55		6.18	8.48		5.76	3.52		4.86	6.37		3.41	2.86	
Rpk	<0,3	µm	25	mm	0.22	0.23		0.23	0.27		0.22	0.16		0.2	0.19		0.19	0.19		0.24	0.19	
			120	mm	0.2	0.21	**0.20**	0.18	0.15	**0.19**	0.16	0.13	**0.17**	0.22	0.15	**0.18**	0.18	0.18	**0.17**	0.22	0.15	**0.18**
			180	mm	0.19	0.16		0.14	0.15		0.16	0.19		0.18	0.16		0.15	0.15		0.14	0.15	
Rk	0,6-1,6	µm	25	mm	0.57	0.54		0.53	0.52		0.45	0.47		0.52	0.49		0.48	0.57		0.58	0.54	
			120	mm	0.49	0.42	**0.49**	0.47	0.41	**0.47**	0.46	0.39	**0.45**	0.54	0.42	**0.48**	0.46	0.42	**0.48**	0.47	0.44	**0.48**
			180	mm	0.48	0.44		0.41	0.47		0.44	0.47		0.48	0.44		0.47	0.5		0.43	0.41	
Rvk	1,2-3,2	µm	25	mm	0.72	2.03		0.61	0.92		0.83	1.08		0.9	0.46		1.02	1.96		0.63	1.25	
			120	mm	0.79	0.94	**1.09**	0.8	0.52	**0.78**	1.01	0.41	**1.31**	0.97	0.59	**0.81**	0.66	0.66	**1.09**	0.34	0.81	**0.69**
			180	mm	1.28	0.77		0.67	1.17		1.18	3.32		1.27	0.69		0.99	1.24		0.58	0.5	
Mr1	<10	%	25	mm	8.97	8.88		10.04	9.53		9.31	9.57		9.16	10.37		9.54	8.9		8.13	9.12	
			120	mm	8.77	8.79	**8.66**	8.59	8.75	**9.03**	9.35	8.19	**8.90**	9.34	9.32	**9.32**	8.38	9.23	**8.39**	7.65	8.7	**8.48**
			180	mm	7.97	8.55		8.58	8.66		8.85	8.13		8.93	8.77		7.93	6.38		8.26	9	
Mr2	70-90	%	25	mm	87.7	86.53		88.97	88.78		86.26	88.47		87.06	89.7		86.78	86.47		87.87	87.74	
			120	mm	85.45	86.06	**85.91**	87.2	85.72	**87.09**	86.32	86.98	**86.73**	88.57	87.07	**87.16**	85.63	86.33	**86.22**	87.75	87.36	**87.16**
			180	mm	85.31	84.43		85.53	86.31		86	86.36		85.03	85.55		85.78	86.35		85.9	86.34	

Due to Rvk parameter being lower than specification, piston scuff issue might be expected as oil film could not be formed properly. On the other hand, it was considered that porous structure of coating would prevent scuff issue.

Measurement results of BB49 cylinder block diameter are summarized in Table 6.5.

Table 6.5 : Deviation from bore specification in BB49 cylinder block.

	BB49											
	1.Cylinder		2.Cylinder		3.Cylinder		4.Cylinder		5.Cylinder		6.Cylinder	
	0°	90°	0°	90°	0°	90°	0°	90°	0°	90°	0°	90°
20mm	15	11	7	8	-6	8	0	3	12	16	-2	-7
60mm	15	11	5	8	-5	8	-1	4	10	17	0	3
105mm	14	12	4	9	-2	8	0	5	11	17	2	-1
140mm	12	13	6	10	-2	7	3	6	13	17	0	0
195mm	11	14	7	8	2	5	5	6	15	16	0	0
Avarage	12,8		7,2		2,3		3,1		14,4		-0,5	

The Table 6.5 shows that diameters are within the specification. Diametrical tolerance is 0/+0.022mm.

After honing operation, honing parameters were measured before test for BB49 cylinder block. Honing parameters measurement results is represented in Table 6.6.

Table 6.6 : BB49 Pre-test honing parameter measurement.

					BB49																	
					Cylinder 1			Cylinder 2			Cylinder 3			Cylinder 4			Cylinder 5			Cylinder 6		
					0°	90°	Average	0°	90°	Average	0°	90°	Average	0°	90°	Average	0°	90°	Average	0°	90°	Average
Ra	0,3-0,7	µm	25	mm	0.25	0.29	**0.21**	0.25	0.2	**0.20**	0.2	0.23	**0.20**	0.19	0.3	**0.24**	0.15	0.18	**0.18**	0.13	0.15	**0.14**
			120	mm	0.17	0.18		0.17	0.2		0.16	0.22		0.23	0.18		0.14	0.15		0.12	0.13	
			180	mm	0.19	0.2		0.19	0.2		0.23	0.15		0.2	0.32		0.27	0.17		0.12	0.16	
Rz	3-5,7	µm	25	mm	5.11	4.81	**4.35**	5.02	3.4	**4.36**	4.85	4.66	**4.75**	4.61	6.51	**6.06**	1.55	2.51	**2.83**	1.67	1.68	**1.90**
			120	mm	3.4	3.79		2.76	3.86		3.3	5.98		6.88	4.24		1.79	2.05		1.22	2.03	
			180	mm	4.61	4.36		4.49	6.65		6.96	2.75		5.42	8.72		5.75	3.3		1.42	3.37	
Rpk	<0,3	µm	25	mm	0.24	0.27	**0.22**	0.18	0.27	**0.20**	0.28	0.19	**0.19**	0.21	0.22	**0.20**	0.26	0.33	**0.25**	0.23	0.24	**0.22**
			120	mm	0.2	0.17		0.21	0.14		0.18	0.15		0.17	0.17		0.21	0.29		0.19	0.2	
			180	mm	0.2	0.21		0.18	0.21		0.19	0.15		0.21	0.2		0.22	0.21		0.18	0.27	
Rk	0,6-1,6	µm	25	mm	0.58	0.57	**0.50**	0.53	0.6	**0.49**	0.56	0.5	**0.46**	0.47	0.5	**0.46**	0.44	0.51	**0.44**	0.39	0.45	**0.39**
			120	mm	0.47	0.43		0.49	0.44		0.41	0.44		0.47	0.41		0.4	0.41		0.37	0.37	
			180	mm	0.45	0.47		0.45	0.45		0.43	0.39		0.44	0.48		0.45	0.41		0.36	0.42	
Rvk	1,2-3,2	µm	25	mm	1.09	1.44	**0.88**	1.18	0.63	**0.78**	0.7	1.11	**0.84**	0.75	2.08	**1.23**	0.23	0.34	**0.58**	0.19	0.24	**0.28**
			120	mm	0.52	0.68		0.47	0.74		0.57	1.12		1.19	0.72		0.35	0.25		0.2	0.34	
			180	mm	0.82	0.74		0.76	0.9		1.09	0.46		0.84	1.81		1.7	0.61		0.2	0.49	
Mr1	<10	%	25	mm	10.33	9.93	**9.55**	8.72	9.93	**8.99**	11.01	7.86	**9.50**	10.82	8.74	**9.32**	12.61	11.71	**11.80**	12.44	11.44	**11.09**
			120	mm	9.48	8.79		8.78	7.88		9.53	9.36		7.8	8.15		11.85	12.16		9.68	10.6	
			180	mm	8.75	10.03		10.08	8.54		10.78	8.43		9.79	10.64		10.76	11.72		10.6	11.77	
Mr2	70-90	%	25	mm	88.31	87.81	**87.38**	87.76	87.88	**86.99**	87.7	87.33	**87.02**	88.14	87.63	**86.79**	88.18	89.02	**88.23**	89.12	89.71	**88.99**
			120	mm	88.73	86.89		87.72	84.97		87.97	87.29		86.48	86.48		88.49	87.84		89.11	88.57	
			180	mm	86.41	86.1		86.85	86.78		85.16	86.67		86.47	85.56		88.14	87.72		88.43	88.99	

The Table 6.6 indicates that honing parameters are out of specification which are worse than BB37 results. So again scuff is an expected issue for this block.

As it can be seen from the Figure 6.5, honing pattern are not visible for BB49. Surface is found to be too smooth.

Figure 6.5 : BB49 Bore surface after honing.

6.2.2 Tribology test

Federal Mogul presented their study on friction, bore wear, and ring wear properties of PTWA coating with different materials in 3rd Ford Global Friction Symposium which was held in April 2012. [38]

The test method was Oscillating Rig Test (SRV System). The test details are represented in Figure 6.6 and Table 6.7.

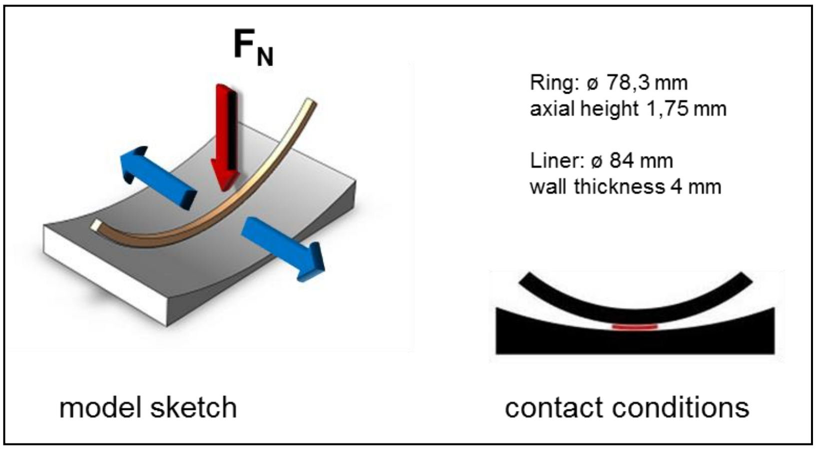


Figure 6.6 : Schematic of test setup.

Table 6.7 : Test conditions

Test Conditions	
Motion	Oscillation
Normal Force [N]	100
Stroke [mm]	4
Temperature [°C]	120
Average Speed [m/sec]	0,32
Frequency [Hz]	40
Duration [h]	4
Oil	5W30 Ford First Factory

Ring and coating materials tested in the study are:

Liner:

PTWA 1 Iron with 0,1% by weight of carbon: Cost efficient feedstock material

PTWA 2 Iron with 0.8% by weight of carbon: Improved wear resistance compared to PTWA 1. First choice for spray repair of “Puma“ diesel engines (Transit)

PTWA 3 Iron with 18% by weight of chromium (316L): Increased corrosion resistance compared to C-Steel materials (important for synthetic and aggressive fuels, e.g. ethanol, high sulphur)

Ring:

Cr-Steel: Benchmark, serial material for top compression rings in gasoline engines nitride

PVD CrN-based: Used in high loaded gasoline engines, best friction coefficient for grey cast iron liners

CKS: Chromium coating with aluminum oxide particles – high wear resistance in diesel engines

Friction coefficient results are shown Figure 6.7.

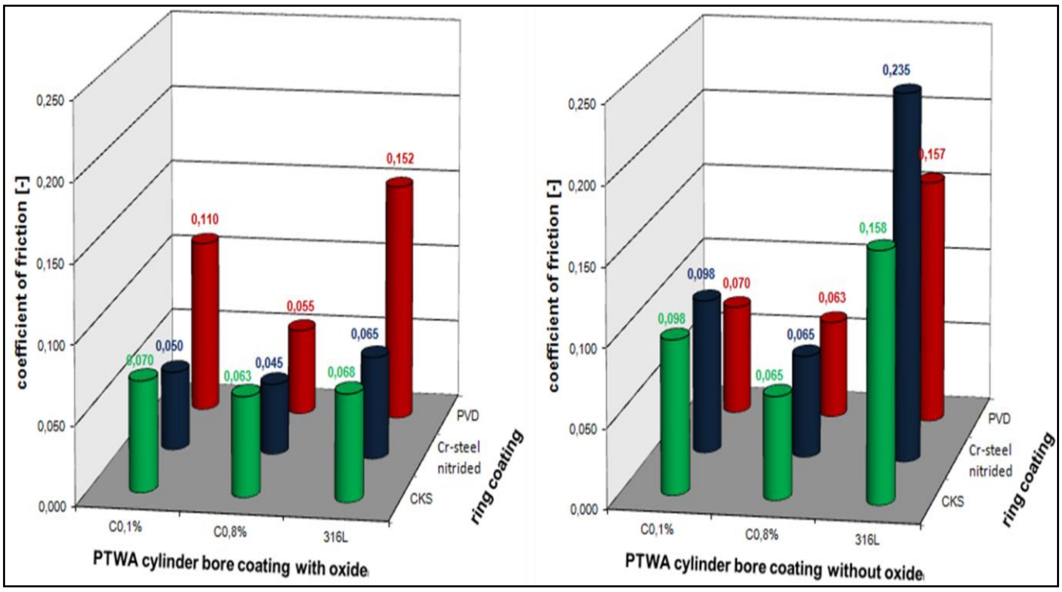


Figure 6.7 : Coefficient of friction.

- Lowest friction measured for nitride ring on PTWA 0.8%C steel with oxide
- Friction is lower for PTWA with oxide compared to PTWA without oxide independent of ring coating
- Highest friction for PTWA 316L without oxide

Ring wear results are represented in Figure 6.8.

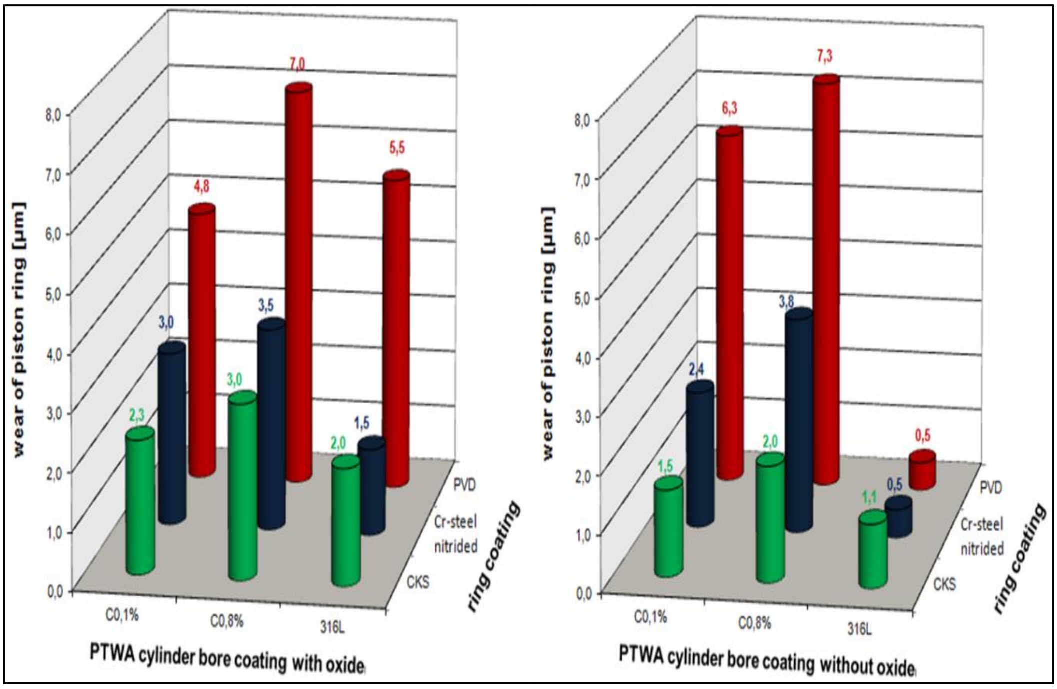


Figure 6.8 : Ring wear.

- CKS: lowest ring wear running against PTWA 0,1%C bore coating without oxides
- Cr-steel nitride: lowest ring wear running against PTWA 316L bore coating with oxides
- PVD: highest ring wear compared to CKS and nitride ring.

Liner wear results are represented in Figure 6.9.

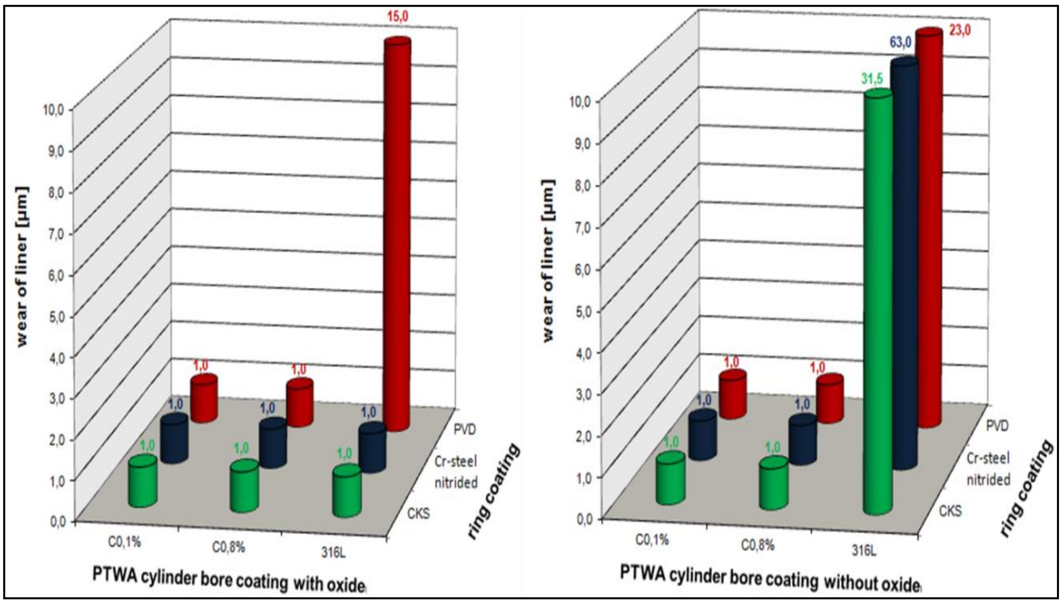


Figure 6.9 : Liner wear.

- Very low wear (~1µm) for PTWA bore coating, except the combination PVD piston ring with 316L with oxide
- Highest wear for PTWA 316L bore coating without oxides

The results of study can be summarized as:

- Lowest friction was achieved with the combination nitride piston ring with PTWA 0.8%C bore coating including oxides
- Lowest total wear (ring and bore) was achieved with the combination CKS coated ring and PTWA 0,1%C bore coating and nitride piston ring and PTWA 316L with oxides
- Taking into account all characteristics (friction, ring and liner wear), the most potential combinations are:

i. Cr-steel nitride ring with PTWA 0.8% by weight of carbon and with PTWA 316L coated cylinder bore including oxides

ii. CKS ring with PTWA 316L bore coating with oxides [38].

The results show that 0.8%C seems the best choice.

6.2.3 Design verification testing

6.2.3.1 Test cycle

400 hours High Speed Test test was defined for the engines built coated blocks with 10W40 Castrol Oil. The reason of selecting this tests are ; a)Test data from previous test which had been performed with standard cylinder block was available for comparison, b) It is a recommended test to see wear of cylinder block and power conversion components including piston and rigs. The aim of PTWA in this thesis is to investigate its durability and wear resistance and to decide if PTWA application for remanufacturing Ecotorq 9L engine is a possible solution or not. During the test engine parameters as power, oil consumption and blow-by would be monitored and compared with previous results to detect any coating wear or delamination. The matrix in Figure 6.10 shows the relation of test and mechanism works.

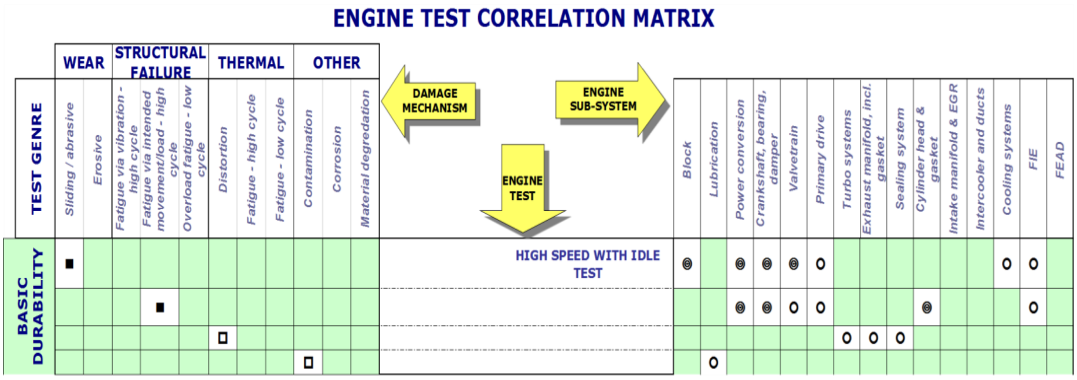


Figure 6.10 : Engine test correlation matrix.

Test cycle is represented in Figure 6.11.

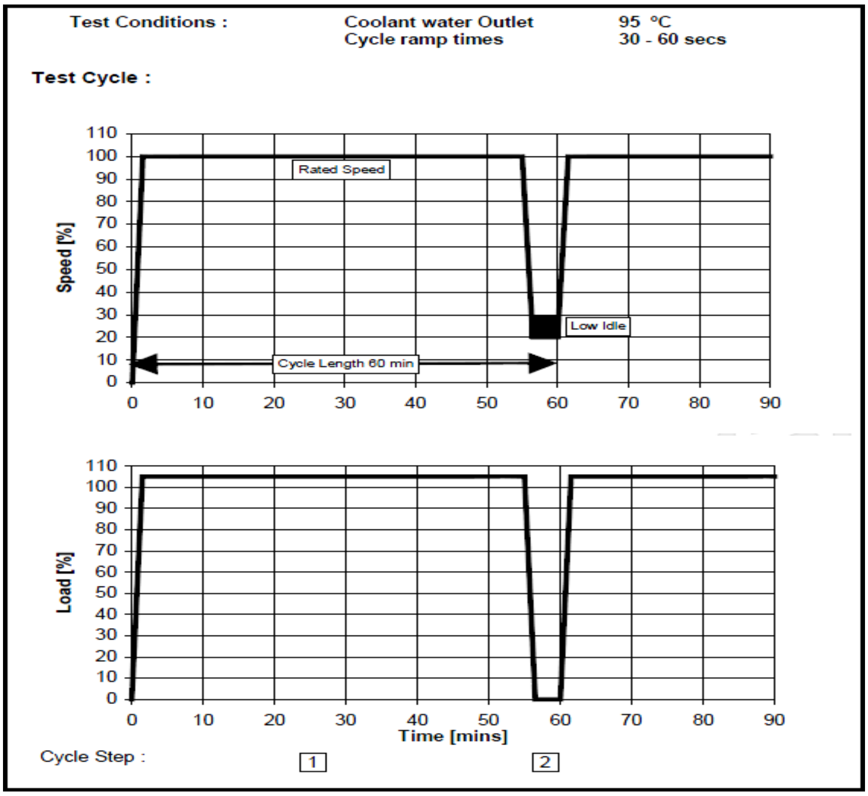


Figure 6.11 : High speed test cycle.

6.2.3.2 Previous tests

The high speed test results of which to be used for comparison was performed with Ecotorq 9L 380 PS engine in 2011. Results showed that power starts from 385PS and drops to almost 370PS.

The power –torque curve from this test is represented in Figure 6.12.

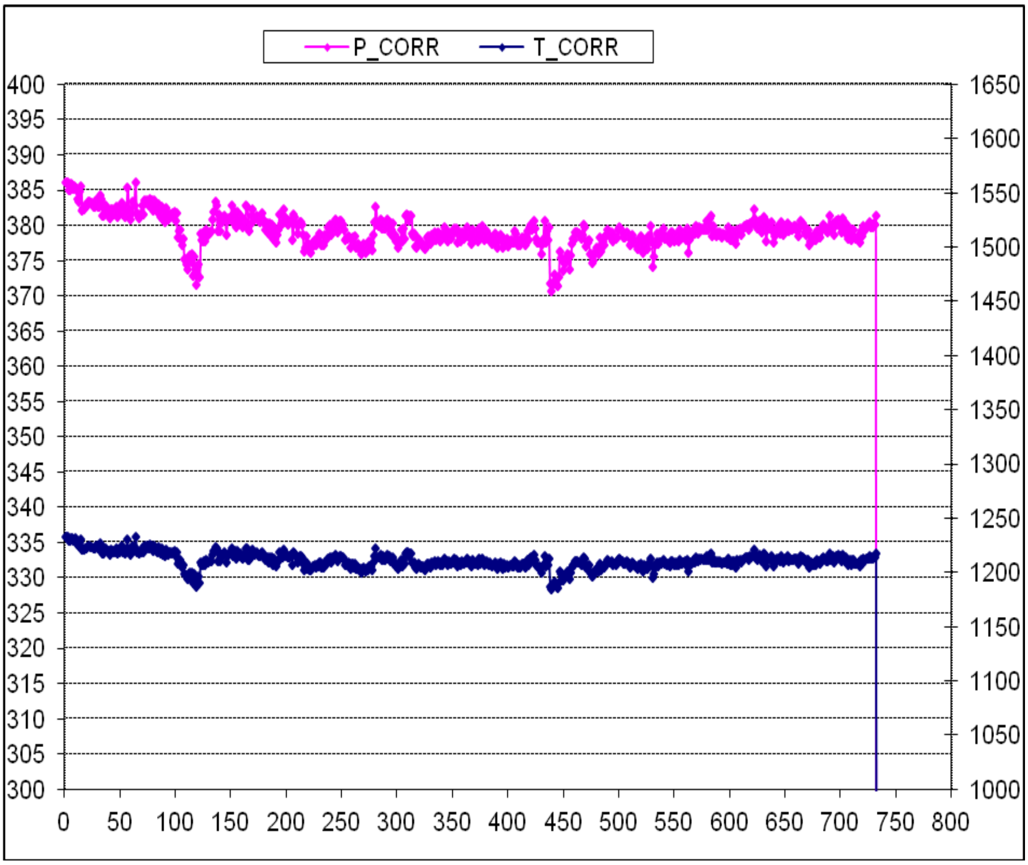


Figure 6.12 : High speed test power-torque curve in 2011.

Blow-by measurement is represented in Figure 6.13

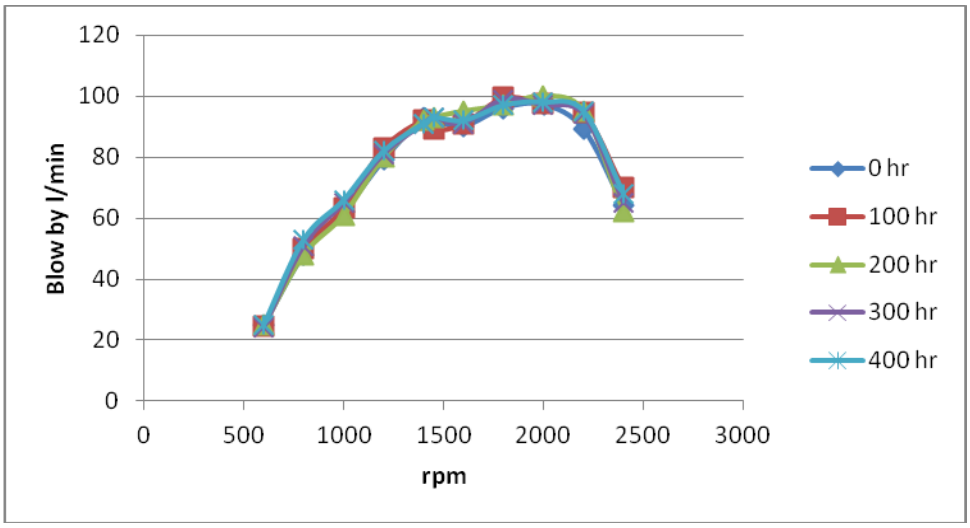


Figure 6.13 : Blow-by results of high speed test in 2011.

Oil consumption results are represented in Figure 6.14.

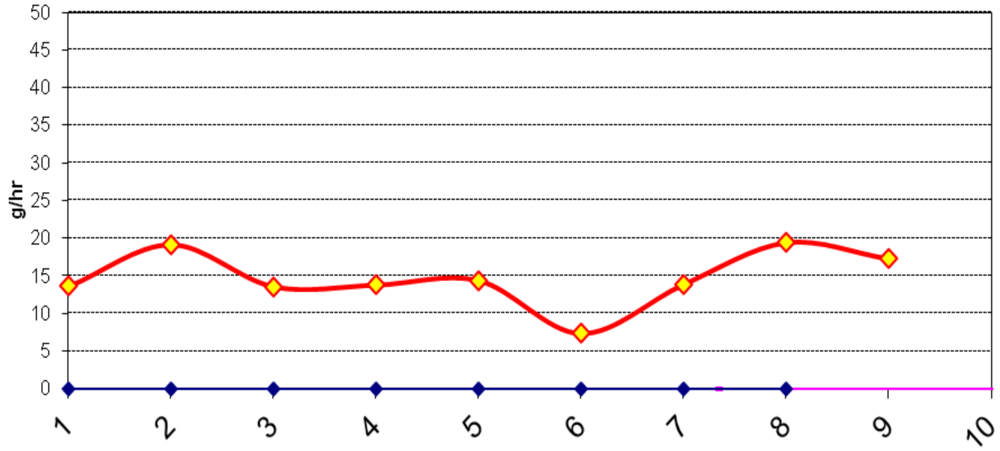


Figure 6.14 : Oil consumption values of high speed test in 2011.

6.2.3.3 Currents test results

The engine with BB37 cylinder block has completed the test without any reported issue.

Power curve in Figure 6.15 shows that engine power starts from 387PS and drops to 379PS. Power is measured at every 50 hours.

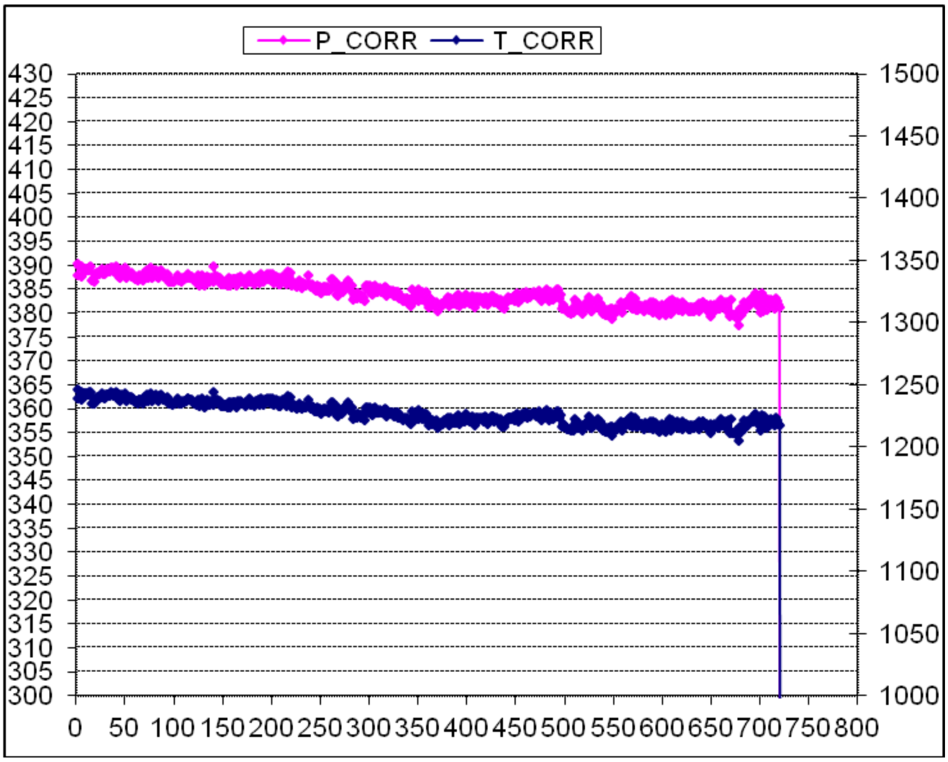


Figure 6.15 : Power-torque curve.

Figure 6.14 indicates that power and torque drop. The power is set to 380PS with +/-2% deviation which means power can deviate from 388 to 372PS. So it can be said that engine with coated block gives more power than current production engine.

Similar comment can be done for measured torque values. +/-5% variation for torque tends to torque variation between (1220Nm+/-5%) 1159 and 1281 Nm. BB37 result indicates that torque curve again shifts upwards.

The expected trend of power curve is as starting from lower power and in time increasing of power. It is due to aging of injectors. However 400 hours is not sufficient for aging of injectors, and the decreasing trend most probably is due to mechanical friction increase.

Figure 6.16 indicates blow by measurement results. Results show that blow-by decreases in time.

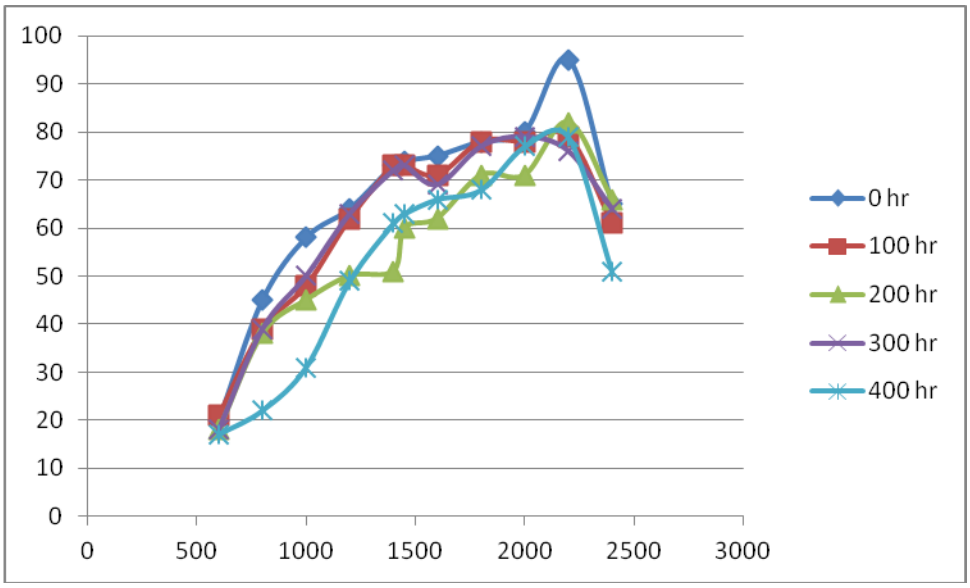


Figure 6.16 : Blow-by.

Oil consumption for the engine changes between 15,6 gr/h and 28,5 gr/h as shown in Figure 6.17. Specification is 18-26 gr/h. The peak for oil consumption to 28,5 gr/h is thought to be originated from any other components other than cylinder bore and piston ring interactions as it is not steady state.

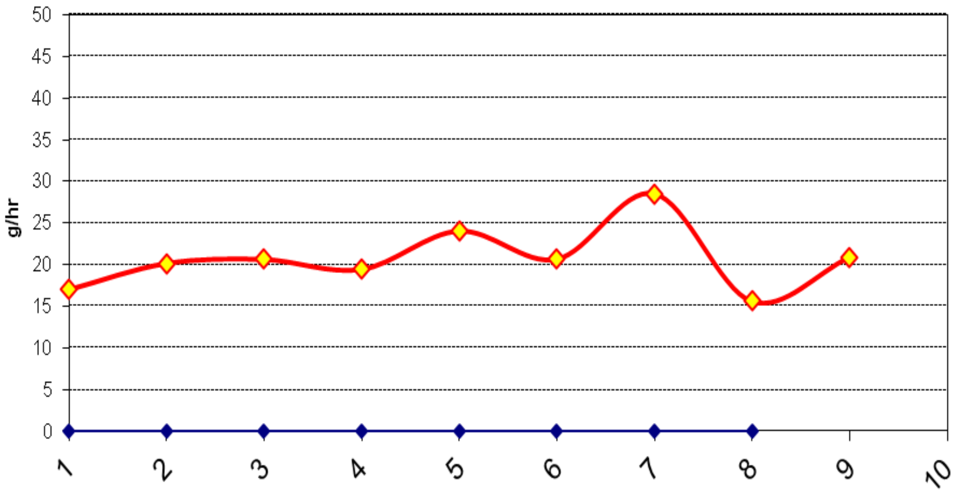


Figure 6.17 : Oil consumption.

6.2.3.4 Comparison

In order to understand the difference and/or similarity between coated and uncoated blocks, tests results are superposed as below (all 3 compared tests have same test cycle with same oil. Only the engine number BC1276 is calibrated to 400PS.

Power-torque comparison is represented in Figure 6.18. It can be concluded that no loss on power or torque has been observed due to PTWA application.

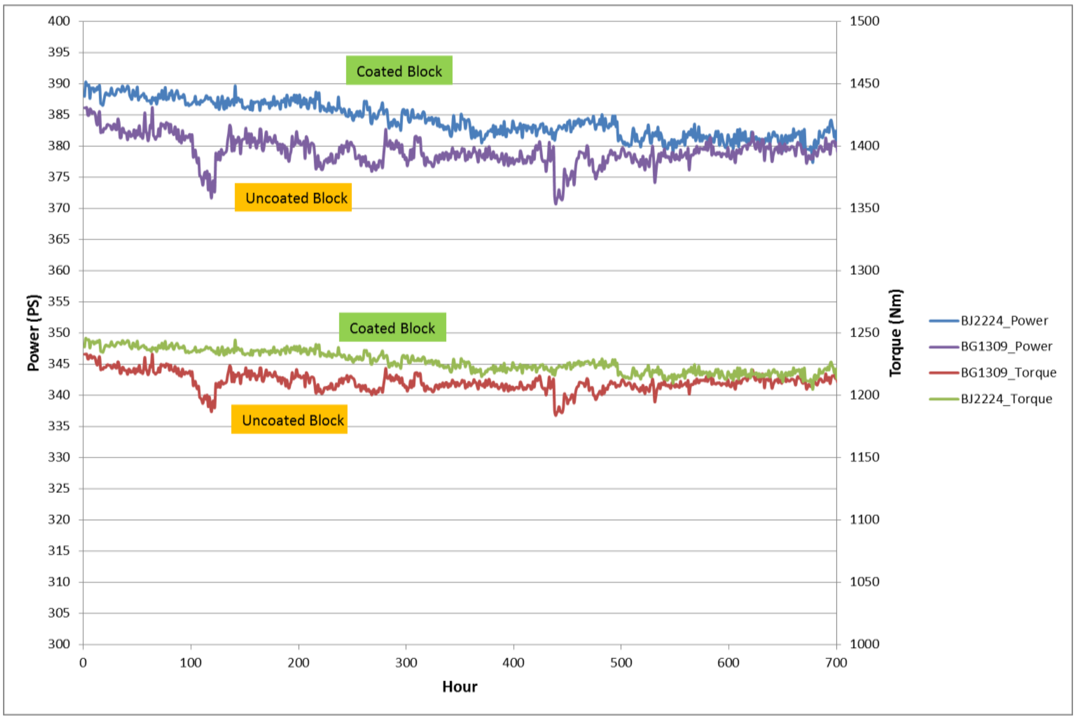


Figure 6.18 : Power- torque comparison.

Although oil consumption seems to be increased with coated block, this may be due to porous structure of coating surface. On the other hand, as consumption did not follow a continuous trend, the reason could be other components. Oil consumption comparison is represented in Figure 6.19. It can be concluded that no higher oil consumption has been observed due to PTWA application and wear resistance of PTWA is found to be suitable for remanufacturing application.

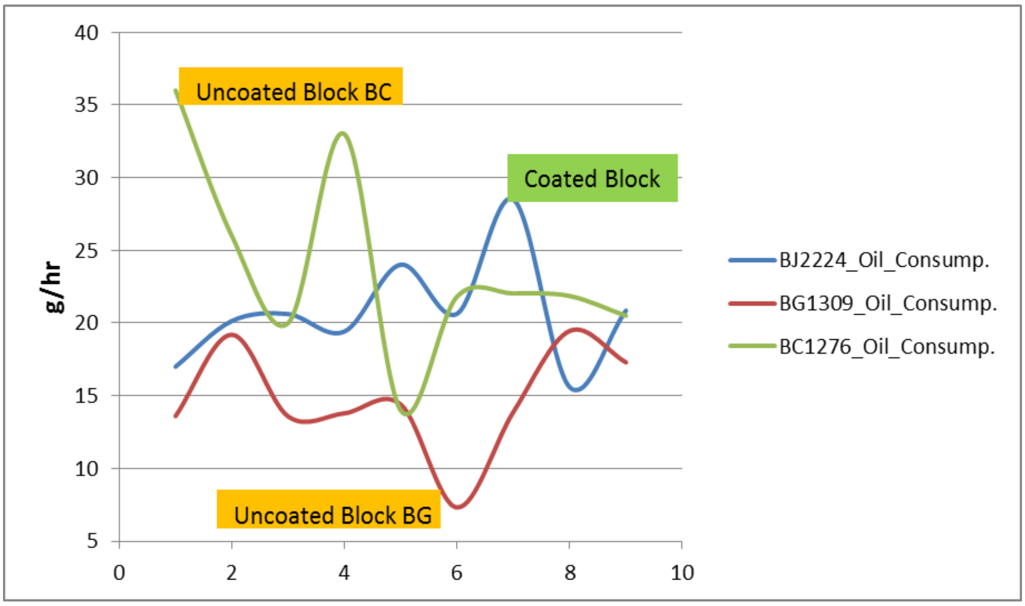


Figure 6.19 : Oil consumption comparison

Blow-by has been decreased compared to previous engine. The reason is considered to the roughness of cylinder bores.Since the cylinder bore surface is smoother, sealing of combustion gas from crankcase is more efficient. Blow-by comparison is represented in Figure 6.20. It can be concluded that no higher blow-by has been observed due to PTWA application and wear resistance of PTWA is found to be suitable for remanufacturing application.

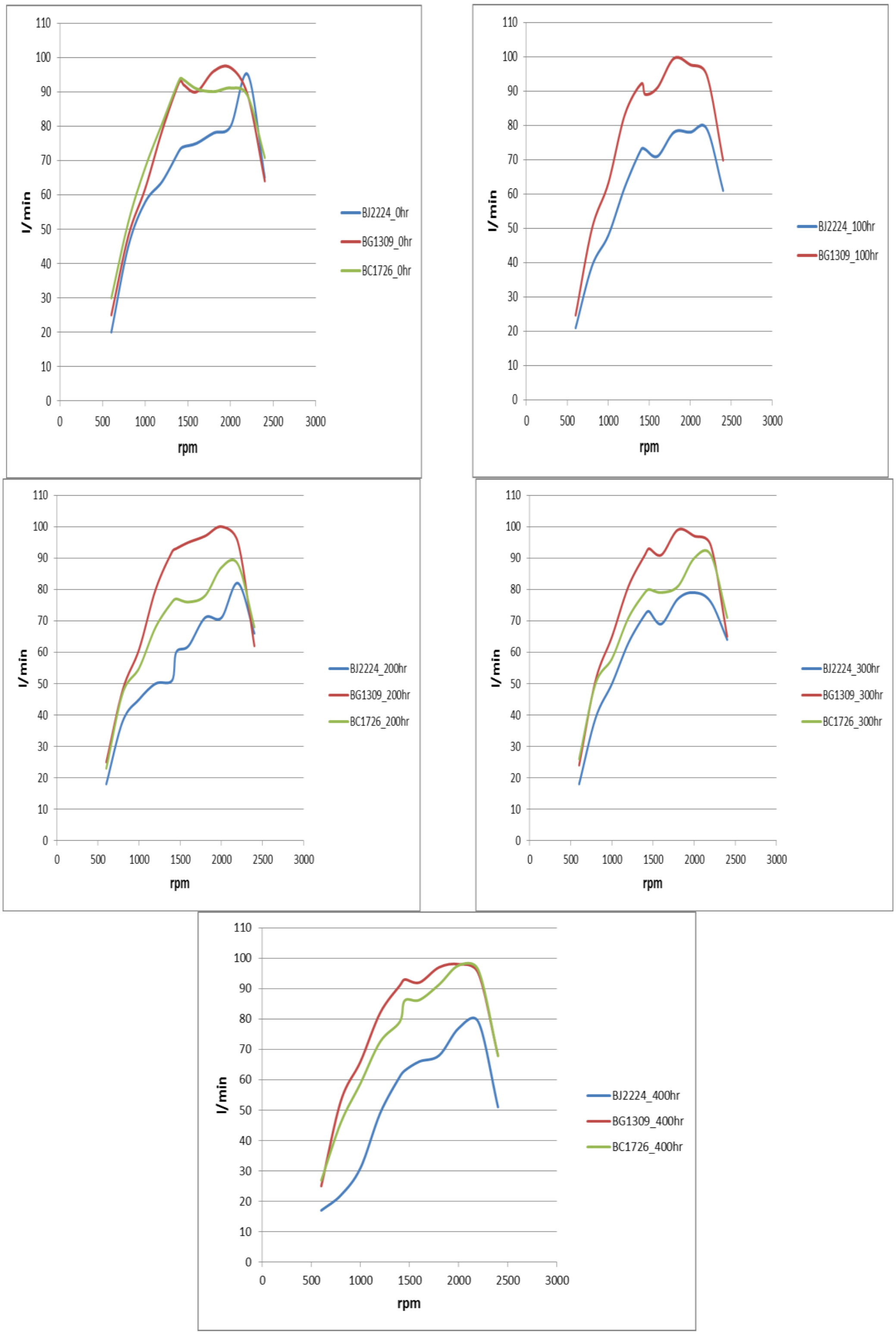


Figure 6.20 : Blow-by comparison.

Oil analysis

Oil samples had been taken within every 50 hours and analyzed by supplier. Soot and viscosity were checked to see whether there was any problem with oil itself. Moreover by checking and comparing Fe oil and percentage of soot, it can be decided on whether any excessive and any excessive combustion gas flow to oil are seen during testing. Results from coated block and an uncoated block (same test cycle with same type oil) are compared to see any difference. Figure 6.21 shows soot contamination, the first graphs on left hand side belong to coated block, and ones on right hand side belong to an uncoated block.

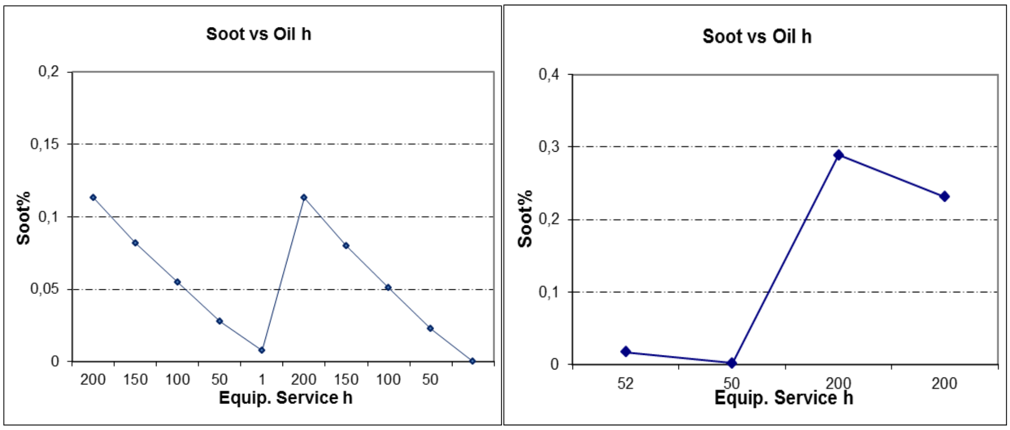


Figure 6.21 : Soot vs oil.

Soot formation seems to be less than uncoated block which is also supported by the blow-by data.

As expected for both cases, viscosity of oil increases in parallel with increase of soot percentage. Viscosity results are represented in Figure 6.22 (Left: Coated block Right: Uncoated block).

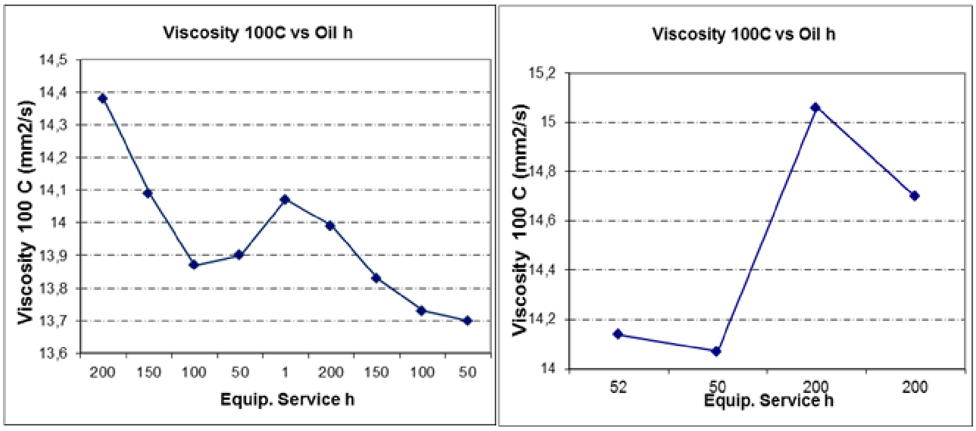


Figure 6.22 : Viscosity.

The Figure 6.23 (Left: Coated block Right: Uncoated block) indicates that wear of cylinder bore wall and /or piston rings were less with coated block compared with uncoated block which means coating of cylinder bores improves the surface contact of rings and bore wall. According to this result it can be conluded that 0.8%C steel coating provides harder surface which is more wear resistant compared with CGI material and is found to be suitable material for Ecotorq 9L cylinder block for remanufacturing purpose.

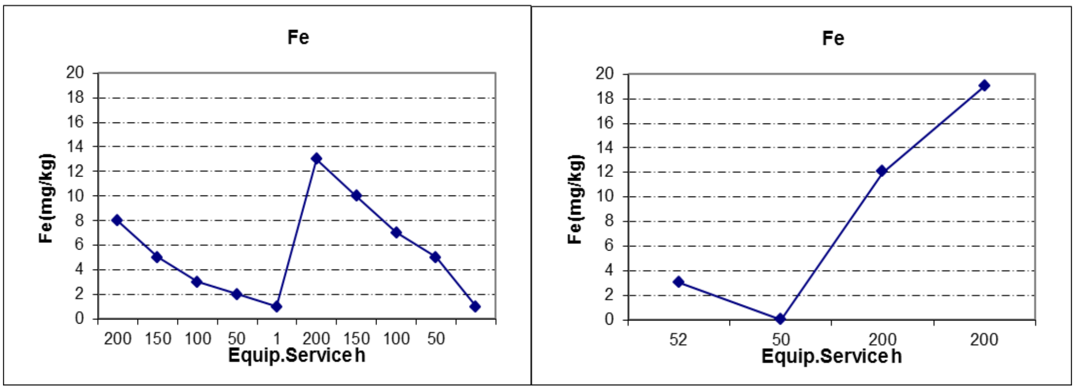


Figure 6.23 : Fe in oil.

The Table 6.8 shows the diameter measurement after test for BB37 cylinder block. When it is compared to pre-test measurement in Table 6.3, it can be concluded that no excessive wear observed. Maximum wear occurred in second cylinder as 17 microns.

Table 6.8 : Deviation from bore specification in BB37 cylinder block (Post-test).

	1.Cylinder	2.Cylinder	3.Cylinder	4.Cylinder	5.Cylinder	6.Cylinder
20mm	-0,023	-0,023	-0,024	-0,026	-0,022	-0,02
60mm	-0,015	-0,014	-0,016	-0,017	-0,015	-0,016
105mm	-0,009	-0,009	-0,011	-0,012	-0,01	-0,01
140mm	0	-0,003	-0,006	-0,007	-0,005	-0,004
195mm	-0,002	-0,005	-0,008	-0,008	-0,006	-0,007
Avarage	-0,0098	-0,0108	-0,013	-0,014	-0,0116	-0,0114

7. CONCLUSIONS AND RECOMMENDATIONS

The scope of this test was to investigate potential of PTWA coating application for cylinder block remanufacturing purpose. The test which has been performed during the thesis work proved that PTWA is a promising option to traditional cylinder block remanufacturing methods which have a lot of disadvantages mentioned in the study.

As BB49 engine with three different coating materials per bore hasn't completed the test, we weren't able to see and compare the effects of these coating material for engine performance, thus wear resistance. However, test with BB37 engine proved that 0.8%C-steel as coating material has potential to be used for remafacturing of Ecotorq cylinder blocks. Addition to that, during the study it was found that 0.8%C-steel has the cost advantage on the other two materials.

In order to give full sign off for Ecotorq cylinder block remanufacturing with PTWA application, the remaining test for sign off should be completed.

On the other hand there is no facility in Turkey for PTWA application yet due to high initial investment cost. But as explained in the study, new cylinder block design will require remanufacturing with PTWA due to decreased wall thicknesses. It is believed to be available in Turkey in near future as some remanufacturing companies have already started their investigations on PTWA implementation.

The PTWA application as remanufacturing method has also potential for automotive companies to reduce their warranty costs. Any failure related with cylinder block and piston assembly requires short block change for vehicles under warranty. In addition to cost of short block assembly, automotive companies have to pay extra cost due to engine number registration. By application of PTWA for remanufacturing, automotive companies can reduce their warranty costs in 50%.

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