ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

EFFECTS OF THERMAL SPRAY COATING ON ENGINE PERFORMANCE AND CYLINDER BORE SURFACE

M.Sc. THESIS

Mersin HÜRPEKLİ

Department of Mechanical Engineering

Materials and Manufacture Graduate Program

JUNE 2013

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ISIL PÜSKÜRTME KAPLAMANIN MOTOR PERFORMANSI VE SİLİNDİR BOŞLUĞU ÜZERİNDEKİ ETKİSİ

YÜKSEK LİSANS TEZİ

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HAZİRAN 2013

Mersin Hürpekli, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID **503091336**, successfully defended the **thesis** entitled "**Effects of Thermal Spray Coating on Engine Performance and Cylinder Bore Surface**", 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	....
Jury Members :	**Assoc. Prof. Dr. Hüseyin KIZIL** İstanbul Technical University	....
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Date of Submission : 03 May 2013
Date of Defense : 14 June 2013

Dedicated to my beloved family,

FOREWORD

The master thesis where written during the time-period from spring 2011 until spring 2013, under the teaching supervision of Dr. Turgut Gülmez, Istanbul Technical University of Istanbul.
I want to thank my team leader and my collegues in Ford of Turkey, Germany and North America of being help during the development of this thesis, Gehring and GTV of being so supportive with usage of necessary hardware for coating application, and of course my family with our new comer.

May 2013

Mersin HÜRPEKLİ
(Mechanical Engineer)

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ABBREVIATIONS

Al	**:** Aluminum
CGI	**:** Compacted Graphite Iron
CO	**:** Carbon Monoxide
Cr	**:** Chromium
Cu	**:** Copper
DC	**:** Direct Current
FCSD	**:** Ford Customer Service Division
HP	**:** Horse Power
MCrAlY	**:** (Nickel/Cobalt/Iron) Chromium Aluminum Yttrium Alloy
Mo	**:** Molybdenum
Ni	**:** Nickel
NOx	**:** Nitrogen Oxides
PTWA	**:** Plasma Transferred Wire Arc
Ta	**:** Tantalum
Ti	**:** Titanium
W	**:** Tungsten
WC-Co	**:** Tungsten Carbide Cobalt

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EFFECTS OF THERMAL SPRAY COATING ON ENGINE PERFORMANCE AND CYLINDER BORE SURFACE

SUMMARY

The content of thesis is investigation of Plasma Transferred Wire Arc (PTWA) sprayed coatings on cylinder bore walls by using a 0.8% C-steel wire feedstock. The thermal spray coatings are analyzed for their microstructure depending on different applications. The influence of PTWA coating inside the cylinder bore on engine performance is investigated. The coating quality in view of the coating thickness, porosity, oxide content, different oxide types and hardness of coating layer is investigated for the effect on engine performance. PTWA coating on cylinder bores is a new field for coating application and automotive industry. There are few comprehensive experiments or tests performed to understand the effect on engine performance.

Thermal spray coating tecniques are coating processes in which melted or softened materials are applied onto a substrate by impact. The sprayed material is called as feedstock. It is heated up electrically or chemically with combustion flame. Thermal spraying is a group of processes wherein a feedstock material is heated and propelled as individual particles or droplets onto a surface. A common feature of all thermal spray coatings is their lamellar grain structure resulting from rapid solidification of small globules, which are flattened from striking a cold surface at high velocity. The coating structure is heterogeneous relative to wrought and cast materials. This is due to variations in the condition of each individual particle during impact. It is almost impossible to ensure that all particles are exactly same in size and achieve the same temperature and velocity. In general, thermally sprayed coatings contain porosity that varies 0,025% to 50% because of low impact energy, shadowing of unmelted particles, and shrinkage effects. The effect of porosity is also investigated in the study.

One of the key issues of coatings is preparation of substrate surface to be sure that sufficient bonding strength is achieved. The two things for preparation of substrate are cleaning and roughing of surface. These provide an active surface required for good bonding. To increase bonding strength, it is required to increase surface area. The rough surface profile promotes mechanical keying. Mechanical keying is essential for binding coating on surface. Cooling and solidification of most materials are accompanied with contraction or shrinkage. This generates a tensile stress within the particle and a compressive stress within the surface of substrate. As the coating is formed, so are the tensile and compressive stresses built up. Built up stress limits the coating thickness. For example, high shrinkage materials like some austenitic stainless steels are prone to high levels of stress build up and thus have low thickness limitation. This can be improved with roughing of surface.

In the study, atomization gas is selected per literature survey and what is expected from the coated surface. Almost all thermal spray-coating systems use air for

atomization of molten material. Chemical reactions occur during spraying due to high temperature. In the meantime, oxidation occurs as well. Metallic particles oxide over their surface; hence an oxide shell is formed. Oxides are generally harder than parent material. Coatings of high oxide content are usually harder and more wear resistant. On the other hand, oxides in coating are detrimental towards corrosion, strength and machinability properties.

To achive better engine performance, cylinder block bore surface material must have high wear resistance and capable of withstanding high firing pressures about 100 to 200 bars. The porosity level of material must be below 1% and the maximum pore size must be below 500µm on running surfaces. In order to meet this functional requirements, the engineering materials used to manufacture the product must posses high strength, high modulus of elasticity, wear resistance, scuffing resistance, and corrosion resistance. The material of cylinder block bore must be of a sufficient hardness to resist the wearing effect of pistions as they slide up and down on the cylinder bore wall. One another important requirement for block bore surface is lower friction of coefficient that is related with surface hardness, in general. Friction between the cylinder block bore surface and the piston rings has major impact on the effiency of an engine. The 40% of total vehicle power losses due to friction.

To sum up, the main reason for utilizing sprayed coatings on cylinder bore is to improve tribological properties of surface. The most attractive application of spray coatings on parent material is the surface modification of cylinder bores. It is due to reduce the energy loss by friction and weight loss by wear, and to promote lightening of vehicles. The results of testings and literature indicate coating works well for friction reduction.

ISIL PÜSKÜRTME KAPLAMANIN MOTOR PERFROMANSI VE SİLİNDİR BOŞLUĞU ÜZERİNDEKİ ETKİSİ

ÖZET

Plazma İletimli kaplama (PTWA) ve bunun motor blokları üzerindeki uygulaması tezin konusu oluşturmaktadır. Tez çalışması kapsamında motor bloğu silindir boşluğu %0.8C-çeliği ile kaplanmış ve bunun etkileri incelenmiştir. Farklı tipte ısıl püskürtme ile yapılan kaplamaların mikro yapıları incelenmiş ve PTWA'nın silindir boşluğu üzerindeki etkileri araştırılmıştır. Buna göre motor performansına etkileri irdelenmektedir. Bahsi geçen kaplamanın kalitesi kaplama kalınlığı, kaplamanın boşluklu yapısı, oksit içeriği, içerdiği oksit tipi ve kaplamanın sertliği gözönünde bulundurularak incelenmektedir. Bunlardan yola çıkarak da PTWA kaplamanın motor performansı üzerindeki ektisi ortaya çıkartılmaya çalışılmaktadır. PTWA kaplama otomotiv endüstrisinde yeni bir uygulama olup konu ile ilgili detaylı yapılmış çalışmalar yaygın değildir. Bunun yanında kaplamanın motor performansı üzerindeki etkisi gösterebilecek çalışmalar ya yoktur ya da yeni bir alan olduğundan dolayı otomotiv endüstrisi bilgiyi halka açık hale getirmemiştir.

Isıl püskürtme ile kaplamalar temel olarak, ergitilmiş ya da yumuşatılmış malzemenin alt tabakaya püskürtülmesi ile yapılmaktadır. Eriyik haldeki malzeme, alt tabakaya darbe etkisi ile yapışmaktadır. Püskürtülecek olan malzeme elektrik ile ya da yanıcı gazlar ile ısıtılmaktadır. Isıtılan malzeme alt tabakaya genel olarak damlacıklar olarak püskürtülmekte ve püskürtme yüksek parçacık hızlarında gerçekleşmektedir. Bu sebeple hemen hemen bütün ısıl kaplamalarda kaplama malzemesi yüzeyde pullu bir katman oluşturmaktadır. Kaplanan malzemin uygulanma şekli ve yüzeyde oluşturduğu yapı gözönünde bulundurulacak olursa, kaplamanın anizotropik özelliklere ve homojen olmayan iç yapıya sahip olacağı aşikardır. Bu da kaplama yapılırken prosesteki değişkenliklerden kaynaklanmaktadır. Ard arda yapılan kaplama işlemlerinde bile prosesin aynı sıcaklıkta olmasını sağlamak ve aynı hızlara sahip ergimiş metal parçacıkları elde etmek neredeyse imkansızdır ki parçacık boyutlarının aynı olmasını beklemek makul değildir. Genel olarak bütün ısıl kaplamalarda %0,025 ile % 50 arasında boşluklu yapılar oluşmaktadır. Boşluklu yapılar da düşük darbe enerjisi, yüzeyde ergimemiş metallerin varlığı ve çekintilerin oluşması gibi nedenlerden dolayı oluşmaktadır. Tez çalışmasında olumsuz etki olarak düşünülebilecek olan boşluklu yapının sürtünme üzerindeki etkisi incelenmektedir.

Isıl püskürtme kaplamalarda ergimiş metalin alt tabaka yüzeyini kaplama mekanizması mekanik kilitleme ya da mekanik bağlama ile açıklanabilir. Ergimiş metalin sahip olduğu yüksek kinetik enerji ve eriğiyin akışkanlığı ile yüzeyde mikro çukurlara nüfuz eder. Bununla birlikte mikro tepelerin etrafına sarınır. Katılaşma hızı 10^{-8} ile 10^{-4} s arasında olduğu düşünülürse çukurcuklara dolan ve tepecikleri saran eriyik hızla katılaşır ve burada çekme-basma kuvvetlerinin yardımı ile yüzeye tutunma sağlanır.

Kaplama malzmesinin kaplanan yüzeydeki bağlanma dayanımı alt tabakanın ne kadar iyi hazırlanmış olduğuna bağlıdır ki ısıl kaplamalarda yüzeyin hazırlanması önem arz etmektedir. Yüzey hazırlama işlemi yüzeyin pürüzlendirilmesi ve temizlenmesi aşamalarından oluşur. Böylece iyi bir bağın oluşması için etkin bir yüzey hazırlanmış olur. Temel olarak bağlama mukavemetinin arttırılması yüzey alanının ne kadar olduğuna bağlıdır. Kaba ya da pürüzlü bir yüzey de bunu sağlamaktadır. Bununla birlikte pürüzlü bir yüzey mekanik kilitlenemeyi de sağlamaktadır. Temel olarak mekanik kilitlenme kaplamanın yüzeye tutunmasında rol alan mekanizmadır. Birçok malzemede soğuma ve katılaşma sonrasında çekinti oluşmaktadır. Bu da kaplama malzemesi içerisinde çekme kuvvetinin oluşmasına, alt tabaka yüzeyinde de basma kuvvetinin oluşmasına neden olmaktadır. Alt tabaka üzerine kaplama yapıldıkça çekme ve basma kuvvetleri de her defasında oluşmaktadır. Isıl kaplamalarda oluşan çekme basma kuvvetleri kaplamanın kalınlığını sınırlamaktadır. Örnek olarak, soğuma esnasında yüksek çekinti gösteren östenitik paslanmaz çelik kaplama malzemesi olarak kullanıldığında yüksek kuvvetlere maruz kalır. Böylece bu tip çeliklerle elde edilebilen kaplamanın kalınlığı nispeten daha incedir. Yine de alt tabakanın pürüzlendirilmesi ile kalınlık bir miktar daha arttırılabilir.

Isıl püskürtme endüstrisinde yüzey pürüzlendirme işlemi genel olarak kumlama ile yapılmaktadır. Ancak, motor silindir boşluğu için kumlama yapılmasının sakıncaları vardır. Kumlamada kullanılan parçacıklar arasında Korondum da bulunmaktadır. Bu sert parçacıklar motor bloğunda yağ besleme kanallarına ya da su pasajlarına girip motor çalışması esnasında hasara neden olabilir. Diğer bir yöntem ise su jeti ile pürüzlendirmedir. Bu yöntemde yüksek basınçlı su pompalarına ve özel ekipmanlara ihtiyaç duyulmaktadır. Bu sebeple de pahalı bir yöntemdir. Bununla birlikte su jetinde kullanılan suyun korozif olmasından dolayı sadece alüminyum alaşımlı bloklarda kullanılabilir. Demir alaşımlı blokların korozyona uğramasına neden olmaktadır. Maliyet ve uygulanabilen alan çeşitliliği dolayısı ile yeni bir yöntemin geliştirilmesi gerekmektedir. Braunschweig Üniversitesi Makina Takımları ve İmalat Teknolojileri Enstitüsü bu amaçla "kırlangıç kuyruğu" adı verilen kesme takımlarını geliştirmiştir. Bu sayede hem ergimiş metale alt tabaka yüzeyinde mükemmel bir tutunma yüzeyi sağlanmış hem de seri üretime kolayca entegre edilebilen ucuz bir yöntem geliştirilmiştir.

Tez çalışmasında püskürtme gazı olarak hava seçilmiştir. Seçim yapılırken kaynak taramasından elde edilen bilgiler ışığında kaplanmış yüzeyden beklenen performans gözönünde bulundurulmuştur. Bununla birlikte hemen hemen bütün ısıl kaplama sistemlerinde ergimiş metalin püskürtülmesinde hava kullanılmaktadır. Kaplama prosesinde ergimiş metalin püskürtülmesinde kullanılan hava dolayısı ve yüksek sıcaklık sebebi ile kimyasal reaksiyon meydana gelmektedir. Bunların sonucu olarak da oksitlenme kaçınılmazdır. Ergimiş metal parçacıkları böylece oksitlenmekte ve kaplama esnasında alt tabaka yüzeyinde oksit tabakası oluşturmaktadır. Genel olarak da oksitler ana metalden daha serttirler ki bu da malzemenin aşınma direncini arttırmaktadır. Diğer taraftan ise yüzeydeki oksit tabakanın korozyon, dayanım ve işlenebilirlik açısından olumsuz etkileri olduğu söylenebilir.

Motor bloğunda kullanılacak olan malzeme hem motor dayanımında hem de motordan kaynaklı sürtünmelerde etkin rol oynamaktadır. Günümüzdeki gaz salınımı düzenlemelerini sağlayabilmek için silindir içi basınçlar sürekli arttırılmaktadır. Daha önceki yıllarda 100 bar olan iç basınçlar bugün 200 bar civarındadır. Bununla birlikte daha iyi motor performansı için silindir içindeki sürtünmelerin de azaltılması gerekmektedir. Bu sebeple silindir içinde kullanılan gömlek ya da ana malzemenin de aşınma direncinin yüksek olması beklenir. Bunu sağlamak için günümüzde yüksek dayanıma sahip, yüksek aşınma ile kazınma direnci olan ve korozyon direnci yüksek olan mühendislik malzemelerinin kullanılması zorunluluk göstermektedir. Genel olarak bu gereklilikleri sağlaması için silindir boşluğu yüzeyinin en fazla %1 oranında boşluklu olması ve boşluğun en fazla 500 µm olması gerekir. Araçtaki kayıpların %40'ının sürtünme kaynaklı olduğu düşünüldüğünde sürtünmenin azaltılmasının önemi ortaya çıkmaktadır. Motor içindeki sürtünmeler de büyük oranda silindir duvarı ve piston segmanları arasındaki sürtünmeden kaynaklanmaktadır. Bunlar gözönünde bulundurulduğunda blok silindir duvarı malzemesinde beklenen gereklilikler daha net anlaşılabilir.

Demir bazlı kaplamalar hem aşınma özellikleri ile hem de ucuz olmaları dolayısı ile tercih edilmektedir. Düşük karbon alaşımlı çelik PTWA ile kullanıldığında ve atomize gazı olarak hava kullanıldığında silindir boşluğu için tercih edilebilir bir kaplama malzemesi elde edilmiştir. Alaşımdaki demir yüksek sıcaklık ve hızlı katılaşma oksidi olan Wustite'ı meydana getirir. Wustite sert bir oksit olup aynı zamanda tribolojik bir malzemedir. Yani kendi kendine yağlama özelliği vardır. Bu da motor bloğu silindir yüzeyi için istenen bir özelliktir.

Sonuç olarak, ısıl püskürtme kaplamaların silindir iç yüzeyine yapılmasının altında yatan baş neden yüzeyin tribolojik özelliklerinin iyileştirilmesidir. Böylece silindir duvarı ile piston segmanları arasında meydana gelen sürtünmeden kaynaklı kayıplar en aza indirgenmiş olacak ve daha hafif araçların üretilmesine imkan sağlayacaktır. Tez çalışması kapsamında yapılan kaynak taraması ve testler de bunun mümkün olabileceği yönünde umut verici sonuçlar vermiştir. Çalışma daha da genişletilerek kaplama uygulaması seri üretime uygun hale getirilerek daha hafif ve daha az gaz salınımı yapan çevreci motorların üretimi mümkün kılınabilir.

1. INTRODUCTION

The content of the thesis is the investigation of Plasma Transferred Wire Arc (PTWA) sprayed coatings onto cylinder bore walls by using a 0.8 % C-steel wire feedstock. The thermal spray coatings are analyzed for their microstructure depending on different applications. The influence of PTWA coating inside the cylinder bore on engine perfromance is investigated. The coating quality in regard to the coating thickness, porosity, oxide content, different oxide and hardness are investigated for effect on engine performance. The plasma current with an adapted feed rate influences the coating quality, particularly the coating thickness, the coating porosity, the coating hardness and coating oxidation of the PTWA sprayed coating. For the pre-processing of the substrate, surface different mechanical roughened profiles are investigated. Certain simple taped thread profiles fail because of fewer under-cuts in the profile structure, where as an optimized mechanical roughened profile as for example the “dove tail” can result in adhesion strength values up to 55 MPa for a PTWA spray coating. A Ni/Al bond coat in place of a mechanical roughened profile show no delamination or destruction of the spray coating after the honing process.

1.1 Purpose of Thesis

In recent years, automotive industry faces a difficult and versatile problem; such as, producing more economical engines with higher performance output according to customer expectations. In the meantime, it is mandated to reduce exhaust emissions with legal regulations and environmental concerns. The main objective is to manufacture silent, cheaper and lighter new generation green engines with low exhaust emissions, which also show higher performance and consume less fuel. All these expectations have solved partially by increasing the peak firing pressure and modifying the design.

The purpose of thesis is to investigate different applications of thermal spray coating, and to understand the effect of PTWA spray coating on engine performance with selected material. PTWA coating on cylinder bore is a new field for coating application, and there are not enough experiments or tests performed to understand the effect on cylinder bore and engine performance, such as; power-torque increase, fuel economy and oil consumption.

Thermal spraying techniques are coating processes in which melted (or softened) materials are applied by impact onto a substrate. The material sprayed called as feedstock is heated by electrically as done in plasma or arc, or chemically with combustion flame. Thermal spraying is a group of processes wherein a feedstock material is heated and propelled as individual particles or droplets onto a surface [1]. A common feature of all thermal spray coatings is their lamellar grain structure resulting from the rapid solidification of small globules, flattened from striking a cold surface at high velocity. A common representation of thermally sprayed particle is as shown in the Figure 1.1.

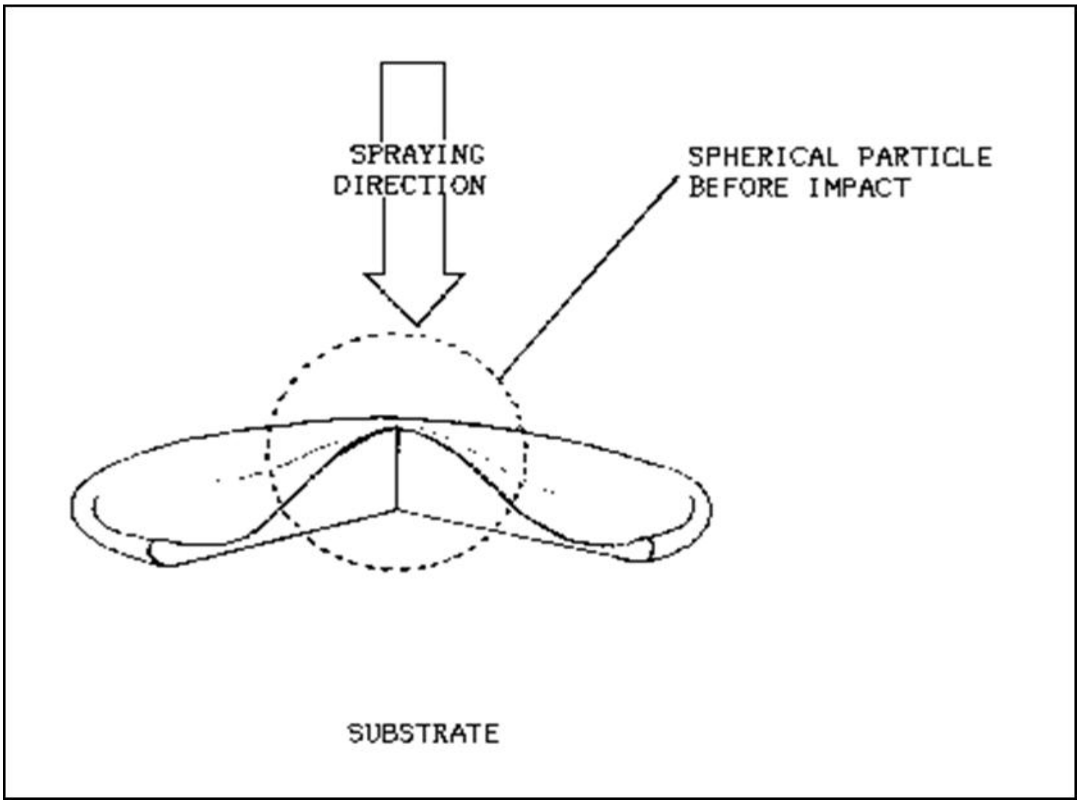


Figure 1.1 : Schematically view of thermally sprayed spherical particle impinged onto a flat substrate.

Thermal spray coating is distinguished from other currently used coating technologies with coating thickness and material used as feedstock. Nowadays, electroplating, physical and chemical vapor deposition, which are not mentioned in detail here, are most commonly used techniques and the thickness of coating can be achieved is few millimeters. On the other hand, the coating thickness over a large area at high deposition rate can be achieved with thermal spray coating. The thickness range is around few microns to several millimeters. Moreover, variety of feedstock is another important feature. Coating materials available for thermal spraying include metals, various metal alloys, ceramics, plastics and composites. Feedstock is used as either powder or wire form, based on the application. The feedstock is heated to a molten or softened state and accelerated towards substrate in the form of micrometer-size particles. Schematic view of the process is shown in Figure 1.2. Combustion of gas or electrical discharge is main source of energy for thermal spraying.

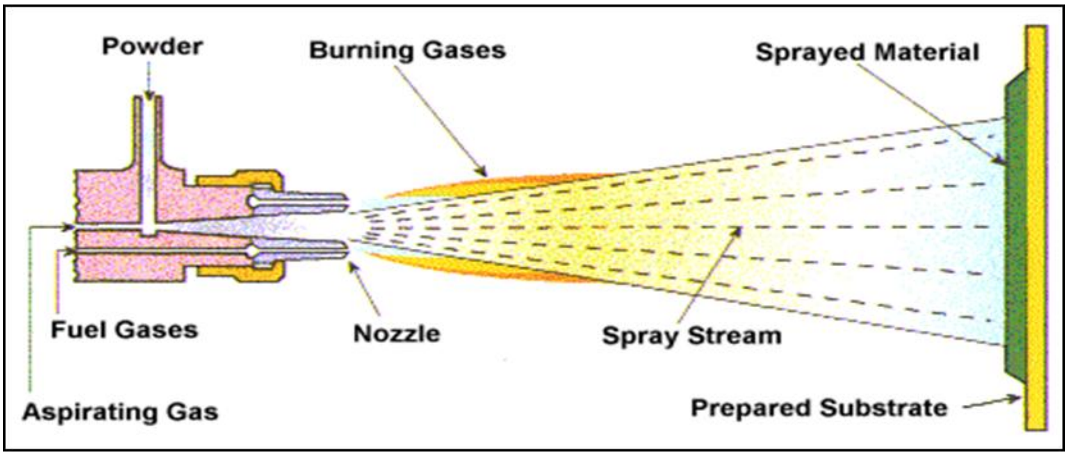


Figure 1.2 : Schematic representation of thermal spray coating.

The coating thickness on substrate is the result of accumulation of numerous sprayed particles as shown in Figure 1.3.

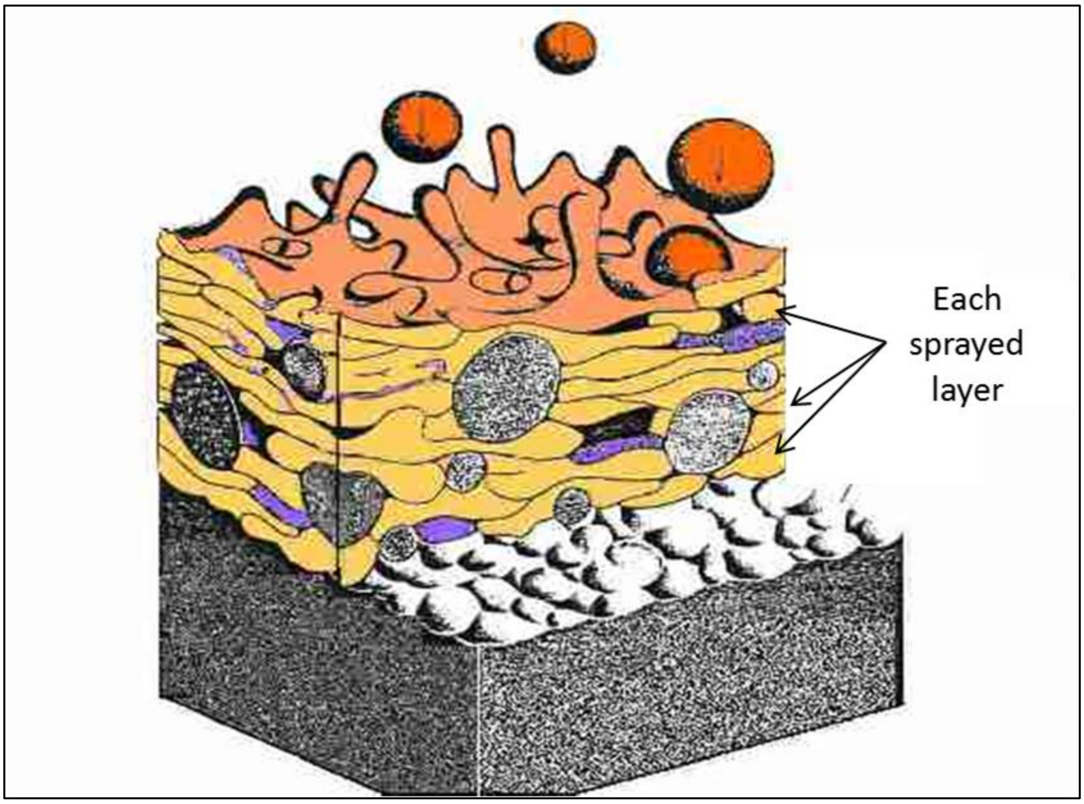


Figure 1.3 : Schematic diagram of coated metal layers.

The one of most important parameter is coating quality and is usually assessed by measuring its bond strength, substrate surface roughness, coating hardness, porosity, and oxide content. In general, the coating quality increases with increasing particle speed. The general properties of thermal spray coatings are mentioned in following sections.

1.1.1 Bonding

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

- Mechanical keying or interlocking
- Diffusion bonding or Metallurgical bonding
- Other adhesive, chemical and physical bonding mechanisms -oxide films, Van der Waals forces, etc.

The factors affecting bonding quality are:

- Cleanliness
- Surface area
- Surface topography or profile
- Temperature (thermal energy)
- Time (reaction rates and cooling rates, etc.)
- Velocity (kinetic energy)
- Physical and chemical properties
- Physical and chemical reactions

The two important things for preparation of substrate are cleaning and roughing of surface. These provide an active surface needed for good bonding, in view of chemically and physically. To increase the bonding strength it is required to increase the surface area. The rough surface profile promotes mechanical keying.

In general, the cooling rate of a single molten particle during impact of the substrate is in order of 10^6 K/s. In this short time very limited thermal interaction occurs. The molten metal solidifies in a very short time so there is not too much time to heat the substrate up.

The mechanism of bonding is related with diffusion bonding depending on time and temperature. Increase in thermal and kinetic energy increasing chances of metallurgical bonding as well (depend on temperature, velocity, enthalpy, mass, density and specific heat content etc.). Thermal spray materials like Molybdenum, Tungsten, Aluminum and metal composites produce so called “self bonding” coatings. These materials have comparatively high bonding strengths (increased metallurgical or diffusion bonding) and can bond to clean polished surfaces. To elaborate, Molybdenum and other refractory metals have very high melting points thus the interaction between substrate and coating particles is increased due to higher temperatures involved and longer cooling cycles (time and temperature dependence of bonding strength). Likewise, higher preheat temperatures for the substrate increase diffusion bonding activities but also increase oxidation of the substrate that could adversely affect the bonding strength.

High kinetic energy thermal sprayings that are High Velocity Oxy-Fuel (HVOF) and cold spray (more detail will be given later) produce high bond strengths due to high velocity impacts. Metallurgical or diffusion bonding occurs on a limited thickness (max. 0.5 μm with heat affected zone around 25μm), in general [2].

1.1.2 Coating structure

The most of thermal coating systems use air for atomization or coating itself conducted in air. Chemical reactions occur during spraying due to high temperature. In the meantime, oxidation occurs as well. Metallic particles oxidize 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 indicate lamellar or flattened grains appearing to flow parallel to the substrate. The structure is anisotropic. Hence, the physical properties are different in longitudinal and transverse. Strength in the longitudinal (parallel to substrate) direction can be 5 to 10 times that of the transverse direction (across the coating thickness).

The coating structure is heterogeneous relative to wrought and cast materials. This is due to variations in the condition of the individual particles on impact. It is almost impossible to ensure that all particles are the exact same size and achieve the same temperature and velocity.

All conventionally thermally sprayed coatings contain some porosity that varies between 0.025% and 50 %. It is due to:

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

The above interactions can cause the coatings be very different materials chemically and physically.

1.1.3 Stress

Cooling and solidification of most materials are accompanied with contraction or shrinkage. As particles impact, they rapidly cool and solidify (with 10^6 K/s cooling rate). This generates a tensile stress within the particle and a compressive stress within the surface of substrate. As the coating is formed, so are the tensile stresses in the coating built up. In general, a thickness is reached where the tensile stresses exceed that of the bond strength or cohesive strength and coating failure will occur. It is schematically shown in Figure 1.4.

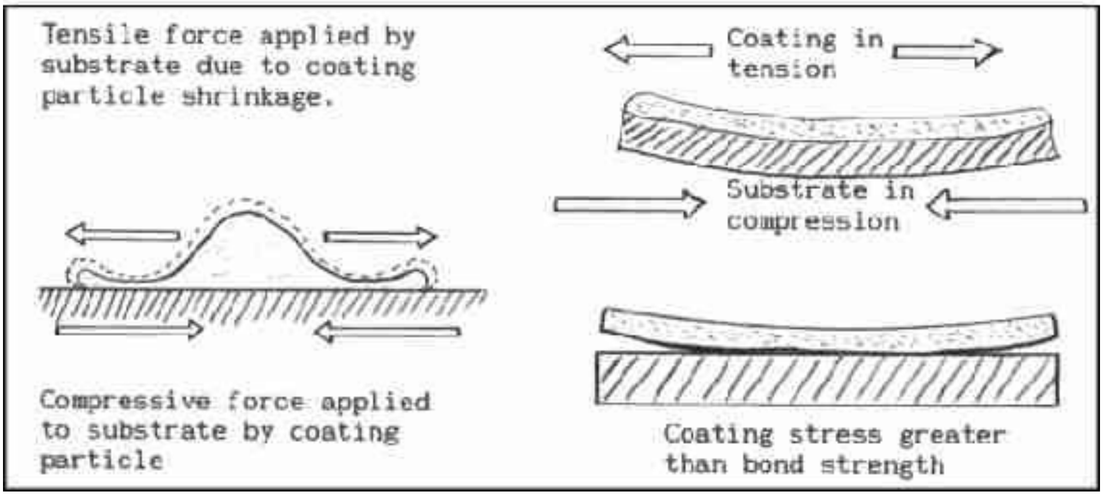


Figure 1.4 : Schematic representation compression and tension.

High shrink materials like some austenitic stainless steels are prone to high levels of stress build up and thus have low thickness limitations. Generally, thin coatings are more durable than thick coatings. Spraying method and coating microstructure influence the level of stress build up in coatings. Dense coatings are generally more stressed than porous coatings.

Contrary to that just mentioned, the systems using very high kinetic energy and low thermal energy (HVOF, cold spray) can produce relatively stress free coatings that are extremely dense. This is thought 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.

1.1.4 Porosity

Porosity can be detrimental in coatings with respect to:

- Corrosion
- Surface finish (after machining)
- Strength, macro hardness and wear characteristics

On the contrary, porosity is important with respect to:

- Lubrication (porosity acts as reservoir for lubricants)
- Increasing thermal barrier properties
- Reducing stress levels and increasing thickness limitations
- Advancing shock resistance properties

1.1.5 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 are detrimental towards corrosion, strength and machinability properties.

1.1.6 Surface texture

Generally, the as-sprayed surface is rough and textured. The rough and high bond strength coatings are ideal for bond coats for less strongly bonding coatings. Many coatings have high friction surfaces as-sprayed and this property is made use of in many applications. Some plasma sprayed ceramic coatings produce smooth but textured coatings important in the textile industry. Other applications make use of the abrasive nature of some coating surfaces. Thermally sprayed coatings do not provide bright high finish coatings without finishing like that of electroplated deposits.

1.1.7 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 require a substrate for support.

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

Surface properties such as wear resistance and hardness are usually good, but the properties are more specific 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.

The table below summarizes the general trend of coatings and wrought/cast material, there are always be exceptions. The comparison does not take into consideration that coatings are usually supported by a substrate. Coatings are generally only used to give surface properties; such as, wear resistance and not to add strength.

Table 1.1 : Comparison of coating and wrought/cast materials.

Property	**Coating**	**Wrought/Cast**
Strength	Low (5-30%)	High (100%)
Ductility	Very Low (1-10%)	High (100%)
Impact Strength	Low	High
Porosity	High	Low
Hardness	Higher (micro hardness)	Higher (macro hardness)
Wear Resistance	High	Low
Corrosion Resistance	Low	High
Machining	Poor	Good

It should be kept in mind that coatings are to be considered in their own properties not the properties of original material prior to spraying since they can be different physically and chemically.

2. TYPES OF THERMAL SPRAY

2.1 Introduction

In this section brief information about recently used thermal spray processes are given. Later, more details about the Plasma Spray Coating will be given.

Cast iron liners are low-cost, durable, and easy to manufacture, which are the key criteria for mass produced automobiles. That solution was perfectly fine until the government mandated that automakers reduce their fleet fuel consumption average. Now the automakers are searching into new ways or resurrecting old solutions to increasing automobile fuel economy. While cast iron liners are a cost effective solution now, they have the inherent disadvantages in weight, size, thermal conductivity, differential thermal expansion and recyclability compared to the potential alternative materials. Particularly the deformation of the liner leads to an increased oil and fuel consumption and increasing emission. The liner-equipped engine is still unnecessarily large, still has differential expansion and reduced heat dissipation issues, still needs a heavier and larger cooling system, etc.

The majority of the issues regarding thermal sprayed coatings for cylinder blocks deal specifically with process types and not thermal spray in general. The most basic of the drawbacks of the thermal spray coatings is the weakness of the bond between the coated material and the Aluminum. If the coating is not applied properly, over time delamination can occur, stripping away the coating and exposing the soft Aluminum block material. Once that happens, premature wearing occurs and eventually the engine will lose compression resulting in engine failure. Additionally an issue with thermal spray processes pertains to any high velocity spray coating. The coated material deposited on the substrate has splatter morphology from the high velocity impact of spherical particles striking the surface. Inconsistency in coating properties occurs when the particles splatter against the substrate generating pores in the coating. This can lead to cracking of the coating. Splatter morphology is more of a concern with HVOF thermal spray because it utilizes high speeds to atomize the coating material and with the short spray distances inside the cylinder bore splatter morphology is more prevalent. In addition, during the application of the HVOF thermal spray overheating of the Aluminum cylinder block can occur because the particles are still extremely hot when they bond with the substrate. Overheating can damage the block by distorting it and possibly even changing the microstructure of the Aluminum. 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 the cylinder blocks to be prepared 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.

2.2 Cold Spray Coating

Cold spraying has been introduced in 1990s, and had been introduced by Dr. Antolli Papyrin and colleagues at the Russian Academy of Sciences.

The Cold Spray process basically uses the energy stored in high pressure compressed gas to propel fine powder particles at very high velocities. Particles are accelerated to very high speed by the pressurized gas that is forced through a converging-diverging nozzle. Solid particles with sufficient kinetic energy deform plastically and bond metallurgical to the substrate to form a coating. Bonding relies on sufficient energy to cause significant plastic deformation of the particle and substrate. Under the high impact stresses and stains, interaction of the particle and substrate surfaces probably cause disruption of oxide films promoting contact of chemically clean surfaces and high friction generating very high localized heating promoting bonding similar to friction or explosive welding. The critical velocity is needed to form bonding depends on the materials properties, powder size and temperature, and it varies between 500 and 1500 m/s.

Coatings at present are limited to ductile materials like Aluminum, stainless steel, copper, titanium and alloys. Hard and brittle materials like ceramics cannot be sprayed in the pure form, but may be applied as composites with a ductile matrix phase. Substrate materials are also limited to those that can withstand the aggressive action of the spray particles. Soft or friable substrates will erode rather than be coated. Soft metals such as Cu and Al are best suited for cold spraying, but coating of other materials (W, Ta, Ti, MCrAlY, WC–Co, etc.) by cold spraying has been reported [3].

The particles remain in the solid state and are relatively cold, so the bulk reaction on impact is solid state only. The process imparts little to no oxidation to the spray material, so surfaces stay clean which aids bonding. No melting and relatively low temperatures result in very low shrinkage on cooling, and with the high strain induced on impact, the coatings tend to be stressed in compression and not in tension like liquid/solid state reactions of most of the other thermal spray processes. Low temperatures also aid in retaining the original powder chemistry and phases in the coating, with only changes due deformation and cold working.

The deposition efficiency is typically low for alloy powders, and the window of process parameters and suitable powder sizes are narrow. To accelerate powders to higher velocity, finer powders smaller than 20μm are used. It is possible to accelerate powder particles to much higher velocity using a processing gas having high speed of sound (Helium instead of Nitrogen). However, Helium is costly and its flow rate, and thus consumption, is higher. To improve acceleration capability, Nitrogen gas is heated up to about 900 ºC. As a result, deposition efficiency and tensile strength of deposits increase [3]. The schematic view of Cold Spray Coating is as shown in the Figure 2.1.

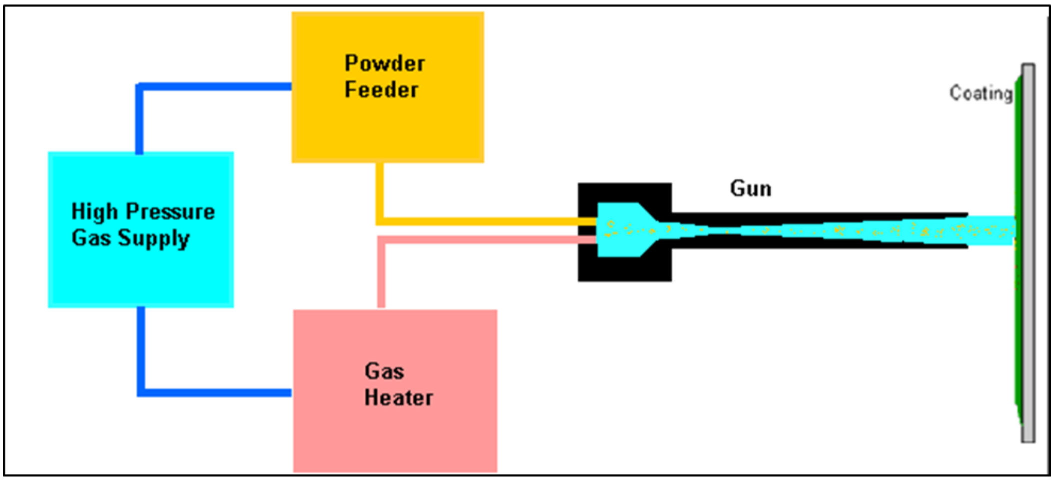


Figure 2.1 : Schematic view of Cold Spray Coating process.

To sum up, the advantages and disadvantages of process can be summarized as:

Advantages:

- Low temperature process, no bulk particle melting

- Retains composition/phases of initial particles
- Very little oxidation
- High hardness, cold worked microstructure
- Eliminates solidification stresses, enables thicker coatings
- Low defect coatings
- Lower heat input to work piece reduces cooling requirement
- Possible elimination of grit blast substrate preparation
- No fuel gases or extreme electrical heating required
- Reduce need for masking

Disadvantages:

- Hard brittle materials like ceramics cannot be sprayed without using ductile binders
- Not all substrate materials accept coating
- High gas flows, high gas consumption.
- Helium very expensive unless recycled
- Still mainly in research and development stage, little coating performance/history data

2.3 High Velocity Oxygen Fuel Thermal Spray Process (HVOF)

HVOF had been developed during 1980s as a mixture of gaseous or liquid fuel and oxygen is fed into a combustion chamber, where they are ignited and combusted continuously. The resultant hot gas at a pressure close to 1 MPa emanates through a converging–diverging nozzle and travels through a straight section. The fuels can be gases (Hydrogen, Methane, Propane, Propylene, Acetylene, natural gas, etc.) or liquids (Kerosene, etc.). The jet velocity at the exit of the barrel greater than 1000 m/s exceeds the speed of sound. A powder feed stock is injected into the gas stream, which accelerates the powder up to 800 m/s. The stream of hot gas and powder is directed towards the surface to be coated. The schematic view is given in Figure 2.2.

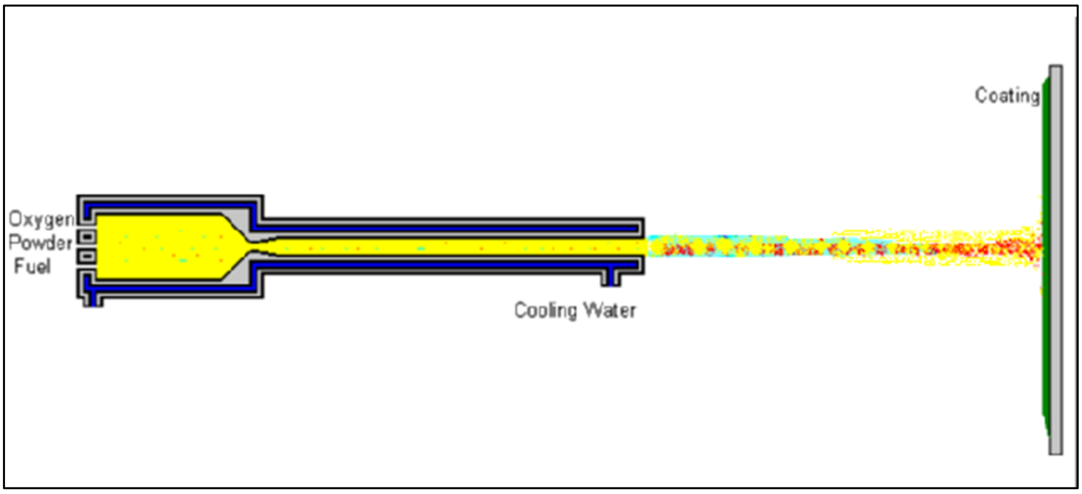


Figure 2.2 : Schematic diagram of HVOF process.

The powder partially melts in the stream, and deposits upon the substrate. 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 the other processes [3]. Powder particles are then injected into this gas stream. The stream is then directed toward the substrate being coated, to create a dense, durable coating with less than 1% porosity [4]. HVOF coatings are used in applications requiring the highest density and strength not found in most other thermal spray processes.

HVOF coatings may be as thick as 12 mm. It is typically used to deposit wear and corrosion resistant coatings on materials, such as ceramic and metallic layers. Common powders include WC-Co, Chromium carbide, and Alumina. The process has been most successful for depositing cermet materials (WC–Co, etc.) and other corrosion-resistant alloys such as stainless steels, Nickel-based alloys, Aluminum, hydroxyapatite for medical implants, etc. [3].

Today, more than 60 % of the engines for passenger cars are produced in cast Aluminum alloys with some concrete examples [5]. This change is brought by the need to reduce vehicle weight in order to improve fuel economy. Unfortunately, tribological properties of pure and unprotected Aluminum are poor comparing with gray cast iron. Among the variety of surface modification processes available for Aluminum alloys, HVOF thermal spraying is a cost effective promising technique that is, capable of solving problems such as wear, corrosion and thermal stability, by depositing a thin layer onto the substrate, thereby satisfying the required surface specification.

2.4 Detonation Thermal Spray Process

The Detonation gun basically consists of a long water cooled barrel with inlet valves for gases and powder. Oxygen and fuel (acetylene most common) is fed into the barrel along with a charge of powder. A spark is used to ignite the gas mixture and the resulting detonation heats and accelerates the powder to supersonic velocity down the barrel. A pulse of Nitrogen is used to purge the barrel after each detonation. This process is repeated many times a second. The high kinetic energy of the hot powder particles on impact with the substrate result in a build up of a very dense and strong coating. The schematic diagram is given in Figure 2.3.

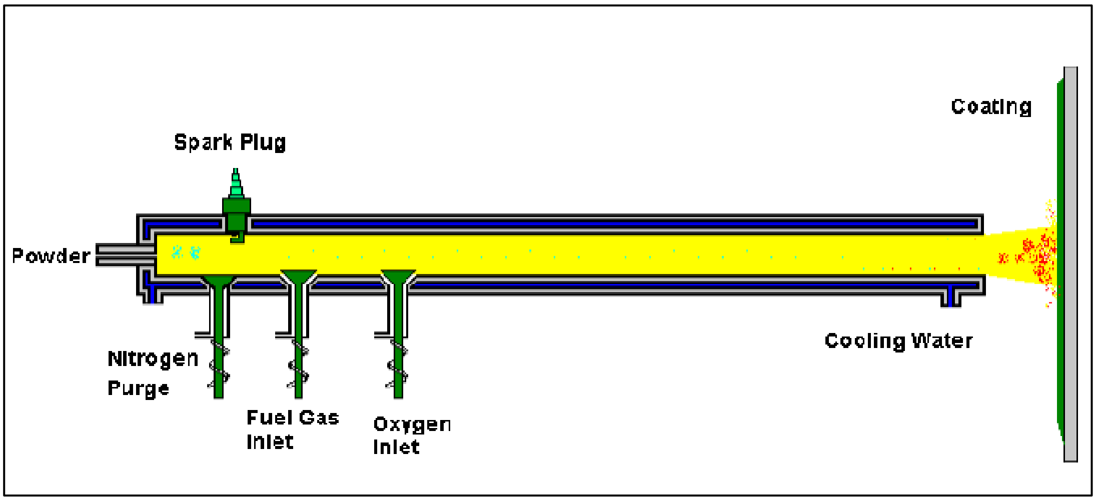


Figure 2.3 : Schematic representation Detonation Thermal Spray process.

2.5 Electric Wire Arc Thermal Spray

Pair of electrically conductive wires that are the material to be coated are melted by means of an electric arc. The molten metal is atomized by compressed air and propelled towards the substrate surface. As in the all thermal spray coating processes the impacting molten particles on the substrate solidify rapidly to form a coating. The schematic view is shown on Figure 2.4.

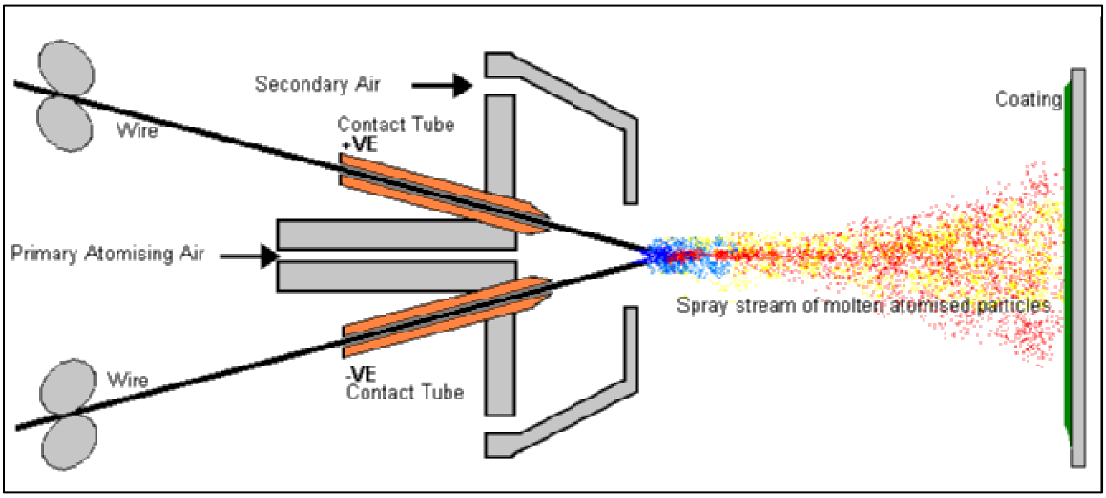


Figure 2.4 : Overview of Wire Arc Thermal Spray process.

Electric wire 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 wire 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 Aluminum and machine element work on large components. This process is commonly used for metallic and heavy coatings [3].

2.6 Plasma Transferred Wire Arc

More details will be provided later since the main topic of thesis is this process. In this section broad information is given just to distinguish the process from others and compare with them. Plasma transferred wire arc is another form of wire arc spray that deposits a coating on the internal surface of a cylinder, or on the external surface of a part of any geometry. It is predominantly known for its use in coating the cylinder bores of an engine, enabling the use of Aluminum engine blocks without the need for heavy cast iron liners. A single conductive wire is used as feedstock for the system (Figure 2.5).

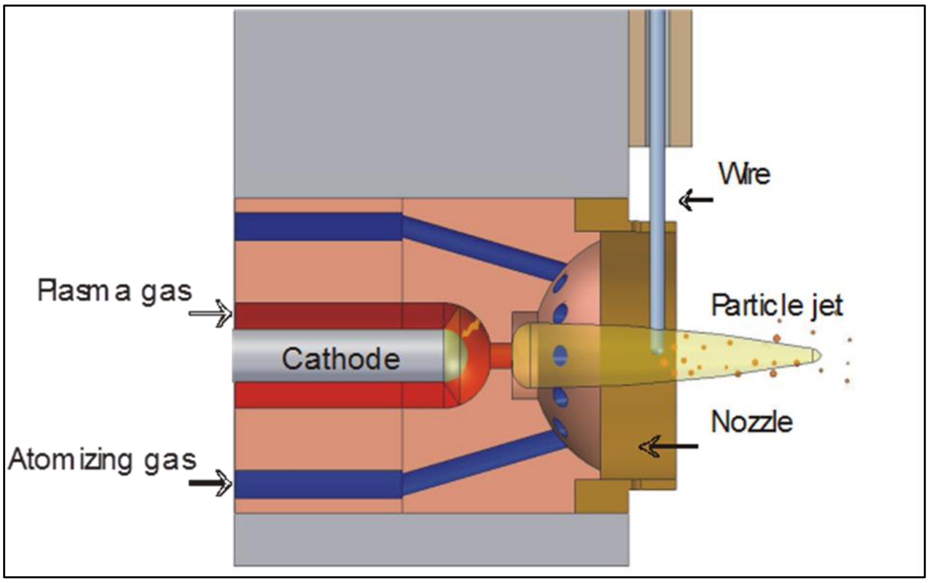


Figure 2.5 : PTWA process principles.

A supersonic plasma jet melts the wire, atomizes it and propels it onto the substrate. The plasma jet is formed by a transferred arc between a non-consumable cathode and the type of a wire. After atomization, forced air transports the stream of molten droplets onto the bore wall. The particles flatten when they impinge on the surface of the substrate, due to the high kinetic energy. The particles rapidly solidify upon contact. The stacked particles make up a high wear resistant coating. The PTWA thermal spray process utilizes a single wire as the feedstock material. All conductive wires up to and including 1.6mm can be used as feedstock material, including "cored" wires. PTWA can be used to apply a coating to the wear surface of engine or transmission components to replace a bushing or bearing.

2.7 Plasma Thermal Spray Coating

The Plasma Spray Process is basically the spraying of molten or heat softened material onto a surface to provide a coating. Material, typically in the form of powder is injected into a very high temperature plasma flame, where it is rapidly heated and accelerated to a high velocity. The hot material impacts on the substrate surface and rapidly cools forming a coating. Sometimes material is as a liquid [6], suspension [7] or wire.

The plasma spray gun comprises a copper anode and tungsten cathode, both of which are water-cooled. Plasma gas (Argon, Nitrogen, Hydrogen, and Helium) flows around the cathode and through the anode that is shaped as a constricting nozzle (Figure 2.6). The plasma is initiated by a high voltage discharge that causes localised ionisation and a conductive path for a DC arc to form between cathode and anode. The resistance heating from the arc causes the gas to reach extreme temperatures on the order of 10^4K, dissociate and ionise to form a plasma. The plasma exits the anode nozzle as a free or neutral plasma flame (plasma which does not carry electric current) which is quite different to the Plasma Transferred Arc coating process where the arc extends to the surface to be coated. Cold gas around the surface of the water cooled anode nozzle being electrically non-conductive constricts the plasma arc, raising its temperature and velocity. Powder is fed into the plasma flame most commonly via an external powder port mounted near the anode nozzle exit. The powder is so rapidly heated and accelerated that spray distances can be in the order of 25 to 150 mm [8].

The molten droplets flatten, rapidly solidify and form a deposit. Commonly, the deposits remain adherent to the substrate as coatings; free-standing parts can also be produced by removing the substrate. There are a large number of technological parameters that influence the interaction of the particles with the plasma jet and the substrate and therefore the deposit properties. These parameters include feedstock type, plasma gas composition and flow rate, energy input, torch offset distance, substrate cooling, etc [9].

The feedstock consists of a multitude of pancake-like lamellae called 'splats', formed by flattening of the liquid droplets. As the feedstock powders typically have sizes from micrometers to above 100 micrometers, the lamellae have thickness in the micrometer range and lateral dimension from several to hundreds of micrometers. Between these lamellae, there are small voids, such as pores, cracks and regions of incomplete bonding. As a result of this unique structure, the feedstock can have properties significantly different from bulk materials. These are generally mechanical properties, such as lower strength and modulus, higher strain tolerance, and lower thermal and electrical conductivity.

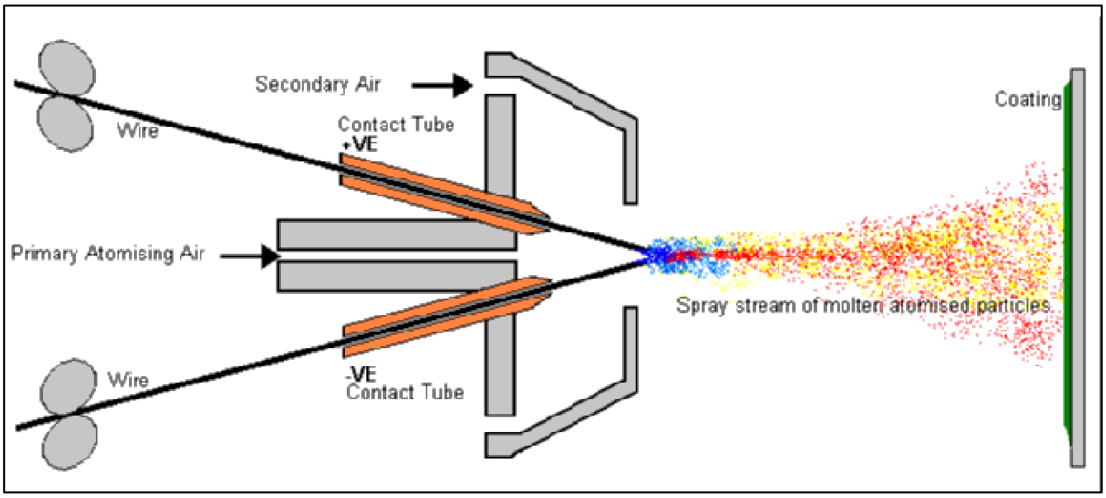


Figure 2.6 : Plasma Spray process overview.

Plasma spraying has the advantage that it can spray very high melting point materials such as refractory metals like tungsten and ceramics like zirconia unlike combustion processes. Plasma sprayed coatings are generally much denser, stronger and cleaner than the other thermal spray processes with the exception of HVOF and detonation processes. Plasma spray coatings probably account for the widest range of thermal spray coatings and applications and make this process the most versatile. Disadvantages of the plasma spray process are relative high cost and complexity of process.

This technique is mostly used to produce coatings on structural materials. Such coatings provide protection against high temperatures (for example thermal barrier coatings for exhaust heat management), corrosion, erosion, wear; they can also change the appearance, electrical or tribologic properties of the surface, replace worn material, etc.

2.8 Plasma Jet Theory

To well understand how plasma is formed and why different gases are selected for plasma gas, it is needed to discuss about the theory behind the plasma. Plasma is an electrically conductive gas containing charged particles. When atoms of a gas are excited to high energy levels, the atoms loose hold of some of their electrons and become ionised producing a plasma containing electrically charged particles - ions and electrons. The plasma generated for plasma spraying usually incorporates one or a mixture of the following gases:

- Argon
- Helium
- Nitrogen
- Hydrogen

Plasma flames for thermal spraying can produce temperatures around 7.000 to 20.000K far above the melting temperature (and vapour temperature) of any known material. The extreme temperature of the plasma is not the only reason for the effective heating properties. If for example Helium gas is heated to around 13,000K without a plasma forming, it would have insufficient energy for normal plasma spraying. Nitrogen on the other hand heated to 10.000K going through dissociation and ionisation forming a plasma is an effective heating media for thermal spraying, being able to supply about six times more energy than an equal volume of Helium at 13.000K (Figure 2.7). The plasma is able to supply large amounts of energy due to the energy changes associated with dissociating molecular gases to atomic gases and ionisation, which occur with little change in temperature.

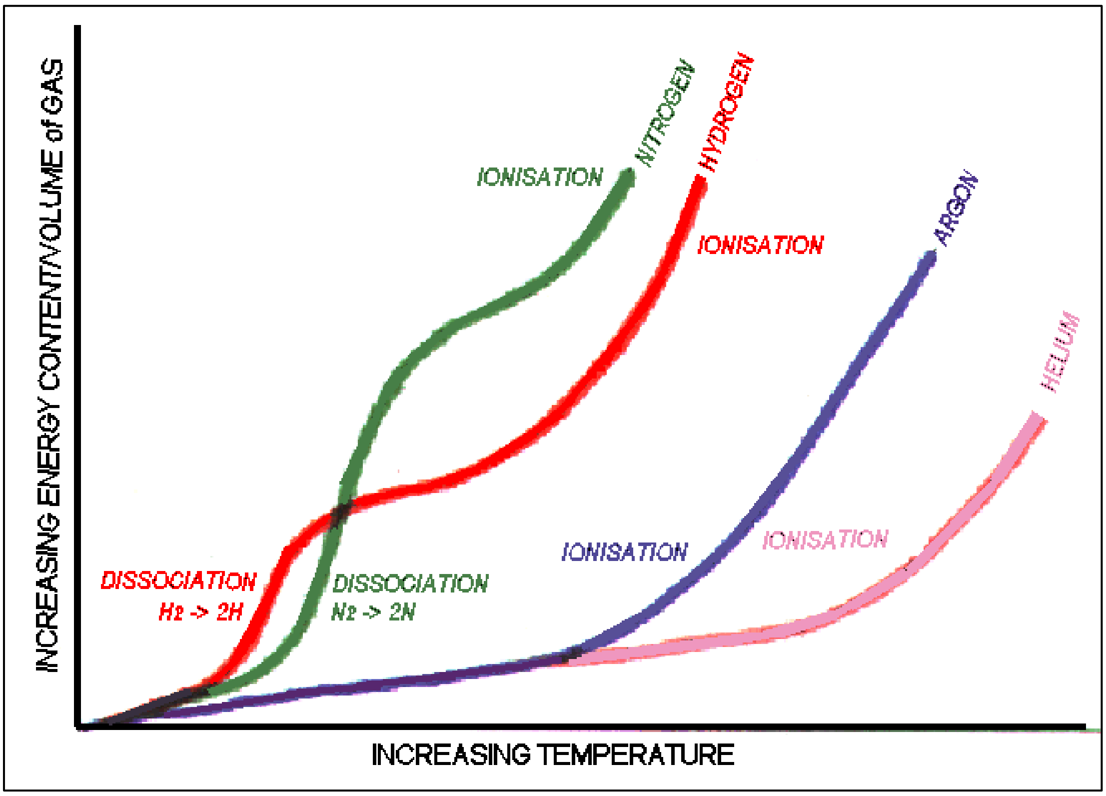


Figure 2.7 : Plasma Gas vs. Temperature.

$$N_2 + E = 2N \qquad \textbf{(2.1)}$$

Diatomic molecule of Nitrogen with energy gives 2 free atoms of Nitrogen **(2.1)**

$$2N + E = 2N^+ + 2e^- \qquad \textbf{(2.2)}$$

2 free atoms of nitrogen with energy gives 2 Nitrogen ions and 2 electrons **(2.2)**. The reverse process provides most of the energy for heating the spray material without a dramatic drop in temperature:

$$2N^+ + 2e^- = 2N + E \qquad \textbf{(2.3)}$$

$$2N = N_2 + E$$

Nitrogen and Hydrogen are diatomic gases (two atoms to every molecule). These plasmas have higher energy contents for a given temperature than the atomic gases of Argon and Helium because of the energy associated with dissociation of molecules. Argon and Helium are monatomic gases (the atoms do not combine to form molecules). These plasmas are relatively lower in energy content and higher in temperature than the plasmas from diatomic gases.

Nitrogen is a general-purpose primary gas used alone or with Hydrogen secondary gas. Nitrogen also benefits from being the cheapest plasma gas. Nitrogen tends to be inert to most spray material except materials like Titanium.

Argon is probably the most favoured primary plasma gas and is usually used with a secondary plasma gas (Hydrogen, Helium and Nitrogen) to increase its energy. Argon is the easiest of among them to form plasma and tends to be less aggressive towards electrode and nozzle hardware. Most plasma is started up using pure Argon. Argon is a noble gas and is completely inert to all spray materials.

Hydrogen is mainly used as a secondary gas; it dramatically effects heat transfer properties and acts as anti-oxidant. Small amounts of Hydrogen added to the other plasma gases dramatically alters the plasma characteristics and energy levels and is thus used as one control for setting plasma voltage and energy.

Helium is mainly used as a secondary gas with Argon. Helium is a noble gas, is completely inert to all spray materials, and is used when Hydrogen or Nitrogen secondary gases have deleterious effects. Helium imparts good heat transfer properties and gives high sensitivity for control of plasma energy. It is commonly used for high velocity plasma spraying of high quality carbide coatings where process conditions are critical.

3. INTRODUCTION TO LUBRICATION

Lubrication is the sliding of two solids on each other by means of gaseous, liquid, or solid lubricant at the sliding interface to reduce friction and wear. Moreover, it is in order to dissipate heat and/or carry away debris that is generated during the sliding process. There are many forms of lubrication processes depending on geometry of contacting bodies, the roughness and texture of surfaces, the load on the contact surface (or geometry), the pressure and temperature of media, the speed of rolling and sliding, the environmental conditions, the physical and chemical properties of lubricant, and the material composition.

One of the most important parameters of lubrication between two solids, and the one important in the thesis is surface roughness. Surface roughness and its lay orientation with respect to surface motion can have a significant influence on lubrication performance in the regim of mixed lubrication, where the load is shared between the lubricant pressure and the asperities. Roughness effects are particularly important in counterformal contacts because the majority of these contacts operate in mixed lubrication. Progressive wear failure and sudden scuffing failure are dependent on the lubrication process influenced by the micro-roughness geometry; the contact temperatures in the conjunction also influence them.

Heavy friction, wear, and surface damage are the result of breaking the joint formed during sliding of two surfaces in contact with each other. In this case, many high points on the surfaces carry load. The total tangential force required to shear these peaks is usually high. To reduce the frictional force that is due to high shear force, and allow easier sliding, a lubricant is used to separate the surfaces either totally or partially.

There are three types of lubrication conditions: thick-film lubrication, thin-film lubrication and boundary lubrication. Those are not mentioned in details in this study, only general information is given. Thick-film lubrication is used when the total separation of surfaces by a lubricant film thickness many times larger than the size of the lubricant molecules. In thick-film lubrication, the fluid pressure carries load. If the load is shared by the fluid pressure and contacting surfaces, it is called as thin-film lubrication or mixed lubrication. That is the type seen during vehicle engine running between cylinder bore and piston rings. When the entire load is carried by only contacting surfaces, the most severe condition, it is called boundary condition [10]. Those three regimes are distinguished per the load, speed, lubricant viscosity, contact geometry, and surface roughness of both surfaces. The figure below indicates those three regimes, a typical Streibeck curve, depending on lubricant viscosity η, angular velocity of cylindrical contact N, and the average contact pressure P.

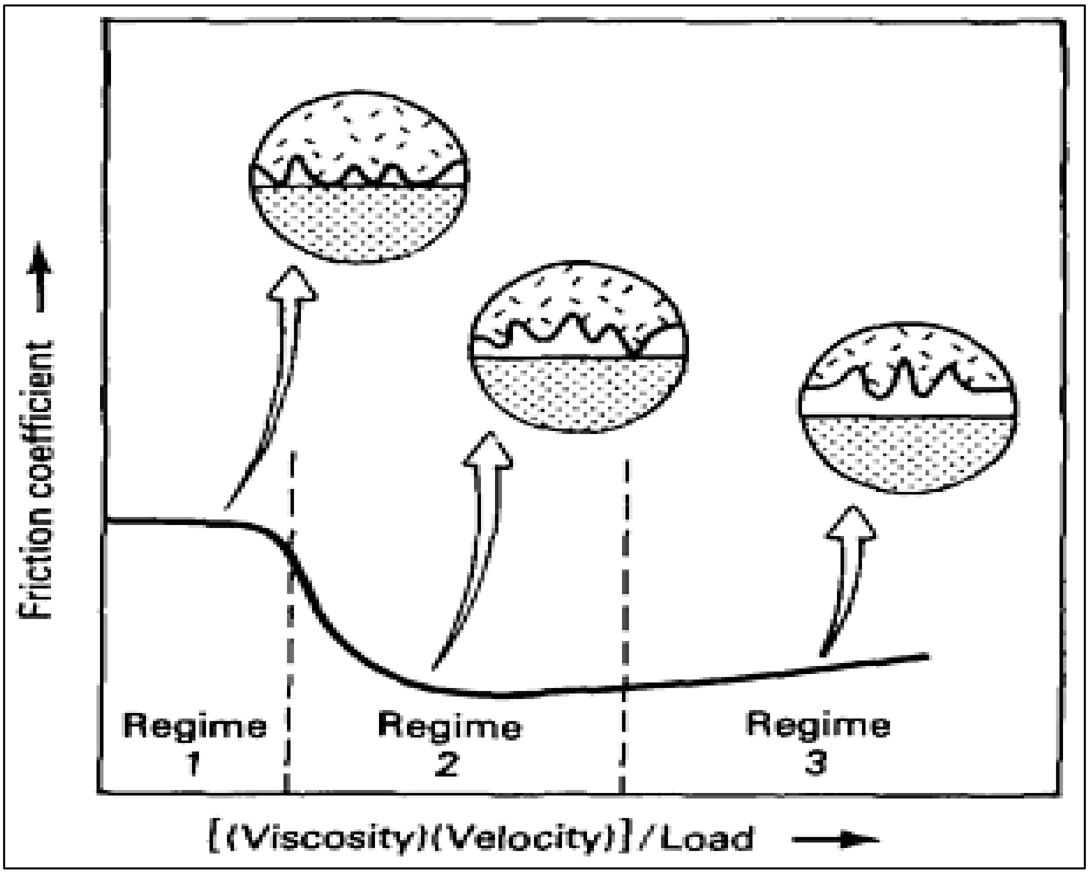


Figure 3.1 : Regime 1. Boundary lubrication; Regime 2. Thin-film lubrication; Regime 3. Thick-film lubrication [10].

All engines are to be lubricated in order to preserve the integrity of the system for its designated lifetime. The extreme temperatures in internal combustion engines make lubrication complex. The lubricants that are suitable for use in these engines are expected to reduce friction, dissipate heat from internal parts, minimize deposit formation, and prevent corrosion and wear [11].

The lubricant or oil is delivered from a reservoir to those parts of the equipment that require lubrication and cooling. The lubricating system can be full-pressure, splash, or modified-splash types [12]. Most automotive engines use a full-pressure system, in which the oil is pumped from the oil sump to the main bearing and connecting rods, and then up the connecting rods to the piston pin. In overhead valve engines, a portion of the pumped oil travels through push rods (in some cases), over rocker arms, past valve stems, and down the valve guides. In many engines, the cylinder walls and piston pins depend on splash lubrication by the oil that is thrown off the main bearing. Figure 3.2 shows the lubrication system of a cam-in-block overhead valve engine [12].

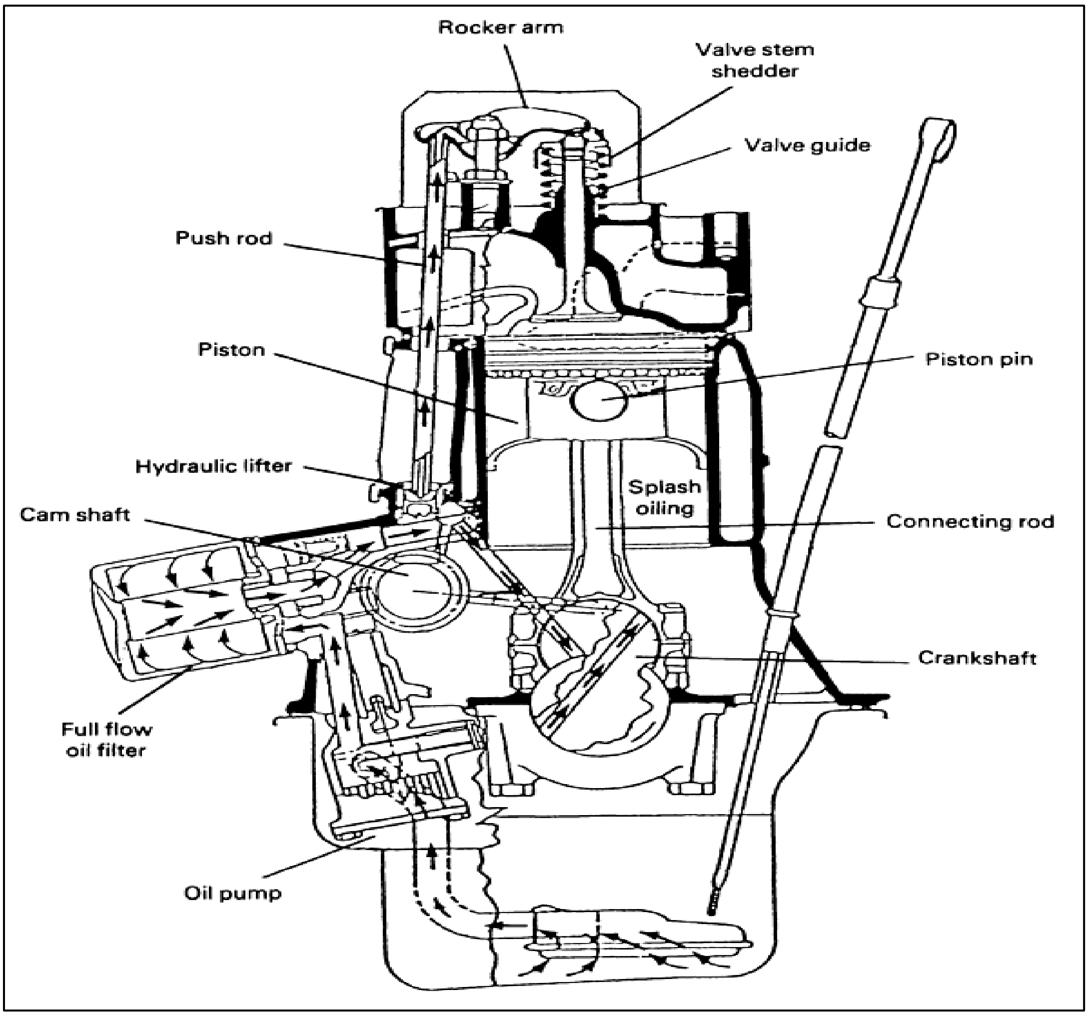


Figure 3.2 : Lubrication mechanisms in cam-in-block overhead block valve engine.

The main function of lubrication is to reduce friction by forming a film between two mating parts that slide or roll over each other. As mentioned before the strength and durability of oil film is related with the viscosity of oil, the speed of moving part and load exerted on surfaces. As know from Streibeck curve, the friction coefficient is related with viscosity η, speed N and pressure P. The ratio of (η.N)/P is directly proportional with oil film thickness, on the other hand inversely proportional to friction coefficient (Figure 3.3). One of the main point in this study is the lubrication thickness. Even when all parameters that viscosity, speed and load are kept constant, the coefficient of friction can be reduced.

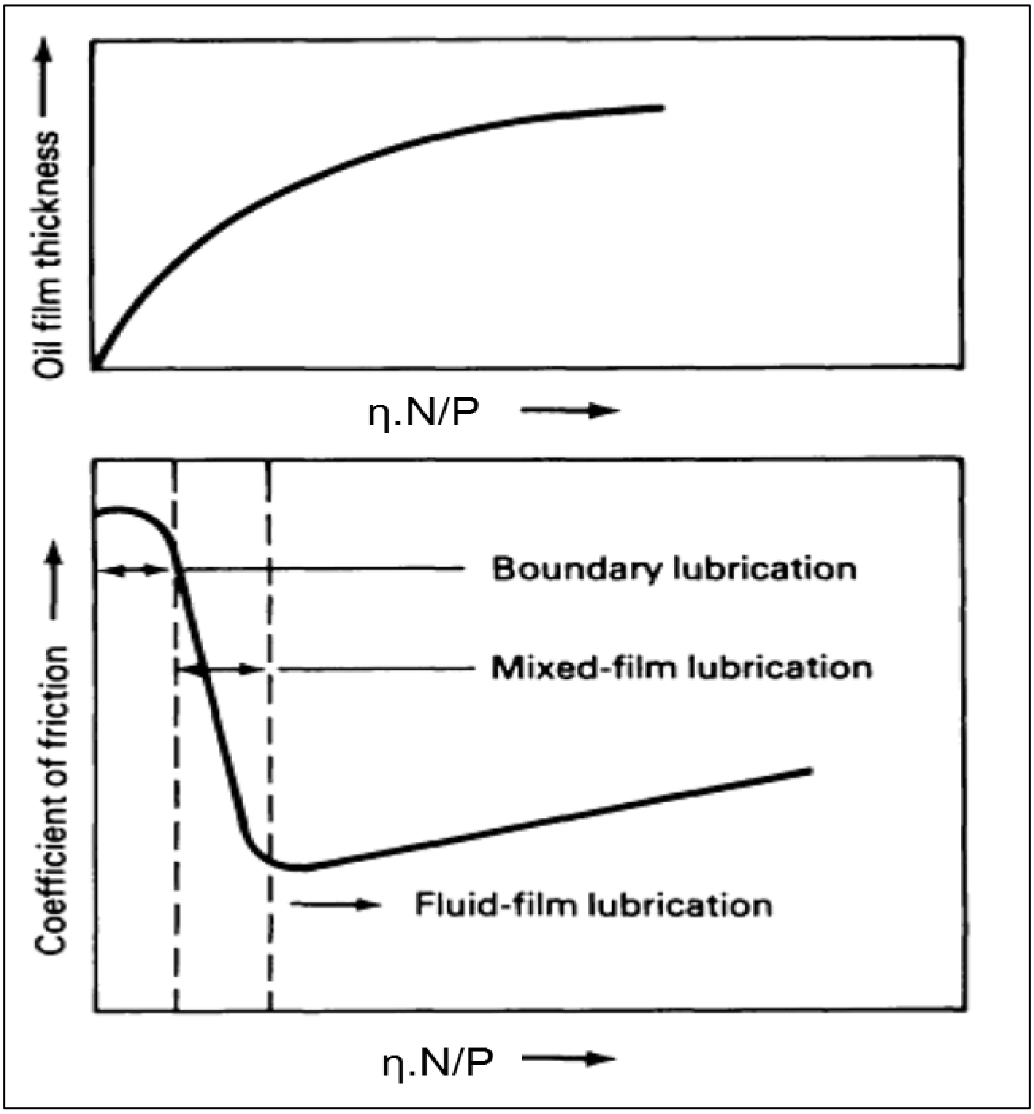


Figure 3.3 : Streibeck Curve showing lubrication regimes and relations [12].

4. WEAR

4.1 Introduction to Wear

In broad meaning, wear is erosion or removal of material from moving solid surfaces that roll on each other. Wear is related to interaction between surfaces and more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface [13].

The study of the processes of wear is part of the discipline of tribology. The complex nature of wear has delayed its investigations and resulted in isolated studies towards specific wear mechanisms or processes [14]. Some commonly referred to wear mechanisms (or processes) include:

- Adhesive wear
- Abrasive wear
- Surface fatigue
- Fretting wear
- Erosive wear
- Polishing wear

The mostly seen wear between cylinder block bore surface and piston rings, which are the main subject of in this study, is combination of abrasive and polishing wear. So only those are mentioned here.

Abrasive wear occurs when a hard rough surface slides across a softer surface [13]. ASTM International (formerly American Society for Testing and Materials) defines it as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface [15]. Abrasive wear is commonly classified according to the type of contact and the contact environment. The type of contact determines the mode of abrasive wear. The two modes of abrasive wear are known as two-body and three-body abrasive wear. Two-body wear occurs when the grits or hard particles remove material from the opposite surface. The common analogy is that of material being removed or displaced by a cutting or plowing operation. Three-body wear occurs when the particles are not constrained, and are free to roll and slide down a surface. The contact environment determines whether the wear is classified as open or closed. An open contact environment occurs when the surfaces are sufficiently displaced to be independent of one another. Figure 4.1 indicates abrasive wear types. Two-body systems typically experience from 10 to 1000 times as much loss as three-body systems for a given load and path length of wear [16].

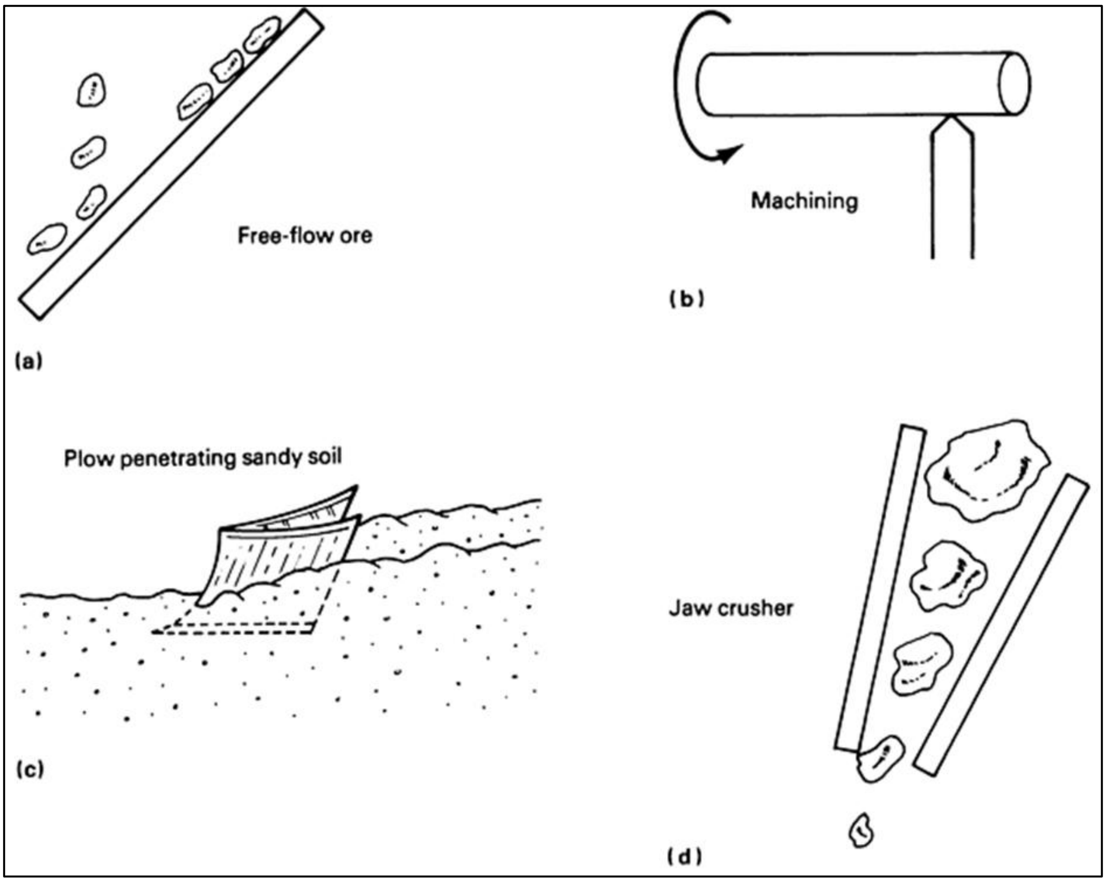
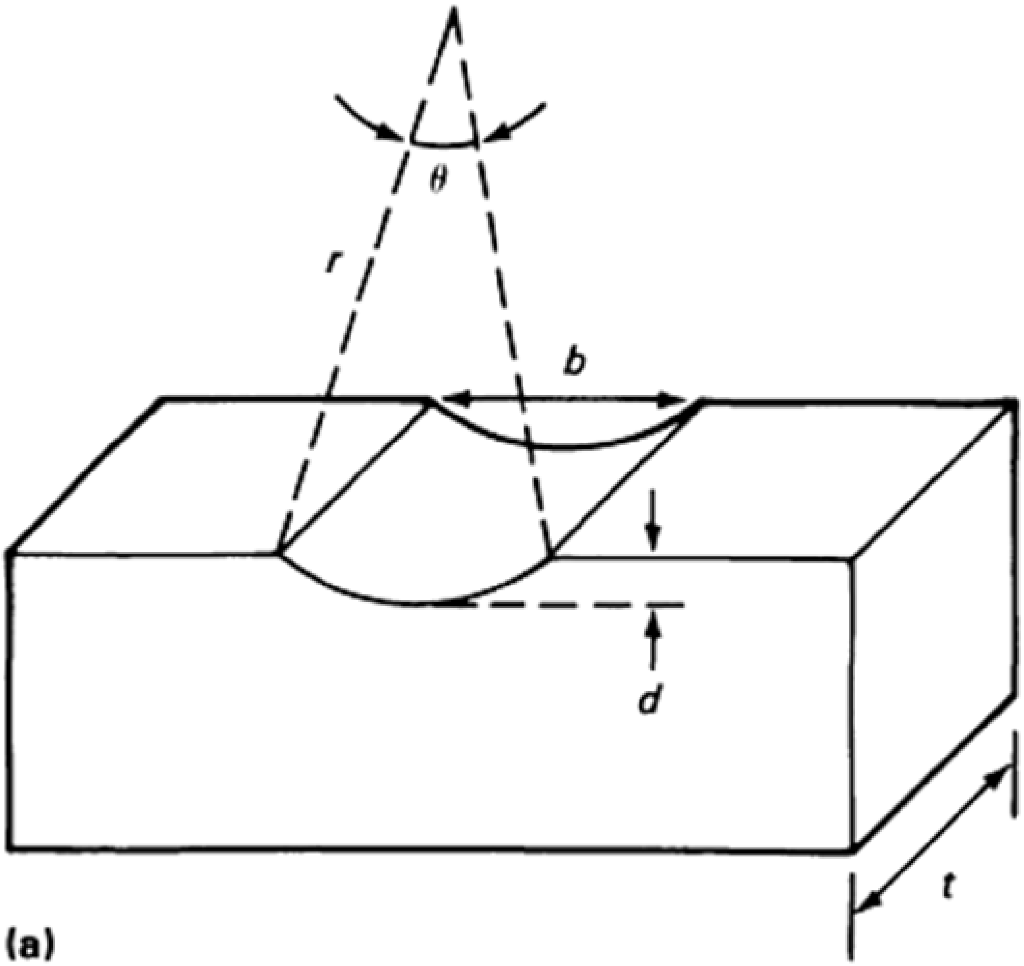


Figure 4.1 : Types of contact during abrasive wear. (a) Open two-body. (b) Closed two-body. (c) Open three-body. (d) Closed three-body.

Polishing wear describes interactions between two solids that remove material from, while at the same time producing a polished finish on, the surface of at least one of the two. This definition is not, however, a precise one because the surface condition known as a polish cannot be defined quantitatively. The term is, in fact, merely one of common usage describing a surface that reflects light brightly and that produces a clear image of distant objects in the manner expected of a mirror.

4.2 Wear Measurement

There are many methods to measure the amount of wear. The measurement techique "Area Measures of Wear" is used in the study, since it is more representative how wear occurs between cylinder bore surface and piston rings. Contact solid surfaces produce material loss over a localized area on the solids. In many cases, those areas of wear loss can be measured and are proportional to the amount of wear. Examples would include worn areas on gear teeth, on bearing retainers, and on sliding pads with contoured surfaces. If the curvature of the surface is known, then the amount of wear can be quantified on the basis of the area worn. Because many tribological components involve area contacts, as contrasted to point or line contacts, area measures of wear are important. One frequently used laboratory test system comprises a stationary block and a rotating ring. ASTM Standard G77 [17] concers with lubricants and material wear, utilize this type of system. Although the initial contact between the two specimens is nominally a line (there is actually a small lateral width associated with elastic deformation along the contact line), the resulting scar on the block becomes a curved rectangular surface as the two components wear. The volume worn from the block can be calculated from the two scar dimensions and the ring (or scar) curvature, but it is also common to find the projected scar area reported. The ASTM involves scar width measurement only because it specifies the specific block size, scar length and ring diameter. Figure 4.2 shows a schematic of the worn volume in this type of geometry and the geometric relations that are used to calculate wear volume under the assumption of an ideal scar shape. In the figure (a) Worn volume of block specimen, where t is block width in mm, r is radius of ring in mm, D is 2r (diameter of ring) in mm, b is average scar width in mm, is sector angle in radians, and d is scar depth in mm. (b) Geometric relations used to calculate wear volume, assuming ideal scar shape [17].



(a)

Scar width $= b = D \sin \frac{\theta}{2}$

Scar volume $= \frac{D^2 t}{8} (\theta - \sin \theta)$

where $\theta = 2 \sin^{-1} \frac{b}{D}$

Scar volume $= \frac{D^2 t}{8} \left[2 \sin^{-1} \frac{b}{D} - \sin\left(2 \sin^{-1} \frac{b}{D}\right)\right]$

(b)

Figure 4.2 : A schematic of the worn volume.

4.3 Wear of Internal Combustion Engine Parts

Cylinder block of internal combustion engine 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.

The cylinder 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. 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.

Cylinder block bore surface material must have high wear resistance and capable of withstanding high pressures of 100 to 200 bars in engines with high peak firing pressures [18]. The porosity level of the material must be below 1% and the maximum pore size must be below 500 microns on the running surfaces [18]. 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. 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 [19]. Scuffing is the phenomenon characterized by mass movement of surface elements to form linear scratches and local welds on surfaces in relative motion [20]. Wear and scuffing occurs on the cylinder bore surface when the lubrication conditions deteriorate. It is known that wear on the cylinder bore surface is promoted when acid adheres to the bore surface during engine warm up because of sulfur in the fuel [21]. Figure 4.3 below is a graph showing the sulfur concentration in gasoline in various parts of the world.

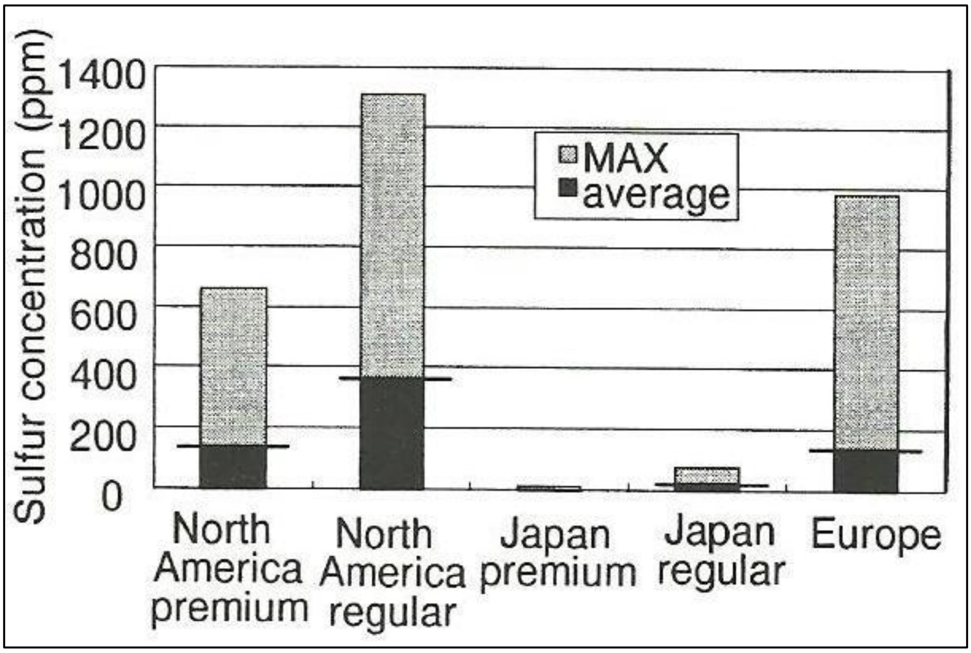


Figure 4.3 : Sulfur Concentration in unleaded fuel [22].

Another important requirement for cylinder block material is its coefficient of friction. Friction between the cylinder block bore 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 [23]. Over half of that power loss can be attributed to the frictional loss between piston rings and cylinder bores as shown in Figure 4.4. Therefore, in order for the alternative to be a viable option for replacing cast iron liners the more it can reduce the frictional loss between the cylinder liner and the piston ring.

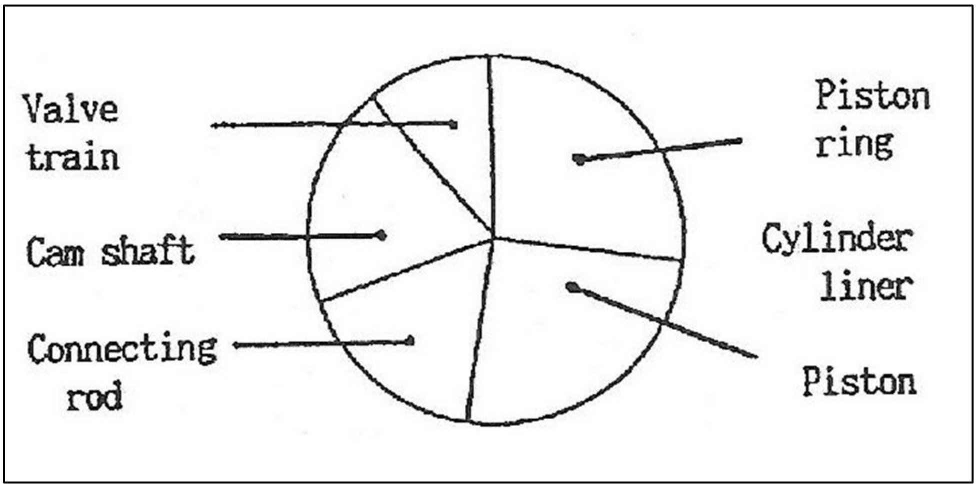


Figure 4.4 : Breakdown of friction loss for engine components [24].

The Table 4.1 defines key characteristics of cylinder block material must posses.

Table 4.1 : Cylinder block material characteristics.

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	

4.4 Wear of Metals

Cast iron is a general term used to a family of engineering materials including gray iron, white iron, malleable iron, and nodular iron. These irons have very different compositions, casting characteristics, and heat treatments, which result in physical, chemical, and mechanical properties of wide variation.

Cast irons are unique tribological materials that can be used in a range of applications, particularly those in which wear resistance is important. The matrix of these materials can be varied from pearlite to martensite, in order to support graphite, which is a solid lubricant. Hard phases can be varied to resist abrasion. The primary characteristics of gray and nodular irons are described later, in terms of very general selection guidelines since the gray iron and nodular iron are most widely used in engine cylinder block assembly.

Excess carbon in gray iron is present in the form of flakes of graphite in a matrix that varies from all ferrite to pearlite. Gray irons are brittle and have relatively low strength and hardness properties. Graphite provides good damping capacity, and its thermal conductivity value is higher than that for steel. Graphite cavities provide chip-breaking qualities, which allow free machining with short chips. A fractured surface would appear gray and dull, because of the presence of graphite. Because graphite is an excellent solid lubricant, it offers good sliding wear resistance with a relatively low coefficient of friction.

The flake like graphite is converted to nodular form in ductile or nodular iron. Hence the brittleness of gray irons, due to flakes, is diminished and, with suitable heat treatment, a steel-like structure can be produced. Because pure materials and rather special melting procedures are required, cost is increased significantly, but the improvement in mechanical properties allows these irons to compete with heat-treated.

It is recommended that both microstructure and hardness values at and close to the surface be checked for all critical wear applications. The matrix structure of cast irons usually contains one or more of these constituents: ferrite, pearlite, cementite, phosphide eutectic, martensite, bainitic transformation structures, austenite, and graphite.

Ferrite in cast iron is essentially a single-phase solid solution of silicon in amounts that vary with graphite structure, cooling rate, and silicon content. The amount tends to increase as the cooling rate decreases and the silicon content increases, and the graphite approaches the undercooled form. Fully ferritic structures are normally only obtained by annealing. Ferrite should be avoided in all wear parts.

Pearlite consists of alternate lamellae of ferrite and cementite. The degree of fineness depends on cooling rate. The finer the pearlite, the stronger (harder) is the iron. This is a highly desirable matrix for sliding wear resistance.

Cementite in the massive eutectic form is a hard white constituent formed during solidification, and in the lamellar form in pearlite, where it is formed by the transformation of austenite through the critical temperature. Eutectic carbides can increase hardness for wear resistance. Harder carbides can be obtained by alloying with Cr and Mo.

Phosphide eutectic occurs in two distinct forms in cast irons with more than 0.06% Phosphorus. The normal form is pseudobinary, which consists of ferrite and iron phosphide. The true eutectic forms from the liquidus as austenite plus iron phosphide. Upon cooling, the austenite transforms to ferrite and pearlite, and, with iron phosphide, gives bulk hardness between 420 and 600 HV. It is desirable to improve the sliding wear resistance of gray irons, it markedly increases tool wear in machining operations.

Martensite is a fine acicular, slow-etching structure, normally produced either by very rapid cooling (quenching) of austenite through the critical temperature range or by alloying. The presence of martensite achieves maximum hardness in parts that require abrasion resistance.

Acicular or bainitic transformation structures are produced by either isothermal quenching or alloying. They are often referred to as acicular ferrite and are softer and tougher than martensite, but harder and stronger than pearlite. These acicular structures range from the upper bainites or acicular ferrites to martensite, depending on the transformation time, composition, and other factors. Austempered parts provide resistance to the more hostile stress conditions encountered in gear trains, for example.

Austenite can be made stable at room temperature by the addition of alloys, such as Nickel and Manganese. These irons are not normally used for wear resistance.

To compare the wear resistance of gray cast iron that is most widey used material in engine blocks, wear properties of Carbon steels need to be discussed. Later, mechanical properties are compared.

Carbon steels are those major hardening agent is Carbon. Alloying elements such as Chromium, Vanadium, and Molybdenum for improving hardenability are not found in these steels in any significant amount. Carbon steels containing less than 0.4% C are not hardenable by heat treatment and are not used very much for sliding or rolling contact applications. Carbon steels have wide and diversified use in tribological applications. Application, rather than specific composition, has determined the need for this class of materials. When selecting steel based on its wear-resistance properties, the total cost of the steel and its heat treatment must be considered. The following steels, which may have suitable wear-resistance properties in specific applications, are listed in order of increasing total costs:

- Low-carbon steels, such as 1020, not heat treated
- Simple high-carbon steels, such as 1095, not heat treated
- Directly hardened carbon or low-alloy steels, either through-hardened or surface-hardened by induction or flame process
- Low-carbon or low-alloy steels that are surface-hardened by carburizing, cyaniding, or carbonitriding
- Medium-carbon chromium or chromium-Aluminum steels that are hardened by nitriding
- Directly hardened high-alloy steels, such as D2 high-Carbon high-Chromium tool steel (1.50C-12Cr), that contain particles of free carbide
- Precipitation-hardening stainless steels (mainly for applications involving elevated temperatures and corrosive environments, as well as excessive wear)
- Specialty steels produced by powder metallurgy (P/M) or mechanical alloying techniques

Wear resistance tends to increase with hardness, but it decreases as toughness increases. This is an important relationship in applications that require both wear resistance and impact resistance. The correlation between wear resistance and toughness for a variety of ferrous alloys is shown in Figure 4.5. The data in Figure 4.5 indicate that for most ferrous alloys, there is a trade-off between wear resistance and toughness. In some alloys, altering the carbon content is a simple method for adjusting these properties. Area A shows wrought and cast low-alloy steels; area B shows austenitic manganese steels; area C is region of variety of heat-treated steels; and finally area D indicates high-chromium white cast irons

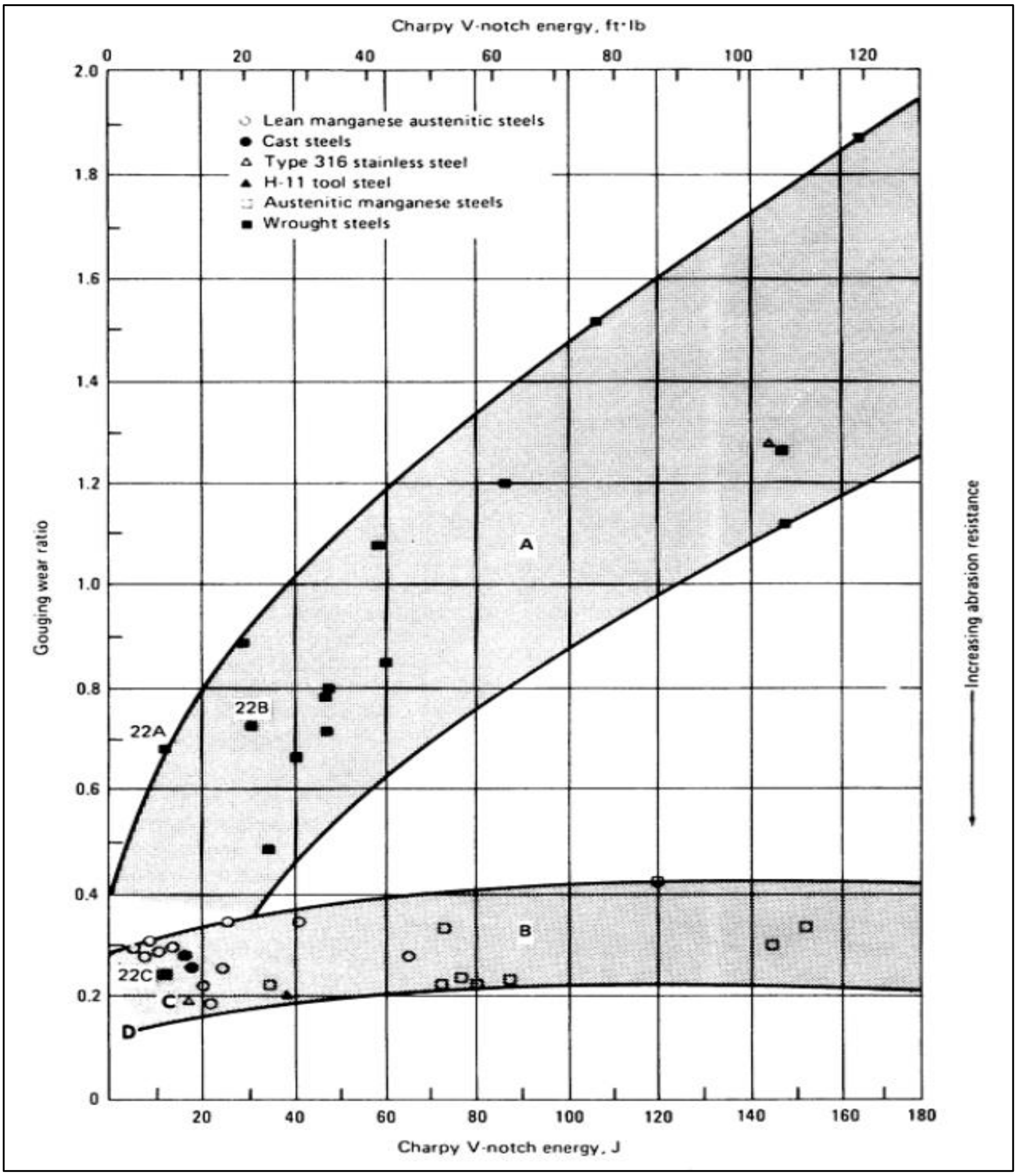


Figure 4.5 : Relationship between resistance to gouging abrasion and toughness of selected materials. [25].

The wear resistance of ferritic steel is improved by hardening, either throughout the section or superficially. The maximum hardness depends on the Carbon content of the steel and the amount of martensite (that is efficiency of quenching). Carbon content also affects hardness and wear-resistance through the formation of various simple and complex carbides. Wear properties depend on the type, amount, shape, size, and distribution of carbides present, in addition to the properties of the matrix (for example, hardness, toughness, and stability). Despite this complexity, a correlation for relative wear content is possible.

Annealed unalloyed metals hardness data can be used as a guide to abrasive wear resistance. These data were obtained using a two-body abrasion with an abrasive hardness much greater than that of the metal samples. The Figure 4.6 compares hardness and wear-resistance of metals.

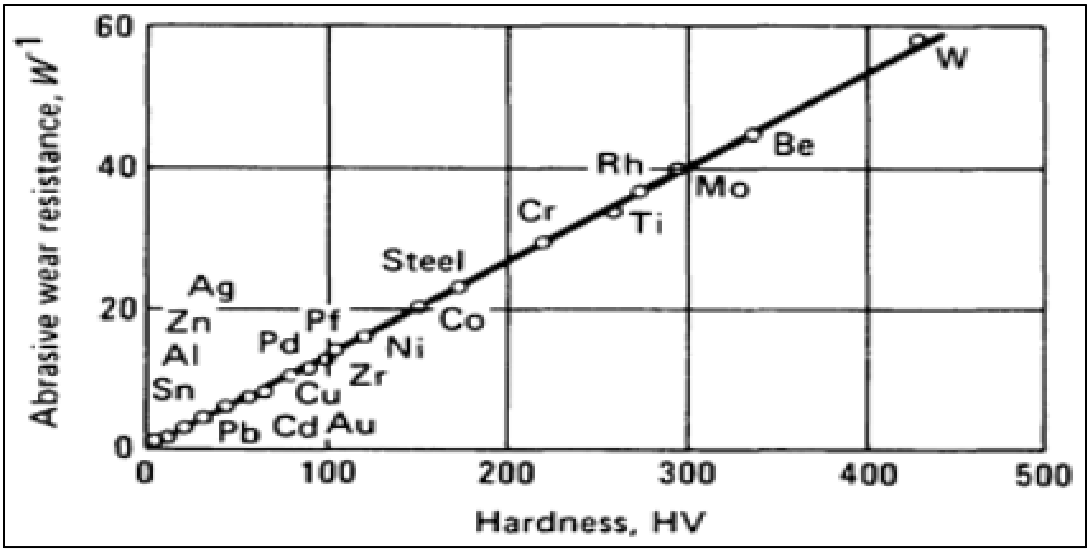


Figure 4.6 : Abrasive wear resistance versus hardness for annealed unalloyed metals and steel [26].

It can be conluded that increasing hardness leads to decrease in wear resistance. To compare cast iron and carbon steel in view of wear performance, hardness values are to be checked.

Table 4.2 : C-Steel and cast iron mechanical properties [27].

Material	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Hardness (HB)
0.2% C Steel	210	350	130
0.4% C Steel	210	600	170
0.8% C Steel	210	800	230
Cast Iron (CGI)	100	450	200

5. ENGINE PERFORMANCE

The main focus is engine block itself. So, in this section engine performance is evaluated based on cylinder block performance.

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. Thermally sprayed oxide coatings demonstrated excellent wear resistance as well. The problem being that the coatings are so hard, they can damage the piston and piston rings, more so with the thermally sprayed oxide coatings.

A cylinder block material's ability to resist scuffing is another important characteristic. As discussed earlier, scuffing occurs right after the engine is turned on and the cylinder block is still cold. The importance of scuffing has led several researchers to develop scuffing resistance testing comparing the alternative materials to cast iron for cylinder block bore surfaces. The scuffing resistance testing had similar results as the wear resistance testing, which would be expected because both tests have similar setups and rely on similar material behavior. Simply stated, the test involves a reciprocating load that is cycled over the test material to emulate the action of the piston and piston rings on the cylinder bore surface. Material/scuffing is observed and recorded. Cast iron again demonstrated the best scuffing resistance followed by the Nickel ceramic coating applied by the electroplating process. The thermally sprayed oxide coating also performed well in scuff resistant testing.

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. The Figure 5.1 below indicates how the efficiency of internal combustion engines changes with engine speed and the losses due to friction or thermally. Engine efficiency decreases with lower speed due to increasing thermal losses. Likewise, increasing engine speed leads to higher friction losses. The most effecting factor is cylinder bore and piston rings interaction.

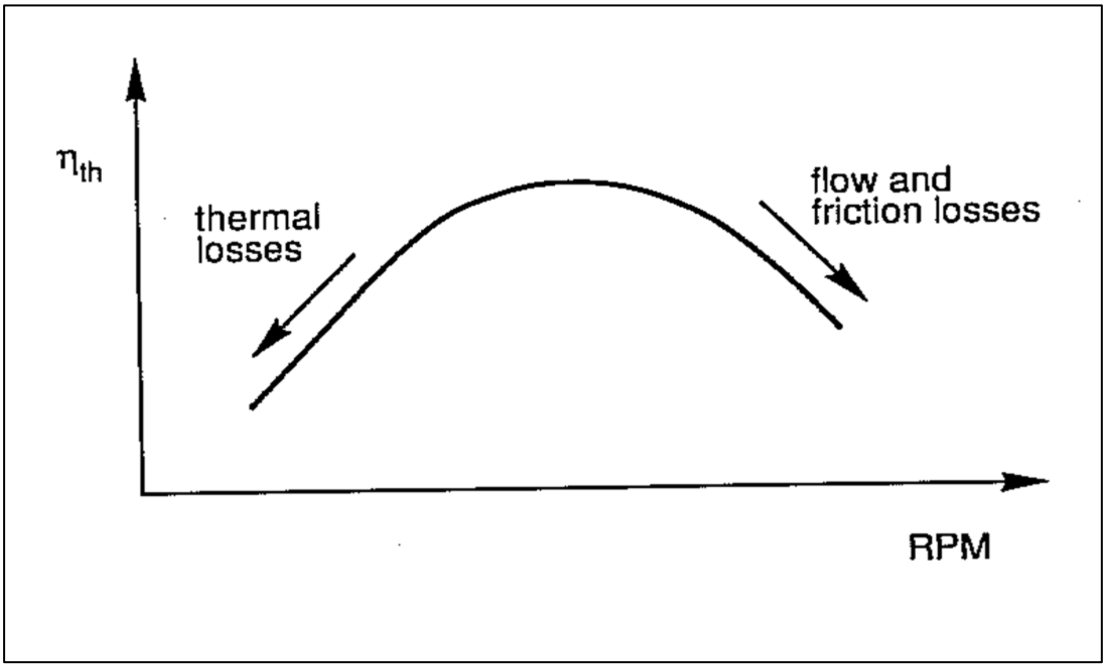


Figure 5.1 : Engine efficiency change with engine speed [28].

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 a key for reducing the coefficient of friction. Material performances are dependent upon the hardening particles dispersed in the parent alloys. The more evenly the particles are dispersed in alloy, the better the material can provide a smooth sliding surface while maintaining the ability to retain oil for lubricating purposes. Cast iron is the basis of the comparison and demonstrates acceptable performance.

Fuel economy or fuel consumption is the measurement of how much fuel the automobile's internal combustion engine uses over a given distance. In the US the unit of measure is mile per gallon. This category is important to validate the assessment of replacing cast iron liner on Aluminum cylinder blocks. Engine fuel economy will become more important to automakers in the near future due to the increased government regulations. Researching the alternatives has led to the conclusion that typically the Aluminum alloys and the coatings can increase the vehicle's fuel economy on average by 3 to 5%.

Engine emissions are the byproducts of the automobile engines combustion processes that exit the tailpipe of an automobile and enter the atmosphere. The subject of automobile emissions has become more important in recent times due to the increased awareness of their impact to the planet's ecosystem. The government's increasing the regulations solves multiple issues; it decreases the amount of automobile emissions which has a positive impact on the environment. The results here for this comparison are the same as the fuel economy results. Each alternative holds a slight advantage over the previous solution of lining the cylinder bores with a cast iron sleeve. This stems from the fact that each alternative slightly increases the fuel efficiency of the engine which will decrease the engine emissions by a small amount.

Engine performance for purposes of this comparison relates to how each alternative affects engine longevity, power production and maintenance. Coating alternatives, thermal spray, exhibit excellent performance at elevated temperatures allowing for automakers to design the engine to operate at a higher compression ratio. That creates a hotter combustion process putting more stress on the cylinder block and other engine components. In terms of longevity and maintenance, cast iron liners have proven to be a perfectly viable solution as a result of being used consistently for many years.

Engine performance prior to serial production of engines can be checked and /or confirmed with dynomomoeter testings. There are many dynnomometer testings performed to evaluate an engine as a whole or special testings for only one or few parts of engine. Dynamometer durability testing plays a very important role in engine design verification process as it is still the most reliable method to ensure the product quality before starting mass production. To ensure that the new engine as designed and manufactured will perform in a manner that increases customer satisfaction, the stresses present in the dynamometer durability test has to be representative of those an engine will meet in customer usage. Thus, it is an important task to derive proper test cycles for dynamometer tests, as they should definitely be correlated to customer usage in order not to under/over test the subject.

6. PLASMA TRANSFERRED WIRE ARC

The main reason for utilizing sprayed coatings on cylinder bore is to improve tribological properties. The most attractive application of spray coatings on substrates is the surface modification of cylinder bores in the automotive industry to reduce the energy loss by friction and weight loss by wear, and also to promote lightening of vehicle [29].

The new legislation for increasing the minimum fuel consumption average for an automaker's fleet changes the design requirements for the automobiles sold. The two major approaches for increasing automobile fuel economy is to improve powertrain efficiency and to reduce the rolling resistance. The best approach for improving powertrain efficiency is to reduce friction loss and the best approach for reducing the rolling resistance is to reduce vehicle weight.

Reason for increased fuel consumption awareness is the growing concern of pollution generated by automobile emissions. Research showed that the carbon dioxide (CO_2) produced from burning gasoline and diesel fuel in automotive engines is contributing to global climate change [30].

The PTWA (Plasma Transferred Wire Arc) process was developed by Flame-Spray Industries and the Ford Motor Company [31]. Ford FGTL is licensing the process through FSI Flame-Spray Industries to Nissan, Caterpillar, Honsel, VW, Detroit Diesel, PSA, KS Kolbenschmidt, NEMAK, HS Technik, Austria (2013), Autocraft (2013). 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 as shown below.

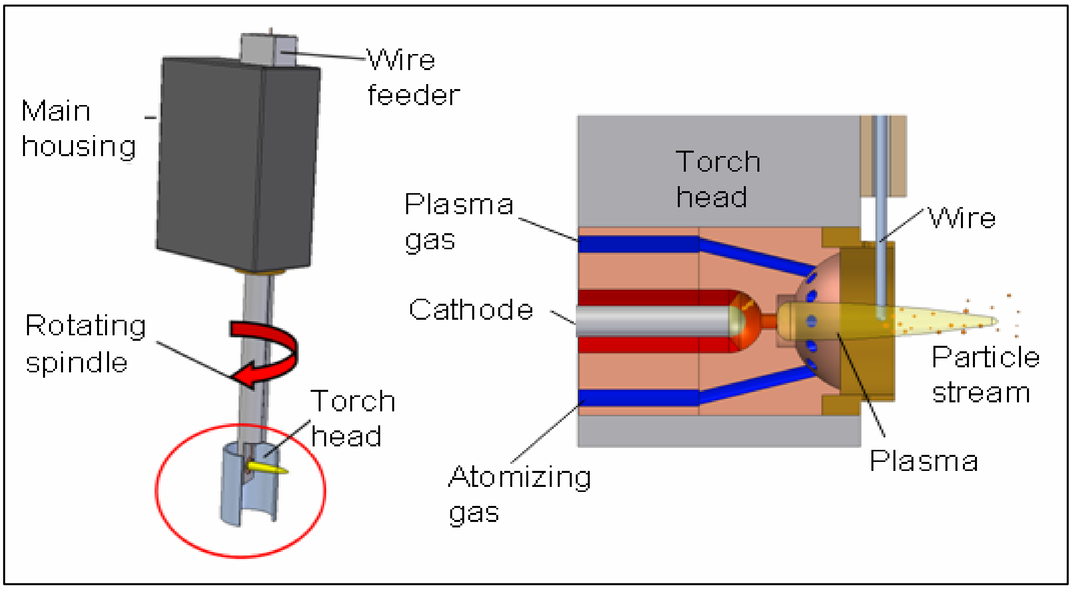


Figure 6.1 : Schematics of PTWA System and torch head.

The head is mounted to a rotating barrel, which rotates with up to 600 rpm. The wire is fed perpendicularly to the center orifice of the nozzle. The plasma gas is introduced through tangential bore holes situated in the cathode holder to ensure a vortex is created. 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 hyper sonic velocity. The elongated plasma is transferred to the consumable anode, the wire, completing the electrical 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 (about 8.5 bars) together with the atomizing gas strips the molten particles from the end of the wire. Thereby a stream of finely atomized particles is created, which is accelerated towards the substrate at high speed. The torch in this process rotates around the wire. The atomizing gas can be any non-combustible gas. A mixture of Argon and Hydrogen can be used as the plasma gas, and compressed air is used to atomize and accelerate the molten particles. The system is suitable to coat cylinder bores with a diameter of 35 mm to 350 mm. Due to the high speed of the spray particles of up to 130 m/s very dense coatings with a porosity of less than 2 % can be applied with the PTWA system [32]. The particle temperature thereby reaches a temperature of approximately 2000°C. The use of compressed air leads to finely divided high temperature iron oxides within the coating if e.g. alloyed steel is used as feedstock. Because of the consumable wire anode and the design of the gun head, no water cooling is required, which limits the systems dimensions and improves its reliability.

The mechanism of bonding to the surface in thermally sprayed coatings is mostly mechanical interlocking. 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 6.2.

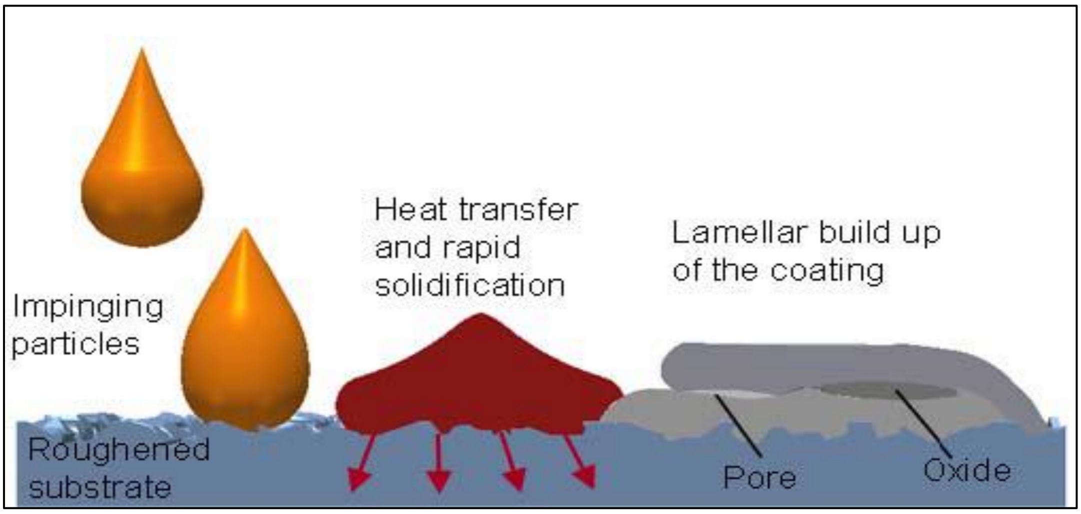


Figure 6.2 : Formation of a thermally sprayed coating.

The standard surface roughening process for the thermal spray industry is grit blasting to create a rough surface resulting in sufficient bond strength. However, for the cylinder bore applications grit such as Corundum may remain within the many internal passages of the engine block, which can come loose during operation and later cause engine breakdowns. Another roughening possibility lies within the high pressure water jet blasting process, where water is used with high pressure and accelerated towards the substrate surface. Due to its high kinetic energy the water stream partially removes the surface and leaves a finely structured topography, characterized by the required undercuts. However, this process requires expensive high pressure water pumps and can only be used for Aluminum blocks.

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 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 6.3. The process is not only characterized by good integrity, 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 [33].

One another method to activate the surface pre-spraying is just roughening process that also followed in this study.

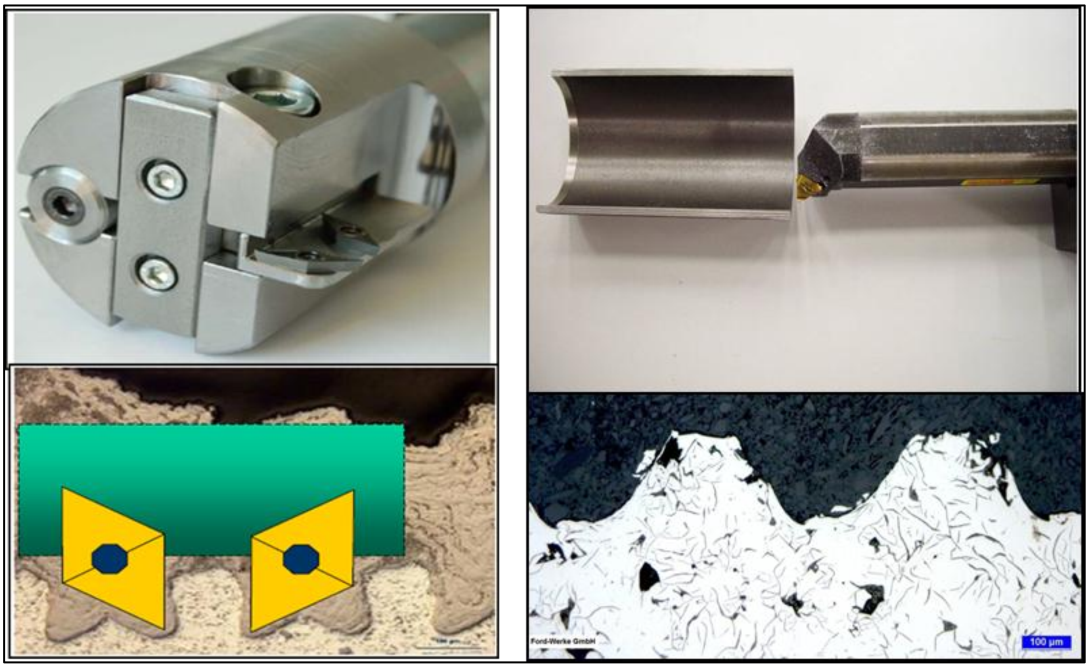


Figure 6.3 : Cross section of a PTWA-sprayed and honed of steel coating.

The bonding strength can be summarized with the graph below.

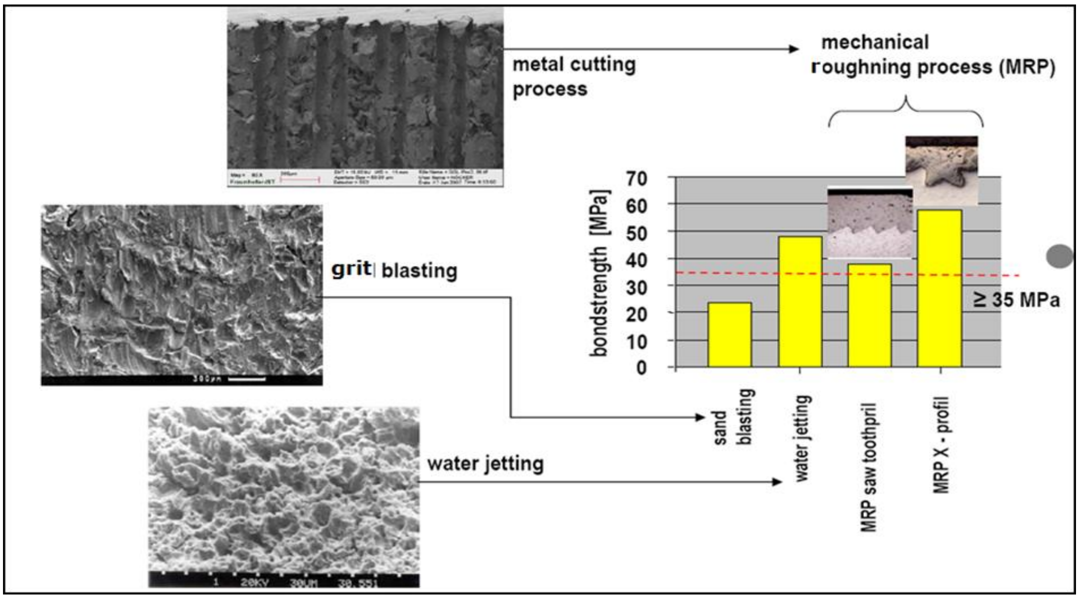


Figure 6.4 : Bonding strength.

6.1 Carbon Steel Coatings

Iron based coatings have the potential for very good favorable wear properties combined with a low cost level due to relatively low priced alloy materials [34]. 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 HV 0.3 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 shear plane it acts as low shear strength, lubricious oxide. Depending on the thermal spraying process, and of course on the parameters chosen, the amount of Wuestite varies [32].

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 (Figure 6.5). 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 [35].

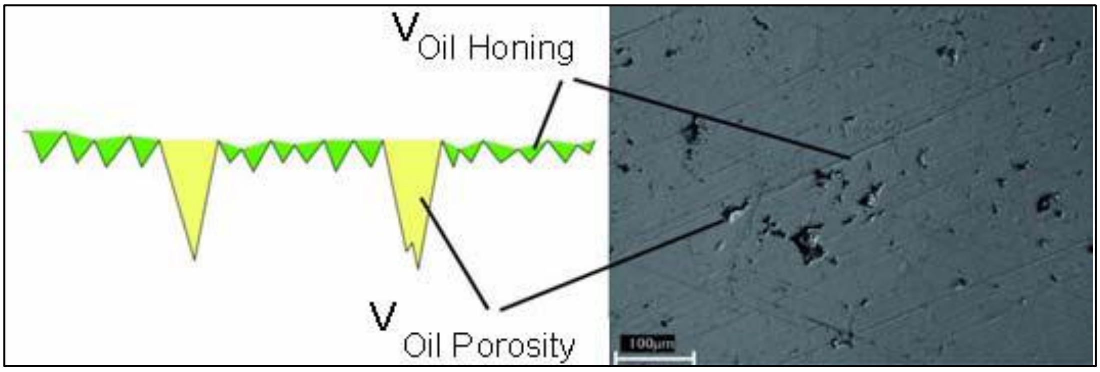


Figure 6.5 : Schematic of the different oil storage capacities of a sprayed and honed coating (left), SEM-picture of a honed surface (right).

Figure 6.6 below shows a cross section of a honed PTWA thermal spray coating. The micrograph shows some porosity within the coating, pores that were machined open at the surface and some finely distributed Wuestite particles.

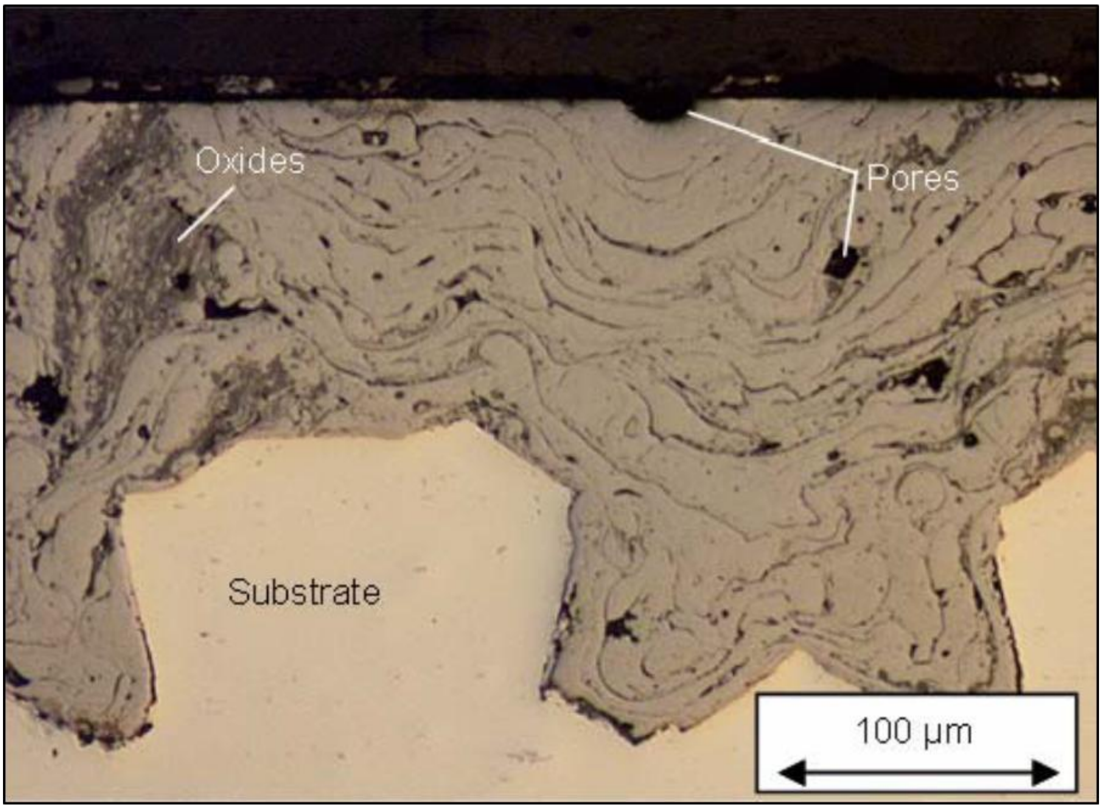


Figure 6.6 : Cross section of 0.1% C-steel coating applied with the PTWA.

There is a number of thermal spray processes used in various industries today. However, thermal spray technology is relatively new to the automotive industry, especially for coating the surface of cylinder block bores. For an automotive engine block application thermal spray requires special adaptation to the existing spray systems used in other industries. Typically the diameters of cylinder bores in modern passenger car engines are smaller than 100 millimeters. The spray gun head needs to be able to rotate coaxially in the cylinder bore to avoid having to rotate the cylinder block relative to the spray gun. The gun head with the plasma generator or the combustion chamber and the nozzle are mounted at the bottom of a rotating spindle. Ford Motor Company was one of the early pioneers in the automotive 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. An arc is created between a tungsten cathode and the copper nozzle acting as the anode. DC power is sent down the cathode and anode. The power is transferred from the arc to the steel wire feedstock, which is negatively biased to provide a sufficient conducting path. The plasma gas is fed through the center of the gun radial ports in the cathode assembly to produce a vortex and to atomize the molten coating. A secondary high velocity gas with carefully controlled oxygen content is introduced just past where the plasma stream intersects the wire arc. The molten iron globules combine with the oxygen in the secondary air to form Wuestite an oxide of iron. Wuestite is 70% harder than the steel matrix on which it forms [36]. The presence of iron oxides, specifically Fe_2O_3, in the plasma spray coating has been shown to significantly increase the wear resistance [36].

6.2 Ford Engines and Other OEM's Engines

The process discussed in the previous section is mostly utilized for remanufacturing purposes. 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. Earlier testing has shown that sprayed low alloyed steel wires perform as well or better than the cast iron they are replacing. Therefore, to maintain low costs for remanufacturing, work has focused on the low alloy carbon steel as opposed to the amorphous coatings with embedded nano-scale crystallites. However, the early testing was for gasoline engines and more recent testing has shown that for diesel engines a feedstock with higher carbon content may be required to meet the higher mechanical load. Initial testing was performed to determine the best low alloyed steel to use with the PTWA system.

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 HP and the 2012 version of the GTR has a 3.7 liter six cylinder engine twin turbocharged engine producing 530 HP. The coating reduces friction between the piston rings and the cylinder bores allowing the engine to build rotational speed quicker so that the motors produce more power. In the Mustang the plasma sprayed coating saves almost 4 kilogram weight over the previous generation which had a cast iron lined Aluminum cylinder block [37]. Fuel economy has also increased 5% over the old model.

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. Recent development in rotating plasma spray guns using plasma powder spray process offers a cost-effective versatile high throughput surface engineering tool for cylinder bore applications [38].

To qualify the plasma spray process for production level vehicles Ford performed both laboratory and real world testing. It conducted many dynamometer and endurance testing in the laboratory. Plasma spray lined engines exhibited half the amount of wear of iron linings in a 300 hour full power endurance test [39]. Ford also put together a fleet of vehicles with the plasma sprayed cylinder blocks that were driven on various North American roads in different climates cumulatively for over a million miles. After testing, Ford’s PTWA process was considered a success with the test data to back it up. Results from Ford’s testing showed that friction was greatly reduced, on average 6.8% below the values characteristic of traditional cast iron liners and 14.1% below cast iron engines [40]. At large, PTWA coated engines had decreased fuel consumption, reduced wear, weight, and cost compared to their cast iron counterparts [37].

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 6.7.

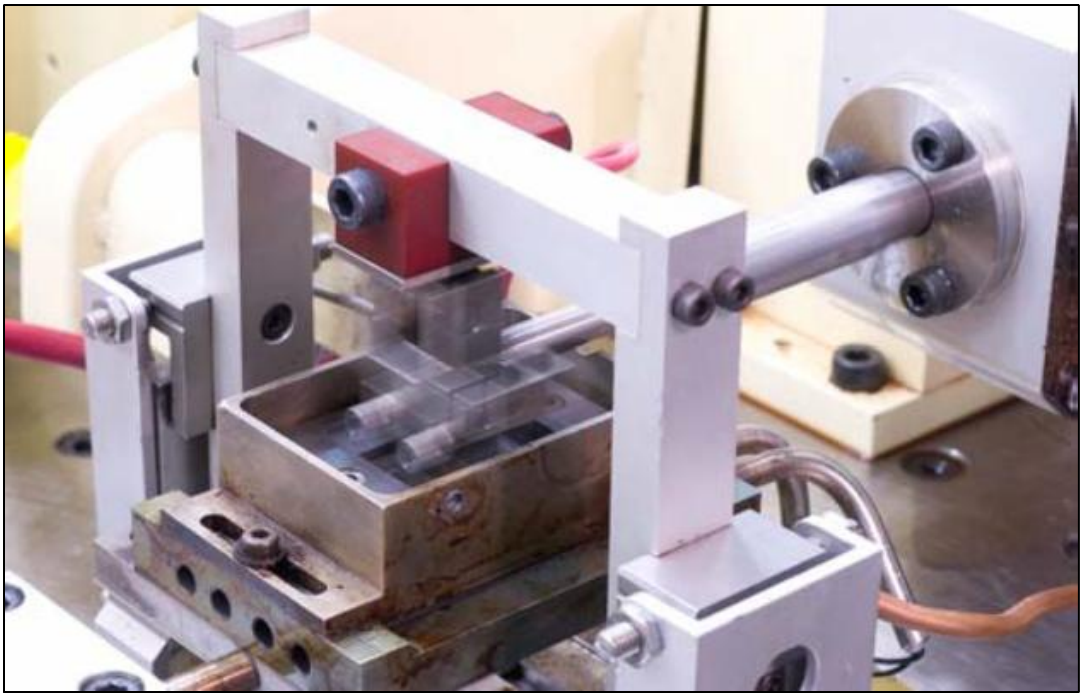


Figure 6.7 : Wear test equipment to test the thermal sprayed carbon steels.

Samples were produced with the PTWA thermal spray process using three different spray wires: low carbon steel, medium carbon steel and high carbon steel. The results of these tests shown in Figure 6.8 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.

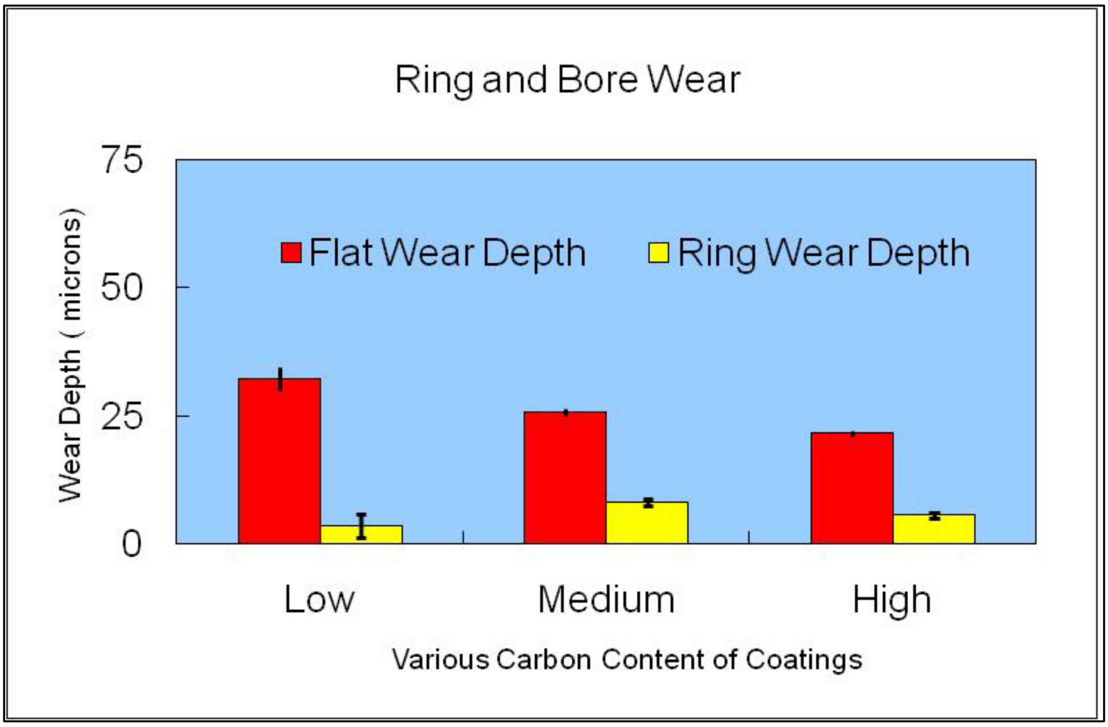


Figure 6.8 : Wear test results from reciprocating testing of TD5 piston rings on PTWA thermal spray coatings.

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, and Land Rover TD5, Ford 2.7L Diesel, Ford Zetec, BMW M62, and Caterpillar 3116.

The information below is gathered to give idea about the current situation in PTWA coating in automotive industry with the help of Clemens Veerport from Ford Motor Company, Aachen, Germany.

Caterpillar has successfully PTWA spray repaired Caterpillar 3116 engines. 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 hours 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.

NISSAN, Yokohama: Start in 2009 V6 engine for GT-R sport car, about 10.000 engines per year.

FORD: Mustang 5.4l, 525hp, since Oct. 2011 5.8l 650hp, casting and spraying done at Martinrea-Honsel, Germany: Completely machined blocks are shipped to Romeo Engine Plant for assembly (5000-7000 blocks/year).

Spray repair for Navistar Powerstroke V8 cast iron diesel blocks used in Ford F150 Pick-up Trucks: Start of spray repair in October 2011 at Caterpillar, Franklin, Indiana, USA, about 20.000 V8 blocks are planned per year.

The PUMA engines have been spray repaired starting in March 2013 at Autocraft, Grantham, UK for FCSD.

SCANIA Trucks: Expensive MMC Metal-Matrix-Composites. Because they worked since a long time on that coating material and had qualified it for their engines, they could not change over to PTWA wire spraying. A system was installed by Sulzer Metco.

MAN Trucks: They have just started with GTV to look for a good wear and corrosion resistant spray wire: They know that for high EGR ratio engines that is required to use high Cr-Ni alloys which of course are much more expensive than the standard 0.8%C-Steel or the AlCrO-Praxair Wire (Fe-25%Cr-5%Al) which we sprayed for our engines. They look into the Praxair cored wire 140MXC (Fe-30% Cr-3%B) as well as new Fe-30%Cr-6%Ni-4.2%B) which it had been developed for the cast iron brake rotors.

MAN B&W Diesel, Jörgensen Liners: They work in the new EU Project HERKULES together with Gehring and others to develop a wear resistant PTWA spray coating that can last 10 years in a ship engine and what is thick enough that it can be honed inside the ship with a flexible honing system, without removing the engine from the boat. Therefore, the thickness of those coatings has to be as high as 800μm. The project started officially on January 2012.

Daimler Trucks, Mannheim: In 2011, Daimler wanted to use PTWA technology to spray repair their truck engines with 0.8%C-Steel because their own spray system would not allow to spray a dense coating which could be honed by a conventional honing stones and would run with the standard ring pack. Their 6-9% porous coating could lead to high oil consumption in combination with a conventional honing.

VW/AUDI/Porsche: VW is the only OEM who has used thermal spray technology in serial production, by the SulzerMetco powder plasma spray process. Since 2002, they have used expensive Fe-Mo-powders for the 5 cylinder diesel blocks for passenger cars. However, last year they stopped this engine, now the spray process is only used for the V10 in the Touaregg and the W16 Buggatti 1200HP blocks. VW has a PTWA demo system and together with Porsche and Audi they are running tests with PTWA technology. Main interest is the use of corrosion resistant wire for alternative fuels like ethanol and especially M15 in China. They study duplex stainless steels and other material. PTWA C-Steel coating are already qualified at Porsche; however, the corrosion resistant alloys show ring wear especially at high speed. GTV is looking into the use of Nitrogen atomization gas because they believe that the oxides are causing the ring wear.

VW is using the powder plasma spray repair in their Kassel remanufacturing plant. The cast iron blocks, cast at Halberg, are bored oversize and then they apply the coating.

Daimler: They use in their V8 6.3l AMG engine and for their new V6 diesel conventional 0.8%C-Steel; however, sprayed with Nitrogen as atomizing gas so that they can by-pass the Ford Fe-Fe-Oxide patent. However, they must have noticed as well that the ethanol and methanol fuels are causing wear damage. Because they had to use Nitrogen, their coating is very porous. Until recently it is considered that 6-9% porous coating inferior to dense 2-4% coating. However, it might very well be that this porous coating is leading to a better friction behavior than a dense PTWA coating. Gehring calls the pores “micro-pressure chambers” and that the oil is pushing the rings away from the cylinder bores. Thus no wear leads to less friction. However, even if those porous coatings show lower friction, it might not be possible to use it for truck application because the porous coating should lead to under-corrosion, it has to be tested.

BMW: They also use 0.8%C-Steel for gasoline engines sprayed by Nitrogen in order to avoid an infringement with Ford.

6.3 Ford Cylinder Block Remanufacturing

Globally, PTWA coating of Ford cylinder blocks is approved/released process for remanufacturing. Ford blocks are made of GJL200, and the I4 engines have 100/125/155 HP power, and I5 engine is 200 HP.

Ford EU considered overbore, liners and PTWA and due to a number of failures in overbore and liner route that have persuaded and engineered, the PTWA method as the approved Global Remanufacturing solution for the engine. The design of the block and the level of bore distortion limited the possibility of using overbore approach, so the favorite alternative was a liner. Unfortunately, when a sample of liner installation had been done, 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, 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 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 hours 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.

According to history and results of PTWA utilization, it is approved process for Ford cylinder blocks remanufacturing. The process described in the engineering specification is as follows:

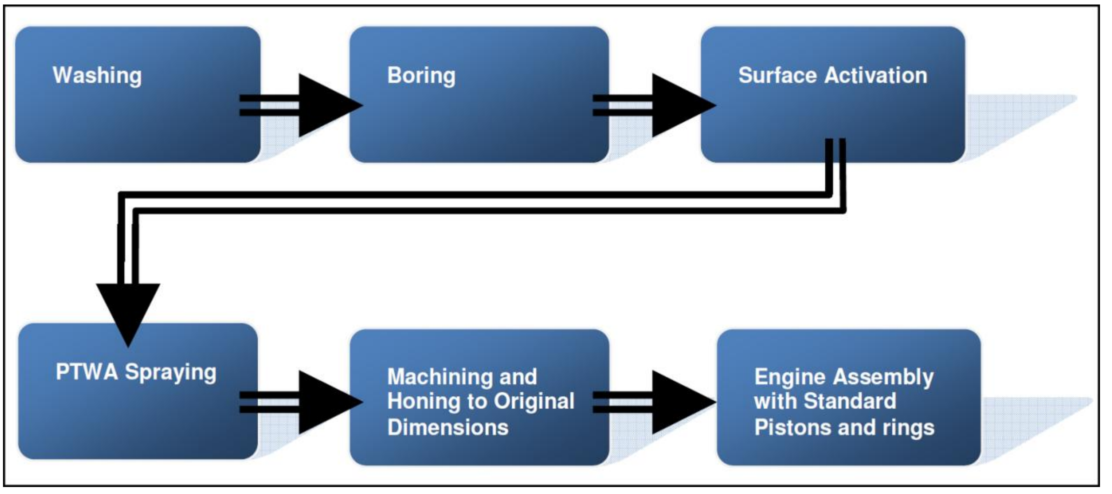


Figure 6.9 : PTWA process introduced for Ford blocks.

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

6.4 PTWA Application for Heavy Duty Engine Block

6.4.1 Preparation for coating

When all the studies mentioned in previous sections are considered, it can be concluded that heavy duty engine (Ecotorq 9.0L) cylinder bores coating with PTWA is new and challenging topic. The main goal of study is utilization of PTWA coating in view of wear resistance that affects to power, fuel consumption, and indirectly oil consumption. According to results of the study, remanufacturing of the block bores with PTWA can be considered for future works.

The process is as described for Puma blocks in Figure 6.9.

What was done prior to coating is:

- From cast block to prototype one, only machine fire deck surface of block and bores
- Leave 0.5 mm stock on fire deck surface of block during machining
- Fine boring and roughing bores 0.5 mm oversize in diameter (Actual bore diameter: 115 mm, oversize bore diameter: 115.5 mm)

- No need for honing of bores, only apply dry roughing (without coolant)
- Utilize VCI paper (rust proof brown paper) for packaging
- Cover all bores with VCI paper attentively
- Final machine in Ford Otosan plant

6.4.2 Selection of coating material

One another challenging issue with the 9.0L block cylinder bores coating is selection of coating material that is the wire material. The first considered one is 0.8%C steel since it is approved for Puma blocks and almost all appliers use it. However, it was not sure about the lubrication effect of 0.8%C (or wear resistance) when compared with graphite particles in GJV 450 material. The rationale is FeO formation in coaing and its hardness.

To understand the effect of coating with different materials and prove the effect of 0.8%C steel for Ecotorq engine, two cylinder blocks had been coated. One had been coated with 0.8%C for all 6 bores, and one had been coated with 0.8%C steel (A), 17% Cr steel(B) and 20%Cr-5%Al(C) per 2 bores (Figure 6.10).

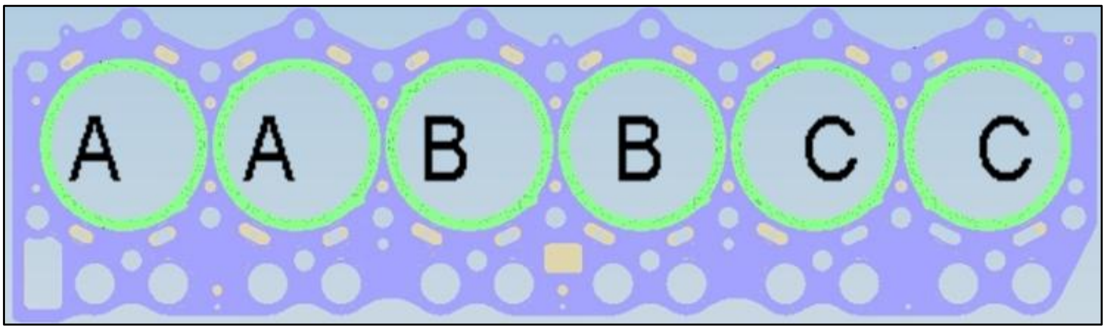


Figure 6.10 : “A” with 0.8%C, “B” with 17%Cr and “C” with 20%Cr-5%Al.

6.4.3 Measured parameters

Honing of bores had been performed by Gehring according to honing specification of 9.0L block to use same piston ring pack. D30 honing stones are used. The honing specification is:

Table 6.1 : Honing parameters.

Ra	Rz	Rpk	Rk	Rvk	Mr1	Mr2
0.3-0.7 µm	3-5.7 µm	<0.3 µm	0.6-1.6 µm	1.2-3.2 µm	<10 %	70-90 %

The engines are numbered as BB37 and BB49. BB37 has been coated with single material, and BB49 had been coated with 3 different materials. BB37 parameters are summarized as below tables.

Table 6.2 : Cylinder bore diameters deviation in 1/1000mm with torque plate.

	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 6.2 shows that diameters are smaller than expected and special rings had been ordered for smaller diameter cylinder bores. Diametrical deviation is 0/+0.022mm.

The Table 6.3 indicates that honing parameters are out of specification.

Table 6.3 : BB37 measured honing parameters (Pre-Test).

					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	0.24	0.19	0.21	0.20	0.2	0.21	0.25	0.22	0.17	0.20	0.22	0.4	0.24	0.21	0.25	0.19
			120	mm	0.21	0.2		0.2	0.16		0.22	0.14		0.22	0.16		0.19	0.18		0.16	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	6.22	3.45	4.4	4.47	6.18	5.03	5.71	4.9	2.85	4.35	5.44	7.38	5.17	4.02	5.87	3.91
			120	mm	5.27	7.3		5.46	3.58		6.03	2.33		5.2	3.89		3.04	3.95		2.28	5.04	
			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	0.20	0.23	0.27	0.19	0.22	0.16	0.17	0.2	0.19	0.18	0.19	0.19	0.17	0.24	0.19	0.18
			120	mm	0.2	0.21		0.18	0.15		0.16	0.13		0.22	0.15		0.18	0.18		0.22	0.15	
			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	0.49	0.53	0.52	0.47	0.45	0.47	0.45	0.52	0.49	0.48	0.48	0.57	0.48	0.58	0.54	0.48
			120	mm	0.49	0.42		0.47	0.41		0.46	0.39		0.54	0.42		0.46	0.42		0.47	0.44	
			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	1.09	0.61	0.92	0.78	0.83	1.08	1.31	0.9	0.46	0.81	1.02	1.96	1.09	0.63	1.25	0.69
			120	mm	0.79	0.94		0.8	0.52		1.01	0.41		0.97	0.59		0.66	0.66		0.34	0.81	
			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	8.66	10.04	9.53	9.03	9.31	9.57	8.90	9.16	10.37	9.32	9.54	8.9	8.39	8.13	9.12	8.48
			120	mm	8.77	8.79		8.59	8.75		9.35	8.19		9.34	9.32		8.38	9.23		7.65	8.7	
			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	85.91	88.97	88.78	87.09	86.26	88.47	86.73	87.06	89.7	87.16	86.78	86.47	86.22	87.87	87.74	87.16
			120	mm	85.45	86.06		87.2	85.72		86.32	86.98		88.57	87.07		85.63	86.33		87.75	87.36	
			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	

It is expected that piston scuff would be an issue during testing since oil film cannot be formed properly (Rvk is too low). On the other hand, porous structure of coating would prevent scuff issue.

Table 6.4 : BB37 measured honing parameters (Post-Test)

					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	40	mm	0.14	0.14	0.19	0.19	0.33	0.18	0.12	0.18	0.17	0.12	0.17	0.17	0.27	0.14	0.25	0.13	0.22	0.25
			120	mm	0.17	0.30		0.12	0.09		0.20	0.17		0.14	0.26		0.33	0.25		0.20	0.46	
Rz	3-5,7	µm	40	mm	1.83	2.29	2.65	3.34	3.16	1.93	1.77	3.58	3.26	1.52	3.12	1.67	4.80	1.88	2.94	1.72	1.61	2.12
			120	mm	2.66	3.83		0.15	1.07		4.86	2.83		0.33	1.71		2.18	2.89		1.57	3.57	
Rpk	<0,3	µm	40	mm	0.20	0.17	0.17	0.13	0.12	0.14	0.23	0.15	0.25	0.08	0.69	0.36	0.13	0.06	0.27	0.10	0.28	0.49
			120	mm	0.16	0.14		0.19	0.14		0.29	0.32		0.38	0.29		0.42	0.48		0.76	0.80	
Rk	0,6-1,6	µm	40	mm	0.37	0.15	0.31	0.33	0.37	0.29	0.27	0.16	0.24	0.35	0.42	0.49	0.57	0.22	0.61	0.22	0.63	0.71
			120	mm	0.35	0.38		0.32	0.15		0.23	0.29		0.33	0.85		1.02	0.62		0.75	1.22	
Rvk	1,2-3,2	µm	40	mm	0.26	0.34	0.95	1.09	1.61	0.82	1.08	0.62	0.75	0.60	0.45	0.45	0.38	0.49	0.49	0.39	0.26	0.76
			120	mm	0.71	2.48		0.37	0.23		0.45	0.84		0.47	0.30		0.56	0.54		1.38	1.02	
Mr1	<10	%	40	mm	8.98	15.80	10.90	13.80	13.20	10.03	10.90	13.70	13.70	5.87	5.21	7.82	13.40	6.91	11.58	26.50	11.40	16.20
			120	mm	5.61	13.20		7.32	5.81		8.78	21.40		7.49	12.70		13.50	12.50		15.60	11.30	
Mr2	70-90	%	40	mm	81.40	73.10	81.23	79.80	79.80	77.90	68.20	76.50	72.55	86.30	83.70	81.18	87.40	70.70	82.30	82.50	86.20	83.13
			120	mm	84.90	85.50		87.10	64.90		66.70	78.80		66.70	88.00		89.30	81.80		78.50	85.30	

The post-test measurements indicate that surface of cylinder bores get smoother.

BB49 parameters are summarized as below tables. The Table 6.5 shows that diameters are within the specification. Diametrical deviation is 0/+0.022mm.

Table 6.5 : Cylinder bore diameters deviation in 1/1000mm with torque plate.

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

Table 6.6 : BB49 measured honing parameters (Pre-Test).

					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	

As can be seen from the Figure 6.11, honing marks are not visible. Surface is too smooth.

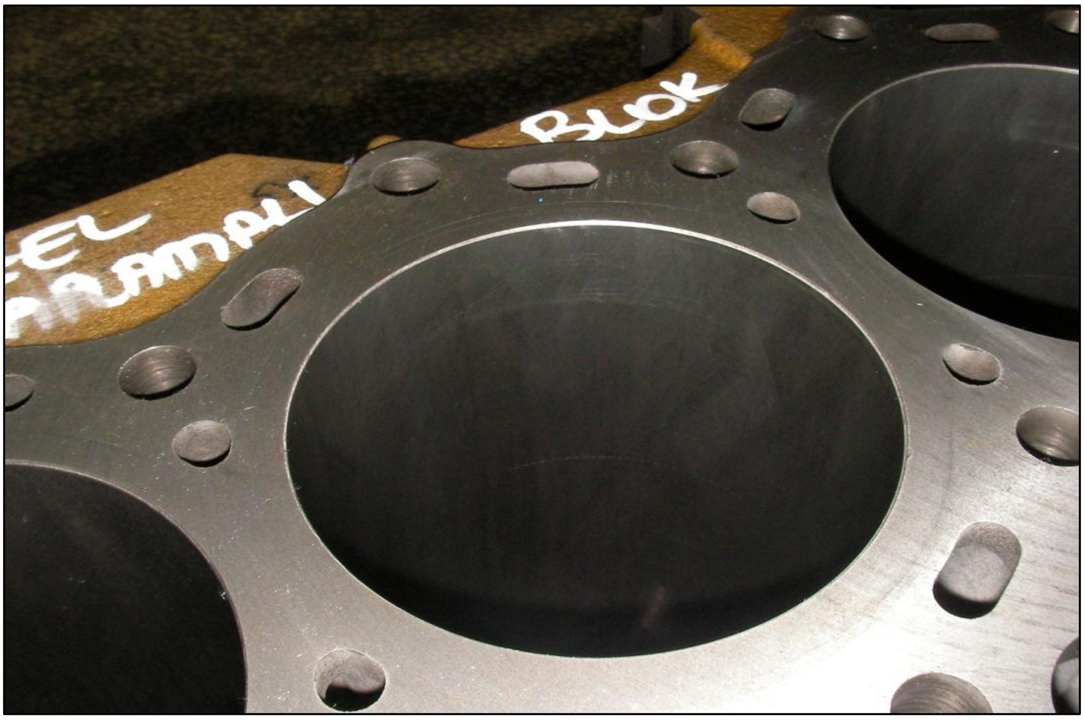
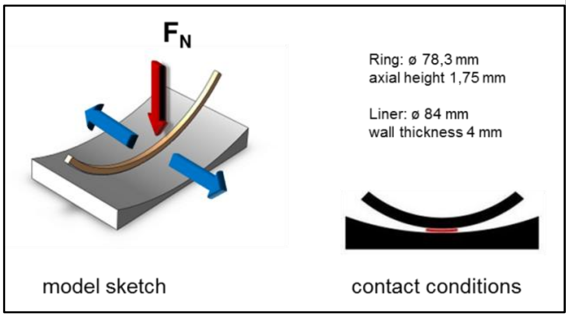


Figure 6.11 : BB49 cylinder bore after honing.

6.4.4 Tribology testing

Federal Mogul presents friction, bore wear, and ring wear results in 3rd Ford Global Friction Symposium that was held in April 2012. The study includes PTWA coating with different materials of cylinder bores and friction/wear characteristics [41].

The test method used is Oscillating Rig Test (SRV System). The test details are as below:



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

Figure 6.12 : SRV testing details.

Material selection and coating 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 (Ford 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

In the following figures friction coefficient, ring and liner wear results are shown.

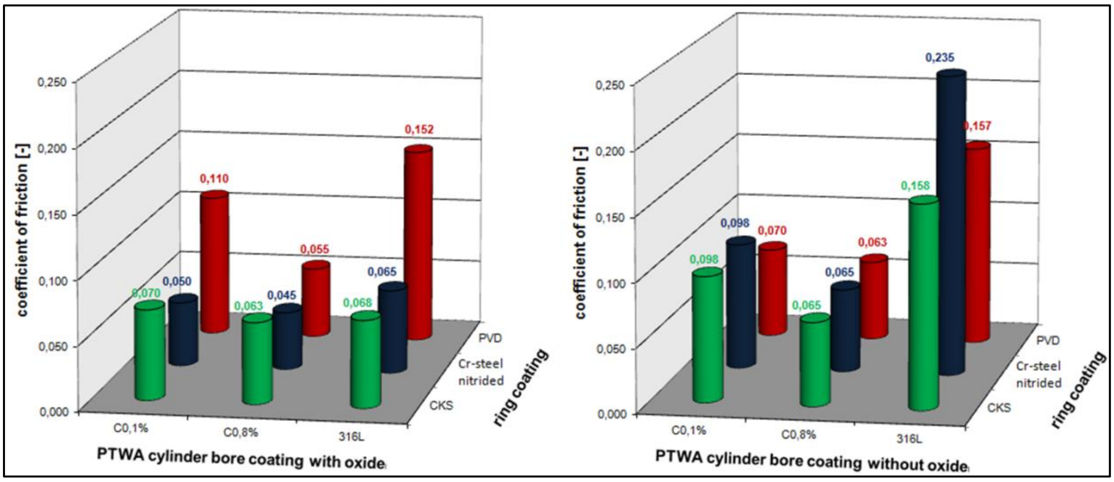


Figure 6.13 : Coefficient of friction.

- Lowest friction measured for nitride ring on PTWA 0.8%C 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

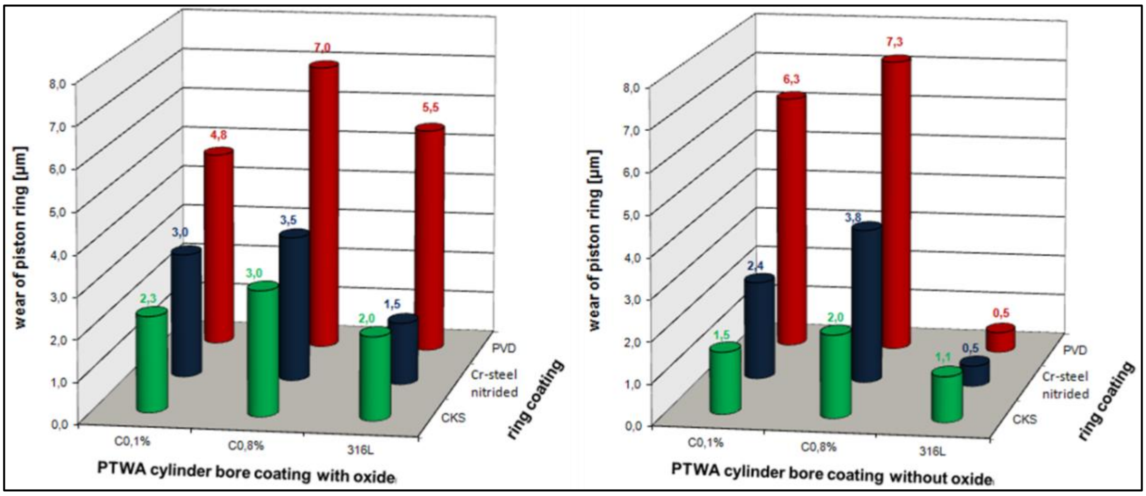


Figure 6.14 : Piston ring wear.

- 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

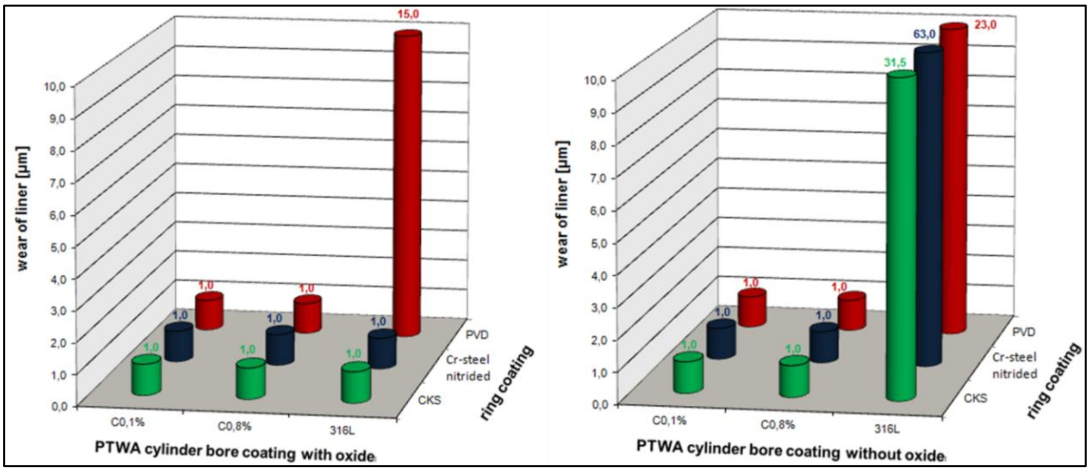


Figure 6.15 : Liner wear.

- 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%C and with PTWA 316L coated cylinder bore including oxides
    ii. CKS ring with PTWA 316L bore coating with oxides

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

6.4.5 Verification testing

The test defined for the engines that are built with BB37 and BB49 blocks is 400 hours High Speed Test with 10W40 Castrol Oil. Since test results of Ecotorq 9.0L current engine are present, it is selected for comparison. At the end of test bore diameters and honing parameters are measured. One of the most important losses in engine is friction. The lubrication is applied to reduce the friction. The aim of PTWA in this thesis is reducing friction. So per relation in Figure 6.16 the increasing engine speed results in more friction [28]. Hence it is expected that engine performance would reduce. The High Speed Test is selected because of the test cycle. The matrix below shows the relation of test and mechanism works, and in the Figure 6.17 test cycle is defined.

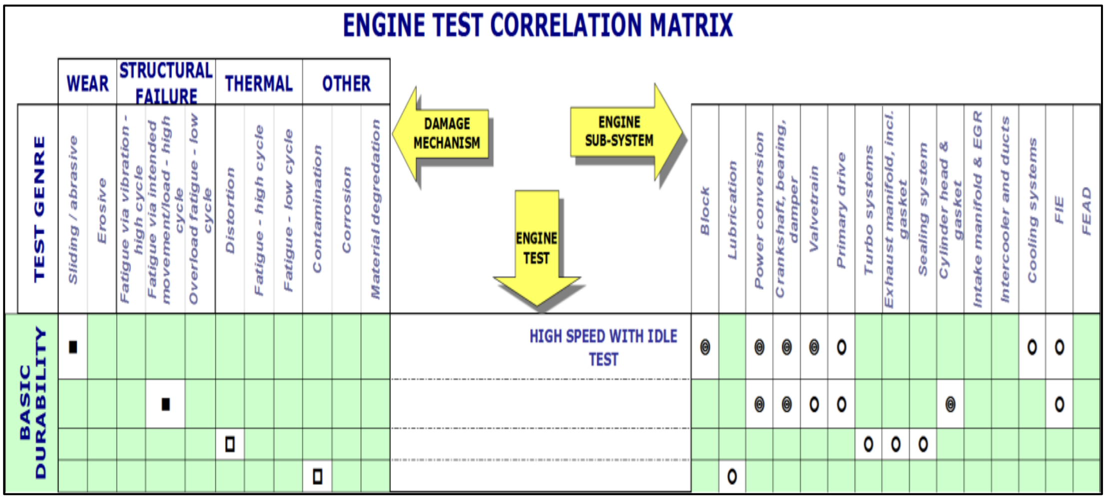


Figure 6.16 : Test decision matrix.

The figure below defines one test cycle. The engine runs at full load and high speed. Hence, maximum friction loss is expected due to high piston speed.

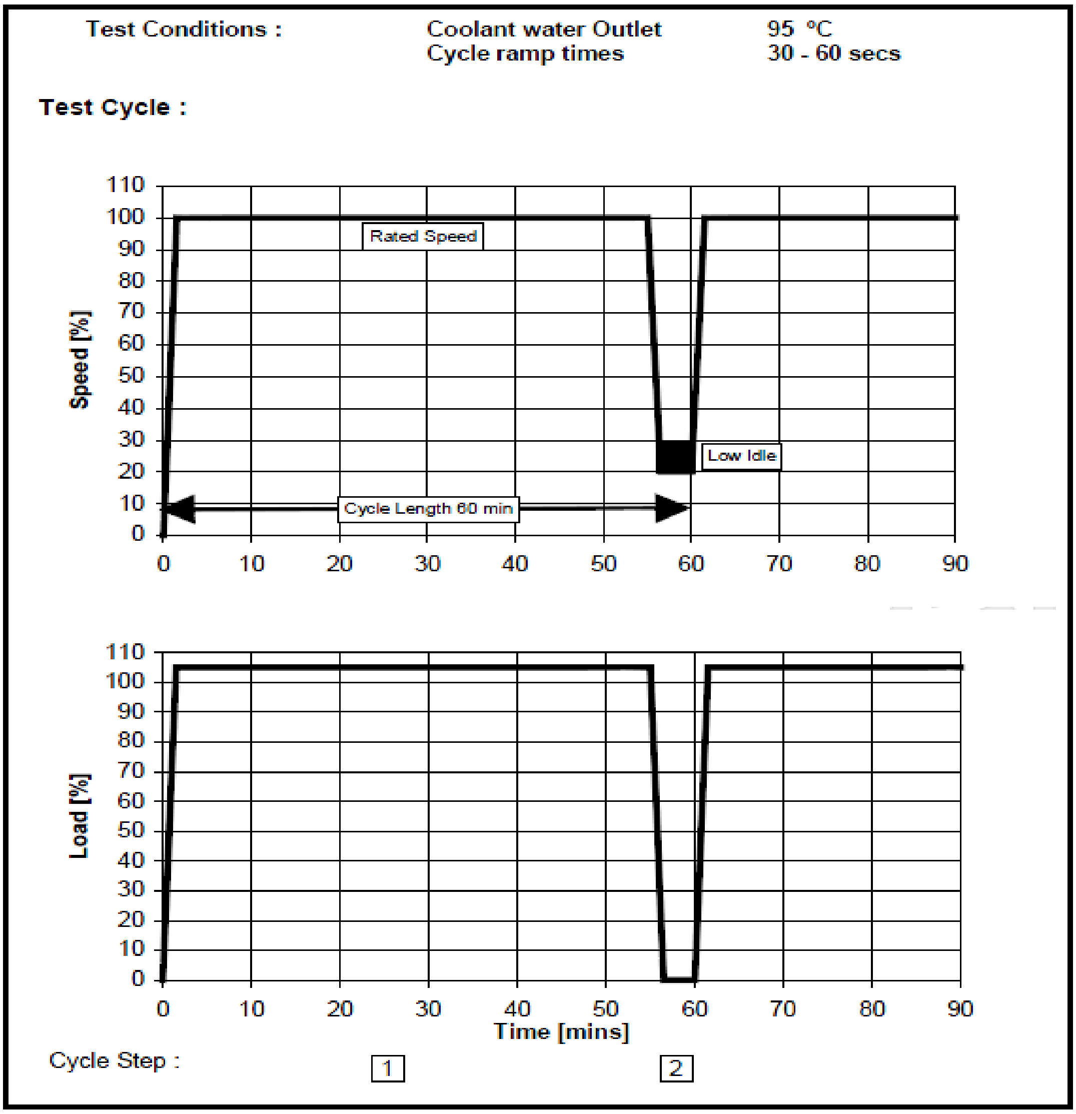


Figure 6.17 : High Speed Test cycle and condition.

6.4.6 Previous testing results

A Ford engine has a successful history during PTWA coating remanufacturing specification studies. Three engines were run and all of them passed the tests with no concern. In addition two Puma engines tested in FCSD Transit Fleet Test Cars. One of them had been tested 80K km, and the other one 187K km.

In 2011, one High Speed Test (9L 380PS engine) performed, and results show that power starts from 385PS and drops to almost 370PS in Figure 6.18.

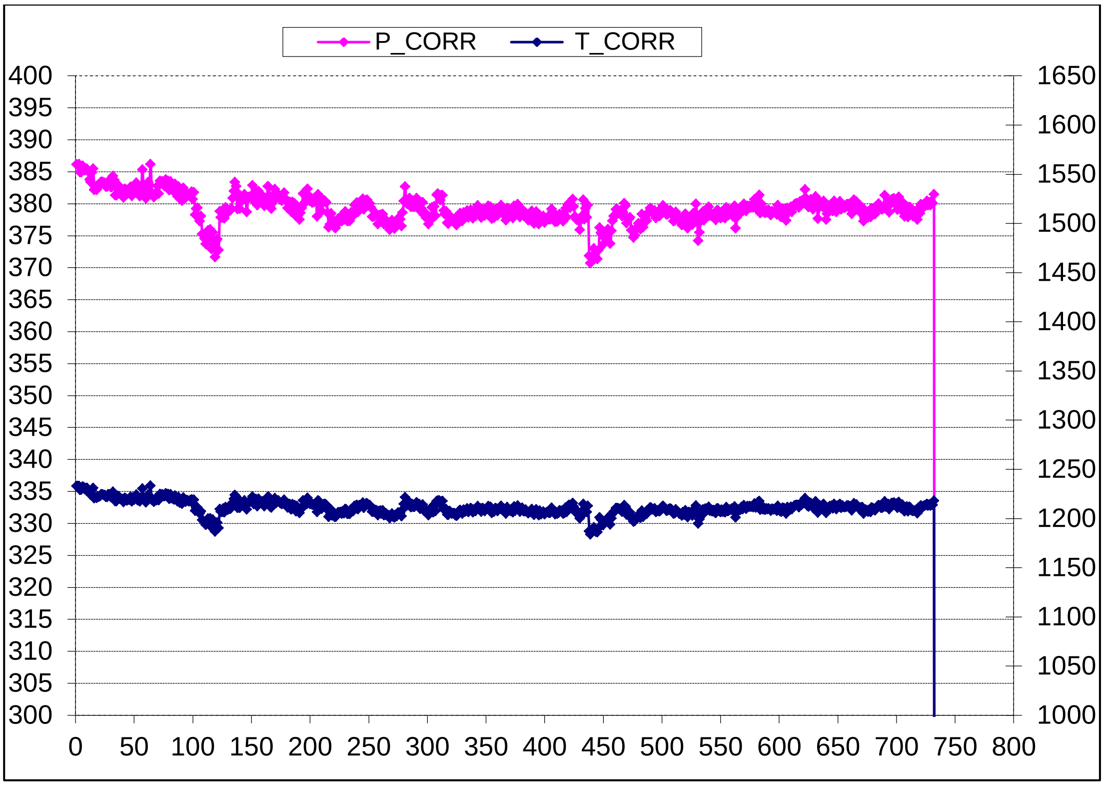


Figure 6.18 : High Speed Test power curve.

Figures 6.19 to 6.21 show the blow-by, oil consumption and fuel consumption results of one of 9L 380 PS engine.

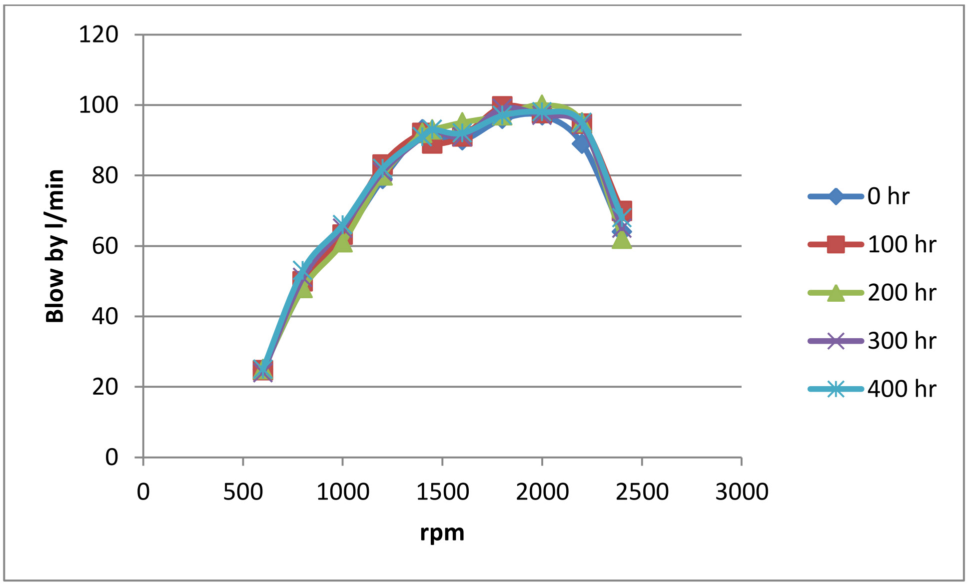


Figure 6.19 : Blow by measurement.

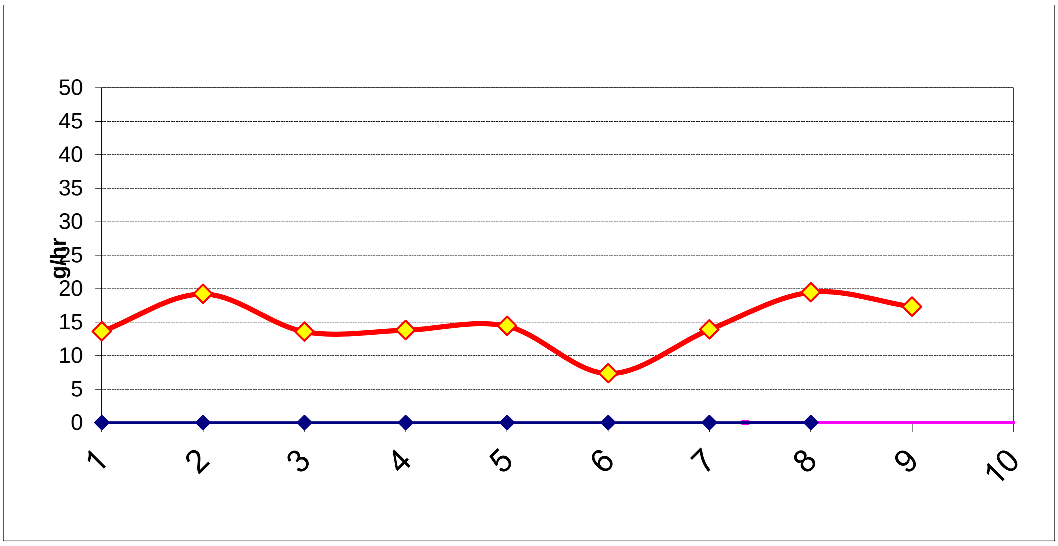


Figure 6.20 : Oil consumption.

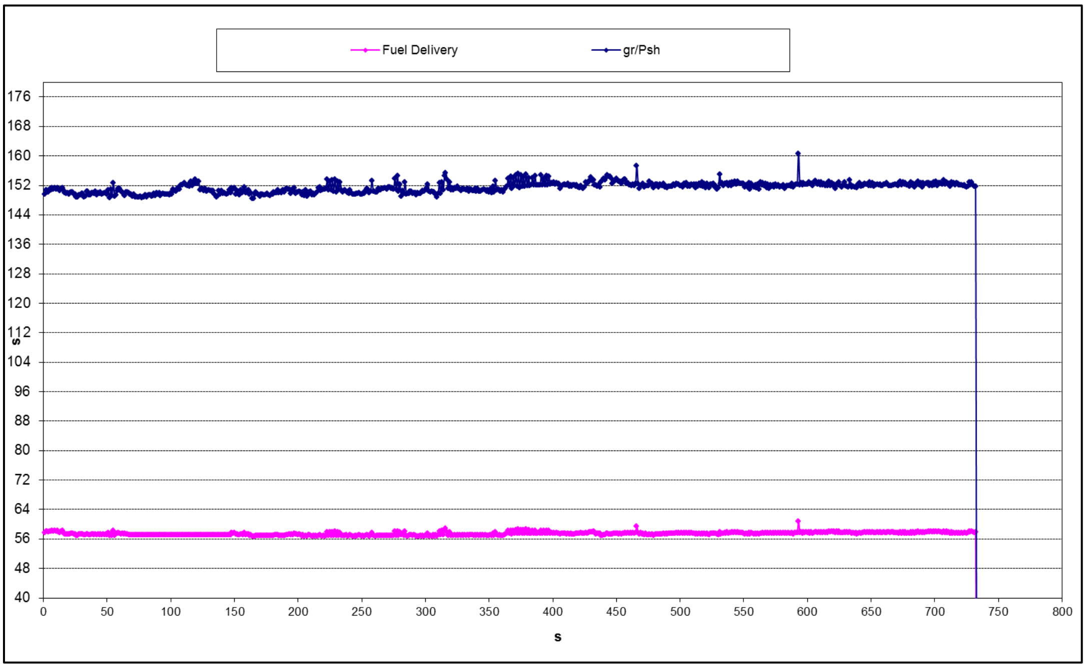


Figure 6.21 : Fuel consumption.

Following fuel consumption figures are from 9L 400PS engine. When the specific fuel consumption data is investigated, it is seen that in time fuel consumption increases up to 160 gr/Psh and more (Figure 6.22). Average fuel consumption of engine is 156 gr/Psh (Figure 6.23).

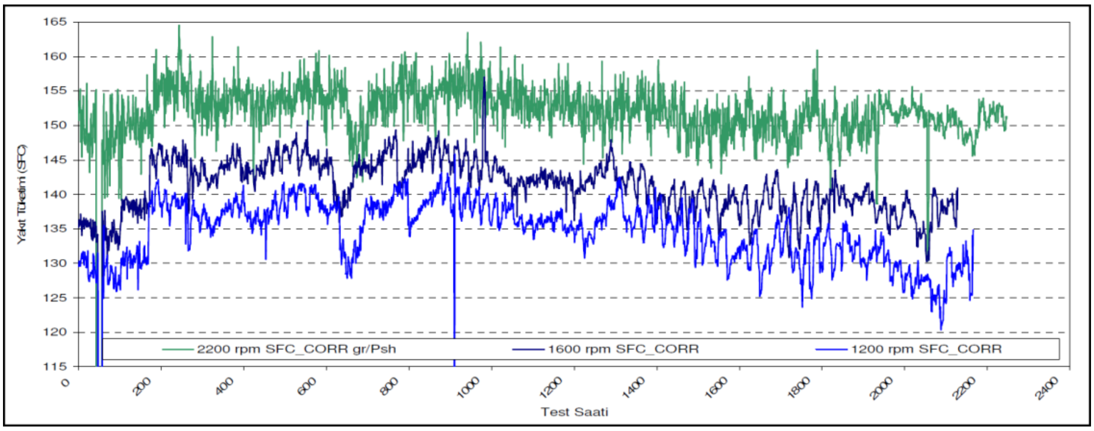


Figure 6.22 : Fuel consumption for different engine speeds.

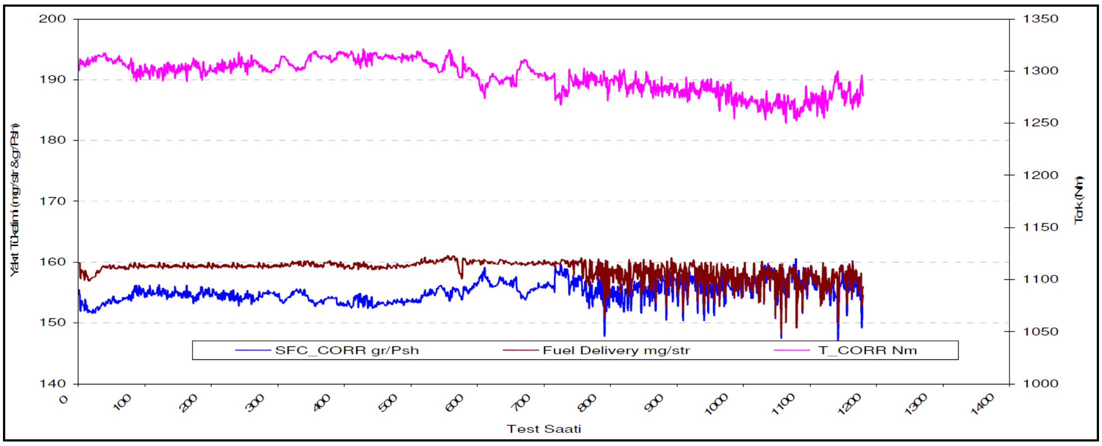


Figure 6.23 : Specific fuel consumption.

6.4.7 Current testing results

The engine with BB37 has finished the test without any reported issue. Power curve below (Figure 6.24) shows that engine power starts from 387PS and drops to 379PS. Power is measured at every 50 hours.

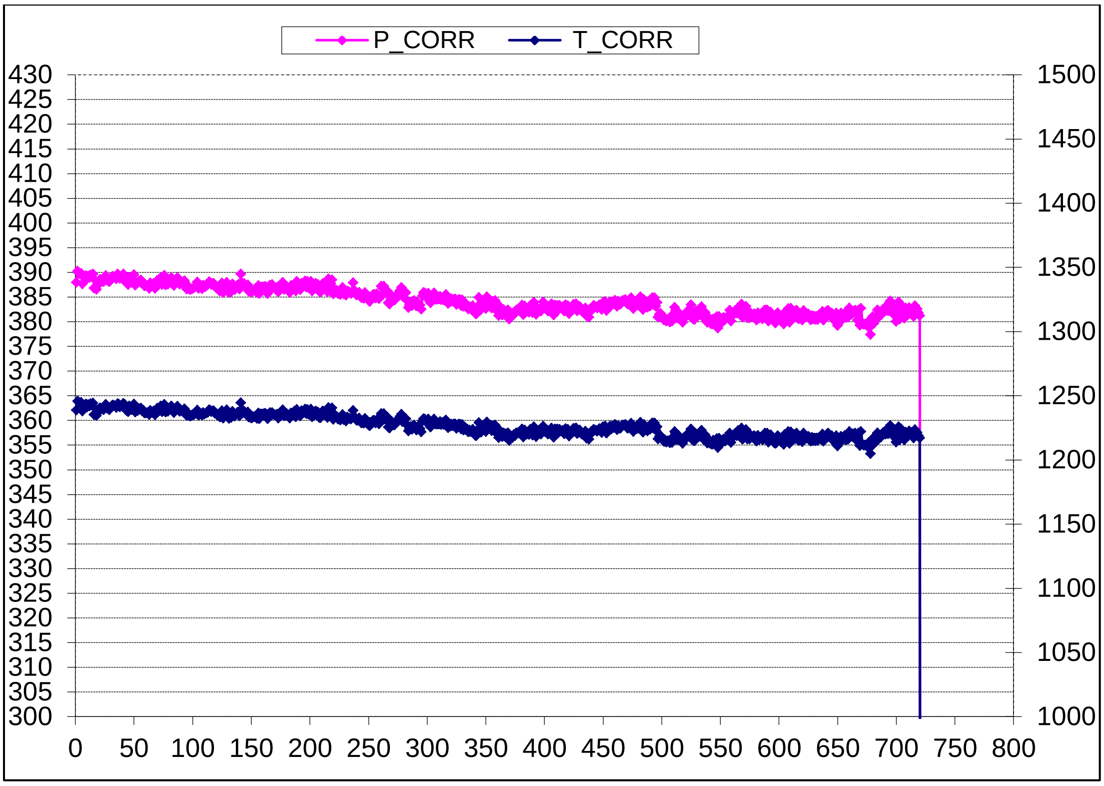


Figure 6.24 : Power and torque trend curve through testing.

Figure 6.24 indicates that power and torque drop. The power is set to 380PS with +/-2% deviation. So 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 wear of fuel injection parts. However, 400 hours of running is not sufficient for wear of the parts, and the decreasing trend most probably is due to mechanical friction increase.

Figure 6.25 indicates blow-by measurement results. Results show that blow-by decreases in time and it is much lower than the results of previous engine (Figure 6.19).

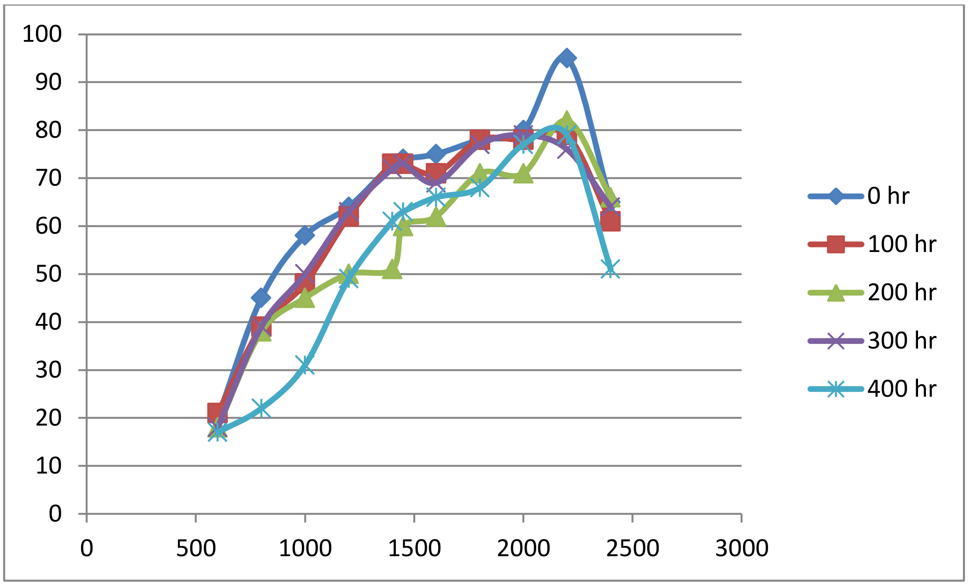


Figure 6.25 : Blow-by of BB37.

Oil consumption for the engine changes between 15.6gr/h and 28.5gr/h. Specification is 18-26gr/h. In Figure 6.26, oil consumption of the engine shows that it is within the limits.

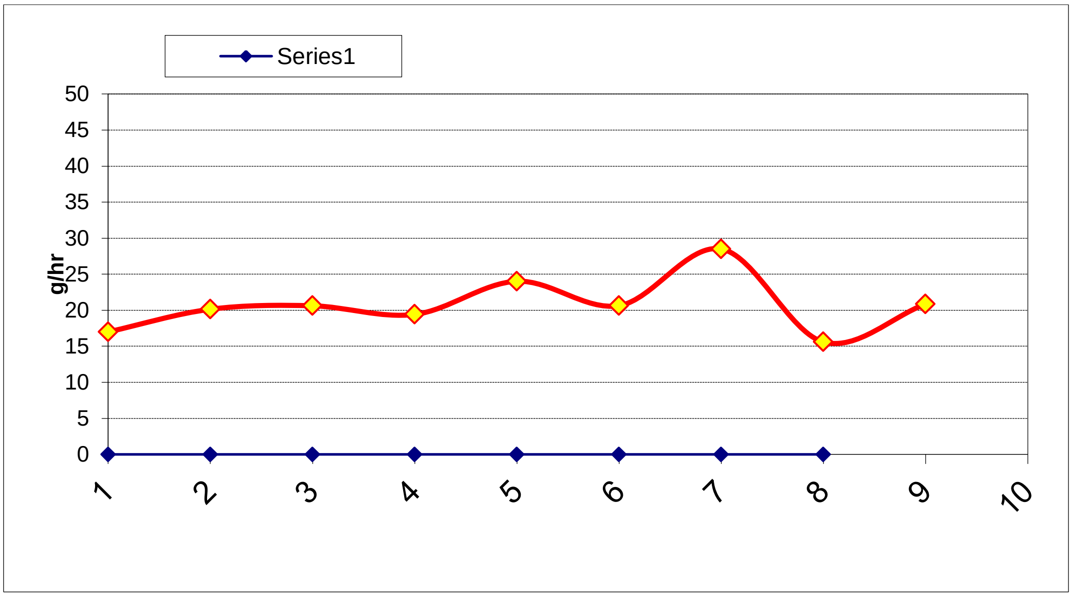


Figure 6.26 : Oil consumption of BB37.

The average specific fuel consumption of coated engine is 153gr/Psh (Figure 6.27), and it is 156gr/Psh, in current serial production engine. So, there is almost 2% specific fuel consumption reduction. That implies, the coated engine has lower friction and runs in more efficient way.

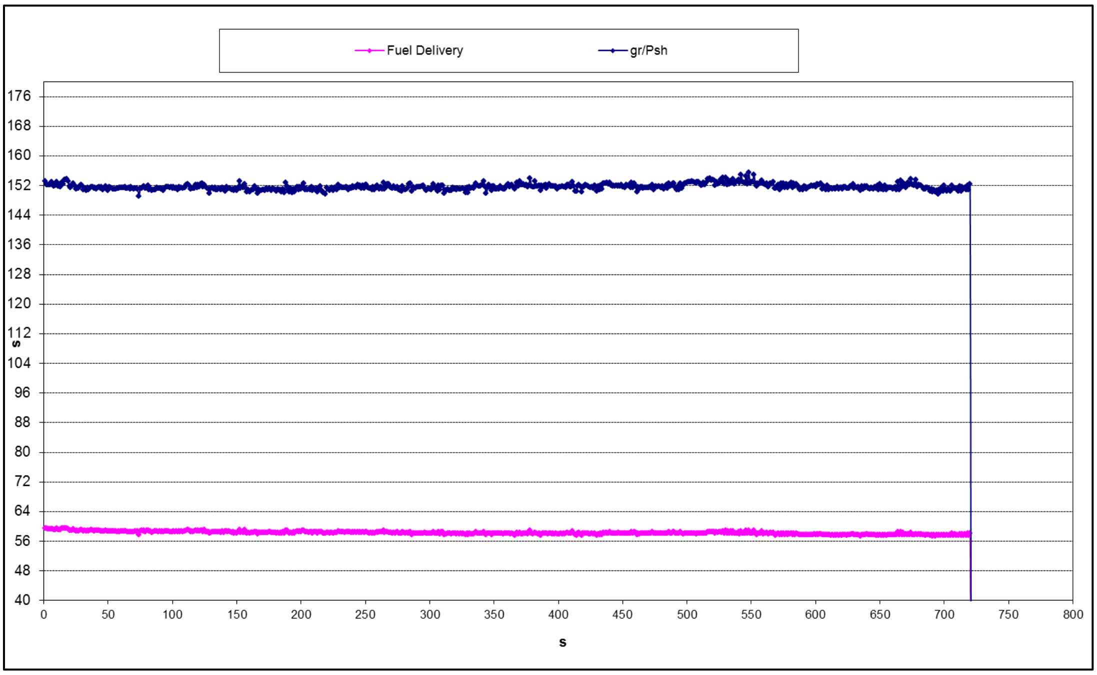


Figure 6.27 : Fuel consumption.

To well understand the difference and/or similarity between coated and uncoated blocks, tests results are superposed as below. All three compared tests have same test cycle with same oil. Only the engine number BC1276 is calibrated to 400PS. So the specific fuel consumption (SFC) needs to be taken into account for comparison in view of fuel consumption for this engine.

Power Torque:

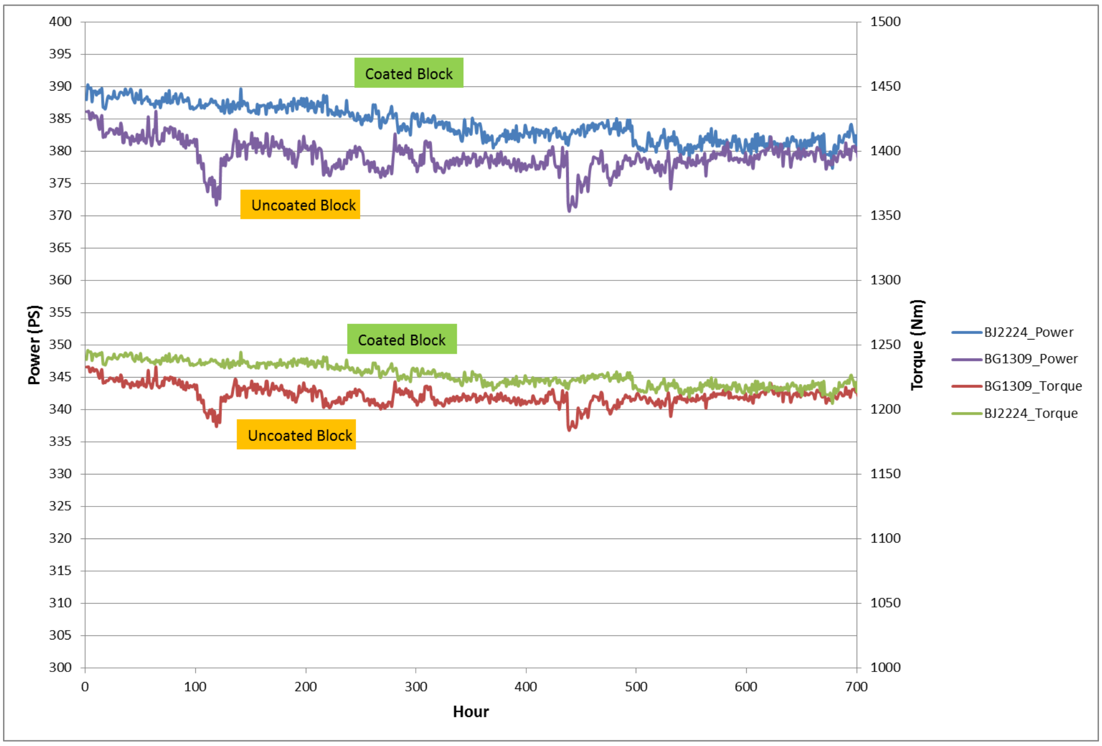


Figure 6.28 : Power-Torque comparison.

Oil Consumption:

Oil consumption increases with coated block (Figure 6.29). This may be due to porous structure of coating surface.

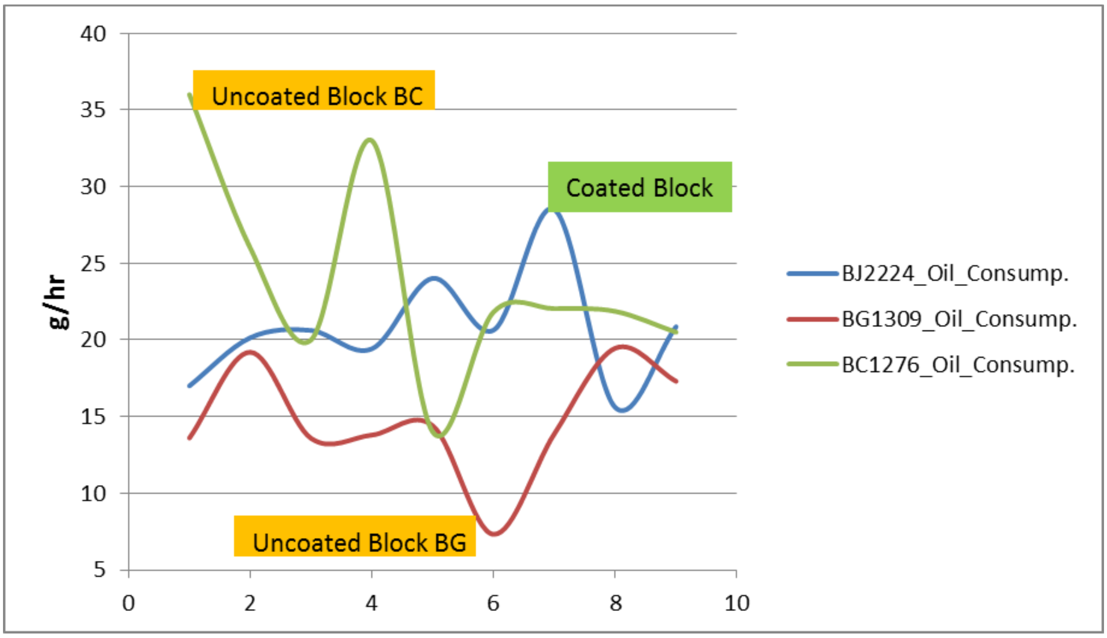


Figure 6.29 : Oil consumption comparison.

Fuel Consumption:

Even the fuel consumption increases (Figure 6.30), it may be related with power increase. However when the specific fuel consumption is investigated, it is seen that engine runs more efficient.

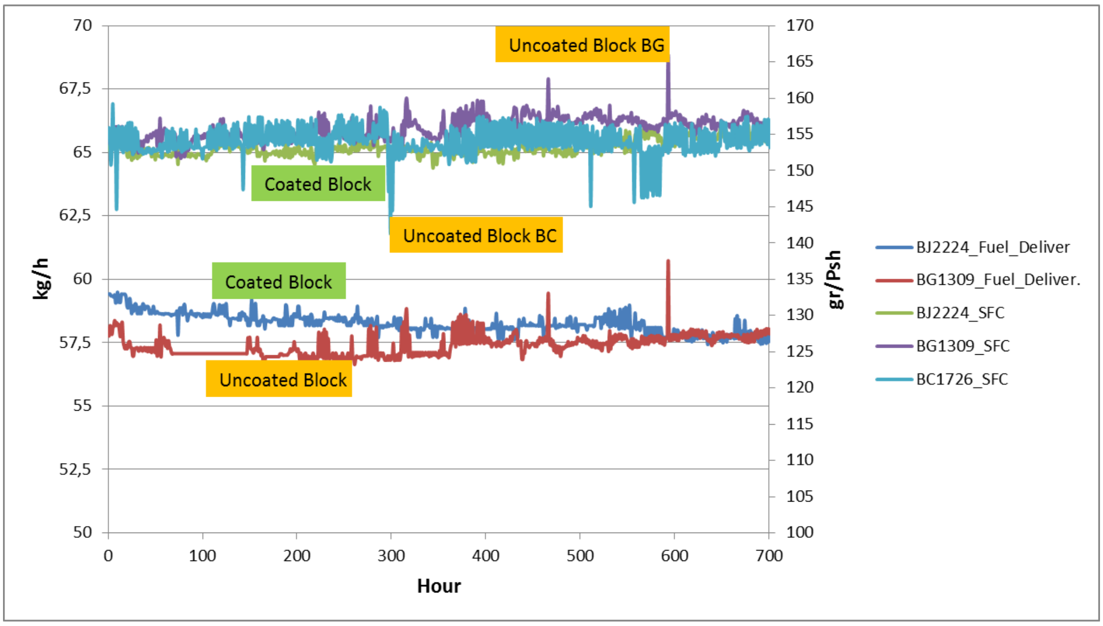


Figure 6.30 : Fuel consumption comparison.

Blow-By:

Decrease in blow-by is observed. Since the cylinder bore surface is smoother, sealing of combustion gas from crankcase is more efficient. Figure 6.31 compares the blow-by of different engines.

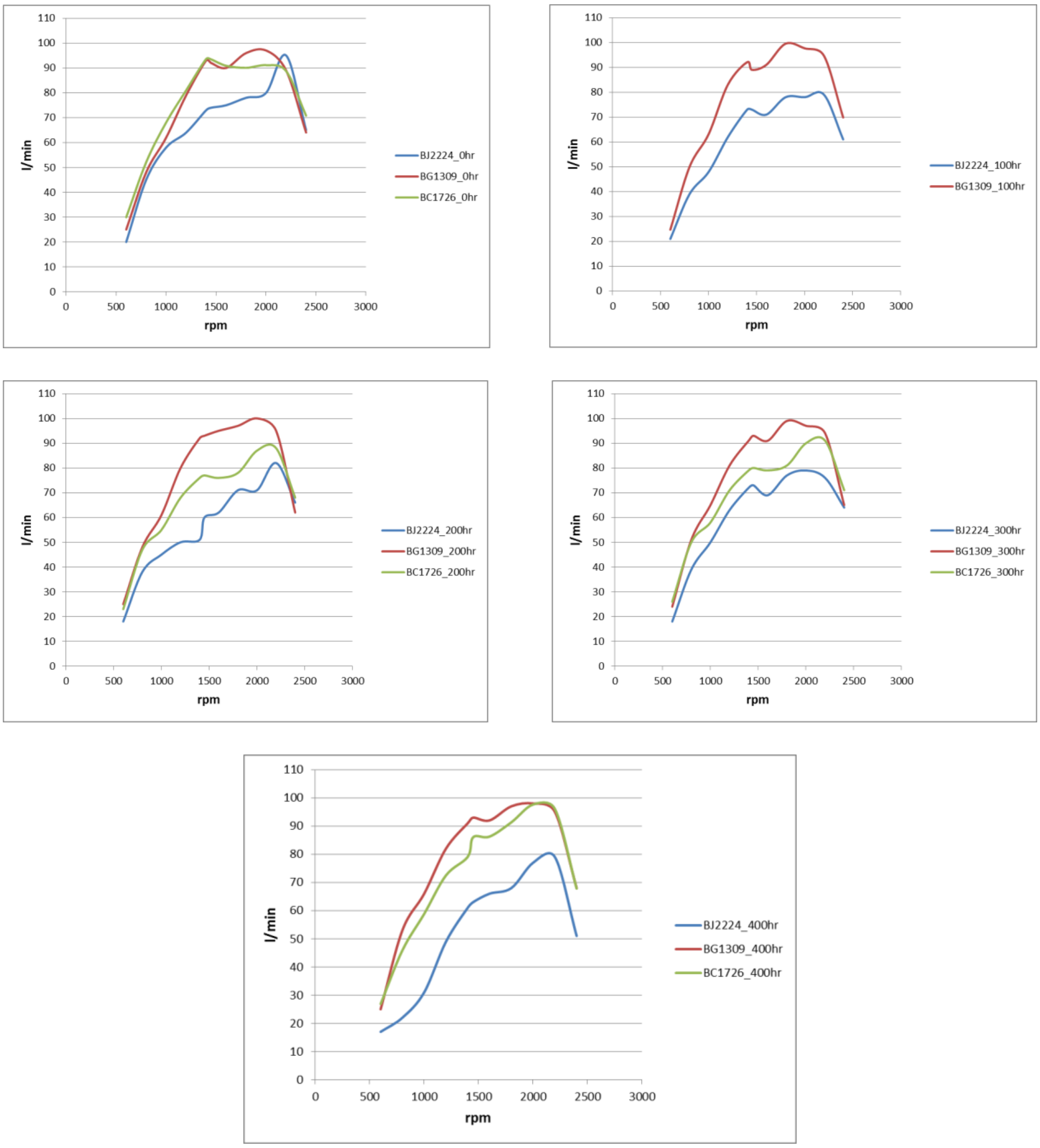


Figure 6.31 : Blow-by comparison in 100 hours intervals.

Piston nominal pre-test and post-test measurements indicate that there is 10 µm reduction of diameter [5]. This is due to wear occurrence on the piston. Normal wear rate is reported as 30 µm by the piston supplier.

Oil Analysis:

Oil samples had been taken with 50 hours interval and analyzed by oil supplier. Soot and viscosity are checked to see whether there is any problem with oil itself. Moreover by checking/comparing Fe in oil and percentage of soot, it can be decided on whether any excessive combustion gas flow to oil is seen during testing. Results from coated block and an uncoated block (same test cycle with same type oil) are compared to see any difference. The first graph, in Figure 6.32, on left hand side belongs to coated block, and one on right hand side belong to an uncoated block.

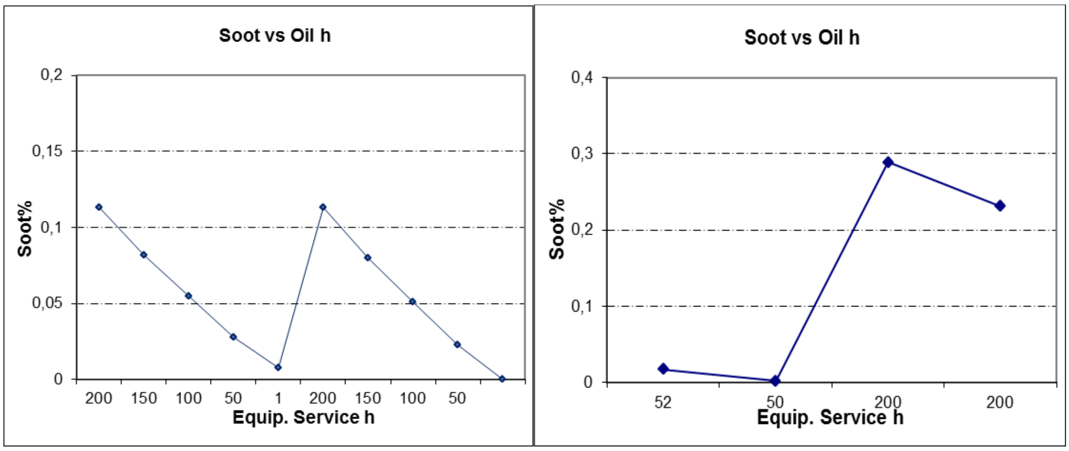


Figure 6.32 : Soot vs. Oil (Left:Coated block, Right:Uncoated block).

It can be said that soot formation is less than uncoated block. The blow-by data also supports this case. Blow-by of coated block is less as well.

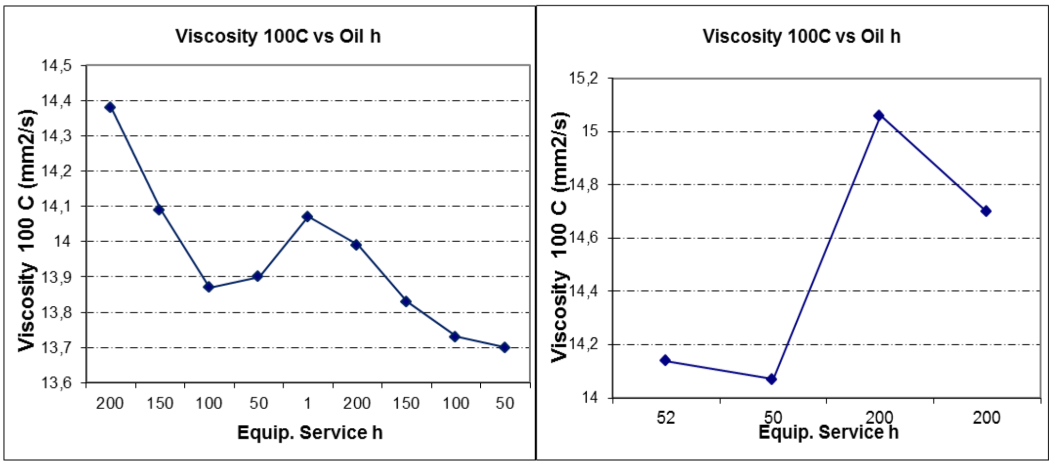


Figure 6.33 : Viscosity (Left:Coated block, Right:Uncoated block).

As expected for both cases, viscosity of oil increases in parallel with increase of soot percentage (Figure 6.33).

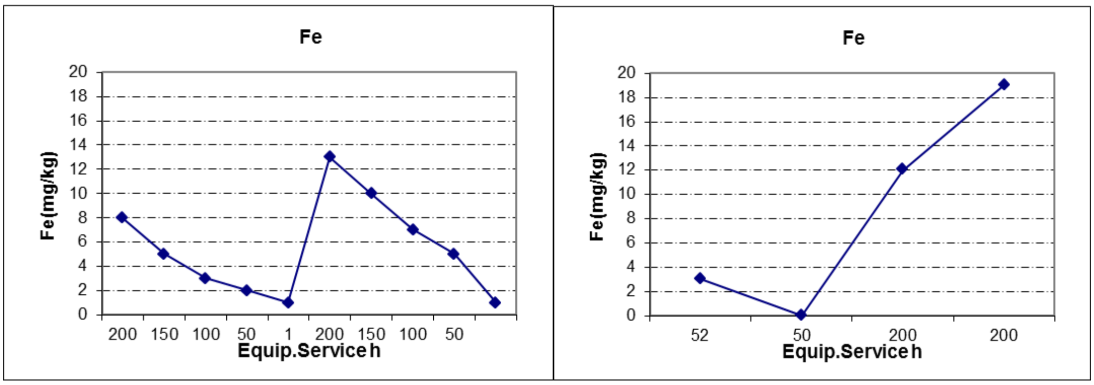


Figure 6.34 : Iron in Oil (Left:Coated block, Right:Uncoated block).

The Figure 6.34 above indicates that wear of cylinder bore wall and /or piston rings are less in coated block. That means coating of cylinder bores improves the surface contact of rings and bore wall. Thus, the question whether 0.8%C steel coating provides harder surface when compared with CGI material is answered. It can be conluded that 0.8%C steel coating provides harder surface, and more wear resistant surface than cast iron.

7. CONCLUSIONS AND RECOMMENDATIONS

The test has been performed during the thesis work sheds light on the issue whether PTWA coating on cylinder bore surface works and increases engine performance. The study indicates that friction and wear are decreased, and hence engine power increases by using 0.8% C-steel.

In recent years, regulations related with emission mandates emitting lower NOx and CO gases. The automobile makers work on after treatment systems to decrease emission level to acceptable limit without sacrificing engine performance. One solution on engine side is using exhaust gas recirculation system (EGR) that uses exhaust gas once during combustion with fresh air. This creates a corrosive media. So, it needs to be worked on more corrosion resistance coating materials. During the thesis work, it was also studied with BB49 cylinder block, as using Cr and Al alloys of iron. However, it was seen that the sufficient bond would not be provided and at very early stages of testing, it fails. The coated material was come out from bore surface. As a further study of the thesis, this can be studied and tested again by using different mechanical roughing of bore surface.

REFERENCES

[1]**Tanner, Sulzer Metco** (2008). *Thermal Spray,* Issue 4, pp. 124

[2]**CED Engineering** (1999). *Thermal Spraying Technology and Applications*, January 29.

[3]**Kuroda, Seiji; Kawakita, Jin; Watanabe, Makoto; Katanoda, Hiroshi** (2008). Warm spraying—a novel coating process based on high-velocity impact of solid particles. *Sci. Technol. Adv. Mater. 9* (3): 033002

[4]**Movahedi, M.H. Enayati, and C.C. Wong** (2010). Structural and Thermal Behavior of FeCrMoPBCSi Amorphous and Nanocrystalline HVOF Coatings, *Journal of Thermal Spray Technology,* pp. 1093-1099

[5]**Hieu Nguyen** (2005). Manufacturing Processes and Engineering Materials Used in Automotive Engine Block, *Materials Science and Engineering Section B, EGR250,* pp. 18

[6]**Paulussen, S; Rego, R; Goossens, O; Vangeneugden, D; Rose, K**. (2005). Plasma polymerization of hybrid organic–inorganic monomers in an atmospheric pressure dielectric barrier discharge. *Surface and Coatings Technology 200*: pp. 672.

[7]**Leroux, F; Campagne, C; Perwuelz, A; Gengembre, L**. (2008). Fluorocarbon nano-coating of polyester fabrics by atmospheric air plasma with aerosol. *Applied Surface Science 254* (13): pp. 3902

[8]**Sulzer Metco** (n.d). *Thermal Spray Equipment Guide*

[9] http://www.zircotec.com/page/plasma-spray_processing/39 Plasma spraying process, date retrieved 2009-07-07

[10]Friction, Lubrication, and Wear, *ASM Metal Handbook Volume 18*, pp. 143

[11]**F.X. Sieloff and J.L. Musser** (1982). What Does the Engine Designer Need to Know About Engine Oils? *paper presented to Detroit Section of the Society of Automotive Engineers*, March

[12]**W.B. Chamberlin and J.D. Saunders, Automobile Engines** (n.d). CRC Handbook of Lubrication, Vol 1, CRC Press, pp. 3-44

[13]**Rabinowicz, E.** (1995). Friction and Wear of Materials *New York, John Wiley and Sons*

[14]**Jones, M., H., and D. Scott, Eds.** (1983). Industrial Tribology: the practical aspects of friction, lubrication, and wear, *New York, Elsevier Scientific Publishing Company*

[15]**ASTM** (1987). *Standard Terminology Relating to Wear and Erosion, Annual Book of Standards,* Vol 03.02, pp. 243-250

[16]**ASM** (n.d.). Friction, Lubrication, and Wear, *ASM Metal Handbook Volume 18*, pp. 337

[17]**ASTM** (1983). Ranking Resistance of Materials to Sliding Wear using Block-on-Ring Wear Test, G 77, *Annual Book of ASTM Standards*

[18]**Valtierra-Gallardo, Salvador et al.** (2008). Wear-Resistant Aluminum Alloy for Casting Engine Blocks with Linerless Cylinders, *Patent Application – Publication Number: WO 2008/053363 A2*. 8 May 2008.

[19]*http://en.wikipedia.org/wiki/Wear* Wikipedia, The Free Encyclopedia. Wikimedia Foundation, Inc.

[20]**Hirst, W.** (1975). Scuffing and It's prevention, *Tribology Practical Reviews, I Mechanical Engineer*. Copyright 1975.

[21]**Murakami**. (1995). Diesel Engine Sulfuric Acid Corrosion Wear Analysis, *Automotive Engineering Society Theses, Vol. 26, No. 4* pp. 45-50

[22]**Takami, Toshihiro, et. al. Toyota Motor Corp. Masago Yamamoto, Toyota Central Research and Development Labs, Inc.** (2000). MMC All Aluminum Cylinder Block for High Power SI Engines, *Society of Automotive Engineers, Inc., 2000. 2000-01-1231.*

[23] *http://www.uschrome.com/Aluminumenginepaper.html* US Chrome Corporation. Technical Information: Aluminum Engine Paper, Copyright 2007

[24]**Funatani K., K. Kurosawa, et. al.** (1994). Improved Engine Performance Via Use of Nickel Ceramic Composite Coatings (NCC) Coat, *SAE Technical Paper Series 940852*. February 28, pp. 89-96

[25]**D.E. Diesburg and F. Borik** (1974). Optimizing Abrasion Resistance and Toughness in Steels for the Mining Industry, *Symposium on Material for the Mining Industry, Climax Molybdenum Co*.

[26]**M.M. Khruschov** (1974). The Principles of Abrasive Wear, *Wear, Vol 28*, pp. 97-99

[27]**SAE Handbook** (1986). *SAE Handbook*, pp. 2.15

[28]**Decher** (1994). Energy Conversion: Systems, *Flow Physics and Engineering*

[29]**A. Vencl, A. Rac, I. Bobic, Z. Miskovic** (2006). Tribological Properties of AlSi Alloy A356 Reinforced With Al2O3 Particles, *Tribology In Industry*, pp. 27-31

[30]**U.S. Environmental Protection Agency Inventory of U.S**. (2010). *Greenhouse Gas Emissions and Sinks: 1990-2008*, April 15

[31]**N.N. Flame-Spray Industries, Inc**. Port Washington, NY, USA, *www.flame-spray.com* date retrieved 2011

[32]**Cook, D., Kowalsky, K., Zaluzec** (2003). M. Development of Thermal Spray for Automotive Cylinder Bores, *International Thermal Spray Conference 2003*, Orlando, FL, May 5-8, 2003, USA, pp.143-147

[33]**Barbezat, G.** (2003). Low-Cost High-Performance Coatings Produced by Internal Plasma Spraying for the Production of High Efficency Engines, *International Thermal Spray Conference 2003, Orlando, FL*, May 5-8, 2003, USA, pp. 139-142

[34]**Kirpal Ravi , Batra N.K , Kumar Sunil** (2011). Dry sliding behavior of thermal sprayed ferrous coatings on Aluminium alloy

[35]**Verpoort, C., Blume, W., Broda, M., Orlamünder, F., Holdik, K., Kollinger, S., Bobzin, K., Ernst, F., Zwick, J., Schläfer, T., Schreiber, F.,. Wenz, T., Schwenk, A., Flores: G.** (2007). Thermisches Beschichten von Aluminium-Zylinderlaufbahnen mit nanokristallinen Schichten im Rahmen des BMBF-NanoMobil-Projektes, *MTZ Konferenz Motor 2007, Neckarsulm*

[36]**Bobzin, K., F. Ernst, J. Zwick, T. Schlaefer, D. Cook, K. Kowalsky, K. Bird, D.H. Gerke, R. E. Sharp, K.R. Raab, and S. Lindon.** (2007). Thermal Spraying of Cylinder Bores with the PTWA Internal Coating System, *Proceedings of the 2007 Fall Technical Conference of the ASME Internal Combustion Engine Division: October 14-17, 2007, Charleston, South Carolina. New York, NY.: American Society of Mechanical Engineers*

[37]**Ford, Matthew; Fisher, Matthew** (2010). Method for Coating Combustion Engine Cylinders by Plasma Transferred Wire Arc Thermal Spray, Paper. April 30, 2010.

[38]**Wuest, G. et al.** (1997). The Key Advantages of the Plasma-Powder Spray Process for the Thermal Spray Coating of Cylinder Bores in Automotive Industry, *SAE International Congress & Exposition, February 1997*. pp. 33-43

[39]**Barbezat, G.** (2003). Low-Cost High-Performance Coatings Produced by Internal Plasma Spraying for the Production of High Efficiency Engines, *Thermal Spray 2003: Advancing the Science and Applying the Technology: Proceedings of the 2003 International Thermal Spray Conference, 5-8 May, 2003, Orlando, Florida. Materials Park, OH: ASM International, 2003*. Pp.141-142

[40]**Millikin, Mike, ed.** (2008). Ford Developing Thermally Sprayed Nano-Coating for Cylinders to Reduce Friction, Support Lighterweight Construction, *Green Car Congress. BioAge Group*, April 17.

[41]**Federal Mogul** (2012). Reibungssymposium Ford, April 2012

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