EXTENDING STARTER MOTOR LIFE VIA OPTIMIZATION OF COMMUTATION SYSTEM PARAMETERS

by

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Submitted to the Sloan School of Management and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements For the Degrees of

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Abstract

Concomitant to espousing that quality is job one is the commitment to total customer satisfaction. For Ford's starter motor organization, this means satisfying even the most demanding segment of its customers - the 95th percentile customer. This customer starts his car at least ten times more often than the average car user. The implication of this is that this customer segment experiences starter motor failure much earlier than the warranty life of the motor. If this customer segment is satisfied, not only will cost associated with warranty be reduced but it will also send the strong message that Ford is indeed totally committed to satisfying all its customers.

This thesis is the culmination of six and a half months of work to provide direction towards extending the life of the starter motor. Different functions associated with the technology behind starter motors were identified. Experts from each function were invited to form a cross-functional team. Factors that greatly affect the life of the starter motor were investigated by developing experimental motors and testing them on durability stands. Wear rates from each motor were measured. The measurements were analyzed to determine the wear behavior and which combination of factors produces the longest life starter motor. These results led to a prescription for developing a starter motor with a useful life that satisfies the 95th percentile customer.

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1. Introduction

1.1 Project Motivation

Ford Motor Company's Ypsilanti Plant manufactures permanent magnet starter motors. These motors have to pass engineering specified durability tests whereby the starter's actual function is simulated repeatedly for a given number of cycles. A cycle is equivalent to a "start" of a vehicle. A 20K minimum cycle is required for the motor. Ford's starter motors have been failing this requirement since November of 1992. Failures exhibit brush and commutator wear. The challenge to consistently surpass the 20K specification is compounded by a directive from Ford Management that states that starter motors, by model year '95, should satisfy 55K durability cycles.

The rationale behind the directive is founded on Ford's desire to satisfy the 95th percentile customer. These are customers who are engaged in the delivery business, e.g., United Parcel Service. These customers, on average, require 15 starts per day compared to ordinary customers who average 2 starts per day.

1.2 Description of the Plan and Methodology

This thesis is based on a project whose main objective is to provide direction towards the development, at low cost, using as much as possible available and existing technology, of a starter motor which meets the 55K durability life cycle requirement. Part of the challenge of this project is to find an approach that achieves this goal given constraints in time which in this case is six and a half months and availability of material and machine resources.

In engineering, one is often faced with having to develop a product without having to resort to a rigorous theoretical analysis which is usually undertaken with the hope of arriving at a close-form solution. This situation arises when the physical phenomena that control the product system are so complex that accurate methods of analysis are not available. The starter motor product is one such system in which arriving at an analytical solution that fully explains its life would be difficult. It requires knowledge from several fields that include electromagnetism, materials science and mechanics. To date, there is nothing in literature that combines all the knowledge from these fields into a unified set of governing equations that relate to starter motor life. Hence, an alternative way of characterizing life needs to be taken.

The alternative way that was used in this project was design of experiments. While one may argue that this approach is approximate, it can be nonetheless very effective. Its effectiveness rests, to a great degree, on how much of the physics involved in starter motor technology was captured in the design of experiments. To adequately represent the physics, a cross-functional team composed of members representing different functions that relate to the technology behind starter motors was formed. This team had people who had been working in electromagnetism, materials science and design of motors. In addition to considering the physics, the design of experiments required the creation of experimental starter motors that needed to be tested. Thus, people who were engaged in manufacturing, prototyping, testing and metrology were included in the team.

There are many benefits to having a cross-functional team:

- There is greater insight into the requirements of the project.
- There is greater understanding of potential pitfalls.
- There is greater understanding of potential solutions.
- There is greater understanding of the interaction between the proposed solutions which can give rise to additional solutions.

- It provides knowledge of the reasons why one idea is stronger or weaker than another.

Significant wear in the brush-commutator interface led the team to concentrate its investigation on the starter motor's commutation process. In particular, the team focused on the brush-commutator environment as the system. Figure 0 shows a rough sketch of the commutator and a brush. The following chapter will discuss commutation in greater detail.

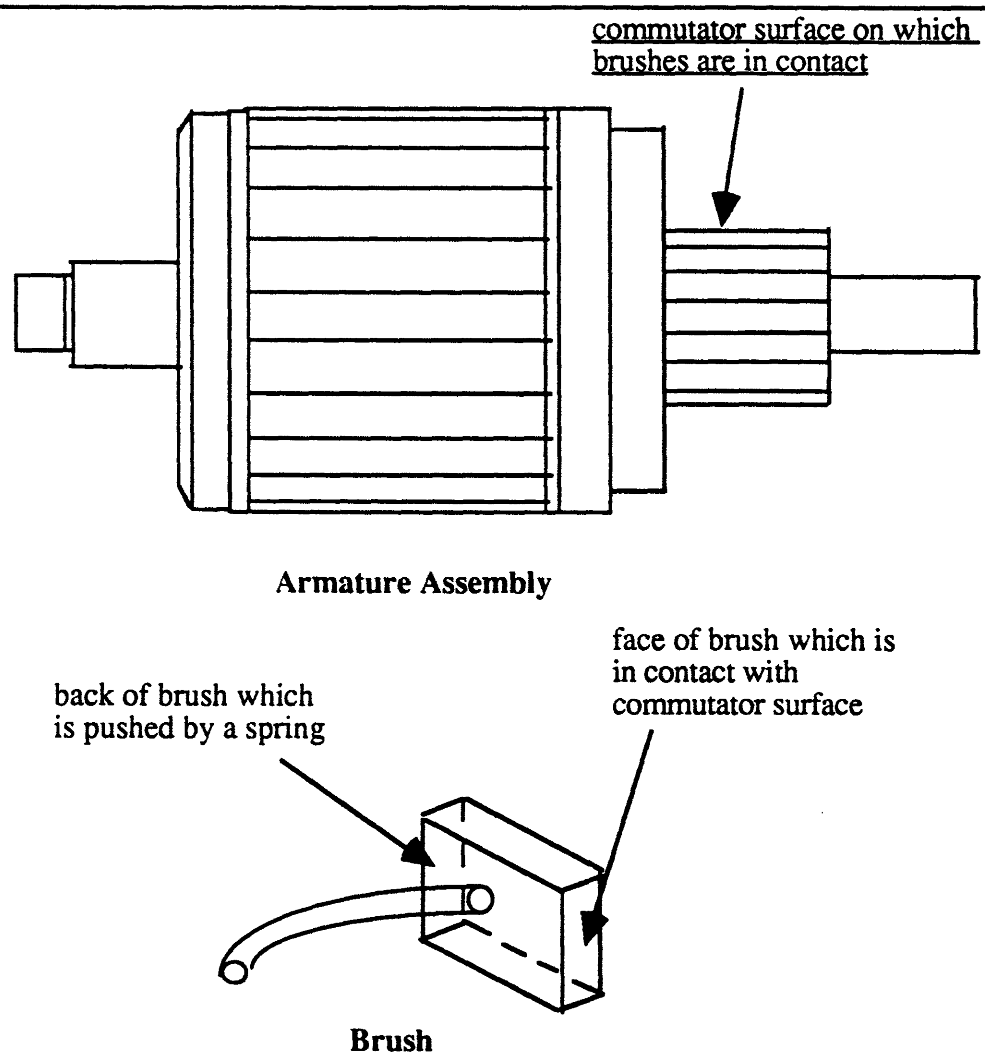

Figure 0: Pictorial Representation of Commutator and Brush

2. Starter Motor Commutation

2.1 Introduction

Commutation is the process of current reversal in armature coils which takes place while the coils are bridged by brushes at the segments to which the ends of the coils are connected. The armature is that part of the motor which rotates and carries the winding connected to the external circuit and in which the principal e.m.f. is induced. It refers to the complete assembly of the winding with core and commutator. A commutator is an assembly of bars of segmental section, insulated from each other and connected to the coils of the armature winding. The assembly comprises a hollow cylinder on which brushes bear. The arrangement serves to connect each of the sections of the armature winding in turn with an external circuit connected to the brushes. A brush is a conductor serving to provide, at a rotating surface, electrical contact with a part moving relatively to the brush.

The usual information available on brushes from catalogues are density, specific resistance, hardness, transverse strength, etc. To a designer of motors who is concerned with motor life these values are practically useless. What may be useful are information on some operational parameters such as typical voltage range, maximum operating speed, and current carrying capacity since these values relate directly to the operation of the motor. But more helpful to the designer concerned with motor life are values on contact drop, coefficient of friction, and filming action. In order to understand what these parameters mean to the motor engineer, we need to look at how they relate to brush operation (Morganite Electrical Carbon Limited, 1988).

2.2 Brush Operation and Characteristics

2.2.1 Brush Operation

The main purpose of a brush is to conduct electrical energy from the stationary external source to the rotating member. Toperform this perfectly, the brush must be in full contact with the rotating surface at all times. In addition to acting as a contact, a commutator brush must also function as a switch in combination with the rotating commutator. The brushes must continuously reverse the current in the coils as the armature rotates. To do this, a particular coil is short circuited and the energy that has been stored in the coil's magnetic field is dissipated. A reversed current is then built up in this coil. This process of short circuiting and then dissipating locked energy may cause the brush and/or the commutator to be damaged such that their wear rates become excessively high. A brush must possess appropriate characteristics to go through this process.

2.2.2 Brush Characteristics

Contact drop is a voltage drop or loss between the commutator and a pair of brushes resulting from the passage of current It is the brush characteristic responsible for restricting the short circuiting current when the brush is in contact with two adjacent commutator bars. For starter motor applications, it is important that a brush material is selected that has a high enough allowable contact drop to accommodate realistic losses. Contact drop is not a sole function of brush composition. It is also directly affected by brush film. The thicker the film, the higher the contact drop.

For a brush not to erode rapidly, it has to deposit a uniform film on to the commutator surface. The process of brush filming is a complex relationship among brush composition, humidity and ambient temperature, moisture content of the surrounding atmosphere, and contaminants. Solvent vapors, silicone vapors, grease or oil mists, and silicone adhesives are particularly harmful to film formation. This is most true in totally enclosed motors since the trapped fumes will cause the film to become unstable.

The coefficient of friction directly relates the normal pressure applied on the brushes to the surfacial force experienced by the commutator. It is highly dependent on the film quality that has been deposited on the commutator surface. Low coefficients of friction allow for high surface speeds of the commutator. Brushes with characteristically low coefficients produce less arcing due to minimal brush bounce.

2.2.3 Mechanical Considerations

Mechanical considerations that affect brush operation are commutator roundness, bar to bar variation and spring pressure. Commutator non-roundness implies asymmetry which translates to unbalanced pressure transferred to the brushes. Depending on the seriousness of non-roundness from commutator to commutator, one may expect unequal brush life expectancies. Bar to bar variation affects the contact drop as the transition from full contact to non contact is experienced by the brush. Spring pressure is directly related to the coefficient of friction which in turn affects filming and contact drop.

2.3 Manifestations that Lead to Shortened Motor Life

The more common symptoms of shortened motor life that occur during motor operation are arcing, threading, and excessive brush wear. More often than not, combinations of these symptoms occur making it difficult to find the root causes. A surge or direct high energy arc between the two polarities or between one of the polarities and ground, can happen when there is heavy arcing between the trailing edge of the brush and the trailing edge of the commutator bar. This usually occurs during a sudden vibration causing the brush to be separated from the commutator.

When brush material gets wedged in a commutator slot, a form of arcing called ringfire occurs. This material bridges the gap between bars and if it has a conductivity high enough to transport a significant amount of current then it will glow to a red or white color and since the commutator is rotating a glowing ring will be produced. This is evidence of energy losses since the slots are being loaded and that some of the energy is being shunted around one or more armature coils. A remedy to this situation is to ensure that no contaminants that cause the brush residue to become sticky are present.

Threading occurs when commutator "skin material" is machined out of the commutator leaving threads or grooves on the surface. This situation happens when inadequate filming takes place which may be due to the presence of a chemical contaminant. Inadequate film and brush hardness cause the brush to act as if it was a lathe to the commutator resulting to the formation of thread marks that are on the order of hundredths of an inch deep. If manufacturing processes can not ensure a contaminant free commutator then contaminant cleaning additives should be built into the brush and this will permit the brush to form its own characteristic film.

Excessive brush wear can be the consequence of several factors. In addition to brush grade being an obvious factor, side wearing of the brush is another which leads to the formation of a wedge shaped brush. When this happens, the problem is one whereby there is an improper electrical connection between the brush and the external source. Rather than the current being transmitted through a wire or a spring, it reaches the brush by jumping between the holder and the brush. This leads to side wear of the brush and ultimately premature failure. Another important consideration is environmental in nature. Operating in an environment without sufficient moisture in the ambient atmosphere can cause brush material to be eroded very rapidly.

3. Starter Motor Tests

3.1 Introductory Statement

There are several tests that the Ypsilanti plant conducts that establishes minimum standards of performance and durability required of a starter motor designed for cranking internal combustion engines. These engineering tests are in addition to material inspections, dimensional checking, and in-process controls. Of the potential ways of testing, there were three types that were initially considered for the project: battery rundown, durability testing, and performance test. The Battery Rundown was later on deemed inappropriate, given our project objective and thus excluded from the testing. Further explanation on this is provided in the commentary section of this chapter. This chapter describes each of these tests (source: Ford Engineering Specifications for Starters) and provides an evaluation of their relevance in lieu of the goal of extending the life of the starter motor. The chapter ends with a discussion of why a more direct wear measurement is needed in combination with durability testing and performance measurement.

3.2 Battery Requirements

The following battery requirements are applicable for Durability Testing:

- The ampere - hour capability of the battery must be equal to that of the largest battery released for use with the starter.
- The battery must be unused and not more than 60 days old.
- Prior to use for durability test, the battery must be checked for high rate discharge performance.
- Battery specific gravity must be checked, recorded once daily, and must maintained in a fully charged condition.

- Test batteries shall be replaced when they can not be maintained in a fully charged condition, i.e., with a 1.230 specific gravity.

3.3 Extended Engine Durability Testing

In this test procedure, starters must meet a minimum life of 20 kcycles (1 kcycle = 1,000 cycle) under the following conditions without failure. Testing is continuously performed until starter motors fail.

Durability testing is cyclic testing where each cycle goes as follows:

(1) Energize starter

(2) Crank and start engine. Cranking duration is not to be less than 0.95 seconds nor more than 1.05 seconds.

(3) Allow engine to reach 1000 to 1200 RPM with the starter engaged.

(4) Allow the starter to overrun for not less than 0.95 seconds, nor more than 1.05 seconds.

(5) De-energize and disengage the starter.

(6) Starting cycle shall be run at 2 starts per minute.

The drive flange and armature may be lubricated every 10,000 cycles. The drive clutch temperature must not exceed 150 degrees Fahrenheit.

3.4 Battery Rundown

Separate from the Durability Testing is the Battery Rundown Test which is performed in two dissimilar test environments. In one environment all the engine, battery and starter are at room temperature (68 to 80 degrees Fahrenheit) and in another environment at 0 degrees Fahrenheit also called Cold Cranking Test. For the room temperature case, the engine is cranked continuously without ignition for a maximum of five minutes. For the Cold Cranking Test, the engine, battery, and starter are cold soaked for a period of 16 hours at 0 degrees Fahrenheit. The test will be conducted with no fuel and the specified low temperature oil in the crank case. The starter must continue cranking the engine until the battery is discharged. For each of these tests, upon completion, the starter motors are further tested on a durability test and must satisfy a minimum life of 10,000 cycles. Durability testing is continuously performed until starter motors fail.

3.5 Test on Performance Characteristics

The starter motor is placed on a stand where its performance characteristics can be measured and combinations of performance characteristics called performance curves can be plotted and compared with acceptable standards. Plots that result from this test are: current drawn Vs torque applied, angular velocity in RPM Vs torque, and voltage Vs current. From this test comes three sets of results:

(1) Free Spin Test

This test consists of energizing the starter, in unloaded condition, from a constant voltage source. Applied voltage, current draw, and limits for armature RPM are specified on the applicable performance curve. Acceptable test values must be obtained within the first five seconds of energization.

(2) Running Torque Test

This test consist of coupling the starter on a variable loading device and providing a power input with a voltage current regulation curve as specified on the applicable performance curve.

(3) Stall Torque Test

Stall torque is the torque required to initiate motion of a starter motor that is fully loaded condition. The stall torque of the sample starter motor must meet or exceed the torque indicated on the applicable performance chart.

3.6 Commentary

None of the aforementioned tests individually or in combination directly relates to wear. The battery rundown test is basically a way to thermally stress the starter motor via continuous cycling without a load until failure by overheating As a simple and easy stress test it is acceptable. It was designed for cases when drivers, in response to disengagement or "non-starting", elect to continuously turn on the key with the hope of starting the car when in fact the most likely result is starter destruction due to heat build-up. The spirit behind the battery rundown test is to prevent or postpone heat build-up from happening. The battery rundown test has little value in terms of wear testing because it is a short term test and wear is a long term phenomenon. The mechanical wear mechanism which results from friction simply does not have time to work.

It has been suggested that the motor torque per ampere ratio which can be calculated from the performance measurement test be used as a measure of wear. This is an extremely dangerous suggestion because there is no direct correlation between wear and this ratio. The measured ratio well depend on:

- magnet strength - material properties and charge
- gear friction
- bearing friction
- airgap length

Attempting to infer wear from motor torque per ampere is thus not scientifically sound.

Durability testing is essentially two things. One, it determines whether the starter surpasses the 20,000 cycle specification and two, when the starter fails. One can not deduce wear behavior from this test. Only if we know how the wear behaves can we say something meaningful on how to satisfy the 55,000 cycle goal.

3.7 Measuring Wear Directly

Various ways were suggested to measure wear directly. The most direct and convenient way that the team proposed was simply to puncture the sides of the starter motor housing in such a way that the brushes are exposed allowing the deflections of each of the brushes due to cycling to be measured by a depth gauge. The measured deflection is taken to be the total wear, i.e., sum of the brush and commutator wear. Once this direct measurement was established the following procedure was followed for every experimental starter motor:

(1) Determine the zero cycling and thus zero wear depth gauge reading of each starter motor;

(2) Subject each of the experimental starter motors to prescribed number of cycles using durability test stands;

(3) Measure depth gauge readings of the motors;

(4) Conduct performance measurement on the motors;

(5) Repeat (2) to (4) until motor failure is reached.

This procedure allowed for the dynamic measurement of wear. It is important to have an idea of how the wear pattern looks like. Knowing the wear pattern helps us to determine how feasible it is to add more wearable brush and commutator material. For instance, if the wear pattern exhibits a plot that "shoots up" as cycling increases as with an exponentially increasing behavior then this behavior may imply the addition of brush material on the order of inches to reach 55 kcycles. Obviously, this can not be done and therefore this would necessitate major changes in starter motor design.

The person who took the depth gauge measurement was requested to go through a "Measurement Capability Analysis" which is a standard repeatability and reproducibility measurement test at Ford Motor Co. that metrology workers take to determine how accurate they take measurements. The person's standard deviation of measurement was found to be 0.012 mm. For the purpose of this project, we believed that this was small and thus we have confidence on the reliability of the measurements.

4. Robustness Experiment

4.1 The Concept of Robustness

Implicit in our desire to develop starter motors with long lives is the idea that we want all motors that we produce to have lives that are consistently long, i.e., with very litlle motor life variabality. The issue of variability is directly related to the concept of robustness. This chapter introduces the concept and discusses how we implemented measures to achieve it.

My initial formal exposure to the concept of robustness was when I took a course under Dr. Don Clausing at M.I.T. His teaching on the topic was so intuitive and simple that it brings home the idea clearly and meaningfully. I would like to introduce the robustness concept using his teaching with the hope that I could effect the same response that I had at that time to the reader.

Robustness is minimal performance variability under actual conditions of use. As an illustration, consider two target shooters, Bill and George. The result of their first round of ten shots each is shown in Figure 1. Observation of the result indicates that not one of Bill's shots hit the target while George had one bull's eye hit. We further observe that all of Bill's shots are tightly localized on one spot while George's were scattered everywhere. Who is the robust shooter? Who would you recommend to be the sniper for a very important mission?

Bill is the robust shooter. It is conceivable that Bill will have an easier time finding what to adjust, probably simple defogging of his rifle's telescope, in his shooting to move his tightly localized shots towards the bull's eye. George, on the other hand, will have a difficult time adjusting his shots because in addition to defogging his scope, he has to modify his posture, breathing rhythm, body position and other factors that control his shooting. In the second round, bets must be on Bill.

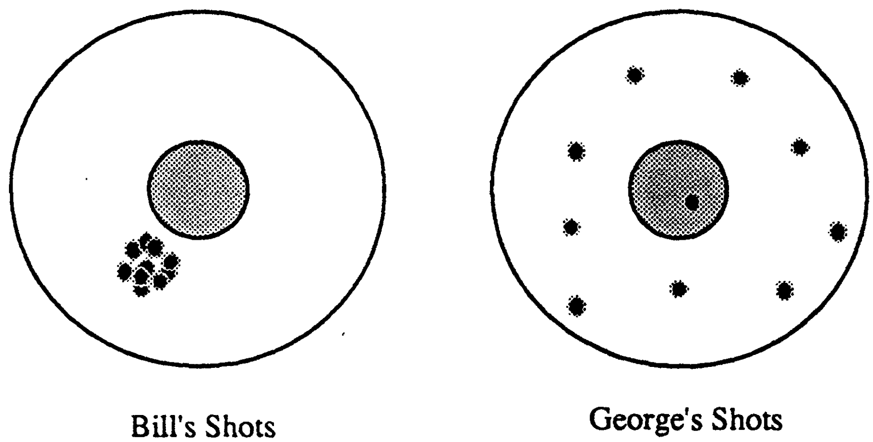

Figure 1: Illustration of Robustness (Clausing, 1994)

This example illustrates several key points about robustness:

- *An appropriate performance metric is needed* . If the sole criterion for choosing the best shooter was the number of bull's eye hits then George would be declared the winner. Choice of what to consider as the performance metric that determines our decision to regard one to be better than another is very critical that it behooves the decision maker to select the appropriate metric.

- *Tests are important* . If we had allowed one round of shooting , i.e., subjecting our shooters to only one condition, then it would be conceivable that someone may say that the results were not very convincing. In addition, we would not know the result of the adjustments made by the shooters. Well planned experimentation is an essential feature of robustness.

- *Minimization of variability is the major step* . Variability is generally the effect of individual or combinations of non-optimized factors that can be adjusted and factors that can not be intentionally changed in actual conditions. One can imagine that reduction of variability involves optimization of more than one factor, and therefore, not trivial.

- *Adjustment to the target is normally easy.* When minimum variability is achieved and the results (shots) are not on target, this is an indication that there is probably only one factor that when adjusted will result in hitting the target. Identification of this adjustment factor that maintains minimum variability is the logical next step in attaining robustness.

- *There are factors that are controllable and non-controllable.* The shooters can, depending on their preferences, choose a certain posture, body position, breathing rhythm, etc. These are some of the factors that they have direct control. There are, however, factors that they can not control which are called noise and can tremendously, in a detrimental variability increasing manner, affect the performance of the shooters, e.g., environmental visibility and comfort of their firing position as when they are in a tight position like being in a trench.

The above pointers suggest an enhancement to our definition of robustness. Robustness is consistency in intended performance even in the presence of noise via optimization of carefully selected parameters. In the following sections, we apply the pointers to our study of the starter motor.

4.2 The Metric

We want to define a metric that when measured and analyzed would direct us to a reliable evaluation of a motor's robustness. In the language of optimization, the metric is the objective function. After optimization, even though the maximum theoretical life is achieved, the life of the motor can only go a finite amount. Hence, we know that there is a reasonable life expectancy for the optimized motor. Once this optimized life has been established, we want all the motors that are produced to have a life variability around this expected life to be as small as possible.

The metric that was chosen was the amount of wear induced on both the brush and the commutator, as measured by a depth gauge, for every one thousand cycles of energizing experienced by the starter motor, WEAR/KCYCLE. There are several advantages to using this metric:

- <u>It is a measure of energy dissipated at the known "weakest link" of the starter motor</u>. Metrics that capture energy transfers are ideal because they indicate how efficiently the product is converting input energy into useful output energy. One can rationalize that when the motor is inefficient then the brush and commutator, which by historical information have been shown to fail the earliest by excessive wear, would capture that inefficiency by indicating a relatively high value of WEAR/KCYCLE and a relatively low value for an efficient one.
- <u>It allows for determining wear behavior</u>. Since wear measurements are taken after prescribed intervals of cycling, a relationship between wear and kcycles can be established. The result of this dynamic investigation is very valuable information. As far as the author's research is concerned, no known wear behavior for starter motors exists. Once the behavior is learned, we will be in a position to recommend if radical changes in the design or simple addition of brush material are needed to satisfy a certain specification for starter motor life.
- <u>It is easy to measure.</u> No elaborate measurements nor fancy equipment are necessary to obtain this ratio. Simple use of a reliable depth gauge is sufficient and fast. Ease of measurement becomes important especially if one is conducting a design of experiment where several experimental samples are needed. The easier and simpler to measure, the faster the results are taken, the lesser the cost since one is using unsophisticated equipment and shorter worker time, the lesser the confusion, and the more reliable the results.

- It leads to shorter time testing. Once the wear behavior has been established, one can predict with a measure of certainty how long the starter motor's life will be. Thus, this is a strong incentive not to test to failure which is time consuming and stressful to the testing machines. Instead of using say "X kcycles" as a specification which is primarily due to the practice of fail testing, one can use a characteristic benchmark measure say "mm of wear/kcycles".

4.3 Control Factors and Levels

Control factors are parameters that can be specified freely and up-front in the experiment. In addition to selecting the control factors that we felt greatly affect the life of the starter motor, we had to decide on the ranges over which these factors were to be varied, and the specific levels at which runs were to be made. In choosing the levels for each factor, we tried to as much as possible choose levels that are wide and very different but feasible. Doing this would emphasize the effects of level differences. This part of the design of experiment was where practical experience and theoretical understanding were very much needed. Control factors and their levels, together with the rationale for their selection follow:

- Spring Set-up Contact between brushes and the commutator is made possible by the pressure imparted by springs onto the brushes. If we take wear as a form of frictional degradation then it is easy to understand that wear is directly related to some power of spring pressure. It is interesting to note that the spring set-up used in the starter motors manufactured at Ford is very different from that of its competitors. While all the competitions' spring set-up that we examined use torsional type constant force springs, the type that is currently used in the Ypsilanti Plant is a compression type force spring. There are advantages to using a compression type spring. One, it allows for fast manufacturing. The springs are mounted on a molded plastic brush holder. The spring set-up was designed such that automation can be accommodated. Two, the weight of the brush/spring combination is, relative to competition, lighter. The torsional spring on the other hand, would require manual assembly and thus longer manufacturing. Furthermore, since the torsional springs are usually mounted on metal holders, the resulting weight is heavier. Disadvantages on using the compression spring\plastic brush holder assembly include brush holder warpage or pulverization under high heat and lack of room for additional brush material because the compression spring occupies space that could be otherwise used for more brush material. For the torsional type springs, the metal holder, unlike plastic brush holders, does not trap heat but convect heat out. They also provide more space for brush material.

Figures 2 and 3 show the force vs displacement behavior of the two types of springs. These plots were obtained by creating a fixture that allowed for both types of springs to be loaded until full compression was attained and then unloading the spring until the spring expanded to a total displacement of 0.25 in. which was a little more than 6 mm, the maximum observed distance the brush can travel before failure. During the unloading phase, the force imparted by the spring as it displaced was monitored and a plot of force vs displacement was obtained. Observation of the plots indicate that for the compression spring, given by Figure 2 the maximum force at the compressed state is about 4.5 LB and the force linearly decreases to about 1.5 LB after traversing a quarter of an inch of displacement. The torsional spring, however, has, for most of the displacement region, a fairly constant force of about 3 lbs. The torsional spring used here was a modified type of spring in that we "kinked" the end of the spring which pushed the brush. On the other hand, the normal type of torsional spring, from hereon called "unkinked"

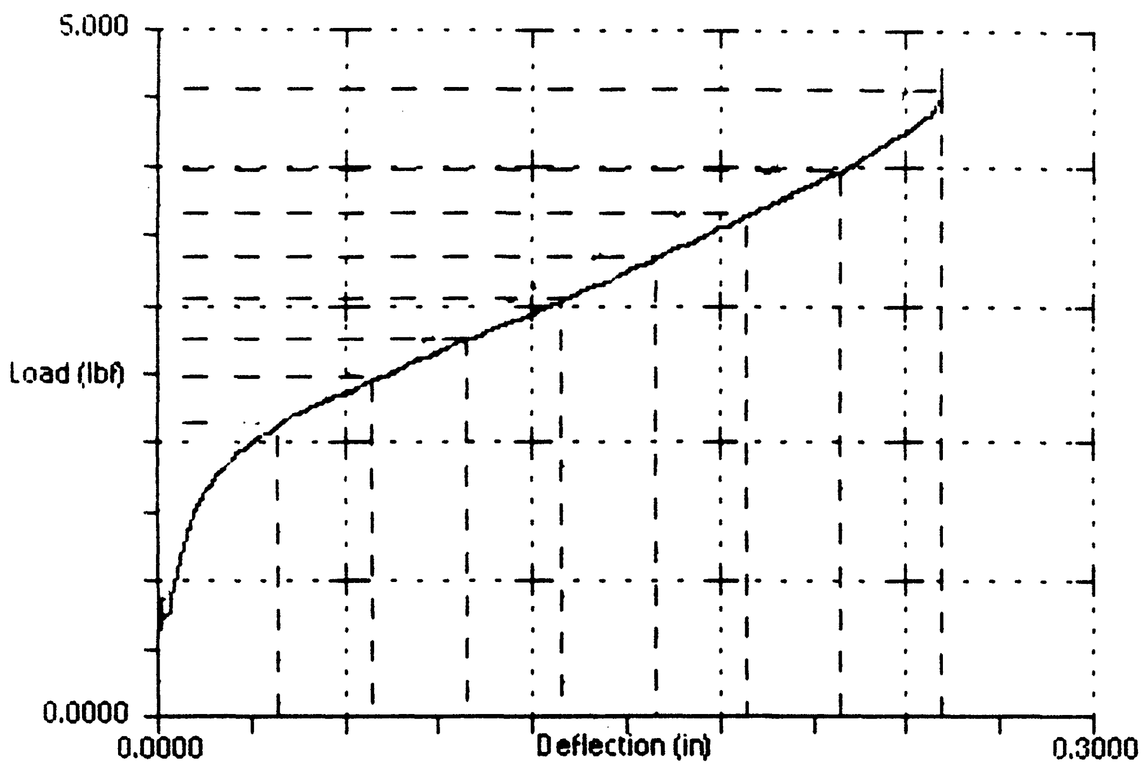

Figure 2: Spring Force vs Displacement for Compression Type Spring

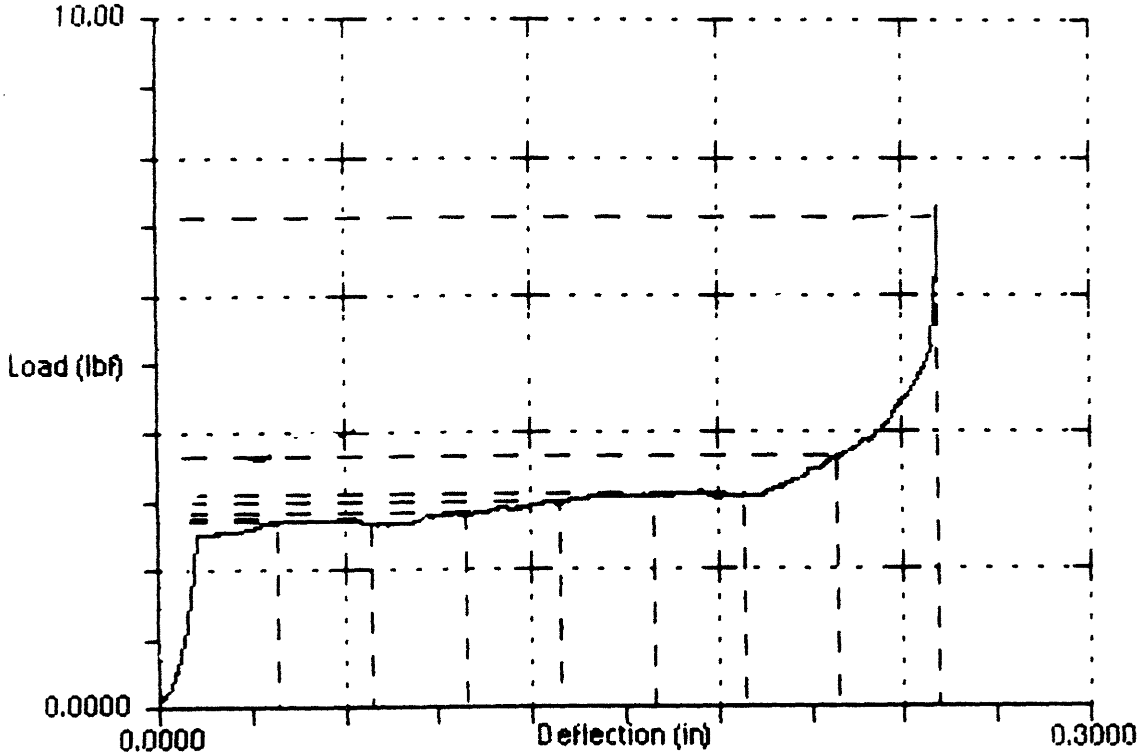

Figure 3: Spring Force vs Displacement for "Kinked" Torsion Spring

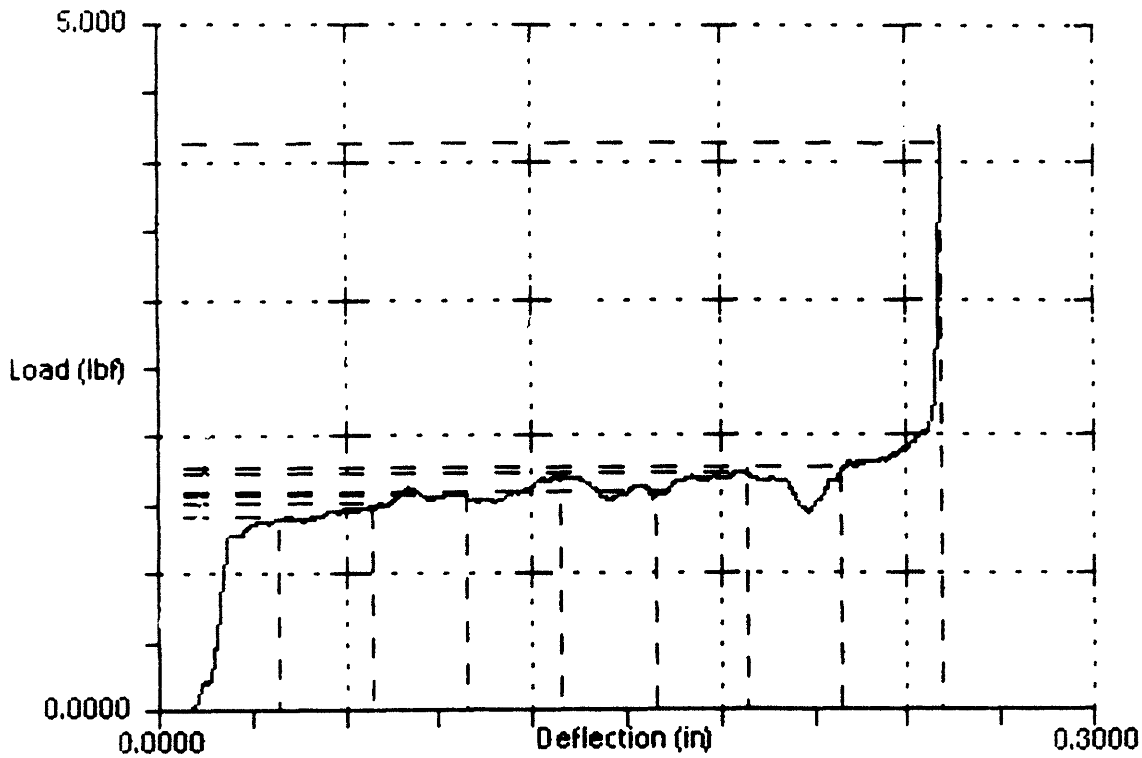

Figure 4: Spring Force vs Displacement for "Unkinked" Torsion Spring

torsional spring, has a force vs displacement plot shown on Figure 4. The same constant force behavior is apparent except that the "unkinked" torsional spring gives a lower constant force of about 1.7 lb.

For the levels of this factor, we used two levels. The first level is the compression type spring set-up and the second level is the "kinked" constant force set-up. The "kinked" torsional spring set-up which provides a higher constant force was chosen over the "unkinked" torsional spring because experience as related by engineers suggested that at the failed state of the starter, after disassembly, they observed that the springs hardly exert any force on the brush and thus the brush loses contact with the commutator. It was thus believed that the higher constant force would remedy that problem of losing contact near the end of the brush's life. Thus, the "kinked" torsional spring which imparts a higher constant force over the "unkinked" springs was used. We did not, however, ignore the "unkinked" torsional spring. We used it during the confirmation experiments.

- <u>Brush Type</u> The function of the brush is basically to provide electrical contact with the commutator. The contact characteristics of the brush are thus important in fulfilling this function. The behavior of the brush at the contact surface is related to the physical properties of the brush material. We examine in the following some of these properties that relate to the brush's contact characteristics.

Density and Porosity Manufactured brush materials are porous with roughly a sixth of their volume being comprised by air spaces. These air spaces are so structured that air can pass through them with difficulty. The distribution and size of these air voids affect brush performance. If the voids are not too large and are few in number such that brush wear debris could not block the passage of air then stability of contact behavior at high commutator speeds can be attained. Dense brush materials, however, have good wear resistance and yield long brush life but suffer from instability of contact at higher commutator speeds. This implies that there is a trade-off between choosing dense brush materials over ones which are not.

Resistivity Contact characteristics as described by contact resistance, coefficient of friction and thermal conductivity of the brush have a greater influence than the resistivity per se of the brush material in learning about the current carrying capacity of a brush. However, measuring resistivity is a useful quality control procedure. Since contact resistances are usually 10 times that of the resistivity of the material itself, knowing the resistivity of the brush material provides us with information on the contact resistance during actual operation.

Thermal Conductivity It is conceivable that as the heat, due to the rubbing action between the brush and the commutator, originates at the brush contact surface, the temperature at this contact surface will be orders of magnitude higher than that of rest of the body of the brush. Carbon, which is the main element of brushes, oxidizes or burns in air at temperatures in excess of 350 degrees centigrade. Hence, the brush material should have a thermal conductivity adequate for this operation. If not, the heat being generated at the contact surface will not be conducted away at a sufficient rate. This will lead to the formation of spot temperatures at the surface and because spot temperatures are characterized by high concentrated temperatures this can cause a great amount of wear by burning.

Elastic Properties Brushes are subjected to tremendous dynamic loading. Commutators are never perfectly circular nor smooth. Irregularities in the form of slightly raised bars and/or non-uniform roughness are always present. The brush spring assembly alone can not carry the cyclic loading from the commutator. The resilience and the damping have to be largely carried by the brush material itself. For the brush type control factor, three levels were chosen. The first level, Carbone, is the nominal level which is the type currently used. The second level is Melco and the third is Hitachi.

- Angle of Negative Brushes With reference to Figure 5 , the two negative brushes are located below the horizontal centerline. The angular location of these brushes with respect to the horizontal, is denoted by X on the figure. Experience working on a similar wear problem on wiper motors was the genesis for including the angular position of the negative brushes as one of the factors. The basic engineering rationale for including this factor is the principle of "make and break" in electromechanical systems. The positive and negative brushes should continuously "make" electrical contact with the commutator as it rotates. Since there are gaps between commutator bars, there will be times when a portion of the brush will not be in contact with the commutator. At X equal to 30 degrees, the leading edges of both the positive and negative brushes reach the commutator bar gaps at the same time and thus "breaking" electrical contact. During that "break", a fraction of the electrical energy, since only a portion of the positive and negative brushes break at the same time, that is carried by the brushes will have to be suddenly released into the air in the form of sparks. For current flowing on the order of O(100) amperes, these sparks can be significant to cause wearing at the brush edges. Three levels were selected for this factor. First level was at 30 degrees which was the nominal. Second level was 25 degrees and third level was 35 degrees.
- Total Brush Shift Angle The total brush shift angle is denoted by Y in Figure 5. It is the angle made by the brush assembly composed of all brushes

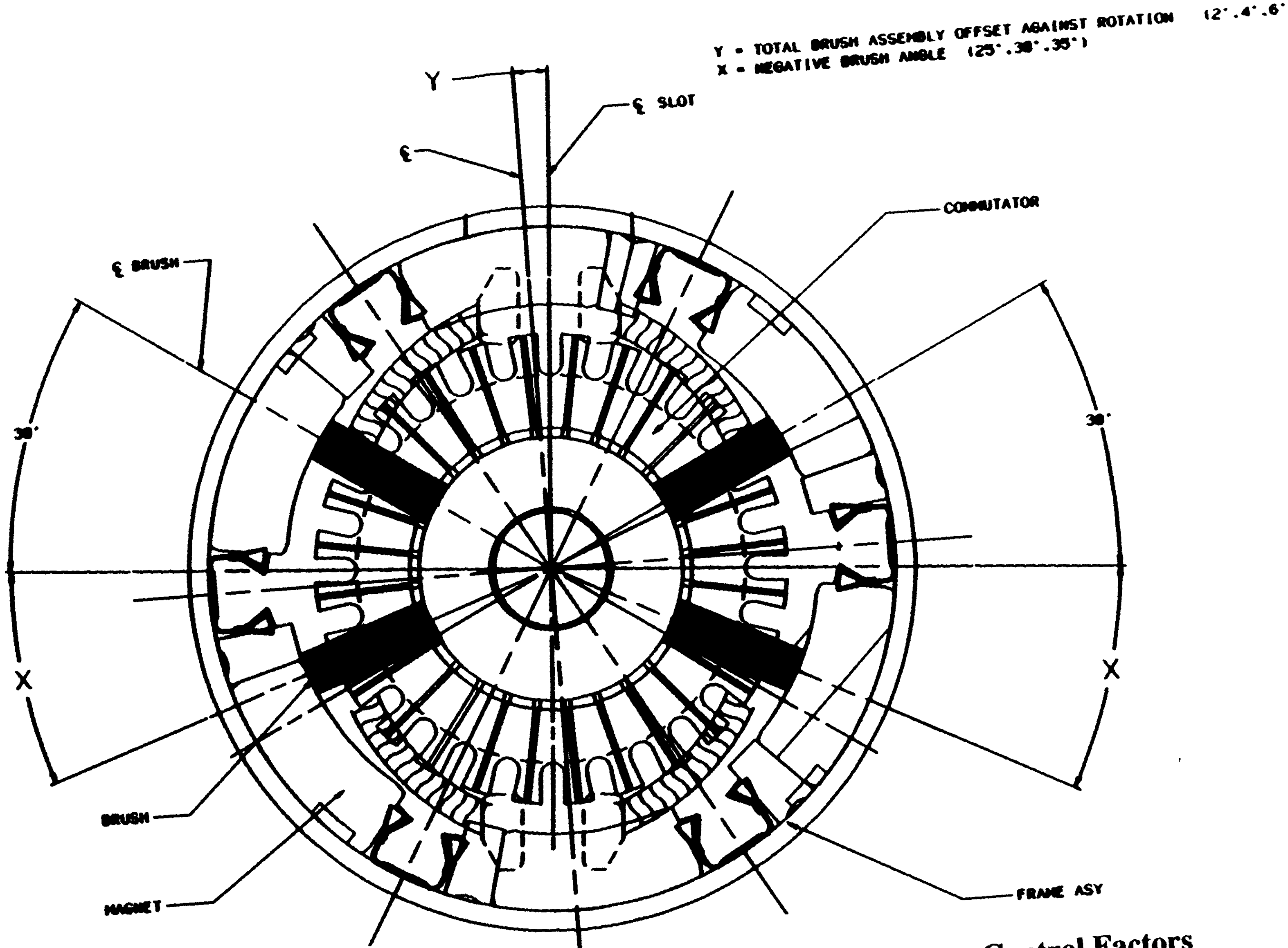

Figure 5: X-Section of Starter Motor Showing Angular Control Factors

with respect to the vertical centerline. To understand the justification for including this, it is necessary that we revisit the commutation process. A quick reference back to section 2.2 may be helpful. The principle of commutation draws upon the reversal of current in an armature coil when the commutator segments to which the armature coil is connected pass under a conducting brush. During this period, the coil is short circuited by the brush, and the current must be reduced from its original value to zero and then built up again to an equal value but in the opposite direction. The shape of the resultant field, which is the combination of the field from the six magnets and the field created by current, and the time expended during this interval are very important from a brush\commutator wear standpoint. Optimum commutation occurs when the brush assembly is oriented at a position coinciding with what is called the resultant magnetic neutral location. The significance of this location is that if the vertical centerline of the brush assembly is oriented far from this neutral position, significant sparking would occur.

The importance of this factor has been proven with blower and wiper motors. The nominal total brush shift angle is at 4 degrees. No one really knows whether this is the optimum position. We introduced two other levels. The second level is at 6 degrees and the third level is at 2 degrees.

- <u>Commutator Material</u> Commutator materials are chosen to have tough pitch and high conductivity characteristics so that the commutator segments have the necessary resistance to creep which is slow deformation due to centrifugal and thermal stresses. Cold worked copper is softened significantly at temperatures typical during baking operations or as a result of sustained overload running. When softening is a concern, use can be made of an alloy with a silver content.

The commutator material currently used does not have silver. We used another commutator material which has silver content to compare with the present material. We refer to the first level for the commutator material factor as copper and the second level as silver bearing.

A table summarizing the control factors and their corresponding levels is shown on Figure 6.

Control Factors	Level 1	Level 2	Level 3
A. Spring Set-up	compression	torsion	
B. Brush Type	Carbone	Melco	Hitachi
C. Angle of Neg. Brushes	30 degrees	25 degrees	35 degrees
D. Total Brush Shift Angle	4 degrees	6 degrees	2 degrees
E. Commutator Material	copper	silver bearing	

Figure 6: Table of Control Factors and Levels

4.4 Noise Factors

When we hear phrases like a product performing " in tightly controlled conditions", " in a hermetically sealed environment " or " in a vacuum", we conjure laboratory settings whereby the results that are obtained are on target. However, when we subject the same product to actual conditions in the customer environment, the performance of the product is hardly always on target. This is so because in the former, the product's performance environment is insulated from factors that cause performance variability. These factors are called noise factors. An essential aspect of robustness optimization is that the resulting product should be insensitive to noise. For successful product development, robustness should be done early in the development process to avoid design rework and scrap.

Noise factors can be generally classified into three types. We examine these types as they relate to starter motor performance.

- Environmental Starter motors should function anytime and anywhere in the customer environment. This means that if a starter motor functions in summer, it should also function in winter. If it functions in a dry climate region, it should also perform in wet conditions.
- Within Product Variation Owing to variabilities in the manufacturing processes, we can not expect that one manufactured starter motor is exactly identical to another one. Manufacturing variabilities lead to variabilities in the starter motor parameters from motor to motor.
- Deterioration When the starter motor is finally in the hands of the customer, it is subjected to continuous use in all sorts of customer conditions. Over time, some of the components of the motor will deteriorate and as have been observed, deterioration has been in the form of excessive wear which leads to motor failure.

Time did not permit us to capture all three noise types. We focused on deterioration. Wear is the mode of failure and we would like to determine the optimal robust settings that minimizes it. We simulate deterioration by cycling the experimental starter motors repeatedly, monitoring each motor's wear behavior until failure. This was done in the same environmental conditions, i.e., on stands in a close room at the same temperature each time tests were done (A discussion on environmental conditions is presented in Chapter 6. We chose not to induce "within product variations" because the improvement in motor life that we were after was more than two-fold from about 20 Kcycles to 55 Kcycles and we thought that "within product variations" which would be mere, small dimensional rearrangements, would not give the desired two-fold effect. In addition, we rationalized that this type of variation was inherent in the development of the starter motors and will be accounted for in randomization. By randomization, we mean running experimental conditions in a random sequence. The advantage of randomization is that it averages out the effects of all other factors not identified or some factors that can not be measured or controlled in the experiment.

4.5 Production of 18 Motors and Running the Experiments

We used an L18 orthogonal design array as shown in Figure 7. Eighteen different starter motors were needed to be produced. Time was our greatest concern. Among all the project activities, production and testing would require a considerable amount of time investment. Gathering work-in process starter motor parts in production and bringing them over to the prototype shop for assembly and then running the assembled experimental starter motors on the durability stands were subject to unfortunate random events, e.g., machine breakdowns, creation of scrap samples, and unavailability of prototype time. So as not to seriously compromise our timing, we had some of the work outsourced. In particular, the job associated with the creation of brush holders that would accommodate torsional springs was outsourced.

In running the experiments on the durability stands, we used nine stands at a time. After a prescribed number of cycling, the nine were taken off the stands , sent to the metrology lab for depth gauge (or wear) measurement, and then were run through a performance characteristic test before being placed back on the durability stands for further cycling. During all this time, while the original nine were being measured, the other set of nine were being cycled on the durability stands.

Starter #	Factor A	Factor B	Factor C	Factor D	Factor E
1	compression	carbone	30	4	copper
2	compression	carbone	25	6	silver brg
3	compression	carbone	35	2	copper
4	compression	melco	30	4	silver brg
5	compression	melco	25	6	copper
6	compression	melco	35	2	copper
7	compression	hitachi	30	6	copper
8	compression	hitachi	25	2	silver brg
9	compression	hitachi	35	4	copper
10	torsion	carbone	30	2	copper
11	torsion	carbone	25	4	copper
12	torsion	carbone	35	6	silver brg
13	torsion	melco	30	6	copper
14	torsion	melco	25	2	copper
15	torsion	melco	35	4	silver brg
16	torsion	hitachi	30	2	silver brg
17	torsion	hitachi	25	4	copper
18	torsion	hitachi	35	6	copper

Figure 7: L18 Orthogonal Array

The generally prescribed number of cycles went as follows. 12 Kcycles on the first round, an additional 7 Kcycles on the second to make a total of 19 Kcycles, 6 Kcycles after that to make 25 Kcycles total and then continuous cycling to failure. Expectedly, not all of the experimental motors could go all the way through this cycling prescription because some would fail early. The rationale behind the cycling prescription was based on the results from a lead starter that we ran on the durability stands and whose wear response we measured. This lead starter was a regular production starter that was not part of the 18 experimental starter motors. Figure 8 shows the wear vs kcycles for this lead starter motor. The goal was to choose an initial number of cycles large enough so that the resulting wear among the experimental motors were dramatically different from each other. Large differences allow us to see differences easily. This initial number of cycles was arbitrarily chosen to be 12 kcycles

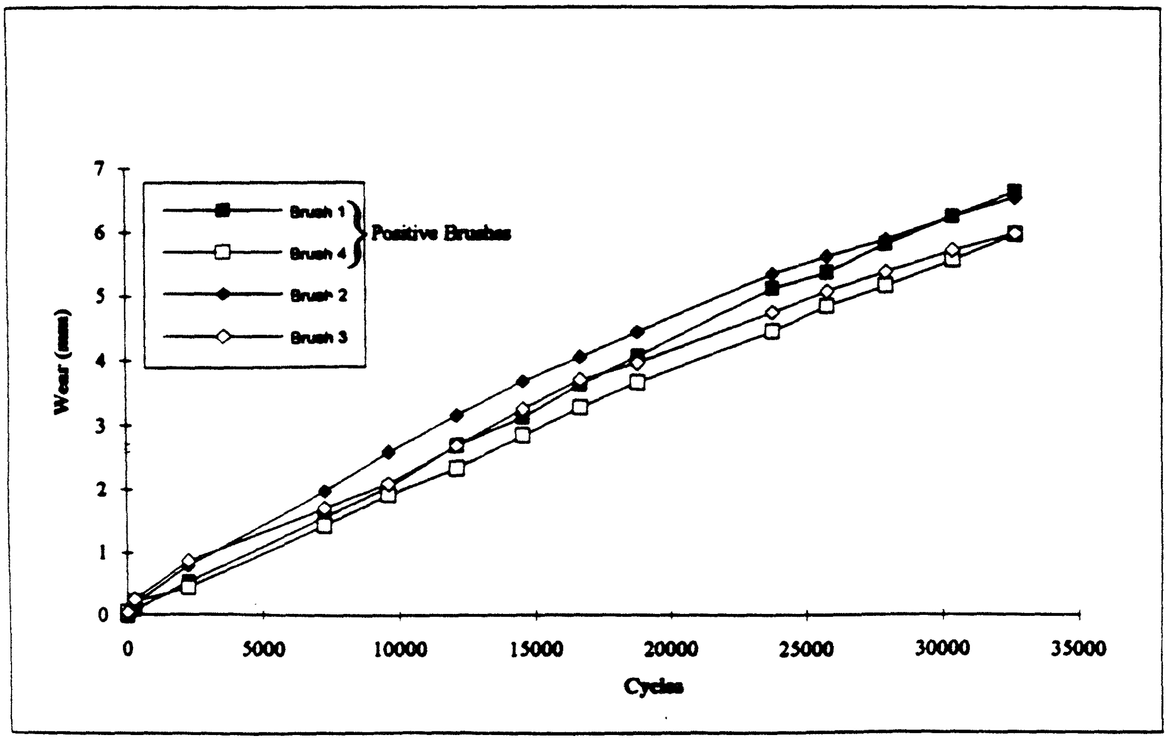

Figure 8: Wear vs Kcycle for Lead Starter Motor

5. Experimental Strategy: Analysis of Results and A Critique

5.1 Wear Behavior

From the depth gauge measurements taken on each brush, we were able to plot the wear behavior associated with each brush for all eighteen starter motors. Figure 9 shows six wear behavior patterns for quick reference. An important observation is that the wear patterns show strong linearity regardless of changes in control factors and number of cycling. The Appendix shows all the eighteen plots corresponding to all motors investigated. The implications are far reaching. One, the linearity tells us that we can determine, by simple linear extrapolation, how much more wearable material is needed to reach the desired 55 kcycle objective. Two, the goal of the optimization is to as much as possible flatten the wear vs kcycle curve. Three, the data support the claim that failure is reached, on average, after 6 mm have been worn out. Lastly, future tests need not be done until starter motor failure. One can just run the starter motors a few hundred cycles and then predict their lives. This approach will allow for lesser testing time which means relief for the testing machines, lower cost and faster development.

5.2 Orthogonal Array

The robustness design concept, also known as parameter design, was popularized by Dr. Genichi Taguchi. It is intended as a cost-effective approach for achieving the best performance of products and processes while reducing performance variation. For this starter motor life study, we were looking at the commutation process as the system. We have already classified the system parameters into control parameters, a noise parameter and a performance metric. Let the control parameters be denoted by **c**, the noise parameter by **n** and the performance metric by y. There are, in general, several settings of **c** at which the

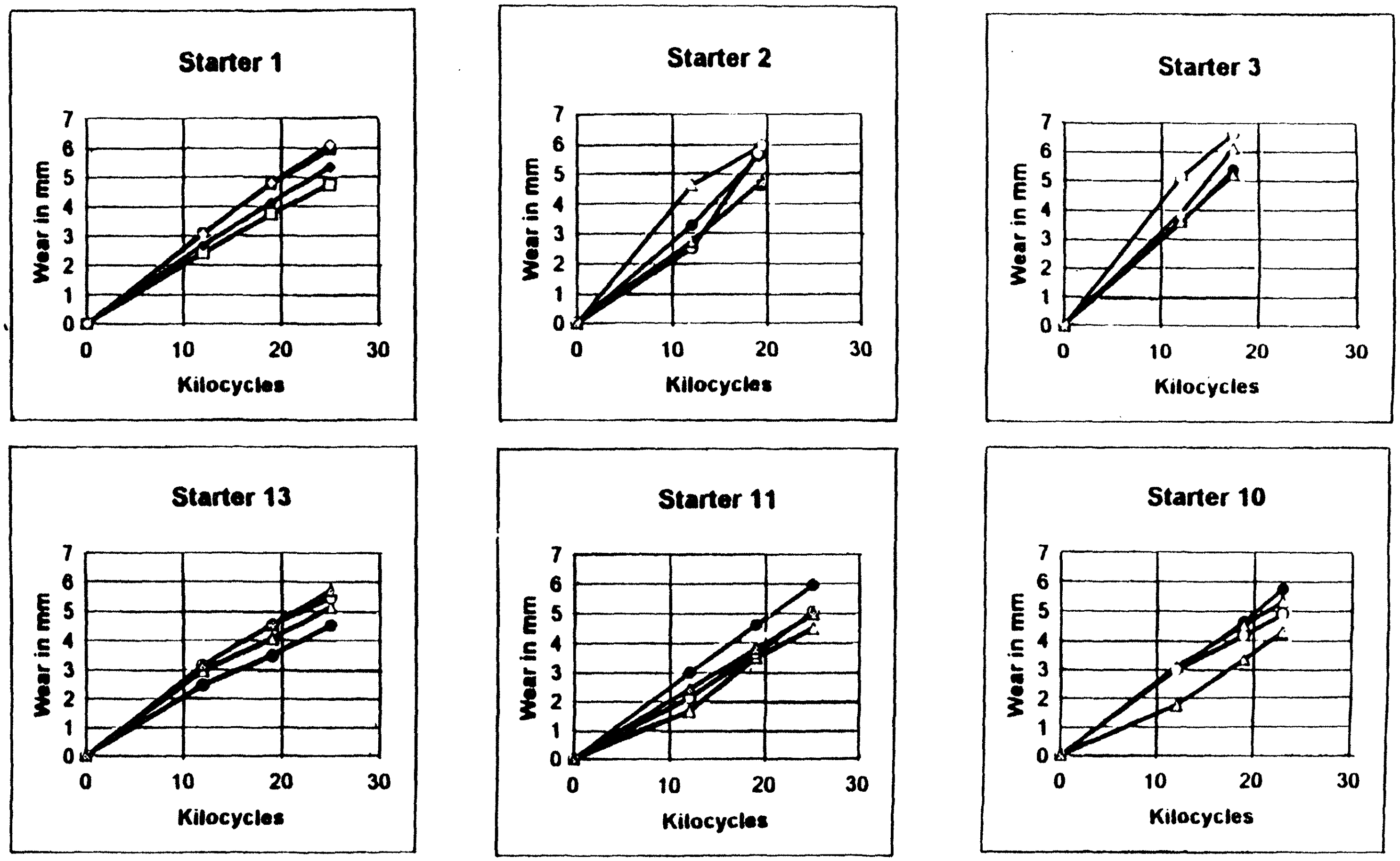

Figure 9: Sample Plots of Wear Behavior Showing Strong Linearity

system can perform, on the average, at the best performance levels. There will be, among these settings, a number of settings at which the system is least vulnerable to rapid wear due to the noise **n.** The essential idea in parameter design is to identify, through exploiting interactions between control parameters and noise, appropriate levels of control parameters at which the system's performance is robust against the noise **n.**

Dr. Taguchi has also done extensive studies on how to identify the levels of **c** that would achieve robust performance. He suggests the use of statistical design and analysis of experiments. An orthogonal array, which is sometimes referred to as control or inner array, is used to vary the control parameters **c**. For this project, we have used an L18 orthogonal array. The 18 experimental starter motors were subjected to an outer noise array that was structured to allow for the evaluation of the effects of noise. The noise structure that we used was that of varying repetitions of cycling which we believe leads to a fairly good simulation of deterioration effects. Parameter design problems are, according to Dr. Taguchi, classified into different categories with each category having a performance measure, which he calls "signal-to-noise" (SN) ratio. For our motor life problem, we would like the wear rate (mm of wear per kcycle) to be as small as possible. This wear rate is the metric. Dr. Taguchi proposes the use of the SN ratio, -10log(average of the sum of squares of the metric) as the measure of variability for parameter design problems of this nature (Phadke, 1989). From the SN ratios the main effects of each factor can be calculated. We extended our analysis by using another performance measure obtained from a least squares fit of the wear pattern of each of the four brushes. We called this least squares fit, beta with units of wear/kcycle. Like the SN ratios, we obtained eighteen betas corresponding to all starter motors and performed a main effects analysis. Figure 10 shows how these performance measures were calculated. With these

The depth gauge measurement matrix for a typical starter motor k, where k = 1, 2, ...,18 starter motors, is given by:

	Q_{1k}	Q_{2k}	...	Q_{jk}	...	Q_{pk}
1	X_{11k}	X_{12k}	...	X_{1jk}	...	X_{1pk}
:	:	:	:	:		:
i	X_{i1k}	X_{i2k}	...	X_{ijk}	...	X_{ipk}
:	:	:	:	:	:	:
4	X_{41k}	X_{42k}	...	X_{4jk}	...	X_{4pk}

where X_{ijk} = starter motor k's depth gauge measurement for brush i after Q_{jk} kcycles.

The associated wear rate matrix for starter motor k is given by:

	R_{1k}	R_{2k}	...	R_{jk}	...	$R_{p-1,k}$
1	Y_{11k}	Y_{12k}	...	Y_{1jk}	...	$Y_{1,p-1,k}$
:	:	:	:	:		:
i	Y_{i1k}	Y_{i2k}	...	Y_{ijk}	...	$Y_{i,p-1,k}$
:	:	:	:	:	:	:
4	Y_{41k}	Y_{42k}	...	Y_{4jk}	...	$Y_{4,p-1,k}$

where Y_{ijk} = starter motor k's wear rate as experienced by brush i after R_{jk} of additional cycling

= $(X_{ijk} - X_{i,j-1,k}) / R_{jk}$, R_{jk} = $Q_{jk} - Q_{j-1,k}$

From the matrices shown above, we can calculate performance metrics. Expressions for the wear rate metric, beta, which was obtained via least squares, and the SN ratio, eta, for starter motor k, are shown, respectively, as follows, with n denoting the number of measurements and $\overline{Q}_{\bullet,k} = \frac{1}{p}\sum_{j=1}^{p} Q_{j,k}$.

$$\overline{\beta}_k = \frac{\sum_{i=1}^{4}\sum_{j=1}^{p}\left\{\left(Q_{j,k} - \overline{Q}_{\bullet,k}\right)X_{i,j,k}\right\}}{4\sum_{j=1}^{p}\left(Q_{j,k} - \overline{Q}_{\bullet,k}\right)^2} \qquad \eta_k = 10\log\left\{\frac{1}{\frac{1}{n}\sum_{i=1}^{4}\sum_{j=1}^{p-1} Y_{i,j,k}^2}\right\}$$

Figure 10: Calculation of SN and Wear Rate Metric

performance measures as input, a software called JMP created by SAS Inc. was used to perform main effects analyses and predict best performance at the optimum levels. Results from this software, using both SN ratios and betas indicate similar results with the optimum levels as follows:

A	spring set up:	constant force torsional spring
B	brush type:	Hitachi
C	angle of negative brushes:	30 degrees
D	total brush shift angle:	4 or 6 degrees
E	commutator material:	copper or silver bearing

The wear rate response graph at these optimum levels shown in Figure 11 suggests that we may expect the best wear rate to be 0.14 mm/kcycle. A confirmation experiment was performed to determine if this value can be met. We show the results from the confirmation in the next section and discuss them in the last section of this chapter. At this stage, however, we can make a few observations. There are two factor level changes from the current levels that can be done to effect an improvement in motor life: Hitachi for brush type and torsional springs for spring set-up. The other levels need not be changed. Brush type has the greatest effect. Conversion to Hitachi is thus highly recommended. To compare the optimum condition with that of the current, a response graph with the factors at the current levels is presented in Figure 12. At these levels, the expected wear rate is 0.23 mm/kcycle. It is interesting to note that if we divide 6 mm, which is the average length known to be worn away before failure, by 0.23 mm/kcycle we get an expected life of 26 kcycles which is practically the same as historically observed.

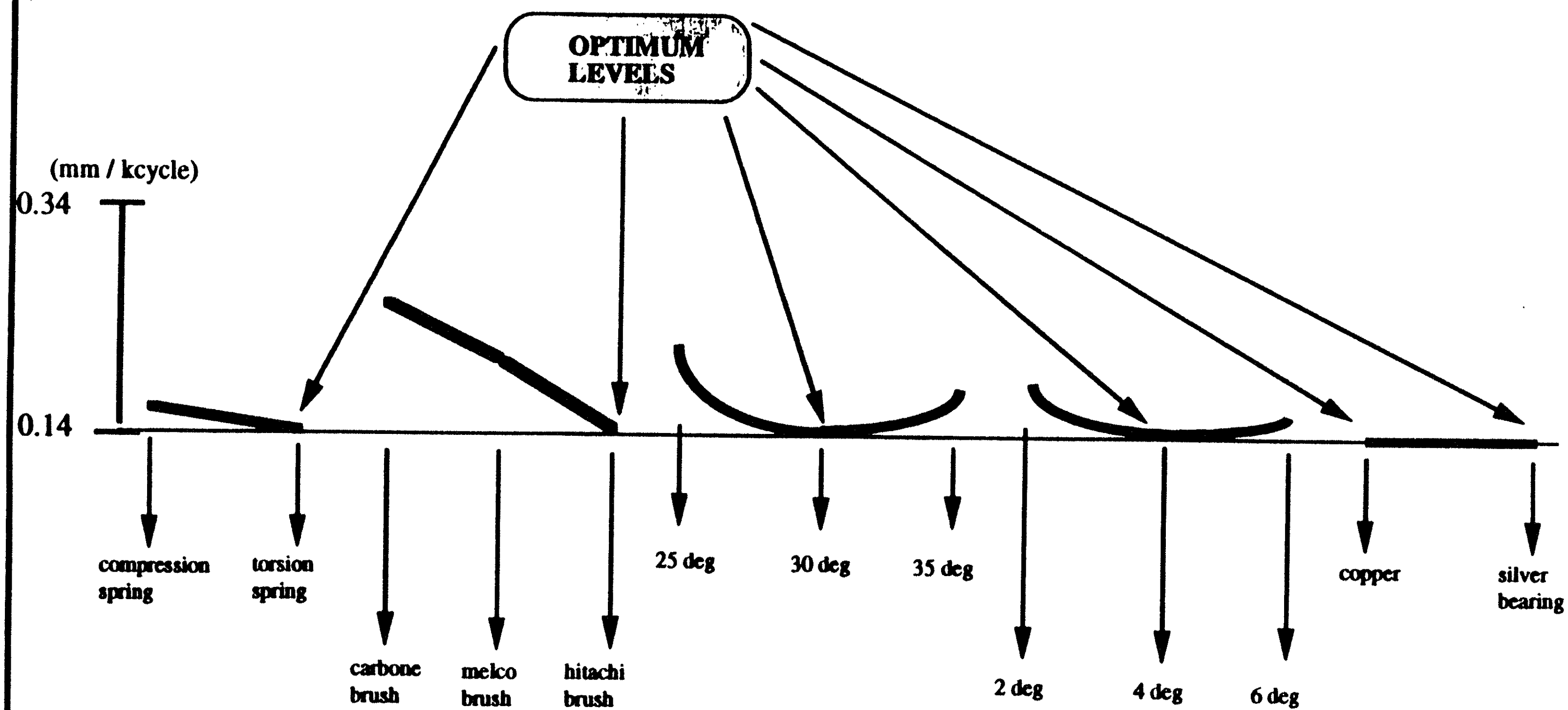

Figure 11: WEAR RATE RESPONSE GRAPH AT OPTIMUM LEVELS

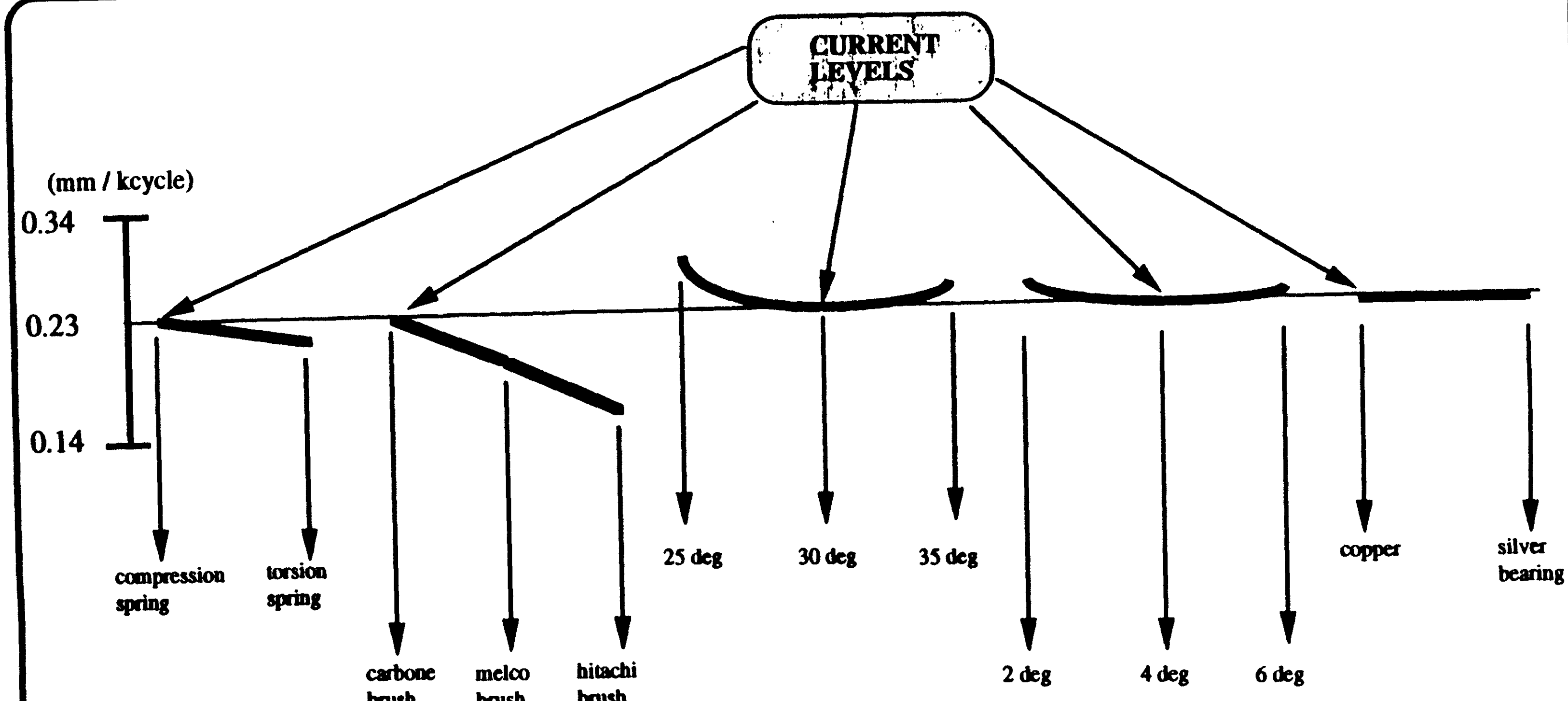

Figure 12: WEAR RATE RESPONSE GRAPH AT CURRENT LEVELS

5.3 Confirmation

To verify the assumptions that are implicit in Dr. Taguchi's approach, he recommends conducting one or more tests at the predicted optimum levels to confirm that the predicted performance is actually realized. Two motors were assembled using Hitachi brushes, torsional springs and with all other control parameters unchanged for the confirmation experiments. The two were different from each other in that one had a "kinked" torsion spring and the other used an "unkinked" torsion spring. The motor with the "kinked" spring was run up to 12 kcycles and yielded a wear rate of 0.19 mm/kcycle while the motor with the "unkinked" spring was run up to 10.436 kcycles and gave a wear rate of 0.16 mm/kcycle. The reason for running the motor with the "unkinked" spring was that since the "unkinked" spring provides a lesser pressure on the brush the resulting friction would be less and wear would thus be less. Given the results from the confirmation experiments, the predicted wear rate of 0.14 mm/kcycle appears to be unrealistic. However, the confirmation runs showed that the optimum motor with a 0.16 mm/kcycle wear rate, still yielded better results than the current motor with an improvement of 25%.

Since the wear that was measured was the total wear from the brush and the commutator material, it was not obvious where to add more material, whether on the brush or the commutator, in order to reach 55 kcycles. To know which one, we disassembled all 18 failed experimental starter motors and measured the outer diameter of all commutators. Multiple diameter measurements were taken on each commutator. These multiple diameter measurements plus information on the original specified outer diameter of the commutator and the allowable specified wearable commutator bar length of 0.508 mm, allowed us to determine if the commutators wear first before the brushes at failure. Analysis of this information shows that the amount of material that was worn away on average was 0.15 mm. This was considerably smaller than the allowable which therefore suggests that the brush wears to failure first and thus material addition should be done on the brush. If we are going to use the 0.16 mm/kcycle wear rate, to reach 55 kcycles, about 9 mm of wearable brush material would be needed. As mentioned earlier, about 6 mm of brush material is observed to be worn away when the motor fails suggesting an addition of 3 mm of brush length This length of 6 mm is reasonable because when 6 mm is reached, the shunt which is connected to the brush gets in the way of the spring in pushing the brush thereby causing little contact between brush and commutator.

5.4 Critique

The experimental strategy that we adopted is based on Dr. Taguchi's parameter design which is also known as the robust design approach. His ideas on quality improvement were introduced in the United States over ten years ago and ever since, his approach for achieving robust products and processes has generated a great deal of interest among people concerned with quality. This section attempts to inform future users of Dr. Taguchi's approach of some of the major issues associated with robust design. The author hopes that by going through this, the results of this project would be better understood and have meaning. When we did our robust design, we categorized the factors into control factors **c** and noise factors **n**. There are three sets of interactions that arise from this division: between control and noise factors, **c x n**; ; among noise factors, **n x n** and among control factors, **c x c**. The **c x n** interactions are exploited through the use of an inner (control) array and an outer (noise) array. This formalized and rigorous consideration of the effects of noise is a significant contribution of Dr. Taguchi. Before robust design became popular, there was a single-minded concentration on the mean of the response of interest. Variability was addressed simply through randomization. The underlying assumption is that variability is constant across the design levels. Engineers, however, know intuitively that this assumption is often not true. If noise factors are critical but not made a systematic part of the design of experiments, a significant portion of the variability may be captured non-uniformly over the design region and render the results unreliable. Dr. Taguchi's noise array is meant to intentionally induce the effects of noise, especially those which have a large effect on product\process performance, at each point of the control array so that control factor levels can be determined that make the product\process insensitive to the effects of these noise factors.

Of the two other interactions, **n x n** interactions do not play a significant role in making the performance robust to noise effects but the **c x c** interactions, their role in affecting a product's robustness against noise, their existence and how to handle them are aspects in Dr. Taguchi's approach that require discussion.

It is not true that Dr. Taguchi's approach assumes that **c x c** interactions do not exist. Dr. Taguchi recognizes their existence but explicit in his approach is an attempt to design an experiment such that they are eliminated or their effects are overwhelmed by the effects due to main control factors and **c x n** interactions so that additivity, which allows for the transferability of findings across experimental design conditions, is achieved.

There are practical reasons that support approaches that can achieve the desired results without having to deal with **c x c** interactions. Firstly, having to deal with these interactions is expensive and time consuming because a much larger number of experiments would be required to study the same number of control parameters. Secondly, the concept of interaction is not easily understood by the shop floor worker nor many engineers. Thirdly, transferability of design results from the laboratory to manufacturing and then to the customer may be compromised. This means that if we take the condition during which experiments are performed to be a control factor with three levels - laboratory, manufacturing and field, then it is easy to understand that if **c x c** interactions are strong say in the laboratory then these interactions can also occur in the other conditions of experimentation. Thus, the robust design approach seeks additivity of results such that results can be transferred across different conditions and this can be obtained if **c x c** interactions can be eliminated or minimized.

Dr. Taguchi believes that **c x c** interactions can be made ineffective via careful selection of the appropriate SN ratios, performance metric, control factors and their levels, noise factors and the orthogonal array. He gives suggestions on how to select the performance metric - should be a continuous variable as opposed to discreet; has a monotonic response, i.e., unidirectional with respect to individual changes in control factor settings; and should be a measurable energy usage variable.

The robust design approach can be disturbing in a number of ways. Its weaknesses can explain the difference in our predicted outcome and the result of the confirmation runs. Firstly, what if you can not find a performance metric that is continuous and has the measurable energy usage characteristic? It is also not always obvious which metric to use. Moreover, the approach constrains you to use only one metric through which you generate data and then calculate SN ratios. There may be multiple performance metrics worth investigating and the robust design approach does not offer a way of handling this. In the starter motor experiments, for example, in addition to wear rate, we could have also used temperature measurements. Temperature measurements relate to the heat that was expended during testing and may be a good indicator of motor life condition. Secondly, while the selection of control and noise factors and their interactions are very important, one can argue that designation of factors into control and noise is definitional. Also, as an extension to this, in our experiments, there may be other noise factors that are important which were not included and whose interaction with the control factors was significant. These other noise factors may be changes in environmental conditions such humidity and temperature. These noise factors may be very important but difficult to induce in a controlled way during experiments. Thirdly, claiming that confirmation runs determine the soundness of the approach may not be always true. While a confirmation run may meet the predicted optimum outcome, one should not hastily think that this in fact is the most robust point because there are times when use of a higher resolution design of experiments may lead to an even better point. Finally, and perhaps most importantly is the lack of a formal way of dealing with control factor interactions which could conceivably result in not meeting the predicted outcome. For the L18 array, we used only five of seven possible columns. Investigating the main effects associated with the two empty columns suggests strong interactions because of comparable magnitudes among the other five columns. Prior to selecting an orthogonal array, Dr. Taguchi suggests that if engineers suspect that strong interactions exist, sliding factor levels should be used. However, he does not encourage engineers to become accustomed to including interactions.

6. Conclusions / Recommendations

The project was a learning experience. The key points learned from it are as follows:

- Wear behavior is strongly linear, exploit the linearity. The testing facility will greatly benefit from this finding. Traditionally, all durability tests are performed until failure. This implies that starter motors in queue for testing wait for the motors on the testers to fail before they can be tested. Waiting is, on average, over a week. From my own experience, the testers are always busy and the queue of motors is always long. The linearity of wear behavior suggests that we do not have to test to failure to determine the life of motors. Only wear rates need be measured and this will take only a fraction of the amount of time devoted to failure testing. Total conversion to this approach may not be realistic as some people may not be comfortable on the idea of not knowing exactly how many cycles it takes for motors to go before failure. A compromise would be to use both methods of teting in the sense that given a large number of different motors to be tested and the experimenter would like to determine which type of motors last the longest, what he could do is run all the motors for a specified number of cycles and then measure the wear rates. He can then establish a cut - off wear rate level that determines which motors need to be tested further. This process is repeated until a last batch of motors are left. Then this last batch can then be tested to failure.
- More confirmation runs are needed. Since we used only two motors during confirmation, it is highly possible that due to variations we could not duplicate the predicted outcome. We have determined, however, from the orthogonal array experiments that about a 25% improvement in motor life can be attained by using Hitachi brushes and "unkinked" torsional springs with Hitachi brushes

contributing a large 20% of the improvement. To continue good relationships with the present brush supplier, it may be a good idea to encourage the present suppliers to actively improve their brushes and to use the Hitachi brushes as benchmark.

- The brush wears to failure first before the commutator does and hence any additional wearable material will have to come from the brushes. To attain 55 kcycles, use optimum control factor levels and 9 mm of wearable brush material, which is 3 mm longer than the current brush length. One way to achieve this without physically adding material is to 1) move the location of the wire shunt further towards the spring and 2) decrease the diameter of the wire. These adjustments will maximize the use of the brush whose total length currently from face to face is a little more than 10 mm. We could not have made this recommendation had we not known that the wear behavior is linear.
- Create a library of experiments that allows for further understanding of the motor. Variations in environmental temperature is a major problem. Engineers say that the performance of starter motors during winter is different to that during summer. We did not capture the effects of temperature changes in this project. We subjected the 18 starter motors to fairly the same temperature conditions. This was so because there was no durability testing set-up at the time that would allow us to capture temperature differences. This, however, does not imply that we can not use what we learned from our experiments. If in the future such a temperature facility would be available, another experiment can be run using 18 experimental starter motors having the same characteristics as what we have used. Run the same number of durability testing on them but under a different temperature condition. The results can then be combined with what were obtained previously. Similar experiments can also be done. By building on previous work, development of better starter motors will be faster.

A Note on Teamwork

This document has so far concentrated on the technical aspect of the internship. This focus on the technical side is not surprising because associated with it are quantifiable measures which when established leads to easy measurements, fairly reliable results, tangible products and easy reporting. People and team performance are in turn, for the most part, greatly measured by quantifiable metrics as well. Quantifiable metrics minimize confusion and provide people with a sense of security and teams with orderliness. The net effect is that people have been conditioned into thinking that the worth of the team is measured by what it delivers by the end of the the day, the tangible piece of evidence that implies, "Here is the result of our work. We've met our targets!" At least as equally important with the technical aspect, and yet not equally given attention is the learning associated with team behavior. This imbalance in attention is understandable because it is difficult to attach a measure to team behavior. Measuring team behavior is something new and strange especially to people who are the products of the artisan and mass production schools of thought. What remains persistent, however, in this age of information is the idea that the organization that will triumph in the next century is the organization that has learned how to harness individual strengths towards team success. I do not intend to provide a prescription for developing successful teams. Rather, I would like to share, if you will, what I have learned about team behavior with the thought that by understanding how teams behave, we get closer to determining ways and means of how to form and manage successful teams.

Let me begin by saying that the road towards successful teamwork is evolutionary in nature. A team goes through different stages of development: forming, storming, norming and performing (Interact Performance Systems, 1990). When people say that they are used to working in teams, implying that they are team players who believe that if the other members are team players as well then nothing can go wrong, they are being simplistic in that it is not a matter of nothing can go wrong but a matter of reaching the final stage of team growth as soon as possible. This suggests that a team from the initial stage of formation has to go through a learning experience that may be painful or enjoyable before it reaches maturity which is represented by the performing stage during which, ideally, the team performs with the noise, drama, and precision similar to that of an expensive quartz watch.

Forming When I first joined an existing team of three people and later on expanded the team by forming a cross-functional team, the main concern that I had in mind was having the right people. And by right people, I mean people who would bring to the team the necessary talent that will allow the team to achieve its goal in a high quality, timely and effective manner. I went about forming the team by asking for referrals from upper level management. The resulting team was composed of members coming from various work organizations: advanced engineering, production, prototype, metrology, etc. The intial stage of joining a team is always a testing stage when individuals determine if they can "stomach" looking at, talking to and making decisions with each member of the team. Each member wants to know if he is accepted by the other members and if he can accept them. At this stage handshakes are performed, smiles are exhibited and pleasantries are exchanged. Members tend to be on their "best behavior". The members are polite, watchful, guarded, and a little impersonal. First impressions count, and each member surely does not want to create a bad impression of himself.

Storming After the forming stage, which can be referred to as the "honeymoon" stage, members work more closely together and find themselves facing issues and addressing disagreements. Before forming the team, it was easy for each member to blame faults on other organizations, eg, engineering blames manufacturing for not tightening tolerances, production places the blame for not having to ship the right number of products on engineering because it interfered with production by running experiments. Now, disagreements are resolved face to face in a team setting. This is arguably the most awkward stage in that nobody relishes the experience of being placed in hot water nor take the unenviable positon of placing a member in it. This is the stage when members generally become defensive when confronted, when power struggles between factions exist and new alliances within the team are formed. The team's aspiration at this stage is that by discussing and facing disagreements, understanding and acceptance of differences will follow. The danger is that non-satisfactory resolutions may lead to demotivation, hidden agenda, confrontation, and stubborness. Those who become uncomfortable with conflicts will attempt to be passive and yearn for simply waiting for the job to end. Ignoring disagreements is not healthy because it will put the team back to stage one and thus impede the team's growth.

Norming The process of storming allows individual members to express all their points of disagreements and learn more about their differences. They go through this process until they realize that they need to get back on track, become organized and start working towards the team's goal. In the norming stage rules are established. Each member becomes more accepting and even forgiving at the slight hint of criticism. A new sense of openness prevails among the members. Nobody feels that he is an outsider. No one feels that the team is torn apart. Members become more comfortable talking about their differences. At this stage the team will focus on the task at hand and on the strengths and weaknesses of each individual member. Based on an assessment of the capabilities of each member, delegation of duties will follow. The team will establish procedures, set-up the mechanism for feedback on work that is being or has been done, provide training for members and make further decisions. The concern at this stage is that team members may get pigeon-holed in a task and may be labelled according to the roles they assume: the "whiner", the "leader", the "slow", etc. Some members may be comfortable with these roles others not. The roles can hamper individual development. The team should be careful so that discontentment may not prevail and thus, halt the team's progress towards the next stage.

Performing In this final stage, the team matures into one that values and supports diversity, recognizes individual capabilities and provides support to others when help is required. What is distinctive about this stage is that individual members take on the selfless initiative to helping everyone in the team develop their talents. Individual members become competent in performing various tasks. Roles become more flexible as a consequence. Even though other members are better at particular jobs than others, the team allows members to experience the variety of jobs. The idea behind behind this flexible, open and supportive characteristic is oneness, that individual members need not feel insecure about taking on different roles because in the eyes of the team , if everyone throws away their biases then a natural "balance " in terms of what individual members should or should not do will inevitably be reached.

Recognition of this evolutionary nature of team growth is important in that the main goal should be reaching the final stage as soon as possible. The final stage is the only one that adds value to the customer and thus mature teams spend most of their time in this stage so as to better satisfy the customer.

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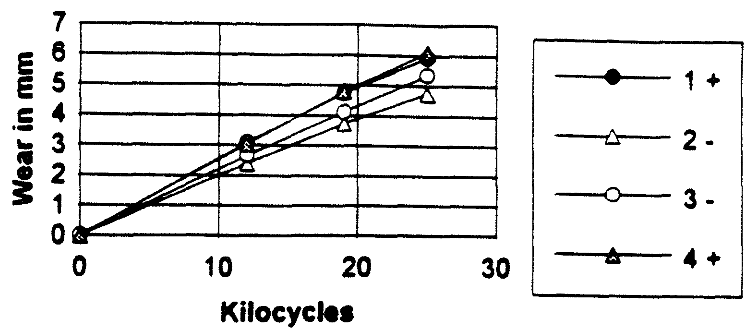
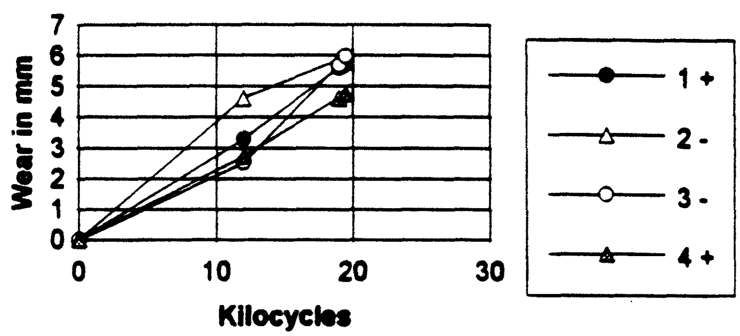
Appendix

This appendix shows the wear vs kcycle plots of all 18 starter motors used in this projects. The numbers 1,2,3,4 with the associated signs of "+" or "-" refer to the four brushes present in a starter motor.

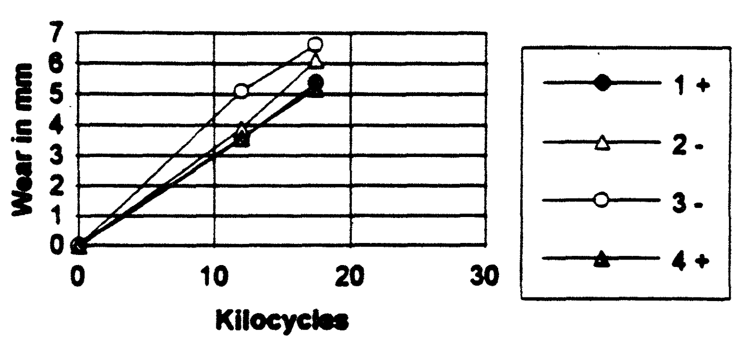
Starter 1 (compression spring, 30 deg,carbone, 4 deg, copper)



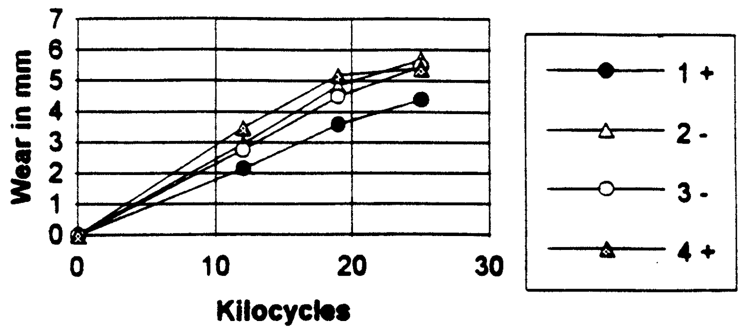
Starter 2 (compression spring, 25 deg, carbone, 6 deg, silver)



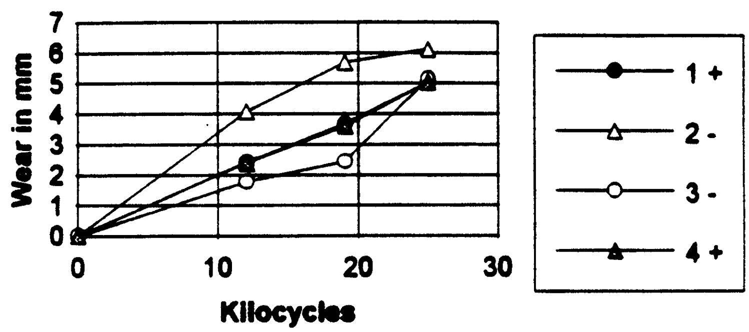
Starter 3 (compression spring, 35 deg, carbone, 2 deg, copper)



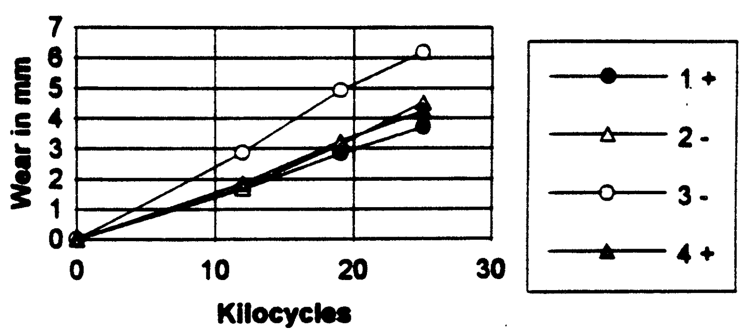
Starter 4 (compression spring, 30 deg, Melco, 4 deg, silver)



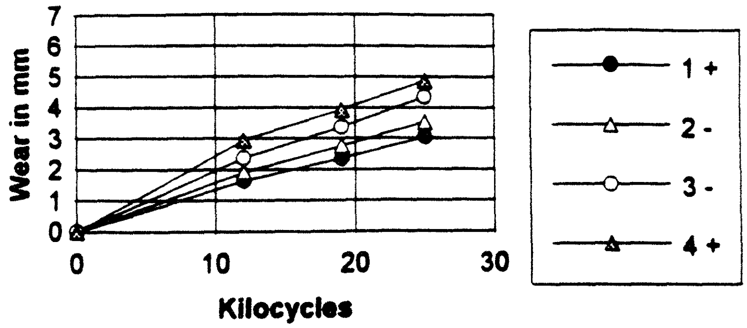
Starter 5 (compression spring, 25 deg, melco, 6 deg, copper)



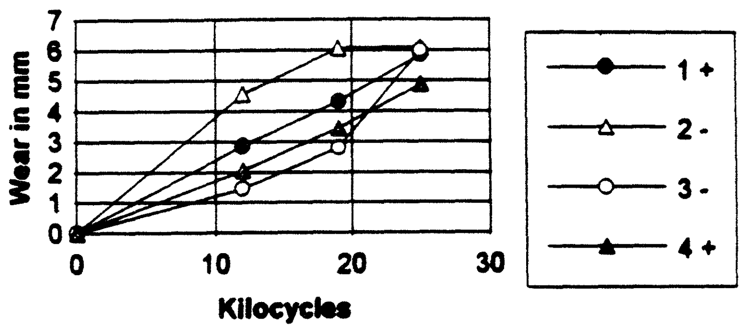
Starter 6 (compression spring, 35 deg, Melco, 2 deg, copper)



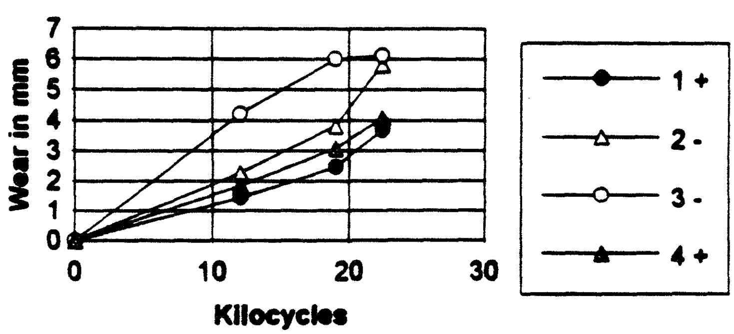
Starter 7 (compression spring, 30 deg, Hitachi, 6 deg, copper)



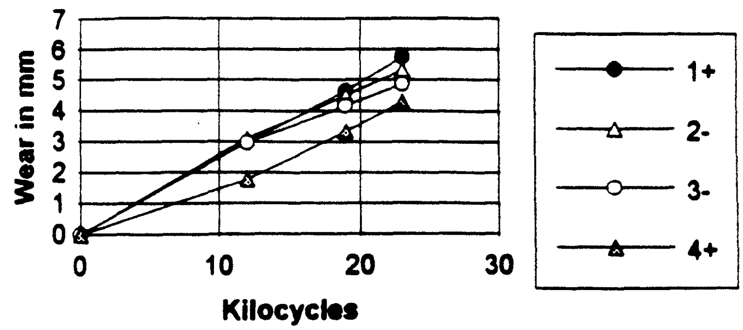
Starter 8 (compression spring, 25 deg, Hitachi, 2 deg, silver)



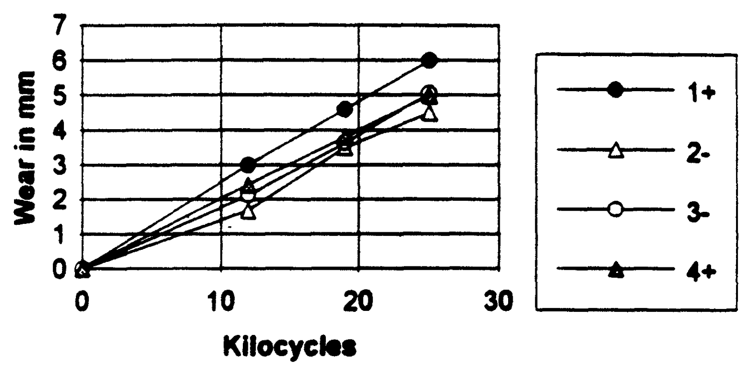
Starter 9 (compression spring, 35 deg, Hitachi, 4 deg, copper)



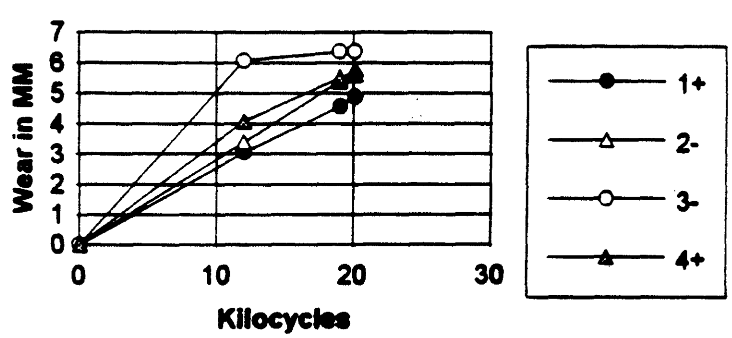
Starter 10 (torsion spring, 30 deg, carbone, 2 deg, copper)



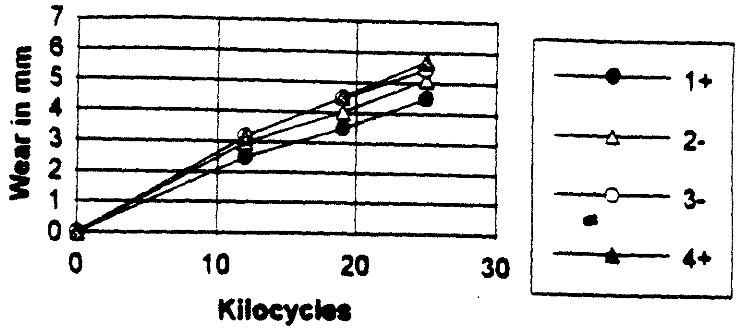
Starter 11 (torsion spring, 25 deg, carbone, 4 deg, copper)



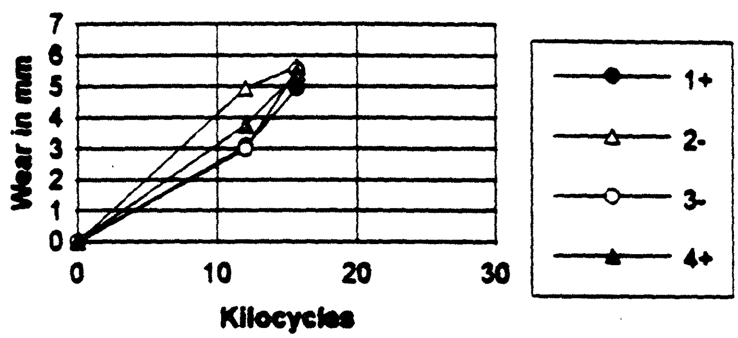
Starter 12 (torsion spring, 35 deg, Carbone, 6 deg, silver)



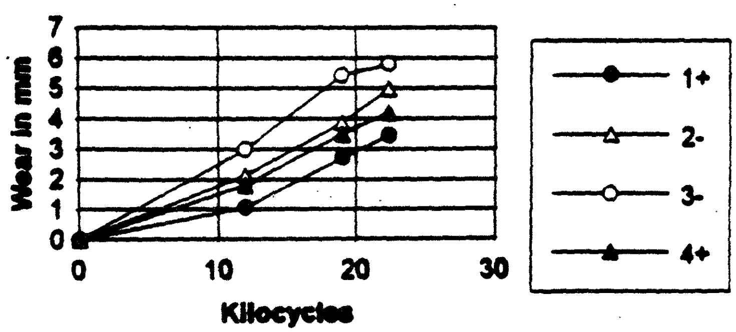
Starter 13 (torsion spring, 30 deg, Melco, 6 deg, copper)



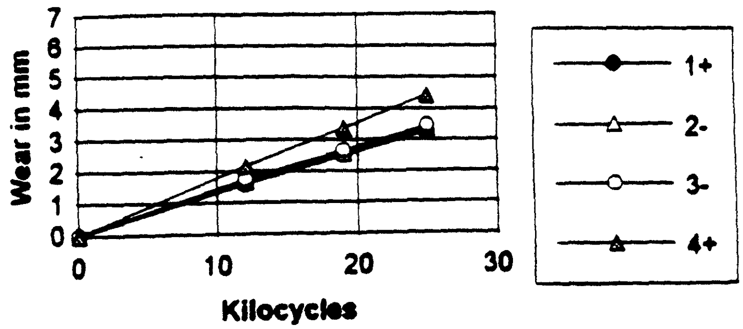
Starter 14 (torsion spring, 25 deg, Melco, 2 deg, copper)



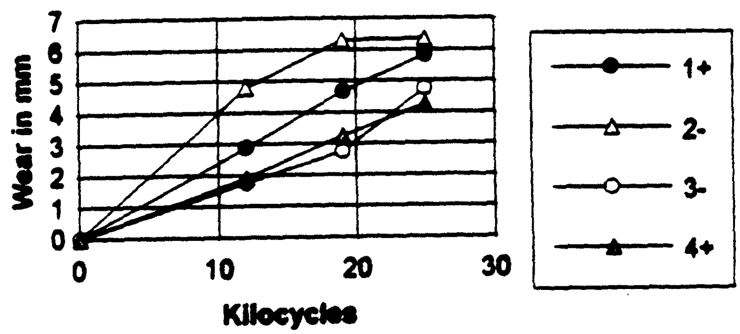
Starter 15 (torsion spring, 35 deg, Melco, 4 deg, silver)



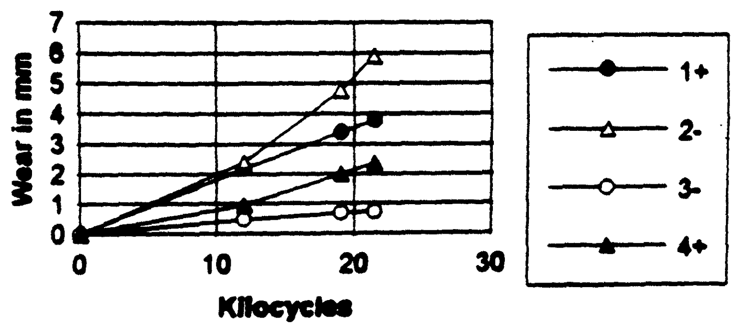
Starter 16 (torsion spring, 30 deg, Hitachi, 2 deg, silver)



Starter 17 (torsion spring, 25 deg, Hitachi, 4 deg, copper)



Starter 18 (torsion spring, 35 deg, Hitachi, 6 deg, copper)



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