CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter the recent trend in automobile sector regarding vehicle performance improvement, research works on both transmission and timing chains attempted by many scholars and other related research works on tribology are discussed.

2.2 RECENT TREND IN AUTOMOBILE SECTOR

In early part of the 20\textsuperscript{th} century in automotive field, most of the studies were concentrated on performance of engines and gear boxes. Recently, due to stringent pollution norms, many works are carried out in engines. Extensive study on alternate fuel for engines and fuel cells are being carried out to reduce the use of fossil fuels, which is fast depleting in the earth and causes global warming due to release CO, CO2 and other harmful gases along with thermal radiations. Crashworthiness, total vehicle weight reduction to cut down fuel consumption, aesthetic appearance of body are given due importance nowadays. In the area of materials, increased uses of composites, high strength steels and aluminium alloys are also the recent trend in automotive sectors, due to many advantages. New tribo-materials are being developed for automotive components to meet high temperature, high pressure and increased velocity conditions. Use of sensors and electronic gadgets to improve performance of vehicle and passenger safety aspects are given due importance in recent years.
Global competition has initiated aggressive industrial and economic progress. This trend demands higher productivity levels in automotive manufacturing sector. Since there is a demand to improve the performance and reliability of two wheelers, especially motorcycles, there is a need to improve its components’ performances also to increase the total reliability. Transmission chains used in two wheelers are single strand roller chains with mostly 12.7 mm and 15.875 mm pitches. Smaller pitch chains are suitable for high speed applications compared to larger pitches due to small variation in velocity, whereas larger pitch chains are suitable for transmitting high torques. Two wheeler manufactures use different design parameters to highlight their product features, with different engine power, torque and acceleration characteristics and the total number of chain links for each model are either same or different.

Chains are lubricated with grease and are totally enclosed in two wheelers, to avoid dirt and dust particles accumulation, thereby reducing the wear rate. The main problem associated with transmission chain is elongation due to wear. Even though wear is inevitable, any reduction in wear will reduce the chain elongation and consequently reduce noise due to impact and vibrations. The following are the contributions in the literature on timing and transmission chains, tribological aspects of wear and lubricants by many scholars.

2.3 PERFORMANCE OF TIMING AND TRANSMISSION CHAINS

Although chain drives are used for a long time, most of the published research on it has been concentrated to the latter half of the 20th century. The impact between a chain roller and sprocket tooth may lead to such undesirable conditions as roller breakage, noise, heating, and wear of
sprocket teeth. Binder et al (1948) proposed an analytical method to investigate roller impact on sprockets that help to reduce the impact forces for the improvement in chain performance. Vibration on tight span of chain was studied both analytically and experimentally by Binder and Mize (1949) similar to string vibration.

Velocity of chains varies proportionally as PCD and speed of sprockets. But at a given speed and PCD, velocity of chain fluctuates as the sprocket rotates, due to polygon action. Morrison (1952) modeled a chain link system and was the first to discuss the polygonal action on chains. Later, many authors attempted to study on polygonal actions but no fruitful solution have been arrived to reduce it.

Static analysis of chains was presented first by Binder (1956). At later stages many researchers in their research work on roller chains, quoted the study made by the author and his contribution in the classical text book on “Mechanics of Roller chains”.

Mahalingam (1958) showed that dynamic loading of chain system is similar to forced vibrations, due to polygonal action of chains. The author also noted that beyond a certain critical speed, higher speeds produced lower dynamic loads. This reduces impact, but in practice it may not be possible to operate in this speed range due to speed variations in chain drives.

Turnbull and Fawcett (1975) made an approximate harmonic analysis of the acceleration of the sprockets using Fourier analysis. A dynamic chain model using a discrete dynamic method was developed by Fawcett and Nicol (1979.) They introduced boundary conditions for the link entering the span. They reported that the load was not the same on each tooth and varied with pressure angle and number of teeth.
Naji and Marshek (1983), made a study to determine the load distribution for an elastic roller chain on an elastic sprocket. The effect of friction and sprocket rotation on load distribution is discussed.

Load distributions on sprocket tooth and chain strands were studied by Eldiwany and Marshek (1984), with the help of a model and experimental analysis. The authors reported that the load distribution was not same on each tooth and varied with pressure angle and number of teeth. The authors also made a study on the effect of lubrication, misalignment, sprocket rotation at low speeds on load dynamics.

Naji and Marshek (1984) in their study made an analysis for determining the effect of pressure angle and the chain articulation angle while chain roller meshing with a sprocket tooth. They reported that the pressure angle and the chain articulation angle of the engaged rollers varied due to pitch difference between chain link and sprocket teeth.

An experimental study to measure the load distribution in steel roller chains on polymer sprockets and to determine the effect of material modulus of elasticity, tight-side load and slack-side load and pitch difference was reported by Eldiwany and Marshek (1989). They found that the roller chain load distribution was depending on elastic properties of chain and sprocket, the pitch difference between the sprocket tooth and chain link and the friction between roller and sprocket tooth surface. They also found that variations in pitch could cause a chain link load to be as high as 150% of the tight side load. Chains with beyond 3% elongation would have adverse effect on loads due to elongated pitch.

The effects of pitch difference, friction, and centrifugal forces on the load distribution of a roller chain, load distribution on chain links and
sprocket teeth based on the angle of rotation of the sprocket were studied by Naji and Marshek (1989). They reported that friction caused a higher tooth load on a driven sprocket than that of a drive sprocket. They also reported that due to wear of chain, the roller teeth of a sprocket were subjected to a higher load level and were more vulnerable to failure than the pin teeth. This phenomenon may be due to negligible change in pitch in a roller link which may not match with worn out sprocket teeth, whereas pin link adjusts itself to match worn out sprocket due to wear of pins.

Chain pitch with sprocket pitch mismatching due to improper manufacturing leads to jumping over teeth phenomenon. Also, after chain elongation over 3%, chain pitch increases and may not mesh properly with sprocket tooth causing the phenomenon of jumping over. Yixing et al (1990) in their study reported that jumping over teeth occurred more easily at the driven sprocket than at driving sprockets. Driven sprockets normally have more no. of teeth than drive sprocket and in any chain drive; chain wrapping will be more on larger sprocket. Obviously, due to cumulative effect of pitch variation due to wear or excessive loading chain jumping over teeth phenomenon takes place.

Conwell et al (1995) made an experimental study of link tension and found that the tension in a chain link had been increasing very rapidly as the link exit the driven sprocket. Impact force tends to increase as chain tension increases. The magnitude of the horizontal component of the impact force increases more rapidly than the magnitude of the vertical component as the chain speed increases, indicating that the angle of impact (as measured from a vertical line) increases as chain speed increases.

An integrated experimental and analytical modeling approach has been developed and used to examine general impact/noise characteristics of
automotive type timing chain drive systems by Liu et al (1995). The authors made a comparative type evaluation between various system parameters and/or operating conditions. More than chain noise, engine noise is more. Hence, any possible reduction of engine noise would be more beneficial.

Low (1995) in a technical note had presented selection of chain using computer. The author used algorithms, which were based on the existing equations for the mechanics of the drives, including the geometry and the power transmission capabilities. The models used by the author for calculation are mostly from equations from ASA hand book.

A new chain testing machine, which is different from classical four-square test machine, to load the chain drive up to three horsepower over a wide range of chain speeds was devised by Conwell et al (1996). It had features with adjustable center distance between sprockets, and with an adjustable angle of approach for engagement of the chain with an instrumented sprocket. Instrumentation provides continuous recording and monitoring of chain performance and would be helpful to understand chain dynamics practically.

Liu et al (1997) made a study of roller meshing dynamics, which integrates the local meshing phenomena with the global chain sprocket system dynamic behavior. They found experimentally and analytically that the meshing sound pressure level was closely related to the chain speed and its vibrational characteristics. At lower speeds, sound pressure level and its frequency will be less due to lower impact.

In bicycles, based on kinematics, using non circular sprockets for both drive and driven sprockets, chain behaviour were studied by Freudenstein and Chen (1991). Earlier research works reported using non
circular sprockets either for drive or for driven sprockets. But non circular sprockets are not used in practice due to large velocity variations in addition to polygonal action.

The chain drive system for a bicycle differs from the industrial standard types not only in its size but in its operation. A high degree of lateral flexibility is required in bicycle chain for it to operate with non coplanar sprockets having an effective misalignment of 3 deg or more. Kidd et al (1999) in their study presented the results of an investigation evaluating the forces present in a statically loaded bicycle for a range of sprocket sizes and angles of misalignment. Results indicated that localized bending arising between chain and sprocket could increase or decrease the strain on the side plates by a substantial fraction of the direct strain due to chain tension. In general misalignment in motorcycle may cause adverse effect due to high chain speed like non uniform loads on plates which may lead to failure by fatigue.

Troedsson and Vedmer (2001) made a study of chain drive at moderate and high speeds to evaluate the forces acting on chain drive. They used 15.875 mm pitch chain for their study and found that inertia forces at higher speeds could not be neglected. They suggested using tensioners to reduce transverse oscillations, which increased tension on tight and slack span reducing torque transmission. That is why tensioners are not used in final drive of motorcycles.

Spicer et al (2001) investigated bicycle chains drive both theoretically and experimentally. They found that the efficiency of chain drive depend on the sprocket size and chain tension load. Large sprockets provide more efficiency and reported that higher chain tension load leads to higher efficiency.
Due to increasing engine speed and vehicle speed, chains are subjected to high speeds, which cause high dynamic load. In order to understand the behaviour of chain under high speed, Troedsson and Vedmar (2001) established dynamic model since static models used in earlier works did not provide sufficient results at high speeds. In their results, they reported that the tension forces in the tight span were more affected by the variation coming from dynamic effects, than the slack span.

An acoustical model relating dynamic response of rollers and its induced sound pressure was developed by Zheng et al (2001). The authors made a study with Finite element techniques and numerical software to model and simulate the acceleration response of each chain roller for noise level prediction of a chain drive under varying operating conditions. They found that predictions were in reasonable agreement with the experiments.

Pan and Shiel (2002) conducted experiments to reduce silent chain noise in cab-motorcycles. They have focused on noise source, transmission path and response and reported that a pipe frame with plastic body cover dramatically changed the characteristics of response mechanism.

Lodge and Burgess (2002), in their work made an improved chain link tension model for roller chain drive. The authors reported that the model allows the tension of a link to be evaluated more quickly and for a wider range of tight and slack span tensions than before. They have also proposed a new model to find transmission efficiency of a chain and validated with experimental work.

In motorcycles, an effective method of reducing a drive chain noise is still not developed. Sugita et al (2002) made a study on motorcycle chain noise and reported that mechanism of chain noise could be classified
into two: low frequency noise originated from chordal action according to the degree of chain engagement and high frequency noise generated by impact when a chain roller hits sprocket bottom. Using urethane resin damper and urethane resin roller, the noise emanated from chain was found to be reduced. However, such an effort will be useful only if the engine noise could be effectively muffled.

Timing chain noise problem is being studied by many researchers to identify and suppress high frequency whine noise at 1000Hz even though engine runs at 50Hz. Sopouch et al (2003) in their work modeled timing chain system and attempted to evaluate theoretically by considering mass visco-elastic contact characteristics of each link or tooth separately.

Alessandrini and Orecchini(2003) in their paper highlighted the need for dedicated and specific driving cycles for key areas such as big towns (high population density, high vehicle density, high ‘in area’ use of vehicles) and made a survey in Rome and provided the results giving average speed, stopping cycles and other relevant parameters. Most of the vehicles are undergoing this status in a busy city environment.

Young and Marshek (2003) designed and developed a new roller chain sprocket tooth form for engine camshaft drives in an effort to reduce the noise levels during meshing. They conducted experiment to compare the noise levels of the asymmetrical sprocket tooth profile to that of a standard ISO sprocket tooth profile and reported that the random-asymmetric tooth profile was found to reduce the meshing frequency noise levels compared to the symmetrical ISO tooth form. Asymmetric tooth profile may have two different pitches that take care of proper seating of pin link and roller links which are having a different pitch due to assembly constraints.
A simulation method that enabled the timing chain load and the valve train driving torque to be predicted, while taking account of the fluctuation of the crankshaft rotational speed, was established by Takaghishi et al (2004).

Two different ways of modeling the contact between the rollers and sprockets were presented by Pedersen (2005), one using a circular shaped tooth profile and the other using the shape of a real tooth profile. The model with a real tooth profile proved superior to the model with a circular tooth profile. Circular tooth profile with cylindrical roller surface can cause compatibility related problems.

Calvo et al (2006) made an experimental study of timing chain vibration and found timing chain vibration was higher and suggested to test engine at manufacturing end for acoustic quality for continuous monitoring and improvement. Not only timing chain noise study is important but also study of engine noise in total is required to suppress to minimum possible level.

The chain acceptance criteria during manufacturing stage have been mostly based on the dimensional; breaking strength, fatigue strength and metallurgical properties of components. Using the concept of reliability, the acceptance criteria based on wear of chains for an inspection time of 150hrs, has been proposed by Xu et al (2006). The authors in this paper based on reliability study, proposed acceptance criteria based on consumers as well as producer’s risk.

Joyce et al (2006) devised a photoelastic stress analysis technique used to determine the contact stresses in an automotive chain drive tensioner. In their work, a replica tensioner was made from epoxy resin and tested in a
variety of configurations. The test results showed that the measured impact stresses were found to be several times higher than those which would have been calculated from a static analysis. This is obviously due to dynamic loading effect.

Konyha et al (2007) have demonstrated that by using multiple linked views of timing chain, simulation data simplifies and accelerates the analysis. The authors used the segmented curve view features (global/local binning, color mapping and brushing), which proved to be extremely useful.

A dynamical analysis of hydraulic chain tensioners combining experiments and simulation has been presented by Wang (2008). Simulation has been done based on CFD- a highly efficient formulation, which allowed to use it in fast timing drive simulations. Comparison between simulation results and experimental results has been made.

Avramidis (2008) has developed a system to measure loads on a timing chain. The system consists of a special sprocket transducer and associated telemetry equipment. The conventional camshaft sprocket has been replaced by the special sprocket transducer, which senses the torque and transmits it by means of telemetry to recording equipment. With this system, it is made possible to investigate the parameters that affect timing chain life and resulted in an improved timing chain design.

2.4 WEAR STUDY

The present work mainly deals with investigation of wear, which causes elongation of chain. From the literature survey on transmission chain, it is found that not much research work has been carried out especially using analytical technique on wear and related aspect of chain elongation, due to
many variables. Also, no attempt has been made to relate chain life with pin, bush hardness, finish, dimensional tolerance and assembly characteristics and other parameters. In order to investigate wear of chain, in depth knowledge on wear studies of related mechanical engineering applications are essential. In this context, the literature study on wear applications is made, which are discussed hereunder.

Brockley (1961), in his study of oscillating bearing reported that minimum wear occurred for equal hardness of pin and bush, but the increase of wear for greater hardness difference was small. Dissimilarity of material pairing is recommended design practice. For high load-capacity applications it was suggested that a moderate hardness difference was acceptable from wear considerations and that such a condition gave protection against seizure. Smooth lapped finishes were less wear-resistant than ground finishes possibly due to higher order frictional heating and causing material damage. Variation in the maximum velocity of sliding demonstrated that low velocity increased wear probably due to ploughing and stick slip forces and that as velocity was increased, wear diminished to a constant value.

Wear study reported by Bayer (1968) shows that the engineering models for zero wear and measurable wear can be combined to provide an analytical means of predicting the initial wear behavior in a sliding system. This combination should be a valuable aid in the wear analysis of sliding mechanisms, since it provides a means of analytically relating wear to the normal design parameters.

Rabinowicz and Stowers (1972) constructed a nomogram using Archard’s wear principle to find wear volume, wear volume per unit sliding distance and specific wear rate. Drozdov (1976), in his study attempted to find a calculation of the life of mechanisms such as gears, hinges and shaft bushes
operating under unlubricated or solid film lubricated conditions in air and in vacuum. The author reported that the method of calculating the life of standard mechanisms provided a comparative estimate of the wear resistance of materials used under different operating conditions and in various mechanisms.

Phenomenon of wear is more complex than what has been understood. Wear depends not only on intrinsic properties of materials but also on extrinsic properties. Wear measurements do not yield same result and there is a scatter, even if the experiments are conducted under identical conditions and are conducted repeatedly by same person as reported by Rabinowicz (1980). The same phenomenon was reported in another wear study using same material and similar experimental conditions by Walbridge and Dowson (1987) and they have reported that different studies on wear showed wider scatter. Obviously wear is stochastic phenomenon influenced by multi various parameters.

The wear process of pure aluminum was studied by Ohmae and Tsukizoe (1980) using a finite element elastic-plastic analytical computer program. The authors indicated that the present FEM analysis did not give a satisfactory explanation of all the complexities of wear mechanisms and reported for further work on both dislocation interactions and crack propagation.

The influence of an external d.c. magnetic field on the diffusive wear of two rubbing bodies represented by idealized asperities was investigated by Muju and Ghosh (1980). The magnetic field affects the fracture characteristics at the asperity junction giving different wear rates owing to the presence of the magnetic field. Numerical calculations and experimental observations for mild steel rubbing against brass support the
predictions that the application of an external magnetic field enhances diffusive wear at an asperity junction. It may be surprising to note diffusion wear between brass and steel and that magnetic field influencing a non magnetic material. But the phenomenon reported by the authors may be due to eddy current development in brass similar to wattmeter wherein aluminum is used.

The study of wear mechanisms was carried by Berthier and Play (1982). The authors reported that surface examination of dry oscillating bearings revealed three different contact zones and wear was not solely a material property but was also dependent on the mechanical environment (geometry, kinematics, loads etc.).

Karamis and Odabas (1991) in their work reported that there exist a relation between hardness and carbon content in medium carbon steels as done in earlier works. They found that by increasing carbon content wear resistance increased. Of course upto certain percentage beyond which brittleness may imparted.

A reliability-based approach was presented for the design of three-speed automotive transmission systems by Rao and Tjandra (1995). The reliability-based design results were compared with those obtained by a deterministic design procedure. The effects of variation of design parameters, such as the reliability of the system and coefficient of variation of the input speed were also studied.

Borruto and Taraschi (1995) in their work made a study on the influence of factors viz. hardness, roughness and surface degreasing on wear and made an attempt to set the optimal conditions for standardized tests.
Yang et al (1996) conducted wear tests for metallic sliding friction. The results obtained from the wedge–wear tests performed in this investigation indicate that ratcheting and low-cycle fatigue are working in combination to produce wear but that low-cycle fatigue plays a more prominent role than does ratcheting in the process.

So (1996) in his work pointed out that the use of a pin-on-disc configuration for investigating the wear mechanism or behaviour of solid materials differ from published data and some existing theories could not be applied to such a configuration directly. This is due to different arrangements of the rotating pin and the stationary pin under the same load and speed and bulk temperatures of the rubbing specimens increased with the duration of testing, which may eventually arrive at a steady state. Moreover, the friction coefficient increases with sliding speed when the applied load on the rubbing specimens is over certain levels. Under such conditions the contact pair will experience scoring rather than pure sliding. The author in this paper provides a more reasonable method for the calculation of temperatures and the real and apparent contact areas.

The effect of different plasma coating on improvement of wear and corrosion resistance on plain carbon steel was carried out by Wang et al (1997) and reported to have performance to be at par with stainless or alloy steels.

The deterministic model formulated by Archard is frequently used in adhesive wear studies. However, its parameters, such as material-hardness and wear-coefficient show a considerable variation around their nominal values; this variation necessitates a statistical framework for studying the wear law. Qureshi and Sheikh (1997) in their work made load as variables while the geometry and material of the friction couple were kept constant.
The generated data were analyzed using simple statistical methods. The randomness of wear and hardness were modeled by the Weibull distribution, whereas the wear coefficient was modeled by a lognormal distribution.

Contact modeling of two rough surfaces under normal approach and with relative motion is carried out to predict real area of contact and surface and subsurface stresses affecting friction and wear of an interface. A comprehensive review of modeling of multiple-asperity contacts in dry and wet conditions was presented by Bhushan (1998).

Tribology in general and automotive tribology in particular, is so complicated, that the community needs to use every tool available. Everson and Ohtani (1998) in their study indicated that use of various equipments viz. scanning force microscopy (SFM), nano hardness techniques, surface forces apparatus (SFA), computer modeling, vibrational spectroscopy, UHV-surface science techniques, and micro calorimetry for better understanding of wear phenomena. They are currently being used, in conjunction with more traditional techniques, to further both practical and fundamental knowledge of automotive tribological systems.

The rapid, world-wide spread of automobiles has necessitated the development of improved technologies for environmental protection, resource utilization and customer satisfaction. As the designs of automotive components have changed, emphasis has shifted to tribological approaches. New tribo-materials are needed for automotive components that must run at higher temperatures, higher pressure and increased velocity conditions. Enomoto and Yamamoto (1998) in their literature outlines current issues related to tribo-materials in passenger cars.
Lubrication is one of the important methods of preventing fretting damage owing to a remarkable reduction in the coefficient of friction. Zhou and Vincent (1999) in the review paper provided the known facts concerning the lubrication in fretting situations.

Suk et al (1999) made wear study and they reported a technique that involved photographically imaging the specimen under test as a function of wear cycles and subtracting the initial image for identification of wear sites and quantification of wear. From the differential images, the level of wear was determined by calculating the surface area of the worn region. They reported that this method allowed one to visualize and gain further understanding of the wear process by viewing the series of images as time-lapsed photography.

The problems associated with determining the ‘three-body’ rolling particle abrasion resistance of soft materials such as polymers and soft metals were studied by Trezona and Hutchings (1999). The ball-cratering micro-scale abrasion apparatus, initially developed for testing hard coatings, has been used to study the behaviour of soft materials: poly methyl methacrylate PMMA, pure aluminium of commercial grade, tool steel and, as a reference hard material, glass-bonded alumina have been used.. The wear volume produced by the micro-scale abrasion test was proportional to the normal load for soft materials at low loads. At higher loads, even with the use of pitted balls, the wear volume was reduced as the increased pressure on the wear contact discourages particle entrainment and led to ridged wear scars.

Tribological parameters are one of reasons for wear scatter, which are not considered in many works. As an attempt to reduce scatter Ravikiran (2000) proposed a new model for wear quantification and reported that the
model would reduce scatter since it has taken care of the variations in contact area.

Hardness is the mechanical property mostly used to characterize the wear resistance of materials. In abrasive wear, the ratio between abrasive hardness and worn material hardness—$HA/HM$—is used to establish the wear severity of a pair of materials in a wear system. Pintaude et al (2001), in their study reported that the effect of abrasive particle size on wear rates could be explained based on the variation of the $HA/HM$ micro hardness ratio values with applied testing loads. This is size effect on crushing loads.

Bettge and Starcevic (2001), in their study on wear of disc brakes noted that interference microscopy combined with additional software provided the quantitative description of wear surfaces accurately.

The transformation of frictional energy to heat is responsible for increase in the temperature of sliding bodies, especially at the spot-to-spot contacts, i.e. the real contact area. The temperature rise at the peaks of the contacting asperities can be of a high order of magnitude but of short duration due to the tiny area of contact. Kalin and Vižintin (2001) studied the effects of the tribological interface between silicon nitride and steel under dry and boundary lubricated fretting conditions. They found that there was a significant difference in flash temperature between low and high displacement amplitude fretting. Variation of thermal conductivity and coefficient of friction significantly affected the calculated flash temperatures.

Czichos (2001), in his review paper provides some examples of the basic interfacial facets of tribology – from bulk continuum to atomistic/discrete phenomena – in a macroscopic, microscopic, and nano-scale point of view. For tribo-testing it is important to characterize the
tribo-system under study by an appropriate choice of a systems envelope and to consider the hierarchy of interaction levels.

Guo and Luo (2002) made a study on fretting wear on polymers using experimental technique and reported that polyimide, High Density Polyethylene and Ultra High Molecular Weight Polyethylene demonstrated their good fretting wear resistance. Polysulfone not only caused wear on itself but also generated more severe damage on the steel ball than the metallic specimens. This may be due to corrosion due to sulphur.

There are several methods for measuring wear volume. For instance, the change in the weight of a specimen before and after a wear test can be measured by electronic balance; the change in displacement can be measured by a linear variable displacement transducer; or the difference in the sectional area from the measured surface profiles with a profilometer can be calculated. The accuracy level is limited due to inherent problems in all these methods. Cho et al (2002) proposed a new technique for estimating an unworn original surface profile, using a profilometer and digital filtering. The technique easily and rapidly estimated the unworn original profile with a high accuracy.

Akdogan (2002) presents results of an investigation to assess the performance of aluminium bronze coatings and molybdenum coatings both filled with PTFE and deposited on steel substrate in rolling line contact. The experimental results show that both types of coating studied have an outstanding wear and surface fatigue resistance. Under pure rolling conditions, the aluminium bronze coating was found to be more wear resistance than molybdenum coating. More than molybdenum, molybdenum sulphide MoS₂ would have been a better choice.
Siniawski (2003) made a study on coatings and investigated changes in the abrasiveness of a thin B4C coating sliding against a steel ball. The asperity angle of attack was examined as a function of sliding distance and it was observed that the number of sharp asperities (indicated by large asperity angles of attack) decreased as the number of cycles (sliding distance) increased.

Subramonian et al (2003), in their research work compared the life of the new Pb-IP coating done in vacuum and reported that the life was about 2.4 times larger than that of the conventional Pb-IP coating. It is seen that the coating with the thicker graded interlayer (of the new Pb-IP coating) has led to an extended endurance life without any change in the value of the coefficient of friction.

On macroscale many studies have been made on wear mechanisms and experimental studies have been carried out with well known theories. On nano scale, wear study has been done in recent years. D'Acunto (2004) proposed a model on abrasive and adhesive wear in low applied load condition in a nano scale.

DLC/WC/WS2 (WCS) nano composite coatings having low friction coefficient under various sliding conditions were experimentally investigated using a pin-on-disk test instrument by Wu et al (2005). Characterization results confirm that mixed components dominate the sliding behavior of these composite coatings. A simple lubricating layer of graphitic carbon or WS2 was not found on either the wear tracks or pin surfaces. Thus, the lubrication mechanisms involved in sliding are more complex than expected.
Schaake et al (2005) in his research work used the method of quantitative single-asperity wear-rate measurement on different grades of polyethylene, which has taken short span of time. They have reported that this measurement technique could potentially be used to screen a large number of materials for their wear sensitivity in a short time.

The effect of wear rate on contact frequency is found to have some influence apart from test parameters, namely sliding speed and contact load. At contact frequencies above 9 Hz, the dominant wear mechanism is oxidational wear, while at frequencies below 4 Hz the dominant wear mechanism is adhesive wear, transition from adhesive to oxidational wear is found from the type of debris generated as reported by Navas et al (2006).

Laukkanen et al (2006) made a study on the surface fracture mechanisms that are the origin to wear, by three-dimensional finite element method (FEM) on tribological contact of a diamond ball sliding with increasing load on a thin titanium nitride (TiN) coating on a steel substrate. They reported that during sliding of the spherical tip on the surface, the residual stresses in the coating were relaxed under the tip due to the plastic deformation of the substrate (compression and tensile relaxation). A layer of high residual tensile stresses produced by the sliding action with tensile stresses at the top of the surface and compressional below was suggested to have an effect on formation of flake-like wear debris.

Effects of ageing conditions at various temperatures, load, sliding speed, abrasive grit diameter on tribological response of 6351 aluminum alloy have been investigated by using artificial neural networks by Durmus et al (2006). The experimental results were trained in an ANNs program and the results were compared with experimental values. It was observed that the experimental results coincided with ANNs results.
Sevim et al (2006) made an experimental study and found that there exist a linear relationship between the abrasive wear resistance and hardness, depending on abrasive particle size. However, the relationships for the heat-treated steels showed positive intercepts on the ordinate depending on particle size. The authors also reported that prior to their study, effects of abrasive particle size on wear resistance have been studied extensively and reported that none of these studies was satisfactory in finding suitable relation between the abrasive particle size and wear rate. They also found that heat-treated steels have lower resistance to wear than non heat-treated steels of the same hardness. This may be due to coarsening of grain size due to annealing heat treatment whereas non heat treated steel may have fine grain size due to cold working.

Hattoria and Watanabe (2006) in their study made an attempt to estimate fretting fatigue strength and life based on wear process. Generally, mechanical wear is divided into 3 stages: wear- in, normal wear and rapid wear. It is important to judge, which wear mode of the machine can reduce failures. Abundant information on machine wear can be taken from lubricant, especially wear particles in it. Wear particles show the amount of wear and information of wear stage directly. If wear is high, more wear particles are formed and this information is acquired by collecting wear particles in oil. Jing and Ni (2006) designed wear particle detection sensor and tested the same in their wear study (similar to wear debris analysis by ferrography).

When two surfaces are brought into contact the maximum contact pressure, real area of contact and surface/subsurface stresses contribute to friction and wear, which are functions of surface roughness material properties and interfacial loading conditions. Maximum contact pressure and surface/subsurface stresses are highly dependent on stiffness and hardness of
the layers and the substrate layer thickness as reported by Cai and Bhusan (2007).

Austenitic stainless steel AISI 316L is used in several industrial applications, mainly due to its excellent corrosion resistance. But it is poor in wear performance. De Las Heras et al (2007) have found that a combination of DC-pulsed plasma nitriding and plasma assisted PVD coating, as a surface treatment, improved the material fatigue and wear resistance without affecting the corrosion.

He et al (2008) have made a study on frictional heat between the contacting surfaces. The analyses made are useful for designers, particularly those facing thermal management challenges in sliding contacts.

Pauschitz et al (2008) in their research work gave an outline of the current status and future trends of wear at elevated temperature of selected metallic materials. This study may be useful for stainless steel chain performance improvement at high temperatures.

2.5 LUBRICATION ASPECTS

From the literatures study on wear, it is understood that one of the main contributing factors is lubrication, method of applying lubricant, the type of lubricants and frequency of lubrication. Chain manufacturers provide general recommendation regarding lubrication for chains in their catalogues (RCN 2007, DID 2007). These methods are also given in many texts. There is very little research available regarding lubrication of chain. Hence, a detailed knowledge is required to understand the phenomenon of lubrication in engineering applications especially for automotives. In this context literature study on lubrication is made, which are discussed below.
Davies et al (1983) have made a study of wear performance of roller chain for camshaft drives, with particular reference to engine condition and its effect on lubricating qualities of automotive oils. They developed chromised pin chain giving exceptional extra life, combating the effect of lube oil contamination.

Surface finish influence wear to a greater extent and the method of checking surface finish also matters. Whitney and Schwab (1986), in their study noted that Nodular iron crankshafts required greater care in finishing than forged steel crankshafts. They recommended Scanning electron micrographs and optical cross section photomicrographs, and additional parameters measured by tracing equipment, for surface evaluation. They reported that greater care is required for finishing of crankshaft surfaces to acceptable level.

Lubrication plays an important role in chain wear and depends on number of factors like viscosity, EP additives, method of lubrication and the frequency of lubrication. Peeken and Coenen (1986) in their work reported that the wear life of a roller chain could be extended considerably by optimal lubrication conditions. The oil should be supplied to the underside of the chain drive where the slack span leaves the driving sprocket with the help of a spraying pipe, or a nozzle with a flat section jet. Anti-wear and extreme pressure additives are useful in reducing wear. Graphite as an oil additive is ineffective but Molybdenum disulphide shows a high efficiency.

While rolling contact fatigue life of steels has been much improved by the improvement of cleanliness in steels due to progress in steel making techniques, the demand for longer bearing fatigue life has been ever-increasing, Tsushima et al (1986). The authors reported that under debris contaminated lubrication such as in automobile transmissions, there were
some cases, where carburized bearings did not show such longer fatigue life. They found that by making core hardness higher than usual (over HRC 50), the bearing fatigue life of carburized tapered roller bearings greatly increased, not only under debris contaminated lubrication but also under heavy loading conditions.

The four-ball wear machine is used to assess the wear resistance properties of lubricating oils or greases. The traditional method of measuring a lubricant’s effectiveness is by running the test for 1 hr and measuring the resulting wear scar. Wright et al (1989), in their work conducted experiments to determine the wear rate of lubricated sliding surfaces using a variation of the standard ASTM D 417282 four-ball wear test. In their experiments, the relative displacement between the balls was recorded continuously using a linear variable differential transducer (LVDT) and a data acquisition system. They have reported that with a single test, more information was obtained by calculating the wear volume and specific wear rate rather than simply the average wear scar diameter.

The effects of lubricant on wear of piston rings were studied by Priest et al (1999) and found the interaction between lubricant, wear and dynamics of piston rings. The sensitivity of film thickness and friction between piston ring and cylinder wall on wear of rings were reported.

Farcas and Gafitanu (1999) in their research work on the parameters that influence grease lubrication on service life of bearings confirmed that when using greases at normal operating temperatures, at the beginning of the running period the film thickness was greater than that obtained when using only base oil.
Voevodin et al (1999) made a study on tribological composite material consisting of nano crystalline transition metal dichalcogenides and carbides embedded in amorphous DLC were produced. The WC/DLC/WS2 nano composites had a very attractive combination of wear resistance, low friction coefficient, long endurance in vacuum and unique friction recovery in dry/humid environmental cycling. These properties are specifically useful for aerospace tribology.

Eriksson et al (2000) in their work noted that greases are widely used as rolling bearing lubricants due to their ability to stay close to the lubricated area in a rolling bearing, thereby acting as a combination of lubricant reservoir and external debris sealing system. Even though greases apparently work well in many bearing applications, the mechanisms of grease lubrication are not yet fully understood. At least three different ways of lubrication have been proposed in their work.

Eriksson et al (2000) also made a study using optical interferometry in a standard ball-and-disc apparatus and a high-speed video camera with light enhancer. Thickener particles entering a grease-lubricated elasto hydrodynamic (EHD) contact were traced as they passed through the contact in pure rolling. They have also reported that smaller fibres passed through the contact and keep their shape and size when passing the contact both in the beginning and after over rolling.

Thin solid films, or coatings, have been used extensively for enhancing mechanical properties for various applications in the last three decades. Diamond-like carbon (DLC) is used for better lubrication. DLC-type coatings have a beneficial effect in decreasing wear to a large extent and also for using in abrasive wear situations, which in this case results in a longer
service life and can be used to run in lower-viscosity lubricants for higher efficiency (Sjöström and Wikström 2001).

Jayatilleka and Okogbaa (2001) reported that Accelerated Life Tests (ALT) which are useful in identifying Potential Failure Modes of products at the design stage, before they are put to use in practical situations or environments. Early failures have adverse effect on both the image and the market share of the manufacturer. An ALT was carried out to identify failure modes and optimize critical design parameters.

Tung and McMillan (2004) made an overview of various lubrication aspects of a typical power train system including the engine, transmission, driveline, and other components. They reviewed the current standard ASTM (American Society for Testing and Materials) test methods for engine lubricants and other compilations of automotive standards.

Lee and Priest (2004) made a study of chain wear performance using different lubricants. The lubricants tested were a wax spray, PTFE spray and drip fed light oil. The test rig allowed measurement of the power saved by the lubricant in running the chains and sprockets. Chain length and component masses were also taken before and after running the chains and sprockets under load on the test rig. The results clearly show that any lubricant is preferable to none. The drip fed oil provided the greatest power saving and wear protection between the chain rollers and pins and the spray lubricants provided the highest level of protection between the rollers and sprockets. This study shows that lubrication plays a very important role in reducing wear of chain drives.
2.6 SUMMARY

From the literature study on transmission chains, it is found that most of the works were carried out on timing chains of four wheelers mostly on impact load, noise and meshing dynamics. Motorcycle chain noise study was made in one research work and reported that there was no effective method to control noise. The effects of misalignment of sprockets, use of elliptical sprockets in bicycle were reported in few studies. The effect of polygonal action and variation of chain load during meshing with sprockets impact of rollers, factors that contribute towards chain noise and other related factors that influence chain performance were reported in various literatures. An experimental setup with lower power to measure tension and impact forces in roller chain drives was developed in one of the research works.

Wear is directly related to chain load and from the above literature study, it is found that chain load is influenced by number of teeth of sprockets and pressure angle. It is also found that load is more in drive sprocket side and varies from tooth to tooth and almost very less load in slack span and increases at driven sprockets. This study helps to find the average load acting on drive and driven sprocket side, which is discussed in section 3.6. Finally, from the above literature study, it is understood how chain noise is influenced by wear and helps to find means of reducing chain noise by reducing wear.

It is observed from the literature studies that not much research work has been carried out on wear and related aspect of chain elongation especially in analytical method, due to many factors that cannot be controlled. Also, no attempt has been made to relate chain life with pin and bush hardness, finish, dimensional tolerance and assembly characteristics and other parameters. But there are reports of effect of chain lubrication study on chain as early in 1986 done by Peeken and Coenen. In an another study by
Lee and Priest (2004), the effect of lubricants and its mode and frequency of application on chain wear has been discussed. In both the studies, the authors have not made any field trial and used only rig testing machine for 500-600 hrs which do not represent the full life period of a transmission chain.

From the literature study on wear, the factors that influence wear characteristics are material, surface characteristics like surface finish, hardness, sliding distance, supporting area, load acting on the surface, friction coefficients and other related parameters that affect wear performance. This study is useful to find the most critical factors that affect wear performance of chains, which are discussed in section 3.5.

From the literature study on lubrication, the influence of lubricant on wear is understood. Whatever may the surface characteristics of mating parts, which are having relative movement, lubrication plays a vital role in reducing wear. The characteristics of lubricant, the method and the frequency of lubrication also influence wear performance.

The above literature studies bring forward the importance in selecting the investigation on motorcycle chains for wear and fatigue. The current research is carried out to study the existing motorcycle performance theoretically and validate the theoretical result with field study, also to improve the performance of motorcycle chains by suitable design modifications. The theoretical wear study and the proposed chain design modification have not been carried out in any of the literature study. In this direction the current research work is carried out, which are discussed in the subsequent chapters.