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Surface finish optimization by modification of milling cutter parameters.

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SURFACE FINISH OPTIMIZATION BY MODIFICATION OF MILLING CUTTER PARAMETERS

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ABSTRACT

This work presents the results of a series of tests undertaken to improve the mill cutting process of the finish milling station used to machine the sprocket face of an aluminum transmission housing. The tests were performed using the actual high volume, transfer line machinery.

A series of twenty optimization tests were performed to understand the effects of spindle speed, feedrate, tool path, depth of cut and cutter rotation. It was determined that the optimized machining process improved the average roughness micro finish readings by 32 % and 65% in the two areas of concern on the sprocket face. This was accomplished using a milling cutter that was originally producing inferior part quality with baseline parameters. It was found that the optimized process produced an acceptable micro finish of the sprocket face surface throughout the life of the milling cutter, a significant improvement from previous performance.

To better understand the structural response of the complex work piece, a finite element analysis model was used to understand predicted deflections when various machining parameters were altered.

Modal analysis was performed on the work piece to understand the frequency response functions to form a basis of the natural frequency characteristics of the work piece. This analysis indicated a natural frequency conflict with the second order of tooth passing frequency.

This work outlines several techniques that can be used to optimize a machining process with minimal disruption to the manufacturing process.

ACKNOWLEDGEMENTS

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This thesis would not have been possible if my employer, General Motors of Canada, had not provided me the opportunity to document improvements made to their machining process.

I am truly grateful to **Dr. Yusuf Altintas** from the University of British Columbia, who instilled the idea that a machining problem could be solved by using the theories of metal cutting to understand the elements of chatter.

Special thanks must be given to **Mr. David Easton** and **Mr. Eugene Barrette** of General Motors for their technical assistance in this project.

I am indebted to **Mr. Ken Regier** of General Motors, for his assistance in conducting the series of studies performed on the equipment and organizing the data for analysis. The finite element analysis simulations and spindle vibration analysis used this thesis would not have been possible if not for the assistance of **Mr. Chip De Grace** and **Mr. Hap Hanna** of the General Motors Math Based Group.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

Figure		Page

NOMENCLATURE

k	Stiffness	$\frac{kg}{s^2}$

Greek Symbols

ω_n	Natural frequency	Hz
ζ_n	Damping coefficient	$\frac{kg}{s}$

Subscript Notation

R_a	Average roughness	μm
F_r	Radial force vector	$\frac{kg-m}{s^2}$
F_a	Axial force vector	$\frac{kg-m}{s^2}$
F_t	Tangential force vector	$\frac{kg-m}{s^2}$
Hz	Hertz	$\frac{1}{\text{second}}$

List of Abbreviations

C.N.C.	Computer numerically controlled
D.O.E.	Design of experiments
F.R.F.	Frequency Response Function
F.E.A.	Finite element analysis
P.C.D.	Polycrystalline diamond
rpm	Revolutions per minute
U.S.L.	Upper Specification Limit
V.F.C.	Variable frequency controller
4T40E	Four speed transverse axle electronic transmission

Glossary of Terms

Datum	A defined (x,y) point or plane to measure from; reference point (0,0)	

Units

μm	Micrometers or micron .i.e. 10^{-6} m	
mm	Millimeter .i.e. 10^{-3} m	
m	Metre, base unit of length (SI)	
kg	Kilogram, unit of mass (SI)	
M	Mass of system	kg
N	Newton, unit of force (SI)	$\frac{kg-m}{s^2}$
μin	Microinch, unit of length	
in	Inch, unit of length	
Ft	Foot, unit of length	
°F	Temperature in degrees Fahrenheit	
lb	Pound, unit of weight	
psi	Pound per square inch, unit of pressure	$\frac{lbs}{in^2}$

1. INTRODUCTION

In today's global marketplace, a competitive advantage translates into profits. Automotive manufacturers worldwide are constantly trying to achieve ways to produce components that are lighter and easier to manufacture. This is in an effort to reduce costs and minimize the vehicle's weight, thus producing a more desirable product.

Components such as a vehicle transmission housing tend to be a light thin walled casting which can be configured in a variety of shapes to comply with space constraints within the vehicle and various drive arrangements. In the component design process, mathematical models or tools such as finite element models (FEM) assist in evaluating and optimizing the structural integrity of the component. Strengthening ribs placed in strategic locations can minimize or eliminate machineability concerns. In some instances, compromises must be made at the design stage that trade off the benefits of weight savings in lieu of the ease of manufacturability. The result is generally in favour of weight savings as long as the component meets the validation requirements for structural durability.

1.1 The Component Being Studied

The component being studied is the General Motors Powertrain four speed front wheel drive two-axis transaxle electronic (4T40E) transmission housing, also referred to as the transmission case. The area of interest is the sprocket face and is also known as the flange face. This face mates with the external side cover as well as the internal channel plate/valve body assembly. High pressure and low pressure hydraulic oil circuits are routed throughout the sprocket face. The external flange of the sprocket face that mates with the side cover is of tremendous importance as a poor surface finish creates an inferior gasket surface, thus producing an opportunity for an oil leak. Figure 1-1 shows the function of the sprocket face as it interacts with the various components. The external side cover and channel plate are labelled details 1 and 27 respectively. The gaskets used between the sprocket face and these components are details 5 and 28 respectively.

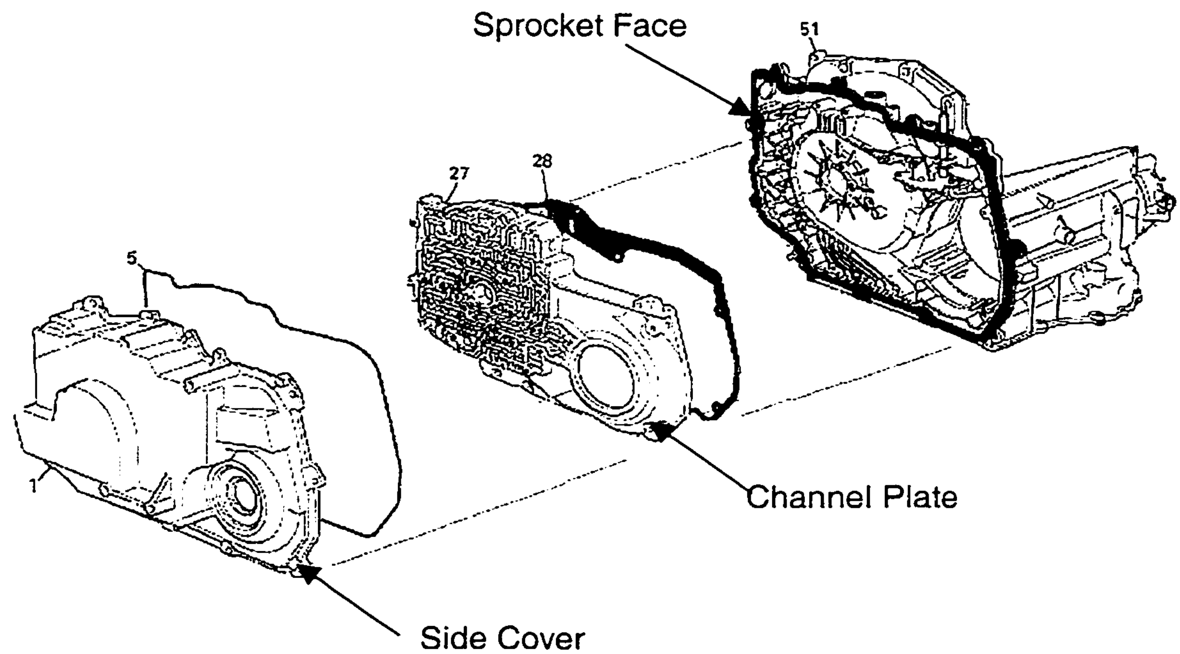


Figure 1-1 Exploded View of Sprocket Face Mating Components

1.2 Machining Processes for Large Flat Surfaces

In the design of a machining process for milling the transmission housing sprocket face, two common practices are generally used. The first commonly used machining process for large surfaces is slab face milling. Slab milling utilizes a large diameter milling cutter to machine the surface in one direction across the face. With the introduction of the technology of computer numerical controlled (CNC) machining techniques, profile face milling has become the second commonly used practice for milling applications. Profile face milling utilizes a CNC path and a smaller diameter cutter to machine the surface in a predetermined machining path. Each machining process has its advantages and disadvantages.

1.2.1 Slab Face Milling Process

The process of slab face milling consists of a large diameter milling cutter moving in one direction across the surface at a fixed feed rate. The spindle speed is fixed at a constant rotational speed. The spindle is mounted at an angle to the work piece surface to only allow the leading edges of the milling cutter to machine the part. As the cutter rotates, the inserts leave the surface of the work piece which allows the previously milled surface to remain unmarked from the passing milling inserts. This is commonly known as 'toe' on the cutter. If the inserts on the back of the cutter were to contact the previously machined surface as the cutter rotates, 'heeling' occurs, producing an undesirable scuffing pattern on the machined surface. The process of slab milling allows either up-milling or down-milling operations depending on spindle rotation and cutter geometry.

Ergonomically, the large diameter cutters are difficult to exchange, and require assist devices to lift and position the cutter during tool change. Figure 1-2 illustrates a slab milling tool path to machine the sprocket face of the transmission housing.

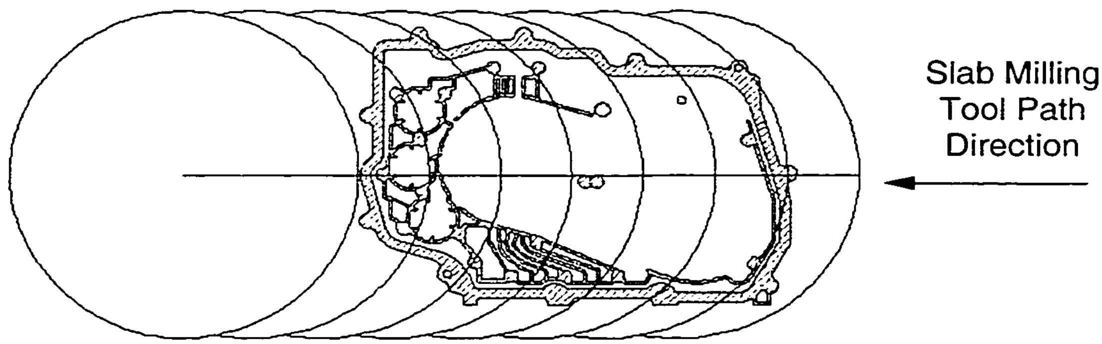


Figure 1-2 Typical Slab Milling Tool Path

1.2.2 Profile Face Milling Process

Profile face milling has become a popular process for mill cutting applications with the proven technology of CNC controlled axis machines. The machining path can be programmed to map across the part in two axes simultaneously increasing the machining flexibility. A benefit of this process is the smaller diameter milling cutter which is ergonomically easier to exchange during tool changes, and less expensive to purchase than the larger slab cutters.

The mechanics of the process require that the spindle must be mounted perpendicular to the workpiece as the leading edge of the milling cutter changes with the direction of feed. Based on the tool path, up milling and down milling operations are achieved. Figure 1-3 illustrates a CNC profile face milling tool path.

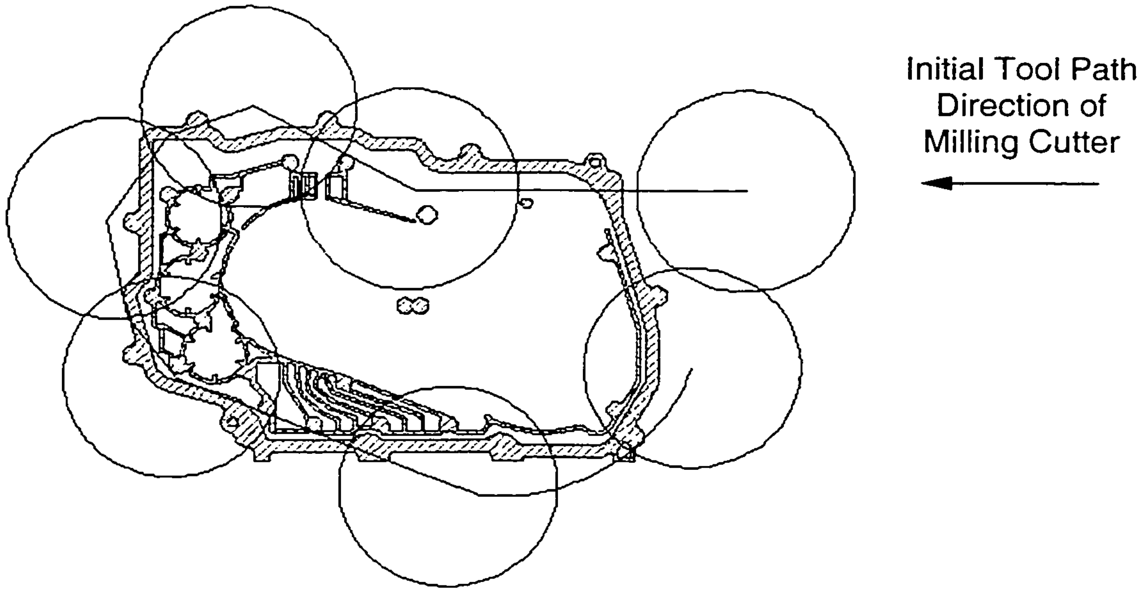


Figure 1-3 Profile Milling Tool Path

1.3 Significance of the Problem

Two areas on the sprocket face flange are of interest as illustrated in Figure 1-4. Tooling marks can be seen in these two areas after the milling cutter has machined approximately 10,000 pieces. These marks remain for the remainder of the tool life, which rarely exceeds 30,000 pieces before the measured micro finish in these two areas of the sprocket face have degraded to unacceptable conditions. The result is unscheduled tool changes to replace the milling cutter. This is unfortunate as the milling cutter is equipped with polycrystalline diamond (PCD) inserts, which should perform to a scheduled tool life replacement of 65,000 pieces providing an acceptable micro finish throughout that life. This problem results in higher operating cost due to equipment downtime for unscheduled tool changes and the cost to replace milling cutter inserts.

The maximum allowable micro finish is 1.6 μm on all areas of the finish machined sprocket face as defined by the part print. The micro finish of the surface after a tool change measures 0.750 -1.0 μm on average.

Poor micro finish is the primary part print characteristic which does not meet specifications. Although not detrimental to the quality of the transmission due to the areas in which the poor quality exists, the part print specifications dictate an unacceptable part. Other part print characteristics that need to be understood include the sprocket face surface measured to a datum, parallelism and flatness of the surface. It is not fully understood how or if these characteristics are related to the poor micro finish experienced. These characteristics are important, as the machined sprocket face is a primary machined part print datum in which all internal features of the transmission measure to this surface for transmission function.

The significance of the poor micro finish experienced in two areas of concern on the sprocket face is illustrated in Figure 1-4. Area 1 has a micro finish measurement that exceeds part print requirements as well as being visually unacceptable. The area appears to have a condition where the cutter inserts have "heeled" or scuffs on the previously machined surface as the cutter passed across this area.

The second area of concern in Area 2 has distinct tooling marks in the machined surface, which also exceeds micro finish requirements. The spacing of the distinct tooling marks is equal to the feedrate per revolution of the milling cutter. There is speculation that the part may have a natural frequency that coincides with the milling cutter's tooth passing frequency. This would cause the part to vibrate in rhythm with the revolution of the cutter.

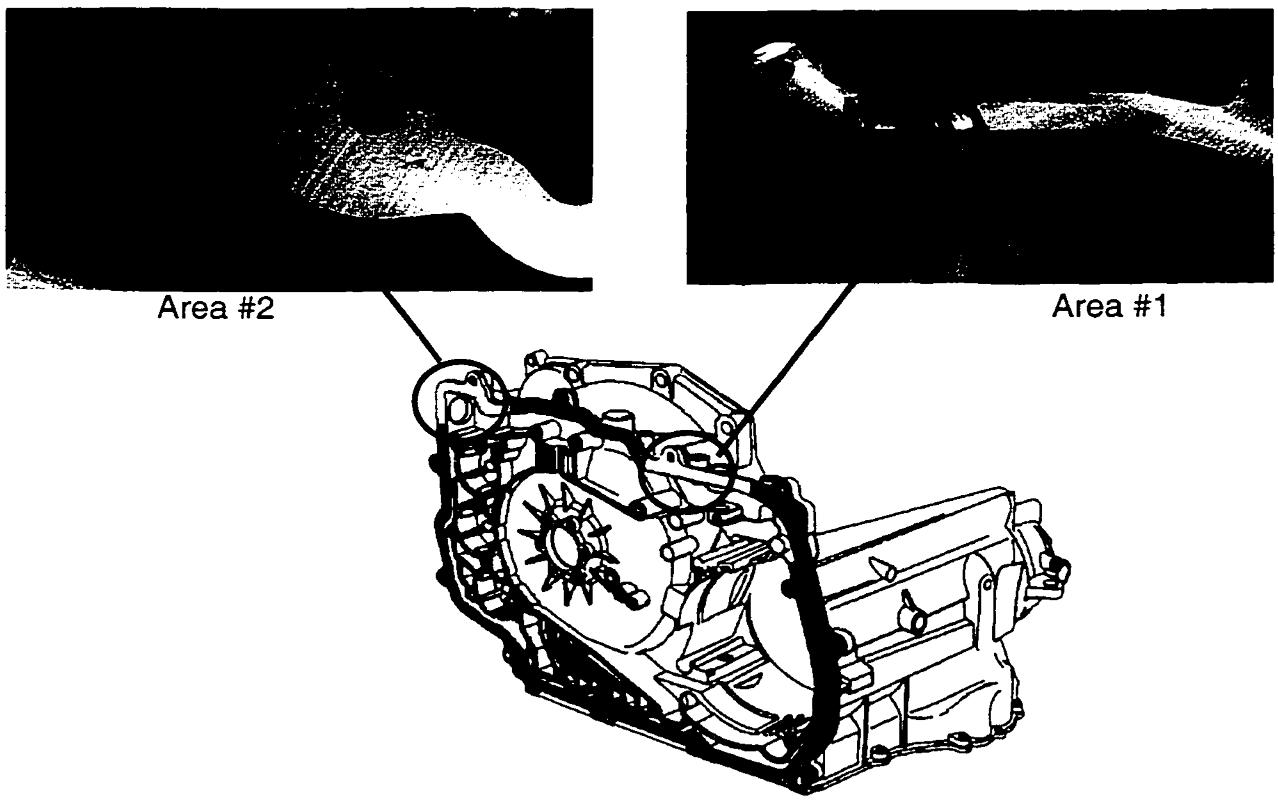


Figure 1.4 Current Surface Finish Problem on Sprocket Face

1.4 Part Fixturing

An important aspect of part quality in machining is proper part fixturing. The position of the clamping elements relative to the machine tool direction and position will dictate the part stiffness and stability during machining.

In the application being studied, the case is fixtured to a pallet in three areas. The transmission case has three cast pads extending from the thin wall cast structure. The pads are located on the centerline of the casting for structural stability. The primary purpose of the pads is to provide clamping positions for machining. The pads are used for part location on the pallet in machining, and therefore serves as an in-process datum, 'M1' to which machined features are measured. The in-process locating datum hole 'M1' is located at clamp #1. Figure 1-5 shows the position of the three external clamping positions of the fixtured transmission case. Subsequent operations use the pads for location as well as part holding.

The top rail of the sprocket face is supported only by the structural integrity of the structure. Additional part stiffening devices are not incorporated into the machine's construction as it has been deemed from past machining experiences that devices with that function often create different part deflections that are detrimental to part quality.

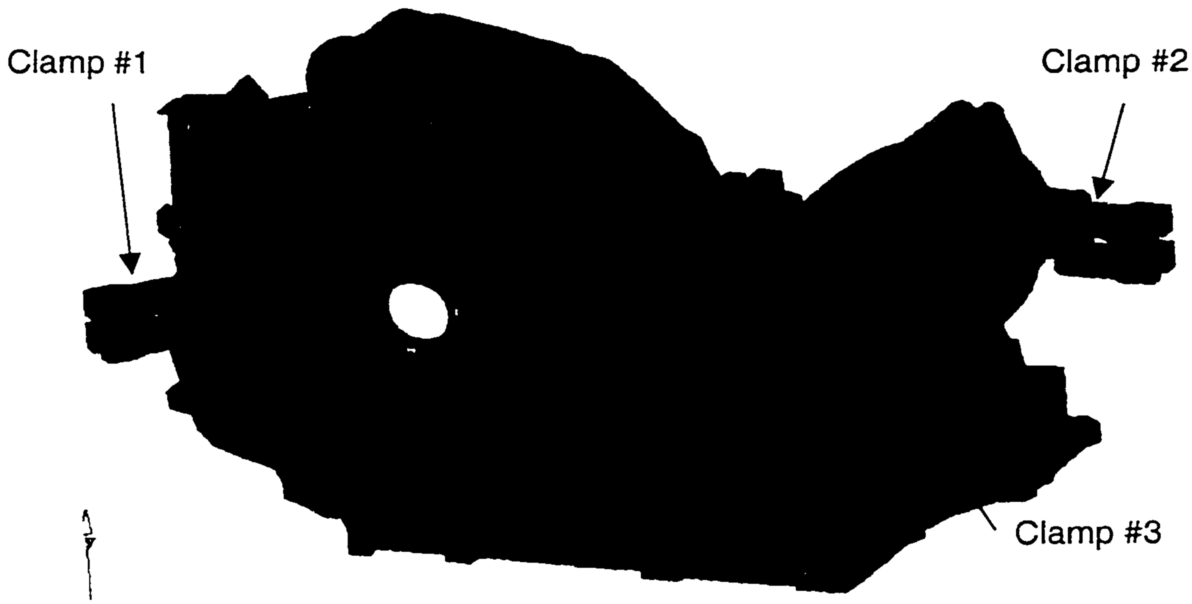


Figure 1-5 Fixture Clamping Points for Machining of Transmission Case

1.5 Statement of the Problem

Machining induced vibration is always a concern when removing material from thin walled castings. Although structurally designed to withstand vehicle induced vibrations, machining induced resonances can often unfavourably excite the natural frequencies of the component as it is being machined. The result is poor surface finish, as well as poor tool life and increased noise during machining.

There are many contributors that affect the natural frequency of the component. Fixed contributors affecting the natural frequency of the fixtured transmission case are the machining station and pallet registry. Modifying the machining station or adding damping structures to the operation is not a pursuable option due to machine design space constraints within the machining station. Variables which can be altered include the feeds and milling cutter speeds, spindle rotation, and the milling cutter path. Justification is required for changing these variables in order to make positive improvements in the surface finish of the machined face.

Understanding the natural frequencies of a component is a common technology in the field of vibrational analysis. The manufacturing industry in general does not utilize the techniques of testing for natural frequencies to diagnose and optimize machining problems due to a lack of the proper equipment and education in the field of modal analysis.

1.6 Objectives of the Study

The objective of the work as presented in this thesis is to optimize the machining parameters of the 4T40E transmission case machining operation to maintain an acceptable micro finish of the sprocket flange face throughout the life of the milling cutter while maintaining flatness and parallelism requirements. The investigation will use finite element analysis methodology to analyse the machining operation numerically. A series of vibration analysis studies using frequency response functions will provide an understanding of the natural frequencies of the transmission housing and of the machining spindle. Upon review and recommendations from the numerical and vibration analysis, the machining parameters of speed of the cutter, feedrate of the cutter, spindle rotation, the depth of the cut and the CNC tool path will be evaluated.

It is also believed that through optimization of the machining parameters, the micro finish can be maintained beyond current tool life conditions of 30,000 pieces between cutter changes.

This thesis will optimize the machining parameters to satisfy the objectives by focusing on the following aspects:

i. Using finite element analysis to evaluate predicted deflections with machining models that vary feed rate, cutter rotation and tool path.

ii. Performing vibration analysis on the machined case in a clamped fixture and of the machine spindle.

iii. Performing experimental testing by varying machining parameters of spindle speed, feed rate, tool path, depth of cut, and cutter rotation.

1.7 Layout of Thesis

The layout of the thesis paper is comprised of a series of chapters. The various chapters are outlined below.

Chapter 2 discusses the important concepts in machining with a review of the literature used in this paper. The references used in this thesis are listed in alphabetical order. The citation of each reference is done by numerical notation.

Chapter 3 contains the numerical and vibration analysis studies that were conducted to better understand the machining problem and provide direction for the optimization testing.

Chapter 4 presents the various tests completed to optimize the sprocket face surface finish.

Chapter 5 reviews the analogy that was used to decide the optimized machining solution.

Chapter 6 summarizes the results of the research and discusses how the objectives of the study have been satisfied.

Chapter 7 provides a list of recommendations for future research opportunities.

Chapter 8 lists the contributions to engineering knowledge and the influence of this work on the manufacturing industry.

Chapter 9 provides a listing of the cited references, additional references used for background material, as well as a company directory for the hardware and software used in the testing.

2. IMPORTANT CONCEPTS AND LITERATURE REVIEW

The machining of a thin walled casting with high volume, mass production equipment has always been a complex task. The review of published literature provided a knowledge base for establishing the objectives of this paper. This has provided a basic understanding of the two types of vibration that can be encountered in a machining system. The theoretical aspects of milling and chatter during machining were reviewed. The literature also provided a basic understanding of surface finish and common measurements methods. Documented project logic flow provides a disciplined approach to problem solving. A review of the Shainin Red X problem solving methodology [12] was examined. The transmission case was modelled using finite element analysis during the process development stage of the product. A summary of those findings predicted how the transmission structure would react to machining forces.

2.1 Types of Vibration in Machining

There are two main types of vibration encountered in a machine tool system: self-excited vibration and forced vibration.

Self excited vibration or 'regenerative chatter' is a type of vibration oscillation that arises through instabilities between the machine, the tool, and the workpiece. Methods of controlling self-excited vibration include increasing the static and dynamic stiffness of the machine structure or reducing the cutting force at the tool. This can be accomplished by selecting a tool holder with more rigid properties or changing the direction and magnitude of the cutting force of the tool [10].

Forced vibrations are generated from two types of typical sources: internal-force and external–force vibrations.

Internal-force vibrations are sources of vibration that are directly related to the machine or cutting process which include spindle imbalance, defective bearings, worn gears and unbalanced internal drive mechanisms. Internal force vibration includes cutting tool impacts from interrupted cuts, which can also be described as self induced vibration. Self induced vibration is due to variations in the cutting forces during machining. The forces associated with mill cutting are required for metal removal. The depth of cut and feed rate in which metal is removed, are directly associated with the magnitude of the cutting force.

External-force vibrations or transmitted vibrations are not associated with the machine tool but are sources of periodic forces, such as nearby machinery or other vibrations which are transmitted through the machinery foundation.

2.2 Theoretical Aspects of Milling

2.2.1 Mechanics of Milling

In a tool room environment, the workpiece being machined generally moves into a rotating cutting tool. The cutting tool spindle is stationary. The feed rate is dictated by the speed at which the table moves. In manufacturing, the parts are generally mounted to pallets or fixtures and are transferred into a station and clamped. A profile milling spindle at the station is a computer numerically controlled (CNC) 3 axis slide which moves side to side, up and down, and in and out to machine the work piece.

During the machining process, a milling cutter removes material in the form of a chip. The result to the work piece is a flat surface. The measurable dimensions of the milled surface are the depth of the surface relative to a datum, the flatness, the micro finish and profile characteristics. The cutting edges of a milling cutter are called inserts or cartridges. Figure 2-1 illustrates insert geometry definitions.

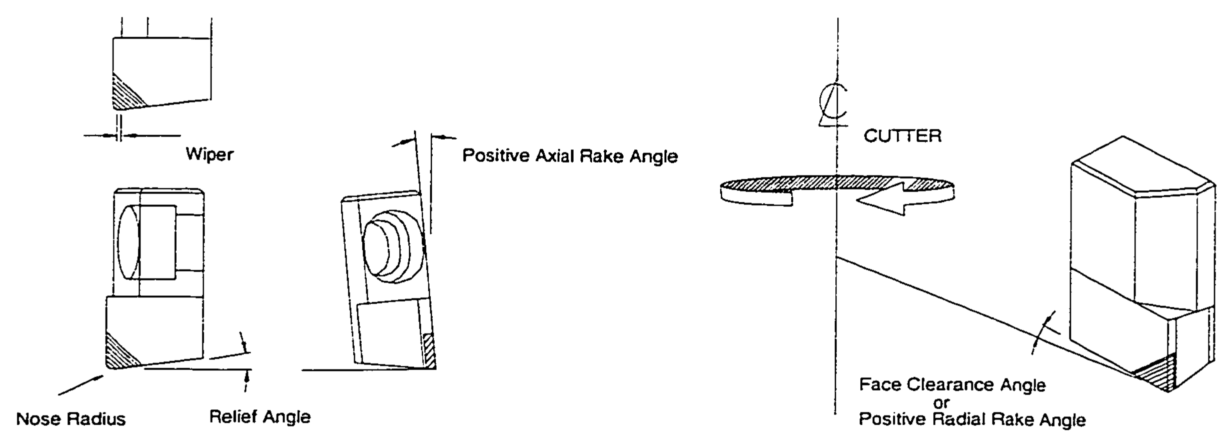


Figure 2-1 Insert Geometry Definitions

2.2.2 Methodology of Chip Formation

Three deformation zones best describe the methodology of chip formation in milling: primary shear, secondary shear and tertiary shear. On the primary shear zone, cutting energy is converted into heat at the shear plane. The secondary shear zone comes from the contact between the rake face of the tool and the chip. The flank of the tool making contact with the work piece creates the tertiary shear zone. The tertiary zone can be minimized or eliminated during milling with proper relief angle on the tool. Machining parameters such as feed rates, spindle speeds, coolant lubricity, and tool rake angles have a strong impact on these deformation zones and the heat generated during cutting. Figure 2-2 illustrates the shear planes during milling and associated frictional heat generated.

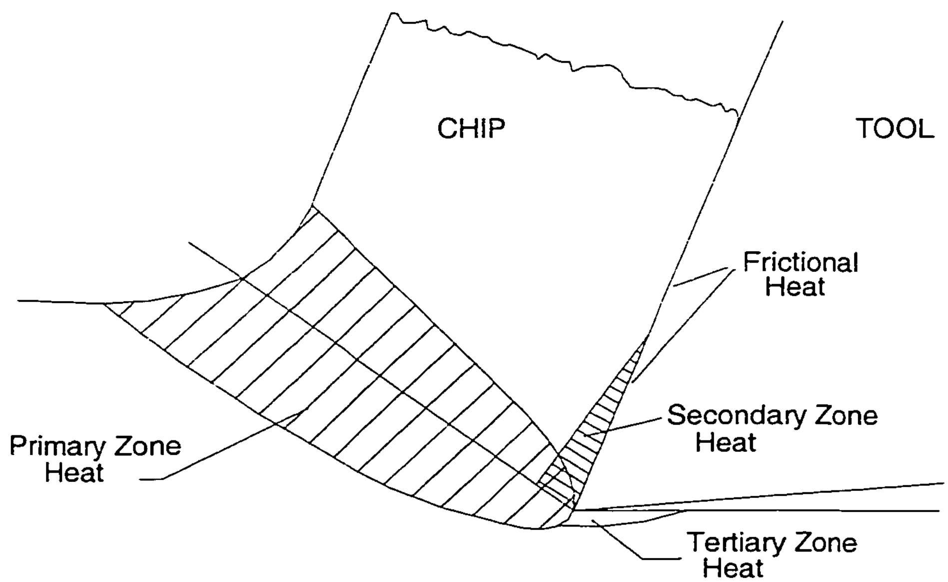


Figure 2-2 Heat Zones From Mill Cutting

The heat that is generated during cutting is affected by many parameters including coolant, but is primarily a function of the rotational speed of the milling cutter. The maximum temperature that a tool may encounter is limited by the melting temperature of the work piece material. For aluminium, the melting temperature ranges between 600°C and 660°C depending on the type of aluminium alloy being processed.

The thicker the chip, the greater the ability for the chip to take away the heat instead of the tool absorbing it. During finish cuts where good surface finish characteristics are desired, the chips produced are small due to slow feedrates and small depths of cut involved. These small chips are unable to effectively carry away the heat generated during cutting. Therefore, the tool must take away the heat. As a result, the tool is exposed to higher temperatures making thermal and mechanical properties of the tool important. The toughness and hardness properties of the tool are important because they determine how well the tool is able to hold the integrity of the cutting edge, making it possible to maintain close tolerances and consistent surface finishes throughout the life of the tool. Polycrystalline diamond (PCD) inserts are the common material used for aluminium machining inserts. Machining processes with coolant help take heat away from the tool even during the light finish cuts where the chips are small.

2.2.3 Forces in Cutting

When the cutting tool engages the workpiece, a plane, called the shear plane, is formed within the workpiece. At this plane, the work piece is subjected to two kinds of stresses, a compression stress and a shear stress [14]. These stresses can be equated to cutting forces acting on the cutting tool.

Cutting forces are dependent on a number of parameters. The axial rake angle of the tool, the feed rate of the process, the cutting coefficients of the work piece, and the depth of cut are all essential parameters in understanding the cutting forces of a process.

Cutting forces are expressed in tangential, axial, and radial forces: F_t, F_a and F_r respectively. Figure 2-3 illustrates these cutting forces acting on the insert.

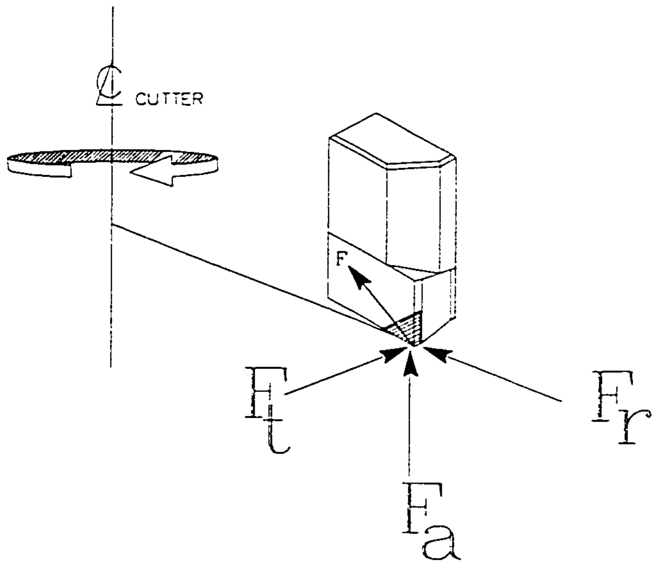


Figure 2-3 Cutting Forces Acting on the Insert

These forces can be translated into forces in the X,Y, and Z directions by knowing the insert geometry. Cutting forces can be measured experimentally with the use of a dynamometer that is mounted under the work piece and firmly supported on the test bed of the machine. Cutting forces are measured in the X, Y, and Z axis directions. Average cutting coefficients for the material being machined can then be calculated by knowing the forces from the dynamometer results. This type of testing has been done on a variety of materials. Although these values may be correct for the testing as presented in the technical papers that they are published in, insert geometry, the type of inserts, and various machining conditions such as coolant will vary the results of the cutting coefficients [3].

Gathering cutting coefficient data about the cutting conditions requires a close simulation of operating conditons. This type of testing is best suited for the laboratory as it is not feasible to mount a dynamometer within production machinery.

2.3 Chatter in Machining

Chatter in machining is severe self excited vibration. When the cutting tool engages the workpiece, the tool starts to vibrate due to the flexibility of the machine structure resulting in variable chip thickness of the work piece. Regenerative chatter evolves when a favourable phasing develops between the vibrations of the cutter and the wavy machined work piece surface finish created by the previous milling insert.

A stability chart is a graphical representation defining a relationship between depth of cut and spindle speed when chatter develops. The characteristics of the graph will be different for different materials and structures. Figure 2-4 illustrates a stability lobe graph. The theory of stability lobes with theoretical to experimental comparisions has been documented by **Altintas** et al.[1] and **Budak** and **Altintas** [2].

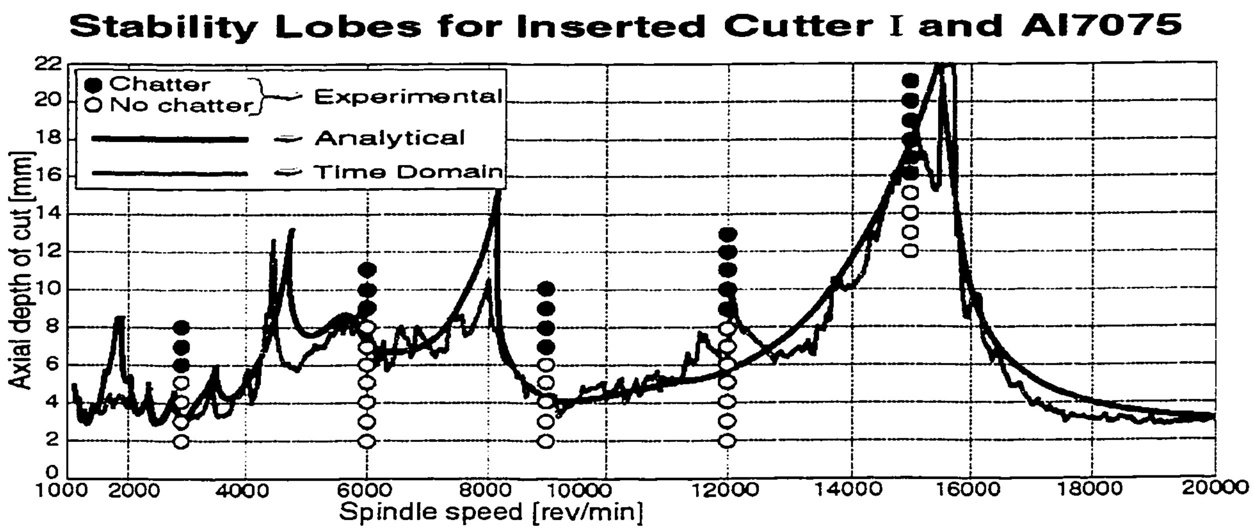


Figure 2-4 Stability Lobe Graph

2.4 Surface Finish

A smooth surface can be distinguished from a rough one in several ways. The surfaces may feel different when touched, or reflect light differently. These methods of distinguishing the finish of a surface are effective in some situations, but remain subjective conclusions when a non-biased measurement is required.

It is first important to understand how the insert of the milling cutter generates a surface.

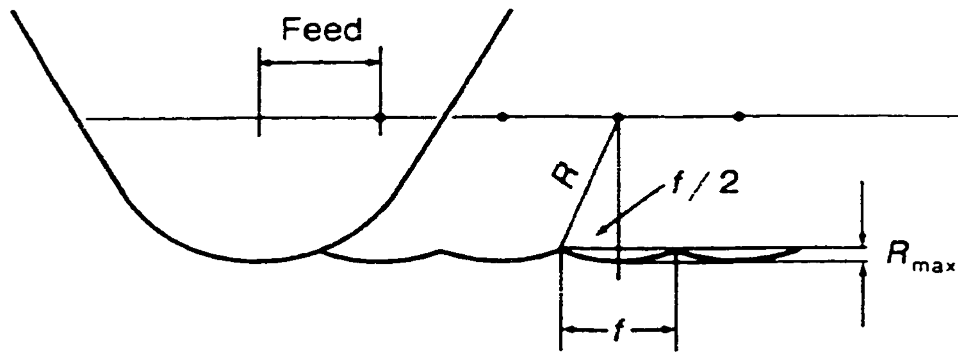


Figure 2-5 Ideal Surface Roughness Dictated by Insert Nose Radius

The insert of radius R is introduced into the workpiece and advanced by a feed distance f between the successive inserts on the milling cutter as seen in Figure 2-5. The peak to valley surface can be calculated theoretically, but is only a theoretical approximation as the chip formation process can change the surface quality [13]. Incorporating wipers behind the insert radius can reduce the height of Rmax. The use of wipers on milling cutter inserts can add to part deflection as the wipers direct forces into the part. An illustration of wiper geometry can be seen in Figure 2-1-Insert Geometry Definitions on page 15.

The quality of a surface can be explained in three characteristics: roughness, waviness, and form. Roughness of a surface is produced only by the method of manufacture, resulting from the process parameters. It is the mark that is left by the tool. Secondly, roughness is a product of the process of the tearing of the material being removed, irregularities in the shape of the tool tip as well as the debris of chips not cleared from the working area. Waviness of a surface is attributed to the characteristics of the properties of the machine, such as improperly balanced cutting tools, irregularities in lead screws that dictate tool feed, and lack of machine rigidity. The third characteristic of surface quality is form, and it is often caused by the workpiece bending or deflecting under the machining tool forces.

These three characteristics are never found in isolation. All surfaces are a result of all three characteristics. Since the functional effects of each characteristic are different, it is generally important to measure each separately. Figure 2-6 illustrates a representation of each characteristic of surface quality.

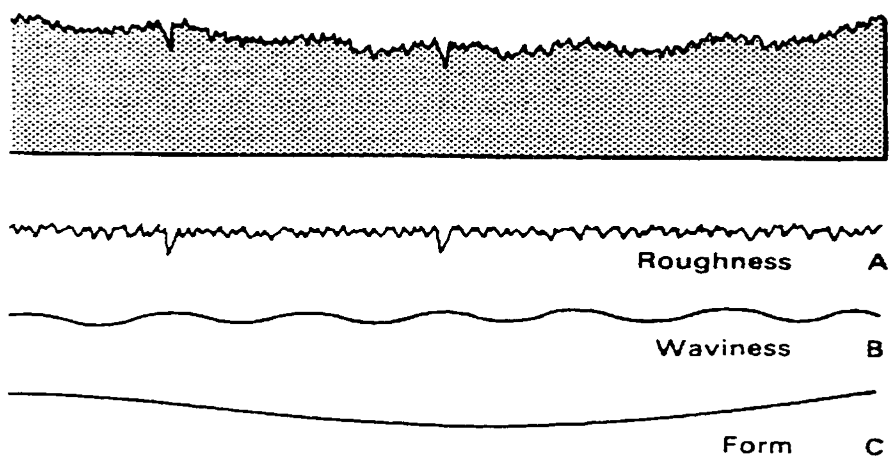


Figure 2-6 Three Characteristics of Surface Quality

It is generally agreed that the most important factor of surface quality is the roughness height [5]. The roughness height can differ across a distance, so an average value is used, denoted as R_a and measured in micro meters (μm). The roughness average is defined as an average of the roughness profile from the mean line over a given distance. The distance is called the sampling length, and is determined to suit the surface under examination. The industry standard sampling length for average roughness readings of a machined surface is 0.8 mm. Data were collected at intervals of 0.25 μm over the 800 μm sampling length. Measurements are generally repeated several times at a given area with an average reading being calculated to provide a higher confidence in the surface integrity.

The measuring device for micro finish readings is a profilometer. A profilometer works on the basic principle of a surface profile recorder. A stylus is pulled across the surface for the sampling length distance. The size of the stylus tip varies with the application, but a common tip radius is 5 μm. Compared to the edge radius on the cutting tool, the stylus tip radius can measure all variation that is created due to machining.

2.5 Vibration Analysis Techniques In Machining

When excessive noise occurs during machining and poor surface finish of the product results, part harmonics and natural frequency are investigated. In a manufacturing environment, investigating the area of part harmonics is rarely pursued due to a lack of understanding in vibration analysis techniques. The areas that are reviewed as possible causes include part fixturing, machine structural integrity, and machining parameters. These methods almost always use trial and error to obtain the desired results.

The concept of employing modal analysis techniques was used on a transmission housing by **Moore** [10] with the focus on understanding the natural frequencies of the part in order to reduce noise during machining. Although Moore found that the relationship of frequency response function (FRF) testing between a free state case and a clamped case was quite similar, the clamped case levels of magnitude were lower due to the damping by the clamps.

The magnitude format of a frequency response function is obtained for each frequency by taking the square root of the sum of the squares of the imaginary and real parts of the FRF at each frequency (i.e. $\sqrt{(\mathrm{Real})^2 + (\mathrm{Imag})^2}$). A combined presentation of magnitude and phase information as a function of frequency is often referred to as a 'bode diagram' [10].

2.6 Shainin Red X Strategy

The Shainin 'Red X' Strategy [12] is a problem solving methodology developed to direct logical decisions and to document the progressional steps. The problem solving logic is a progressive search using a process of elimination. Each stage of the investigation divides the possibilities into two or more broad 'families'. A 'family' is an area where variation can exist. The family found to contain the largest amount of variation must contain the source of the problem, or the 'Red X' and all further investigation is focused on that 'family'. For example, when parts are evaluated from each 'family', the parts that show the largest amount of variation from a particular family indicate that further investigation of the root cause of the variation exists within that 'family'.

The principle of drawing clues from the parts distinguishes this methodology from design of experiments (D.O.E.), control charts and other traditional problem solving approaches.

2.7 Finite Element Analysis

The structural integrity of the 4T40E transmission case has been a concern since the initial process development stage of the product. The transmission case was first modelled by **EASI Engineering** [15] in order to understand the effect of various milling processes on part deflection. A finite element model comprising of solid and plate elements was developed to evaluate the structural integrity of the housing when subjected to various machining conditions.

First, the effects of using a slab milling process on the sprocket face was modelled. The process modelled an 18" diameter slab milling cutter with a tool path proceeding along the sprocket face. The cutter force distribution at the sprocket rail was very unfavourable and caused the face to bend into the cutter. It was predicted that this poor machining practice would lead to chatter and vibration in this area. The magnitude of deflection was 0.163 mm. Figure 2-7 shows the resulting model of the slab milling cutter process.

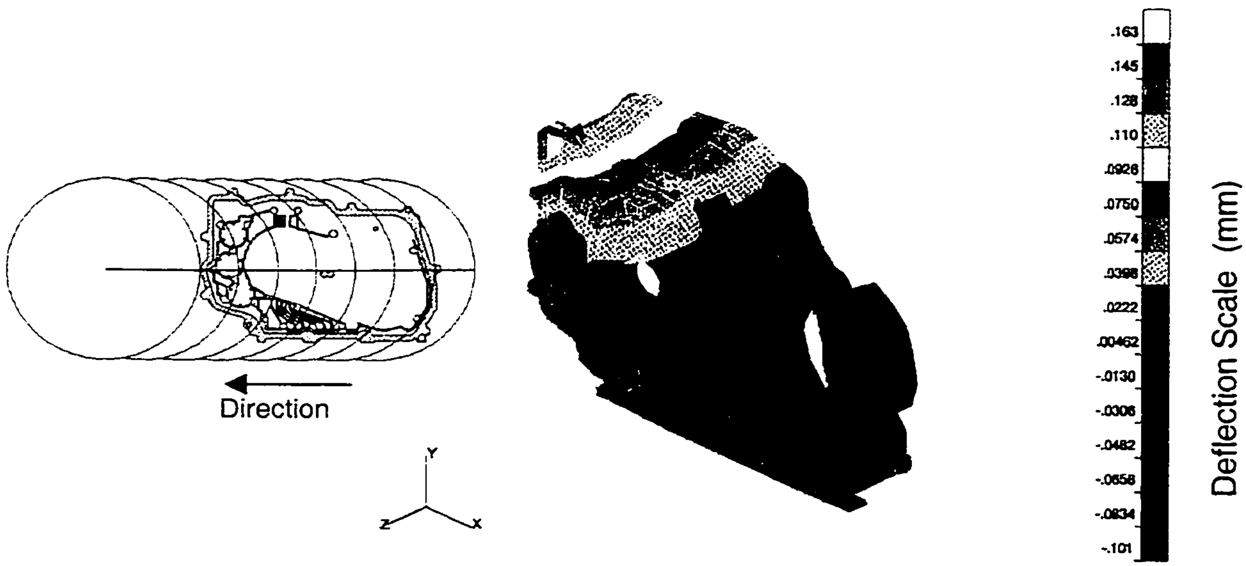


Figure 2-7 Slab Milling Cutter Path FEA Model [15]

Second, the effects of using a profile milling process was modelled. The process modelled a 6" diameter milling cutter with a tool path which profiled the sprocket rail. The change in process reduced the deflection of sprocket face into the cutter across the majority of the surface. The maximum deflection of 0.199 mm was observed to be local, at a bolt boss located centrally along the sprocket rail. This modelling analysis provided the confidence level to process the part with a profile milling operation. Figure 2-8 shows the resulting model using the profile milling cutter process.

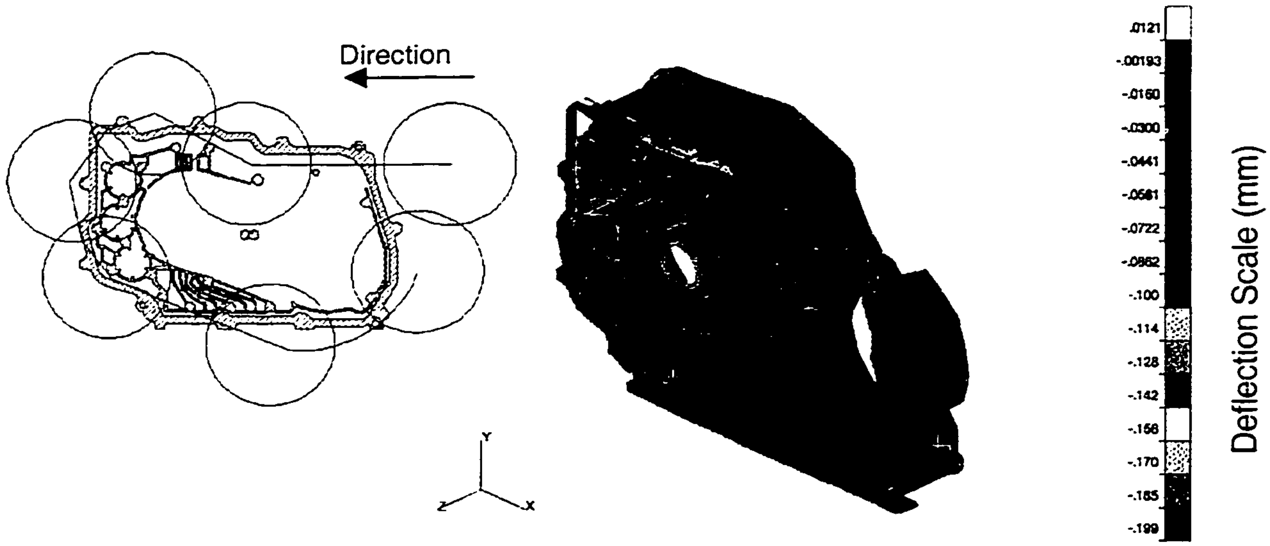


Figure 2-8 Profile Milling Cutter Path FEA Model [15]

The two FEA models provided historical predicted deflection from various machining processes. The decision to utilize profile mill cutting in the current machining operation was based upon the results of these models. However, the areas of part deflection as shown in these models were not reflective of the problems experienced with the current production process. The profile milling tool path and tooling used in the simulation were not used in the current machining parameters. Reviewing the results of the two models, it was understood that changes to the machining process significantly affected the predicted surface deflection of the sprocket face.

3. NUMERICAL AND VIBRATION ANALYSIS

3.1 Numerical Analysis

A finite element model of the fully machined transmission case was used in predicting the flatness error from various milling parameters analytically. The finite element model was comprised of solid and plate elements. The milling force data were estimated using General Motors software called FACEsim [7]. The results of the simulation did not consider the effects of clamping on the case as it was assumed to be rigidly supported at the three fixtured points. NASTRAN [11] version 70.5.0 was the modelling software used for the simulations [6]. The General Motors Research and Development group estimated the cutting forces used and conducted the various milling simulations as presented in this section. The analysis of the simulation results provided a level of confidence in the preparation of designed experiments to optimize the machining parameters.

3.1.1 Finite Element Analysis Model

The 4T40E transmission finite element analysis (FEA) model which was developed in the early 1990's, was re-evaluated using the current manufacturing process information. Insert geometry, tool path, milling cutter feed and speed data were used in determining the cutting forces throughout the tool path. The assumption that part deflection and surface finish are related was the basis for the simulation. A re-evaluation of the model with current process data would provide insight into analysing theoretical part deflection and provide the opportunity to perform various optimization simulations.

3.1.2 Model of Machining Process

The first model simulated the current machining conditions. Figure 3-1 illustrates the tool path used in the simulation. Table 3-1 lists the machining parameters used to calculate the tooling forces in the simulation. The purpose of doing so was to establish confidence in the model with its ability to predict current conditions, as well as to create a baseline for comparison to other simulations.

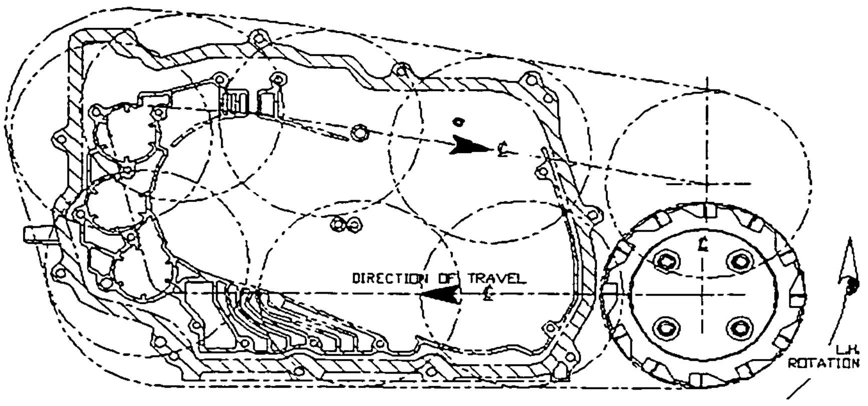


Figure 3-1 Current CNC Tool Path with Left Hand Cutter

Table 3-1 - Machining Parameters for FEA Simulation #1

Cutter Diameter (mm)	200
Cutter Rotation	Left Hand
Spindle Speed (rpm)	2987
Feedrate (mm/min)	5428
Depth of Cut (mm)	0.5
Feed/Insert (mm)	0.152
Insert Geometry	
Axial Rake angle (degrees)	0°
Radial Rake angle (degrees)	7°
Number of Inserts on Cutter	12

The current machining process utilizes a 200 mm diameter, left hand rotation milling cutter. The parameters include a fixed spindle speed, and a constant feedrate throughout the entire tool path.

The FEA model, as presented in Figure 3-2, generated predicted deflections of 146.6 μm along the top rail of the sprocket face. The direction of the deflection was away from the cutter.

Part deflections experienced by machining the part ranged from 170 μm through 250 μm. The results of the FEA were considered to be relatively accurate and the model was accepted for the purposes of comparison. The accuracy error in the model may be explained by only two modelling elements as shown in the thickness of the flange. Conditions such as casting thickness variation on the back of the machined flange are not considered as well.

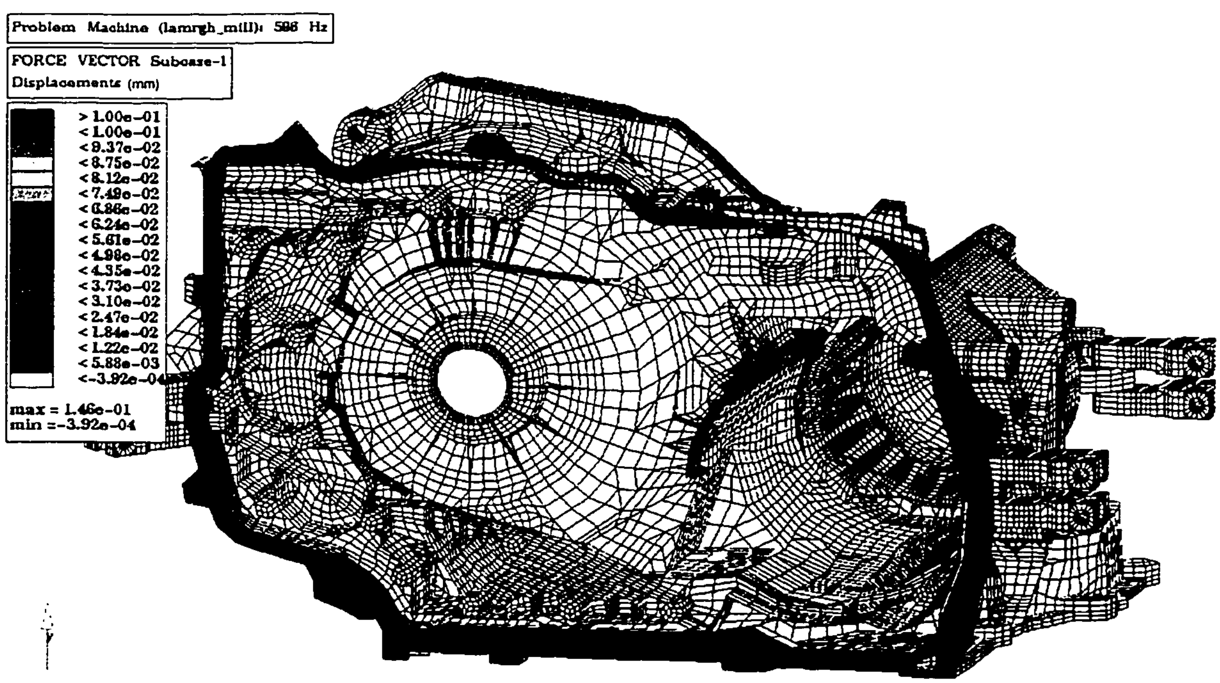


Figure 3-2 Baseline FEA Model of Current Process [6]

The second FEA simulation reviewed the effect of changing the feedrate as the cutter passed over the areas of highest deflection along the top rail of the case. Figure 3-3 shows the predicted FEA results by reducing the feedrate by half the original rate, and doubling the feedrate along the bottom structural rail in order to maintain the cycletime of the cutting process.

Predicted deflections were reduced to 88.6 µm. The direction of the deflection continued to be away from the milling cutter.

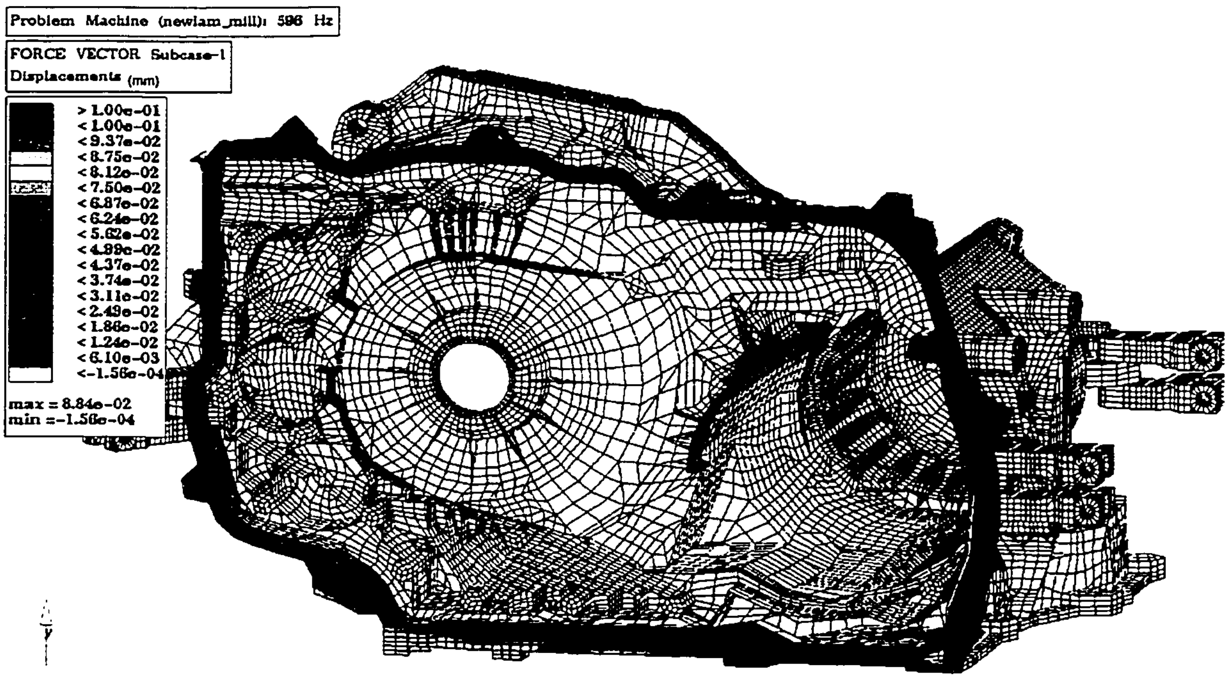


Figure 3-3 FEA Model of Variable Feedrate [6]

A third FEA simulation was conducted to review the effect of changing the cutting path and spindle rotation. The spindle speed and feedrate remained fixed from the baseline, but an alternative tool path and right hand milling cutter were used. The predicted deflections were reduced to 68.3 μm. The direction of the deflection continued to be away from the milling cutter. Figure 3-4 shows the result of the model.

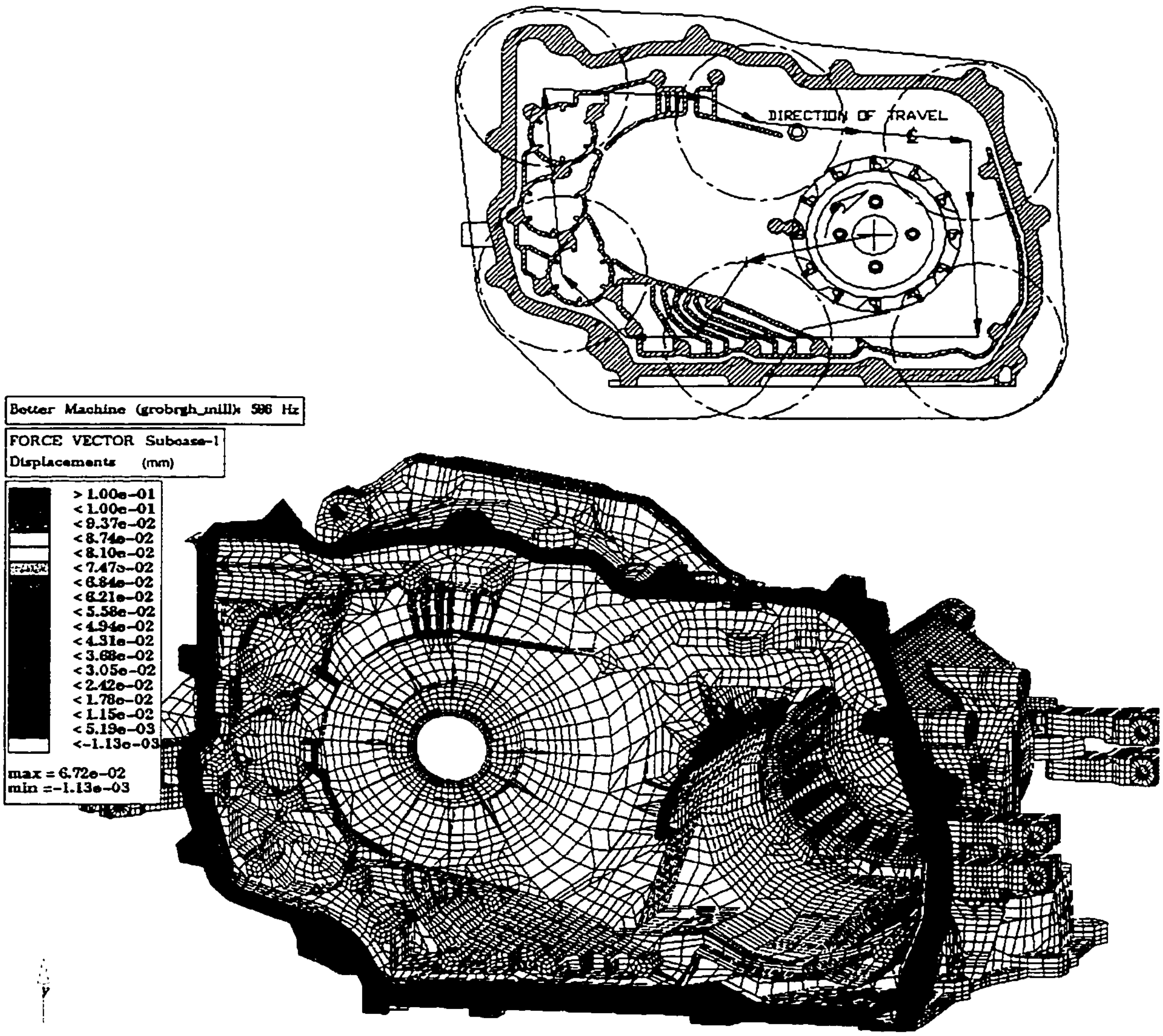


Figure 3-4 FEA Model of Right Hand Cutter Rotation and Tool Path [6]

3.1.3 Comparison of the Three Models

The finite element analysis simulations provided a theoretical analysis of predicting deflections of the sprocket face flange when the machining parameters were altered.

The reduction in feed rate in the second simulation across the areas of interest indicated a reduction in deflection of 58 μm. This analysis predicted a 40% improvement in deflection as compared to the baseline current machining parameters.

The third simulation, which modelled a change in milling cutter rotation, predicted further reduction in deflection of 20 μm, an improvement of 23% as compared to varying the feed rate from the second simulation.

Based on the initial assumption that deflection and micro finish are related, the improvements in reduced deflection as seen in the various FEA simulations created a confidence level that by altering the machining parameters, micro finish could be improved.

3.2 Vibration Analysis

The structural response provides detailed information about the transmission case. This type of information is important to evaluate if any conflicts exist between the natural frequencies of the part and the tooth passing frequency of the milling cutter. Frequency spectra of the spindle were reviewed to understand if internal-forced vibration is involved. The Transfer Function Method was chosen for obtaining modal parameters for the analysis.

3.2.1 Modal Analysis of Sprocket Face

Modal analysis is a powerful technique for obtaining structural response data. It is the process of measuring a structure's modes of vibration. The various modes of vibration, or natural frequencies, provide information of the excitable frequencies of the structure.

The method used to determine the modal parameters of the transmission case was the Transfer Function Method. Frequency response functions were obtained at the various areas of interest on the case sprocket face rail. Data were collected for each point in two trials to increase the confidence level of the data. "CutPro" [4] software was used to evaluate the frequency response functions and obtain the required modal parameters.

3.2.2 Equipment Used to Collect Data

The frequency response functions were collected with a force impact hammer and a piezoelectric element accelerometer. The transfer function measurement program "MalTF" [9] was used to collect the data.

Modal analysis techniques using a standard impact hammer and accelerometer were used in the data collection. Instrumentation documentation can be found in Appendix E.

The accelerometer signal was fed into channel #2 of the analyser. It was found that upon reviewing the power spectrum of the accelerometer signal, the power signal became non-linear after 1800 Hz, and therefore, any data captured beyond that frequency was discarded, as it was prone to errors due to poor signal. The accelerometer was mounted to the workpiece with bee's wax.

The impact hammer provided a force that excited all structural resonances of the clamped case. This signal was fed into channel #1 of the analyser. The shape of the impact pulse governs the frequency content. The impact pulse can be changed with a variety of tip hardnesses and mass extenders. All tests that are reported in this thesis used the steel tip without mass extenders.

3.2.3 Accelerometer Positions

The main objective was to find the natural frequencies of each area of concern and determine if there was a correlation to the tooth passing frequency of the milling cutter.

Figure 3-5 shows the positions of where the accelerometers were placed for the analysis. The X, Y, & Z axis co-ordinate system was used to communicate the position of the accelerometer and the direction of impact with the result graphs. For example, the ZX Axis graph represents a force hammer impacted from the Z direction with the accelerometer mounted from the X direction. The two areas being measured are designated as area 1 & 2 respectively.

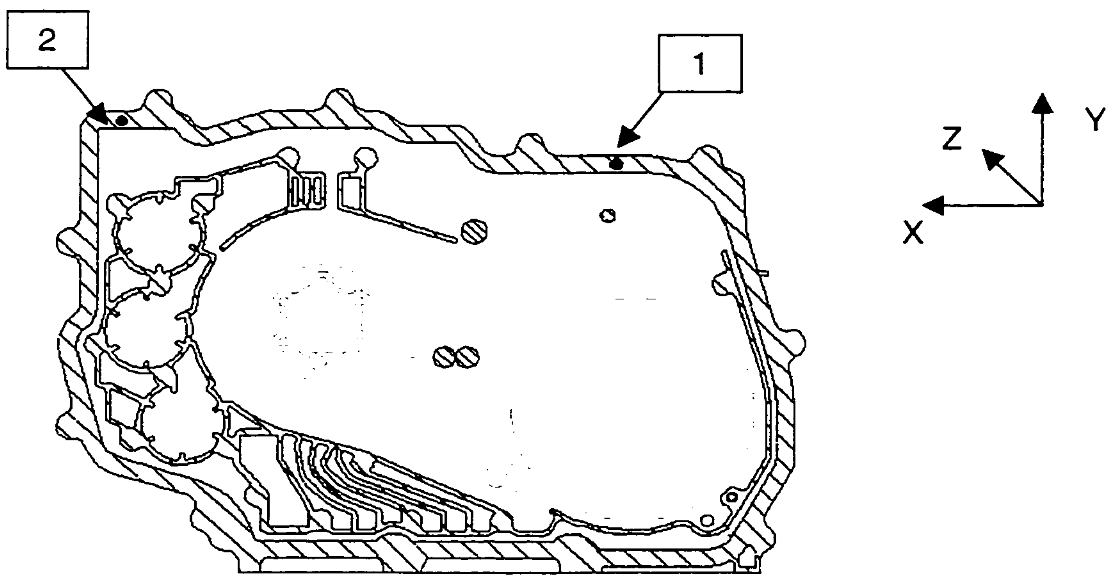


Figure 3-5 Accelerometer Positions on the Machined Face

3.2.4 Test #1 - Machined Sprocket Face Analysis

A series of hammer tests were conducted in order to gather frequency spectra of the clamped case. Collaborative research partners from the University of British Columbia assisted in the data collection as they provided the vibration analysis test equipment for this study.

Test #1 was conducted on a transmission case that was clamped to a machine pallet located on the concrete floor. It was understood at the time of testing that the frequency spectra would not be exact representations since the readings were not taken within the machine. The assumption was made that the weight of the cast pallet, which weighs in excess of 363 kilograms, would provide the structural stability that the machine clamps would normally provide.

Data were gathered at each of the test points. The frequency spectra of the two trials were compared to ensure that the frequencies were repeatable. The small differences in the frequency readings were attributed to impact hammer impacts, as well as how well the accelerometer was mounted to the part.

Upon evaluation of the frequency transfer functions, the power spectrum curves for the accelerometer readings were not linear above 1800 Hz, therefore the readings above that frequency were not considered useful. Appendix A contains the frequency response functions for each of the two trials for the two areas tested.

3.2.5 Analysis of Test #1 Results

The frequency response function in area 1 indicated that there is a distinct natural frequency at 217 Hz. At this frequency, the largest magnitude of excitation occurs as well. The rest of the spectrum has minimal magnitude peaks although there are possible natural frequencies as indicated by the real frequency spectrum changing phase. The frequency spectrum for area 1 is shown graphically in Figure 3-6 and shown numerically in Table 3-2.

The frequency response function in area 2 indicated a significant magnitude peak at 1191 Hz. The entire magnitude spectrum indicated distinct magnitude peaks at each of the natural frequencies. This spectrum is shown graphically in Figure 3-7 and numerically in Table 3-3.

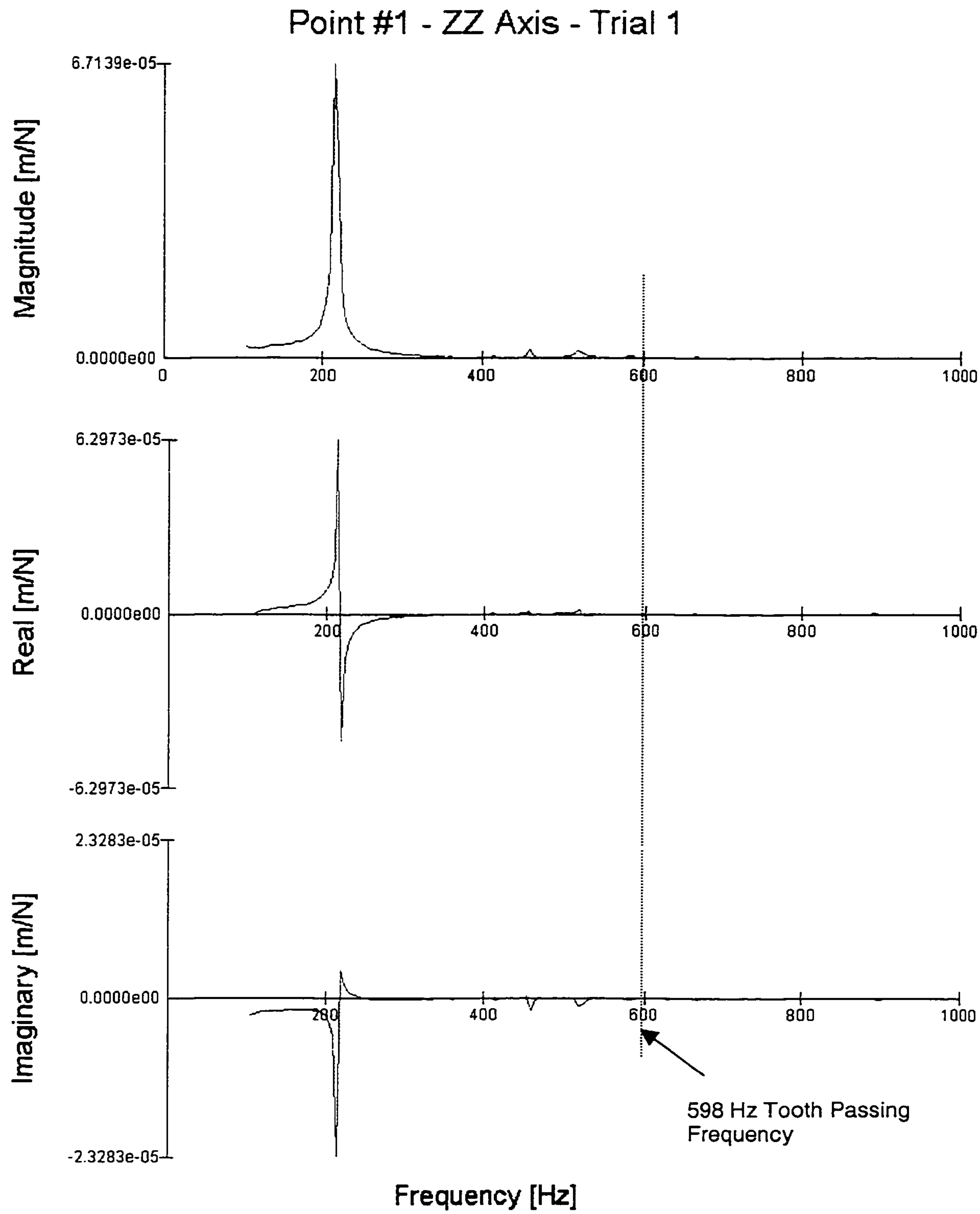


Figure 3-6 ZZ Axis Frequency Spectrum for Area 1

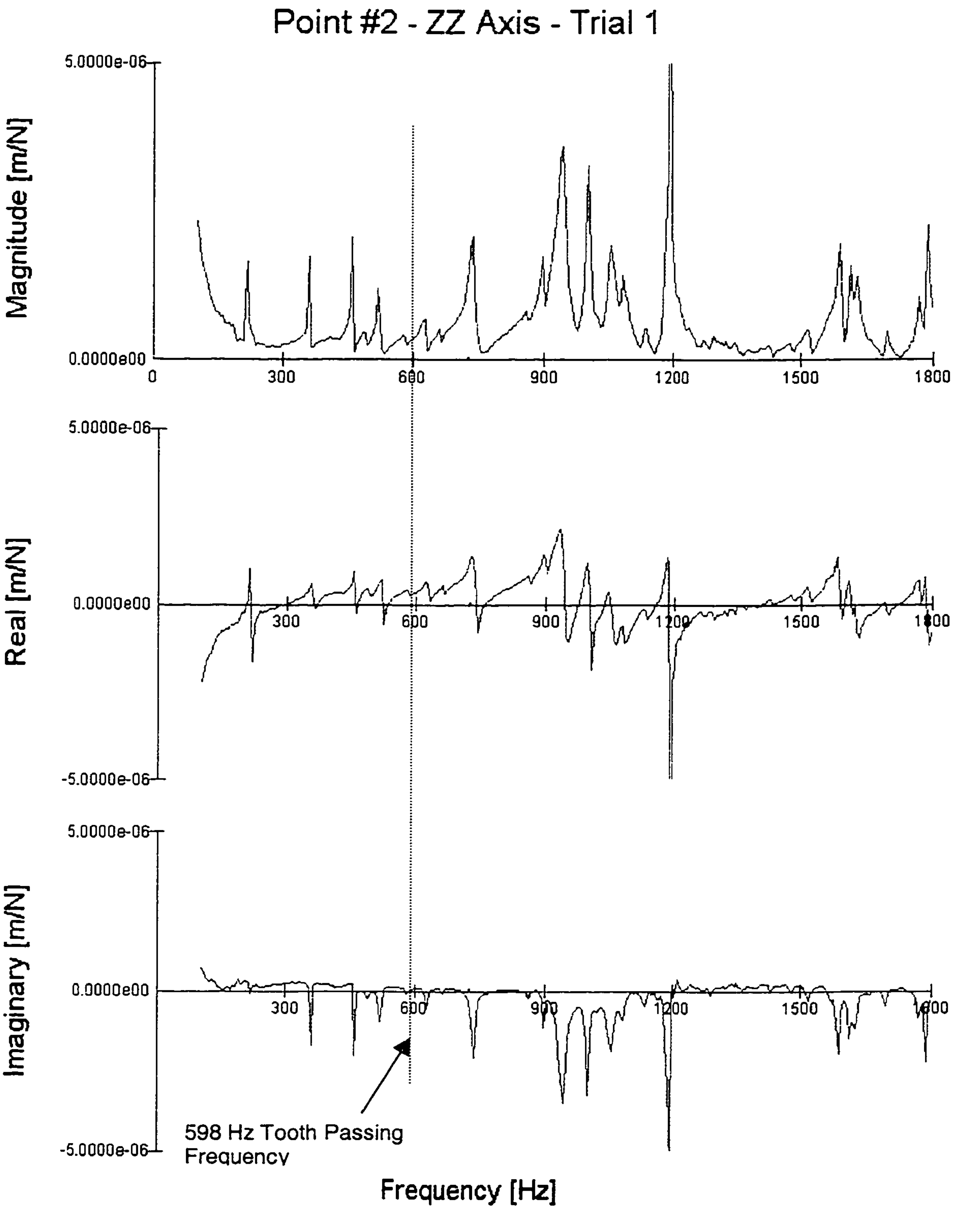


Figure 3-7 ZZ Axis Frequency Spectrum for Area 2

Table 3-2 Natural Frequency Information - Point #1 ZZ Axis Trial 1

Mode #	Natural Frequency ω_η (Hz)	Stiffness k (N/m)	Damping ζ_η (N s/m)	Mass M (kg)
1	217	8.06E+05	0.002354	0.4344
2	458	1.11E+08	0.002011	13.3992
3	520	4.12E+07	0.005577	3.9270
4	667	2.87E+08	0.001512	16.3557
5	894	4.82E+08	0.002774	15.2629

Table 3-3 Natural Frequency Information - Point #2 ZZ Axis Trial 1

Mode #	Natural Frequency ω_η (Hz)	Stiffness k (N/m)	Damping ζ_η (N s/m)	Mass M (kg)
1	217	5.55E+07	2.94E-04	29.8661
2	362	1.20E+08	2.99E-03	23.3114
3	458	2.06E+08	8.21E-04	24.8786
4	520	1.18E+08	3.07E-03	11.0246
5	741	3.70E+07	7.21E-03	1.7062
6	942	1.42E+07	1.01E-02	0.4054
7	1002	4.00E+07	3.38E-03	1.0087
8	1191	5.62E+07	4.03E-04	1.0048
9	1618	7.09E+07	4.46E-03	0.6859
10	1788	1.18E+08	1.80E-03	0.9348

3.2.6 Test #2 - Machine Spindle Analysis

The milling cutter mounted to the spindle was also analyzed with frequency response functions. The General Motors Research and Development group provided the equipment for this test and organized the data for this report [8].

The analysis was performed on the machine spindle to evaluate if natural frequencies exist in the spindle that could be interfering with the frequencies of the case. It was assumed that by taking the frequency response of the machine spindle, the excitable frequencies of the machining station, spindle bearings, and cutter body dynamics would be captured. A series of 5 impulse readings were taken at each test point. In this manner, a reasonable collection of test readings was obtained. The frequency range from 0 to 2500 Hz was analyzed.

3.2.7 Equipment Used to collect Data

The magnitude spectrums were collected with the same model force impact hammer and a piezoelectric element accelerometer. The data collection was done with a Zonic data collection and analyser unit [17]. See Appendix E for instrument details.

3.2.8 Accelerometer Positions

In order to gather frequency information about the machining spindle, data was collected in the machining station with the milling cutter mounted on the spindle. An accelerometer was mounted to the milling cutter in four independent positions on the milling cutter face. The accelerometer was mounted perpendicular to the machined face with bee's wax. The impulse hammer was impacted in the 180º position opposite from the accelerometer. The hammer imposed a force in the same axis as the accelerometer's direction of measurement. Figure 3-8 illustrates the various accelerometer positions.

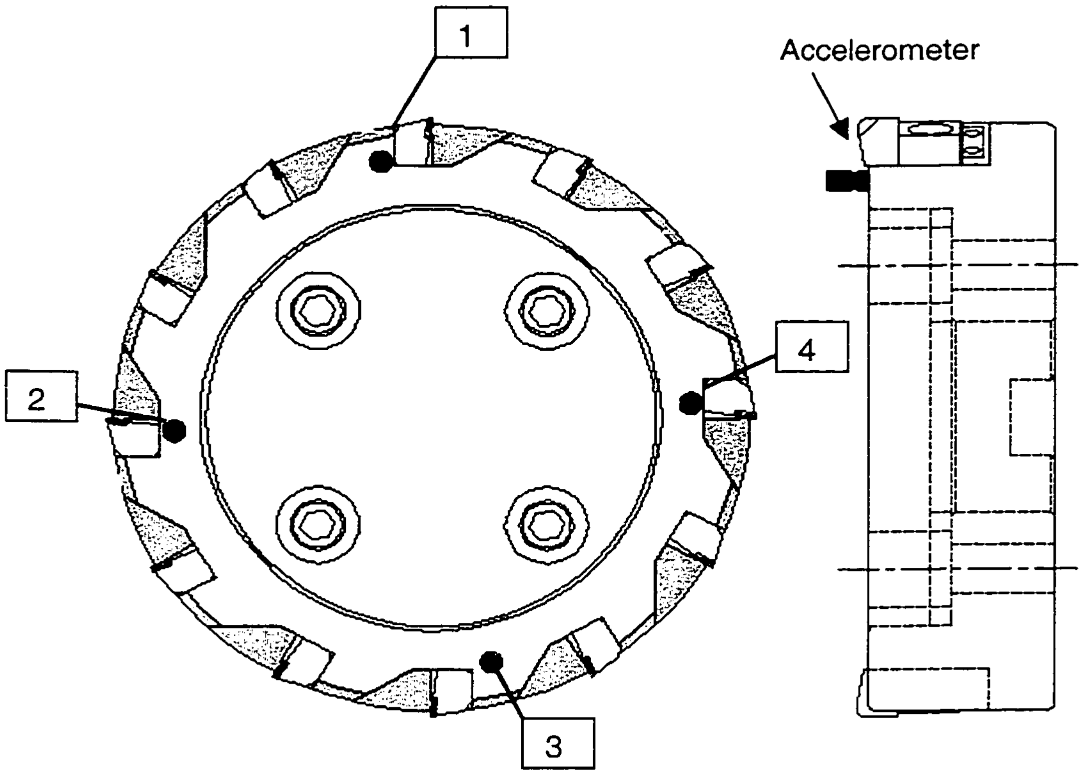


Figure 3-8 Accelerometer Positions on Milling Cutter

3.2.9 Analysis of Test #2 Results

A scaled magnitude frequency spectrum was obtained for the machine spindle structure. The graph in Figure 3-9 represents a comparison of the magnitude spectrums from each of the four positions plotted versus frequency.

It can be seen from this graph that the significant magnitudes of excitation activity occurs at a frequency of 1315 Hz. This frequency does not coincide with either the operating frequencies of the machine spindle or the milling cutter's tooth passing frequency. There was concern that a resonance condition would arise if one or more of the operating frequencies coincided with a major peak on the resonance curves. The Y axis of the graph is a scaled magnitude of deflection rather than an absolute value. For the purpose of this study, considering only the relative magnitude of the peaks for comparison of each position is valid as the excitable frequencies were of interest and not the magnitude.

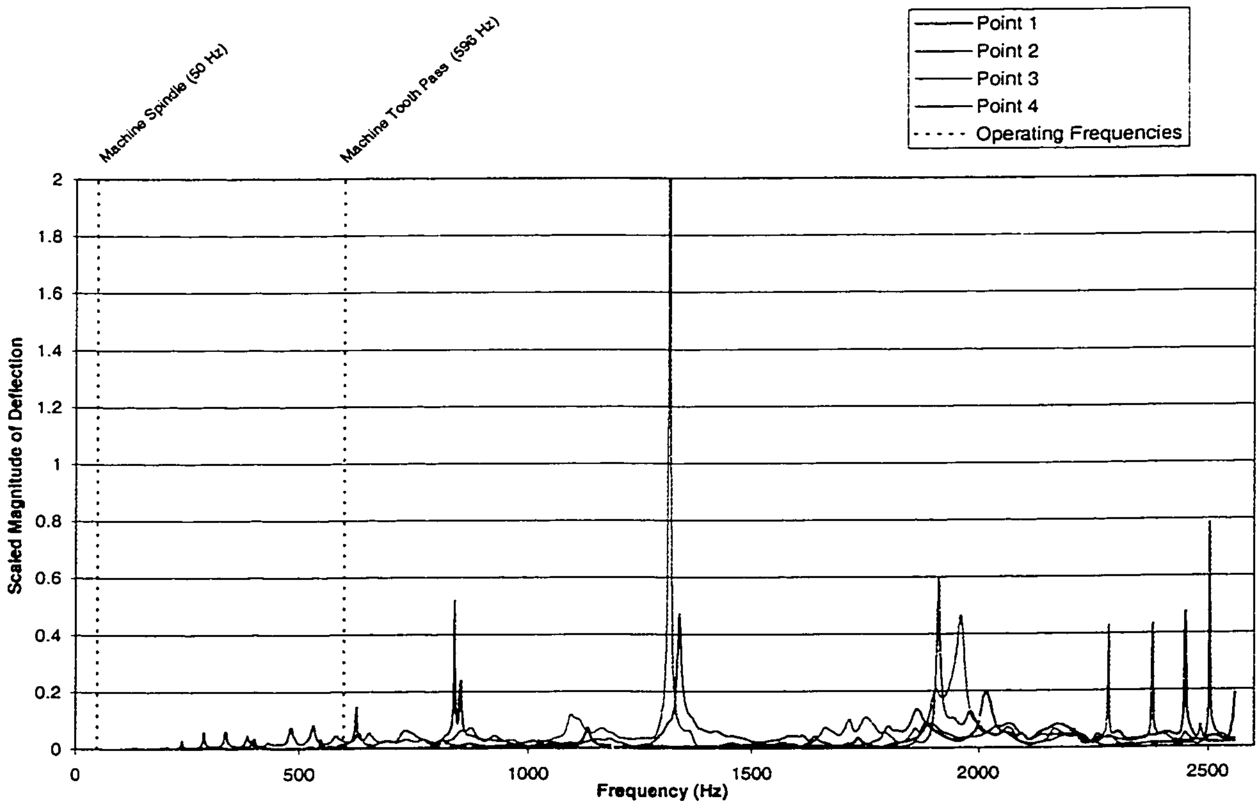


Figure 3-9 Scaled Magnitude Frequency Spectrum of Machining Spindle [8]

3.2.10 Comparison of the Vibration Analysis

The frequency response testing of the transmission case and machine spindle provided an analysis of the natural frequencies that exist in the component and in the machine structure.

The testing of the machined case provided natural frequency information about the two areas. With this frequency data, the excitable frequencies of the transmission case were now understood. The frequency information provided the supporting data for spindle speed selection for the optimization studies.

The testing of the machining spindle provided frequency information about the spindle as well as the machine structure. The information gathered provided a knowledge base about the frequency characteristics of the spindle and that the excitation frequencies did not coincide with the operating frequencies.

4. EXPERIMENTAL ANALYSIS

The machining parameter optimization studies focused on the machining parameter variables which considered the speed of the cutter, feed rate of the cutter, spindle rotation, the depth of the cut and the CNC tool path.

4.1 Study #1 – Effect of Spindle Speed, Feed Rate, and Tool Path

The first of two studies investigated the effect of changes in feed rate, spindle speed and CNC tool path on the surface finish of the transmission sprocket face in the areas of concern. The performance metric used in the study was micro finish readings as measured with a profilometer. Part characteristics of flatness, parallelism and surface position to a datum were also measured for each of the tests to ensure these characteristics were not adversely affected.

4.1.1 Conditions of the Study

The study was performed using the sprocket face finish machining station of the production transfer line. There was no particular order to assignment of pallets used to clamp the parts. The previous operation was qualified to ensure the in-process manufacturing location pads were within part print limits. The milling cutter used in the study had been mounted cleanly with no debris between the mounting surfaces of the spindle and the milling cutter face. The milling cutter had previously machined 30,000 parts and was producing an unacceptable surface finish. The expectation was to be able to regain part quality using the same milling cutter, which otherwise would have been replaced. The parts used were rough machined to remove casting variation from the surface, leaving 0.5 mm of material for the finishing operation to machine.

4.1.2 Constraints of the Study

The machining station had programmed "soft stops" that dictated the travel of each axis. This constraint limited the type of tool paths which could be used as the centre of the milling cutter could not exceed this working window. Figure 4-1 illustrates the 'working window' imposed onto the current tool path.

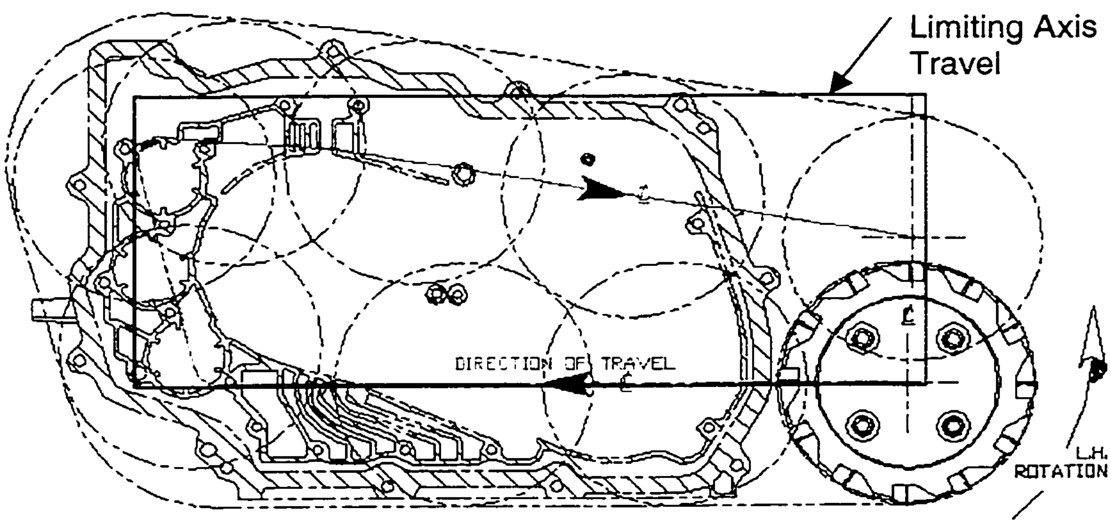


Figure 4-1 Limited Axis Distance – 'Working Window'

4.1.3 Measurement Equipment

4.1.3.1 Surface Finish

The measuring instrument used to measure surface finish was a Taylor Hobson Model Surtronic 3+ profilometer [16]. This unit measured the average surface roughness (Ra) over a 0.8 mm distance. See Appendix E for instrument details.

4.1.3.2 Flatness, Parallelism, and Position

A Zeiss FC900 co-ordinate measuring machine was used to measure and collect the data related to flatness, parallelism and position of the sprocket face to the in-process datum (M1).

4.1.4 Method of Study #1

The purpose of this study was to determine the influence of tool path, spindle speed, and feed rate on the visual and measured quality of the micro finish on the sprocket face. Part print characteristics of flatness, parallelism and position to a datum were also measured to determine whether these features changed.

A series of sixteen tests was used in this study. The study was comprised of eight significantly different test programs numbered Test #1 through Test #8. In each of the tests, parts were machined with a spindle speed of 2987 rpm and 4480 rpm. Feed rate was reduced in the areas of concern of the sprocket face during the Test #2, Test #4, Test #6 and Test #8. The current machining parameters used in production was the baseline or Test #1. The various tool paths and the CNC programs can be seen in Appendix B.

Spindle speed was changed using a variable frequency controller that altered the spindle motor's input voltage frequency. The effect of the frequency change altered the current drawn, resulting in higher motor speed but a drop in horsepower of the motor. The change in horsepower was not significant, as the spindle did not stall during machining. An input frequency of 60 Hz resulted in a spindle speed of 2987 rpm, and an increase in input frequency to 90 Hz, resulted in a spindle speed of 4480 rpm.

Feed rate was altered in a line item within the CNC tool program. Feed rate, was varied between 2417, 3000, 5428, and 6000 mm/min.

A total of 80 parts were used in study #1. Table 4-1 contains a matrix comparison of the tests performed in Study #1. Four areas on the sprocket face were of concern during this study to understand the changes in micro finish. The four areas can be seen in Figure 4-2.

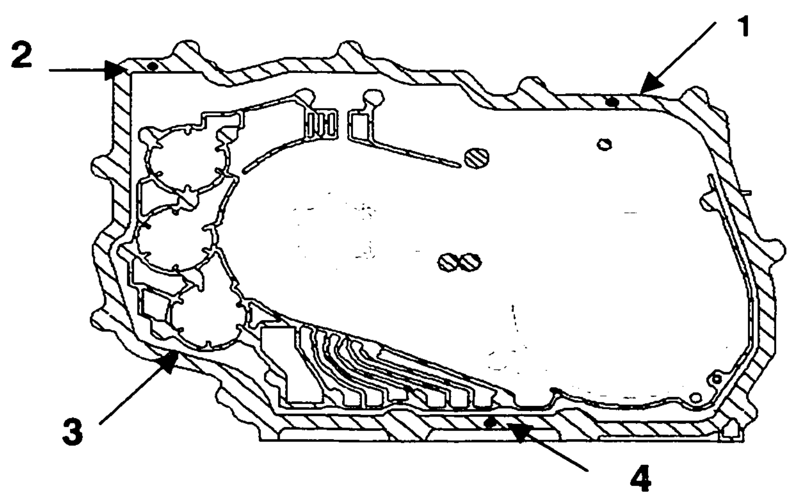


Figure 4-2 Areas of the Sprocket Face Measured in Study

Table 4-1 Comparison of Tests Performed in Study #1

	Test ID Number	Spindle Speed: 2987 RPM	Spindle Speed: 4480 RPM	Feed Rate: 6000 mm/min	Feed Rate: 6000/3000 mm/min	Feed Rate: 5428 mm/min	Feed Rate: 2714/5428 mm/min	Tool Path: Current	Tool Path: Reverse current path	Tool Path: Four point -no interpolation	Tool Path: Tracing part path	Description of Test Criteria
TEST#1	T1-C	■		■				■				**Current CNC tool path,spindle speed, & feedrate** to gather baseline parts
	T1-90		■	■				■				Effect of altering **spindle speed** with baseline tool path and feed rate
TEST#2	T2-60	■			■			■				Effect of **1/2 the current feedrate in areas 1 & 2** with baseline tool path and spindle speed
	T2-90		■		■			■				Effect of **1/2 the current feedrate in areas 1 & 2** and **increased spindle speed** with baseline tool path
TEST#3	T3-60	■				■			■			Effect of **"as purchased" feedrate and a REVERSED current tool path** with baseline spindle speed
	T3-90		■			■			■			Effect of **"as purchased" feedrate and a REVERSED current tool path** with **increased spindle speed**
TEST#4	T4-60	■					■		■			Effect of **1/2 the "as purchased" feedrate in areas 1 & 2** with the **REVERSED current tool path** and baseline spindle speed
	T4-90		■				■		■			Effect of **1/2 the "as purchased" feedrate in areas 1 & 2** with the **REVERSED current tool path** and **increased spindle speed**
TEST#5	T5-60	■				■				■		Effect of altering the tool path and **"as purchased" feedrate** with baseline spindle speed
	T5-90		■			■				■		Effect of altering the tool path and **increased spindle speed** with "as purchased" feedrate
TEST#6	T6-60	■					■			■		Effect of **1/2 the "as purchased" feedrate** with baseline spindle speed and the altered TEST #5 tool path program
	T6-90		■				■			■		Effect of **1/2 the "as purchased" feedrate** with **increased spindle speed** and the altered TEST #5 tool path program
TEST#7	T7-60	■				■					■	Effect of a **"centre of cutter tracing part" tool path** and **"as purchased" feedrate** with baseline spindle speed
	T7-90		■			■					■	Effect of a **"centre of cutter tracing part" tool path** and **"as purchased" feedrate** with **increased spindle speed**
TEST#8	T8-60	■					■				■	Effect of a **"centre of cutter tracing part" tool path** and **1/2 the "as purchased" feedrate** with baseline spindle speed
	T8-90		■				■				■	Effect of a **"centre of cutter tracing part" tool path** and **1/2 the "as purchased" feedrate** with **increased spindle speed**

4.1.5 Results of Study #1

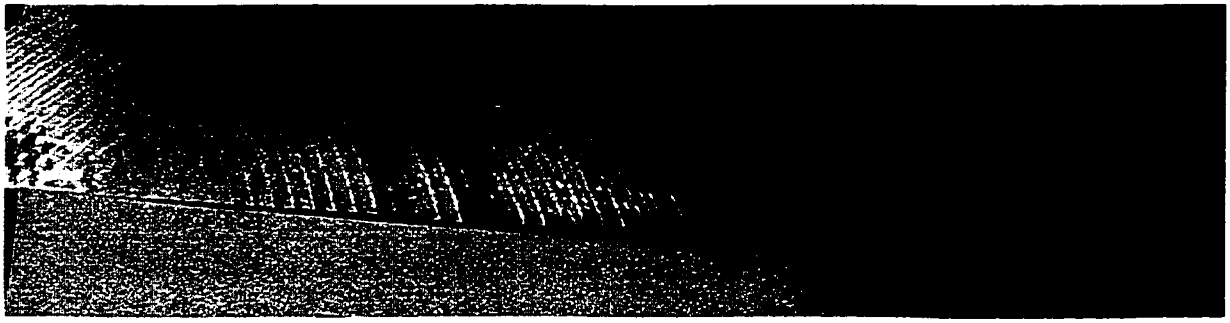
The study uncovered some interesting results. The various tests improved micro finish readings by 32% in area 1 and 65% in area 2 using a milling cutter which prior to the study, was producing parts with a poor surface finish. It should be noted that during all sixteen tests, the measured micro finish of areas 3 and 4 were very stable, varying 0.019 mm and 0.055 mm respectively. This was anticipated as the clamping points structurally supported these areas.

The effect of each independent variable will be reviewed. Photo images of the results of each test can be seen in Figure 4-3 through Figure 4-6 for area 1 and in Appendix C for area 2.

4.1.5.1 Effect of Spindle Speed

Spindle speed was a significant contributor to improving surface finish. It became evident when the spindle speed was increased from 2987 rpm (T1-C) to 4480 rpm (T1-90). The "scuffing" marks which were apparent in the baseline part, were eliminated when the spindle speed was increased. Figure 4-3 provides photo images of the comparison. Comparing the tests performed, changing spindle speed improved the measured micro finish results by an average of 31% and 68% in area's 1 and 2 respectively from baseline.

Figure 4-7 graphically illustrates the impact of changing the spindle speed on micro finish readings. The micro finish readings collected in each of the four areas have significant variation at 2987 rpm for each test performed. With the higher spindle speed at 4480 rpm, the tighter clusters indicate less variation in micro finish between the four areas.



Test #1- T1-60 Hz - Baseline Current Program

Test #1 - T1-90 Hz

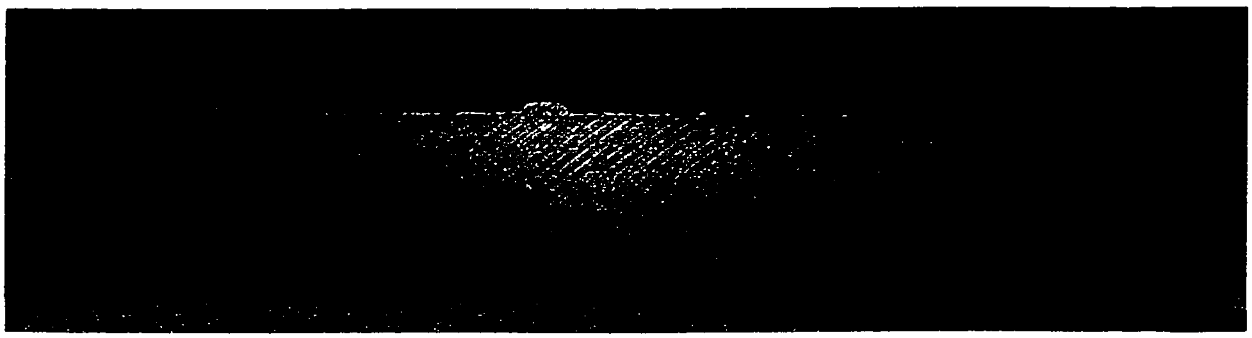
Test #2 – T2-60 Hz

Test #2 – T2-90 Hz

Figure 4-3 Area 1 Images from Test #1 and Test #2

Test #3 - T3-60 Hz

Test #3 – T3-90 Hz



Test #4 – T4-60 Hz

Test #4 – T4-90 Hz

Figure 4-4 Area 1 Images from Test #3 and Test #4

Test #5- T5-60 Hz

Test #5 – T5-90 Hz

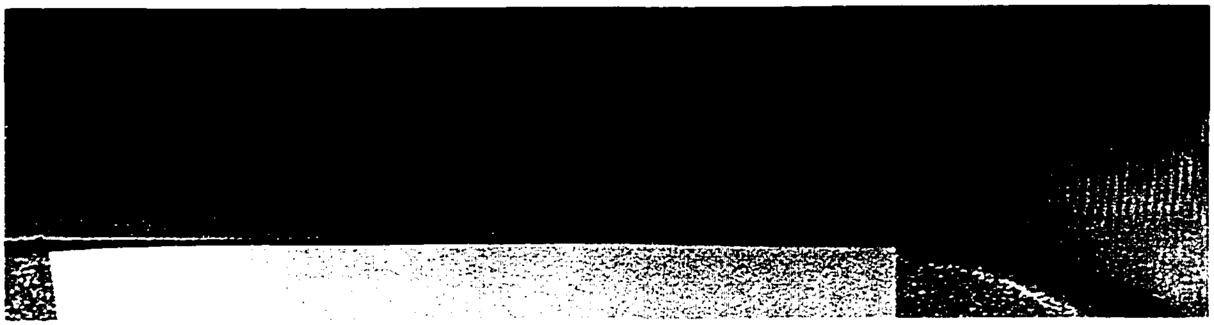
Test #6 – T6-60 Hz

Test #6 – T6-90 Hz

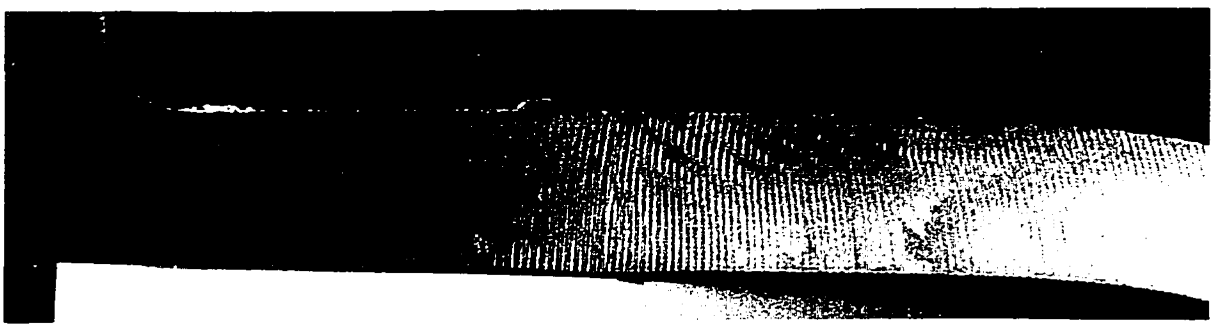
Figure 4-5 Area 1 Images from Test #5 and Test #6

Test #7- T7-60 Hz

Test #7 – T7-90 Hz



Test #8 – T8-60 Hz



Test #8 – T8-90 Hz

Figure 4-6 Area 1 Images from Test #7 and Test #8

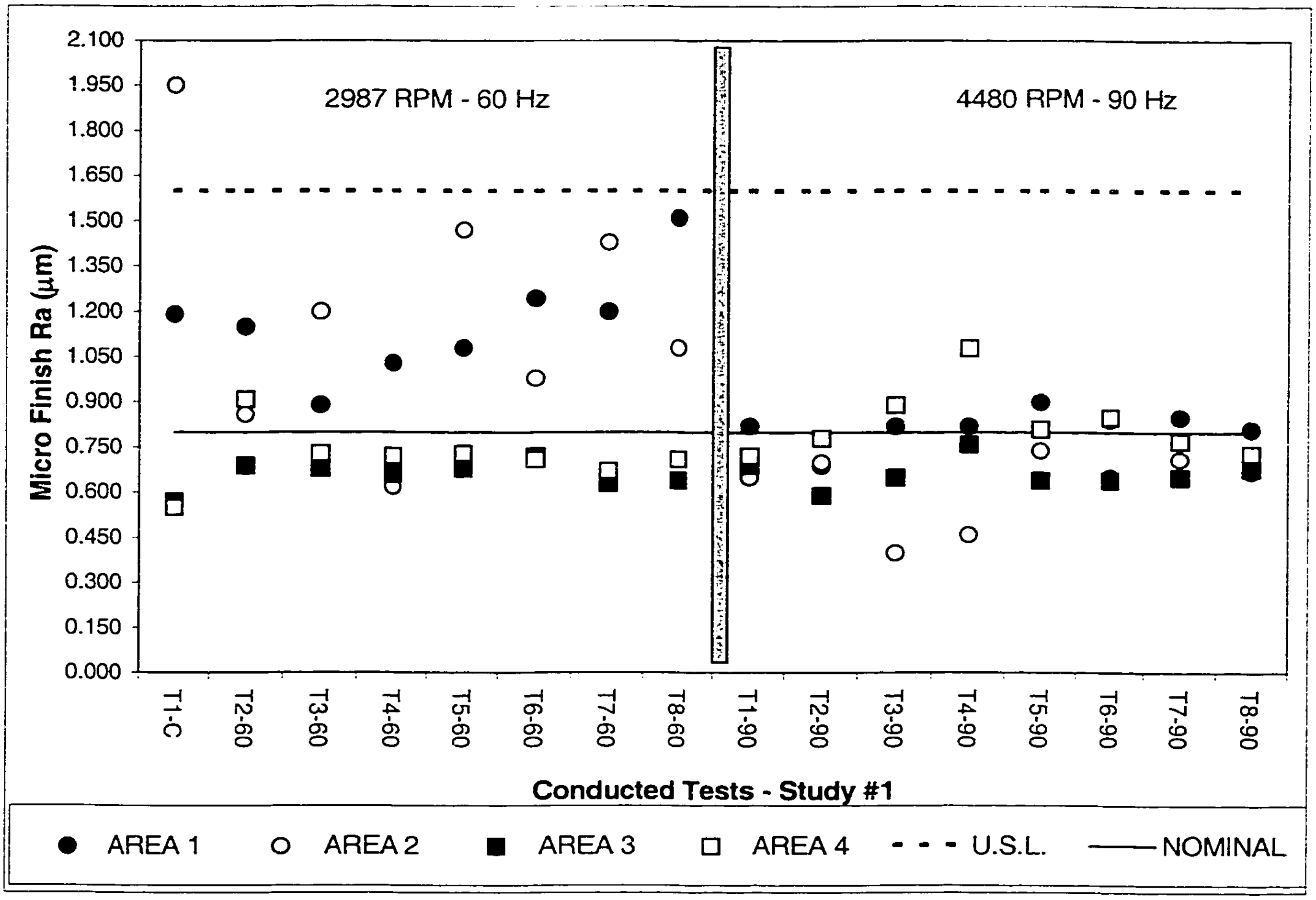


Figure 4-7 Effect of Spindle Speed on Micro Finish Readings

4.1.5.2 Effect of Feed rate

Feed rate was not a significant contributor to improved visual surface finish as tooling marks continued to exist with the slower feed rate. Test T2-60 had a baseline tool path with a feed rate that was reduced from 6000 mm/min to 3000 mm/min across the two areas of interest. In area 1, the defined "scuffing" marks that existed in the baseline were still evident in this test. The visual tooling feed marks are spaced closer together indicating the slower feed rate, the reduced feed rate was unsuccessful at eliminating the "scuffing". Photo images of area 1 can be seen in Figure 4-3.

The reduced feed rate showed an improvement in measured micro finish in area 2. The average micro finish readings in area 2 were reduced from 1.95 mm to 0.86 mm or a 56% improvement.

4.1.5.3 Effect of Tool Path

The tool path was a significant contributor to improving surface finish. The elements of tool path deemed to be important included positioning the centre of the milling cutter as close to the sprocket face rail as possible. Tool paths that used a radius arc to turn direction did not seem to have any significantly different results as compared to a tool path that changed direction after coming to an exact stop point (i.e. Test #5). Micro finish measurements and visual inspection of area 2 verify these observations. Photo images of area 2 for all sixteen tests can be seen in Appendix C.

4.1.5.4 Effect of Feed per Insert

The significance of feed/insert was not fully understood until reviewing the data from the various tests. Feed/insert can be defined as material removed per insert per revolution. Increasing the spindle speed resulted in a lower feed/insert. Similarly, slowing the feed rate also lowered the feed/insert. This is important because the tests with the same feed/insert provided very different micro finish results. It can be concluded from this graph that feed per insert is not a significant parameter for improved surface finish due to this fact. Figure 4-8 shows a summary of the tests with the same feed/rev.

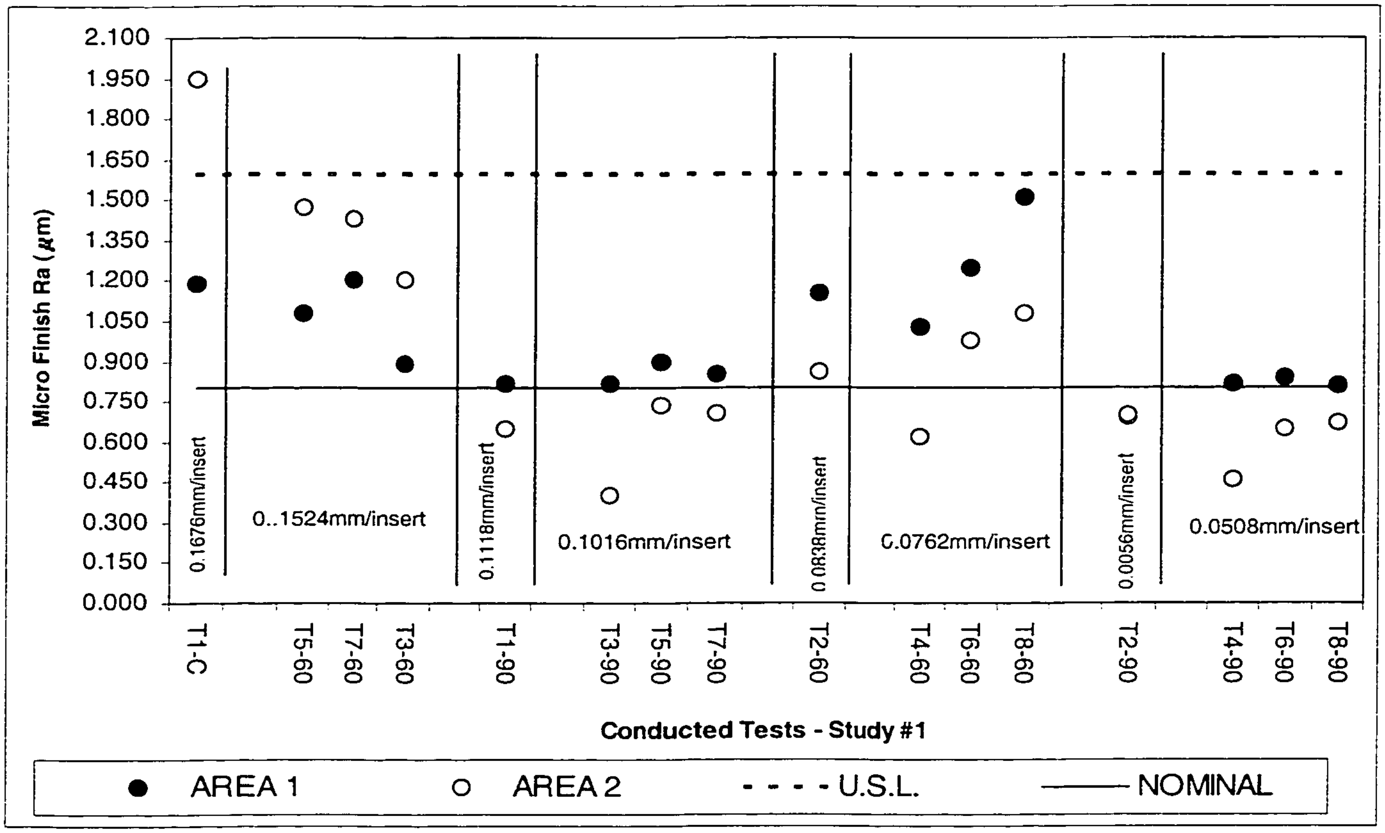


Figure 4-8 Feed per Insert Comparison

4.2 Study #2 – Effect of Cutter Rotation and Depth of Cut

The second of the two studies investigated the effect of changes in spindle rotation and depth of cut on the surface micro finish. The performance metric used in the study was micro finish readings as measured with a profilometer.

4.2.1 Conditions of the study

The study was performed using the production transfer line at the sprocket face finish machining station. Test #7 was installed in the machining station shortly after the conclusion of Study #1 to test if cutter life could be increased, and therefore it was used in the depth of cut study. There was no particular order to assignment of pallets used to clamp the parts. The previous operation was qualified to ensure the in-process manufacturing location pads were within part print limits. The milling cutter used in the study had been mounted cleanly with no debris between the mounting surfaces of the spindle and the milling cutter face.

The depth of cut testing required that the roughing operation on the transfer line was placed in "by-pass" mode so as to not machine the 'test parts', that had been rough machined with additional finish stock remaining. The milling cutter had previously machined 24,000 parts and was producing surface finish quality comparable to the results when the program was tested during the study. The expectation was to view any changes in micro finish with the various depths of cut.

The second part of study #2 involved using the right hand cutter. For this test, the motor wiring was reversed so the motor would turn in the opposite direction. A new CNC path, Test #9, was installed in the station. A new milling cutter was used for the test. It was not possible to obtain a used right handed milling cutter for this test as no operation in the plant used a right hand cutter. The expectation of this test was to evaluate a potential improvement in surface finish to justify a trial with the right hand cutter in production. The parts used were rough machined to remove casting variation from the surface, leaving 0.5 mm of material for the finishing operation to machine.

4.2.2 Constraints of the Study

As with Study #1, the machining station in the transfer line had programmed "soft stops" dictating the travel of each axis. This constraint limited the flexibility in programming an agile right hand tool path.

4.2.3 Method of Study #2

The purpose of this study was to determine the influence that depth of cut and milling cutter rotation had on the visual and measured quality of the micro finish of the sprocket face. Part print characteristics of flatness, parallelism and position to a datum were also measured.

Two tests were conducted for depth of cut. The first test used five parts that were rough machined leaving 0.75 mm of material for the finish station to remove. The second test used five parts with 1.0 mm of material remaining for the finish station. Test #7 was the tool path used for each test with a spindle speed of 4480 rpm at 90 Hz.

The right hand milling cutter study used one tool path, Test #9. Spindle speed was varied between 2987rpm (60Hz) and 4480 rpm (90Hz). Feed rate remained constant at 5428 mm/min. The four areas of the sprocket face from Figure 4-2 were measured for micro finish.

4.2.4 Results of Study #2

The depth of cut testing did not indicate any significant improvements to micro finish. The right hand cutter with new milling cutter showed a further improvement in measured micro finish results in areas 1, 3, and 4 over the best performing test from Study #1.

4.2.4.1 Effect of Depth of Cut

Testing of various depth of cut processes did not contribute significantly to an improvement to surface micro finish. An increased depth of cut impacted unfavourably area 1. Area 2 produced stable micro finish readings at both depths of cut. Figure 4-9 graphically shows the comparison of micro finish results of this testing. Parallelism and flatness were impacted negatively as well.

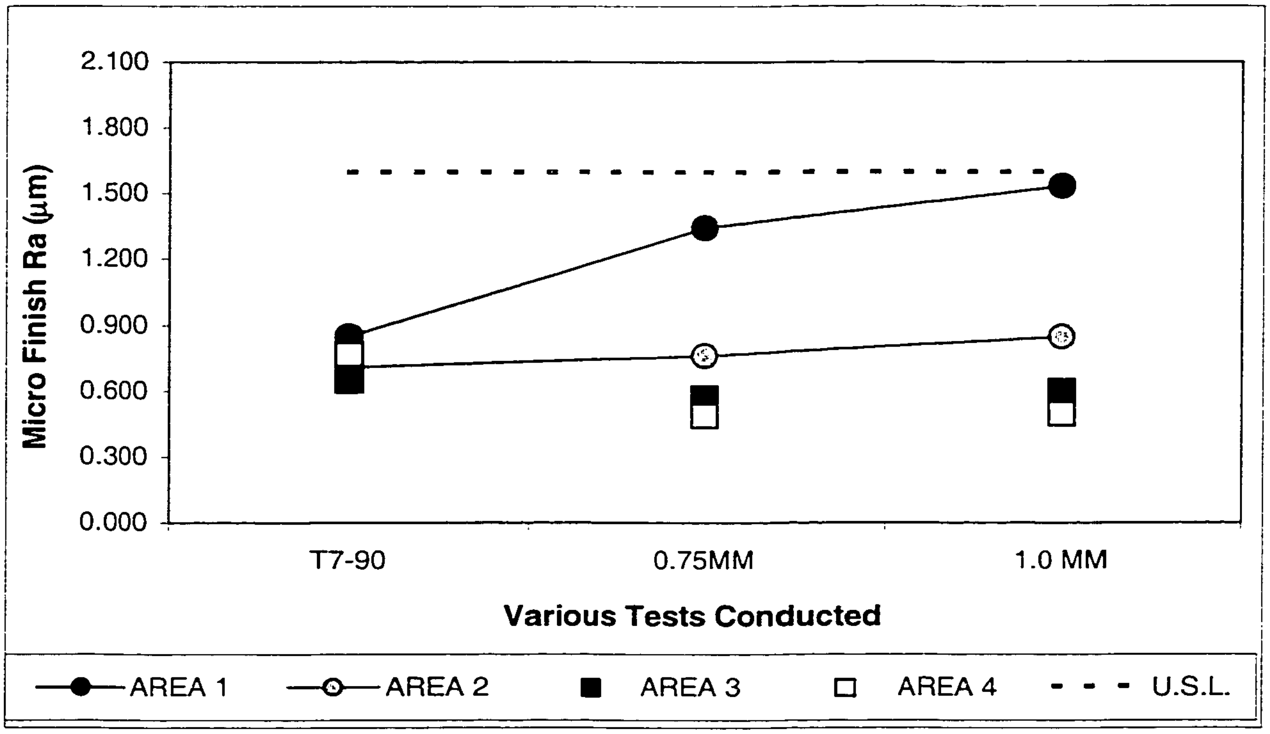
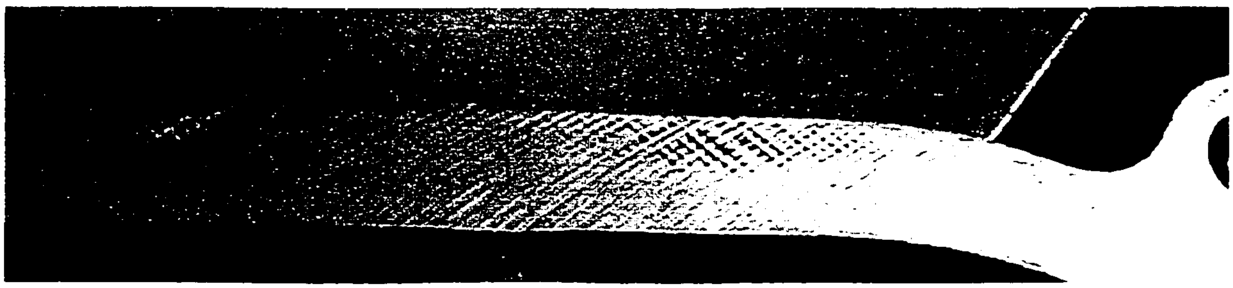


Figure 4-9 Depth of Cut Comparison

4.2.4.2 Effect of Milling Cutter Rotation

The results of the testing with the right hand milling cutter indicated favourable results as compared to the best performing test from Study #1. The photo images of the right hand cutter results are shown in Figure 4-10 and the measured micro finish results are shown graphically in Figure 4-11.

Overall, the right hand milling cutter rotation proved promising. The visual appeal of the surface finish test parts that were machined using the 90Hz spindle speed and right hand milling cutter rotation was "mirror-like" in appearance with no substantial evidence of tool marks. The average micro finish measured at three points in area 1 resulted in an average roughness of 0.62 mm. This was a further improvement of 24% in measured micro finish over the best results from study #1. The comparison is not a true paired comparison to the baseline as the inserts were new, but the results dictate further testing a right hand milling cutter through the life cycle of the inserts.



Right Hand Cutter Test #9 - T9-60Hz

Right Hand Cutter Test #9 - T9-90Hz

Figure 4-10 Area 1 Images from Right Hand Cutter Test #9

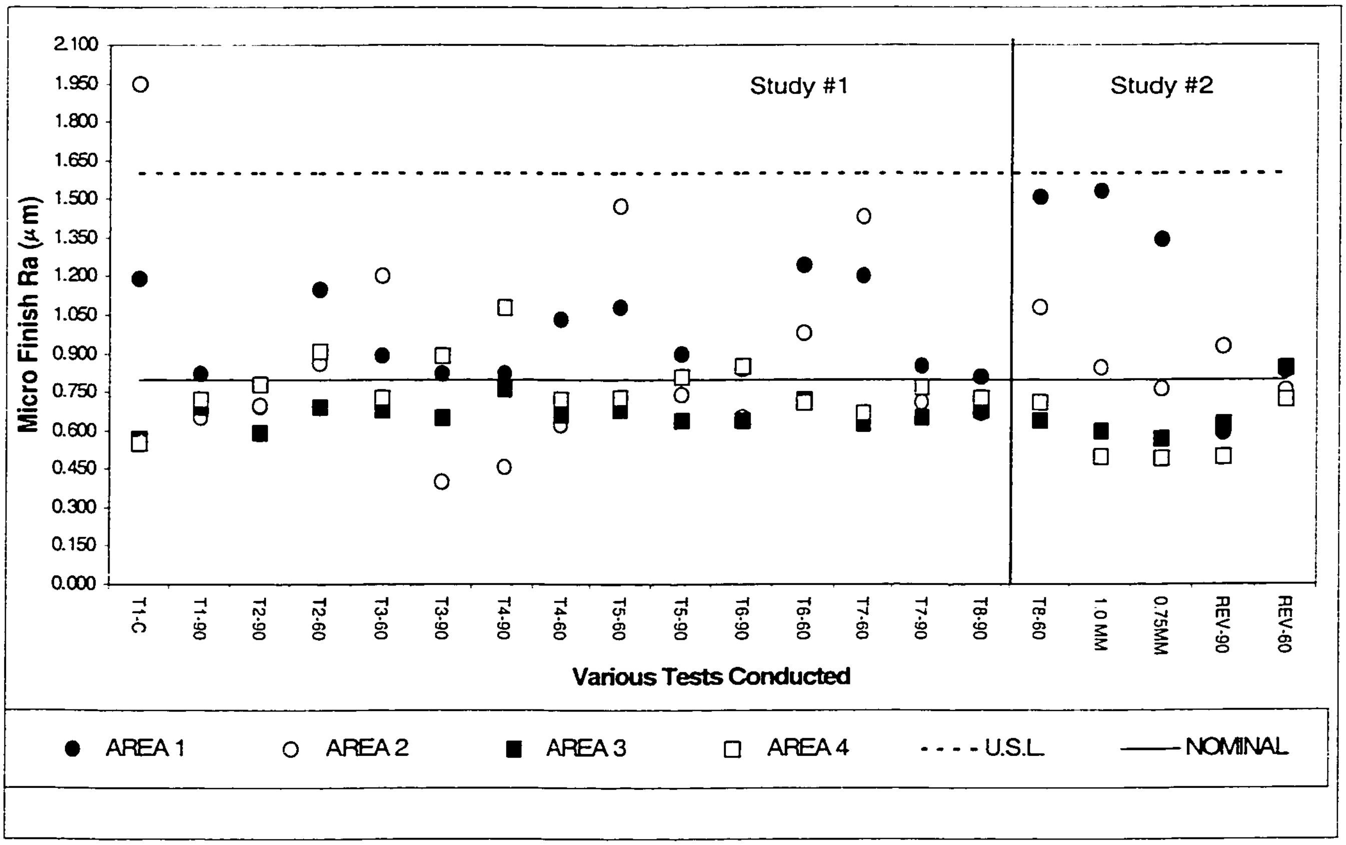


Figure 4-11 Micro Finish Results of All Testing

4.3 Evaluation of Part Print Characteristics

4.3.1 Measured Micro Finish

Micro finish was the primary characteristic to be studied. This characteristic was influenced by the various test parameters. Figure 4-12 illustrates graphically the average micro finish measurements of each area for all tests conducted in the two studies. The five parts from each test were averaged to obtain the plotted values. Appendix F contains the raw data for the plotted results of the tests completed.

4.3.2 Measured Flatness, Parallelism, and Position to Datum

The part print characteristics of flatness and parallelism were studied to determine whether the various testing parameters would change these quality measures. The various tests performed from the two studies indicated variation existed in the measured results of flatness and parallelism. Figure 4-12 illustrates graphically the measured average flatness and average parallelism for the tests performed from the two studies. The five parts from each test were averaged to obtain the plotted values. The graph shows a 0.090 mm range in flatness measurements and 0.180 mm range in parallelism measurements.

The characteristic of the position of the surface to the measuring datum was not influenced by the various tests performed. This characteristic, as measured, is 72.0 mm to a qualified datum point 'M1.' The surface was measured in 35 points around the perimeter of the sprocket face relative to the datum. It was found that when the data were sorted by pallet used to clamp the part during machining, that pallet to pallet variation was the main contributing factor that influenced this characteristic. Figure 4-13 shows an example of the positional measurements and the variation between pallets. The two pallets shown were randomly selected from the test results.

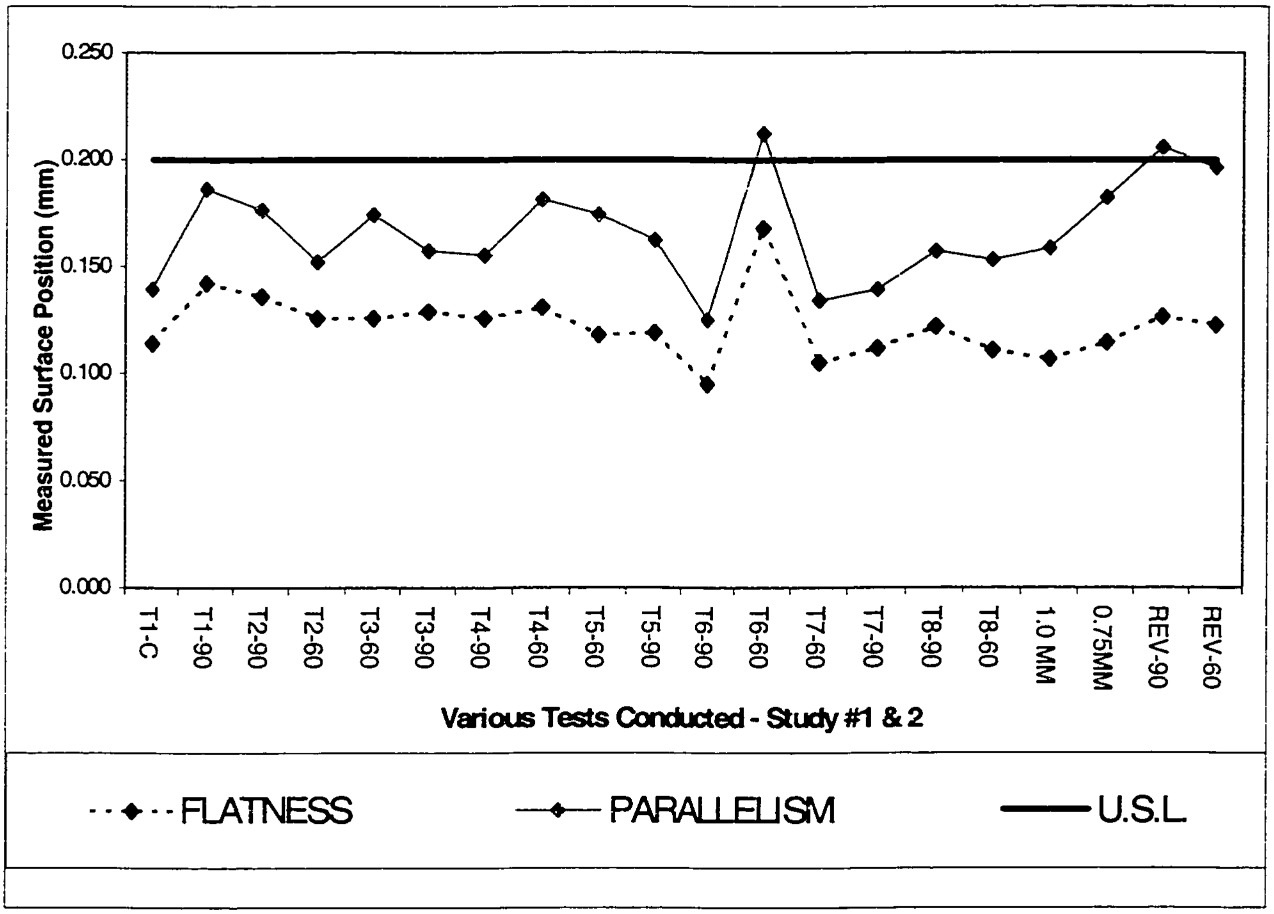


Figure 4-12 Flatness and Parallelism Comparison of the Various Tests

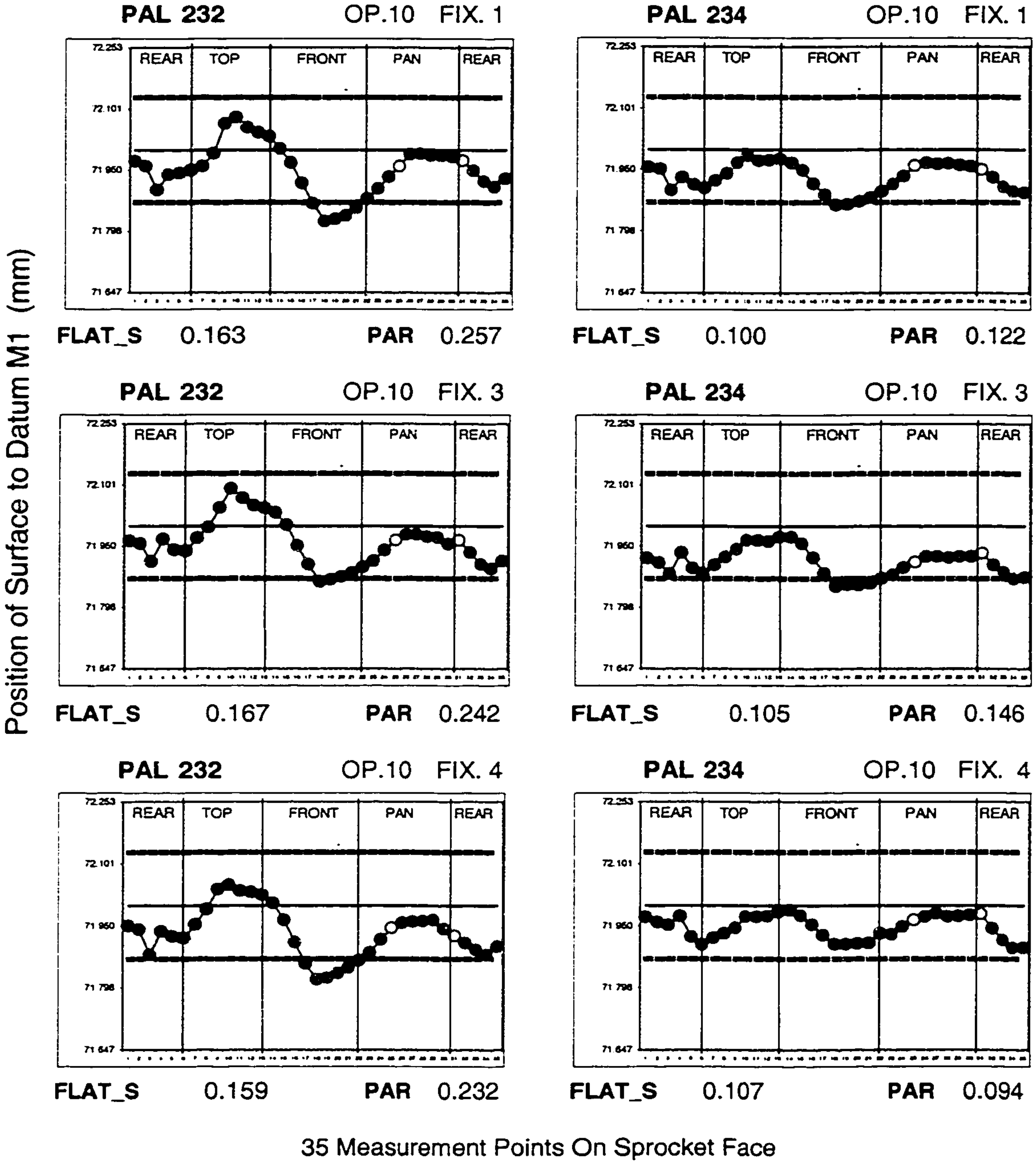


Figure 4-13 Surface Position vs. Pallet Variation

5. OPTIMIZATION

This chapter analyzed the results of the optimization studies and established a decision on what parameters to pursue to truly optimize the machining process within the operational constraints. Elements of station cycle time, risk to the operation, and investment cost to make changes were evaluated in the optimization.

5.1 Cycle Time of the Operation

The transfer line total cycle time was 21 seconds. The cycle consisted of a fifteen second machining station operation and a six second pallet transfer process to index all pallets to the next in-line operation.

The machining station cycle time was not a consideration for the studies but the optimized solution must also ensure that the fifteen second cycle time is not impacted.

Cycle time of the machining station was calculated by establishing the measured distance travelled by the tool path during the machining cycle, multiplied by the feed rate that the milling cutter is travelling. The calculated cycle times for the various tests were verified to be comparable to the actual machining test cycle times. Table 5-1 lists the various tests, the tool path distance, and the cycle time at the feed rate used.

Many of the tests performed exceeded the required machining cycle time. In test situations where the low feed rate led to exceeding the cycle time condition, cycle time can be regained in a number of ways. A combination of increased spindle speed and feed rate can regain lost cycle time while maintaining the same feed per insert of metal removal. The variable frequency controller (V.F.C.) was required for the 90Hz tests, and was still required for regular production for increasing spindle speed to 4480 rpm. With an increase in spindle speed, a higher rated machine spindle was recommended which utilizes ceramic bearings to withstand the higher rotating speeds. Table 5-2 illustrates the calculated machining cycle times for the various tests performed with the cost and risk to the operation to regain the 15.0 second cycle time requirement.

Table 5-1 Comparison of Test Tool Path Distance and Cycle Time

Test Number	Tool Path Distance mm	Feed Rate mm/min	Cycle Time sec
Test #1	1283.36	6000	12.83
Test #2	1283.36	6000/3000	18.76
Test #3	1283.36	5428	14.19
Test #4	1283.36	2714/5428	21.82
Test #5	1467.49	5428	16.22
Test #6	1467.49	2714/5428	24.69
Test #7	1394.92	5428	15.42
Test #8	1394.92	2714/5428	22.47
Test #9	1275.13	5428	14.09

Table 5-2 Comparison of Test Cycle Time vs. Investment Cost

Test Description	Test Feed Rate (mm/min)	Cycletime (sec)	Cost (CDN $)	Change to Process
Test #1 60Hz	6000	12.83	No Cost	No Change to Current Operation
Test #1 90Hz	6000	12.83	$5,500	Install V.F.C.
Test #2 60Hz	6000/3000	19.97	$30,000	8000 rpm spindle
Test #2 90Hz	6000/3000	19.97	$35,500	V.F.C. + 8000 rpm spindle
Test #3 60Hz	5428	14.19	No Cost	No Change to Current Operation
Test #3 90Hz	5428	14.19	$5,500	Install V.F.C.
Test #4 60Hz	2714/5428	22.08	$30,000	8000 rpm spindle
Test #4 90Hz	2714/5428	22.08	$35,500	V.F.C. + 8000 rpm spindle
Test #5 60Hz	5428	16.22	$30,000	8000 rpm spindle
Test #5 90Hz	5428	16.22	$35,500	V.F.C. + 8000 rpm spindle
Test #6 60Hz	2714/5428	24.69	$30,000	8000 rpm spindle
Test #6 90Hz	2714/5428	24.69	$35,500	V.F.C. + 8000 rpm spindle
Test #7 60Hz	5428	15.48	$30,000	8000 rpm spindle
Test #7 90Hz	5428	15.48	$35,500	V.F.C. + 8000 rpm spindle
Test #8 60Hz	2714/5428	22.47	$30,000	8000 rpm spindle
Test #8 90Hz	2714/5428	22.47	$35,500	V.F.C. + 8000 rpm spindle
Right Hand Cutter 90Hz	5428	14.13	$3,000	RH Mill Cutter
Right Hand Cutter 60Hz	5428	14.13	$8,500	V.F.C. + RH Mill Cutter
0.75mm Finish Stock w/ T7-90	5428	15.48	$35,500	V.F.C. + 8000 rpm spindle
1.0mm Finish Stock w/ T7-90	5428	15.48	$35,500	V.F.C. + 8000 rpm spindle

5.2 Optimizing Tool Life

The sharpness of the cutting edge of a machining tool is a function of the total number of parts machined before the tool must be replaced. If the cutting edge of a machining tool can only be subjected to interface with the work piece a finite number of times, then reducing the feed per insert during the machining tests could possibly be detrimental to maximizing cutter life.

The various tests performed did not provide an indication of the projected tool life for this particular machining operation. Tool life can only be evaluated through monitoring in a production environment. Test #7 was implemented on the equipment with minimal cost investment and a small penalty on cycle time to understand the advantages of increased tool life.

5.3 Observations and Results

The various tests performed from the two studies provided the direction to optimize the machining operation.

Upon review of the micro finish results of the various tests performed, tests T1-90, T2-90, T5-90, T6-90, T7-90, and T8-90 resulted in a tight cluster of acceptable micro finish readings that were significantly better than baseline. Flatness and parallelism results were also considered. Tests T6-90 and T7-90 were the only two results that were the same as or better than the baseline results for flatness and parallelism.

Test T6-90 was ruled out due to the long cycle and the investment and lead time that it would take to incorporate the changes. Therefore, test T7-90 was selected as the optimized solution as compared to the other tests as it satisfied the objectives of improved micro finish while maintaining flatness and parallelism requirements. Test T7-90 was installed on the production equipment on the week of October 2,2000.

Tool life was increased by 83% to 55,000 pieces with acceptable micro finish results throughout the extended life. Tool replacement costs were reduced from $30,000 to $13,850 per year for this operation, which is done on two transfer lines. The frequency of tool changes was reduced from 34 to 16 per year, thus providing increased machine availability for additional production.

The station performed at a 0.5 second over cycle condition. The cycle time penalty created by the tool path distance in Test #7 was regained by increasing the frequency controller to 99 Hz producing a spindle speed of 4950 rpm and by increasing the feed rate to 6000 mm/min. This change satisfied three requirements. First, the tooth passing frequency continued to be a non conflicting frequency after being increased to 990 Hz. Secondly, the feed per insert metal removal rate was maintained at 0.1016mm(0.004")/insert, and third, the cycle time was reduced to 13.95 sec which satisfied the process requirements.

Milling cutter rotation provided a significant improvement in the areas of concern. The test REV-90 resulted in a visually superior finish in comparison to all the other tests performed. Test REV-60 provided acceptable micro finish results but tool marks were visually evident. Parallelism and flatness were impacted negatively with the right hand cutter tests as compared to the baseline test.

The tests with various depth of cut did not provide any significant findings. Flatness and parallelism were impacted negatively with the depth of cut tests as compared to the baseline test.

6. CONCLUSIONS

The following conclusions have been reached from the studies completed:

1) Spindle speed significantly influenced the micro finish readings. Upon reviewing the frequency response functions in the two areas of concern, a natural frequency at 1191 Hz in area 2 may have been excited by the tooth passing frequency of 598 Hz as the second order of vibration. By increasing the tooth passing frequency to 896 Hz, the work piece excitation due to the milling cutter was minimized.
2) Milling cutter rotation was identified in the FEA simulation as reducing part deflection by 53% as compared to the baseline model. The right hand cutter test in Study #2 experimentally confirmed the improved micro finish results as a 52% improvement was measured. The testing results justified pursuing a right hand cutter trial on the production machinery.
3) Surface position as measured to the datum was influenced primarily by pallet variation. The tests used within this study did not influence this characteristic.
4) Feed per insert material removal rate of 0.1016mm(0.004") / insert provided stable micro finish readings throughout the 55,000 piece life of the milling cutter.
5) Increasing the depth of cut affected parallelism and flatness readings as well as micro finish results negatively. Maintaining the 0.5 mm final stock removal provided optimum results throughout the cutter life.

The conclusions that were established in this thesis provide a basic guideline for future studies in milling applications. This thesis used a finite element model to predict how the complex work piece would react to changes in machining parameters. The predicted results of the simulations documented the significance of the machining parameters being altered. Combined with modal analysis techniques to gather frequency response characteristics about the work piece, natural frequency data was collected to understand the excitable frequencies of the structure. These data offered direction in justifying the changes in spindle speed. The use of finite element models and modal analysis techniques provided supporting data for the changes made to the machining parameters. With experimental testing to validate the data collected, work piece surface finish was improved and tool life was increased with minimal disruption to production.

7. RECOMMENDATIONS

The following recommendations represent areas of possible continued improvement opportunities for milling cutting applications:

1) The use of 'Frequency Response Functions' to acquire natural frequency information about the work piece should be incorporated into the development stages of a product. Induced forced vibration can be strategically positioned so as to not affect the excitable natural frequencies. An understanding of modal analysis methodologies and an awareness of metal cutting theories are required to use this technology properly.
2) Computer software such as 'CutPro' is another powerful diagnostic tool to predict cutting forces exerted on a work piece, as well as to calculate stability lobes in time domain to understand chatter conditions. By inputting frequency response function data collected from the work piece, the calculated results are realistic for complex work piece geometries. The software requires the user to have knowledge of machining theories as well as the ability to obtain data by using an impact hammer and accelerometer.
3) Further optimization of this study can be achieved by obtaining the frequency response characteristics of the work piece during machining. When the milling cutter is in contact with the work piece, the structural stiffness of the station will influence the work piece stiffness and damping characteristics. A study with the accelerometers attached to the work piece during machining may provide 'real time' data of the excited frequencies of the work piece.

Microphones can also be used to record noise spectrums to understand work piece frequency information.

4) The effect of insert geometry during metal cutting is another area to be pursued. A thorough understanding of metal cutting is required to pursue this recommendation. Studying insert geometry along with the associated cutting forces acting on the work piece can further optimize the results of this study.
5) The effect of CNC tool path on the work piece provided interesting findings. The ability to predict part deflection and cutting forces is available from software programs used in this study. The ability to optimize the CNC program prior to experimental testing could be achieved.

8. Contribution to Engineering Knowledge

This paper has provided evidence that an optimized solution can be obtained to a complex problem through the use of modelling technologies with minimal disruption to manufacturing.

It has been shown that a finite element analysis modelling process can provide an educated direction in solving industrial application problems. By providing correct machining parameters for the model, the analysis results are considered a valid prediction. This tool provides a basis for educated decisions and eliminates much of the trial and error methods of problem solving.

Vibration analysis methodologies, although a very well known technology, are very rarely used in solving manufacturing problems. This is primarily due to a lack of vibration analysis knowledge, and a lack of proper equipment. This study proved that this technology can be used to make educated decisions to optimize machining parameters to maintain part quality while maximizing tool life. Knowledge of modal analysis techniques and an understanding in frequency response functions can provide a higher level of understanding of how to provide a solution with minimal disruption to manufacturing.

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APPENDIX A

Frequency Response Functions for Area 1 & 2

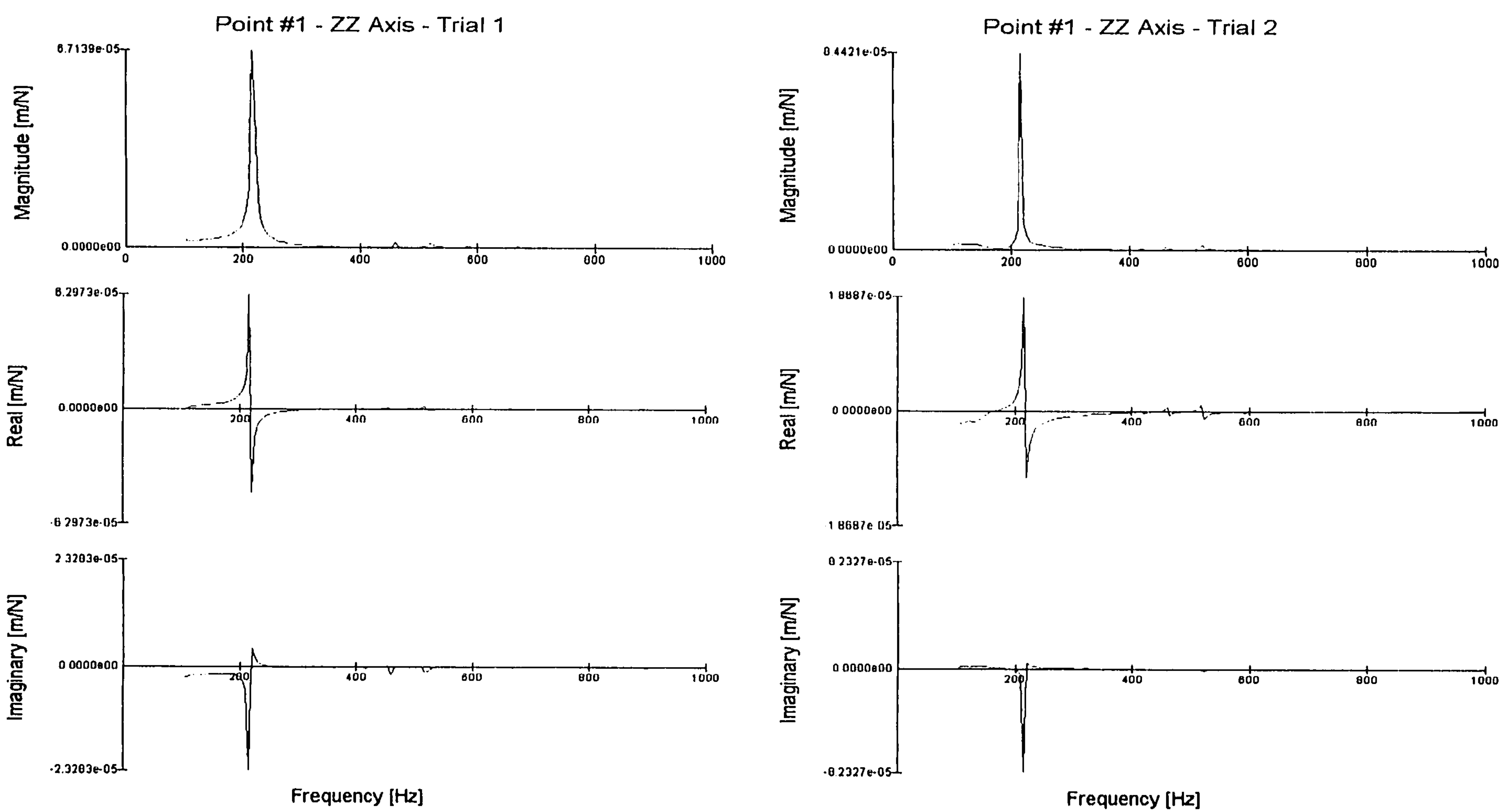


Figure A-1 Transfer Function Plots for ZZ Axis - Point #1

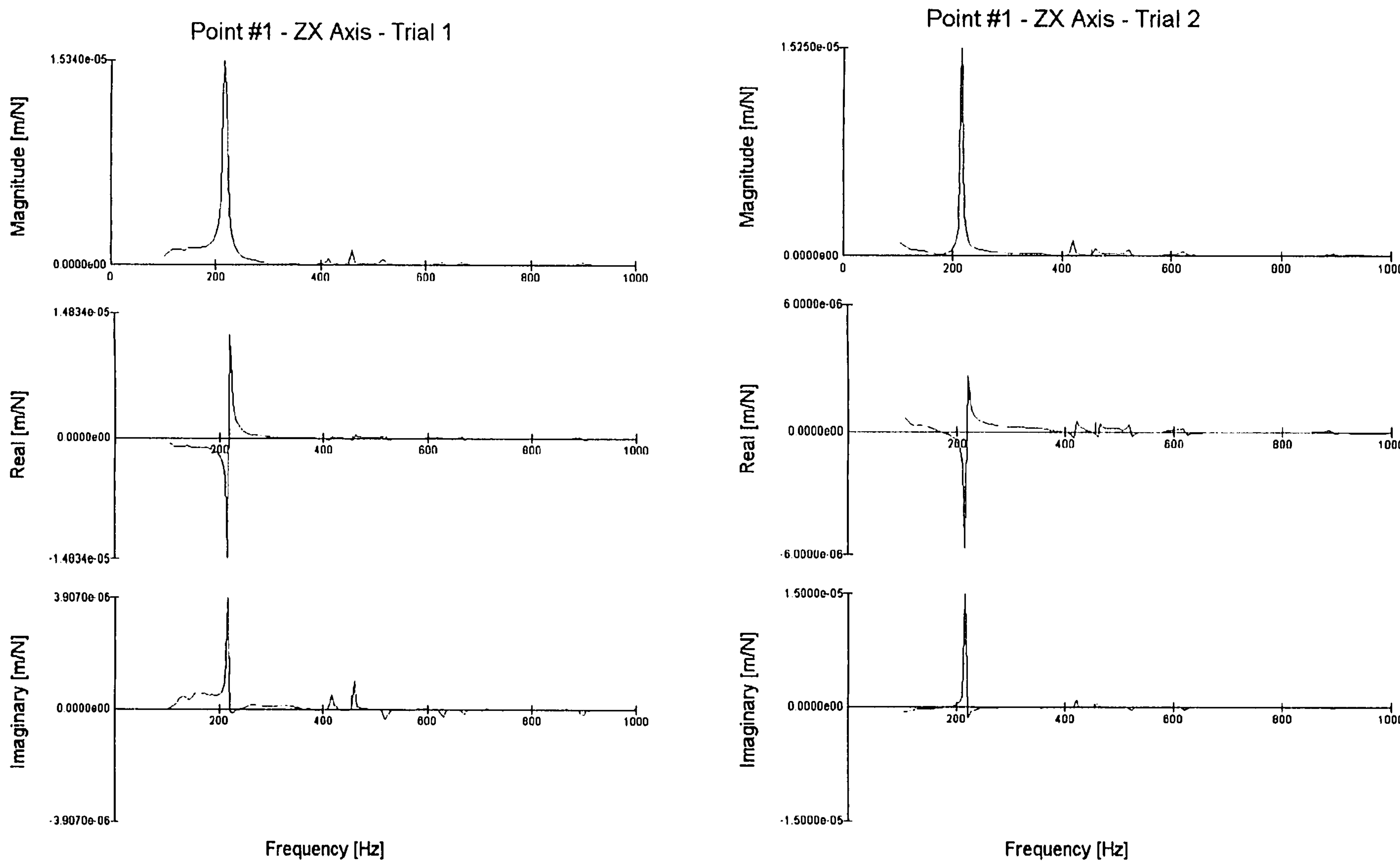


Figure A-2 Transfer Function Plots for ZX Axis - Point #1

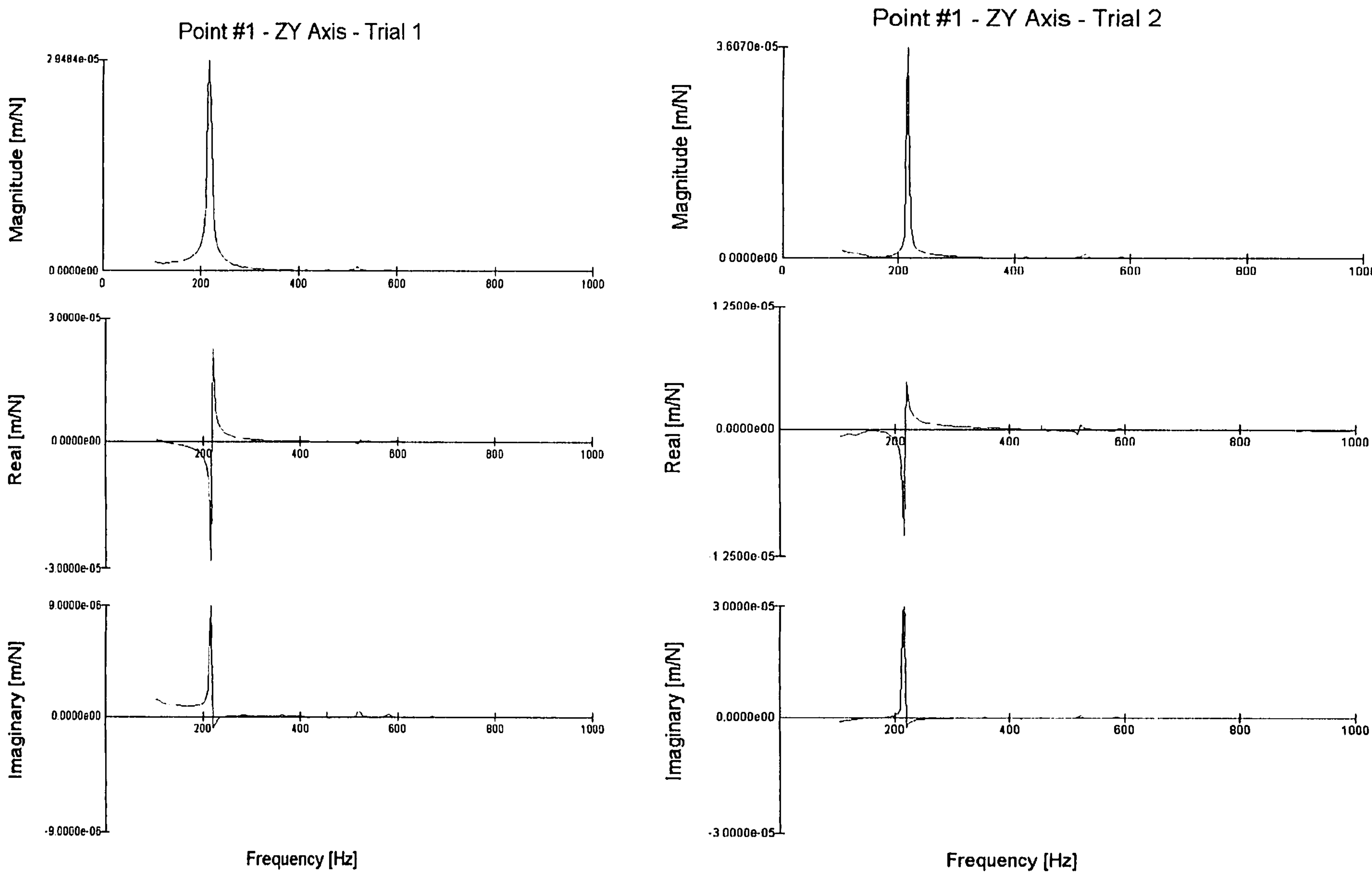


Figure A-3 Transfer Function Plots for ZY Axis - Point #1

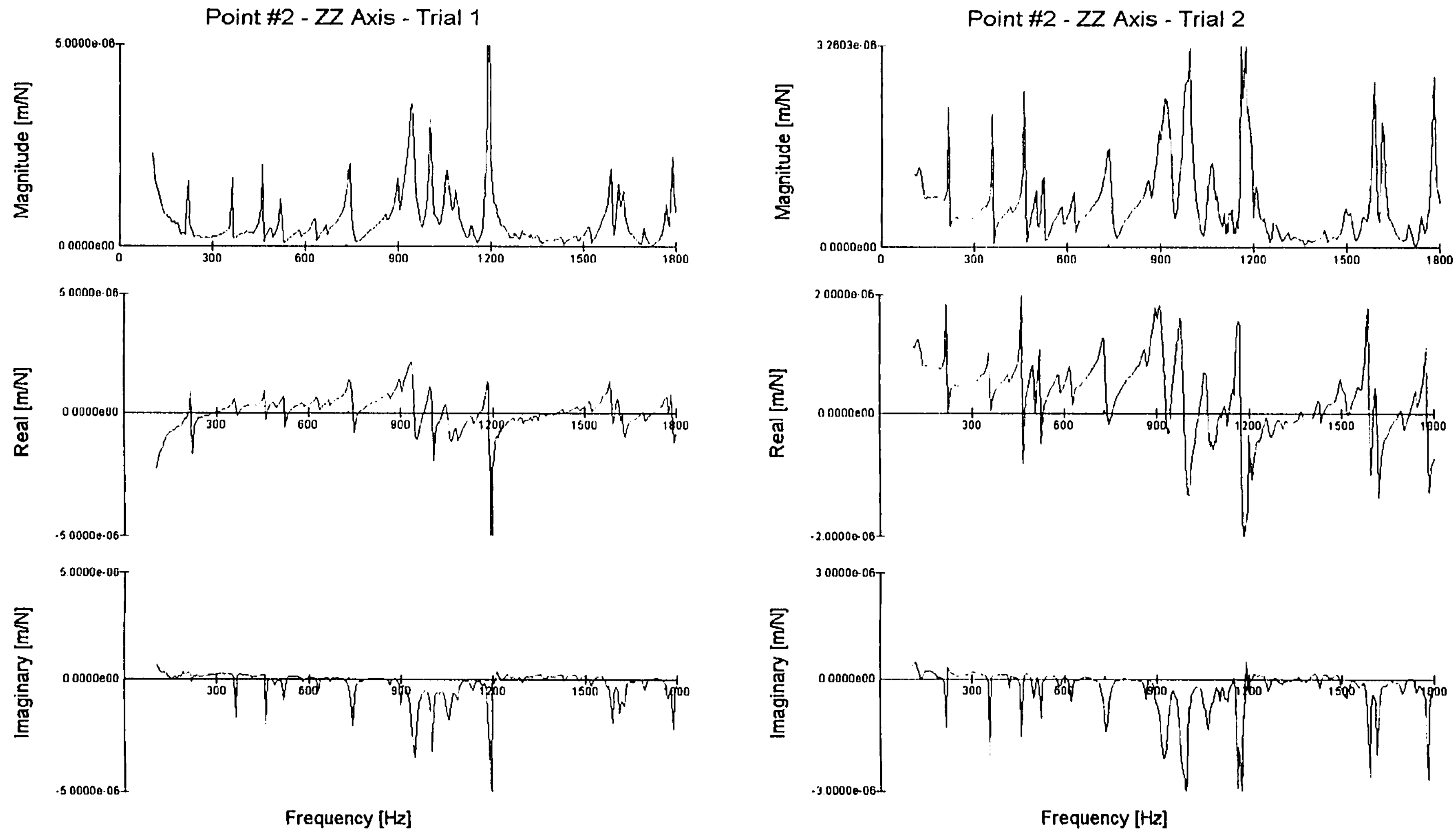


Figure A-4 Transfer Function Plots for ZZ Axis - Point #2

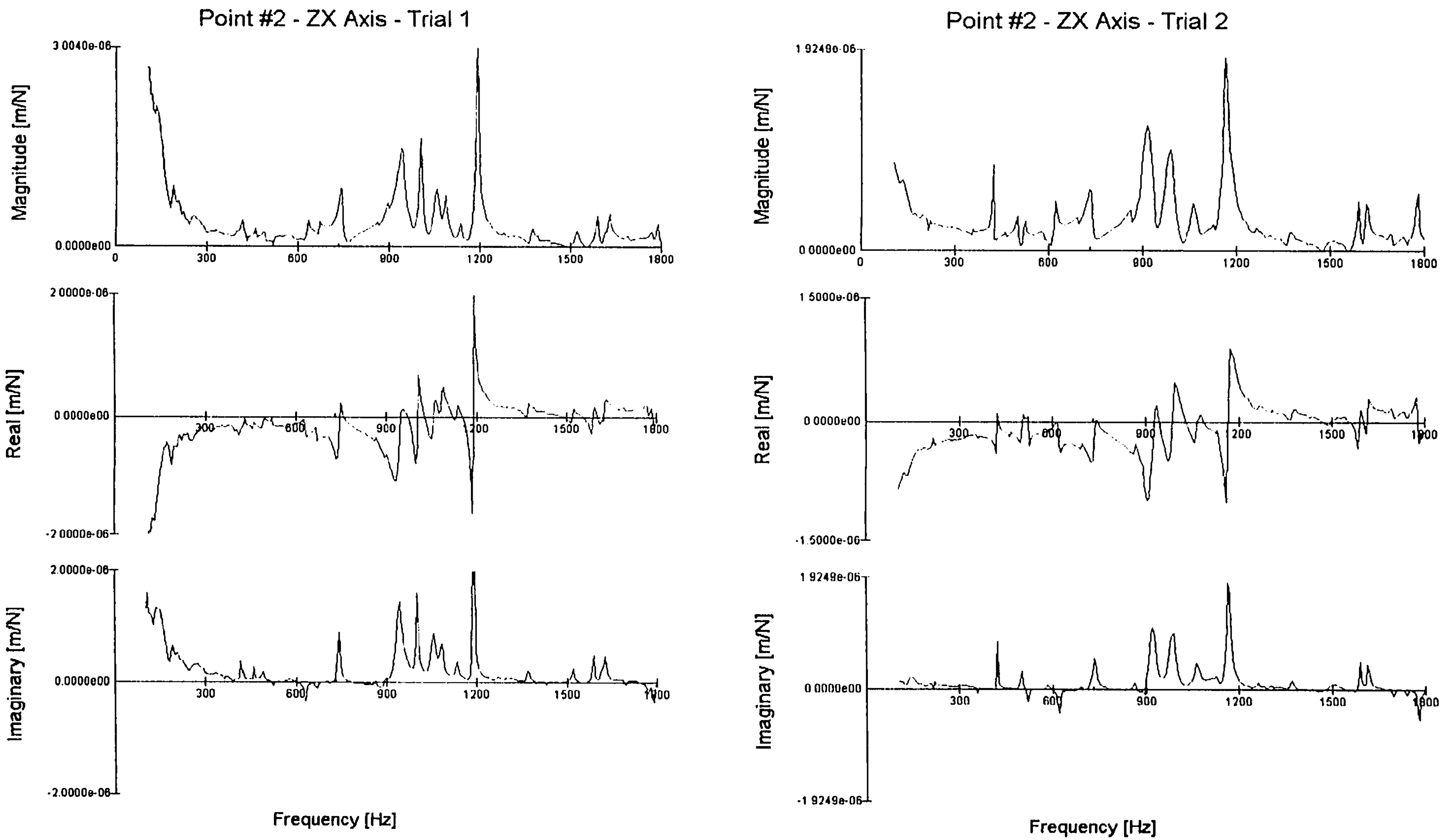


Figure A-5 Transfer Function Plots for ZX Axis - Point #2

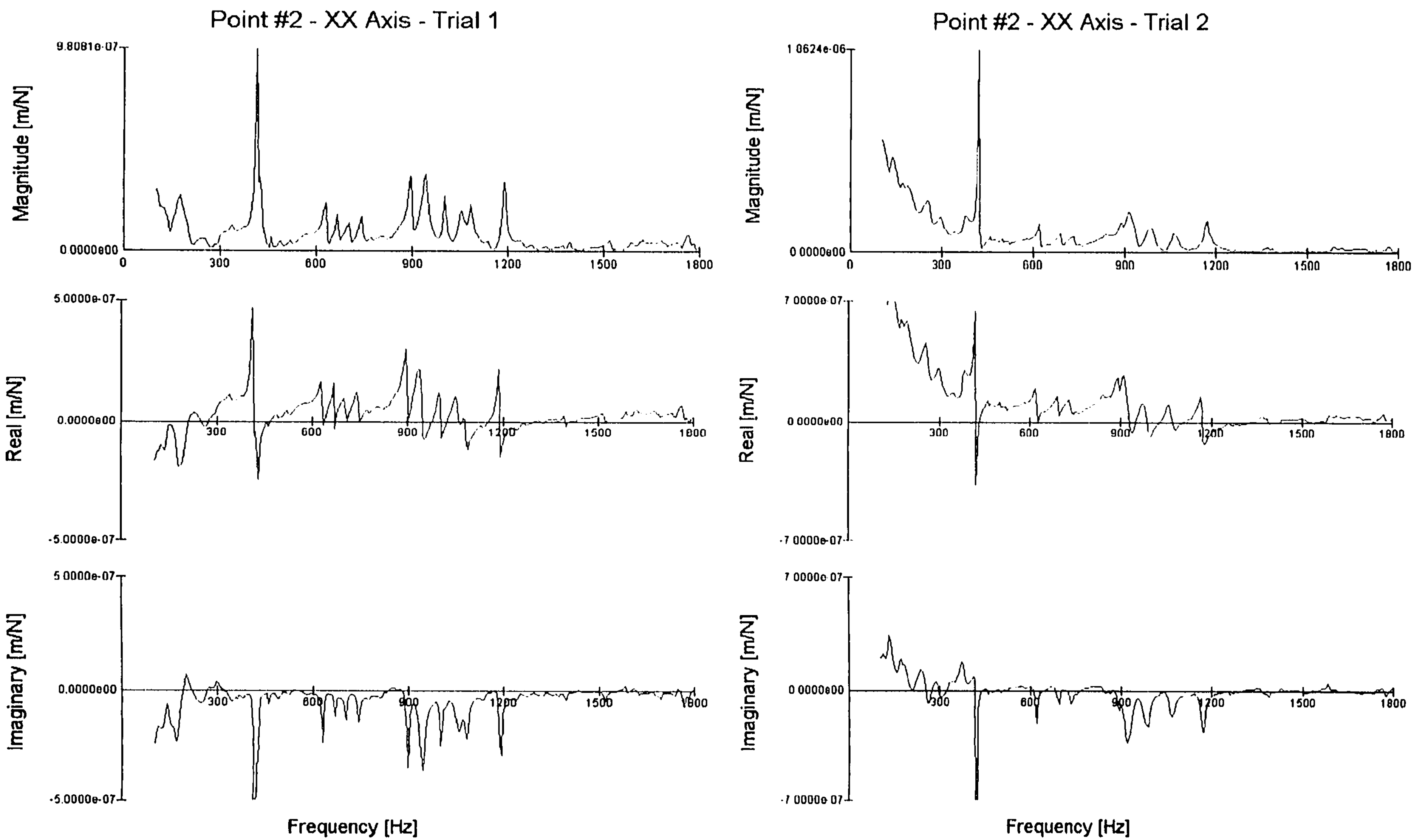


Figure A-6 Transfer Function Plots for XX Axis - Point #2

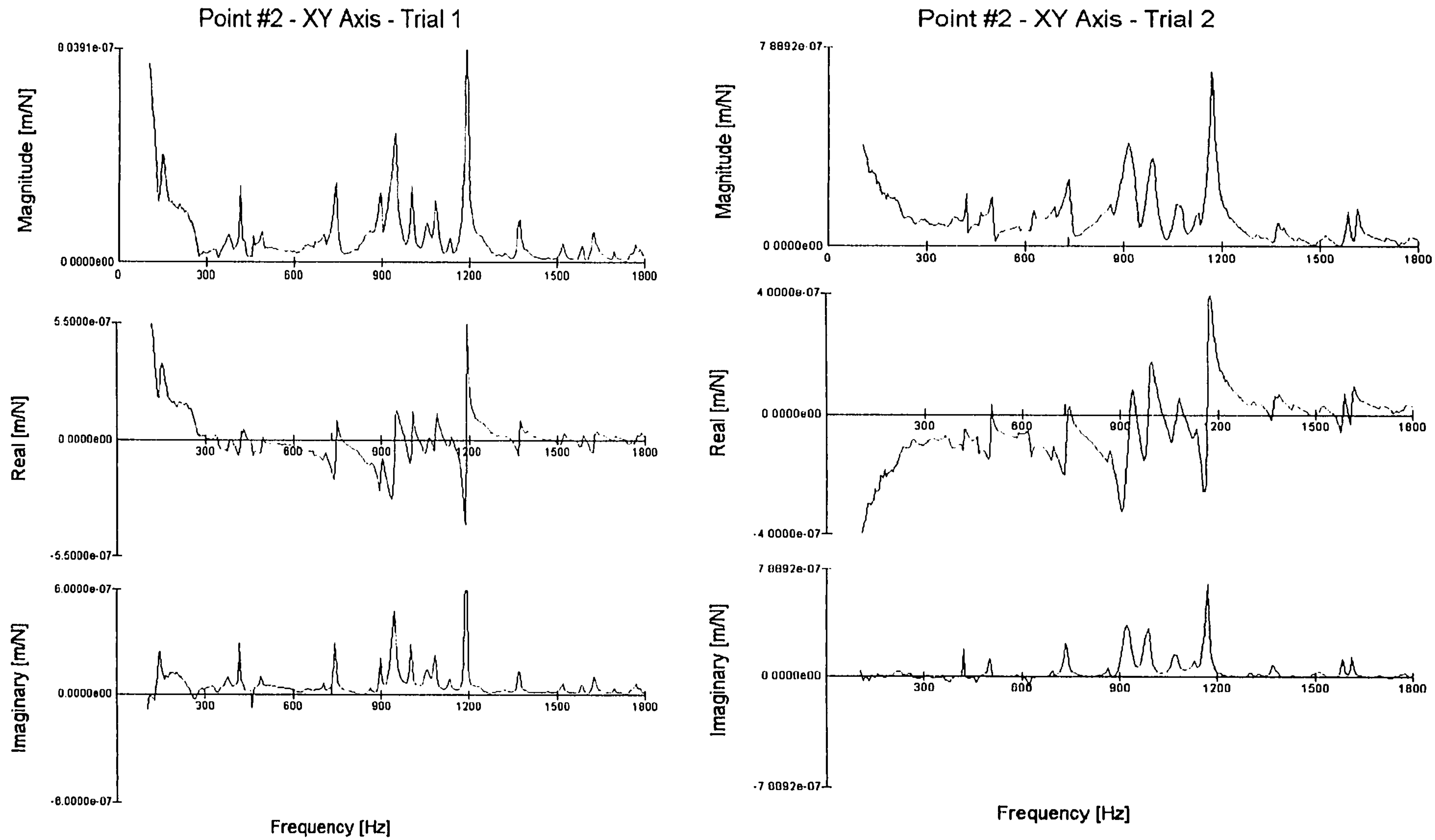


Figure A-7 Transfer Function Plots for XY Axis - Point #2

APPENDIX B

Study Procedures and Tool Path Programs

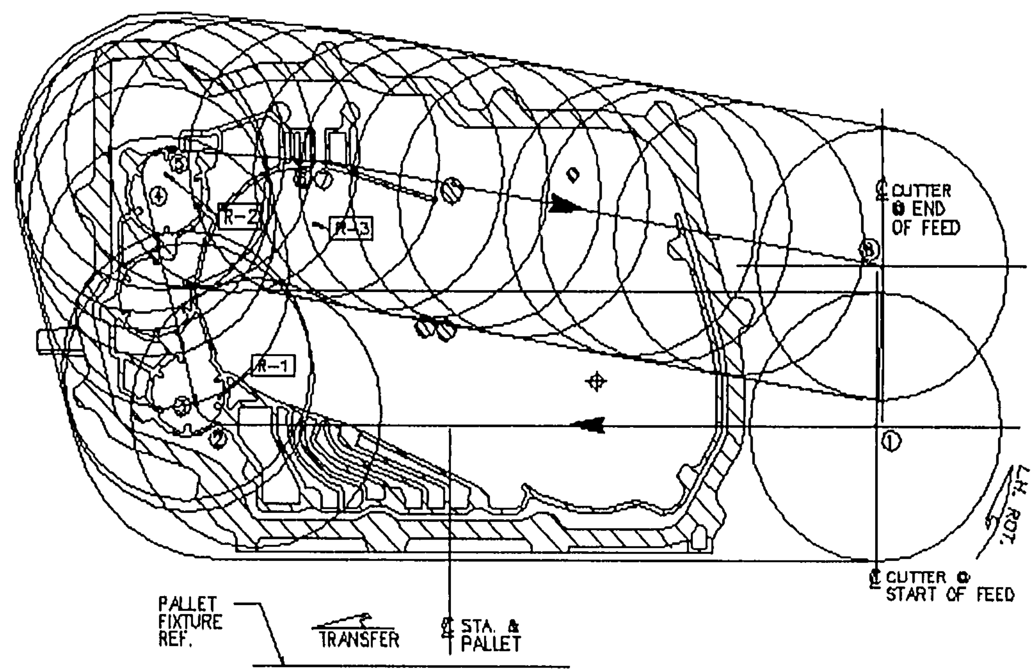
Table B-1 Study #1 Procedure

Sprocket face Study #1

TEST#1	Mount used cutter onto spindle at Sta 29LH Machine 5 pieces with **current program** to ensure poor surface finish Change Variable frequency controller **to 90Hz** and machine 5 pieces
TEST#2	Change to TEST #2 **(variable feedrate current path)** program and machine 5 pieces Change Variable frequency controller **back to 60** Hz and machine 5 pieces
TEST#3	Load TEST #3 (**Reverse path** was original) and machine 5 pieces @ 60 Hz Change Variable frequency controller **to 90Hz** and machine 5 pieces
TEST#4	Load TEST #4 (**Variable feedrate Reverse path** was original) and machine 5 pieces @ 90 Hz Change Variable frequency controller **to 60Hz** and machine 5 pieces
TEST#5	Load TEST #5 (**Four points no interpolation**) and machine 5 pieces @ 60 Hz Change Variable frequency controller **to 90Hz** and machine 5 pieces
TEST#6	Load TEST #6 (**Variable feedrate Four points**) and machine 5 pieces @ 90 Hz Change Variable frequency controller **to 60Hz** and machine 5 pieces
TEST#7	Load TEST #7 (**Tracing CNC Path**) and machine 5 pieces @ 60 Hz Change Variable frequency controller **to 90Hz** and machine 5 pieces
TEST#8	Load TEST #8 (**Variable feedrate Tracing CNC Path**) and machine 5 pieces @ 90 Hz Change Variable frequency controller **to 60Hz** and machine 5 pieces

Test #1 - Current Station Program – LH Cutter 2987RPM, 6000 mm/min
4480 RPM 6000 mm/min

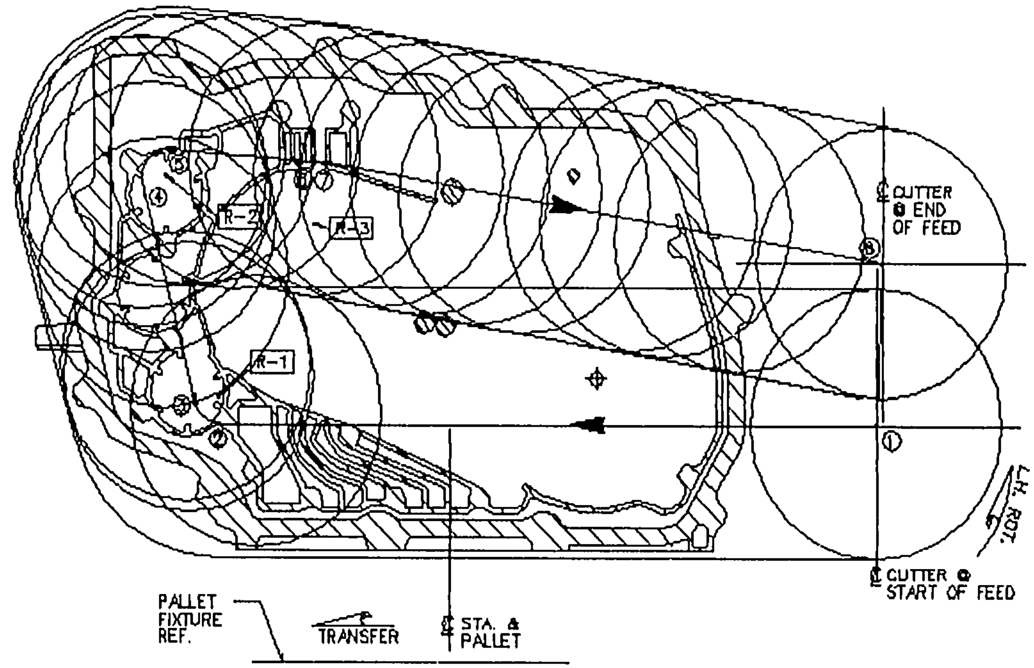
```
%
:0001
N20G90G01X217.0Y-32.35F6000 (PT1)
N30G17X-293.9202Y-32.35 (PT2)
N40G03X-312.3582Y-18.0897R70.95 (PT3)
N50G01X-351.5579Y132.8103 (PT4)
N60G03X-333.1198Y156.6499R70.95 (PT5)
N80G01X-220.0264Y156.6499 (PT6)
N90G03X-212.8167Y156.0563R44.05 (PT7)
N100G01X221.5424Y83.9959 (PT8)
N110M17
N120F6000X217.0Y-32.35
N130M16
N140M02
```




```
:0002
N20G01G90F4000X217.0Y-32.35
N30M16
N500M02
%
```

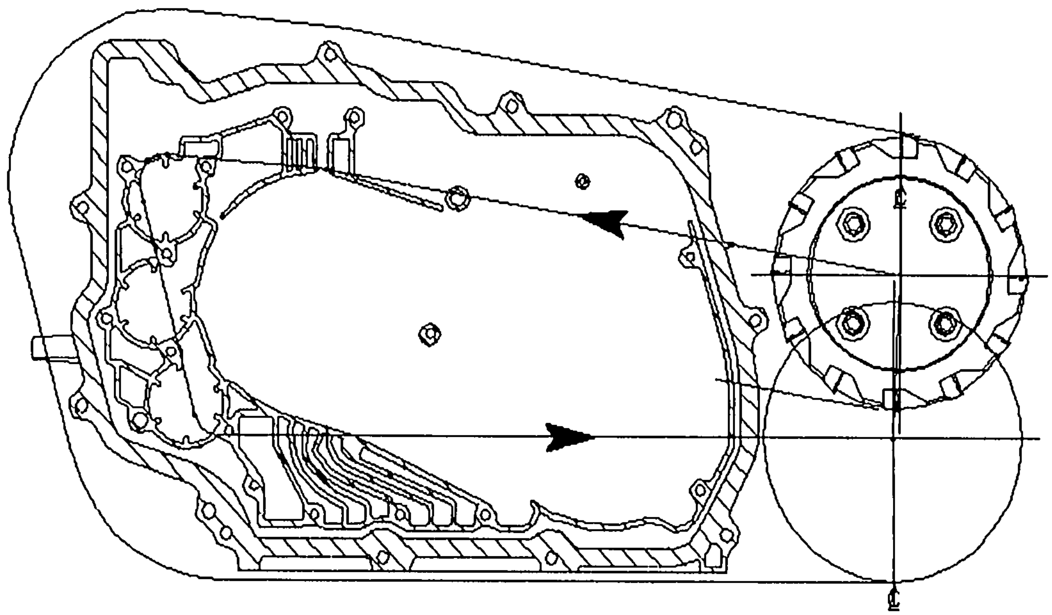
TEST #2 – Variable FEEDRATE - Current Station Program – LH Cutter 2987RPM, 3000/6000 mm/min
4480 RPM 3000/6000 mm/min

```
%
:0001
N20G90G01X217.0Y-32.35F6000 (PT1)
N30G17X-293.9202Y-32.35 (PT2)
N40G03X-312.3582Y-18.0897R70.95 (PT3)
N50G01X-351.5579Y132.8103 F3000(PT4)
N60G03X-333.1198Y156.6499R70.95 (PT5)
N80G01X-220.0264Y156.6499 (PT6)
N90G03X-212.8167Y156.0563R44.05 (PT7)
N100G01X221.5424Y83.9959 (PT8)
N110M17
N120F6000X217.0Y-32.35
N130M16
N140M02


:0002
N20G01G90F4000X217.0Y-32.35
N30M16
N500M02
%
```



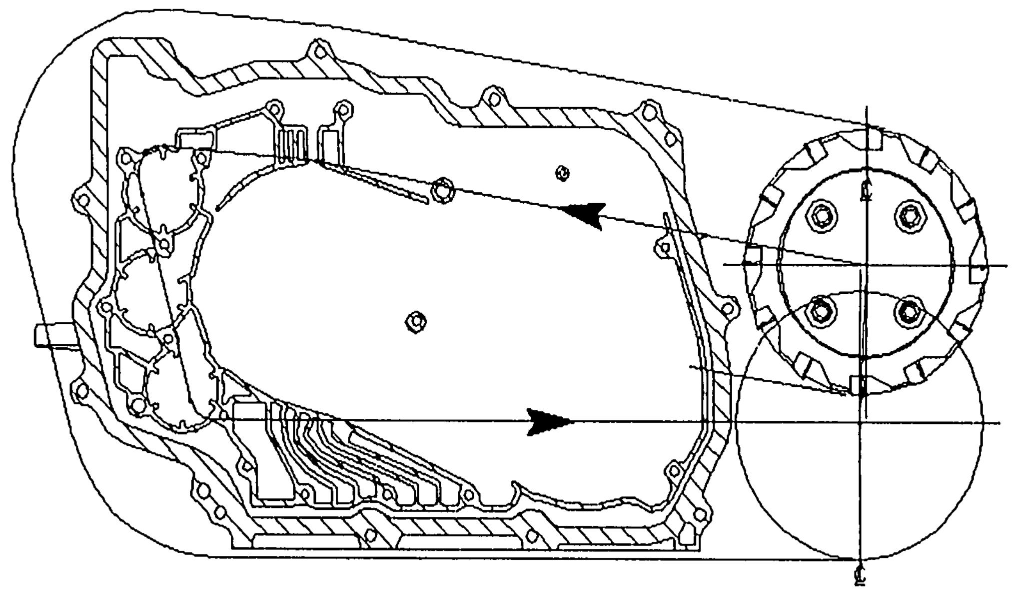
Test #3 - Original tool layout Sta 29LH Program – LH Cutter, 2987 RPM, 5428 mm/min
4480 RPM 5428 mm/min

```
%
:0001
N20G90G01X221.5424Y83.9959F5428
N30G17X-212.8167Y156.0563
N40G03X-220.0264Y156.6499R44.05
N50G01X-333.1198Y156.6499
N60G03X-351.5579Y132.8103R19.05
N80G01X-312.3582Y-18.0897
N90G03X-293.9202Y-32.35R19.05
N100G01X217
N110M17
N120F6000X221.5424Y83.9959
N130M16
N140M02


:0002
N20G01G90F4000X221.5424Y83.9959
N30M16
N500M02
%
```



Test #4 - ORIGINAL w/VARIABLE FEEDRATE Program - LH Cutter, 2987 RPM, 2714/5428 mm/min
4480 RPM 2714/5428 mm/min

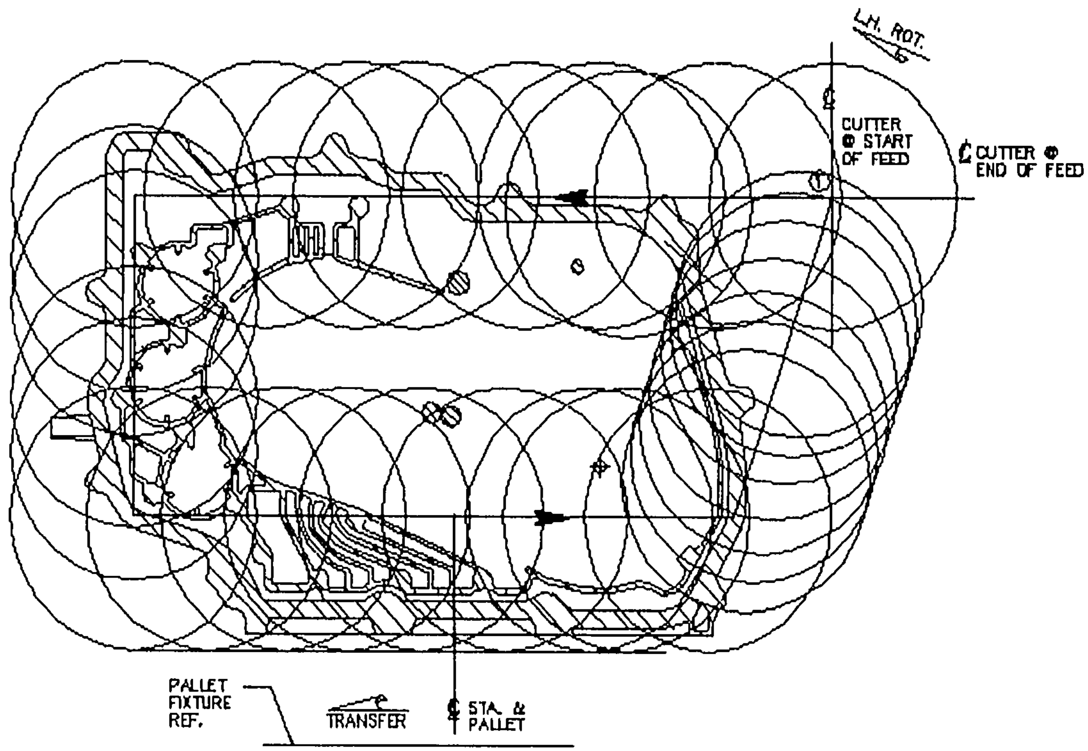
```
%
:0001
N20G90G01X221.5424Y83.9959F2714 (PT1)
N30G17X-212.8167Y156.0563 (PT2)
N40G03X-220.0264Y156.6499R44.05 (PT3)
N50G01X-333.1198Y156.6499(PT4)
N60G03X-351.5579Y132.8103R19.05(PT5)
N80G01X-312.3582Y-18.0897F5428(PT6)
N90G03X-293.9202Y-32.35R19.05 (PT7)
N100G01X217
N110M17
N120F6000X221.5424Y83.9959
N130M16
N140M02
```



```
:0002
N20G01G90F4000X221.5424Y83.9959
N30M16
N500M02
%
```

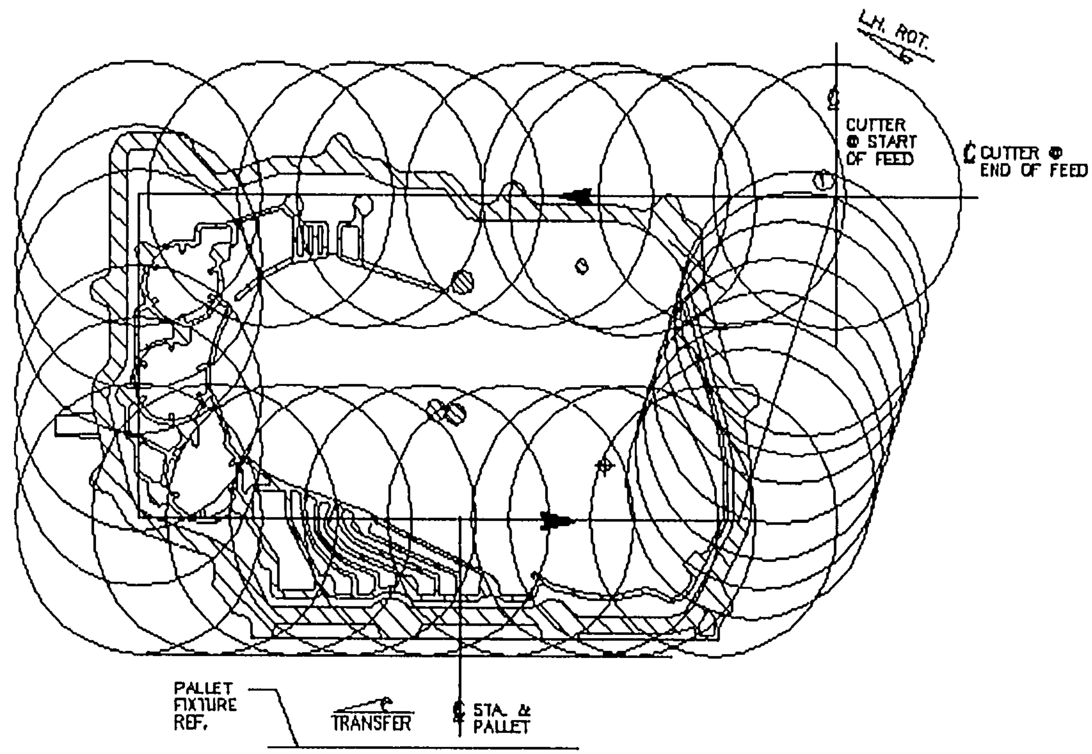
TEST #5 – Four Points, No Interpolation – LH Cutter, 2987RPM, 5428mm/min
4480 RPM 5428 mm/min

```
%
:0001
N20G90G01X182.9264Y199.8472F5428
N30G17X-351.00Y199.5162
N35G01X-351.00Y119.9F5428
N40X-351.00Y-32.35
N50X86.00Y-32.35
N60X182.9264Y199.8472
N80M17
N90M16
N100M02


:0002
N20G01G90F4000 X182.9264Y199.8472
N30M16
N500M02
%
```



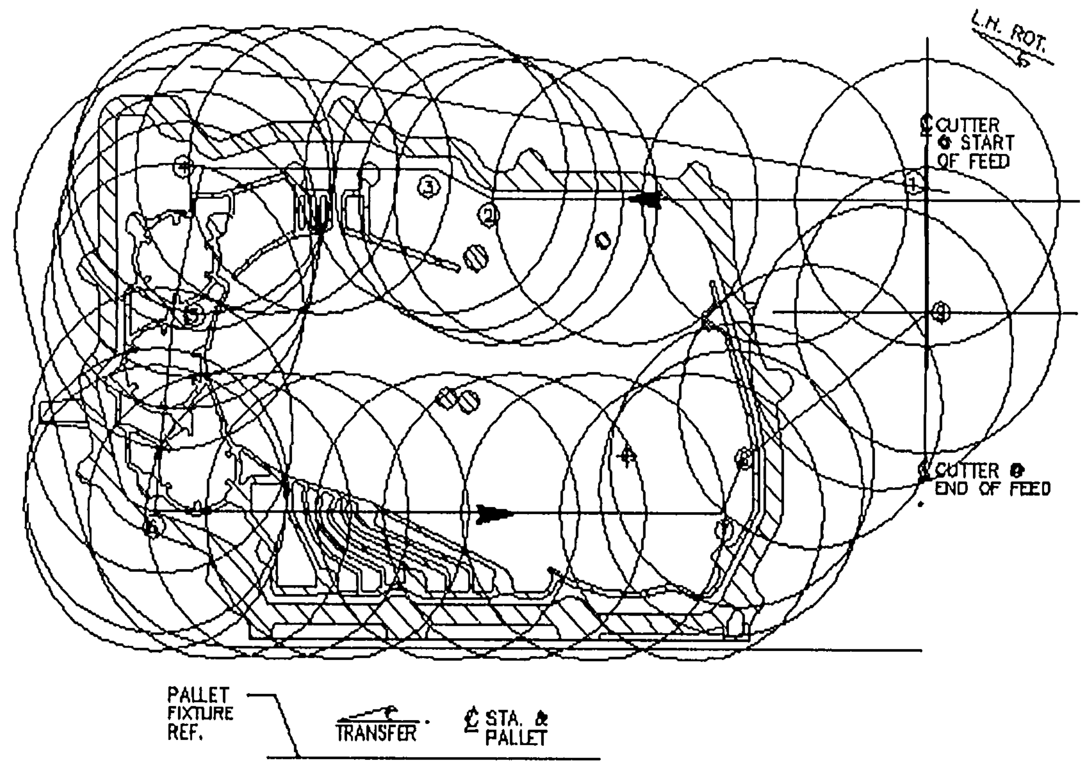
TEST #6 – Four Points, No Interpolation – LH Cutter, 2987RPM, 2714/5428mm/min
4480 RPM 2714/5428 mm/min

```
%
:0001
N20G90G01X182.9264Y199.8472F2714
N30G17X-351.00Y199.5162
N35G01X-351.00Y119.9F5428
N40X-351.00Y-32.35
N50X86.00Y-32.35
N60X182.9264Y199.8472
N80M17
N90M16
N100M02


:0002
N20G01G90F4000 X182.9264Y199.8472
N30M16
N500M02
%
```



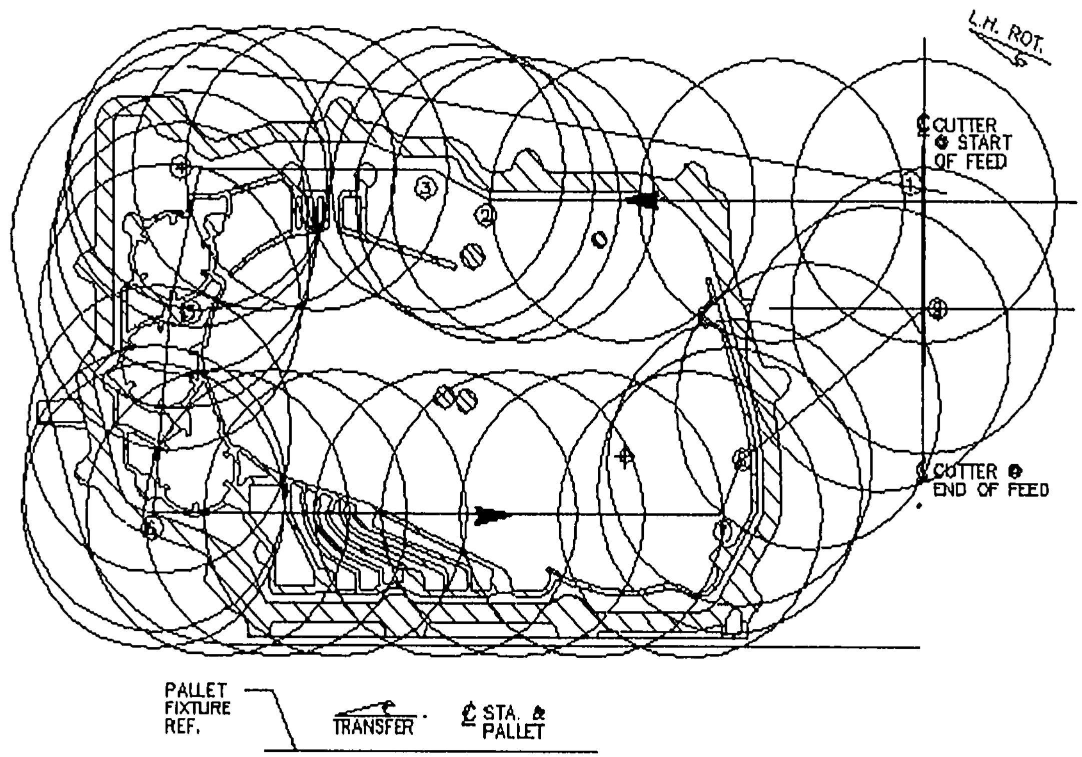
TEST #7 – TRACING CNC PATH – LH Cutter, 2987RPM, 5428 mm/min
4480 RPM   5428 mm/min

```
%
:0001
N20G90G01X221.5424Y175.075F5428
N30G17X-101.379Y175.075
N40X-141.506Y195.175
N50X-314.555Y195.515
N60X-337.127Y101.241
N70G01X-350.663Y-32.35F5428
N80X70.055Y-32.35
N90X85.464Y-2.7137
N100X220.893Y99.988
N110M17
N120F6000X221.5424Y175.075
N130M16
N140M02

:0002
N20G01G90F4000 X221.5424Y175.075
N30M16
N500M02
%
```



TEST #8 – TRACING CNC PATH – LH Cutter, 2987RPM, 2714/5428 mm/min
4480 RPM 2714/5428 mm/min

```
%
:0001
N20G90G01X221.5424Y175.075F2714
N30G17X-101.379Y175.075
N40X-141.506Y195.175
N50X-314.555Y195.515
N60X-337.127Y101.241
N70G01X-350.663Y-32.35F5428
N80X70.055Y-32.35
N90X85.464Y-2.7137
N100X220.893Y99.988
N110M17
N120F6000X221.5424Y175.075
N130M16
N140M02
```



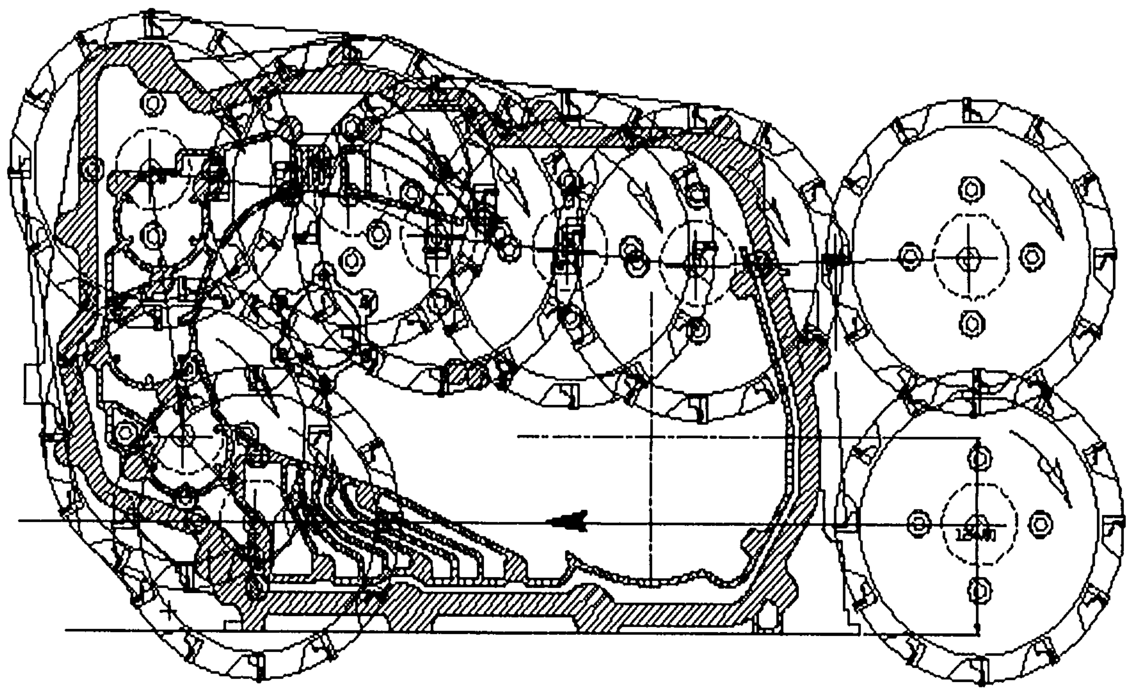

```
:0002
N20G01G90F4000 X221.5424Y175.075
N30M16
N500M02
%
```

Table B-2 Study #2 Procedure

Sprocket face Study #2

1.0mm Depth of Cut	Place Station 3RH - Sprocket Face First Pass Roughing station in "**BY-PASS**" mode Load special parts with 1.0 mm of finish stock remaining. Machine 9 parts through entire machine. Program T7-90 currently being used in production. Record life of cutter.
0.75 mm Depth of Cut	Load special parts with 0.75 mm of finish stock remaining. Machine 9 parts through entire machine. Program T7-90 currently being used in production.
Right Hand Cutter T9-90	Remove cutter and replace with a right hand cutter Switch the Wires on the motor in order for the spindle to rotate in the opposite direction Load **TEST #9 (Right hand CNC Path)** and machine 5 pieces @ **90 Hz**
T9-60	Change Variable frequency controller **to 60Hz** and machine 5 pieces
	Remove the cutter, return the wires to original, reinstall the LH cutter, turn variable frequency controller back to 90Hz and replace the T7-90 CNC program

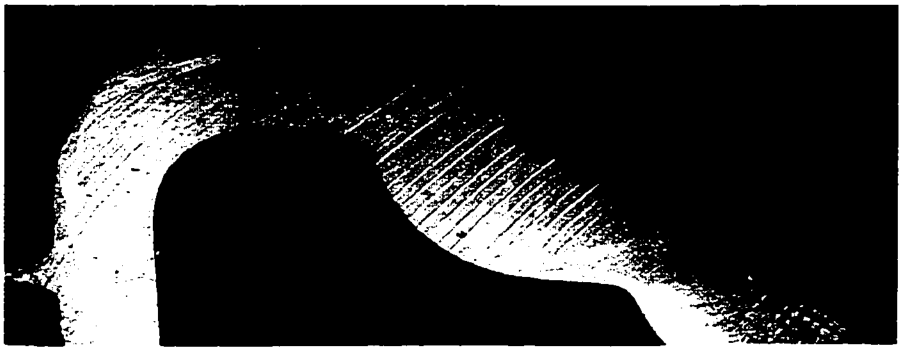
TEST #9 – TRACING CNC PATH – RH Cutter, 2987RPM, 5428 mm/min
4480 RPM   5428 mm/min



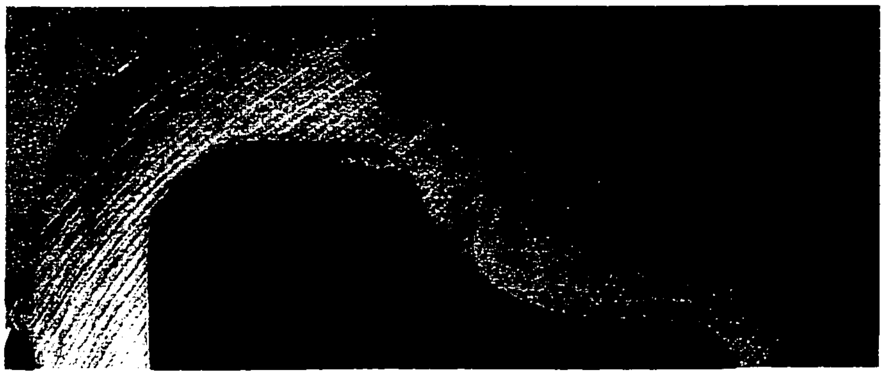
```
%
:0001
N20G90G01X223.286Y-32.35F5428
N30G17X-271.058Y-32.35
N40X-320.120Y-1.455
N50X-342.120Y164.338
N60X-206.216Y149.853
N70X-146.249Y124.393
N80X-56.580Y-115.92
N90X30.665Y105.447
N100X217.2735Y112.2886
N110M17
N120F6000X223.286Y-32.35
N130M16
N140M02


:0002
N20G01G90F4000 X223.286Y-32.35
N30M16
N500M02
%
```

APPENDIX C

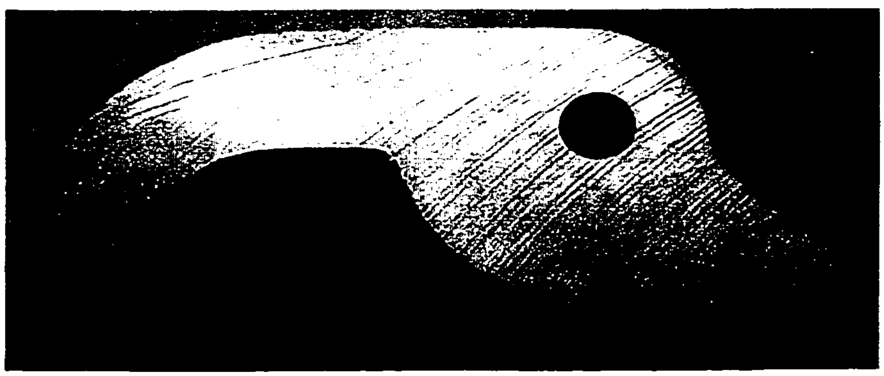
Photo Images of Area 2 Test Parts



Test #1 – T1-60 Hz - Baseline Current Program



Test #1 - T1-90 Hz



Test #2 – T2-60 Hz

Test #2 – T2-90 Hz

Figure C-1 Area 2 Images from Test #1 and Test #2

Test #3 – T3-60 Hz

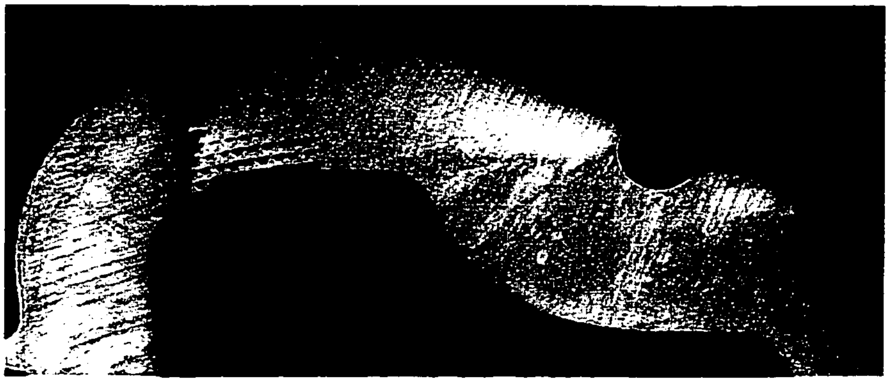
Test #3 – T3-90 Hz

Test #4 – T4-60 Hz

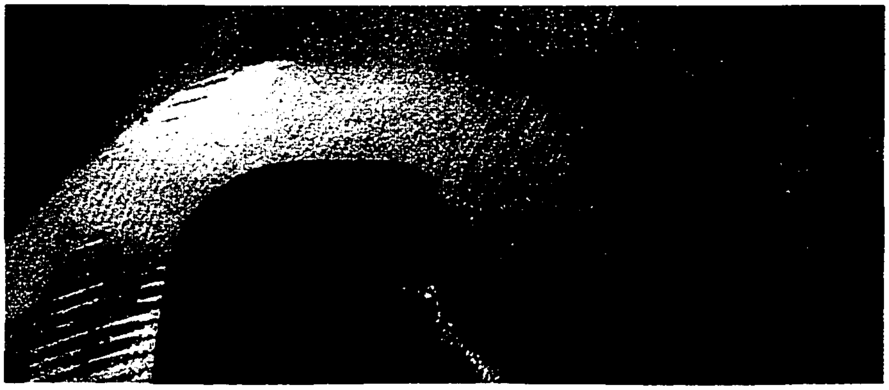
Test #4 – T4-90 Hz

Figure C-2 Area 2 Images from Test #3 and Test #4

Test #5 – T5-60 Hz



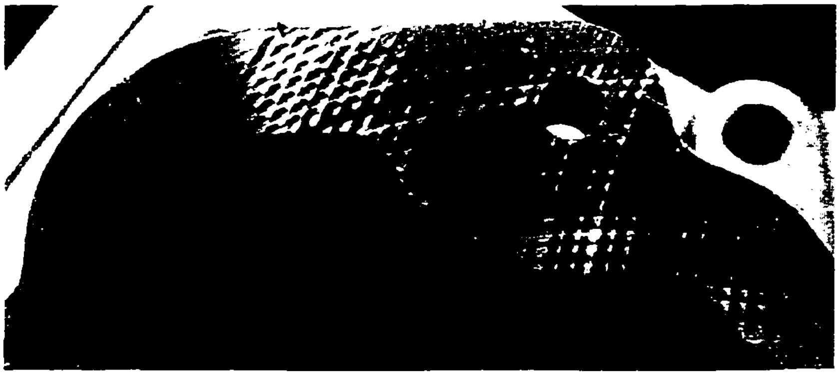
Test #5 – T5-90 Hz



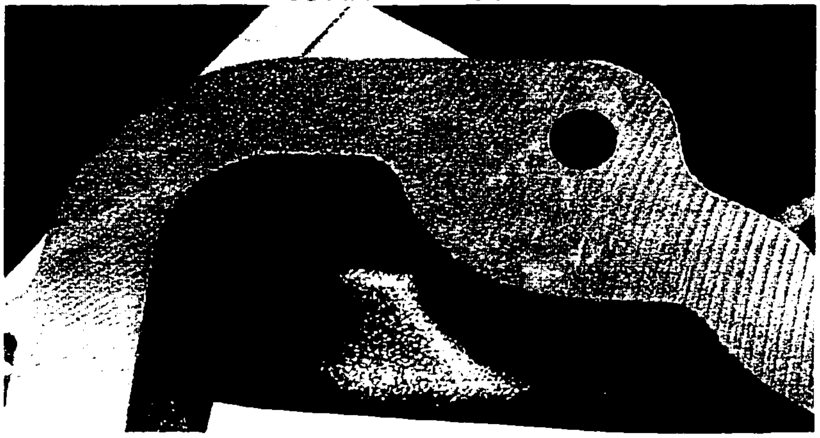
Test #6 – T6-60 Hz

Test #6 – T6-90 Hz

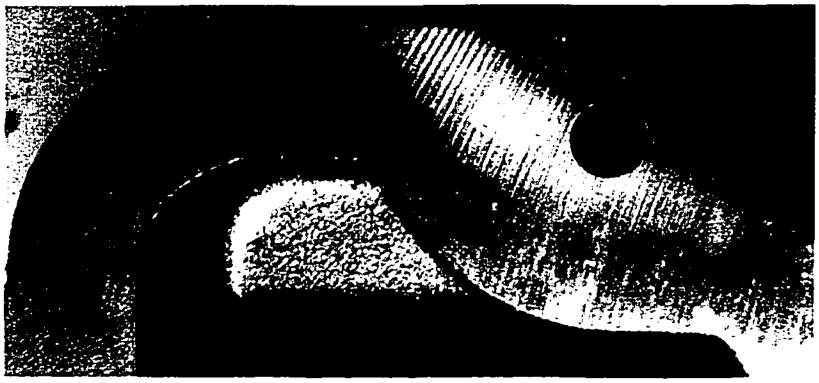
Figure C-3 Area 2 Images from Test #5 and Test #6



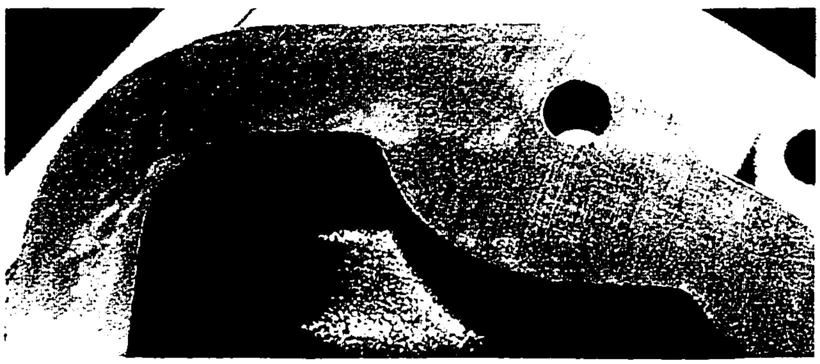
Test #7 – T7-60 Hz



Test #7 – T7-90 Hz



Test #8 – T8-60 Hz



Test #8 – T8-90 Hz

Figure C-4 Area 2 Images from Test #7and Test #8

APPENDIX D

Material Properties of A380 Aluminum

Table D-1 Material Properties of A380 Aluminum

(Source: Die Casting Alloy Specifications, Precision Diecastings, Monroe City, MO [x])

Aluminum A380

Tensile Strength	47,000	psi
Yield Strength	24,000	psi (0.2% offset)
Elongation	3.5	% in 2 in.
Impact Strength, Charpy	3	Ft. lbs.
Brinell Hardness	80-85	(500 kg)
Shear Strength	27,000	psi
Compressive Yield Strength	25,000	psi
Ultimate Comp. Strength	NA	psi
Fatigue Strength	20,000	psi
Specific Gravity	2.71	
Weight per CU. In.	0.098	lbs
Melting point (liquid)	1100	° F
Thermal Expansion	11.5	μin. /in. -°F

composition -per cent	
aluminum	remainder
cadmium	-
copper	3.0-4.0
iron	1.3
lead	-
silicon	7.5-9.5
tin	0.35
maganiese	0.50
magnesium	0.10
nickel	0.50
zinc	3.0
titanium	-
total others	-
total	0.50

APPENDIX E

Instrument Specification Sheet

Table E-1 Instruments Used In Data Collection

Piezoelectric Element Accelerometer

Manufacturer: PCB Piezotronics, Inc.
3425 Walden Avenue
Depew, NY 14043-2495 USA

Model:	#9690
Nominal Sensitivity:	5.17 mV/g (ms^2=0.102g).
Accuracy Range:	1 to 7000Hz (±5 %)

Force Impact Hammer

Manufacturer: PCB Piezotronics, Inc.
3425 Walden Avenue
Depew, NY 14043-2495 USA

Model:	086C03
Frequency Range:	8kHz
Nominal sensitivity:	2.25 mV/N.
Hammer Weight:	1.3N
Handle Length:	203 mm
Accuracy Range:	10mV/lbf

Zonic Data Collector

Manufacturer: Zonic Corporation
50 West TechniCenter Dr.
Milford, Ohio, 45150-9777 USA,

Model:	AD-3542 FFT Analyzer – 2 channel.
Amplitude Characteristics:	Less than ±0.1db (typ.)

Taylor Hobson Model Surtronic 3+ profilometer

Manufacturer: Taylor Hobson Inc.
2100 Golf Road, Suite 350
Rolling Meadows, Illinois 60008-5231, USA,

Model:	Surtronic 3+
Gauge Range:	±150 mm
Accuracy:	2% of reading
Resolution:	1 mm

APPENDIX F

Test data

Table F-1 Test data

AVERAGE	FLAT (mm)	PAR (mm)	AREA1	AREA 2	AREA 3	AREA 4
T1-C	0.114	0.139	1.190	1.950	0.570	0.550
T1-90	0.142	0.186	0.820	0.650	0.690	0.720
T2-90	0.136	0.176	0.690	0.700	0.590	0.780
T2-60	0.126	0.152	1.150	0.860	0.690	0.910
T3-60	0.126	0.174	0.890	1.200	0.680	0.730
T3-90	0.129	0.157	0.820	0.400	0.650	0.890
T4-90	0.126	0.155	0.820	0.460	0.760	1.080
T4-60	0.131	0.181	1.030	0.620	0.660	0.720
T5-60	0.118	0.174	1.080	1.470	0.680	0.730
T5-90	0.119	0.162	0.900	0.740	0.640	0.810
T6-90	0.095	0.125	0.840	0.650	0.640	0.850
T6-60	0.168	0.212	1.244	0.980	0.720	0.710
T7-60	0.105	0.134	1.200	1.430	0.630	0.670
T7-90	0.112	0.139	0.850	0.710	0.650	0.770
T8-90	0.122	0.157	0.810	0.670	0.680	0.730
T8-60	0.111	0.153	1.510	1.080	0.640	0.710
1.0 MM	0.107	0.158	1.53	0.85	0.60	0.50
0.75MM	0.115	0.182	1.34	0.76	0.57	0.49
REV-90	0.126	0.206	0.59	0.93	0.63	0.50
REV-60	0.123	0.196	0.83	0.75	0.84	0.72

(Area 1 through 4 in units μm)

VITA AUCTORIS

1966	Born in Canada
1989	Graduated Bachelor of Applied Science in Engineering in Mechanical Engineering from the University of Windsor, Windsor Ontario
1990	Accredited with the Association of Professional Engineers of Ontario
1989-1996	Process Engineer with General Motors Windsor Transmission, Windsor, Ontario
1996-2000	Senior Manufacturing Engineer with General Motors Windsor Transmission, Windsor, Ontario
2000	Senior Manufacturing Project Engineer with General Motors, Central Manufacturing Engineering, Ypsilanti, Michigan
2001	Currently a candidate for the degree of Master of Applied Science in Mechanical Engineering at the University of Windsor, Windsor, Ontario