EFFECT OF WONDER'S PROCESS CRAFT (WPC) SURFACE TREATMENT ON SLIP AT CAMSHAFT-ROLLER CONTACT IN FINGER FOLLOWER VALVE TRAIN

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A thesis submitted in partial fulfilment of the requirements for the degree of MS Design and Manufacturing Engineering

Thesis Supervisor
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DECLARATION

I certify that this research work titled “Effect of wonder’s process craft (WPC) surface treatment on slip at camshaft-roller contact in finger follower valve train” is my original work. This work has not been presented elsewhere for the award of any degree. The material that has been used from other sources is properly acknowledged / referred.

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LANGUAGE CORRECTNESS CERTIFICATE

This thesis report has been read by an English expert and is free of typing, semantic, grammatical, syntax and spelling errors. Thesis report is also prepared according to the format given by the NUST.

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Signature of Supervisor

ACKNOWLEDGEMENTS

I am grateful to Allah Subhana-Watala Who have guided me throughout this research work and for every new idea which You setup in my mind for the improvement. Indeed I could not have done anything without Allah Subhana-Watala priceless help and guidance.

I am generously thankful to my beloved parents who cared me when I was not able of walking and continued to support me throughout my life. I am also extremely grateful to my beloved wife. Without her constant support this piece of work would never be accomplished.

I would also like to communicate special thanks to my supervisor Dr. Samiur Rahman Shah for his help throughout my research work and also for IC Engines course which he has taught me.

I would also like to pay special thanks to Dr Riaz Ahmad Mufti, Major Muhammad Khurram, Muhammad Usman Abdullah and Muhammad Usman Bhutta for their tremendous support and cooperation. Every time I got stuck in something, they came up with the solution. Without their help I wouldn't have been able to complete my thesis. I appreciate their patience and guidance throughout the whole thesis.

I am also thankful to Mr. Fazal Badshah and Mr. Zafar Iqbal Rana for their support and cooperation.

Finally, I would like to express my gratitude to all the individuals who have given assistance to my research work.

DEDICATION

“Dedicated to my exceptional parents, beloved wife and children”

ABSTRACT

Presently all engine makers are continuously struggling for enhancing overall efficiency and reducing fuel consumption during engine operation. Mechanical and thermal losses are mainly responsible for engine fuel losses. Engine manufacturers have made considerable advancements in optimizing design of engine parts, their material and lubricants for minimizing losses in engine operation. In order to further reduce frictional losses, researchers are also focusing on different coatings [1] and surface treatment techniques [2] to be used on contacting metal surfaces in engine operation. Only 12% of the available fuel energy reaches to driving wheels with approximately 15% being dissipated as mechanical losses which mainly comprise of frictional losses [3]. Valve train friction losses are approximately responsible for 7.5 to 21% of total mechanical losses in the engine [4]. Slippage/skidding between rolling contacts can increase friction and wear. Focus of this research work is to check effect of WPC surface treatment process on slippage/skidding at camshaft roller contact in End pivoted finger follower valve train. A series of tests under different camshaft speeds and lubricant oil inlet temperatures have been carried out using both unmodified roller (original) and modified roller (WPC treated roller) to investigate the impact of this surface texturing technique on the slip at camshaft roller contact, experimentally. The results have clearly revealed significant reduction in slip at camshaft roller contact for WPC treated roller as compared to original roller under similar operating conditions at low lubricating oil temperature. In this research report, previous literature review, WPC surface treatment process, experimental setup, data acquisition system, experimental procedure and results have been presented in detail.

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CHAPTER 1: INTRODUCTION

Presently different surface treatment processes are being efficiently used to enhance tribological characteristics of sliding surfaces. Decrease in friction, wear and rise of lubrication & hydrodynamic load carrying capability are few advantages that can be obtained by surface treatment. It is very important to reduce fuel consumption and enhance life span of the engine by reducing wear at the sliding surfaces. In recent times, the working conditions of mechanical contacts has become very rigorous, film thickness of the lubricant between mechanical contacts has been reduced to the surface roughness level. Nowadays, researchers are focusing on varying surface micro topography to get superior results. One of the important methods to enhance tribological characteristic of different mechanical components is by applying surface texturing. This idea of applying surface texturing for reduction in friction at mechanical contacts is not novel. It was introduced by Hamilton et al. in 1965 [5]. By applying different surface texturing patterns in the form of micro dimples or groves on the surface, reduction in friction can obtained [6]. Surface texturing provides resistance to seizing ability by retention of oil in micro dimples [3]. To get maximum benefits, researchers are now focusing to optimize surface texturing parameters like dimple shape, size, position, distribution angle, density and their patterns [7]. In surface texturing process roughness of work piece is enhanced in a special way in order to boost tribological characteristics at the mechanical contacts. This is clearly opposing the idea that smooth surfaces are required for reducing friction.

Existence of slip at camshaft roller contact of Toyota 1NZK engine head was presented by Khurram [8]. In this research, one roller of End pivoted finger follower was WPC surface treated from Fuji Manufacturing's Japan. A specialized engine valve train test rig was used to measure slip at camshaft roller contact of modified (WPC treated) and unmodified rollers.

Aim:

In this study effect of relatively new surface treatment process, Wonder Process Craft (WPC) is studied on slip between roller & camshaft contact in finger follower valve train.

CHAPTER 2: LITERATURE REVIEW

In modern engine valve trains, rolling tappets are preferred to sliding tappets. It is possible that by use of roller followers, the rolling contact between cam and roller can prevent severe wear that exist in the sliding tappets. Conditions causing severe wear like long dwell time & high contact temperature can be avoided in sliding tappets by replacing them with roller followers [9]. The use of the roller converts the cam follower from a sliding contact to rolling contact. Previous investigation by Staron and Willermet, Sun and Rosenberg & Bair et al [10, 11, 12] have shown the use of rolling contact instead of sliding contact result in less power loss. Gecim [13] has found lower power loss in roller followers than in sliding tappets. Miyamura, in 1991 [14] observed that sliding between cam & roller is possible cause of wear between cam and roller.

Theoretical studies showed that during most of one cam cycle. Roller rotated with the same surface velocity as that of the cam relative to the point of contact. At high camshaft rotation rotational frequencies, however, sliding may take place on the cam flanks where the acceleration of the surface of cam is the highest [15].

In early tribological studies for cam and roller followers pure rolling was frequently assumed by Druce et al 1978, Colechin et al & Gecim 1988 [16, 17 and 18] despite researchers were aware of sliding possibility because it was difficult to determine sliding and for simplification of studies. Experimental measurements showed existence of sliding by Bair & Winer, 1990 & Duffy, 1993 [19 and 20]. Existence of sliding at camshaft roller contact was also pointed out by Khurram [8].

2.1 PREDICTION OF SLIP/SLIDING AT CAM-ROLLER CONTACT

If roller rolls on the surface of cam it is subjected to angular acceleration about its rotation axis. When camshaft rotates at very high frequency then angular acceleration of roller about its centre is very high. At very high camshaft speed, friction force at camshaft-roller contact may not be able to keep roller rolling at camshaft surface so slip/skidding takes place. The slip/no slip point is defined as point where torque due to traction force at cam-roller contact is equal to combined torque due to friction forces in the needle roller bearing plus inertia force of the roller [15]. If the combined torque due friction forces in roller needles bearing and inertia of the roller is greater than torque due to traction force at cam-roller contact than slip will take place. This phenomenon occurs at very high rotational frequency of camshaft. At very high camshaft rotational frequency inertia of roller becomes significant and large friction is needed to keep the roller rolling on the cam surface. From above statement we can conclude that reason for sliding is that friction at cam-roller contact cannot provide sufficient friction force to drive the roller. When micro slip occurs at cam-roller contact, sliding velocity increases which accordingly increase friction traction force at camshaft roller contact which reduces slip tendency. In negative slip roller rotates at higher rotation velocity than camshaft. At cam falling flanks a special phenomenon of negative slip happens at cam-roller interface. When surface velocity of camshaft reduces quickly, due to inertia force roller tries to maintain its speed so negative slip occurs. Due to small inertia of roller existence of negative slip by researchers was doubted. Firstly phenomenon of negative slip was observed by Duffy in 1993 [20]. During most of time in cam cycle, roller rotates with similar surface velocity as that of cam. At high camshaft rotational frequency sliding may take place on cam flanks at which acceleration of cam surface velocity is high because roller inertia plays a vital role.

2.2 LUBRICATION REGIMES

The purpose of lubrication is to separate the surfaces that are moving relative to each other with a film of material that can be sheared with low resistance without causing damage to the surface. The role of lubrication regimes is vital for enhancing ability of a sliding/rolling contact to sustain applied load. Single lubricating oil is used to lubricate valve trains, bearings & piston assembly etc and yet different properties are desirable to optimize the performance of each part. Stribeck curve basically represents general characteristics of lubricated moving surfaces [21]. Stribeck curve is a graph between friction coefficient and lubrication parameter shown in figure 1. Lubrication parameter is defined as product of lubricant viscosity and velocity divided by applied load.

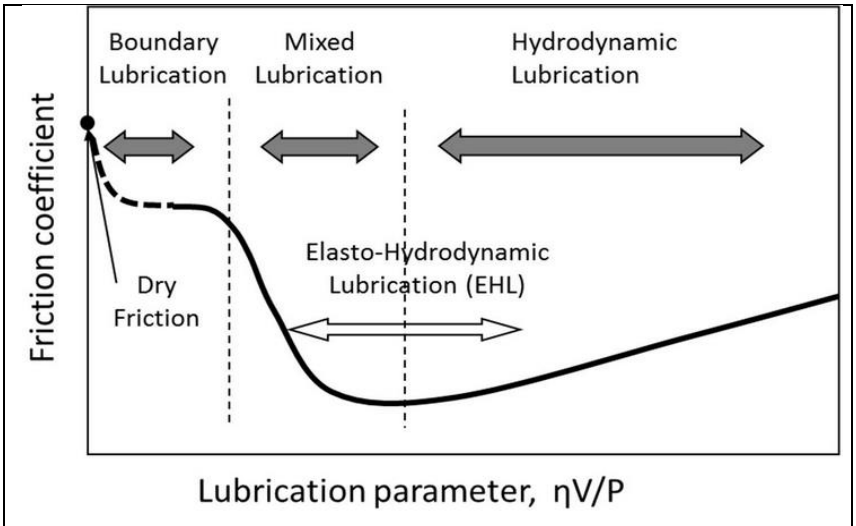


Figure 1: Stribeck curve showing different lubrication regimes

By increasing viscosity and velocity results in moving towards hydrodynamic lubrication and decreasing load has similar effect. Reversely if load is increased and viscosity is decreased by changing lubricating oil or increasing temperature and speed of equipment slows down contact moves toward boundary lubrication. A component may face a range of lubrication regimes during its operation cycle. Base on thickness of lubrication film and its degree of geometric conformity different lubrication regimes can be distinguished. Energy losses in hydrodynamic lubrication mode mainly depends on viscosity of lubricating oil, in Elastohydrodynamic regime depends on traction and in mixed and boundary regime depends on friction. During engine operation, camshaft roller contact may undergo all lubrication regimes but mainly this contact operates in boundary and mixed lubrication modes. Different lubrication regimes are shown in figure 2 below.

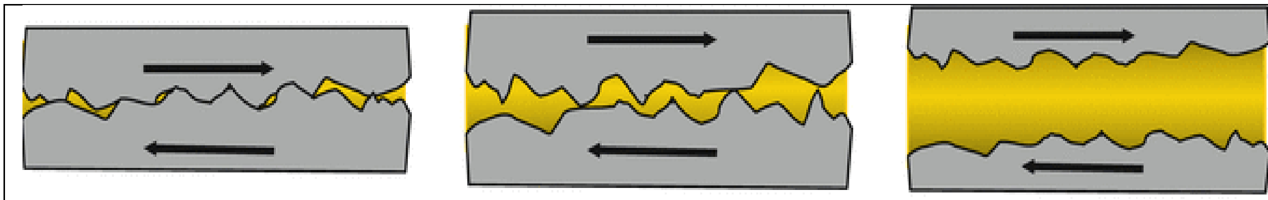


Figure 2: Different Lubrication Regimes (Left) Boundary (Middle) Mixed (Right) Fluid Film

2.2.1 Hydrodynamic Lubrication:

Hydrodynamic lubrication is also known as fluid film lubrication. It is ideal form of lubrication. In this lubrication regime opposing solid surfaces are separated completely by a viscous lubricant film. This lubrication regime is perfect for reduction of wear and friction between the contacting surfaces. Lubricant dynamic viscosity is its most significant characteristic and governs behaviour of the contact. Friction can increase because of lubricant viscous shearing in this type of lubrication.

In Hydrodynamic lubrication behaviour of the contact is mainly governed by the physical characteristics of the lubricating oil like viscosity, and friction characteristics rise due to viscous shearing of the lubricating oil [22].

2.2.2 Elastohydrodynamic Lubrication (EHL):

This is a form of hydrodynamic or fluid film lubrication regime. Elastohydrodynamic lubrication happens due to elastic deformation of solid materials. It creates very high stressed point or line contacts e.g. camshaft and tappet/rollers, rolling bearings and gears. Mostly EHL exists between non conformal contacts [23]. In non conformal contacts, lubricated contacts have high pressure and there surfaces are elastic [24]. Conformal and Non Conformal contact are shown in figure 3.

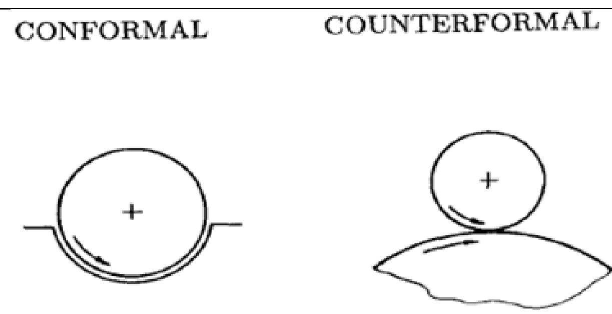


Figure 3: Conformal and Non Conformal contact [24]

Due to large contact pressure, lubricant viscosity increases. Lubricant viscosity increases many thousand times than its viscosity at atmospheric pressure and temperature. Elastohydrodynamic lubrication is nominally also full fluid film lubrication with surface separation, but a more concentrated mechanism where elastic deformation of the surfaces and the effect of pressure on the viscosity are important. At high camshaft speed, EHL may happen at the cam flanks due to higher entrainment velocity of lubricant.

2.2.3 Hard Elastohydrodynamic Lubrication:

This lubrication regime happens in solid materials that are non-conformal and having high elastic modulus e.g. gear teeth, roller bearings and cam with tappet etc. In non-conformal contacts, surfaces do not match; load concentration is on elastically deformed, tiny areas. In these contacts pressure of the lubricating oil film ranges high to .5 to 3 GPa, which is many thousand times higher than in hydrodynamic contacts [25].

2.2.4 Boundary Lubrication:

In boundary lubrication, oil film thickness is so small that contacting surfaces are in complete contact like dry contact. This lubrication regime mainly occurs at high load and low speed. Normally engine valve trains and gears operate in this lubrication regime. The friction properties can be found by both lubricant and solid properties. Lubricant properties are of minor importance and friction coefficient is viscosity independent [26].

The surfaces are in normal contact with behaviour characterized by the chemical and physical properties of thin films of molecular proportions. In this lubrication regime performance of contacting parts mainly depend on boundary film e.g. films formed by chemical reaction, chemically absorbed films and physically absorbed layers of gaseous, liquids or solids. These surface films are 5nm to 10nm thick. In case of boundary and mixed lubrication, lubricant additives and solid material of parts are of paramount importance for forming of reaction films at interacting surfaces.

2.2.5 Mixed Lubrication:

Hydrodynamic and boundary lubrication modes were considered important in past but different contacts operate between these two regimes known as mixed lubrication mode. There is surface asperity interaction to some degree and the characteristics of both Elastohydrodynamic and Boundary Lubrication are influential. In mixed lubrication regime contact properties mainly depend on fluid film and boundary lubrication effects. Physical properties of bulk lubricant and chemical properties of boundary lubricant are important. When temperature or load increases fluid film reduces to mixed lubrication regime. In mixed lubrication regime, load is partly carried by fluid and boundary film.

Different components of machines undergo fluid film, mixed and boundary modes at different instances. With regard to cam and tappet contact, mixed lubrication may be present at the interface if EHL contact is not present due to the unavailability of adequate lubricant at the contact [23].

2.3 VALVE TRAIN DESIGNS

It is very important for engine performance that how efficiently it draw air-fuel charge in the combustion chamber and how efficiently it expels combustion gases out of combustion chamber. Assembly of components required for opening and closing of intake and exhaust valves is called engine valve train. In older engine designs, overhead valves were used and camshafts were located lower but modern engines have overhead cam assemblies. The camshaft can be driven with a timing chain or timing belt or direct gear. Tribological behaviour of different engine parts such as crankshaft bearings or piston assemblies have been mostly known because of remarkable advancements in the recent decades. In comparison, work done on the valve trains is insignificant. The reason might be, the contact between the camshaft and follower are very difficult due to high sliding speeds, highly dynamic loads, poor lubrication and large contact stresses [26]. Valve trains contribute about 6% to 35% of the overall frictional losses in an engine [27 and 28]. This value changes in connection with operating conditions and design. Total frictional losses in an engine valve train are contribution of camshaft/follower, camshaft bearing and follower/valve guide [28]. Valve train frictional losses are less than crankshaft bearings and piston assemblies but they become important at elevated operating temperature and lower speeds [27 and 29]. Engine valve trains are very difficult to design and lubricate efficiently due to wear, reliability and durability problems [30].

End pivoted roller followers and direct acting tappets are two main types of valves train configurations that are widely used in the modern passenger car engines. Limited experiments have been reported on End pivoted roller followers as compared to direct acting tappets because of its complex nature. In End pivoted roller followers, rotation of the roller directly affect performance of the engine in terms of component friction and durability. Fatigue failure chances are minimized due to even distribution of wear, improve the lubrication, and influences the valve train power loss [8]. In this research work, effect of WPC treatment on slip at camshaft roller contact is studied, in finger follower valve train. One roller was WPC treated whereas second was in its original untreated form. The experiments have been performed on a real Toyota 1NZK engine head having end pivoted roller finger follower valve train configuration without any major alteration. Different parts used in Finger Follower Valve Train of Toyota 1NZK head are shown in figure 4 below.

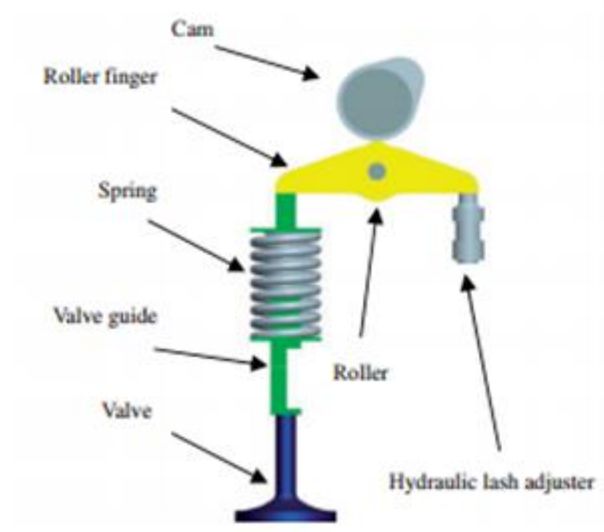


Figure 4: Arrangement of finger follower valve train parts used in Toyota 1NZK head [8]

2.4 VALVE TRAIN TYPES

There are different engine valve train designs but they all are driven by camshaft. We can differentiate between them by number of camshafts and their position. We can assemble camshaft in an engine in two different ways. Overhead valve (OHV) control system in which camshafts are lower and overhead cam (OHC) control system in which camshafts are installed at upper position. The merits and demerits of the some valve train types were discussed by CM Taylor [31]. Different valve train types are discussed below.

2.4.1 Pushrod Type (OHV):

An engine is called overhead valve (OHV) engine that have valve placement above the cylinder head. Pushrod type valve train configuration requires several transmission components like pushrod, plunger, rocker arm bearing, rocker arm etc. for passing on cam stroke to the valve. Due to reduced stiffness this push rod type configuration was shortly at its speed limit. However it offers low wear at cam follower contact due to plenty of lubrication. Pushrod type valve train configuration is shown in figure 5.

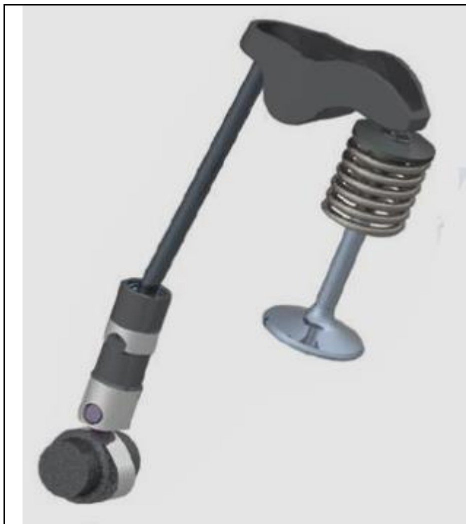


Figure 5: Pushrod Type (OHV)

2.4.2 Centre Pivot (OHC) with Lifter:

Later in order to increase stiffness of valve train pushrod was reduced from pushrod type configuration resulting in development of centre pivot (OHC) with lifter. In this type of valve train configuration now camshaft was located in engine head. It offers medium valve train friction and engine packaging. Centre pivot (OHC) with lifter is used in Ford Escort CVH etc. Centre pivot (OHC) with lifter is shown in figure 6.

2.4.3 Centre Pivot Type (OHC):

Now if we remove lifter from valve train configuration explained above, than location of camshaft will be much higher in engine head thus permitting transmission of cam stroke through rocker arm/finger follower directly. Without lifter Centre pivot type (OHC) configuration offers improvement in valve train friction and engine packaging. Centre pivot (OHC) is used in Honda B18, Porsche etc. Centre pivot (OHC) is shown in figure 7.

 Figure 6: Centre Pivot (OHC) with Lifter	 Figure 7: Centre Pivot (OHC)

2.4.4 Finger Follower Type (OHC):

In roller type finger follower valve train contact between cam and follower is made possible with the help of a rolling bearing. This type of configuration is less stiff than bucket type tappets. It has less moment of inertia than bucket tappets. In this configuration camshaft is situated above the roller and is at centre between pivot element and valve. In comparison to the direct acting tappets cams used in finger follower valve trains have concave flanks, larger lobe radius and small lift of the cam. They are made from accurate steel castings. They offer low valve train friction, good lubrication and small installation space is required. Vehicles using bucket type follower are Toyota Prius, Ford Modular Pinto & Ranger 4 cylinder, Mitsubishi 4G63 & GM Ecotec Chrysler 2.2 L etc. Finger follower type configuration is shown in figure 8.

2.4.5 Bucket Type Follower (OHC):

In this type of valve train, valves are operated directly. The Stroke of the cam is passed directly to the bottom of bucket tappet. In this type of valve train configuration no transmission components are required between valve and camshaft. Bucket tappets have small moving masses and are very rigid thus shows good performance at high speed. It has larger cam lobe than other OHC systems. They adjust valve lash automatically and thus has maintenance free life. Engines using bucket type valve train give’s low emissions throughout their life. Vehicles using bucket type follower are Mercedes Benz, Ford Zetec etc. Bucket type configuration is shown in figure 9.

Figure 8: Finger Type Follower

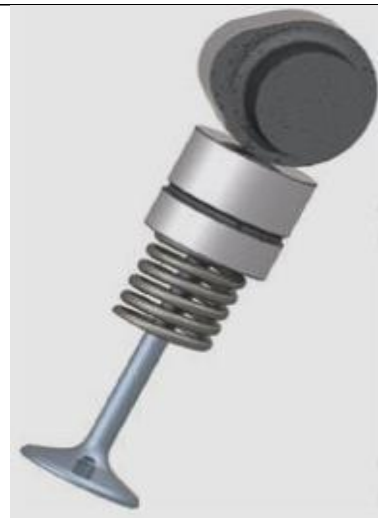


Figure 9: Bucket Type Follower

2.5 WONDER PROCESS CRAFT (WPC)

WPC surface treatment process was invented from the simple idea, what happens if small particles will be used for shot peening process? This easy thought resulted in a huge advancement in surface treatment technology. WPC is not a coating it is a well-known surface treatment method that has been used for many years in Japan. To some extent WPC process is alike to shot peening and even to the sand blasting process as shown in figure 10.

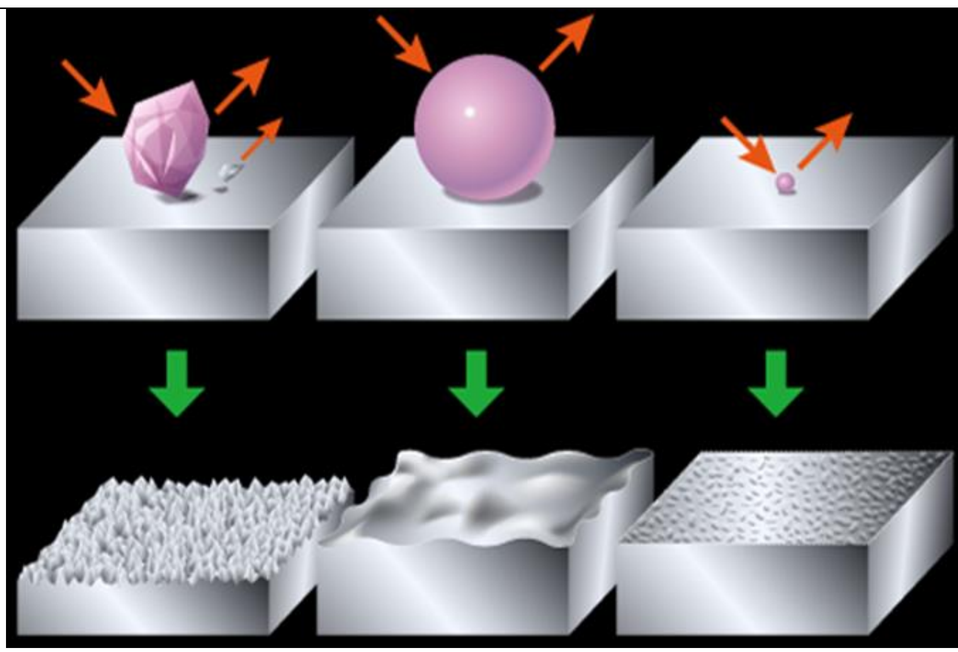


Figure 10: (From Left to right) Sand blasting shot peening & WPC process [32]

In WPC process exceptionally fine dimples are created on the surface of work piece as shown in the figure 11. In engine operation these micro dimples at the surface of part retain lubrication oil, so contact area is less hence reducing friction.

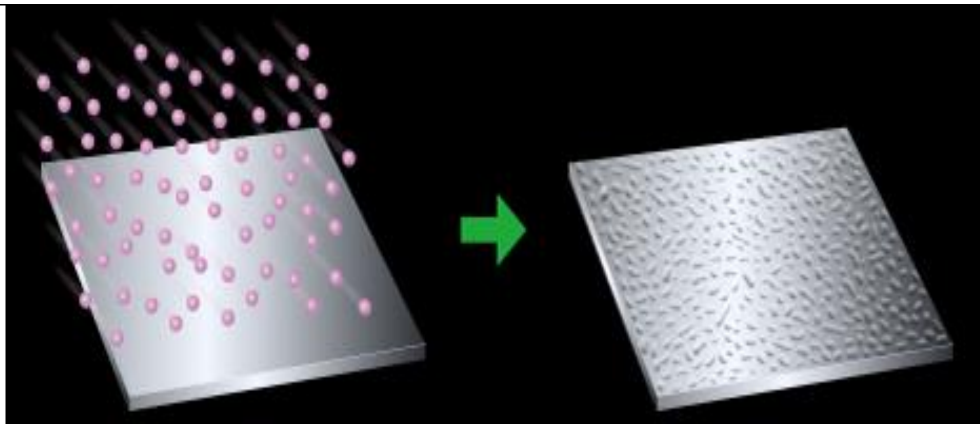


Figure 11: Fine dimples created at the surface of work piece in WPC process [32]

As WPC media is in low micron size, dimples at the surface are not visible with naked eye. WPC treatment marks can be viewed with the help of a microscope. WPC treatment process is kept as trade secret by Fuji Manufacturing's. From actual magnified image of WPC treated roller (Shown in Figure 12) and from internet sources, I have been able to gather few important information about this metal surface improvement process.

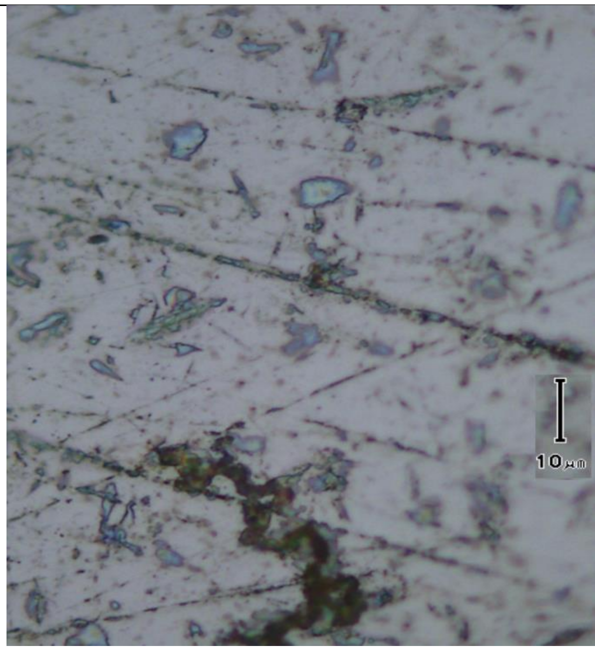


Figure 12: Magnified image of WPC treated roller

In WPC surface treatment process ultra-fine particles of different media are fired at high velocity towards work piece surface. The surface of the work piece is altered permanently due to thermal discharge produced after impact. The surface of work piece is compacted due to impact of small particles thus creating a harder & durable final product.

In sliding metal parts, lubricants are mostly used in different conditions. If lubricant dries up then friction will occur. By spraying abrasive particles at the surface of work piece, its structure becomes surface pressure resistant and forming small indents/dimples at the surface. These dimples store lubricant oil, making difficult for lubricant to dry up and hence preventing friction. In engines using WPC treated parts power output is increased, initial engine running period is shorter and higher fuel efficiency is achieved.

WPC treatment reduces friction on sliding surfaces like pistons, cam rods and crank shafts which need even movement for instantaneous engine reaction. WPC treatment improves strength of engine parts like connecting rods, gear teeth's and springs which are at risk of breaking. WPC treatment also provides defence against seizing of sliding metal surfaces like bearings, piston and pins etc. These parts are under elevated pressure during engine operation.

WPC treatment can also be used on powder metallurgy alloys. Temperature at the surface of powder metallurgy alloy increases by peening of fine particles. As a result powder metal binder will obtain softness and every grain will combine firmly. Structure at the surface will change to high hardness, smooth and adhesion of grains will enhance. By application of WPC treatment, durability and wear resistance of powder metallurgy alloys can be enhanced. In cutting tools made from powder metallurgy we can enhance durability, resistance to chipping and wear resistance by application of WPC treatment.

Metallic material physical properties are limited. In WPC surface treatment process metallic particles are sprayed at the work piece surface. Metallic particles component element is diffused with the surface of work piece. Surface of the work piece is alloyed. A diffused coating is achieved at the surface so strengthening the material of work piece. In order to enhance the adhesiveness of coating and plating WPC treatment can also be used as pre-treatment. Dry plating at room temperature is possible by spraying low hardness and melting point metallic particles.

The machining grooves that are generally created on the surface of the work piece are converted into micro-dimple indentations due to collision of the ultra-fine WPC media particles during WPC treatment process. Dimples formed at the work piece surface due to WPC treatment are not visible to the naked eye. These dimples act as small oil reservoirs at surface of work piece. Hence surface remains lubricated at high working pressure and temperature. Lubricating oil is retained in dimples at surface of WPC treated parts instead of draining it through machining grooves.

During WPC treatment process when very fine media collides at elevated speed at the surface of the work piece it increases compressive stress (shown in figure 13) at the impact surface [33]. At similar time a micro thermal reaction starts that successfully seal minor surface fractures and hence a condensed surface is formed.

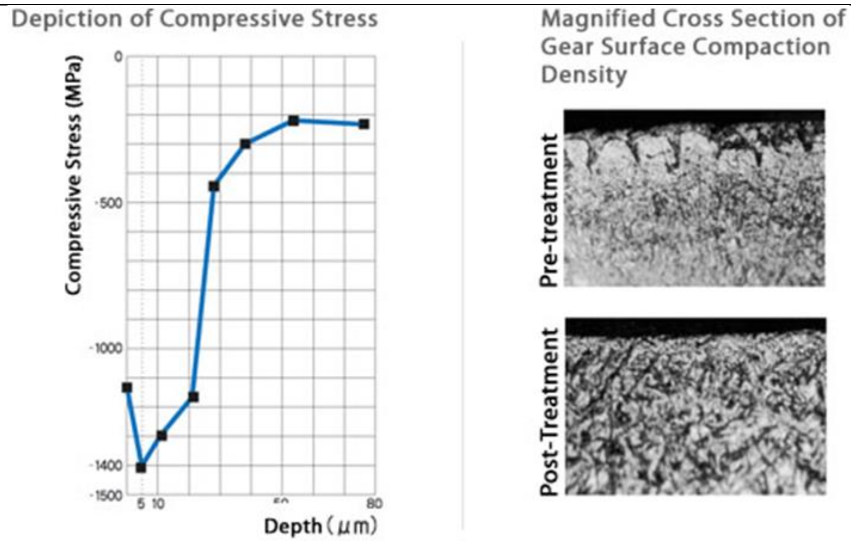


Figure 13: Increase of surface compressive stress and compaction by WPC process [33]

2.5.1 WPC media

Even though WPC process developers will not reveal approximately from what WPC media is made, it looks like baby powder to the informal viewers [34]. We guess that WPC media is made from some type of very hard ceramic with controlled dimensions. WPC media is in small micron range size and the contact velocities at the work piece may be closer to sonic in speed. WPC media particles are so small that its diameter is approximately 50 micron meter which is 1/3000 of conventional shot peening media. Image comparison of shot peening and WPC media is shown in figure 14. In WPC process its media particles are blew by high pressure gas in order to collide with the work piece surface and amazing effects are witnessed.

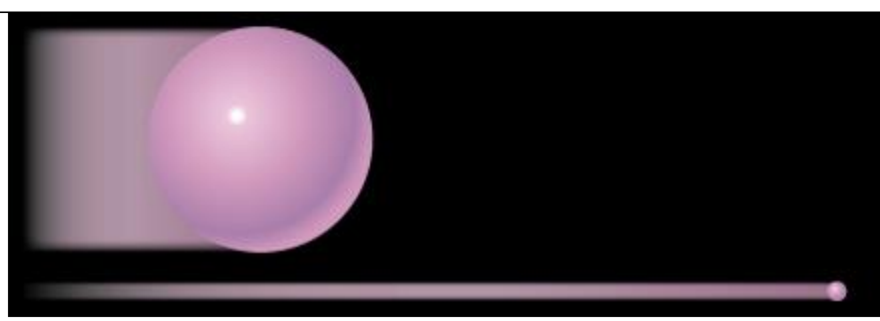


Figure 14: Image comparison of shot peening and WPC media [32]

In addition, solid lubricants such as Molybdenum Disulfide (MoS2) and Tin (Sn) [33] can also be used or added to WPC media in order to insert them in work piece surface. Addition of these solid lubricants in the WPC media can result in lowering friction, enhancing work piece life, add some anti-galling lubricity, extreme pressure characteristics to the surface and increase efficiency. Due to very high impact velocities, these solid lubricant additives are most likely included in the metallic surface of the work piece at a molecular level, thus creating permanent and lasting effect. WPC treatment create slippery hard surface having low friction characteristics.

2.5.2 Differences between WPC treatment and Shot peening

WPC surface treatment process is similar to shot peening. Both WPC & shot peening, involve impacting work piece with sphere-shaped projectiles to create plastic deformation, compressive stress, & grain refinement at the surface. Major differences between both processes are as follows.

- WPC media is many times of magnitude smaller than shot peening media.
- WPC media is much harder than shot peening media.
- Impact velocities of shot peening media are much lesser than WPC media.
- Due to less mass and high velocity, WPC media creates much higher compressive stress and more grain refinement at the work piece surface than shot peening.
- Because of higher velocities of WPC media there are micro level melting and quenching processes going on at work piece surface unlike shot peening.
- WPC results in a very fine grained, slip plane less nano crystalline structure with higher surface hardness at surface of the work piece but in shot peening there is only small change in strength & surface hardness of the work piece.
- WPC treatment results in better fatigue strength fracture resistance & stress corrosion resistance as compare to shot peening.
- WPC treatment will not change dimensions of work piece due to small size of media unlike shot peening.
- WPC treatment can be used for surface treatment of the dies, automobile transmission gears and machine tools blades for which the shot peening cannot be used. Life span of these parts can be extended to the maximum of ten times longer.
- In shot peening process only metal is strengthened, whereas in WPC treatment process fine particles collide at the work piece surface and heat is generated. In WPC treatment rapid heating/cooling is repetitive; therefore WPC treatment has effects unbelievable as compare to the shot peening.

2.5.3 Advantages and Disadvantages of WPC Treatment

Advantages

WPC treatment can be used to reduce friction in different engine sliding contacts by creating micro-dimples at the surfaces of work piece. The main benefits of WPC surface treatment process are as follows.

1) WPC treatment enhances surface finish and hardness of the work piece. It can increase strength, reduce friction in sliding contacts which can indirectly increase efficiency of the engine. Due to dimple formation at the work piece surface contact area between sliding parts reduces so friction will be less.
2) It results in more lubrication at contact point of WPC treated surfaces because dimples created at surface of work piece retain lubricating oil.
3) As a result of above two point’s chances of seizing of sliding surfaces are less.

4) WPC treatment results in less wear at sliding surfaces.
5) WPC does not damage delicate machined parts. Due to low mass of WPC media it can be used for surface treatment of fragile parts. It will not alter tight tolerance parts.
6) By applying it, WPC can enhance service life of different engine parts.
7) WPC treatment can improve fatigue strength & stress corrosion fracture resistance of treated parts [34].
8) Micro dimples formed at the surface of the work piece due to WPC treatment will not damage delicately finished machining parts such as sealing contact areas, bearing seating surfaces, bearing bore and crankshaft fillet.
9) WPC can be used to take the place of different others processes for saving time and money.
10) WPC micro surface dimples reduce wear of work piece by storing wear debris.
11) WPC is well-matched to enhance advantages of different coatings and treatments like DLC, Ion Nitriding, REM, Cryo treatment, Mikronite and different other high performance post treatment parts.
12) WPC treated parts run cooler.
13) WPC treatment prevents burn and scratches.
14) In casting products WPC treatment can be used to correct blow and pin holes.
15) WPC treatment enhances adhesion of plating and coating on the surface.
16) WPC show multiplying effects when it is used with combination of other treatments like carburizing and nitriding.
17) WPC has no considerable disadvantages.

Disadvantages

There are no prominent disadvantages of WPC treatment. Few are summarized below.

1) WPC treatment process is a trade secret so exact details on the process are not available.
2) After WPC treatment of assemblies we have to dismantle and clean them carefully before use.

2.5.4 WPC surface density

In order to check density of WPC surface treatment at the roller surface, a small patch from WPC surface treated roller is taken from magnified image as shown in figure 15. In this image we can see, WPC treatment marks as burn marks at the surface of work piece. These burn marks are created at surface of the work piece due to collision of high speed WPC media particles. Surface area of this small patch is $0.0082615 mm^2$. Now image of small patch was imported in CAD software. In order to find the approximate WPC treatment area, close boundaries around WPC marks were drawn in whole patch as shown in figure 16. In this small patch approximately 135 WPC treatment marks were found.

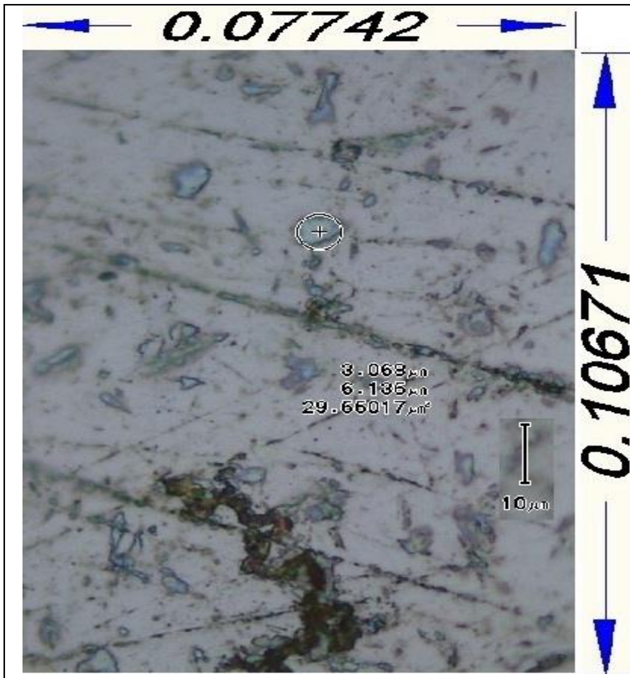


Figure 15: A small patch from magnified image of the WPC treated roller

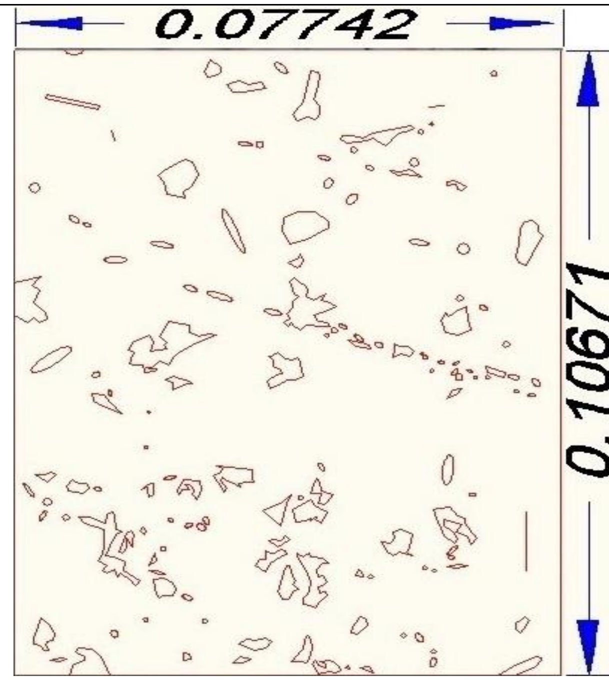


Figure 16: Boundaries drawn around WPC treatment marks in CAD software

In Solid Works software a 3D plate having surface area 0.0082615mm^2 equal to small patch was created as shown in figure 17. Using cut area command patches drawn in figure 16 were reduced from 3D solid plate shown in figure 17. Area of solid plate reduced to 0.0076622 mm^2 due to removal of WPC treatment marks as shown in figure 18.

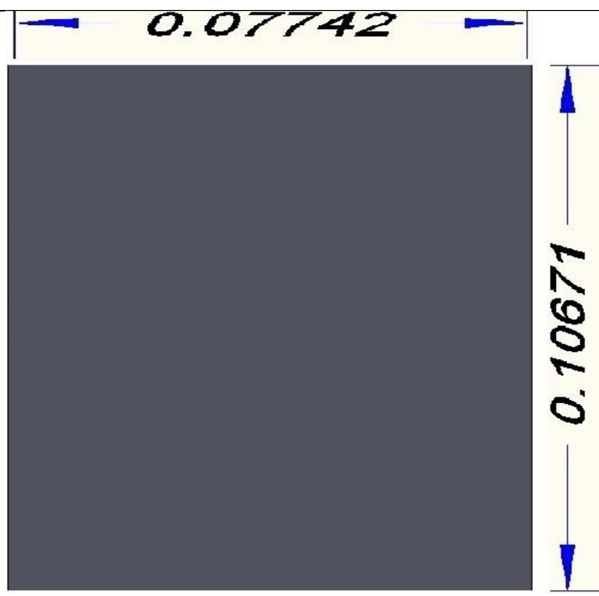


Figure 17: 3D plate having surface area 0.0082615 mm^2

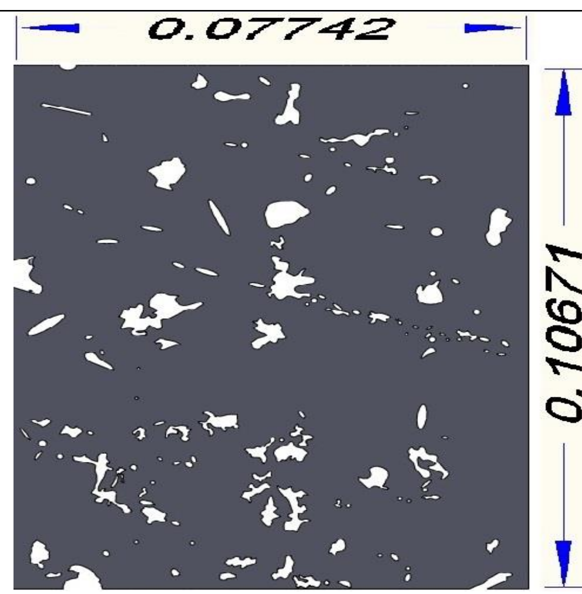


Figure 18: Area of WPC marks removed from solid plate

From this exercise we can conclude that surface area density of WPC treatment marks is approximately 7.25%. From magnified image of WPC treated roller (figure 15, 16 and 18) we can observe that particles used for WPC treatment were of irregular shape.

Using CAD software we can determine the surface area of WPC treatment marks. In figure 19 surface areas of the largest and smallest WPC treatment marks are shown. Colour coding of the largest mark is green and smallest mark is magenta. Surface area of the largest WPC treatment mark (green patch) is 0.0000439 mm^2 and surface area of smallest mark (magenta colour) which is hardly visible is 0.0000001 mm2. Ratio of area between largest and smallest mark is 439.

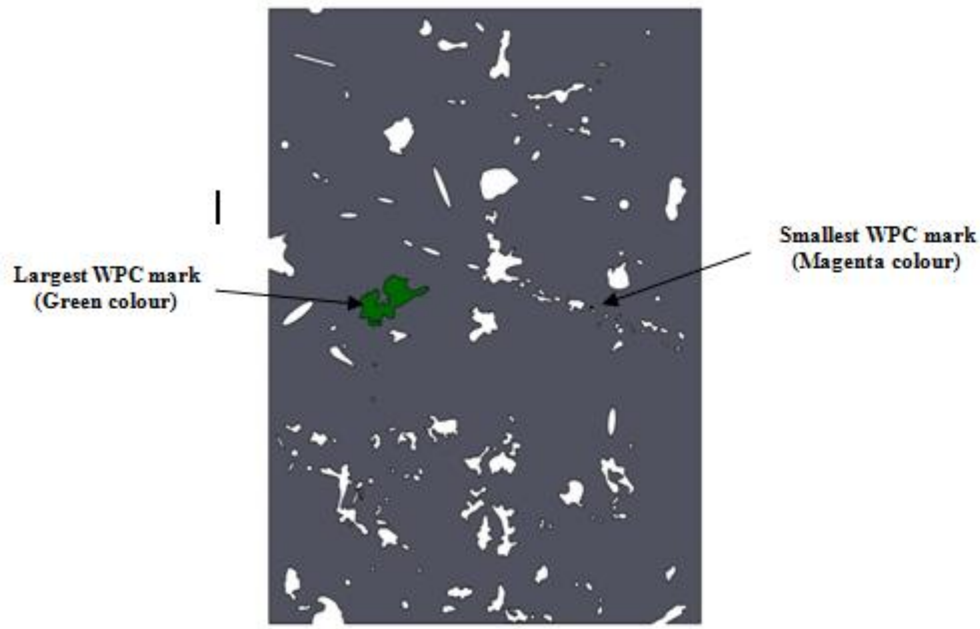


Figure 19: WPC marks, largest shown in green and smallest in magenta colour

CHAPTER 3: EXPERIMENTAL SETUP

Experimental setup for measuring slip at camshaft-roller contact of the end pivoted finger follower valve train consist of engine valve train test rig, instrumentation of the roller and data acquisition system.

In this research, technique used for measuring slip at the camshaft-roller contact is similar, previously used by Khurram [8]. Keeping in view complex arrangement and limitation of space in the finger follower assembly a little giant magneto resistive (GMR) sensor, ADL chip and a small Alnico magnet was used. This roller rotation measurement technique is capable of working in the company of lubrication oil, at elevated temperatures and under high impact acceleration. In this method alteration to the component under study is very less as compared to previous [35, 36 and 20] roller rotation measurement methods.

3.1 ENGINE VALVE TRAIN TEST RIG

In this research, an actual Toyota Prius 1NZK engine head is used in the valve train test rig in order to conduct experiments in actual environment. Engine valve train test rig was developed to assess valve train components. Image of the engine valve train test rig is shown in figure 20 below.

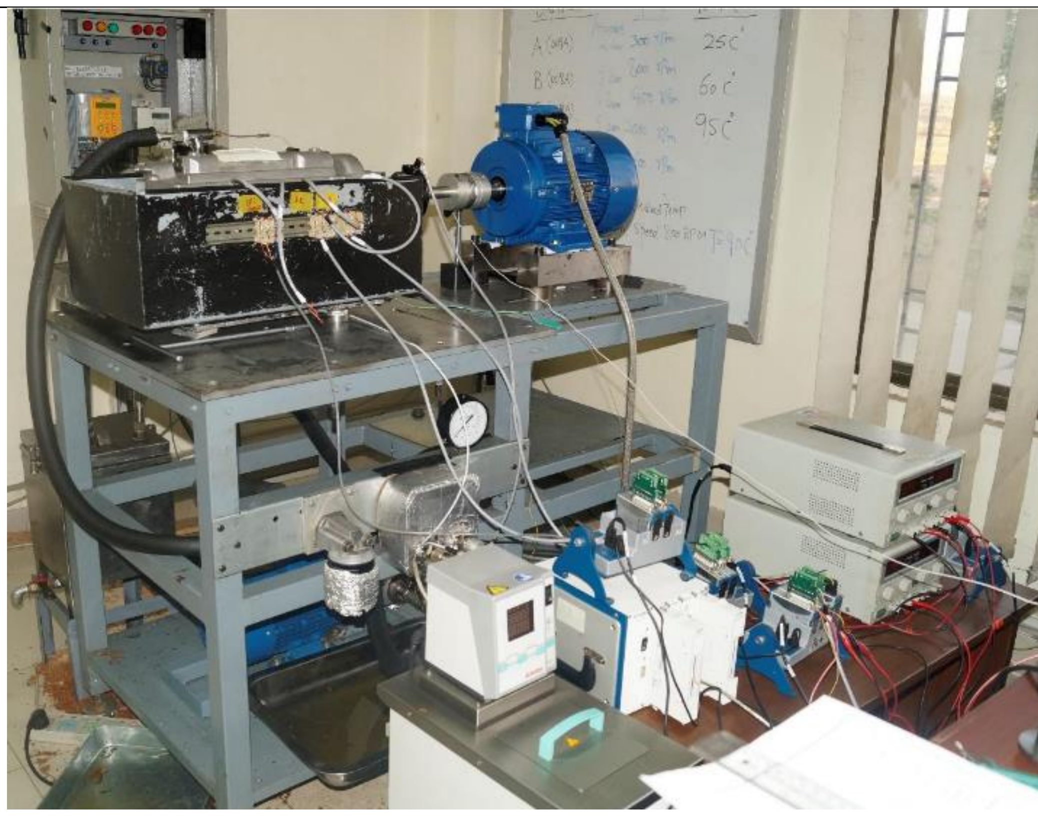


Figure 20: Flexible engine valve train test rig

In engine valve train test rig, Toyota 1NZK engine head is bolted inside oil sump. Camshaft is driven by an electrical motor coupled with a bellow coupling. Camshaft can attain the speed range of 150 to 3000 RPM and speed controller can alter its speed. In engine valve train test rig there is an oil heating arrangement in order to do testing of engine head parts in actual condition. Oil pump is driven by another induction motor which can circulate lubricant oil in engine head. In order to maintain the even oil supply pressure to the engine head during testing a proportional integral derivative (PID) controller was used. In valve train test rig oil supply pressure is monitored by a pressure transducer. In order to reduce heat loss all oil carrying pipes were insulated. Oil temperature is monitored by a thermocouple at oil inlet point of the engine head.

Engine valve train test rig consist of following major part/assemblies.

3.1.1 Engine head

In this test rig Toyota Prius 1NZK or Mercedes Benz engine head can be bolted in the oil sump. These engine heads are driven by variable speed induction motor with the help of bellow coupling. In this research work, Toyota Prius 1NZK engine head was used. Roller used in finger follower assembly number 6 was unmodified whereas roller used in finger follower assembly number 7 was modified (WPC treated), in order to find difference in percentage slip values at camshaft-roller contact between unmodified and modified rollers. Top view of the Toyota Prius 1NZK engine head is shown in the figure 21 below.

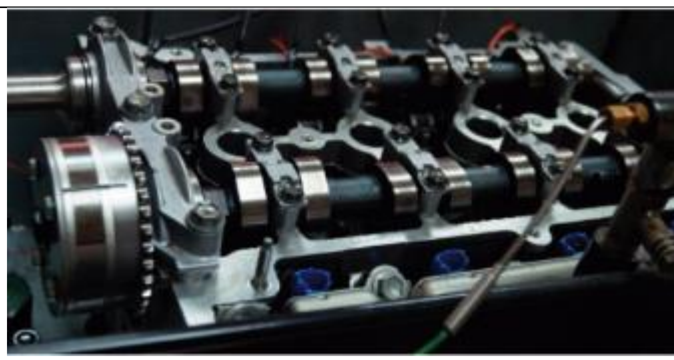


Figure 21: Top view of the Toyota 1NZK engine head

In the engine head cover there is an oil spray channel which provides sufficient lubricant oil to camshaft-roller contact. Toyota Prius engine head has two camshafts, four cylinders and 16 end pivoted roller finger followers having hydraulic lash adjusters. Toyota Prius 1NZK engine head is quite compact because both intake and exhaust valves are at 33.5^{o} angle to each other. In the engine, a timing chain is used to drive both camshafts (intake and exhaust). Every cylinder has two separate valves for intake and exhaust. Intake and exhaust valve are directly operated with two camshafts shown in figure 22.

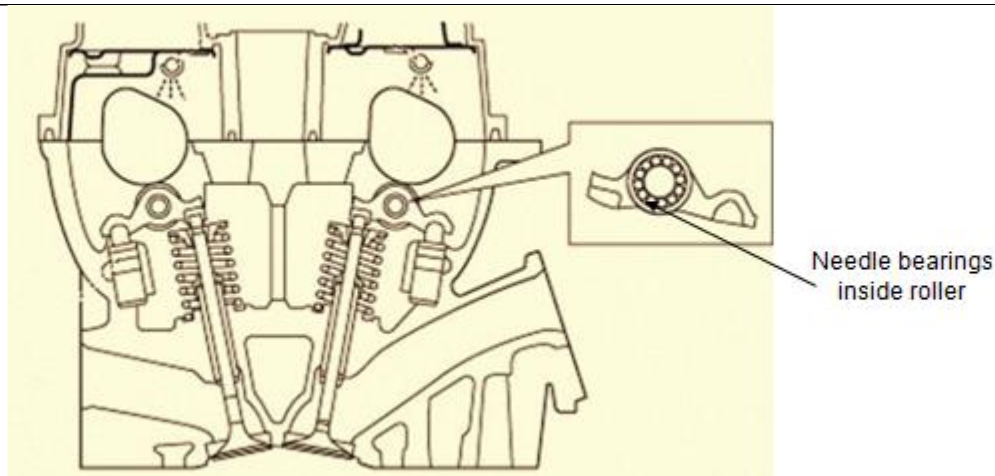


Figure 22: Schematic Of Toyota Prius 1NZK Engine Valve Train [37]

3.1.2 Lubricating oil used

In this testing, group IV base oil was used for lubrication purpose. Base oils Group IV are poly alpha olefins (PAOs). These synthetic base oils are made with a process called synthesizing. They have a much broader temperature range and are good for use in extreme cold conditions and high heat applications [38].

3.1.3 Induction Motor

Induction motor is used to rotate camshaft. Induction motor is connected to a controller and a data acquisition system (DAQ). Controller is used for manual speed change. Computer is connected to DAQ which is used for speed variation. Induction motor is connected to camshaft via bellow coupling. It can rotate camshaft at different speeds (RPMs).Variable speed induction motor used in engine valve train test rig is shown in figure 23.

Table 1:Specifications of the induction motor for driving camshaft

Rated Output	5.5 kW
Revolutions per minutes (RPM)	3000
Weight	42 kg
Number of poles	4
Torque	36 Nm

Figure 23: Below coupling attached with variable speed induction motor

3.1.4 Bellow Coupling

The bellows used in couplings are manufactured from stainless steel which makes them perfect for transmission of torque. Because of bellow thin walls coupling bend easily and remain rigid while transmitting high torsional loads. Bellow couplings easily accommodate different axial motions, angular and parallel misalignments. Bellow couplings can transmit zero backlash free torque [39]. In engine test rig bellow coupling is used to join output shaft of induction motor with camshaft. Below coupling attached with variable speed induction motor is shown in figure 23.

3.1.5 Oil Sump

Oil sump is fabricated from sheet metal. Engine head is bolted in it. It is assembled on engine test rig stand. Lubricant oil coming from engine head falls in oil sump and flows by gravity to the external sump. Figure 24 shows Toyota 1NZK engine head bolted inside oil sump.

Figure 24: Toyota 1NZK Engine head bolted inside oil sump

3.1.6 Oil Pump Driven By Induction Motor

Oil pump is used to pump lubricating oil to the engine head at required pressure. Variable speed induction motor is used to run oil pump. Star coupling is used to connect the oil pump and induction motor as shown in figure 25. Pressure of lubricating oil can be varied by varying speed of induction motor with the help of controller. A pressure gauge is used to check the pressure of oil entering the engine head. Specifications of the variable speed induction motor used for driving oil pump are given in table 2.

Table 2: Specifications of the induction motor for oil pump

Rated Output	1.5 kW
Revolutions per minutes (RPM)	1395
Weight	15 kg
Number of poles	4
Torque	10.3 Nm

Figure 25: Oil pump attached to induction motor by star coupling

3.1.7 Refrigerator / Heat Circulator

In order to replicate the original engine working condition, lubricating oil is required to be heated to working temperature. For this purpose refrigeration heat circulation unit (shown in figure 26) is used to achieve different temperatures of lubricating oil. Lubricating oil is heated indirectly. Primarily refrigerator & heat circulator is used to heat the heating oil and then heat is transferred to lubricating oil with the help of heat exchanger. Specifications of the refrigeration/heat circulation unit used in engine valve train test are given in table 3 [40].

Table 3: Specifications of the refrigeration/heat circulation unit

Manufacturer	JULABO
Model	F25-ME
Temperature range	-28°C to 200°C
Temperature stability	± 0.01°C
Temperature control	PID, cascade
Dimensions (WxDxH)	(230x420x610) mm
Weight	31 kg
Refrigerant	R134a

Figure 26: Refrigerator/Heat circulator

3.1.8 Inline Plate Heat Exchanger

Inline plate heat exchanger is used to transfer heat from heating oil to the lubricating oil. It comprises of various stainless steel heat transfer plates, two covers and four connections. Specifications of the Inline plate heat exchanger used in engine valve train test rig are given in table 4.

Table 4: Specifications of the Inline plate heat exchanger

Maximum working pressure	6 bar
Maximum working temperature	185°C
Dimensions (WxDxH)	(171x159x106) mm
Volume per side	0.54 liter
Weight	3.3 kg

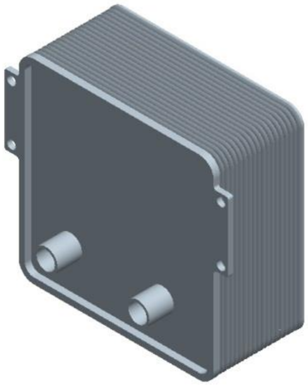


Figure 27: Inline plate heat exchanger

3.1.9 Pressure Transducer

In engine valve train test rig pressure transducer is used to check pressure of lubricant oil entering in engine head. It changes pressure into voltage and transport data to computer using DAQ system. Steady oil inlet pressure is maintained by using pressure transducer as feedback signal for the oil pump.

3.1.10 Analog Pressure gauge

It is used to monitor the pressure of the lubricant oil entering into the engine head.

3.1.11 External Oil Sump

External oil sump is fundamentally an insulated double walled container that is capable of maintaining temperature of the lubricant oil. Lubricant oil is pumped from external oil sump into the engine head after it achieves the required temperature by passing it from in-line plate heat exchanger. External oil sump used in engine valve train test rig is shown in figure 28.

Figure 28: External oil sump

3.1.12 Anti Vibration Table Mount

These are used for precise installation of printing presses, machine tools and other industrial machines. Anti-vibration table mounts are installed on every leg of engine valve train test rig for absorbing vibration and reducing noise level. They are galvanized steel with oil resistant rubber base. Their height can be adjusted with fine pitch screw. Anti vibration table mount used in valve train test rig is shown in figure 29.

Figure 29: Anti-vibration table mount

3.2 INSTRUMENTATION OF ROLLER FOLLOWER ASSEMBLY

Instrumentation of the roller follower assembly was very important and a difficult task. GMR chip falls in class of magnetometer, which can detect the existence of the applied magnetic field across the elements inside the chip. For this purpose GMR magnetometer chip and a target Alnico was used as shown in figure 30.

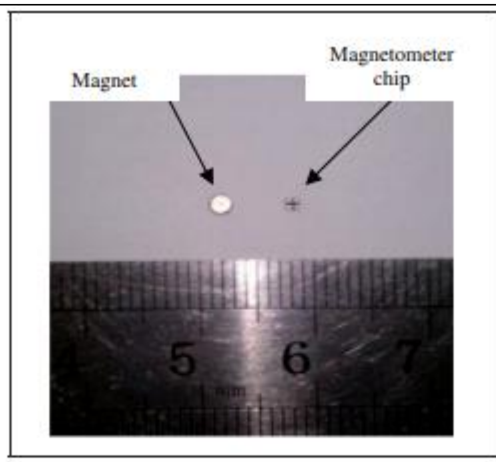


Figure 30: Magnetometer chip and target Alnico magnet [8]

A specifically designed printed circuit board (PCB) of 3mm diameter was manufactured and GMR ADL chip was mounted on it as shown in figure 31. Special slim, bendable Teflon wires were used for connecting sensor with external terminal connection. These wires possess special ability to work at elevated temperatures without any rupture. Computerized numerical control (CNC) machine was used for drilling exact 3.5 mm diameter hole in roller housing side wall so that roller race is in line with drilled hole in order to mount sensor in housing. Now a magnet was required to be fitted in roller race for activating the GMR sensor. For this purpose Alnico magnet having 2mm diameter and 0.5 mm thickness was used as target for sensor. This Alnico magnet has required size and has ability to sustain its magnetic flux at high temperatures. Computerized numerical control (CNC) machine was used to manufacture a hole with 0.6 mm thick and 2 mm diameter in the side of roller race for placing magnet in the roller. For appropriate seating of magnet in hole of roller race a slim layer of epoxy was used. Fine emery paper was used to make sure that hole with magnet is properly flushed with surrounding surface. Now the sensor was mounted in the drilled hole of roller housing.

Sensor is mounted in such a way that sensor can sense magnet mounted in roller race and can produce output signal. Orientation of the sensor in the roller housing is very important for generation of proper output signal. Moreover to avoid disturbance in output signal, proper clearance between sensor and target magnet should be maintained. Slim epoxy layer was used for mounting senor in roller housing. Teflon wires coming from sensor were kept loose for easy movement. Loose plastic sleeve was used to cover Teflon wires coming outside from engine head. Due to ultra small size of sensor it is very difficult to handle. With continuous efforts expertise were developed to prepare and mount sensor with proper orientation for measuring rotation of the roller.

Figure 31:(a) ADL magnetometer chip mounted on PCB (b) Hole in roller housing for sensor mounting (c) Alnico magnet inserted in the roller race (d) Instrumented roller follower assembly

3.2.1 Giant Magneto Resistive Sensor (GMR)

Low hysteresis digital switch (ADL) series sensors are Giant Magneto resistive (GMR) digital Switches (figure 32) designed to operate at very low currents and at low voltages. These sensors are being manufactured with NVE's patented spintronic GMR technology for matchless sensitivity, tininess, low power and precision [41]. Its ICs comprise of CMOS signal processing circuit for converting output of analog sensor element to digital output, GMR sensor element and optional oscillator & timing circuit for power management duty cycling. Inside duty cycle versions save power. GMR sensor has two dissimilar duty cycle frequencies, giving a trade off between power consumption and update frequency. It has integrated latch for ensuring output availability constantly. Constant operating versions have 250 kHz frequency response. ADL Series digital Switches are perfect for battery-operated devices such as water and gas meters, moveable instruments and for any application where very low power consuming devices are requisite. The block circuit diagram of the GMR sensor is shown in figure 33.

Figure 32: ADL series GMR sensors

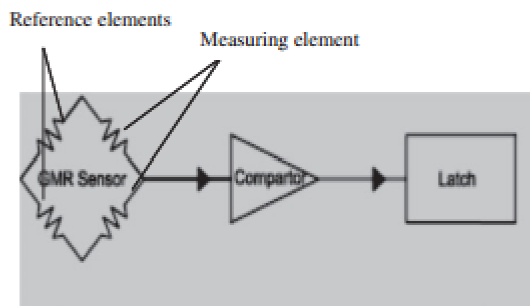


Figure 33: Block diagram of GMR sensor

Its duty cycled versions use less than a micro watt and continuous operating versions use less than a mill watt. It has current sinking output that can sink up to 100 micro amps. It has capability to detect low intensity magnetic fields accurately. These GMR sensors are configured as magnetic switches, in presence of magnetic field its output turns on and in absence of the magnetic field its output turns off. Its magnetic operating point is exceptionally stable over temperature and supply voltage. The magnetic field of either polarity can be applied.

Operation

Magnetic field sensitivity direction is planar to package. When intensity of the magnetic field varies, digital output of the GMR sensor will turn on and off. At the output terminal user must provide a pull up resistor. The figure 34 shows two permanent magnet orientations that will turn on the sensor in the direction of its sensitivity that is planar to the package.

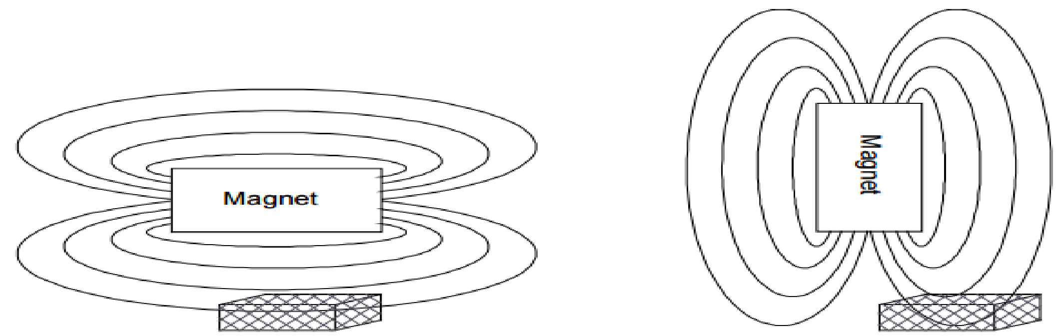


Figure 34: Permanent magnet orientations for activating sensor

Table 5: Key Specifications of the ADL series digital switches

Size	1.1 mm x 1.1 mm x 0.45 mm
Low Voltage Operation	2.4 V
Typical Power Consumption	72 Nano Watt at 2.4 V

For measuring rotational speed of the roller driven by the camshaft, ADL series chip number GMR ADL 9 21-14E was used. Interpretation of its part number ADL 9 21-14E is given in the table 6 below.

Table 6: Interpretation of digital switch part number ADL 9 21-14E

ADL	Low hysteresis digital switch
9	Duty Cycling Continuous
21	Typ. Magnetic Operate Point 20 Oe
14E	1.1 mm x 1.1 mm RoHS ULLGA

3.3 DATA ACQUISITION SYSTEM

In this research, data acquisition system (DAQ) based on National Instruments (NI) hardware and LabVIEW software was used for measuring rotational speed of roller. Camshaft speed, lubricating oil temperature and pressure was monitored constantly during the testing. Data acquisition system (DAQ) based on NI cDAQ-9174, core i3 computer, with a digital module and an analog output module was used for measuring rotation speed of the roller. Counter channel in NI cDAQ-9174 was programmed for measuring roller rotational speed by counting number of magnetic fields applied to the sensor. The digital module NI-9401 was used to connect the sensor output signal with the counter in order to measure the required time of the roller for completing one revolution. This time was then converted to find revolutions per minute (RPM). During testing the sensor was powered by an analog module NI-9263. Measuring and power supply modules were used on the one chassis NI cDAQ-9174 for reduction of electrical noise.

3.3.1 Platform NI cDAQ-9174

NI cDAQ-9174 is a moveable, rough data acquisition platform that integrates connectivity and signal conditioning into modular input/output for directly interfacing with a sensor/signal [42]. By using NIcDAQ-9174 with LabVIEW, we can effortlessly modify how to manage, obtain, present, analyze, and manage our measured data. For research, development and validation, National Instruments provide very high accuracy measurements, programming software, and technical support to ensure so that customers meet their correct measurement and application requirements.

NI cDAQ-9174 is a four slot USB chassis. It can support both analog and digital input/output modules. Its analog input FIFO size is 127 samples per slot. It has four counters/timers. Its resolution is 32 bit. Its counter can measure pulse, edge counting, period, semi period, pulse width and two edge separation. It has output frequency of 0-20 MHz. Its output application types are pulse train with dynamic updates, pulse, equivalent time sampling and frequency division. It has bus interface of Hi-speed USB-2.0. Maximum 15w input power is required by NIcDAQ-9174. It does not support sleep mode. Its temperature operating range is -20 °C to 55 °C. Its weight is approximately 574 grams. Its size is 159.5 mm x 88.1 mm x 58.9 mm. Top view schematic of NIcDAQ-9174 is shown in figure 35 below.

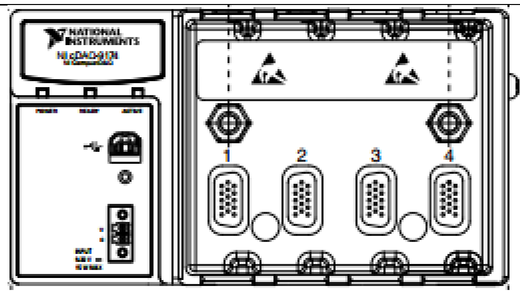


Figure 35: Top view schematic of NIcDAQ-9174

3.3.2 Digital Module NI-9401

Digital module NI-9401 has 8 channels and every channel is well-matched with 5 Volts Transistor-Transistor Logic (TTL) signals and provides 1,000 Vrms transient isolation in between the input/output channels and backplane. For National instrument compact DAQ it has 100 ns bidirectional digital input module [43].

Digital line direction of NI-9401 for input/output can be configured by nibble (4 bits). There are following three configurations for which NI-9401 can be programmed.

a) Eight digital inputs.
b) Eight digital outputs.
c) Four digital inputs and four digital outputs.

NI-9401 can be programmed by using Lab view Professional for high-speed counters, high-speed timers, implementing custom, pulse generation, digital communication and many more. Picture of digital module NI-9401 is shown in figure 36 below.

Figure 36: Digital module NI-9401

National Instruments C Series modules are manufactured to give very high accuracy measurements to cope with demands of control applications and advanced DAQ. Each C Series module can connect to an array of signals and sensors combine and channel to channel separate options for measurement specific signal conditioning. In one rugged package it can meet different applications, environmental requirements and different temperature ranges. Most of C Series input/output modules can work with the NI Compact DAQs.

3.3.3 Analog module NI-9263

NI-9263 is high performance analog output modules for NI Compact DAQ and gives precise signal generation. It has built in signal conditioning and connector can be integrated with screw terminal for low cost and flexible signal wiring. Analog module NI-9263 has 4 channels and it provides (sample rate) simultaneous analog output of 100 kS/s per channel [44]. It has ±10 V output range. It has 16 bit resolution. It has ±30 V overvoltage and short circuit protection. It has a channel to earthen ground double isolation barrier for noise immunity and safety. It gives connectivity by screw terminal. NI-9263 is compatible with Lab View. It consumes chassis power of 625 mW maximum in active mode and 25 µW maximum in sleep mode. Its operating temperature range is -40 °C to 70 °C. Picture of analog module NI-9263 is shown in figure 37 below.

Figure 37: Analog module NI-9263

CHAPTER 4:EXPERIMENTAL METHOD

4.1 ENGINE VALVE TRAIN TEST RIG FLUSHING PROCEDURE

1. Remove the old oil.
2. Wait for complete draining of oil.
3. Change the oil filter.
4. The oil used for testing will be first used as flushing oil.
5. Put the required flushing oil (3.5~4) Litre in the sump.
6. Heat the oil to 90° C.
7. Run the test rig at 800 RPM for 15 minutes.
8. Drain and discard the flushing oil.
9. Bring the engine back to room temperature using air conditioner.
10. Repeat flushing procedure before every new oil change.

4.2 ENGINE VALVE TRAIN TEST RIG TEST RUNNING PROCEDURE

1. At room temperature, put fresh 3.5 litre testing oil in the oil sump.
2. Start oil pump at pressure of 02 bars.
3. Start heating unit and set required testing temperature.
4. Soaking times for different temperatures are as follow.
    - At 25°C half hour running of oil pump.
    - At 60°C two hours running of oil pump.
    - At 95°C two hours running of oil pump.
5. After soaking at required temperature, run induction motor at different speeds 300, 800, 1400, 2000 and 2600 RPMs & record roller speed from the software.
6. Testing time for 300, 800, 1400 RPMs will be 15 minutes, for 2000RPM will be 10 minutes and for 2600 RPM will be 5 minutes respectively.
7. First start testing at 25°C and perform all 300, 800, 1400, 2000 and 2600 RPMs tests.
8. Similarly than perform 60°C tests and then 95°C tests.

4.3 CALIBRATION OF THE ROLLER FOLLOWER ASSEMBLY

WPC treated roller assembly #7 was instrumented. It was calibrated outside the engine before assembling with engine head. A special Teflon material ring having 51 mm outer diameter was manufactured. Internal diameter of the Teflon ring was maintained such that it was push fitted on the shaft of induction motor. A simple fixture was used to hold the roller follower assembly in such a way that roller was touching the Teflon ring. It was also ensured that there was no slippage between interacting surfaces. Roller and Teflon ring diameters are 17 and 51 mm respectively so there speed ratio is 1:3. If Teflon ring will rotate one revolution then roller will rotate three revolutions under no slip condition. During calibration test runs speed of motor was maintained from 500 RPM to 2500 RPM with increments of 500 RPM. During calibration a tachometer was used for counter checking speed of the induction motor. Calibration results are shown in table7 as follow.

Table 7: Calibration results of roller follower assembly				
Motor Speed		Tachometer Speed (RPM)	Glitch*	Roller Speed (RPM)
(RPM)	Percentage (%)			
500	16.67	499	4000	1494.52
1000	33.33	996.7	6000	2984.23
1500	50	1496	6000	4476.84
2000	66.67	1995	8000	5967.08
2500	83.33	2488	8000	7468.31

* A glitch is a short-lived fault in a system. It is often used to describe a transient fault that corrects itself, and is therefore difficult to troubleshoot.

Graphical representation of the calibration data is as follow.

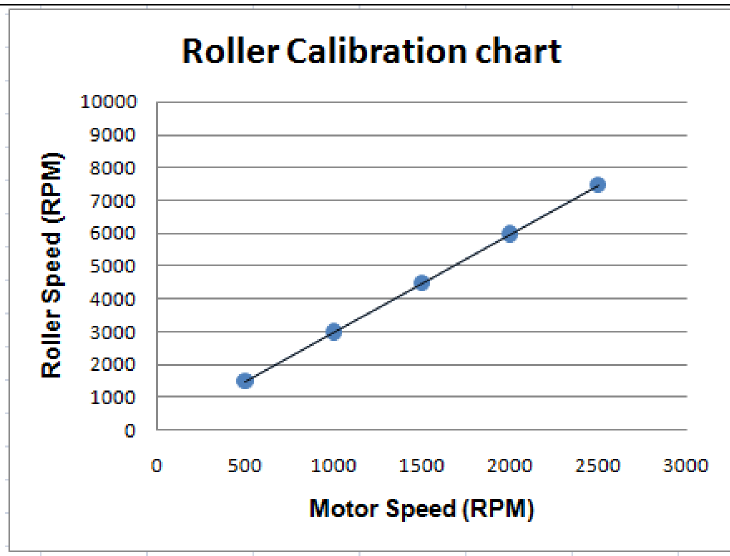


Figure 38: Calibration chart of the roller

4.4 DATA MONITORING AND RECORDING

A special virtual instrument (VI) using LabVIEW was designed for measuring speed of roller revolving during engine operation. This VI was used for monitoring and recording of required data. Front and block diagram of VI are shown in figure 39 & 40 respectively.

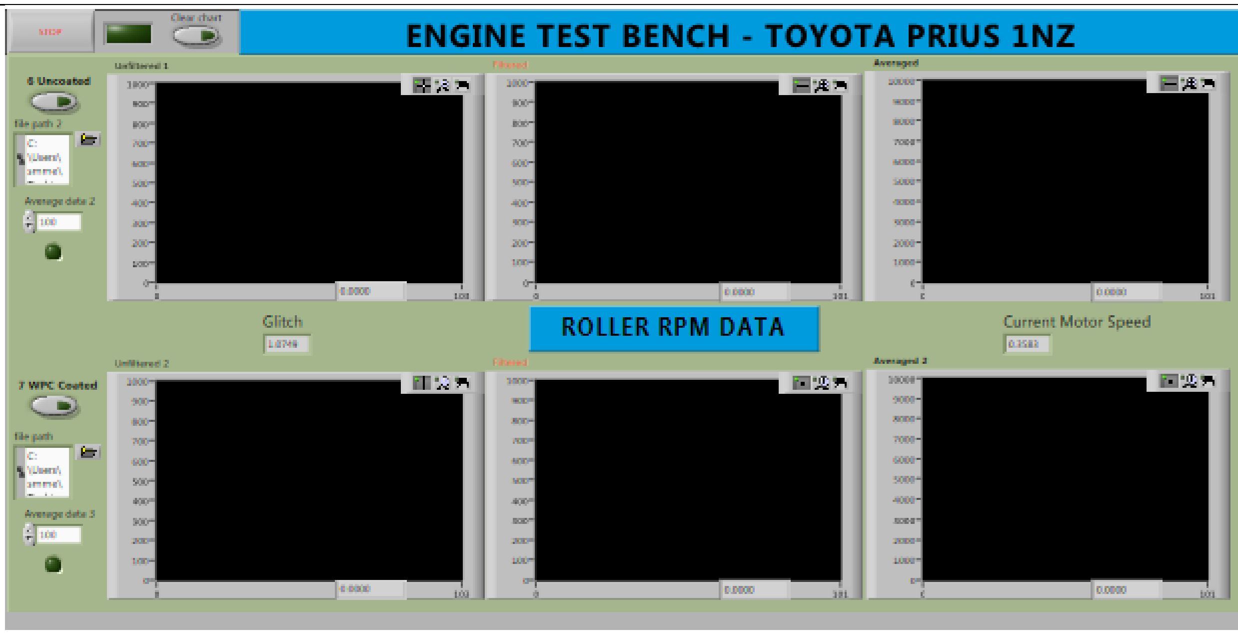
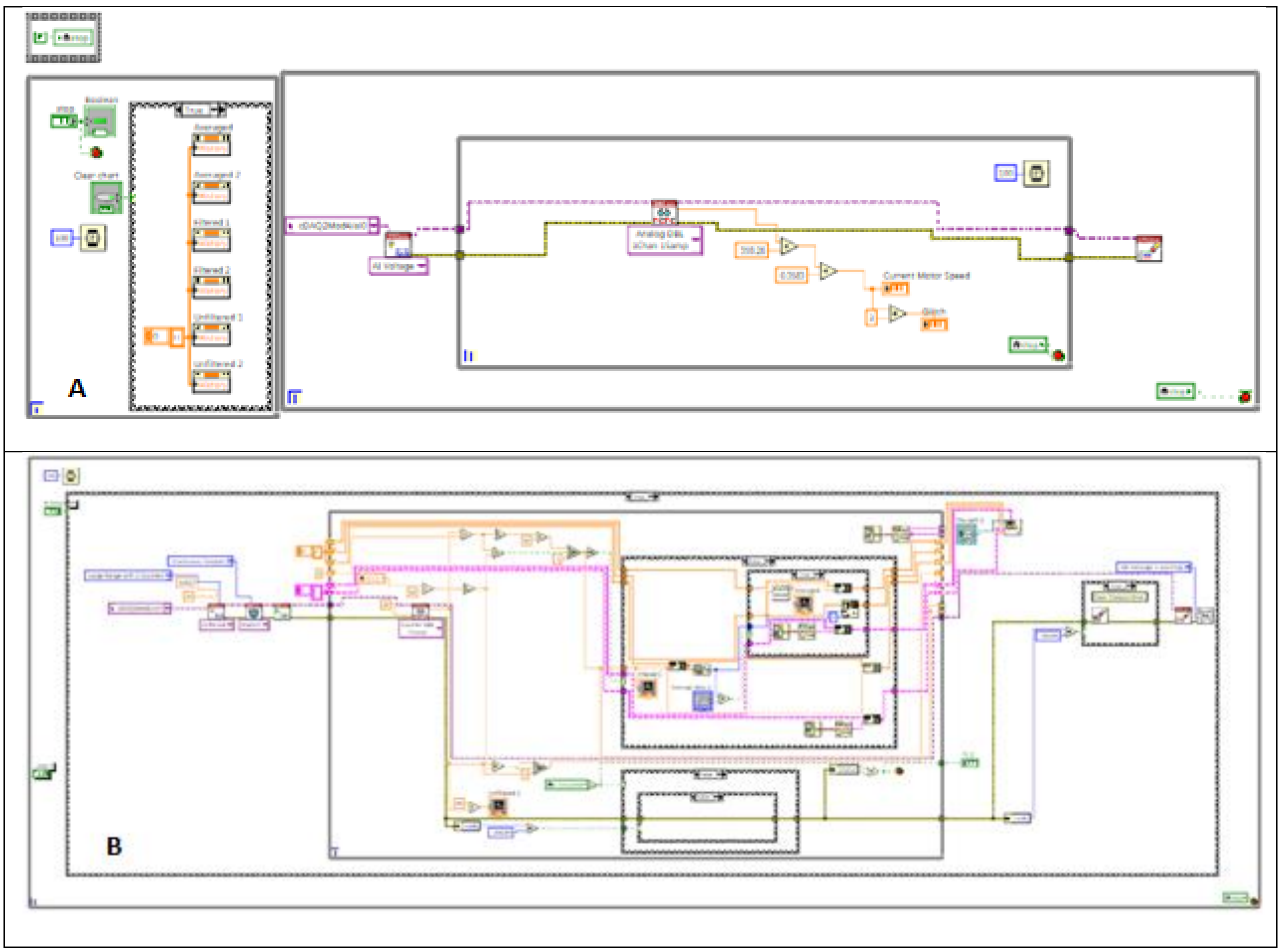


Figure 39: Front Diagram of Program (VI) for Measuring Roller Speed (RPM)



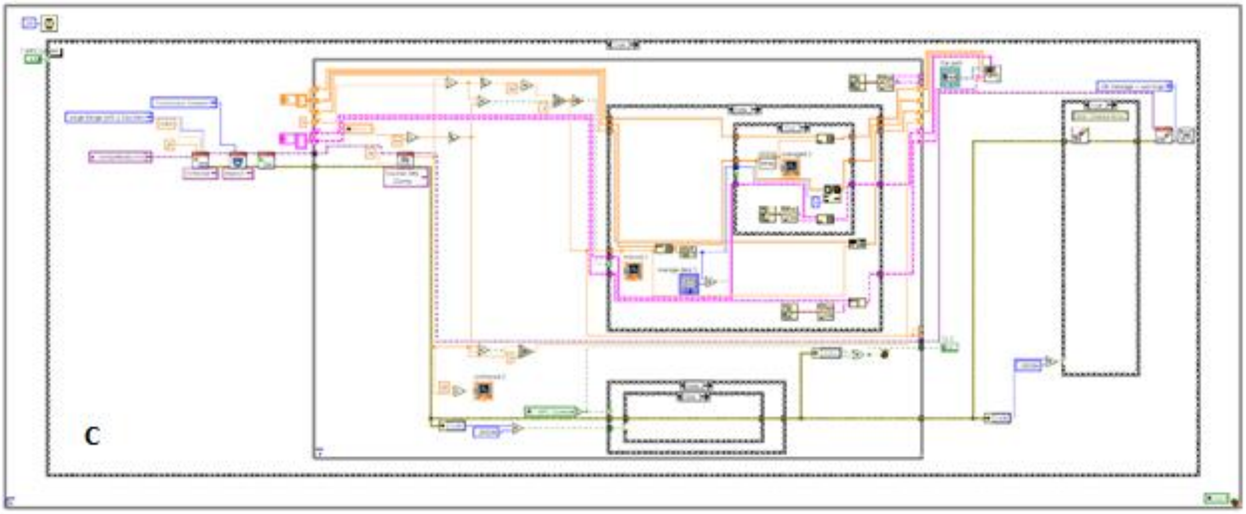


Figure 40: (A, B & C) Block Diagrams of Program (VI) for Measuring Roller Speed (RPM)

CHAPTER 5: RESULTS AND DISCUSSION

The camshaft roller interface is truly a very complex mechanism and is challenging to understand its tribological behavior. In roller finger follower valve train, traction force at camshaft roller contact is very essential to keep the roller rolling on the camshaft surface. In camshaft roller contact, cam surface is driving the roller for rotation. Due to continuous change in cam diameter at the contact, the traction force driving the roller changes at every instant. Therefore roller rotational speed is not constant. During testing this phenomena was also verified, when roller speed was obtained from data acquisition system. Average speed of roller was calculated at each camshaft speed. The roller rotational speeds actual & average for five different camshaft speeds and at lubricating oil temperatures of 25˚C, 60˚C, and 95˚C are shown below in figures 41, 42, and 43, respectively.

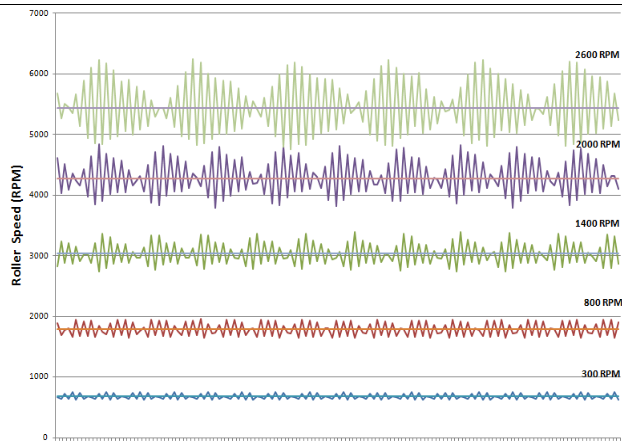


Figure 41: Roller rotational speed actual & average at lubricating oil temperature of 25°C

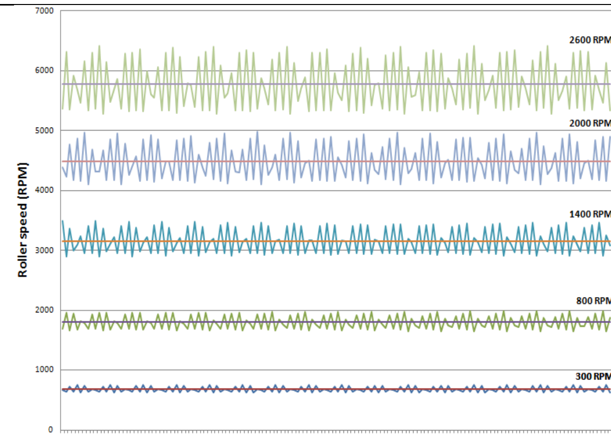


Figure 42: Roller rotational speed actual & average at lubricating oil temperature of 60°C

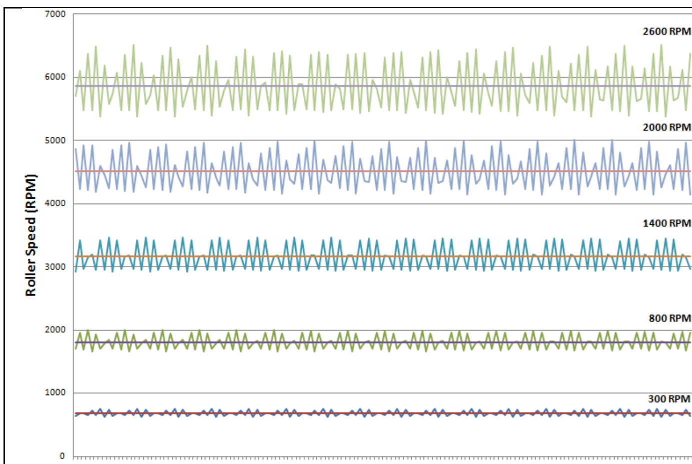


Figure 43: Roller rotational speed actual & average at lubricating oil temperature of 95°C

Actual roller rotational speeds are in waviness form (candies) and are plotted against roller average speed at five different camshaft speeds as shown in figure 41-43. It is obvious from all testing results that the roller rotational speed increases with increase in camshaft speed. At small camshaft speeds of 300 & 800 RPM, there is hardly any variation in roller speeds with the change in lubricating oil temperature as shown in figures 41–43. As the camshaft speeds are comparatively small, thin oil film may be present at the camshaft roller contact due to less camshaft splash resulting in boundary to mixed lubrication. In this situation, metal to metal contact (asperity interactions) will support the traction force and would be enough to keep the roller rolling at the camshaft surface without any noticeable slippage. However, at higher camshaft speeds of 1400, 2000 and 2600 RPM, particularly at low lubricating oil temperature of 25˚C, comparatively thick lubricating oil film will be present at camshaft roller contact due to higher camshaft splash & oil viscosity. The existing traction force would not get the contribution of asperity interactions and will not be able to keep the roller rolling on the camshaft surface leading to more slippage. At higher lubricating oil temperatures of 60˚C and 95˚C viscosity of oil is reduced resulting in higher asperity interaction. Hence traction force at camshaft roller contact is improved resulting in high roller speeds and less slippage. The roller rotational speeds are approximately same at lubricating oil temperatures of 60˚C and 95˚C.

Percentages slip between roller and camshaft contact of Toyota 1NZK engine finger follower valve train was computed. One roller has obtained Fuji Manufacturing's Wonder Process Craft (WPC) surface treatment while other was unmodified. Both rollers were tested at same operating conditions. Tests were performed at three different temperatures 25°C, 60°C, & 95°C of lubricating oil and at five different camshaft speeds 300, 800, 1400, 2000 & 2600 RPM. At lubricating oil temperature of 25°C considerable slip was observed, whereas at higher temperatures of 60°C & 95°C smaller or negative slip values were witnessed. Average roller speed values were used for percentage slip calculation.

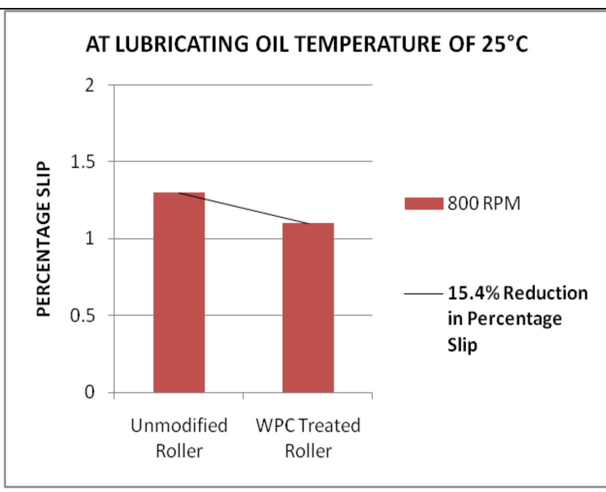


Figure 44: Slip at camshaft-roller contact & percentage reduction due to WPC treatment at 25°C & 800 RPM.

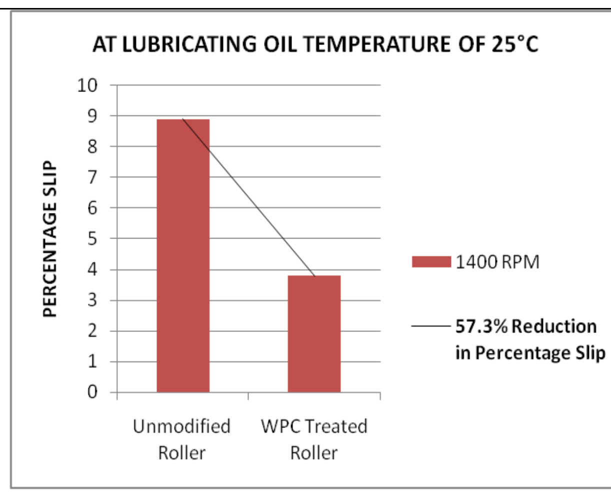


Figure 45: Slip at camshaft-roller contact & percentage reduction due to WPC treatment at 25°C & 1400 RPM.

At lubricating oil temperature of 25°C percentage slip values for WPC treated roller were small as compare to unmodified roller. At camshaft speed of 300 RPM & at oil temperature of 25°C no slip was observed at camshaft–roller contact for both rollers. As camshaft speed increased to 800 RPM percentage slip values at camshaft-roller interface were 1.1 & 1.3 for WPC surface treated roller and unmodified roller respectively.

At camshaft speed of 800 RPM reduction in percentage slip due to WPC surface treatment is 15.38 % shown in graphical form in figure 44. At camshaft speed of 300 RPM & 800 RPM, zero & small values of percentage slip were observed due to less lubrication (small camshaft splash) & asperities interaction. At lubricating oil temperature of 25°C oil viscosity is high and but due to small camshaft operating speed results in boundary & mixed lubrication resulting in less slippage at camshaft-roller contact.

At camshaft speed of 1400 RPM, considerable rise in percentage slip values 3.8 & 8.9 were observed for WPC surface treated & unmodified rollers respectively as shown in figure 45. At high camshaft speed of 1400 RPM, lubrication between camshaft-roller contact increased due to more camshaft splash. Due to more lubrication and high viscosity at low temperature of 25°C less traction force because of asperity interaction at camshaft roller contact results in rise of slippage. At camshaft speed of 1400 RPM & lubricating oil temperature of 25°C, reduction in percentage slip at camshaft-roller contact due to WPC surface treatment is 57.3%.

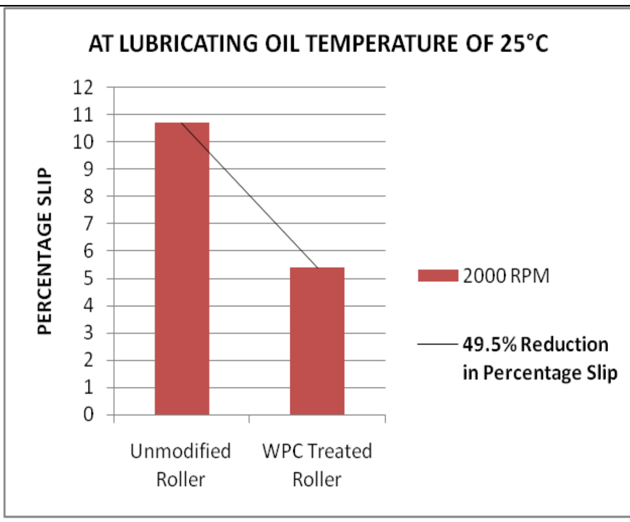


Figure 46: Slip at camshaft-roller contact & percentage reduction due to WPC treatment at 25°C & 2000 RPM

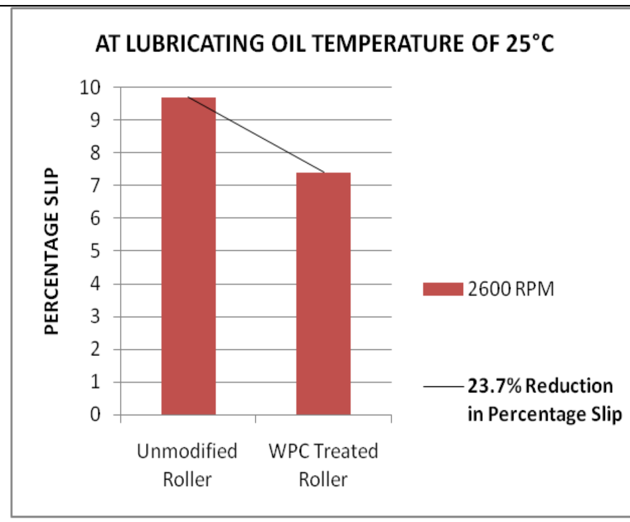


Figure 47: Slip at camshaft-roller contact & percentage reduction due to WPC treatment at 25°C & 2600 RPM

As camshaft speed increased to 2000 RPM percentage slip values of 5.4 & 10.7 were observed for WPC treated & unmodified roller respectively shown in figure 46. Percentage slip value of 10.7 for unmodified roller is also maximum slip observed during testing. At low oil temperature of 25°C and such high camshaft speed less asperity interaction occur at camshaft roller contact due to thicker oil film. Inertia of roller also play important role to increase slip at such high camshaft speed also pointed out by Khurram [8] in his previous research. At lubricating oil temperature of 25°C and camshaft speed of 2000 RPM, reduction in percentage slip at camshaft-roller contact due to WPC surface treatment is 49.53%.

At camshaft speed of 2600 RPM, percentage slip values of 7.4 & 9.7 were observed for WPC treated & unmodified roller respectively shown in figure 47. Percentage slip of unmodified roller reduced from 10.7 at 2000 RPM to 9.7 at 2600 RPM. This is probably due to increase in shear drag that results in decrease in percentage slip as discussed by Khurram [8] in his previous research. Whereas a different behaviour was observed from WPC treated roller where percentage slip increased from 5.4 at 2000 RPM to 7.4 at 2600 RPM. In unmodified roller due to shear of oil film at high camshaft speed lubrication regime change from elastohydrodynamic to mixed lubrication. Due to increase in asperity interaction between metal parts slip reduced at 2600 RPM in unmodified roller. In WPC treated roller percentage slip continue to rise with increase in speed because dimples retain lubricating oil so lubrication regime is not changed due to increase in drag due to shear. At camshaft speed of 2600 RPM & lubricating oil temperature of 25°C, reduction in percentage slip at camshaft-roller contact due to WPC treatment is 23.71%.

At lubricating oil temperature of 60°C, due to increase in temperature, the viscosity of oil is reduced and promotes boundary lubrication. Maximum slip values of 1.6 & 2 were observed for WPC treated & unmodified roller respectively at camshaft speed of 2600 RPM. At camshaft speed of 300 RPM, 800 RPM & 1400 RPM slip for unmodified roller was hardly noticeable as shown in figure 48. At 300 RPM zero slip for both rollers were observed. At camshaft speeds of 800 RPM & 1400 RPM slip values of 0.4 & 0.3 were observed for WPC treated roller, slightly higher than unmodified roller values, this is probably due to retention of lubricating oil by dimples due to the WPC surface treatment.

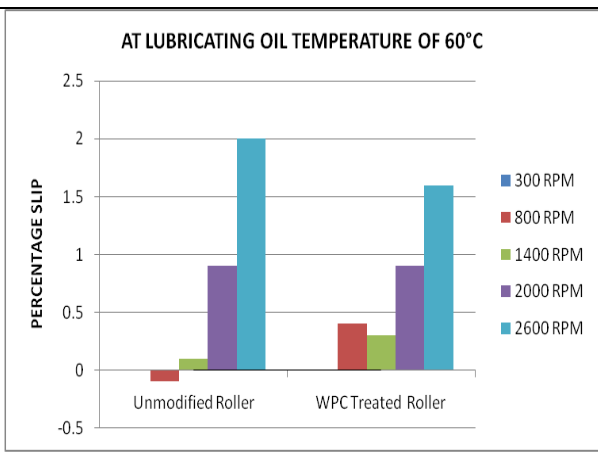


Figure 48: Slip comparison of unmodified & WPC treated rollers at camshaft-roller contact at 60°C & five different camshaft speeds

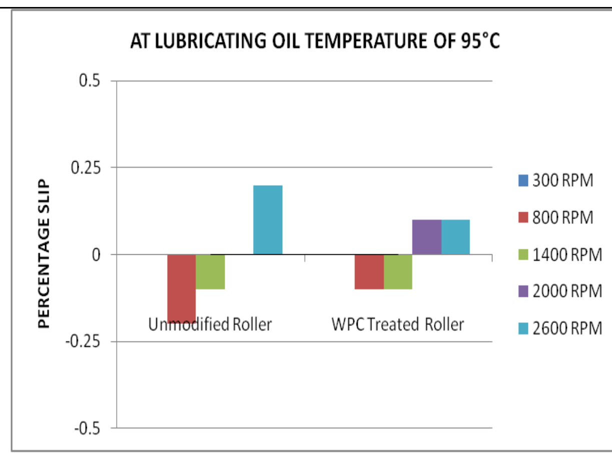


Figure 49: Slip comparison of unmodified & WPC treated rollers at camshaft-roller contact at 95°C & five different camshaft speeds

At lubricating oil temperature of 95°C, lubricating oil viscosity further reduced resulting in boundary lubrication. Slip at camshaft-roller contact was hardly noticeable and maximum slip value was 0.2 shown in figure 49. At this temperature no reasonable difference in percentage slip between WPC surface treated & unmodified roller was observed.

Percentage slip values at camshaft roller contact for roller no. 3 (unmodified) and roller no. 7 (WPC surface treated) at five different camshaft speeds and three different lubricant oil temperatures are shown in table 8. Graphical representation of same percentage slip values are shown in figure 50 & 51.

Table 8: Percentage slip values of unmodified and modified rollers

S. No.	Cam Shaft Speed (RPM)	Roller RPM percentage error	Percentage Slip at 25°C		Percentage Slip at 60°C		Percentage Slip at 95°C	
			Unmodified (Roller 3)	WPC Treated (Roller 7)	Unmodified (Roller 3)	WPC Treated (Roller 7)	Unmodified (Roller 3)	WPC Treated (Roller 7)
1	300	1.4×10^{-5}	0.0	0.0	0.0	0.0	0.0	0.0
2	800	3.8×10^{-5}	1.3	1.1	-0.1	0.4	-0.2	-0.1
3	1400	6.6×10^{-5}	8.9	3.8	0.1	0.3	-0.1	-0.1
4	2000	9.4×10^{-5}	10.7	5.4	0.9	0.9	0.0	0.1
5	2600	1.2×10^{-4}	9.7	7.4	2	1.6	0.2	0.1

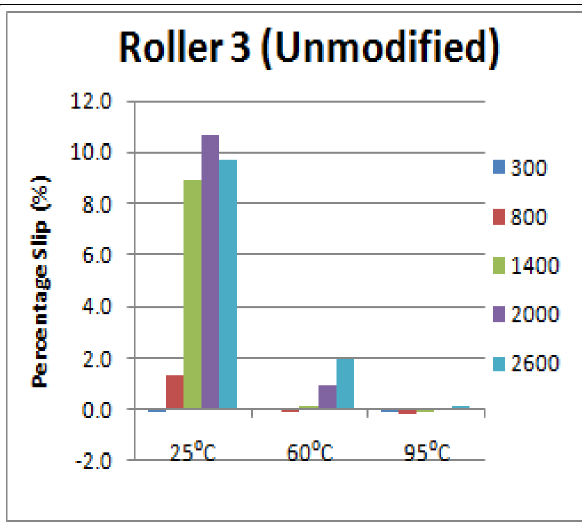


Figure 50: Slip at camshaft-roller contact of roller # 3 (unmodified) at five different camshaft speeds and three different lubricant oil temperatures

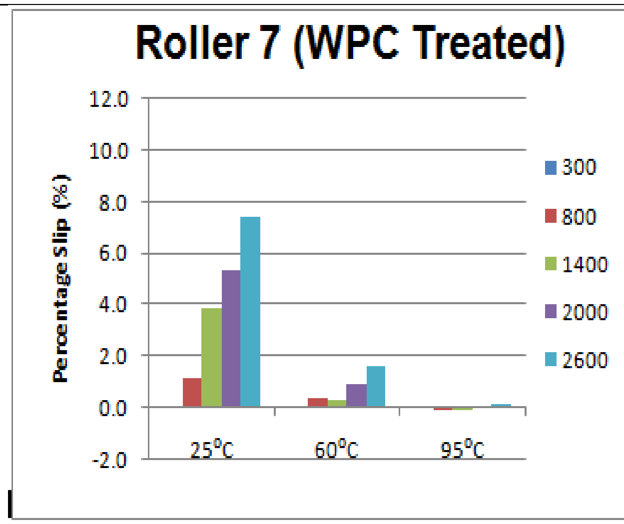


Figure 51: Slip at camshaft-roller contact of roller # 7 (WPC treated) at five different camshaft speeds and three different lubricant oil temperatures

Small negative slip values were also observed at elevated lubricating oil temperatures of 60°C & 95°C. At lubricating oil temperature of 60°C & camshaft speed of 800 RPM negative slip value -0.1 % was observed for unmodified roller, whereas no negative slip for WPC treated roller was recorded at this temperature.

At lubricating oil temperature of 95°C & camshaft speed of 800 RPM and 1400 RPM negative slip values of -0.2% & -0.1% were observed for both WPC treated & unmodified rollers. Negative slip phenomenon was also observed at high camshaft speed during previous research by Khurram [8]. Presence of negative slip was also pointed out by Duffy in 1993 [20] at 1600

RPM in his research. Negative slip between camshaft-roller contact can also be supported by roller inertia although mass of roller is small but when cam surface velocity reduces instantaneously, roller due to its inertia tends to retain its speed that can lead to negative slip.

CONCLUSION

In this research effect of WPC surface treatment in terms of slippage between roller-camshaft contact was studied. The experiments were performed on real production Toyota Prius engine head having end pivoted roller follower. Speed measuring system for the roller consist of a miniature GMR chip installed in roller housing and a target Alnico magnet was installed in the roller race. Tests were performed at different camshaft speed and different lubricant oil temperatures. Experimental results obtained from unmodified roller and WPC treated roller were compared and analysed.

At lubricating oil inlet temperature of 25°C, there was a considerable difference in percentage slip values for unmodified roller and WPC treated roller at different camshaft speeds. Due to WPC treatment reduction in percentage slip ranged from 15.4 % to 57.3% depending upon camshaft speed.

At lubricating oil inlet temperature of 60°C, percentage slip values for unmodified roller and WPC treated roller decrease during entire camshaft speed range. At this elevated inlet oil temperature, effect of WPC treatment on reduction of percentage slip was also minimum. At lubricating oil inlet temperature of 95°C, percentage slip values for unmodified roller and WPC treated roller were hardly noticeable during entire camshaft speed range.

Existence of negative slip was also confirmed at elevated lubricating oil inlet temperatures (60 and 95°C) indicating significance of the roller inertia at high camshaft speeds. This experimental system can be used for comprehensive tribological studies and for investigating the effect of other surface treatment techniques, different coatings and materials on the slip of rollers in roller follower valve trains engines.

FUTURE RECCOMMENDATIONS

- Future testing to be performed on varying engine speed (RPM).
- Future testing to be performed on varying / different drive cycles.
- For measuring single revolution of roller only one combination of sensor and magnet was used during current testing setup. To enhance measurement accuracy it is recommended that a combination of 4, 6 or 8 sensors and magnets to be used for measuring single revolution of roller during future testing.
- In current testing WPC treatment was performed on roller only whereas in future it is recommended that both roller and camshaft to be WPC surface treated for achieving further reduction in percentage slip at camshaft roller contact.
- Group IV Base oil (009A) was used in current testing as lubricating oil. Future testing to be performed using other lubricating oils in order to inquire the effects of changing lubricating oil on percentage slip.

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