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An Investigation of Improving Wear of 390 Die-cast Aluminum Through Hardcoat Anodizing

Michael J. Whiting
Brigham Young University - Provo

AN INVESTIGATION OF IMPROVING WEAR OF 390 DIE-CAST ALUMINUM THROUGH HARDCOAT ANODIZING

by

Michael J. Whiting

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Michael J. Whiting

This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	Robert H. Todd, Chair
Date	Spencer P. Magleby
Date	Kenneth W. Chase

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As chair of the candidate's graduate committee, I have read the thesis of Michael J. Whiting in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for sub-mission to the university library.

Date	Robert H. Todd Chair, Graduate Committee

Accepted for Department

Matthew R. Jones
Graduate Coordinator

Accepted for College

Alan R. Parkinson
Dean, Ira A. Fulton College of Engineering and Technology

ABSTRACT

AN INVESTIGATION OF IMPROVING WEAR OF 390 DIE-CAST ALUMINUM THROUGH HARDCOAT ANODIZING

Michael J. Whiting

Department of Mechanical Engineering

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The objectives of this research were to investigate the wear that occurs on the surface of a Hardcoat anodized die-cast aluminum surface, which was sliding against a composite rubber belt. This research investigated known wear theories and the results for previous testing to understand the mechanisms that were likely occurring in this application. These theories indicated that the wear occurring may be reduced by changing the hardness of the materials involved. Archard's equation gave tangible evidence of this fact, but related to the base material and not a surface coating. It was hypothesized that Hardcoat anodizing would follow the theory of Archard's equation and increase the wear resistance of 390 die-cast aluminum when sliding against a composite rubber belt. Standardized wear tests were implemented in order to test this theory.

The results of the wear tests indicated that the wear resistance of the Hardcoat anodized coating did not follow the wear theories and wore at a higher rate than the base material surfaces. This is likely due to the phenomenon seen by Jiang and Arnell where the surface roughness influenced the wear rate of DLC coatings. They found that there existed a transition point where the wear rate of the surface increased with an increase of surface roughness. The Hardcoat anodized surface was rougher than the surface of the base material due to alloy materials and the processing characteristics of 390 Aluminum die-casting material. Subsequently the Hardcoat anodized surface wore at a higher rate than did the base surface.

A case study was conducted on an ATV to investigate the accuracy of the results from the laboratory testing. This case study showed a significant localized wear groove in the stock CVT drive sheave with little wear occurring elsewhere. The Hardcoat anodized CVT drive sheave did not show evidence of a significant localized wear groove as the stock sheave but indicates that wear occurred more evenly across the surface. This wear is evident due to visible aluminum through the Hardcoat layer. In addition, there was a ridge at the outer diameter of the sheave where the belt could not wear the surface. Both of these items indicated that significant wear occurred on the surface, but the presence of a localized wear groove is non-existent.

ACKNOWLEDGMENTS

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CHAPTER 1 INTRODUCTION

Belt pulleys have been used in many different applications for centuries. The general concept is to transfer power to a secondary device, while relying on a robust system that requires little maintenance or repair. Rubber v-belts have evolved from these requirements because of their ability to meet the above objectives. These belts use their shape to increase the contact surface between the belt and the pulleys and to transfer the power more efficiently. A typical application of a v-belt is in a mechanical system that is generally under constant load. Constant load means the belt transfers the same torque consistently and is not required to accelerate or decelerate. In this type of application, there is little loss in terms of slipping of the belt relative to the pulleys. Many applications are constant mechanical systems as explained making the v-belt an ideal selection.

The development of reinforcing fibers has made possible the use of v-belts in systems that were never before thought possible. Applications with high torque and high RPM require the v-belt to transfer higher loads, while under severe temperature and environmental conditions. These situations have led to the implementation of aramid fibers such as Kevlar® and other such high strength composites as reinforcing fibers integrated into the belt structure. However, these reinforcing materials have caused another problem in the pulley system: wear. When the system is in equilibrium, there is little concern for wear, but if there are accelerations or decelerations in the pulley system the v-belt may slip, causing both belt and pulley wear.

1.1 CONTINUOUSLY VARIABLE TRANSMISSION

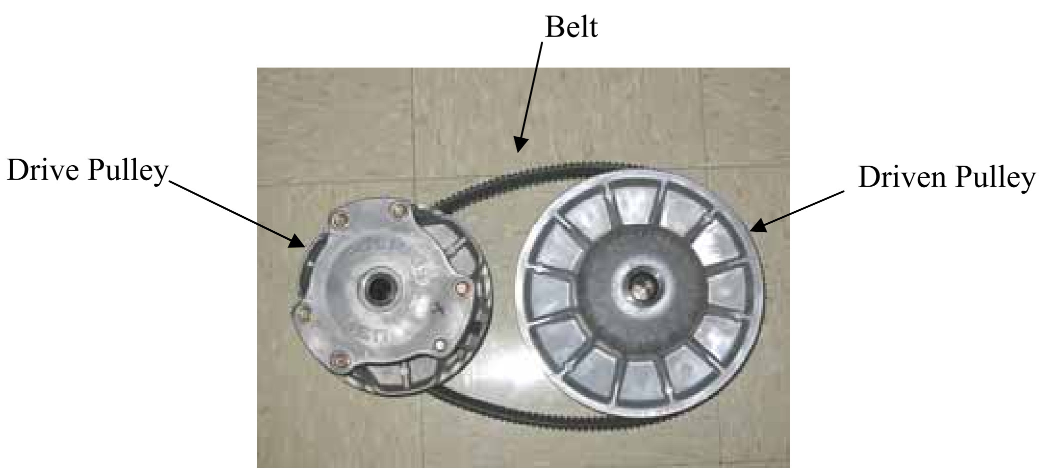

Figure 1.1 Continuously Variable Transmission (CVT)

The Continuously Variable Transmission (CVT), Figure 1.1, is a v-belt/pulley mechanism that exhibits, to some extent, this issue of wear. The CVT performs two main functions; first, varying the ratio from the drive pulley to the driven pulley, and second, disengaging (releasing or unclamping) the v-belt to allow the drive pulley to freely spin without rotating the driven pulley, similar to a clutch. The CVT acquires its ability to function through a system of weights and springs. As the drive pulley of the CVT increases in speed (RPM), weights are forced against fixed rollers through centrifugal force. This force becomes great enough to overcome a pre-loaded spring, which allows a moveable sheave (refer to Figures 1.2 and 1.3) of the CVT to move toward the belt. As the drive pulley speed increases, the side-force increases, pressing or clamping the sheaves against the belt, Figure 1.4 A. The belt begins to rotate initiating the rotation of the driven pulley. As the drive pulley's speed increases the sheaves squeeze the belt up the sheave face, increasing the pulley's pitch diameter, Figure 1.4 B. The belt continues to move up and down the sheave face in relation to the driven resistance torque or the driven pulley RPM, Figure 1.4 C. This is the reason that a CVT is a transmission. It has the ability to automatically change drive ratios according to the requirements of the system.

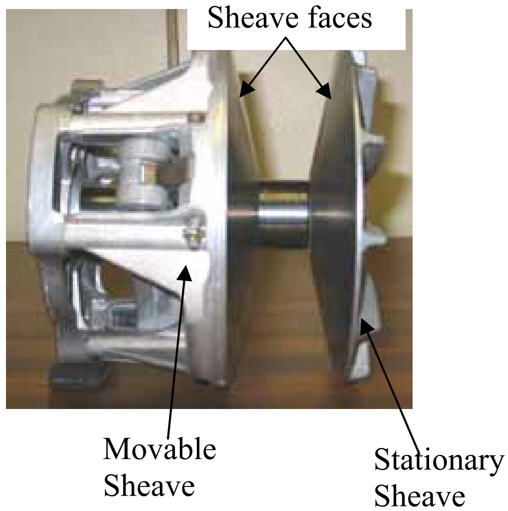

Figure 1.2 CVT drive pulley. The belt begins at the small radius (near the center). At higher speeds, the movable sheave moves toward the stationary sheave, forcing the belt to a higher pitch diameter.

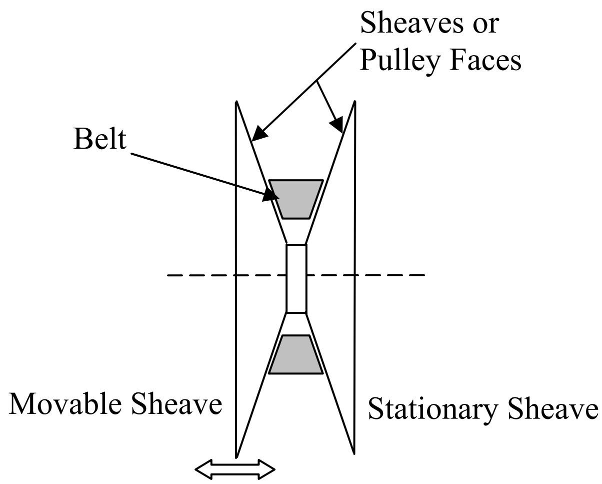

Figure 1.3 Schematic of the belt and sheaves in a CVT drive. As the movable sheave moves toward the stationary sheave, they maintain the "V" shape. This allows the belt to continue to be clamped between the sheaves regardless of its position on the sheave face.

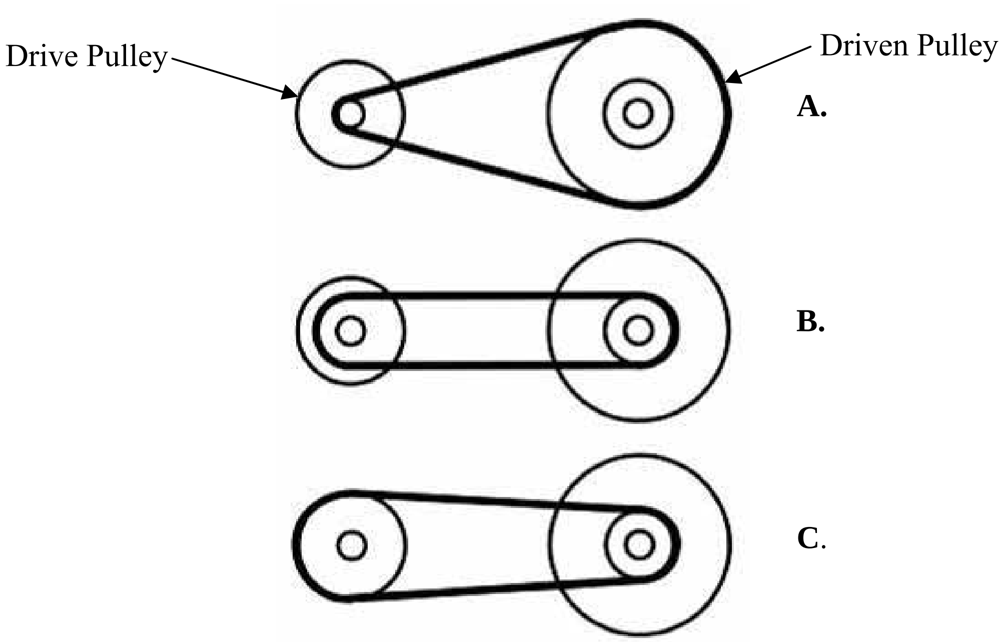

Figure 1.4 Schematic of the various locations of the belt for a running CVT A) Idle or Engagement B) Intermediate C) Overdrive

1.2 SLIPPING CAUSES WEAR

In a CVT, the belt experiences slipping at various locations against its sheaves, but nowhere does the belt slip as severely as during engagement (again refer to Figure 1.4 A). This is when the belt is at its smallest pitch diameter on the drive pulley. This small pitch diameter means that the belt has the least amount of contact area relative to any other sheave position. As the rotating sheaves of the drive pulley are forced together, they clamp on the stationary belt. The sheaves must continue to squeeze the stationary belt until the driven –and hence the entire system- begins to move. This slipping causes the belt and sheaves to wear in the area of engagement. The slipping continues until the CVT pulley system is in equilibrium.

As has been explained, the CVT relies on the motion of the belt up and down the sheave face to change drive ratios. Uneven wear or wear grooves (refer to Figure 1.5) on the sheave faces may hinder this motion. If the belt is prevented from moving up and down on the sheave faces, the CVT loses its ability to function properly. When a wear groove is formed, the belt rides in this groove and can not change ratios until a greater force, caused by an increase in engine RPM, is exerted on the belt forcing it out of the groove. This causes an undesirable lunge or jerky shifting of the CVT. When a CVT has this type of wear it causes, in addition, unnecessary wear and tear on the belt, engine and other components of the drivetrain.

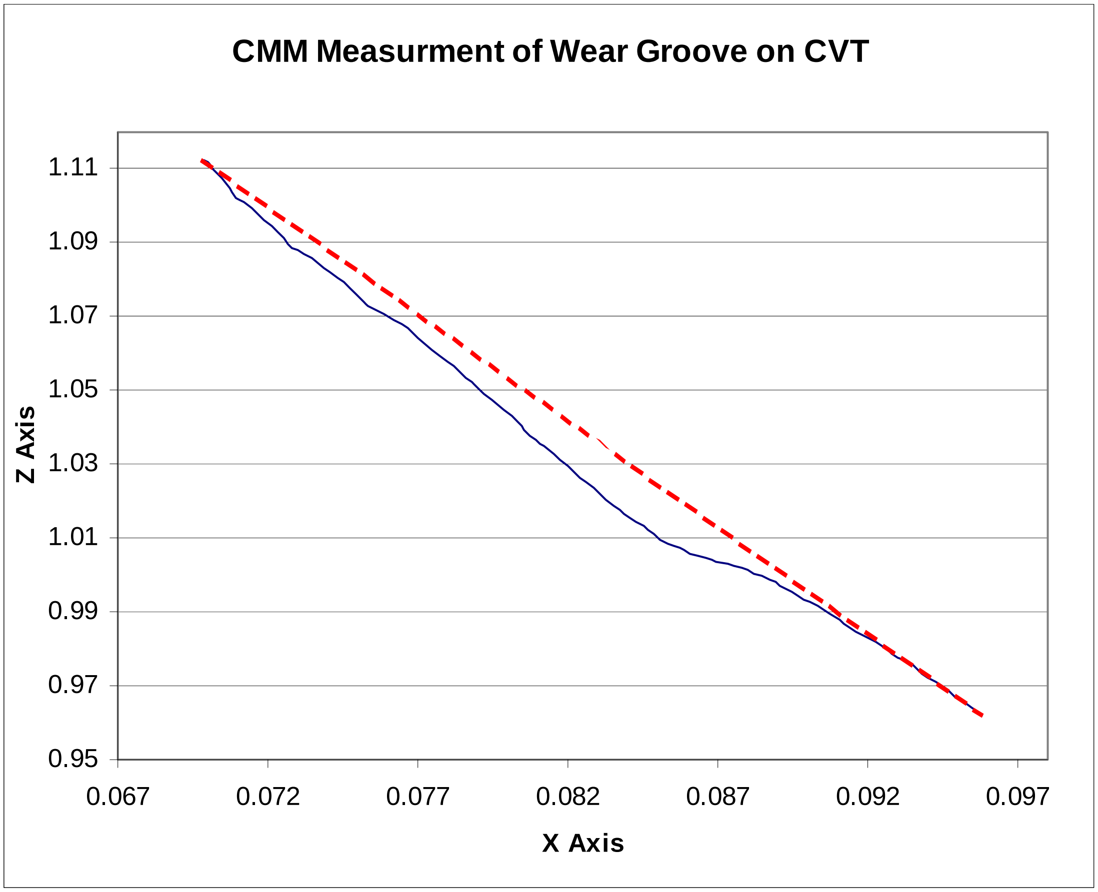

Figure 1.5 Example of a CVT wear groove as measured on a Coordinate Measurement Machine (CMM). The X Axis represents the plane through the rotational axis radially outward (i.e. from the inner diameter of the sheave to the outer). The Z Axis represents the plane perpendicular to the centerline rotational axis. The dashed line indicates the original sheave surface. Units are in inches.

1.3 THESIS STATEMENT AND OBJECTIVES

The hypothesis of this thesis is that the wear of the sheave material used in a CVT can be reduced through surface hardening processes. A decrease in wear can be achieved while the CVT drive characteristics of the belt/pulley system are retained. Surface hardening is often implemented to increase wear resistance. There are, however, no known studies of the wear resistance of surface hardening aluminum in belt/pulley systems. This thesis will characterize and measure the wear that is occurring in a CVT belt drive and then compare this wear to the wear that occurs on a hardened sheave. The objective is to find if surface hardening is a reasonable solution to reduce wear in this application.

Previous testing and research has found that increasing the hardness or implementing a harder material may reduce wear [Lepper 1997] [Wilson 1996] [Garbar 2000]. Despite this evidence, the hardening of the CVT sheave and its wear, when in contact with a composite rubber belt, has not previously been examined. The characteristics of interacting materials must be studied on a case-by-case basis to fully understand their wear properties. A study into these wear characteristics may be beneficial because of the many applications of belt/pulley systems. The knowledge gained here can be applicable to other similar interactions. To fully understand this problem, current literature was consulted, which revealed testing and procedures helpful to this study.

A common equation used in studying wear is the Archard Equation (1.1), which relates hardness, H, with the wear volume, V, in a sliding situation:

$$V = \frac{kLS}{H}. \qquad \textbf{(1.1)}$$

Where L is the applied load, S is the sliding distance, and k is the wear coefficient for the material. From the Archard Equation, we see that the wear is inversely proportional to the material's hardness. The hardness in this equation, however, refers to the material hardness and not to the hardness of a surface coating. There are no studies into the accuracy of the Archard Equation with reference to surface hardening.

This thesis adds to the general knowledge of wear by examining the wear characteristics of a v-belt/pulley system in sliding contact, which previously had not been studied. The wear of a CVT may vary from a typical v-belt pulley because of accelerations seen in a CVT, but the applications here may shed light into wear of all composite rubber/aluminum interactions. Therefore, the objectives of this study can be broken down into the following areas:

1. Characterize the wear occurring in the aluminum pulley sheaves as caused by the rubber composite belt. Determine what wear theory best describes the wear that occurs in the CVT.
2. Examine the interactions between the belt and CVT sheaves where wear is occurring. Learn what effects surface hardening has on this wear.
3. Verify that the wear theories and models are accurate in predicting wear, which occurs when the surface has been hardened.
4. Determine the wear coefficient (variable used in the wear equations) for aluminum in contact with a composite rubber belt.
5. Document the results

1.4 SURFACE TREATMENTS

CVT drives typically use 390 die-cast aluminum sheave material, since it is relatively easy and inexpensive to produce. These parts are first cast into a rough shape. Then, critical surfaces are machined to produce the necessary dimensional tolerances and surface finish. One of these machined surfaces is the sheave face. The sheave surface is machined down, removing 0.030-0.040 in. of the as-cast surface material. This process also gives the sheave face the proper angle or profile that matches the angle in the drive belt. Following the initial surface preparation, it is possible for it to be coated, increasing its surface hardness. The process to be studied in this thesis is Hardcoat anodizing because of its ability to change the material properties of the sheave surface. The anodizing process is briefly explained further in the following section.

1.4.1 Conventional Anodizing vs. Hardcoat Anodizing

Anodizing is an electrochemical process where a hard oxide layer is formed on the surface of the aluminum. In its natural environment, Aluminum is a fast-reacting material and corrodes rapidly [Jones 1996]. This corrosion is an oxidation process were the outer aluminum molecules join with oxygen to form Aluminum Oxide, Al_2O_3. The resulting oxide layer is harder than the raw material (substrate) and becomes more resistant to corrosion, yet the layer is very thin, less than a few ten thousandths of an inch thick. Anodizing goes beyond simply forming a thin layer of oxide as occurs naturally. This manufacturing process causes a controlled oxide layer to be formed on the surface. This new anodized layer is thicker (approximately two thousandths of an inch thick for Hardcoat anodizing) and has better environmental protection characteristics than does the naturally occurring oxide layer.

The processing steps of anodizing are [Jobshops 2003]:

1. Place the aluminum part in a cleansing bath to remove impurities and the natural oxide layer that exists on the surface of the part;
2. Run a specified current through the aluminum while it is in an acid bath to cause the aluminum to form a thick oxide surface layer. The duration and current level determine the thickness of the layer.

Anodizing is typically a cosmetic process. An anodized part can take on color and acquires environmental protection. In this way, it is much like painting or other surface coatings, which provide material protection. The amount of wear resistance is limited because the anodized layer is still only a few ten thousandths of an inch thick. Hardcoat anodizing is a similar process to Anodizing, but creates a denser coating. The difference is in the current and bath temperature used during the coating process. The layer created is much harder and thicker than is created with typical anodizing. Its use is primarily for extremely harsh environments.

Hardcoat Anodizing could have many benefits in a CVT such as:

1. The current materials and casting tools can be used with little to no design change.
2. The Hardcoat anodizing process can be relatively inexpensive for large volume production.
3. The Hardcoat layer is typically 0.002 to 0.003 of an inch thick, where half of the layer is imbedded in the original aluminum surface.
4. This layer is molecularly bonded to the part because it is formed from the original aluminum and is not merely a coating such as paint.

1.4.2 Material Selection

If the Archard Equation is correct for this type of situation, then it seems more reasonable to simply use the hardest material possible for the CVT. This would reduce the wear significantly if not totally. Steel, as an example, is a material that is much harder than Aluminum and is inexpensive to use. Some of the challenges of using steel and other materials versus aluminum are:

1. Aluminum is a lightweight metal comparable to many other common metals such as steel. In the applications of a CVT, increased weight can be detrimental because the increased energy required to rotate a heavier part. In

addition, many applications spin the CVT to many thousands of RPM. Using other metals is a liability because of the energy that would be stored in a heavier rotating CVT.

2. Many metals do not form a natural corrosion resistant oxide layer, similar to aluminum. This means that additional processing would be required to protect the material from corroding.
3. Harder metals are more expensive to machine because of tool wear, causing manufacturing costs to rise in the production of the CVT.
4. Not all metals dissipate heat as quickly as does aluminum, meaning the system could potentially become extremely hot.

There are other materials such as titanium that have the characteristics of aluminum; light weight, corrosion resistant, etc. These materials are not as plentiful as aluminum and are typically more expensive to use. These materials, although they may have the same, if not better, wear resistance, would not make the CVT a viable transmission because of increased production costs. Until materials become more accessible or less expensive, aluminum appears to an effective material selection.

1.5 RESEARCH APPROACH

The basis of this study will be a comparison of the wear volume of sheave material removed under running conditions. The Hardcoat anodized sheave will be compared to the current 390-AL sheave material. The test parameters are; hardness of the sheave surface, force of the belt applied to the sheave face and the sliding distance between the belt and sheave.

To test this hypothesis, there must be an understanding of the wear characteristics of the current material, 390 die-cast aluminum. Laboratory Tests will be performed on a Pin-on-Disk and Taber® Abraser to quantify the wear resistance of the current material (390 die-cast aluminum). Then similar tests will be run using Hardcoat anodized samples of the same 390-AL to quantify its wear resistance. The wear resistance will be determined by the amount of material removed during a set number of cycles.

To further learn the effects of Hardcoat anodizing the sheaves, a full CVT will be tested. These tests are to compare the wear occurring in the current material and the wear of the hardened surface while in an actual setup. These tests will be conducted using a dynamometer stand where an engine will drive a CVT system including, a belt, and drive and driven pulleys. A simulated load will be applied using a water brake and the volume of wear will be measured using a coordinate measuring machine (CMM). In addition, a case study of both the stock CVT and the Hardcoat anodized CVT will be run on an ATV for a fixed duration of time and the results will be compared and documented.

From this data other tests will be performed to compare the wear equations to the actual wear occurring. The wear coefficient will be calculated and the results of the tests will be documented.

1.6 Target Market

Why should there be any research in this area? The market for CVT use is overwhelmingly in All Terrain Vehicles (ATVs) and Snowmobiles (referred to as the Powersports market). These vehicles use the CVT to perform the functions of a multi-geared transmission and clutch. Polaris Industries Inc., one manufacturer in the Powersports market and CVT user, reported a forth quarter sales of $431.5 million dollars in 2002. They reported more than one and a half billion dollars in total sales for the entire year, [The Business Journal 2002]. Polaris Industries' sales represent less than one quarter of the entire Powersport's market.

The Powersports market is very competitive as new models are introduced each year. Consumers are driven by performance and quality of the products. Manufacturers must encourage sales of their product in order to stay on top of the market. If the quality of a company's product is perceived as poor, the company stands to lose a significant amount of market share.

Since the Powersports market relies heavily on the CVT for performance, if the CVT does not function well, it will reflect on the overall quality of the vehicles. It is critical that the CVT continues to perform for the entire life of the vehicle. If the CVT wears out before the vehicle, then the consumer may perceive that the entire product line is not manufactured to a high quality standard.

Beyond the recreational vehicle market, the auto industry recently implemented CVT technology into some of its vehicles. The current design of the CVT used in the Powersports market is considered insufficient for use in automobiles. The CVT's main weakness is in the strength of the rubber composite belt. The belt can not withstand the loads of higher-powered vehicles. Automobile CVTs use a steel belt to transfer the torque in place of the rubber belt. Auto manufacturers must use heavier steels or hard alloys for sheave materials in this harsh environment. The information from this research may also lead to the implementation of lighter materials in automobile CVTs. If the wear characteristics of aluminum can become similar to that of steel, it may be possible to replace the steel, thus reducing the weight of the automobile transmission.

1.7 SUMMARY

This research looks into the ability of the wear theories and equations to predict the amount of wear occurring in a 390 die-cast aluminum CVT system, which are surface hardened through Hardcoat anodizing. The research also investigates Hardcoat anodizing as a viable solution in reducing the wear occurring on sheave surfaces, especially in a CVT. This knowledge is significant to the Powersports industry, where CVTs are heavily relied on as a mechanism for transferring power. There is also the potential for this knowledge to be used in other industries where wear is occurring because of the sliding between composite rubber materials and aluminum. The ability to reduce this wear, in essence reduces the cost of the system for down time and repair of worn parts.

CHAPTER 2 BACKGROUND & LITERATURE REVIEW

Wear is "defined as a progressive loss or displacement of material from a surface as a result of relative motion between that surface and another."[ASTM Wear Testing Source Book] Wear itself is not an easily defined science, because it is possible to believe that one form of wear is occurring, when in actuality a different form of wear may be taking place. It is important to understand existing wear theories to assist in defining the type of wear that is occurring between a composite rubber belt and CVT sheaves. The objectives of this chapter, therefore, are to first, explain wear theory and quantification. Second, this chapter discusses the characteristics of anodizing and Hardcoat anodizing. Third, it discusses why Hardcoat anodizing may be a solution to the reduction of CVT wear.

2.1 WEAR THEORIES

The first step in proving the hypothesis of improving wear characteristics through Hardcoat anodizing, is to understand the known theories of wear. This knowledge will assist in identifying parameters, which can be varied to alter the amount of wear that is occurring. Before this hypothesis can be tested, it is essential to understand the mechanisms that exist during wear and the equations that have been developed to predict this wear.

The study of wear is relatively new compared to many other engineering topics. Initial experimental data for wear was taken in the late 1940's [Rabinowicz 1965]. These experiments led to wear theories, which describe mechanisms causing various forms of wear. Some of the more common wear theories include:

1. Corrosive or Chemical
2. Erosion
3. Cavitation
4. Fatigue
5. Fretting
6. Impact
7. Sliding
8. Abrasion

Each of these wear theories is briefly explained below. For additional information into these theories refer to [Rabinowicz 1965] [Blau 1989] [Bhushan 1999].

2.1.1 Corrosive or Chemical Wear

Corrosive wear, which is also termed Chemical wear, occurs when sliding takes place in a corrosive environment. A common corrosive environment is air, where oxygen is the corrosive element. Oxygen bonds with the surface layer of the wear material forming an oxide film. This oxide layer at times becomes a protective layer, but relative motion between the two wear surfaces causes this layer to be removed because the bond between the oxide and substrate is weak. The newly exposed surface will then be corroded again by the oxygen. This continues until the part fails or becomes too worn for proper use. Therefore, corrosive wear requires a corrosive environment (chemical reaction) and a sliding (rubbing) action. This form of wear is much more rapid in industrial applications, such as production of chemical products, mining, or even along coastlines as compared to clean environments [Bhushan 1999].

2.1.2 Erosion Wear

Erosion is damage caused by loose particles impinging on a surface or object. Erosion is similar to loose particle abrasion, which occurs as a form of Abrasive wear, because of the particle interaction. The difference is that erosion is caused by the impact of microscopic particles. These particles causing erosion may actually increase roughness of the surface as the particles remove material from low areas. Meaning the eroding particles are small relative to surface roughness. It is possible for these particles to wear not only at the peak of the asperities but also at the base, increasing the surface roughness. The surface roughness increases when the erosion occurs at the base of an asperity, making the peak relatively higher. In loose particle abrasion, as a comparison, typically only the highest points are removed as the surface becomes smoother [Rabinowicz 1965].

2.1.3 Cavitation Wear

Cavitation is generally considered a subset of Erosion, dealing with the special case of collapsing bubbles causing impacts (high stress concentrations) at the surface. This stress leads to eventual material failure and removal. Cavitation is often co-studied with liquid droplet erosion because of the similarities between the two.

Cavitation wear is typically found in tribosystems (wear/lubrication systems) where fluids are quickly moving along a solid surface. This also works for the inverse, a solid quickly moving through a liquid. Examples of components that may experience Cavitation wear include liquid pump components, propeller blades, chemical process stirring blades, and piping systems. [Blau 1989]

2.1.4 Fatigue Wear

Fatigue wear is the propagation of surface or subsurface cracks caused by repeated loading and unloading along the surface of a part (Figure 2.1). These cracks can grow to a critical stage, or until they join with other cracks, and a large fragment breaks off. Prior to this event (hundreds or possibly millions of cycles) the surface shows negligible wear. For Fatigue wear, the amount of material removed is not the defining factor. The number of cycles the material has undergone until fatigue failure occurs is the more relevant factor.

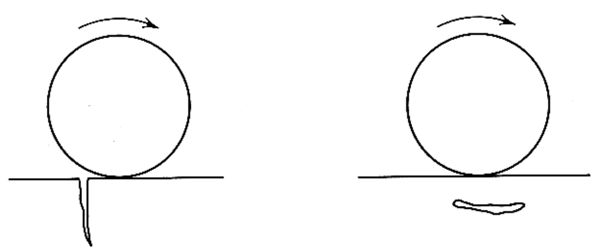

Figure 2.1 Surface and subsurface cracks caused by Fatigue Wear taken from Rabinowicz 1965

From a Hertz or contact stress analysis, the maximum compressive stress is at the surface, but the maximum shear stress is just below the surface (refer to Figures 2.2 and 2.3). These figures indicate that the combination of sliding stress and rolling stress below the surface can cause subsurface cracks to form. When the crack reaches a critical length, a small piece will flake off or spall out. An example of spalling due to Fatigue

Wear occurs in the race of ball bearings, as can be seen in Figure 2.4 [Rabinowicz 1965] [Bhushan 1999].

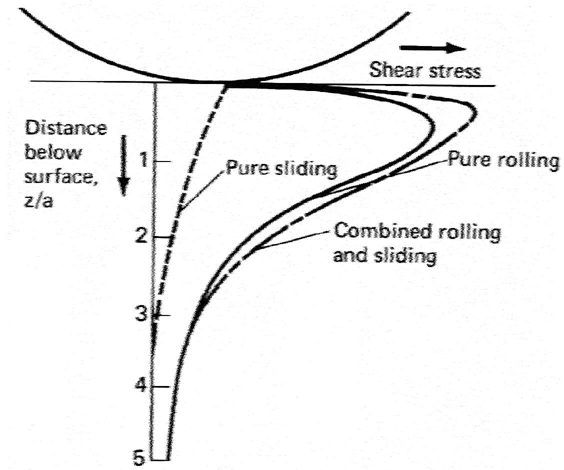

Figure 2.2 Schematic of the magnitude of shear stress as a function of depth below the surface for rolling contact according to Bhushan 1999

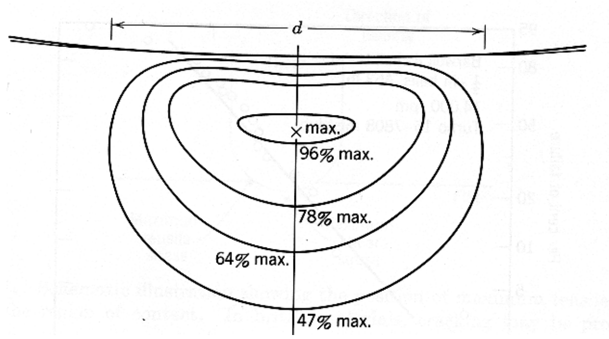

Figure 2.3 Magnitude of the shear stress below the surface according to Rabinowicz 1965

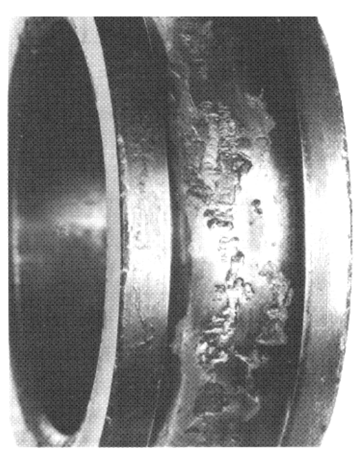

Figure 2.4 Example of spalling that has occurred in the race of a ball bearing. Bhushan 1999

2.1.5 Fretting Wear

Fretting is caused by small oscillations between mating or contacting surfaces. Parts such as splines on a rotating shaft are common locations for fretting to occur, because the mating splines vibrate back and forth relative to one another. Fretting is a common occurrence because many machines are prone to vibration. Many connecting parts that are not rigidly fastened may begin fretting. It is surprising the amount of material that can wear because of such relatively small motions [Blau 1989].

Fretting is essentially adhesive wear and abrasive wear occurring simultaneously. In cases were a reactive material is used, chemical or oxidative wear also is involved in fretting. This is considered a separate wear theory, because of the small oscillatory motion and because the wear is a combination of three other wear theories.

2.1.6 Impact Wear

Impact Wear is wear that occurs because one surface or object impinges on another surface or object, typically at high velocities. This wear is similar to Erosion wear because of the action of the impinging object, but Impact wear occurs on the macroscopic scale and with fewer impacts. Impact Wear is often used as a beneficial material processing method. For example, shot peening is a process where repeated impacts on a surface can improve the fatigue resistance of that surface. Peening can also improve corrosion resistance though a change in the structure of the surface molecules. Impact Wear is not limited to the situation in which there are only many multiple impacts. Forging is an impact process causing wear that may require only one or two impacts.

Impact can cause additional types of wear to occur. Under multiple high load impacts, fatigue wear can occur because of cracks forming below the surface of the impacted part. Abrasion can also occur as the material used for impaction may slide along the mating surface [Blau 1989].

2.1.7 Sliding Wear (Adhesive)

Sliding wear is probably the most common and thoroughly researched form of wear [Blau 1989]. It involves many wear processes found in other wear theories as well as those unique to sliding. Sliding wear is commonly termed “Adhesive” wear because particles from the softer material may adhere to the surface of the harder material. However, in a large number of cases, more than adhesion is involved. The term Adhesive wear becomes misleading because the adhering particles may break off from the harder surface or reattach to the original surface. There may also, in some instances, be no adhesion at all in this type of wear, just loose wear particle formation [Blau 1989]. It is important that the term Adhesive wear be understood as a Sliding wear issue and not only one material adhering to the other. Other forms of wear that are included within sliding or adhesive wear are cold-welding, plowing, scratching, pitting, and delamination, as well as others.

Even though the term Adhesive wear can be misleading, it is more commonly used among the literature than Sliding wear. To minimize confusion and to conform to the majority of authors, Sliding wear will be referred to as Adhesive wear.

2.1.7.1 Quantitative Equation for Adhesive Wear

Based on the results of experiments of various unlubricated material pairs, the majority of which were metallic, it is possible to formulate a theory of Adhesive wear as follows [Blau 1989] [Bhushan 1999] [Rabinowicz 1965] [Archard 1980]:

The amount of wear is generally proportional to the applied load L and the sliding distance S. The amount of wear is generally inversely proportional to the hardness of the surface H that is being worn away. This leads to an equation for volume of wear material removed written by Holm in 1946 [Rabinowicz 1980]

$$V = \frac{kLS}{H}. \qquad \textbf{(2.1)}$$

Where V is the volume of wear and k is a nondimensional wear coefficient, which is dependent on the material being worn. Calculating this wear coefficient will be discussed later in more detail.

Archard (1953) [Rabinowicz 1965] presented a theoretical basis for equation 2.1. His work allows us to attach a definite meaning to the wear coefficient k as the probability that a wear particle will be formed during an interaction. Meaning, as two asperities come in contact to form a junction, there is a probability constant, k that an adhesive fragment will be formed. Archard assumed each particle to be hemispherical in diameter equal to the diameter of the junction, as seen in Figure 2.5.

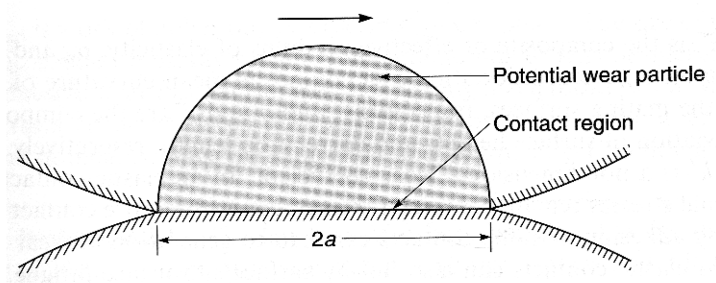

Figure 2.5 Hypothetical model of a hemispherical wear particle at the junction of two asperities taken from [Bhushan 1999]

Consider two surfaces in sliding contact under an applied load L. Archard assumed that during this contact the maximum area of contact is:

$$\delta A = \pi a^2 = \delta L / H \text{.} \tag{2.2}$$

Where δL is the maximum load support contributed to the total load, L. δA is similarly the maximum contribution to the total true area of contact, A. The radius of the hemisphere contact region is a. Archard also assumes that the deformation of the asperity interaction is plastic.

Next Archard assumes that the asperity contact results in a worn particle of volume δV. The dimensions of this worn particle will be directly proportional to the contact size. Physical examination shows that the wear particles are generally equi-axid (equal length) in size and shape rather than layers as explained by Rabinowicz [Rabinowicz 1965]. Thus, δV is expected to be proportional to a^3 strengthening Archard's assumption that the particle shape is hemispherical:

$$\delta V = \frac{2}{3}\pi a^3 \text{.} \tag{2.3}$$

Finally, the asperities are assumed to remain in contact for the sliding distance δS, which is equal to 2a after which contact is broken, and the load is taken up by a new contact:

$$\delta S = 2a\,. \qquad \textbf{(2.4)}$$

Combining equations 2.2, 2.3, and 2.4, results in:

$$\frac{\delta V}{\delta S} = \frac{1}{3}\pi a^2 = \frac{1}{3}\delta A = \frac{1}{3}\frac{\delta L}{H}\,. \qquad \textbf{(2.5)}$$

Archard assumes that only a fraction of all encounters produce wear particles. He termed this the wear coefficient, (k) which has been stated as the probability for contact to form a wear particle. Adding k to the equation, the volume of wear by all asperities is:

$$V \propto \frac{1}{3}\frac{LS}{H} = \frac{k' LS}{H}\,. \qquad \textbf{(2.6)}$$

Where 3k' is equal to k, the wear coefficient from the Holm equation.

This equation is similar to equation 2.1 above and is commonly referred to as the Archard equation. In general, it gives the amount of wear of the softer of the two materials. The Archard equation can also predict the wear of the harder material by using the hardness and wear coefficient of the harder material [Bhushan 1999].

2.1.7.2 Wear Coefficient

As was indicated in the formulation of the Archard equation above, the wear coefficient (k) is a critical part of the wear equation. The wear coefficient has been described as a dimensionless variable, which indicates the probability that a wear particle will be formed during contact of asperities [Archard 1980]. Rabinowicz defined the computation and quantitative assessment of the wear coefficient in The Wear Control Handbook published by ASME [Rabinowicz 1980]. To best describe his definition his writings are included below explaining steps to determine k.

"The first step in the quantitative assessment of wear lies in the computation of the wear coefficient, k, the nondimensional constant in the wear equation. Once the wear coefficient has been obtained, it may be used in a number of ways.

1. To estimate the life of some sliding system. This is the most important use [according to Rabinowicz], and principal limitations are due to the relatively wide scatter and uncertainties associated with the wear coefficient, which introduce corresponding uncertainties in predicting wear life.

2. To determine the type of wear in a system. This use is based on the fact that different types of wear have different rates of wear. In some cases, it becomes clear, simply by considering the magnitude of the wear coefficient, that wear is abrasive rather than adhesive.

3. To determine the type of motion. Sometimes it is possible, by computing the wear coefficient, to determine if sliding is occurring as the result of vibrations or of thermal cycling in a clamped joint, for example

4. In composite systems that are well run-in, it is possible to compute the stress distribution only by knowing the various wear coefficient values which determine the stress directly."

Rabinowicz continues, "It should be noted that quantitative wear analysis is still in its early stages, and the uncertainties associated with wear rate predictions are quite large. Thus, the techniques are more useful in considering design alternatives than in accurately predicting the life of a sliding system."

Rabinowicz stated in reference to the Holm equation (2.1) and the Archard Equation (2.6) where,

$$V = \frac{kLS}{H} = \frac{k'LS}{3H} \tag{2.7}$$

and,

$$k = \frac{k'}{3}. \tag{2.8}$$

"A number of general comments about equation [2.1] should be made. First, although both the Holm and the Archard formulations considered the transfer of wear particles from one surface to the other, in almost all practical situations we are concerned with the formation of loose particles removed from each surface. It has been found that the same equation governs both processes, but with different wear constraints.

Second, equation [2.1] is generally considered to give the amount of wear removed from the softer of the two sliding surfaces and a separate relationship must be found to give the wear from the harder surface. [The method used to quantify this wear is to calculate the wear coefficient using the hardness of the harder material and the amount of wear measured in the harder material, Equation 2.9 [Bhushan 1999]]

$$k_h = \frac{V_h H_h}{LS} . \qquad \textbf{(2.9)}$$

Third, equation [2.1] does not disclose any obvious limits to the values of the wear coefficient. In Holm's equation, he considered that in many circumstances adhesive wear stops when a monolayer of atoms transferred from one sliding surface covers the other surface. This yields a maximum wear coefficient value of 10^{-5}, and it is now known that this is much too low to be a realistic upper limit. Archard defined k', as a probability, which suggests a maximum, value for k' of 1.0, and hence [a k value] of 0.33 [Equation 2.8]. This value, indeed, is never exceeded. A different type of analysis, in which it is assumed that the formation of wear particles is associated with severe plastic deformation, suggests that if k' were greater than 1, more work would have to be done in producing wear particles than is available via the friction process. Thus an upper limit of 1.0 for k' is plausible whether or not the Archard model is correct.

There are no obvious lower limits for the wear coefficient. It is not clear why there has to be a nonzero value of k at all. However, it must be added that, as a practical matter, all sliding surfaces that have been studied lead to the formation of a measurable amount of wear, and hence of a finite value of the wear coefficient."

Rabinowicz also comments on and tests the reliability of tabulated wear coefficient values [Rabinowicz 1980]. These tests were of 240 sliding systems including metals, lubricants and other variables. For each system, the measured wear coefficient was computed and then compared to the tabulated wear coefficient values. A ratio of the measured value to the tabulated value ($k_{measured}/k_{table}$) was calculated to find any correlations between the values. Rabinowicz shows the results of this study in the histogram seen in Figure 2.6.

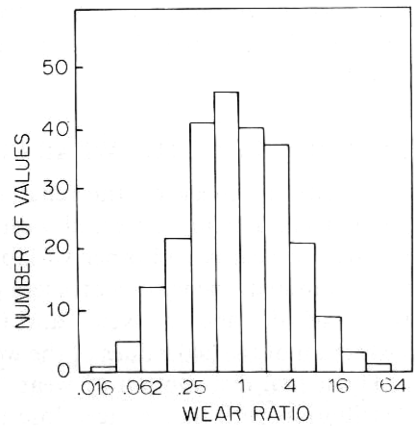

Figure 2.6 Histogram showing the distribution of measured wear coefficients from [Rabinowicz 1980]

From the data, it is evident that on average, the tabulated value is close to the measured value or has a ratio near 1.0. The standard distribution of the data is near the width of two columns in Figure 2.6 or a factor of 4.0. Rabinowicz points out that if the tabulated values are used to select a large number of wear coefficients, 68% of the tabulated values will fall to within a factor of 4.0 of the actual measured value, 95% of the tabulated values will be within a factor of 16.0 of the measured values. This indicates that, when predicting wear it is difficult to have high accuracy in the calculated numbers. It also tends to show that a wear coefficient value must be calculated for each specific application for there to be any significant accuracy in the predicted values.

2.1.8 Abrasive Wear

Abrasive wear occurs when asperities of a rough or hard material slide against a softer material causing damage to the surface of the softer material. This damage differs from Adhesive wear because it is in the form of plastic deformation, forming grooves in the surface. In the case of a ductile material, the plastic deformation due to wear is greater than in the wear of brittle materials and can form a trench where the wear occurs.

In brittle materials, the wear occurs as brittle fracture of the material. This brittle fracture is evident in the wear zone, where there is significant cracking [Bhushan 1999].

There are two general cases for abrasive wear, as seen in Figure 2.7. The first case is where one surface is harder than the other of the two mating surfaces' (a). This is called two-body wear because there are only two surfaces interacting. This is commonly the case in the manufacturing processes of filing, sanding, grinding or honing. The second case is where the hard surface is a third body, usually a small particle abrasive, which is caught between the wear surfaces to cause wear (b). This form of wear is called three-body wear because of the third material. This form of abrasive wear is used in manufacturing processes, such as lapping and polishing. In the above-mentioned manufacturing process, the wear of the surface is desirable. This is not always the case as the abrasive may be a foreign particle or may be a hardened particle that has flaked off one of the joining surfaces.

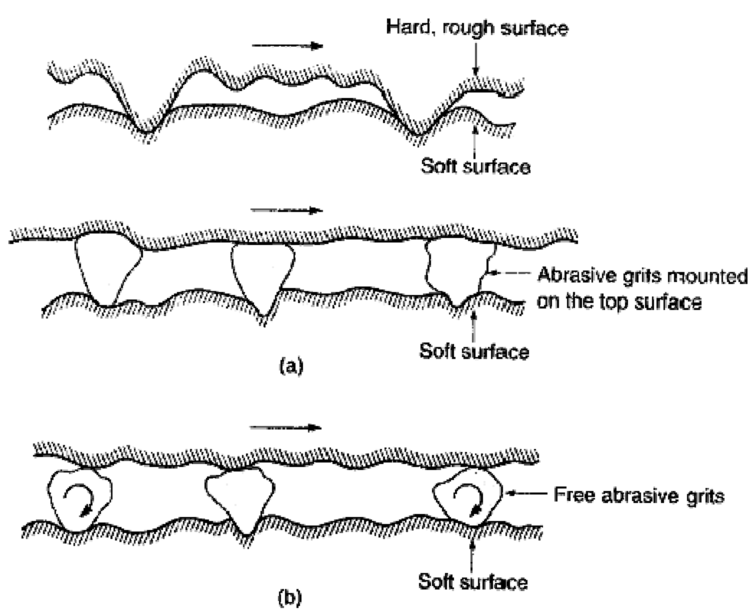

Figure 2.7 Schematics of (a) a rough, hard surface or abrasive particle mounted to the top surface sliding along a softer surface and (b) free rolling or sliding abrasive particles caught between surfaces. At least one of the surfaces is softer than the particles. Taken from [Bhushan 1999]

2.1.8.1 Quantification of Abrasive Wear

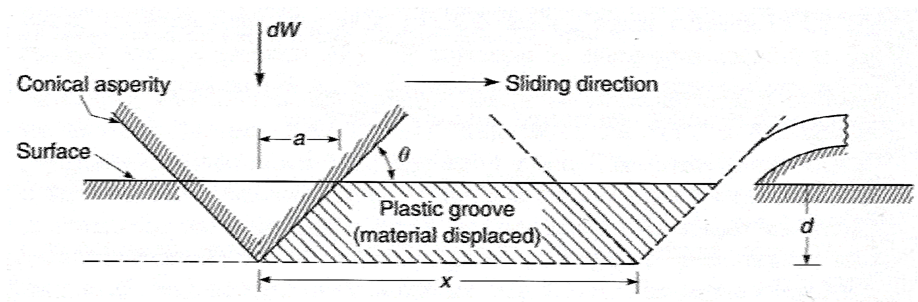

Figure 2.8 A hard conical asperity in contact (sliding) with a softer surface in abrasive wear taken from [Bhushan 1999].

Rabinowicz explained the method to acquire the quantitative expression for abrasive wear [Rabinowicz 1965]. He first considered a simplified model, where the asperities of the harder material are assumed to be conical. The softer material surface is assumed to be smooth with no asperities, Figure 2.8 (refer to Bhushan 1999). The asperity is shown creating a groove track of depth, d, and a width, 2a, in the softer material. As Rabinowicz assumed, the material has yielded under the load of one asperity δL; therefore:

$$\delta L = \pi a^2 H \, . \tag{2.10}$$

Where H is again the hardness of the softer surface. The volume displaced in the distance S is:

$$\delta V = a^2 S \tan\theta \, . \tag{2.11}$$

From equations 2.10 and 2.11:

$$\delta V = \frac{\delta L S \tan\theta}{\pi H} \, . \tag{2.12}$$

Thus, the total displaced volume by all the asperities becomes:

$$V = \frac{LS(TAN\theta)}{\pi H} \, . \tag{2.13}$$

Where TAN θ is a weighted average of tan θ values of all the individual conical shaped asperities. Rabinowicz termed this the roughness factor [Bhushan 1999].

Rabinowicz points out that this equation is similar to the Archard equation (2.6) where TAN θ /π = k/3. He calls this, the abrasion wear coefficient or $k_{abr,}$ which leads to:

$$V = \frac{k_{abr} LS}{H}. \qquad \textbf{(2.14)}$$

Where k_{abr} is again a nondimensional wear coefficient. It includes the geometry of the asperities and the probability that the given asperity removes material rather than plows material. The Archard equation can thus be used in abrasive wear calculations using the abrasive coefficient of wear k_{abr}. This is the case of two-body and three-body wear. According to Rabinowicz, however, the abrasive particles in three-body wear spend about 90% of their time rolling and 10% sliding [Rabinowicz 1961]. This reduces k_{abr} by an order of magnitude for three-body wear. [Bhushan 1999].

2.2 CVT WEAR THEORY

A survey of the above wear theories and initial study of CVT wear indicates that the wear mechanisms probably align best with either the Adhesive (Sliding) wear or Abrasive wear theories. The reason for this is that sliding is the mechanism causing the wear, but abrasive particles can be in the belt material abrading the surface. Two wear theories are selected instead of only one, because it is not known if the wear in a CVT is unique to either an abrasive or sliding phenomenon. Testing may indicate which of the theories is occurring. Rabinowicz points out, that once the wear coefficient has been calculated, its value may indicate the form of wear [Rabinowicz 1980]. In addition, the similarities between these theories of wear indicate that hardening of the material may prevent either of these wear methods from occurring. This is seen in the equations of wear presented, that increasing the hardness of the material reduces the volume of wear.

2.3 HARDENING

As was just stated, analyzing the wear theories and equations indicates that wear is dependent on the hardness of the material. This hardness (H) spoken of in Archard's Equation relates to the material's hardness. In this Thesis we are investigating whether or not the Archard Equation accounts for wear when the material's surface becomes harder through processing. There are no explanations as to whether the Archard Equation will still predict wear when the substrate (base material) is softer than the surface of that material. If the Archard Equation holds true, changing the hardness of the surface may reduce the wear volume produced in an adhesive or abrasive situation, while the desired material properties of the substrate are retained. This knowledge is significant because of the implications surface treatments may have on wear characteristics. This notion is also important to this research because, as has been hypothesized, by changing the hardness of the surface of the CVT, it may be possible to reduce the wear occurring on the sheaves.

2.3.1 Anodizing

When dealing with an aluminum part, especially in a harsh environment, anodizing is commonly looked upon as the solution to seal the aluminum and protect it. Anodizing has become a cost effective method to increase the abilities of the aluminum because it forms a hard layer on the surface. Anodizing has made possible the implementation of aluminum in areas where it was not considered possible [Danninger 1992]. The versatility of anodizing naturally makes it a candidate for solving this issue of sheave wear.

Anodizing is an electrochemical process where a layer of hard Al_2O_3 (Aluminum Oxide) is intentionally formed on the surface of the Aluminum part. It forms a hard (8 out of 10 on the Moh's scale for pure Aluminum Oxide [Budinski 1999]) protective ceramic layer for the aluminum substrate preventing corrosion, of the aluminum part. This oxide layer is formed when oxygen molecules are caused to bond with the aluminum molecules at the surface of the part being anodized. The anodizing process is a method of controlling this oxidation reaction of the aluminum and also controlling the thickness of the oxide layer.

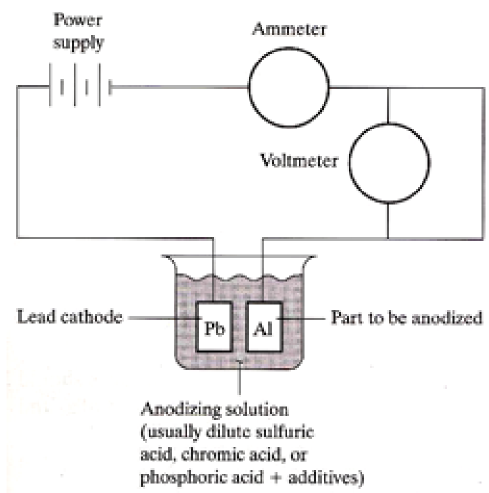

Figure 2.9 Schematic showing an anodizing set up. Taken from [Budinski 1999]

The anodizing process is multi-step requiring specific current densities, materials and bath solutions. A summary of the processing steps of anodizing are [Jobshops 2003], first place the aluminum part in a cleansing bath to remove the natural oxide layer that exists on the surface of the part. Second, run a current through the aluminum while it is in a sulfuric acid bath to cause the aluminum to form an oxide layer. The processing variables are current density (typically 8 to 11 Amps/ft^2) and acid bath temperature (typically 70 to 75^{o}F). In addition to these variables, the duration in the bath also determines the thickness of the layer.

It must be noted that the formation of an Aluminum Oxide layer occurs naturally. This natural layer also protects the aluminum from its environment, but to a lesser extent when compared to an anodized layer. Aluminum naturally is a reactive material, which corrodes quickly forming aluminum oxide, but this corrosion actually protects the aluminum, making it an ideal choice for corrosive environments. Aluminum oxide is unlike iron oxide, which forms on steel, but with low surface adhesion properties. Aluminum oxide molecularly bonds to the surface sealing it from its environment. The new layer of aluminum oxide is inert to its environment. As this layer wears or is removed, the newly exposed aluminum quickly forms a new oxide layer, which is again corrosion resistant [Jones 1996]. The most significant difference between natural Aluminum Oxide and anodizing is that the formation of the oxide layer is controlled. The thickness and uniformity of the oxide layer may be engineered to meet specifications for its use.

Anodizing is different from other surface hardening or material protecting techniques because the surface is part of the original substrate. It is unlike surface coating processes, such as powder coating or electroplating, where the coating material relies on adhesion to the coated surface. Anodizing is a molecular bond between the aluminum and the oxide layer. This means that the adhesion of the surface layer has similar characteristics to the rest of the aluminum substrate. The anodized layer does not easily flake off or chip, as do other coatings. The anodized surface becomes part of the original aluminum. The anodized layer penetrates the surface of the aluminum, again different from other surface coatings.

For most aluminum alloys, anodizing increases the size dimensions of the part by one-half of the thickness of the anodized layer (Figure 2.10). For example, if the anodized layer is 0.001 in. thick, half, 0.0005 in. of the layer is on the surface, and 0.0005 in. of the layer has penetrated below the surface. This causes a problem when an anodized layer is removed. The original part dimensions can not be restored because some of the layer is below the surface and the part is now undersized. [Abbott 1994].

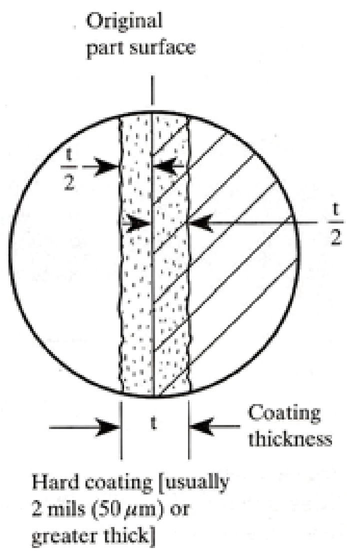

Figure 2.10 Representation of the anodized surface and penetration taken from [Budinski 1999]

2.3.2 Hardcoat Anodizing

Anodizing has three categories or types, type I, II, and III. Type III, traditionally called “Hardcoat Anodizing,” is thicker and denser (harder). A harder surface, assuming the Archard equation holds true, should increase the wear resistance of the part. It has been found in the literature that in applications where wear resistance is a factor, but the strength and weight characteristics of aluminum were also desired, Hardcoat anodizing was typically specified [Mil-A-8625F]. Even with this knowledge, the effects of Hardcoat anodizing on a CVT is not known. As was stated earlier, wear must be examined on a case-by-case basis to fully understand its effects. Hardening of the material does not guarantee improved wear resistance, although this has shown to be the general trend. As will be explained in the following section, the composition of the aluminum alloy has a significant effect on the anodizing process and its ability for improved wear resistance. Before this discussion, we should understand the differences between conventional anodizing and Hardcoat anodizing.

The process of Hardcoat anodizing is different from “conventional” anodizing as described above. The process current density, which controls the oxidation formation on the surface of the aluminum, is higher: 19 to 33 Amps/ft^2 as compared to 8 to 11 Amps/ft^2 in conventional anodizing. Increasing the current density increases the amount of oxygen in the bath. More oxygen enables for more aluminum oxide to be formed. In addition, the temperature of the operating bath must be lower, between 32 to 50^{o}F as compared to 70 to 75^{o}F in conventional anodizing. It has been found through testing that decreasing the temperature of the bath increases the hardness of the anodized layer [Thomas 1981]. These differences between Hardcoat and conventional anodizing cause the resulting oxide layer to be considerably denser and thicker [Abbott 1994]. Typical Hardcoat anodized layers are 0.002 in. thick (0.001 in. build up on the surface and 0.001 in. penetration).

2.3.3 Anodizing vs. Alloy composition

Anodizing and Hardcoat anodizing are effective on many different aluminum alloys because many of the elements used in alloying form an oxide layer similar to that of the aluminum. It is however unfortunate that not all alloying materials react to the anodizing process as well as pure aluminum. In fact, some alloy materials cause adverse affects. Hecker explains [Hecker 1986] there are alloys which are beneficial to anodizing and those that are detrimental.

Die cast aluminum alloys are different from most wrought aluminums. Certain alloying elements increase the cast-ability of the aluminum. For example, increasing the silicon content of the aluminum increases the ability of the molten metal to flow. Hence most die-cast aluminums have a considerably high (>5%) percent silicon [Matweb 2003].

The problem with these alloying elements is the reaction they have during the anodizing process. Silicon does not conduct electricity (inert) and therefore does not anodize. Copper is another alloy that is detrimental to the anodizing process, because it dissolves, causing the anodized layer to become soft and powdery. Since anodizing is a reaction occurring on the surface, if these alloying elements are on the surface, they cause the anodized layer to be either soft or porous [Abbott 1994].

The material used in die-casting the CVT drive to be studied is 390 die-cast aluminum, which alloying elements and percentages are listed in Table 2.1. For comparison, the alloying elements for 6061 aluminum, a commonly anodized material are also included. As can be seen, 390 aluminum has alloying elements that are detrimental to the anodizing process. The question therefore remains; can 390 die-cast aluminum Hardcoat anodize sufficiently to reduce the wear of pulley sheaves? In 1995 Luke Engineering Inc. of Ohio claimed the ability to Hardcoat anodize die-cast aluminum parts [Anon 1995]. Through a different anodizing process, where proprietary additives are introduced into the acid bath, they claim to have the ability to overcome the alloying elements which traditionally cause difficulties. If correct, 390 die-cast aluminum may be Hardcoat anodized to have the required wear resistance to reduce sheave wear.

Table 2.1 Table showing the composition of 390 die-cast aluminum. The alloy composition for 6061 Al is also shown for comparison. Taken from [matweb 2003]

Element	Cr	Cu	Fe	Mg	Si	Ti	Mn	Zn	Al
390 % weight	-	4-5	Max 1.3	0.45-0.65	16-18	Max 0.2	Max 0.1	Max 0.1	Bal
6061 % weight	.04-.35	0.15-0.4	Max 0.07	0.8-1.2	0.4-0.8	Max 0.15	Max 0.15	Max 0.25	Bal

2.4 ABRASION RESISTANCE

We have discussed the fact that anodizing, and especially Hardcoat anodizing, has abrasion resistant characteristics, but what does it mean to be abrasion resistant? What are the characteristics of a surface, which contribute to abrasion resistance? How does Archard's equation relate to abrasion resistance, when no component in the equation accounts for abrasion resistance?

Abrasion resistance can be thought of as the ability of a surface to resist wear. This may seem simple, but the ramifications of abrasion resistance of a particular surface coating can be significant. Available coatings often influence the application and selection of materials. For example, painted or powder-coated carbon steel parts can be implemented in a corrosive or harsh environment in which the base steel normally could not be used. If not for the coating, a more expensive alloy may be required. Coatings used for abrasion resistance are similar to this example. They allow a material that has a lower abrasion resistance to be used in an abrasive environment.

Hardcoat anodizing is an abrasion resistant coating, which has been tested under different processing conditions to find methods of even further improving its wear resistance [Thomas 1981] [Rasmussen 1996]. Testing the relative wear resistance is not as simple as testing the material's hardness as the Archard equation would suggest. The hardness of the anodic coating is not found using traditional methods of indenting the surface with an applied load. The difficulty is that the substrate is much softer than the surface coating. The indenter does not isolate the coating; the substrate also influences test results, misrepresenting the hardness value for the coating.

Thomas explains the need to know the abrasion resistance of anodic coatings [Thomas 1981]. He correlates the abrasion resistance with the hardness of the surface, which means a higher abrasion resistance corresponds to a harder surface. He realizes however, that the relation between hardness and wear resistance is not always correct especially between different materials. He sites a test from 1961, where it was found that hard anodizing often had a wear resistance better than tool steel, which had a higher *measured* hardness.

2.4.1 Abrasion Testing Equipment

There are difficulties in determining abrasion resistance because of the differences in abrasive materials. Generally, it would not be difficult to remove a surface coating using a very hard, abrasive material. Such a test would run for a short duration, but may not be long enough to clearly differentiate the wear resistance between the tested coatings. The inverse is also true, where an abrasion resistant material may not show indications of wear for an extremely long duration. The abrasive media was either softer than the tested material or not hard enough to abrade the surface. This has led to the production of abrasion testing equipment. Many wear tests have been created to mimic wear in particular applications, though there are as many wear testers as there are wear applications [Bayer 1994]. To find more information about current wear testers, refer to ASTM standard G99-95a.

The Taber Abraser is one type of testing equipment produced by Taber Industries. It is an abrasion tester, which rotates a sample flat disk or plate as standard abrasive wheels scuff the surface removing or wearing the material. The sample is weighed before and after the test to find the difference in weight due to wear. This difference in weight is called the Wear Index, which indicates the Abrasion resistance through equation 2.15 as given by Thomas [Thomas 1981].

$$\text{Abrasion Resistance} = 1/\text{Wear Index} \quad \textbf{(2.15)}$$

A higher abrasion resistance number indicates a lower weight loss. One weakness of this abrasion resistance number is that it does not take into account wear resistance over time. A coating may begin very resistant to wear, but later become not resistant at all. This may not show any difference than to a less wear resistant material when the test is averaged over time. To prevent such a disparity, measurements of weight must be taken periodically during the test to map out measured wear resistance over time.

2.5 Methods of Measuring Wear Volume

A critical aspect of performing wear tests is being able to measure the actual amount of wear that has occurred over time. This helps to characterize what is occurring as the aluminum wears. It is possible to understand the rate of wear as the wear groove increases by analyzing the measured wear at certain intervals.

There are various methods for measuring wear. As explained by Ravikiran the common variables to quantify the amount of wear are [Ravikiran 2000]:

1. Wear (V): volume loss-m^3
2. Wear rate (w): volume loss (m^3) per unit of sliding distance (m)-m^3/m

3. Specific wear rate: volume loss (m^3) per unit of sliding distance (m) per unit applied load (N)-m^3/Nm
4. Wear Coefficient: This is similar to specific wear rate except that it is multiplied by room temperature hardness (H)- m^3H/Nm, a non-dimensional number
5. Normalized wear rate: wear rate (w) divided by apparent contact area (A)- w/A a non-dimensional number

These methods may be appropriate for different wear scenarios. For some test methods, the inverse of weight loss indicates the wear resistance, which can be converted to volume loss. For others, where one material is adhering to the other, methods that incorporate measuring a change in weight may not yield accurate results. The results of such tests may actually indicate a weight gain as has been found in some adhesive wear tests [Maejima 1998]. This weight gain may inaccurately represent the wear of the material. For such test results, a method of measuring the wear of the test material that is independent of weight is important to represent correctly the wear of this application.

2.5.1 CMM

A Coordinate Measuring Machine (CMM) takes measurements by using a stylist or probe. The stylist touches a feature on the part and senses its location to within 0.0001 of an inch. The stylist records the position of the part in relation to the surface of the part and references this surface to a known origin. The CMM continues to do this until the data taken represents the surface of the part. Because only the surface profile is measured, the CMM is a machine that can measure the wear of the sheave independent of its weight.

2.5.2 Determining Wear Volume

Determining the amount of material removed during a wear test enables a comparison to be made between separate test samples. The depth of a wear groove can be determined though measuring the surface and calculating the difference from the original surface. For round test samples using one wear path, the depth of the wear groove will be near constant, therefore the average of multiple measurements of the sample can accurately portray the wear path. A representation of the wear groove can then be constructed into a two-dimensional area using a CMM.

The data from the CMM can be used to calculate the volume of wear when imported as points along a plane into a CAD, (Computer Aided Design) program. Since the CMM data is along one plane (straight line), the CAD program creates a representation that is a two-dimensional area. When this area is revolved around a center axis, it represents a three-dimensional volume, or the wear volume. The CAD program can determine the size of the wear volume graphically represented. This information allows for the volumes of multiple wear grooves to be compared and relative wear resistance determined, independent of sample weight.

2.6 SUMMARY

The investigation into the theories of wear and the research of previous work indicated:

1. There was little information concerning the interaction and wear between aluminum and composite rubber belt. In addition, there was no prior work found investigating the wear of the aluminum when in contact with a composite rubber belt.

2. The Archard Equation is the most common generalization for calculating the wear of a system. This equation also requires a wear coefficient, which is a number specific to the materials in contact. There is no documented wear coefficient for 390 die-cast aluminum in contact with composite rubber.

3. The theory behind the Archard Equation is the basis for considering Hardcoat anodizing as a method for improved wear resistance of 390 die-cast aluminum. This theory being, that the volume of wear is inversely proportional to the hardness of the materials in contact.

4. That there was no documentation or research, which correlated the relative wear resistance of a Hardcoat anodized surface to its parent material. Specifically between 390 die-cast aluminum base material and Hardcoat anodized surface.

5. The hypothesis of this Thesis will add to the general knowledge of wear, determining whether Hardcoat anodizing can increase the wear resistance of 390 die-cast aluminum in contact with a composite rubber belt.

CHAPTER 3 TEST PROCEDURE

To test the hypothesis of using Hardcoat anodizing as a method of reducing the wear in a CVT, it is important to reproduce the wear in a controlled setting. This chapter describes the proposed methods for testing, producing and measuring wear. This chapter also explains the basis of the proposed testing methods, and references for further information.

The main objective for laboratory testing was to repeatedly test parameters in a controlled environment. It was not cost effective to run preliminary tests on a fully functional CVT, so initial testing conducted on test stands was implemented to represent the wear occurring in a CVT. Initial testing with a Pin-on-Disk and Taber Abraser test stands produced information into the wear characteristics of 390 Aluminum and surface hardened aluminum. While these tests did not duplicate the actual application in its entirety, previous research has shown that the quantitative behavior should be similar if the same materials are used for each test [Lepper 1997].

3.1 PIN-ON-DISK WEAR TEST (ASTM G99-95A)

In wear testing there are test standards, which are intended to mimic actual service, although it is often difficult to reproduce all scenarios. Therefore, it is desirable to select a test that can reproduce as many parameters as possible. A survey of standard wear tests yielded the ASTM standard G99-95a Pin-on-Disk as a likely test method to incorporate into CVT wear testing because of the similarities to an actual CVT as will be explained.

The ASTM G99-95a, Pin-on-Disk wear test standard requires two test specimens (see Figure 3.1). The first is the pin of a prescribed form and size. The second specimen is usually a flat circular disk, which is spun about its center. The pin and disk are brought into contact usually though the use of an arm or lever and weights. The contact is held constant for a prescribed time duration or linear distance. The amount of wear for each specimen is then measured, through either volume or mass loss. Material permitting, the test can be repeated with the materials for the pin and disk exchanged to determine any effects caused by geometry [G99-95a].

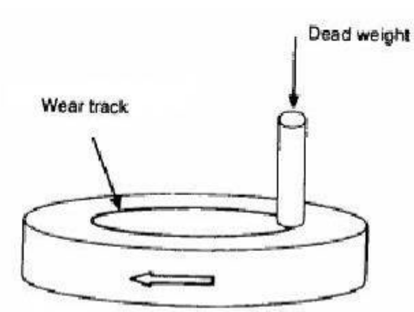

Figure 3.1 Representation of Pin-on-Disk test setup

This standard test method, we believe, may be similar to the sliding motion of the belt against the sheave. The Pin-on-Disk test has many parameters that, when controlled, can mimic parameters of an actual CVT. Beyond these similarities, the advantages of conducting a Pin-on-Disk test are:

1. The CVT sheave can be used as the disk, representing production parts.
2. The disk's rotational motion for the test is similar to a CVT.
3. The belt can be used as the pin material held stationary.
4. Accelerated wear test with 100% sliding between pin and disk.
5. The test parameters are repeatable and controllable.

3.2 MODIFIED PIN-ON-DISK

The ASTM G99-95a Pin-on-Disk wear test was the basis of the test stand designed to reproduce the wear of a CVT (Figure 3.2). The pin was a section of composite rubber belt, through which a load was applied to the disk using weights hung from an arm. The disk was the stationary sheave from a CVT. This disk was rotated at a prescribed speed (RPM) and the number of revolutions were counted. The number of revolutions were then converted to sliding distance of the pin on the disk using equation 3.1.

$$S = 2r \times \pi \times rev \qquad \textbf{(3.1)}$$

Where S was the total sliding distance, r was the radius from the center axis to the pin and rev was the total number of revolutions. An arm pivoted above the disk and weights were hung from one end to cause an applied load to the belt on the disk.

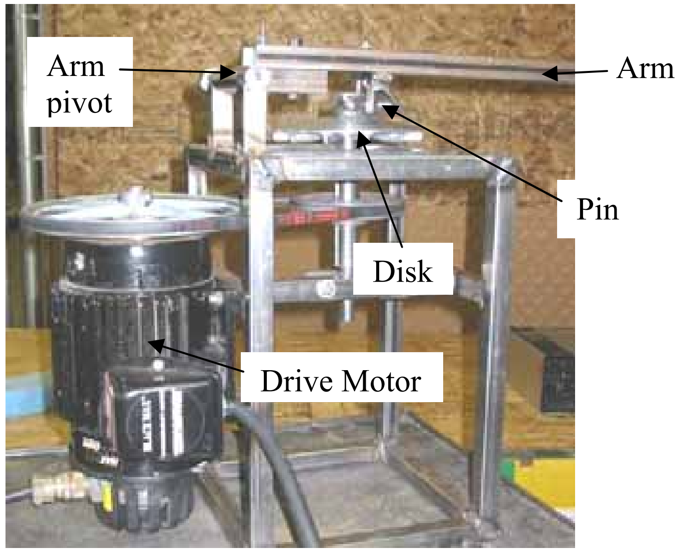

Figure 3.2 Pin-on-Disk CVT belt test stand

This setup deviated slightly from the standard Pin-on-Disk test set up. The first difference was that the pin was not a cylindrical pin with a radiused tip as specified. The belt material was not rigid enough to be in the shape of a pin as the standard describes. Once a load was applied, the belt (pin) would deflect and the results would not be accurate, meaning the loading conditions of the belt would not represent the actual belt loading that occurs. To remedy this problem, a section of belt was cut to 2.25” in length. A fixture was made to cause the belt to have a curvature to match the curvature in an actual application, (see Figure 3.3). Through this fixture, the load was also applied from the weight to the belt and onto the disk.

Figure 3.3 Image showing the pin (belt sample) in the curved fixture which caused it to have the same curvature as the radius of the sheave

The shape of the disk or sheave was also slightly different from the ASTM standard. The CVT sheave is manufactured with an angle, which is intended to mate to the side of the v-belt profile. When the two sheaves are together they make the signature “V” where the inner diameter of the sheaves are near together and the outer diameter of the sheaves are farther apart, (Figure 3.4). Using one sheave as the disk and with it running on a horizontal plane, the shape was no longer a “V”. The middle of the sheave was crowned with the slope going downward and outward (refer to Figure 3.5). It was not a flat surface of a typical disk used in a Pin-on-Disk test. This was acceptable because the belt/sheave interaction was similar to interaction in a CVT. The test was also a comparison between different sheave materials and will be loaded in the same manner.

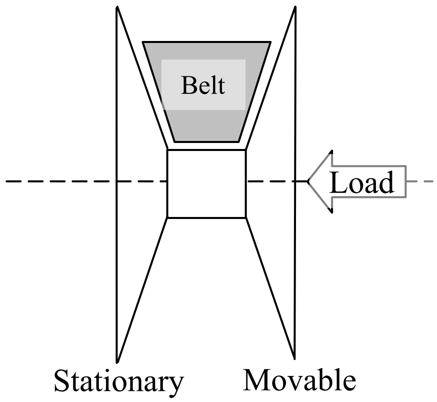

Figure 3.4 Schematic showing two sheaves together, in a "V" shape.

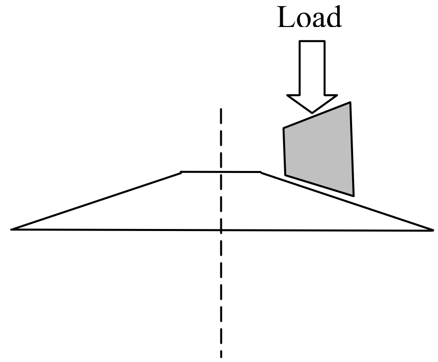

Figure 3.5 A simplified schematic of the Modified Pin-on-Disk test setup. The contact of the belt and sheave are the same as in Figure 3.4. The load is variable

The shapes of the belt and sheave were designed to conform for maximum power transmission. The belt was angled along the sides forming a "V". The belt, like the sheaves, was narrower in the inner-cord (inner diameter) and wider at the outer-cord, (refer to the image of the belt in Figures 3.4 and 3.5). The angle of the belt was near, if not the same as the angle of the sheave. When rotated about a vertical axis (as set up on this test stand), the angles still matched and a vertical load was applied to mimic the actual setup. This meant that the loading of the belt and sheave were similar to what occurs in the actual application. These modifications in many ways, mimicked the CVT, but the simplicity of the Pin-on-Disk was still implemented into the test.

Although in many ways the Pin-on-Disk test set up was similar to the actual CVT application, there were differences between the interaction of the belt and sheave surface.

1. In a CVT, the belt is continuously moving through the sheave. Slipping occurs for a short duration and "fresh" belt material is moving through the system. In this test the belt or pin was fixed.

2. The belt translates along the sheave surface from inner diameter to outer depending on the position of the movable sheave. This motion clears the surface of debris preventing other material adhesion. On the Pin-on-Disk stand, the belt was a fixed distance from the axis of rotation.

The disk was driven by a 2 hp AC adjustable frequency drive motor. The RPM was controlled through a Danfoss VLT® 5000 controller. The total number of revolutions was read using an infrared emitter and detector, which are fed into a data acquisition box.

3.3 TABER ABRASER

An additional method used to test the wear resistance of the CVT material was though the use of a Taber Abraser. This test indicated relative wear resistance between test materials, producing quantifiable results. The Taber Abraser did not reproduce the actual belt/sheave interactions seen by a CVT, but it was learned through a phone conversation with Mike Clark [Mike Clark 2003], a testing engineer with Litens in Canada, that even though the conditions are in some ways dissimilar, it can still be a valid test. He claims that the percentage of difference in wear resistance will be the same for the Taber test and the actual application. For example, if hardening increases the wear resistance by 25% over the base material in the Taber test, it will then increase the wear resistance by nearly the same percentage in the actual application.

3.3.1 Taber Test Samples

The Taber Abraser requires specific test sample dimensions for the test to run properly. These requirements are a 4 to 4.25 in. diameter flat round disk (the test sample may also be square) no thicker than 0.25 in. with a 0.25 in. hole drilled in the center for mounting purposes. A number of 390 aluminum samples were pour cast and then machined to within the Taber size constraints.

Half of the samples remained in their as-machined configuration. The remaining samples were sent to Luke Engineering Inc. of Wadsworth, Ohio, to be coated because of their proprietary Hardcoat anodizing process that is specific for die cast aluminum alloys [Anon 1995]. This process touts the ability to produce a thicker anodized layer than traditional Hardcoat anodizing on die-cast aluminum. The samples were specified to have a 2 mil (.002 inches) thickness anodizing layer, the average thickness for a Hardcoat layer.

3.3.2 Taber Abraser Test Setup

Typical Taber tests compare the wear resistance of a sample of material to known acceptable wear values written in specifications. These tests are not often used for comparison wear tests where the wear resistance of one surface or material is compared to another surface or material. The reason that comparative tests are not often conducted is the interaction of the test surface or material to the abrasive wheels. Meaning, the abrasive wheels may load with the test material (the test material may adhere to the surface of the wheel) and reduce or change the rate of wear. When this occurs the material's wear resistance may be misrepresented due to changes in the abrasive test wheel. This was confirmed through a phone conversation with Alan Jaenecke of Taber Industries [Alan Jaenecke 2003].

To best conduct a comparative test, an H-18 wheel set was selected for the Taber Abraser test because of its potential to negate the effects of loading. The H-18 is made of a vitrified material which is hard and brittle. It was determined that the wheel would breakdown at a high enough rate to prevent loading from occurring. Therefore, the base material and Hardcoat anodized test samples could be tested using the same wheel set, keeping parameters constant.

The test samples were run under 1000g and 250g loading comparing the effects for each scenario. The 1000g test was conducted for 2000 revolutions where the 250g test was conducted for 5000 revolutions. This was done because of the lower wear rate of the 250g test. It was intended to allow sufficient wear to occur that the differences between the base material and Hardcoat anodized surface would be evident. The samples were weighed at intervals of the test using an Acculab VI-1mg scale with a resolution of .001g. This enabled the measuring of the wear, which occurred during the tests.

3.4 FULL CVT TESTING

In order to substantiate the results from tests conducted in a lab, production parts were tested and the results documented. These tests fully represented wear that occurs on the surface of the aluminum CVT. Two tests were conducted, one on a dynamometer test stand using a full CVT, drive and driven and the second on an ATV. These tests were for a comparison between the base material and the Hardcoat anodized surface.

3.4.1 Dynamometer Full CVT Testing

The first full CVT test incorporated a dynamometer to induce a load in a similar manner to an actual scenario. The dynamometer was configured to control the pulley RPM and thus the sheave position. This control allowed the test to be very repeatable between the two test samples. This test utilized a production drive and driven pulley system with a production belt as in an ATV application. Only the drive pulley was modified with the Hardcoat anodized surface. All other components remained in their stock configuration. The combination of weights and springs between the base drive pulley and the Hardcoat anodized pulley also remained constant. Because of the potential duration of this test, components such as bushings and weights were replaced if they began to have an effect on the performance of the system.

3.4.1.1 Dyno Configuration

A simple schematic representing the dynamometer set up is shown in Figure 3.6. The drive pulley was connected to a Sportsman 700 Polaris ATV engine to power the system. The driven pulley was connected to a Super-flo water-brake dynamometer through which resistance or load was induced. The system was set up such that the dynamometer controls the amount of load in the system and the engine compensates for the required RPM setting. As the dynamometer changed the loading, the system was required to adjust, wherein belt slip occurred. The system ran through a preprogrammed cycle of various loads and RPM. This allowed the belt to travel up and down the sheave face and induced slipping on the pulley.

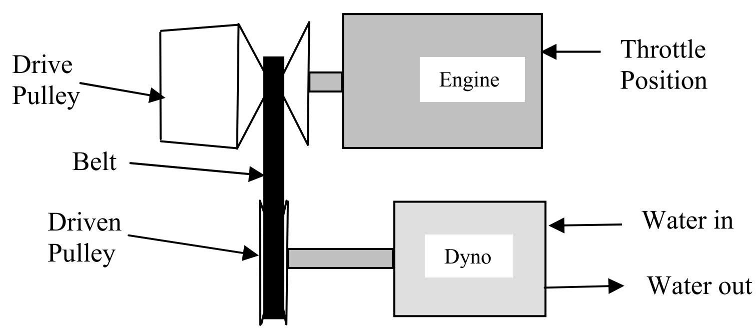

Figure 3.6 Schematic showing water-brake dynamometer.

3.4.1.2 Test Procedure

The stock aluminum drive pulley was run until the performance was affected due to CVT components wearing as explained. At this point, the drive pulley was replaced with the Hardcoat anodized drive pulley and run through the same dynamometer program. The components of the stock pulley were replaced to ensure that it continue to run in a consistent manner. The stock drive was prepared to replace the Hardcoat anodized pulley when its components needed replacing. The number of cycles for each run on each pulley was documented. At the end of the test, both drive pulleys had a comparable number of cycles for appropriate comparison.

3.4.2 Full CVT Wear Case Study

The second full CVT test was a comparison case study of a Hardcoat anodized CVT and Stock CVT ran on a Polaris Sportsman 600 ATV. Initially the stock drive clutch was run until measurable grooving had occurred. The length and duration of the test was recorded and the amount of wear on the sheave surface measured. The Hardcoat anodized surface was then run the same distance over the same course. At the end of this test, the sheave surface was measured and the results of the two tests were compared.

3.4.2.1 Drive Clutch Test Samples

Because of the length and duration of this case study, only two drive clutches were tested. One drive clutch had a production-machined surface (stock) to provide a baseline. The other drive clutch was Hardcoat anodized on both the stationary and movable sheaves to insure uniformity between the belt/sheave interfaces. All other parts of the drive clutches remained in their stock configuration and coatings with similar weights and springs installed to minimize the effects of external variables. This assists in focusing on the differences in wear on the sheave surfaces.

3.4.2.2 Test Procedure

The difficulty of this case study is the repeatability between clutch tests. As has been explained, the CVT system reacts to the engine RPM and the torque feedback through the driven pulley. As the terrain varies, the belt position varies to accommodate the changes in the required power. This variation causes the wear surface to locate at different diameters on the sheave face as the test is run. If the two tests are run at different wear locations, then variables such as belt contact and sheave pressure come into effect, which may cause differences in the results not related to the surface hardness.

In order to ensure that the test would be repeatable, a course was established that allowed a near constant belt position or wear surface. The ATV followed this course for each drive clutch up to the required mileage. The CVT operated in its overdrive position; meaning the drive clutch was compressed fully and the driven clutch fully apart. This belt position was repeatable because the belt can not move any further outward and the position was easily established and held as it was controlled by the limits of the ATV engine and drivetrain.

Once completed, the surface of each sheave was scanned on the CMM to graphically represent the amount of wear that had occurred. This allowed for visualization of the wear that had occurred. The measurements from the two drive clutches were visually compared and inferences made from the CMM scan. The results from this test were then compared to previous tests and correlations made to explain what occurred through the duration of the test.

3.5 WEAR TESTING SUMMARY

Accurately testing wear is difficult because of the many different interactions that may occur during the test. Proper test selection is crucial to produce results, which represent wear occurring during the actual application. The tests described in this chapter are based on research into standard testing methodology. Multiple tests were studied and test selections carefully made based on prior testing and testing standards. Different test methods were selected to substantiate the results of all the testing. These tests influenced the interaction between the wear material and Hardcoat anodized and stock aluminum surfaces.

Not all the tests described in this chapter utilized the materials or geometry found in a composite rubber belt/aluminum pulley application, however as Lepper indicated, the quantitative values would be similar [Lepper 1997]. In the case of a wear comparison between materials such as this one, the percentage of wear occurring during one test would be nearly similar to those of another test [Mike Clark 2003]. This allowed accelerated tests to be conducted, thus giving an indication as to what would occur during the actual application.

CHAPTER 4 RESULTS AND DISCUSSION OF RESULTS

To verify the hypothesis of improving the wear characteristics of 390 die-cast aluminum through a Hardcoat anodizing process, the results of the tests described in the previous chapter must be compiled and examined. These tests are designed to validate this theory through comparing the wear of an uncoated 390 die-cast aluminum surface to the wear occurring on a Hardcoat anodized surface of the same material. Understanding the test results can influence the accuracy of the conclusions and inferences made. The objectives of this Chapter are to report the results of the described tests and then discuss and interpret these results.

4.1 MODIFIED PIN-ON-DISK TEST RESULTS

Table 4.1 lists the tests conducted on the Modified Pin-on-Disk test stand. These tests include many variations of the load and RPM parameters. The variations influenced the system's temperature, especially at the contact surface of the belt and sheave. Although the parameters varied significantly, the results of each test were consistent.

Table 4.1 Modified Pin-on-Disk Tests

Pin Material	Load	RPM	Observations
Belt	133 PSI	950	Rubber adhesion on sheave, belt temp 450°F
Belt	192 PSI	3000	Rubber adhesion on sheave, 5.8 hour test duration
Belt	192 PSI	1500	Rubber adhesion on sheave, 119 hour test duration
Fiber wraps	180 PSI	1780	Sheave surface appeared to coarsen; strands broke apart.
Fiber 1 strand	312 PSI	2000	Unable to fixture strand for extended test period.

Within a small number of revolutions during the testing, it became apparent that the rubber compound from the belt was adhering to the surface of the sheave. A dark, black ring formed at the diameter related to the area of contact between the composite rubber belt sample and the sheave. Instead of wearing at the sheave surface, the asperities would load (fill) with the composite rubber compound as represented in Figure 4.1.

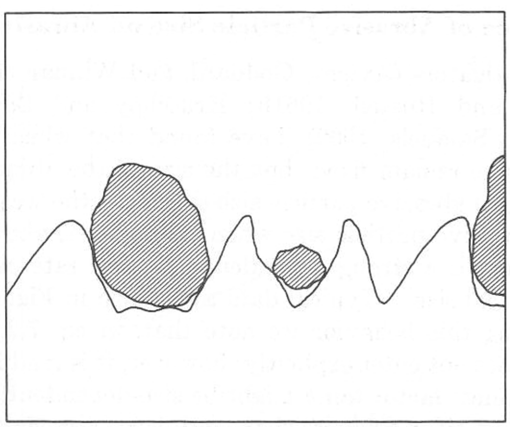

Figure 4.1 Hypothetical representation of loading taken from Bhushan 1999

This Modified Pin-on-Disk test should be considered an extreme wear test because the relative sliding between surfaces was 100%. The composite rubber belt sample remained fixed in place as the sheave rotated about an axis. Under these extreme conditions, there appeared to be another wear phenomenon occurring at the interaction surface. Contrary to results observed in actual applications, wear did not occur on the surface of the sheave even after test durations of over 100 hrs.

Continuing tests on the Modified Pin-on-Disk test stand, tests were conducted using only the aramid fibers found as a reinforcing material in the belt (Figure 4.2). These tests focused on the wear interaction caused by the fibers, eliminating the effects of the rubber. A number of mandrels or test fixtures were used to apply a load to the fibers. The loading and interaction between the fibers and sheave were again similar to the loading in an actual CVT.

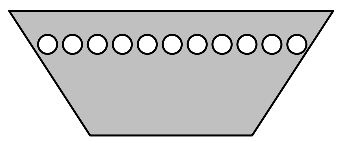

Figure 4.2 Schematic of the cross section of a belt. The aramid fibers are represented by the round white circles. The fibers run the entire circumference of the belt to increase its tensile strength.

To test this interaction, a length of fiber was wrapped around a tapered fixture in order to keep the strands together. These strands were wrapped in a pyramid fashion so a minimal number of fibers were in contact with the sheave, Figure 4.3. In a belt, the strands lay in a row (as seen in Figure 4.2) so it is most likely that only one strand is in contact with the sheave at a time. The pyramid style used here was to ensure that first, only the fiber was in contact with sheave and second, it was an attempt to allow only one strand or a minimal number of strands to be in contact with the sheave.

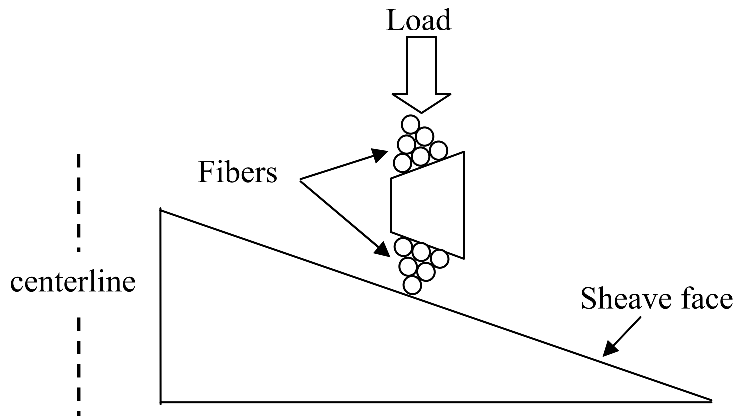

Figure 4.3 Cross section of the test setup using only aramid fibers as the pin. The dashed line represents the centerline of rotation for the disk.

It was observed that the aramid fibers would wear the sheave surface initially as the surface became visibly rough. This action also caused the surface of the sheave to become abrasive. This was evident in the fact that the sheave then began to cut or tear apart the strands until they broke. Multiple tests proved to have the same results.

In order to prevent the aramid fiber strands from breaking, another method was proposed which was to slowly feed a single stand of fiber continuously through a roller as the sheave spun pulling the strand through. This method made it possible for a new, “fresh” fiber strand to be in contact with the sheave surface, (refer to Figure 4.4). This test set up proved difficult to control because the fiber by itself had little rigidity and would deform under load. The spacing between the roller material and the sheave surface was very close and at times would contact. This set up also proved difficult to restrain the fiber strand. If the fiber was not precisely controlled as it was fed into the fixture, it could slip from the fixture, which would contact the sheave. Contact between the fixture and the sheave caused significant wear, scaring and marks on the sheave surface making the test invalid.

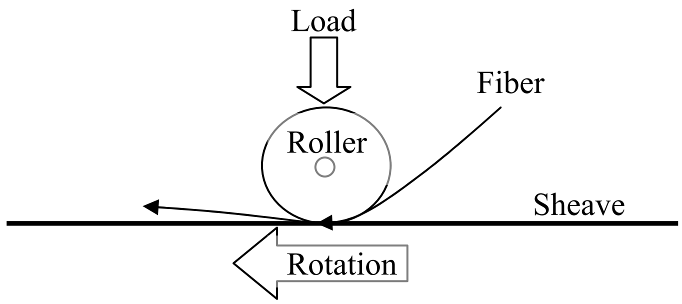

Figure 4.4 Schematic of the Pin-on-Disk test using a continuously fed strand of aramid fiber

4.1.1 Modified Pin-on-Disk Summary

The Modified Pin-on-Disk test revealed that the interaction of the composite rubber belt material and the die-cast aluminum surface was controlled by a different wear phenomenon than that seen in a CVT application. Loading of the belt material on the sheave surface was not present in the actual application. The tests using belt samples indicated rapid material loading, which blackened the surface of the sheave. This is analogous to a car tire that rolls along a road. The tire wears as is evident by the worn tread but does not leave the road black. If the brakes are locked and the tire slides, a different wear phenomenon occurs and a black streak is left on the road.

Tests focusing on the aramid fibers, which reinforce the composite rubber belt, showed indications of wear on the sheave surface initially. This wear was unsustainable as the fiber material began to degrade with a change in wear mechanism.

4.2 TABER ABRASER TESTS

The Taber tests conducted used a standard Taber Abraser and Taber wheel sets as described in Chapter 3. Each aluminum sample was weighed throughout the test using a scale to indicate the rate of material loss or wear rate.

4.2.1 H-18 Wheel Set, 1000 Gram Load Tests

Initial tests were performed as described in Chapter 3 using 1000g load and an H-18 vitrified course wheel set. The results of the tests conducted on the base 390 aluminum are shown in Figure 4.5.

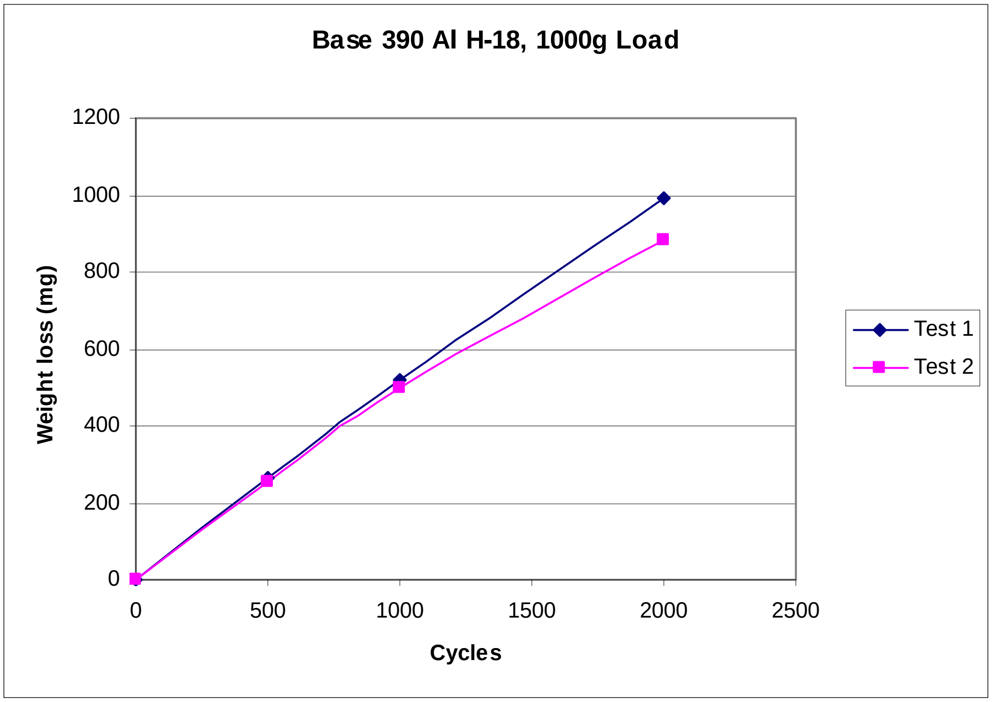

Figure 4.5 Chart showing the Taber Abraser test results using an H-18 abrasive wheel under a 1000g load.

As was apparent from the data shown in Figure 4.5, the wear occurring on the base material was nearly linear. This wear rate was expected as there was no significant protective surface coating and the surface had no greater wear resistance than any other section throughout the sample. The two wear tests began very similarly, although the second test showed a decrease in wear (decrease in slope) near the end of the test. This was likely because the wheel began to load up with aluminum and became less aggressive. Visual inspection of the wheels proved that aluminum was adhering (loading) to the wheel reducing its ability to wear the surface of the test specimen. Up to this point, the Abrasive wheel did not show any indication that the aluminum was adhering to the wheel surface. The wheel had broken down at a high enough rate that loading had not been an issue, as was predicted earlier. This difference between the two tests was insignificant however, because the trend was linear as was expected and the major difference was in the final data point.

Figure 4.6 indicates the wear of the Hardcoat Anodized sample under the same conditions as the base aluminum. More data points were taken during this test than the previous test in order to discover any nonlinear trends that may occur. A change in slope may also be an indication of the Hardcoat surface wearing through.

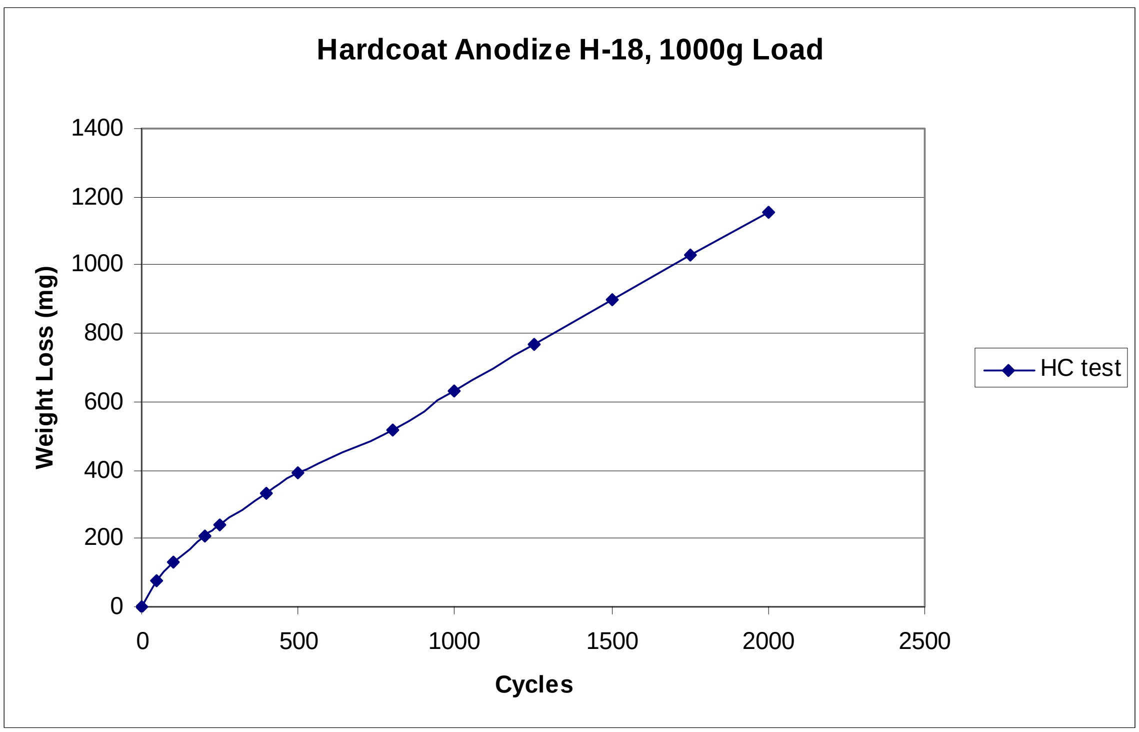

Figure 4.6 Graph indicating the weight loss of the Hardcoat anodized Taber Abraser sample using an H-18 wheel-set under 1000g load.

Examination of the data showed that the wear of the Hardcoat anodized sample initially began at a higher rate and decreased until it became linear or nearly linear. While observing this test the substrate material became visible at nearly 400 cycles although only a minimal amount. The visible base material indicated that the anodized surface was wearing through and the softer substrate material becoming the wear surface. At nearly 500-800 cycles the wear rate decreased and became nearly linear. This change in slope was counter-intuitive because the Hardcoat anodized layer is hypothesized to increase wear resistance according to Archard's equation (2.1).

When the data was compared and the graphs overlaid it was evident that the Hardcoat anodized sample wore more significantly than the base aluminum under the Taber test conditions used, refer to Figure 4.7. Initially the Hardcoat anodized surface wore at a higher rate, but tapered off and the wear rate became nearly linear. It was noted that the linear portion of the Hardcoat anodized wear curve (cycles 800-2000 cycles) was nearly parallel to the base aluminum wear curve. The parallel lines were an indication that the Hardcoat anodized surface had in-fact worn through and the substrate material is now the wearing surface.

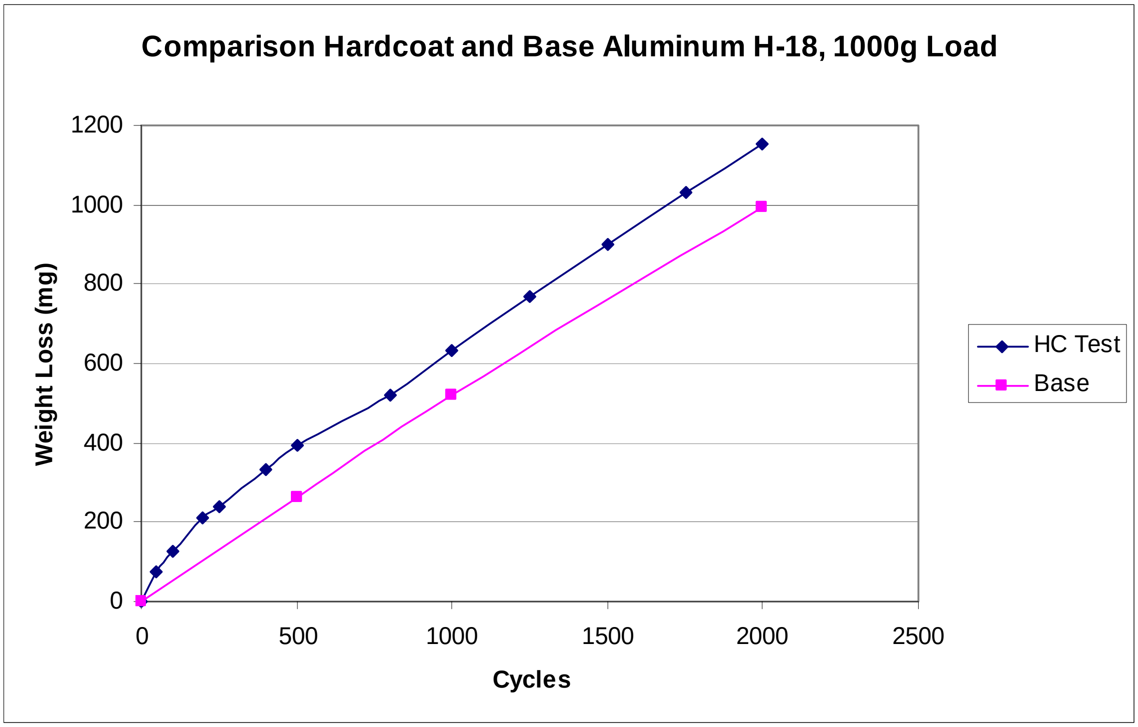

Figure 4.7 Comparison of the Hardcoat anodized and Base aluminum Taber samples using an H-18 wheel-set under 1000g load.

The Hardcoat anodized layer is only a few thousands of an inch thick as described in Chapter 2. When that layer had worn through, the substrate had the same properties as a non-hardened surface, therefore, it was expected that the wear rate would be similar as the data indicated.

An observation made during the test of the Hardcoat anodized sample was the H-18 wheels set wore more rapidly than during the base sample test. At 500 cycles, the wheels were nearly worn to the minimum diameter and at 800 cycles, the wheels were replaced with new wheels. The second wheel set lasted to the completion of the test, but again were at the minimum diameter. It was observed that the two contacting surfaces between the Taber wheel and the test sample were both hard and abrasive therefore both wore at a high rate compared to the base material.

4.2.2 H-18 Wheel Set, 250 Gram load Tests

The base aluminum was first tested under the 250g load and it was quickly evident that the amount of wear occurring was significantly lower from the first round of tests, Figure 4.8. More weight measurements were taken during this round of testing to indicate any nonlinear changes in the wear rate. As was seen from the data in Figure 4.8, the wear rate was still nearly linear, indicating that loading of the wheels was not a significant factor at the 250g weight under these test conditions.

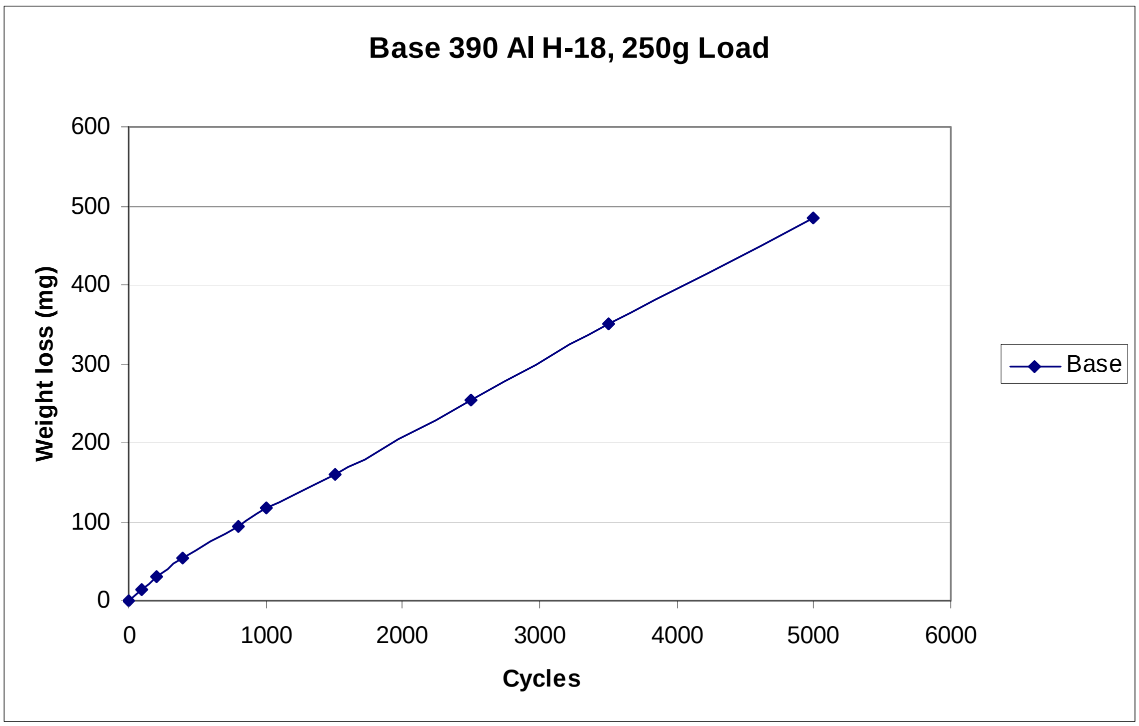

Figure 4.8 Graph showing the wear of the base aluminum under a 250g load using H-18 wheel-set

The Hardcoat anodized sample was tested next to find its wear rate. A similar trend to the previous test was noticed when compared to the first round of testing, in that the wear rate of the Hardcoat anodized sample initially wore at a higher rate then began tapering off, trending toward linear, Figure 4.9. In both the first and now this round of tests, the trends were similar, although the magnitudes of the total wear were different.

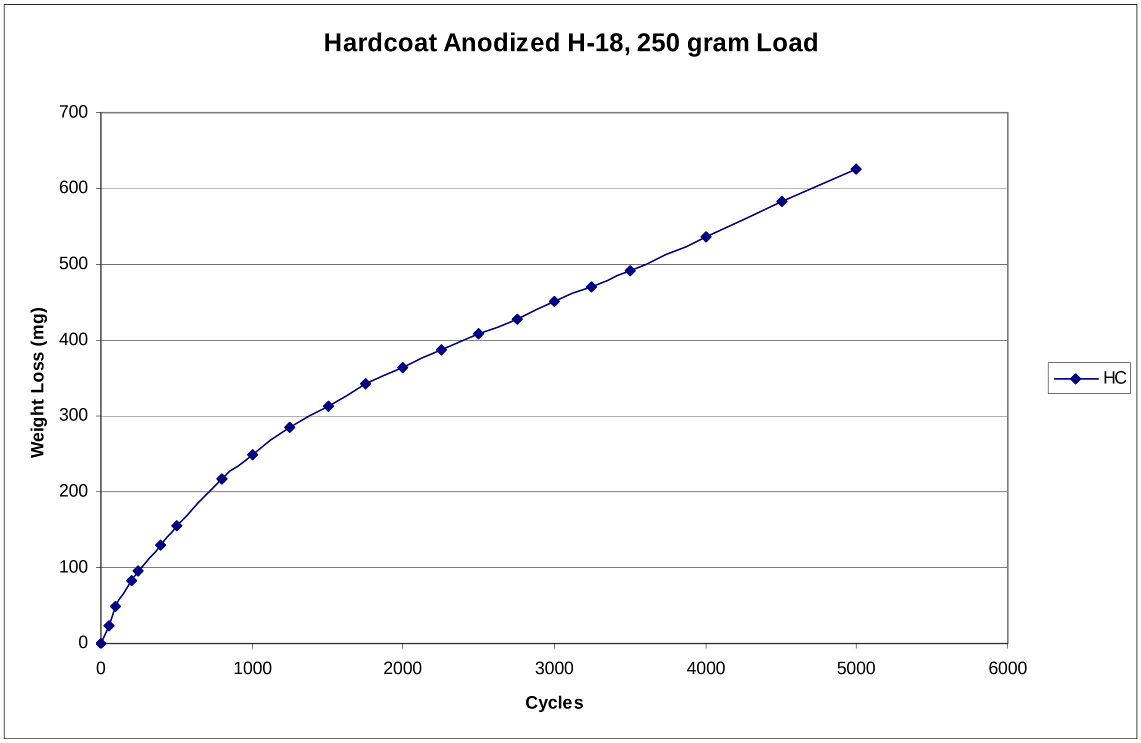

Figure 4.9 Graph indicating the wear rate of the Hardcoat anodized surface under 250g load using an H-18 wheel set.

When the data was overlaid, it showed that the change in load did not have a significant effect on the relative wear rate difference (see Figure 4.10).

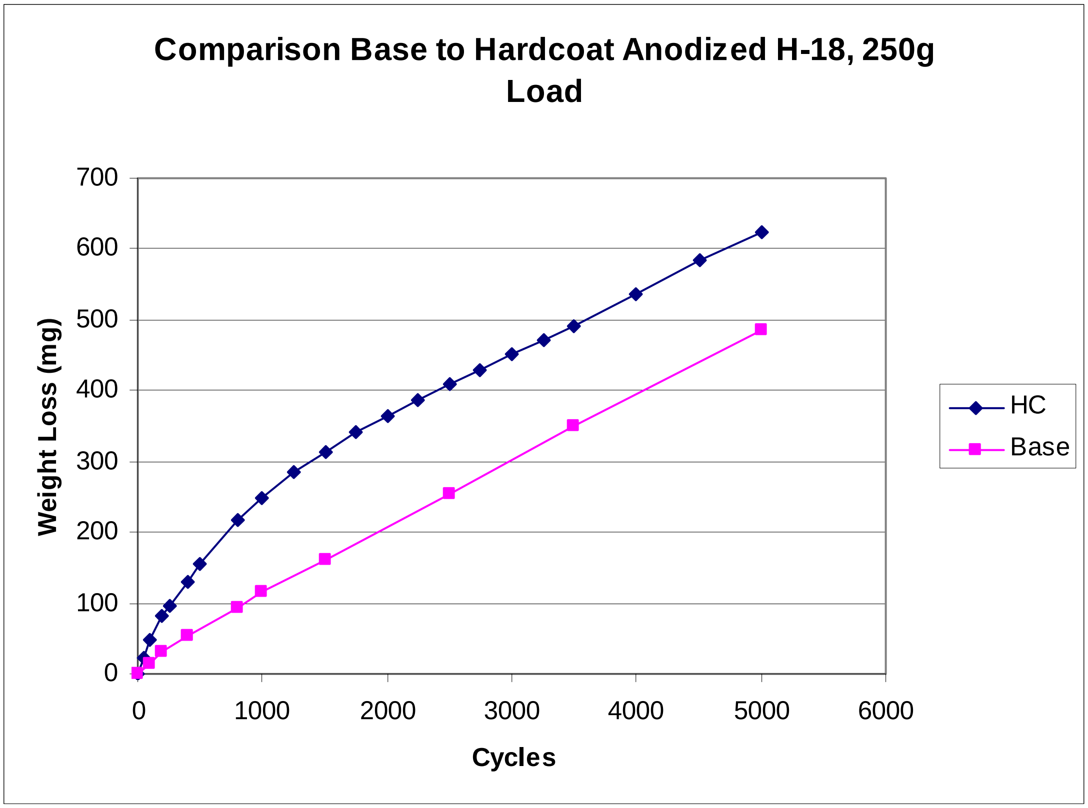

Figure 4.10 Graph showing a comparison between tests on the base aluminum and the Hardcoat anodized aluminum under a 250 gram load using an H-18 wheel set.

The correlation between the 1000g test and 250g test confirmed the fact that for a Taber Abraser test, the wear resistance of the Hardcoat anodized sample was less than the base aluminum sample.

4.2.3 CS-17 Wheel Set, 250 Gram Load Tests

To further substantiate the tests conducted using the H-18 wheel set, an additional set of tests were conducted. These tests used a less aggressive wheel set, CS-17, under a load of 250 grams. The test methodology remained the same for these tests as the previous Taber tests.

The initial tests were conducted on the base aluminum and again there was a reduction of the total amount of wear which occurred compared to the H-18 tests, (see

Figure 4.11). The data did not follow a smooth linear line as did the previous tests due to loading which occurred on the CS-17 wheel. Loading of the wheel was more of a factor during these tests. In order to keep the wear interaction constant, the CS-17 wheel set was resurfaced every 500 cycles to expose a clean (non-loaded) wheel surface.

A trendline was added to the chart to see the linear wear rate of the material, which, according to the R^2 value (representative of the quality of fit, where 1.0 is perfect fit), is a good representation of the trends.

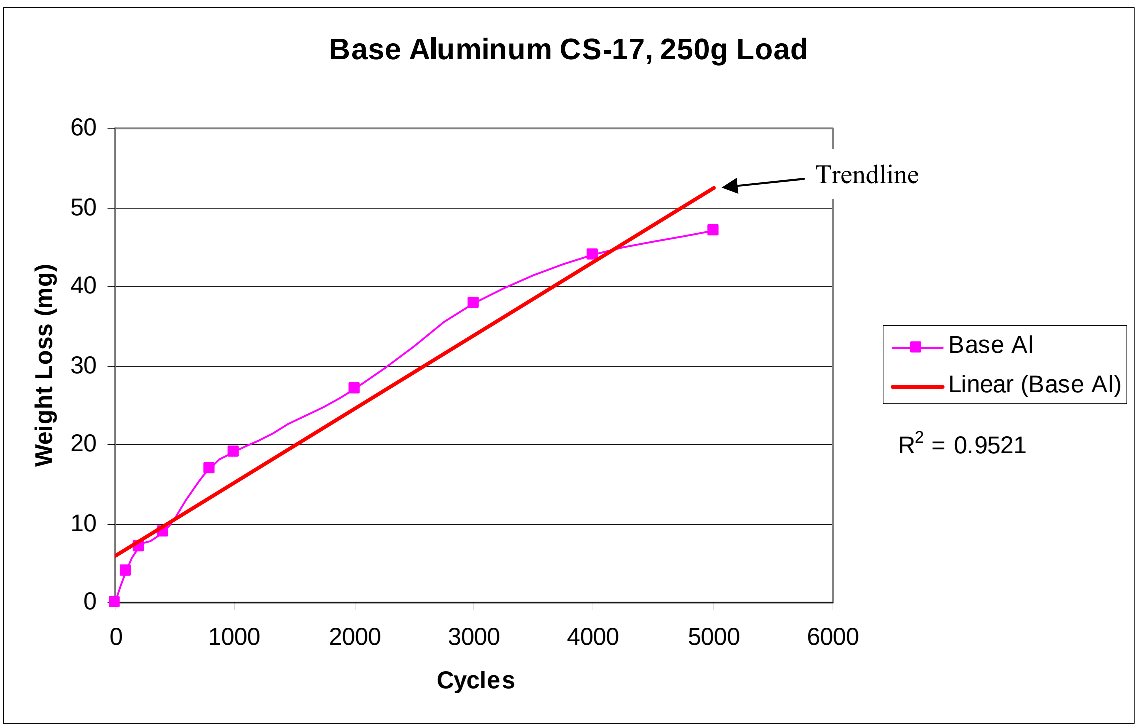

Figure 4.11 Graph depicting the wear rate of the base Aluminum on Taber Abraser. The wear rate began to decrease with an increase of cycles indicating loading of the wheels. A trendline was added to indicate that the overall wear pattern was still nearly linear.

The Hardcoat anodized sample tested using the CS-17 wheel set proved to again support the wear rates seen earlier. As is seen in Figure 4.12 the wear rate again initially began at a high rate and then tapered off to nearly linear. A trendline again was added, because of the effects of loading and to show the general direction or trend of the wear rate.

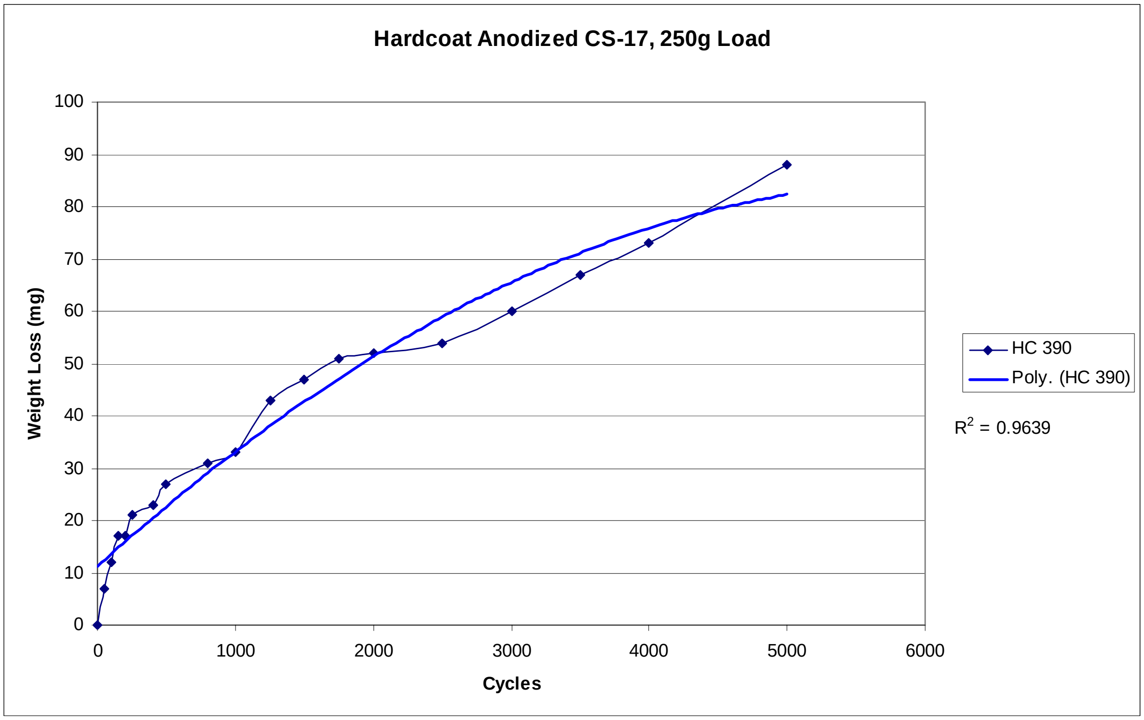

Figure 4.12 Graph depicting the wear rate of the Hardcoat anodized surface. The wear trends were similar to those seen in previous testing, note the trend from cycles 3000-5000 is near linear.

Comparing the two sets of data, there was a similar trend to previous testing (Figure 4.13). The wear rate of the Hardcoat anodized sample began at a higher rate and tapered off to nearly linear (2500-3000 cycles).

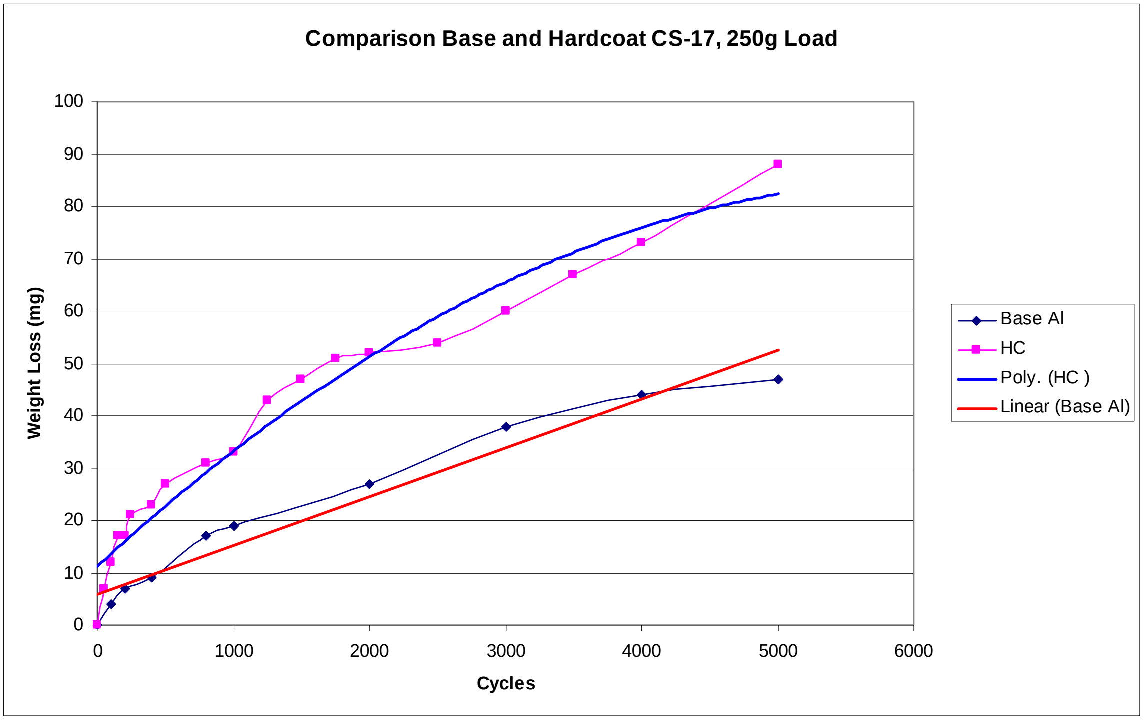

Figure 4.13 Chart showing a comparison between Base 390 and Hardcoat surfaces under 250g load using CS-17 wheel sets. The trendlines indicate that the wear rates are similar in pattern to previous comparisons shown.

4.2.4 Taber Test of Sheave Materials

One limitation to the Taber Abraser test was that the test samples had a required overall dimension and profile. These samples had to be flat and less than 4.25" across (square or round). For many other materials samples were available and are found in acceptable sizes to run on a Taber Abraser, but in the case of die-casting materials, samples have to be cast and machined to work in the system. Therefore, special samples had to be fabricated to adapt to the Taber Abraser set-up.

Each of the test samples for all of the previous Taber Abraser tests were specially made in order to adapt to the test set-up. Flat disks composed of 390-Aluminum were pour-cast into a rough shape and then machined flat into round 4" diameter disks. Some of the disks were Hardcoat anodized while others remained stock. These samples were cast by the same manufacture of the CVT sheaves to be tested, from the same material, but not in the same processing method. There was a possibility that this difference was causing the surface of the Hardcoat anodized sample to interact with the abrasive wheels in a manner to increase their wear rate.

4.2.4.1 Abrasion Test Stand

In order to understand the influence of the test sample processing on the wear data, a special abrasion test stand was constructed based off the Taber Abraser test stand. This test stand used the same principles as the Taber Abraser by scuffing the Taber wheel sets as the sample disk rotated, but the wheels were set at an angle so they contacted the sheave normal to the surface.

Figure 4.14 Figure showing abrasion test stand based off the Taber Abraser design. The two arms were at the same angle as the sheave surface allowing the wheels to rest normal to the surface.

The set-up was similar to the Taber Abraser, Figure 4.14, but with a few modifications to accommodate for the sheave size and angle. Two arms extend forward whereon two abrasive wheels were fastened. These wheels were free to rotate about their axis and they were on bearings in order to minimize drag. The arms were also allowed to pivot on bearings to ensure a constant load when given any variation in surface flatness or runout, similar to the Taber Abraser.   The arms were adjustable along a shaft, allowing the wheels to be located to a smaller or larger diameter on the sheave face. This allowed for multiple test locations on one sheave sample, if desired.   The system was driven by a DC electric frequency drive motor, which was set to run at a similar RPM as the Taber Abraser (approximately 70 RPM). The shaft direction was changed through a geared angle drive mounted to the test stand. In addition, a cycle counter was mounted to ensure duration repeatability of each test.

The stationary CVT drive sheave was separated from the movable sheave and used as test samples (refer to Figure 4.14) for this test. The drive shaft had a taper at the end, which mated to the taper on the sheave. The sheaves rotated on the shaft and the wheels rested on the surface in a similar manner to the belt contact, perpendicular to the surface as has been explained. Because of the size of the sheave, two tests were conducted at an inner and outer diameter location. These locations on the sheave were set by stops fixed to the pivot shaft.

4.2.4.2 Test Procedure

The testing procedure was similar to the original Taber Abraser testing already preformed. Initially, a stock sheave was tested at its outer diameter using a CS-17 wheels set. The abrasive wheels were refaced every 500 cycles because of loading of the wheels, as seen in earlier Taber tests. Refacing ensured the surface interaction remained constant throughout the test. Each test was for 5000 revolutions of the sheave. Once completed, the Hardcoat anodized sheave was tested under the same criteria and again for the same number of cycles. The tests were repeated for two sets of sheaves and on two locations on each sheave, inner and outer diameter.

4.2.4.3 Measuring Wear on Sheave

The Taber Abraser used small disks for test samples, which were periodically weighed, in order to determine the amount of wear that had occurred. Recording the weight of the sample as a function of the cycles was a process that required a high resolution scale to measure small amounts of weight change (in this case milligrams). The stationary sheave and the adjoined steel shaft weighed more than 1000 grams. Finding a scale with the necessary capacity and yet still have the desired fine resolution of 0.001 grams was unreasonable if not impossible. A scale of this capability would likely only exist in a specialized lab and be extremely expensive.

The objective of this abrasion test was to verify the relative improved wear resistance of the Hardcoat anodized surface. Measuring the total amount of wear, which occurred on different test samples run for a comparative amount of time, gave this information. The rate, at which the wear occurred, although informative, was not the goal. Previous Taber Abraser tests showed that the wear rate of the base aluminum was linear. On the Hardcoat anodized samples when the surface wore though, the wear rate was also nearly linear. It was therefore unlikely that the two wear data series would cross. Meaning, if the wear rate of the Hardcoat anodized layer was higher than the base material as was previously seen, the amount of wear would have been more than the base material and then taper down to the same rate or become parallel to the base material. A plot of the data would not show the lines crossing. This would also be the case if the wear rate of the Hardcoat anodized surface were lower initially. It would again become parallel to the base material and never cross.

This understanding of the wear rate on the test samples was important because it facilitated measuring the wear of the sheave at the end of the test instead of throughout the test as done on the Taber Abraser. An improved wear resistance would show less total wear (total volume, as it is proportional to weight) at the end of the test than the base material.

Since determining the change in weight of the sheave was not possible, the amount of wear was measured using a CMM, scanning the surface and comparing the data from the scan as explained in section 2.5.1 of Chapter 2. The CMM output data allowed for a comparison between the multiple scans to understand the effects of the surface hardening. It also provided a visual representation to represent the shape and extent of the wear groove.

4.2.4.4 Results from Taber Test of Sheaves

As expected, the abrasion tests showed wear on the surface quickly for both the stock sheave and the Hardcoat anodized sheave. Visually the wear path was similar to the earlier Taber tests, indicating a similar set up, although the wear amount tangibly did not “feel” as deep as the Taber tests. This may have been in part due to the denser material of the stock and Hardcoat anodized parts because of the die-casting process instead of pour casting in addition to the larger circumference of the wear path.

The wear volumes were determined using CAD. From the tests conducted, the results showed similar trends to the Taber Abraser, although it was not possible to correlate directly the wear volumes that occurred on this abrasion stand. As indicated in

Table 4.2, the Hardcoat surface wore at a faster rate than did the stock sheave or in other words, a greater volume of material was removed on the Hardcoat anodized sheave tests samples as compared to the stock sheave, nearly 44 % more.

Table 4.2 Table showing the average wear volume for the modified Taber abrasion test stand.

Sample	Volume of wear
Stock Aluminum Sheave	14.3 mm^3
Hardcoat Anodized Sheave	20.6 mm^3
Percent difference	144 %

The test conducted on the abrasion stand again substantiated the earlier Taber tests. It reiterated that the wear resistance of the Hardcoat anodized die-cast aluminum was lower than the resistance of the base material.

4.3 FULL CVT TESTING

The final round of testing to understand the effects on wear resistance of Hardcoat anodizing was to test the actual application of a CVT/belt combination. As explained in Chapter 3, two full CVT tests would be conducted to correlate the findings from the lab tests with an actual application. The first test described was a dynamometer test using a water-brake dyno as the load control device. The second test was to be a case study where an ATV would follow a set course until measurable wear had occurred.

4.3.1 Dynamometer Full CVT Results

The dynamometer test quickly demonstrated that the loading capabilities of the dyno were insufficient to cause significant slipping and any measurable wear. The test did however, cause the serviceable components of the CVT, such as bushings, weights, and pins to wear out, requiring replacement. The observation of wear occurring on these parts was evident with a sudden change in engine performance. This test required a significant amount of time and effort to maintain and keep the system running.

Although measurable sheave wear did not occur during this test, it was the first attempt at running a fully Hardcoat anodized drive clutch. It was possible to make some observations concerning how the Hardcoat anodized surface reacted while transferring torque through a belt. One observation was that no adverse effects were noticed because of the hardened surface. Meaning, there were no noticeable performance effects while the coated drive was running as compared to the stock drive. Another observation was that this coated drive clutch required fewer of the serviceable components (bushings and weights) than did the stock drive, although this may be coincidental.

4.3.2 Case Study Results

The results of the case study are shown below in images taken from the CMM scan (Figures 4.17 and 4.21) and will be discussed in more detail later. The scan, however, shows the straightness of the surface with the horizontal line being the average of the straightness, although the surface is tapered. The values shown for the horizontal axis are arbitrary for the purposes of this study as the CMM program assigns them. A scan that is near the horizontal line indicates that the points taken of the surface has little deviation from a straight line or straightness. A scan that is far from the horizontal line indicates that the points taken of the surface has a significant deviation from a straight line. The vertical axis indicates the actual deviation from straightness and is shown in units of inches with the value of each mark as 0.0002 of an inch. This scan was used primarily because of its ability to focus on the changes (wear grooves) in the surface, and not be influenced by the conical shape of the sheave.

4.3.2.1 Stock Drive

The stock drive clutch ran for a distance of 1076 miles before being removed and inspected. As seen in figures 4.15 and 4.16 there was a darkened ring near the outer diameter of both the stationary and movable sheaves. This coloration indicates that the belt spent a considerable amount of running time in this location relative to the rest of the sheave. Also visible was a similar darkened ring near the inner diameter on the stationary sheave. Faint rings in the same region were visible on the movable sheave, but were not nearly as pronounced. The belt rubbing against the stationary sheave surface during idle caused this inner ring. The movable sheave would fully disengage (not contact) the belt during idle thus the full slip condition caused the difference in appearance. There were a number of small scratches on both sheave surfaces in a radially outward direction. These scratches were an indication of dust or other particles caught between the belt and sheave.

Figure 4.15 Image of the stationary sheave off the stock drive clutch.

Figure 4.16 Image of the movable sheave surface of the stock drive clutch

Tangible wear had occurred on the stock drive clutch at the outer ring in the above images, yet no tangible wear was evident at the inner ring, because the belt ran the majority of the time at the outer diameter during this test. These surfaces where examined using the CMM to visually represent the cross section of the sheave surface.

Figure 4.17 represents the entire length of the movable sheave showing the outer diameter to the inner diameter, left to right respectively. A dashed line was added to the figure to represent the original surface of the sheave. The outer groove (left) was visibly more significant than the wear at the inner diameter.

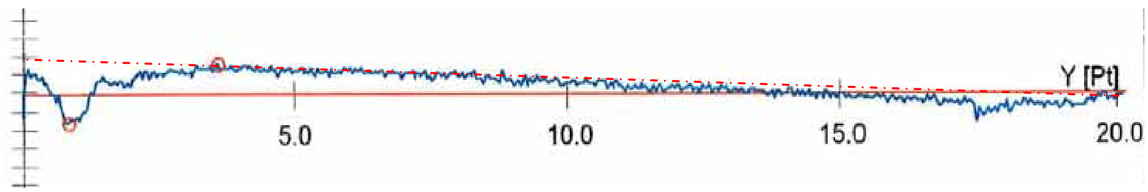

Figure 4.17 Image showing a CMM scan of the stock movable sheave surface. The dashed line has been inserted to indicate the original surface of the sheave. The outer groove is clearly noticeable in this scan.

Figure 4.18 shows a second scan focused in on the groove. This method caused the scan to elongate, again increasing the visibility of the wear groove. It should be reiterated that the values along the horizontal axis are arbitrarily assigned by the CMM program and do not correlate to any position on the sheave face.

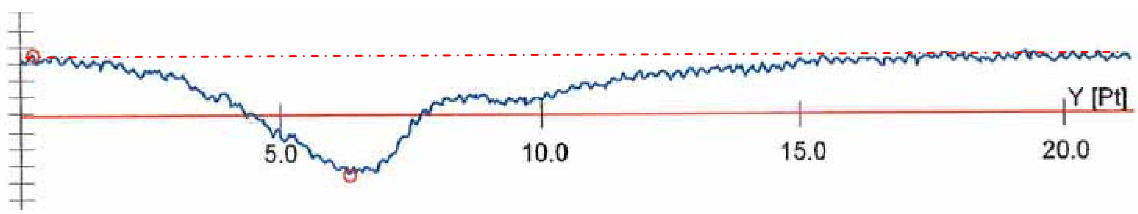

Figure 4.18 Image focused in on the groove at the outer ring. The dashed line represents the original surface of the sheave.

4.3.2.2 Hardcoat Anodized Drive

The Hardcoat anodized drive clutch ran along the same course as the stock drive clutch for a distance of 1078 miles. Similar to the stock drive clutch, rings are located at or near the same inner and outer diameters, refer to figures 4.19 and 4.20. The inner ring was slightly darker on the movable sheave here in comparison to the stock movable sheave. A faint line of base aluminum was evident in the outer ring on the stationary sheave.

Figure 4.19 Image of the Hardcoat anodized stationary sheave.

Figure 4.20 Image of the Hardcoat anodized movable sheave.

There was no tangible wear groove on either sheave as were discovered on the stock sheaves. The surface appeared to be smooth, although there are many noticeable scratch marks on both sheave faces. Similar to the stock clutch, these scratches were likely from dust particles caught between the belt and the sheave face. The inner diameter ring showed significant scratching, although more significant on the movable sheave near engagement. There were darker rings on both sheaves indicating the belt ran in this location for a significant amount of time. There was a faint line where the Hardcoat anodized surface had worn through and the base aluminum was visible.

Figure 4.21 shows a scan, of the entire length of the Hardcoat anodized sheave. It was apparent that wear had occurred on the surface as would be expected, but did not appear to be as concentrated as found on the stock sheave surface. There was a rise near the outer edge, possibly from sheave wear. This rise was not seen on any other scans of other sheaves. There was also a rough area near the inner diameter associated with the dark inner ring found on the movable sheave, Figure 4.20. This area was associated with the scratches previously mentioned on the sheave.

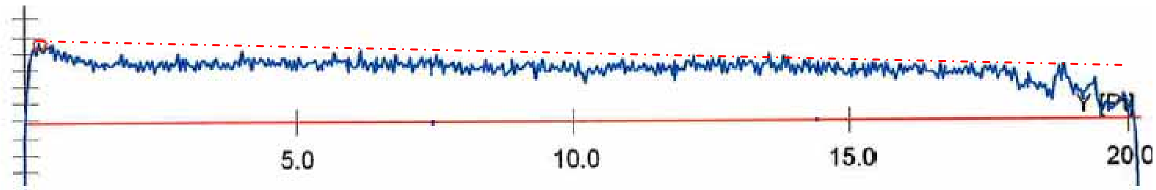

Figure 4.21 CMM scan of the Hardcoat anodized movable sheave.

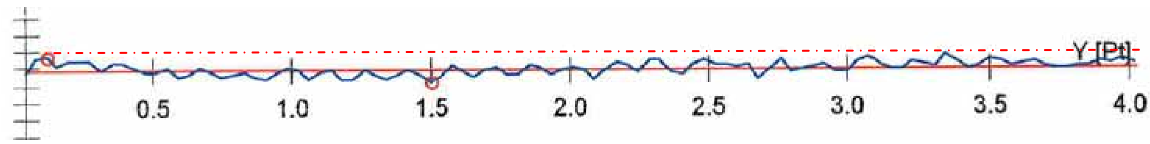

Figure 4.22 CMM scan of the outer ring of the Hardcoat anodized movable sheave.

4.3.3 Discussion of Case Study Results

The evidence form both the CMM scans and a visual inspection indicated that the Hardcoat anodized surface wore as much if not more than the stock sheave. The CMM scans indicated a rise at the outer diameter of the sheave. In order for such a rise to form, material had to be removed around it, suggesting wear occurred on the sheave within this diameter. The CMM scan also indicated that the wear was not concentrated as it was on the stock sheave surface. The wear was evenly distributed along a significant percent of the sheave surface. The wear on the stock sheave was concentrated, forming a noticeable groove. The actual volume of wear appeared to be greater on the Hardcoat surface than the stock surface from the CMM scans.

Visual inspection of the Hardcoat anodized sheave surface also suggested that significant wear had occurred. As was stated earlier, base aluminum was visible near the outer edge of the sheave, indicating that the Hardcoat layer had worn through. The thickness of the layer was between 0.0015 to 0.002 of an inch thick. A significant amount of material had to be removed in order for the base material to be visible. There was no tangible wear groove, however as found in the stock sheave, indicating that the wear was more evenly distributed across the surface.

The performance of the CVT during this test suggested that no wear occurred, however the information gathered about evenly distributed wear explained why there was no noticeable change in the CVT's performance. During the test, no groove formed although wear was occurring. The belt continued to move smoothly along the sheave surface for the duration of the test. The stock sheave did not shift as smoothly and the belt would hang-up in the groove.

4.4 WEAR COEFFICIENT

A significant contribution of this thesis was to calculate and document the Wear Coefficient for the interaction between 390 die-cast aluminum and a composite rubber belt. The Wear Coefficient was neither tabulated nor documented in any of the literature researched. This new knowledge could assist in using the Archard equation to predict the wear that may occur because of this interaction between a belt and die-cast aluminum. This can be important in not only a CVT application, but also all applications that use this or a similar combination of friction materials.

In order to determine the wear coefficient, wheels constructed of belt material (Figure 4.23) where used on the abrasion stand (Modified Taber Abraser) described earlier. The wheel set was sectioned out of a sheet of composite belt material to mimic the side of a belt. The composite belt wheel had aramid fibers that were near or protruding through the edge similar to an actual belt (Figure 4.24). There were also other fibers and compounds in the belt to make it a composite and give it strength. Since these wheels were cut directly from a section of composite belt material, the sides of the belt wheel were similar to that of an actual belt.

Figure 4.23 Image of composite rubber belt wheel (left) cut from V-belt material, used on Modified Taber Test Stand.

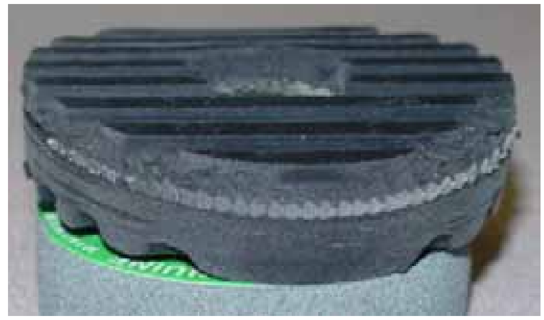

Figure 4.24 Image showing the aramid fibers which are at or near the edge of the wheel. This is similar to the production V-belt.

The composite belt material wheel-set was tested similarly to the Taber wheel sets using the abrasion test stand. The wheel and the sheave contacted in the same manner as would a belt and sheave in an actual application, giving confidence that the results would reflect an actual belt/sheave test.

Similar to the abrasion tests, the sheave surface was scanned on the CMM to calculate the volume of wear that occurred during the test. A volume was created from the coordinates of the scan in CAD and volume identified shown in Table 4.3. Also in this table are shown the other test variables necessary for calculating the Wear Coefficient.

The equation, 4.1 repeated from section 2.1.7.2, described the method of calculating the Wear Coefficient according to Bhushan [Bhushan 1999]. It indicated that it was possible to find the Wear Coefficient for the harder of the two materials by solving for the coefficient k, using the properties of the harder material:

$$k_h = \frac{V_h H_h}{LS} . \qquad \textbf{(4.1)}$$

From this equation, the wear coefficient was calculated to be 6 x 10^{-5}. When compared to documented Wear Coefficients, this value was within an acceptable range for the type of materials interacting [Dunaevsky 1997, Rabinowicz 1980].

Table 4.3 Table listing the wear volume determined as well as other parameters necessary for calculating the Wear Coefficient.

V_h	2.49 mm^3
H_h	120 (Brinnell)
L	428 grams
S	2658287 mm
K	6 x 10^{-5}

4.5 DISCUSSION OF TEST RESULTS

The wear theory discussed in Chapter 2 indicated that increases in material hardness lead to a decrease of surface wear. The tests conducted here indicated that this theory did not prove true for all interactions, specifically surface-hardened materials. Research conducted by Jiang and Arnell offered an understanding into the phenomenon that makes this wear scenario contrary to the known wear theory [Jiang and Arnell 2000]. They conducted a study into the effects of substrate surface roughness on wear rates of hardened surface coatings. Their tests used steel samples of various substrate surface roughness, with Diamond-Like-Carbon (DLC) coatings. The samples were tested on a Ball-on-Disk tester where a hardened ball or spherical tool is loaded against the sample.

Jiang and Arnell's tests found that an increase in surface roughness correlated to an increase in specific wear rate for the materials tested. They discovered from their tests that there was a transition from a slow increase in specific wear rate, to a high wear rate as the substrate surface becomes significantly rougher. Their results indicated that samples with low surface roughness (below the transition point) approximately followed Archard's wear law. They concluded that the contact stresses and wear mechanisms changed when the surface roughness increased beyond this transition point and therefore, Archard's wear law was no longer applicable.

A direct correlation between the study of Jiang and Arnell was not possible because of the difference in materials and coatings used. However, their theories can be incorporated in this wear study and explain why the wear rates were contrary to the wear theories explained in Chapter 2.

Jiang and Arnell's research gave some indication into the wear phenomenon causing the wear rates seen in these wear tests. Under the same premise of Jiang and Arnell's study, surface roughness readings where taken of the Hardcoat Anodized and base 390 Aluminum samples before they were tested. These readings showed a significant difference in surface roughness between the test samples, as seen in Table 4.4.

Table 4.4 Table indicating the average surface roughness of the base aluminum and Hardcoat anodized Taber Abraser samples as well as sheave surface roughness.

	Base Al Taber	Hardcoat Taber	Base Sheave	Hardcoat Sheave
Surface Roughness (µin)	186	*	64.6	353

*** the roughness of the Hardcoat Taber sample was beyond the measuring capabilities of the surface profilometer (999 µin)**

The surface of the Hardcoat anodized sheave was further investigated, using this surface roughness correlation. In all instances the Hardcoat anodized surface wore at a higher rate than did the stock surface. The higher wear rate indicated that the mechanisms for wear particle formation do not exactly coincide with those proposed in the wear theories. When the surface roughness was above the transition point as proposed by Jiang and Arnell, the interaction between asperities became an impact rather than sliding contact. Such an impact caused large particle formation as shown in Figure 4.25.

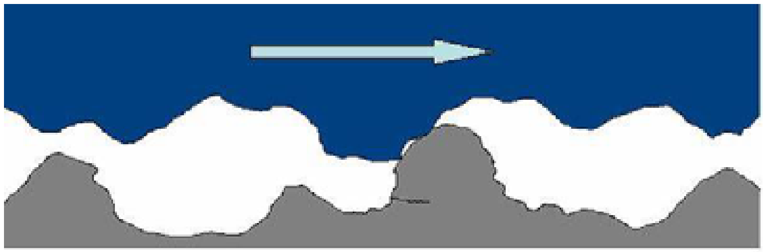

Figure 4.25 Representation of an asperity impact that may occur with a surface roughness above the transition point.

Sections of the Hardcoat anodized test samples were then cut and polished for examination under a microscope. The layer was observed to be rough and porous through and below the surface (see Figure 4.26). These images correlated to the surface roughness values found in the Table 4.4, discussed earlier and are evidence to the wear results from testing.

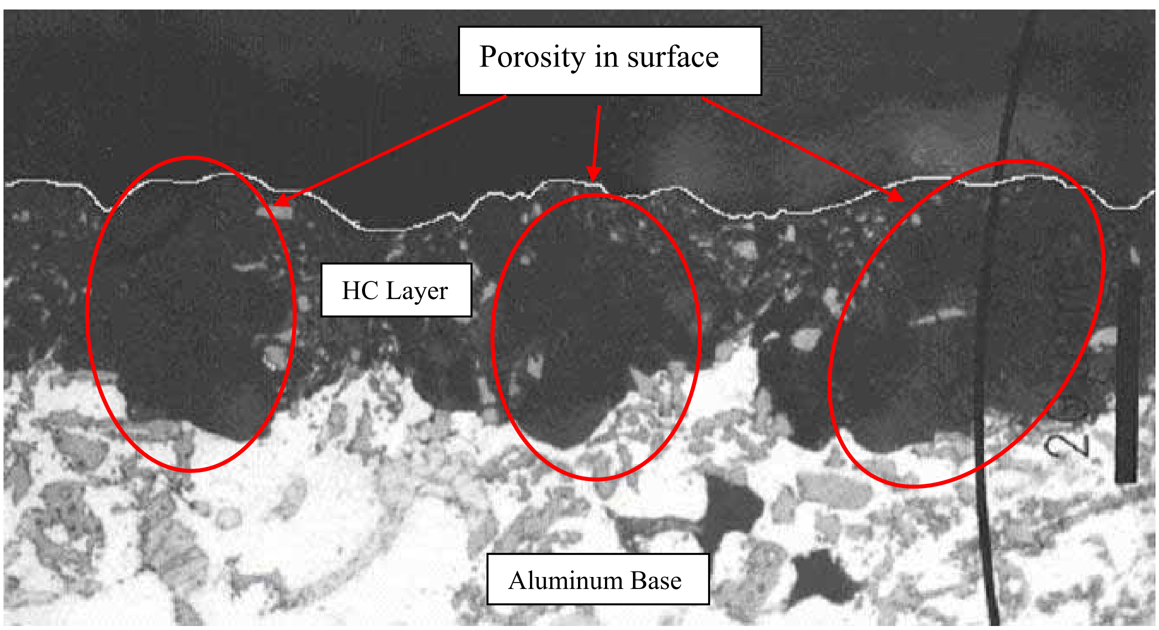

Figure 4.26 Photograph showing the surface roughness and porosity of the Hardcoat anodized layer. The white line has been added to enhance the surface profile against the background.

The surface roughness and wear correlation indicated that the Hardcoat anodized layer on die-cast 390 aluminum wore at a high rate due to the method of contact between asperities. The asperities impacted causing a brittle fracture to occur in the anodized layer and large particle formation. The wear was perpetuated due to porosity and crack propagation, which did not allow the surface to become smooth. The wear rate decreased when the anodized layer was worn through and as the impacts were absorbed in the softer base material.

4.6 SUMMARY OF TEST RESULTS

Multiple wear tests were conducted to understand the wear of a composite rubber belt in contact with a die-cast aluminum surface. Standardized wear tests were the basis for some of the tests, which were modified to test CVT/belt specific applications. In some cases, the wear phenomenon was different than predicted in the wear theories. Other tests required a significant amount of effort and time to complete. Table 4.5 outlines the tests and results conducted for this wear study.

Table 4.5 Summary of Wear Test Conducted

Test	Results	Comments
Modified Pin-on-Disk	Rubber adhesion on sheave surface	Wear phenomenon appears to be different from actual application.
	Aramid fibers roughened surface, breaking fibers	Possible loading methods caused testing to be difficult.
Taber Abraser	HC samples consistently wore more than base samples	Manufacturing process for Taber samples appeared to have an effect on the wear rate.
Abrasion Stand	HC sheave samples lost more volume than base material.	Test results similar to Taber Abraser tests.
Dynamometer	No measurable wear occurred	Investigation necessary into different dynamometer systems to increase loading capability.
Case Study	Localized wear grooved formed in stock sheaves near outer diameter. HC sheaves wore evenly, no groove.	HC sheave wore more evenly across surface with no localized grooving. HC surface appeared to have worn more than base material, correlating with previous test results
Wear Coefficient	Calculated to be $6X10^{-5}$	Value is within range for this interaction.

CHAPTER 5 CONCLUSIONS

The objectives as stated in Chapter 1 of this thesis have been to increase the general knowledge of the wear characteristics of die-cast aluminum. Specifically, the objectives were to look at the wear characteristics of aluminum used in a CVT, its interaction with a composite rubber belt and the effects on wear resistance of Hardcoat anodizing the surface of the base aluminum material. These findings were then compared to the known wear theories. The final objective was to determine the wear coefficient for the interaction of 390 die-cast aluminum and composite rubber belt material. Previous work and research into similar wear scenarios were analyzed in order to understand wear theories and procedures necessary to test the hypothesis. Tests based on this literature were conducted to collect the data necessary to quantitatively compare the wear resistance of the hardened surface to the current stock surface.

This section will draw conclusions from the results found from the wear tests discussed in Chapter 4. It will make inferences into the characteristics and wear resistance of the original and Hardcoat anodized wear surfaces. Possible additional work related to this wear study will be described and the probable outcome of these proposed additional research studies.

5.1 TESTING SUMMARY

1. Several accelerated wear tests were designed and carried out to try to determine the wear mechanism in 390 die-cast aluminum when in contact with composite rubber belt material.
2. Hardcoat anodized die-cast aluminum samples were tested for relative wear resistance when compared to stock aluminum sheaves.
3. A practical method of measuring wear was proposed for objects, which weigh beyond the capabilities of sensitive scales. This method relied on multiple surface scans using a CMM to measure the volume of surface material removed by wear. Then a CAD program was used to analyses the CMM data.
4. Actual field tests of a fully operation CVT on a vehicle were conducted with the surface hardened and with stock sheaves.
5. The field test results indicated that the wear across a Hardcoat anodized CVT was less localized than a stock CVT. However, the total volume of wear across the sheave appeared to be greater.
6. The wear coefficient for the interaction between composite rubber and die-cast aluminum was determined to be 6×10^{-5}

5.2 CONCLUSIONS

1. Because of differences in wear phenomenon, accelerated standard wear tests were not consistently reliable predictors of wear in composite rubber/die-cast aluminum systems. Care must be taken when using

standardized tests for collecting data in such systems as multiple test methods may be necessary to validate the results from each test.

2. Current wear theories failed to assist in pinpointing the wear mechanism occurring in many of the wear tests conducted.

3. Field tests of these types of systems appeared to be necessary to ensure accurate conclusions are drawn from accelerated testing results.

4. Hardcoat anodized CVT sheaves appeared to be superior to stock sheaves in field tests as indicated by vehicle performance. Even though the wear volume may be greater for the anodized sheaves, evenly distributed grooving of the sheaves allowed for smooth CVT operation when compared to the stock test sample. Taber testing indicated however that the wear rate of the Hardcoat anodized sheave would become equal to the stock sheaves as the anodized layer was worn through. This would occur over a longer test duration than conducted for this Thesis.

5. Surface roughness was a significant factor in the results of wear testing Hardcoat anodized die-cast aluminum. This was similar to studies conducted by others for other materials.

6. Variations in hardness was not the only contributing factor influencing wear. The integrity of the surface, i.e. density/porosity of hardened layer caused the wear rate to fluctuate.

5.3 CONTRIBUTIONS

1. The evaluation of the applicability of several variations on standard and modified wear tests to CVT/V-belt applications.
2. The development of a reliable, accurate method for measuring wear volume on a surface using CMM scans of the affected wear surfaces. This is ideal for wear test samples that may be beyond the capabilities of sensitive weight scales.
3. A comparison of Hardcoat anodized and stock 390 die-cast aluminum CVT sheaves in actual field tests of over 1000 miles each.
4. The Wear Coefficient was determined for the interaction of composite rubber belt material in sliding contact with 390 die-cast aluminum.

5.4 FUTURE WORK

1. A new, reliable accelerated wear test method is needed for testing wear of composite belts/pulley drives. This test should simulate actual operating conditions and wear mechanisms. Such a test would enable many different composite belt materials to be tested to improve the wear characteristics of the system. Improved wear may lead to further implementation of CVT's into other applications.
2. Investigate the effects of the surface roughness and density of the Hardcoat anodized layer on wear resistance of die-cast aluminum materials. If the surface roughness and density of the anodized layer is improved, it may reduce the amount of impact interactions and reduce

large particle formation and hence wear. Improving the surface finish may show an increase in wear resistance of the material.

3. Investigate the location and amount of contact stresses in the interface between the base material and the anodized layer caused from the composite belt being in contact with the sheave surface. This knowledge may enable a recommended hardened layer thickness for Hardcoat anodizing of die -cast aluminum pulley systems.

Appendix

Table A. 1 Chart showing the available abrasive wheel sets for the Taber Abraser. Taken from Taber [Taber]

Model	Abrasive Description	Type	Composition	Servicing Required
CS-10F	Mild	Resilient	Rubber and Abrasive Particles	Reface with S-11 disc
CS-10	Medium	Resilient	Rubber and Abrasive Particles	Reface with S-11 disc
CS-17	Coarse	Resilient	Rubber and Abrasive Particles	Reface with S-11 disc
H-38	Very Fine	Non-Resilient	Vitrified and Abrasive Particles	Reface w/ Wheel Refacer & Multiple point tool
H-10	Fine	Non-Resilient	Vitrified and Abrasive Particles	Reface w/ Wheel Refacer
H-18	Medium	Non-Resilient	Vitrified and Abrasive Particles	Reface w/ Wheel Refacer
H-22	Coarse	Non-Resilient	Vitrified and Abrasive Particles	Reface w/ Wheel Refacer
CS-0	Very Mild	Resilient	Non-Abrasive Rubber	None
S-32	Very Mild	Resilient	Non-Abrasive Rubber	None
CS-5	None	Resilient	Wool Felt	None
S-35	Severe Cutting / Tearing Action	Non-Resilient	Tungsten Carbide	Clean with Solvent and Stiff Brush
S-39	None	Resilient	Leather	None

Table A. 2 Taber's list of recommended applications for each wheel set. Taken from Taber [Taber]

APPLICATION	CS-10F	CS-10	CS-17	H-38	H-10	H-18	H-22	S-35	CS-0
Adhesives & Sealants			X				X		
Anodized Aluminum			X		X	X			
Ceramic Finishes			X						
Coatings (Paint, Enamel)	X	X	X						
Concrete Floors							X		
Dental Powder									X
Electroplate		X							
Films	X								
Glass			X		X	X			
Hard Surface Coverings						X			
Home Furnishings							X		
Insulated Wire			X				X		
Laminates		X	X						
Leather (Shoe Soles)						X	X		
Leather Products		X	X			X	X		
Linoleum						X	X	X	
Masonite						X	X		
Optical Products	X	X	X						
Packaging		X	X						
Paper		X							
Paper & Cardboard		X			X	X	X		
Plastics		X	X			X			
Plastics		X	X						
Plating		X	X						
Porcelain Enamel			X						
Printing			X						
Rubber						X	X		
Sanitary Products						X			
Steel					X	X	X		
Textile (floor coverings)						X	X		
Textile (coated fabrics)		X	X			X			
Textiles (pile fabric)				X		X	X		

Textiles (natural & synthetic)		X		X		X	X		
Tile (rubber and asphalt)						X	X	X	
Upholstery				X					
Wax			X			X	X		
Wood						X	X		
Wool		X				X			

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