A STATISTICAL INVESTIGATION OF
SOME MACHINING VARIABLES

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PREFACE

This dissertation is concerned with the general area of machinability. More specifically, it deals with the cutting variables which effect surface roughness and power requirements. This problem has been of concern for many years and it is hopeful that the technique applied here will be of some benefit in the general area.

The statistical technique of analysis of variance has been used in an effort to determine which of the chosen variables, singly or when combined with others, have significant effects on the dependent variables.

I am greatly indebted to several persons for their assistance in this dissertation effort. Professor Wilson J. Bentley has offered valuable counsel during this work. Dr. James E. Shamblin has been most helpful in the direction of this research work. Dr. J. Leroy Folks was most helpful with the statistical design and analysis of my research. I wish to express my appreciation to Dr. Earl J. Ferguson and Dr. Clark A. Dunn for their encouragement and help during the research.

I am indebted to the National Science Foundation for the Fellowship which made the past year of schooling possible.

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CHAPTER I

INTRODUCTION

The most acceptable definition of machinability is the response of a metal to machining. Good machinability indicates satisfactory tool life, good machine surface quality, low power requirement, well 'broken up' chips and consistent dimensional accuracy, either collectively or singularly, depending upon which of these objectives is the one most desired.

Shaw (1) describes the operational characteristics of a cutting tool by a simple word - machinability. The three main aspects of machinability are:

1. Tool life.
2. Surface finish.
3. Power required to cut.

With the growth of research in metal cutting, many studies have been conducted concerning the effects of various tool shapes on cutting, the relationship between cutting speed on tool life, tool forces when cutting various metals, cutting fluids, tool feed, depth of cut, etc. There is no single conclusive manner of determining the machinability rating of materials cut, cutting tools, or cutting fluids. One type of work material may give the best tool life, but another may provide better surface quality and a third the best 'broken up' chips.

Many times one or more objectives may be sacrificed; i.e., minimum cost, metal removed, etc., in order to obtain others. These objectives are not necessarily compatible so that each machining job must be considered and evaluated in accordance with its own particular set of circumstances.

According to Boston (2), surface qualities, by definition, are the physical characteristics of a boundary which separates solid substances. These qualities include such factors as the geometry of the surface in three dimensions, crystal structure, appearance, color, resistance to corrosion, hardness, and size and shape of surface flaws. Standards of surface quality now deal particularly with the geometry of the surface deviations from the nominal surface (cylinder, flat, sphere, etc.). These deviations are of three kinds:

1. Surface flaws.
2. Waviness.
3. Roughness.

All three of these can be specified in inches. Surface flaws are occasional irregularities, such as a scratch or slag inclusion or blow hole; waviness consists of widely spaced irregularities within the waves, which determine what is usually called the 'finish' of the piece.

In the past, industry has not been too concerned about surface finish except for polishing, lapping, and superfinishing. Surface finish has now become a very important variable to consider due to the increased cost of machining operations and the more common use of surface finish as a manufacturing specification. Excessive finish quality cannot be shrugged off on the assumption that it does not cost anything. As reported by Miller (3), one automotive manufacturer that studied the problem estimated each microinch of overfinish increased part costs by an average of one per cent.

Machining processes have a statistical, probabilistic character and their particular feature is a wide range of various external and internal factors affecting the work of the cutting tools. It is necessary, therefore, to establish the relationship connecting the tool life, surface finish, and power with the various factors.

In order to solve definite problems of improving a particular cutting tool or a complete machining operation, it is necessary to know the relationships of the actual process in actual working conditions; i.e., relationships with a statistical and not a functional character. When there are a large number of connections which in some instances cannot be separated, only the total result of the action of many factors can be seen in individual cases. Only one of several factors are of particular interest, while the remainder are side effects obscuring the final result of the investigation.

The disadvantages of the existing laboratory methods of investigating cutting tools are aggravated by the fact that mathematical statistics are not used at all in the analysis and evaluation of the experimental data. The mathematical-statistical method should be used for the evaluation of the data of the actual processes together with the laboratory methods of investigation. If a relationship has a statistical character, then it is not sufficient to establish only the type of connection between the function and the parameters. It is also necessary to insure that a change in the value of the function is connected with a change of the given parameter, and is not due to the influence of other known or unknown factors; in other words, it is necessary to determine the so-called density of the relationship. This can be done only on the basis of mathematical statistics as described by Katsev and Sis'kov (4).

In the past, experiments have been performed by changing one variable at a time over a range of values deemed to be critical for the various metals involved. But to date, very little quantified or qualified data has been presented concerning the interdependent actions of various metal cutting variables such as cutting speed, depth of cut, feed, etc., and their interacting effect on first cut surface finish and power requirements.

The primary objective of this investigation is to determine, by physical experimentation and subsequent statistical analysis, the interdependence of various machining variables and their interacting effect on first cut surface roughness and power requirements. It should also give an indication of which of these dependent variables should be used as a criteria for further investigations of this type if the analysis proves to be of real value in metal cutting.

CHAPTER II

REVIEW OF THE LITERATURE

In 1906 at a New York meeting of the American Society of Mechanical Engineers, F. W. Taylor (5) stated that twenty-six years ago he started an investigation to answer the questions:

1. What tool shall I use?
2. What cutting speed shall I use?
3. What feed shall I use?

He reported at the meeting that the true answer had not been found, but it was still his main objective. During the last sixty years many improvements have been made in the field of metal cutting, but the same questions that faced Taylor remain today. Through the years, there have been some trial and error methods and some in conjunction with experience in an effort to indicate an answer to the questions that puzzled Taylor. Recently, with the advent of new materials and demands on materials, surface finish has become an important measuring criteria to be used in this area of machinability.

Surface qualities, by definition, are the physical characteristics of a boundary which separates solid substances. These qualities include such factors as the geometry of the surface in three dimensions, crystal structure, appearance, color, resistance to corrosion, hardness, and size and shape of surface flaws. Standards of surface quality now deal particularly with the geometry of the surface deviations from the nominal surface (cylinder, flat, sphere, etc.). These deviations are of three kinds: surface flaws, waviness, and roughness, all three of which can be specified in inches. Surface flaws are occasional irregularities, such as a scratch or slag inclusion or blow holes; waviness consists of widely spaced irregularities, such as wide feed marks; and roughness consists of finely spaced irregularities with the waves, which determine what is usually called the 'finish' of the piece (2).

The lay of a surface refers to the direction of the predominant surface marks representing the surface as observed visually. A sketch indicating flaws, waviness, roughness, and lay of surface quality is shown in Figure 1.

The ideal state of a machined surface, as shown in Figure 2, resembles the profile of the tool being used. This profile is rarely ever obtained. The factors causing the deviation from the ideal are:

1. Type of chip formation - discontinuous, continuous, and continuous with a built-up edge.
2. Built-up edge - that portion of a chip which is welded to the face of a cutting tool during the machining operation.
3. Chip-tool interface friction - results in tool wear and subsequent tool failure.

In order to eliminate these deviations and produce a smooth surface, a multi-step procedure is need. Initially, a rough cut followed by finish cutting is required to bring the workpiece down to the desired dimensions. These operations are followed by grinding and some type of superfinishing process depending upon the degree of finish desired.

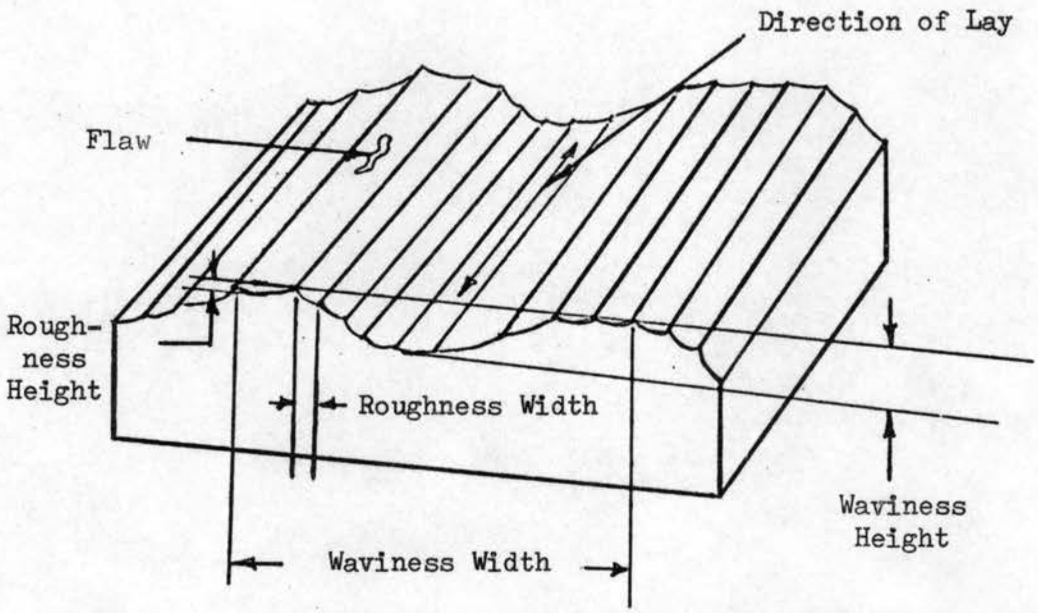

Figure 1. A Sketch of a Magnified Surface Indicating Flaws, Waviness, Roughness, and Lay of Surface Quality

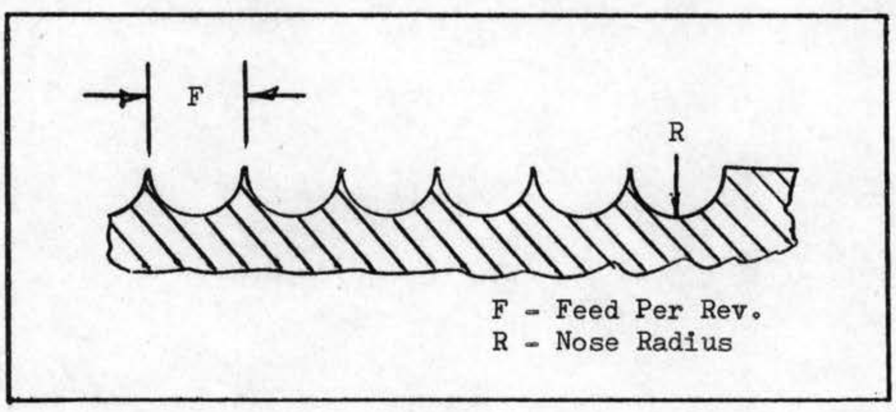

Figure 2. Ideal State of a Machined Surface

Miller (3), commenting on the importance of surface finish as a manufacturing specification for machined parts, stated:

> Close control over surface quality has traditionally been associated with close dimensional tolerances -- on parts that are ground, honed or lapped to size. Finish and size do, of course, go hand in hand in precision applications.
>
> But even when dimensional tolerances aren't particularly tight, there are also good economic reasons for monitoring surface finish. Many shops that must work to specifications on finish have no way of checking finish in production. Their only means of control is to specify feeds, speeds, and/or abrasions that will produce a microinch finish well below the desired value -- in short, overfinish to be on the safe side.
>
> Excessive finish quality can't be shrugged off on the assumption that it doesn't cost anything. One automotive manufacturer that studied the problem estimated that each microinch of overfinish increased part costs by an average of 1%.

Brown (6) has developed a mathematical model for predicting surface finishes based only on the tool radius and the feed of the machine. This again assumes the ideal profile is going to be produced, but experience indicates that this is generally not the case.

It would, therefore, appear that a good machined surface is a necessary essential of the finished product. The fewer the number of operations required to attain the desired surface quality, the less expensive the over-all operation.

Earlier experiments have been performed by Taylor and others that indicate a best combination of variables for a particular cutting operation. For example, it is known that cutting speed has a very definite and predictable effect on surface finish. As stated by Boston (2):

> As the speed is increased, the built-up edge is reduced in size, and a speed is reached, called the optimum speed, at which the built-up edge recedes from the cutting edge and the cutting edge actually produces the machined surface. The surface is not changed further for the higher speeds.

Experiments have been conducted by changing one variable at a time over a range of values deemed to be critical for the various metals involved. The experimenters have been primarily interested in establishing a functional relationship by varying one factor or variable over a range of values and holding all other variables constant (7).

In most machining operations, forces and power consumption are secondary to tool life in their effect on the economics of metal removal. However, in certain cases they may become very important. When discussing machinability with production line people generally power is used as a measuring criteria because the operator understands what is involved when he can see a power reading on a meter.

Four methods are generally used in specifying the power consumed in machining as follows:

1. The gross power, or power to the machine, is the power actually developed by the motor (supplied to the machine tool) when the machine is cutting. It can be measured by use of a wattmeter in the line supplying the motor, in the case of machine tools powered by individual electric motors (neglecting electrical losses in the motor).
2. The net power, or power at the tool, is the power actually supplied to the cutting tool and consumed in removing the metal in a machining operation.
3. The specific power consumption is the amount of power (net) required to remove a unit volume of metal in unit time.
4. The metal removal factor is the volume of metal removed per unit of power (net) in a unit of time.

Only the first of the four general methods for specifying power consumed can be measured directly by a wattmeter and, therefore, is the most widely used and accepted by people dealing with machinability as a production factor.

In the past, power requirements have been considered roughly proportional to the cutting speed, since the rate at which metal is removed is proportional to that speed. With the advent of newer materials, machines and cutting tools, this generalized statement can no longer be substantiated.

As stated in Chapter I, it is believed that machining processes have a statistical, probabilistic character. For instance, it is well known that two different draws of the same metal from the same heat can have different metallurgical properties, such as tensile strength, yield strength, etc. Although certain beneficial relationships can be obtained without the use of statistical techniques, it is clear that certain other valuable results can be obtained by using statistical techniques to analyze qualitative data.

To date, little quantitative or qualitative data have been presented concerning the interdependent actions of various metal cutting variables, such as cutting speed, depth of cut, feed, etc., and their interacting effect on first cut surface finish and power requirements.

A search of the available literature revealed only a few instances of industrial process type experiments conducted under laboratory conditions and subsequent statistical evaluations of the experimental data. Katsev and Sis'kov (4) used correlation analysis to establish the relationship between the life of a tool and the various design, geometrical, physical and mechanical factors associated with the tool. The study consisted of randomly selecting a number of tools (drills, taps, button dies) in a factory. The authors' conclusions were as follows:

1. Using mathematical statistics as a method of analyzing experimental data and as a method of investigation increases the possibility of studying cutting tools and processes.

2. Correlation analysis makes it possible to investigate cutting tools and metal cutting processes in the actual industrial conditions, and to establish relationships taking into account the actual variations of factors in relation to each variable (equations of pair correlation) and also in relation to a number of variables (equations of multiple correlation).

3. The application of mathematical statistics in the investigations makes it possible to establish quantitatively the influence of unknown or neglected factors on the process.

4. Further development of the method of application of mathematical statistics to the investigation of metal cutting is necessary.

J. Taylor (9) used analysis of variance to evaluate the tool wear phase of machinability. Regarding the use of a statistical technique for data analysis he stated:

> The addition of deliberated variations relating to tool geometry, cutting fluid and tool material, makes it essential that tool wear experiments must be carefully designed and the results critically analyzed in accordance with correct statistical procedures.

Lucas (10) used the analysis of variance technique to analyze the data obtained from an investigation of chemical milling. The analysis of the study indicated that some of the interactions were statistically significant, further demonstrating the usefulness of mathematical statistics in metal processing problems.

Kirk (11) used the analysis of variance technique to study interacting effects of machining variables. The results of the study indicated that further investigation should be made with the analysis of variance technique to determine its practicality as a research tool in metal cutting.

Green and Tukey (12) made the statement about analysis of variance as follows:

> Throughout the discussion we shall emphasize what may be considered the major purposes of the analysis of variance: to provide a simple summary of the variation in the experimental data, and to indicate the stability of means and other meaningful quantities extracted from the data (and thus to make more precise our understanding of how much has been learned from the experiment). Many investigators believe that the sole purpose of the analysis of variance is to provide statistical tests of significance and some seem to equate these to tests of meaningfulness. We hope to counteract such views by showing how the analysis of variance can be used to summarize the data effectively and to help in understanding what "goes on" in the experimental situation. While we shall rely on the conventional F test to give some guidance, the primary function of the analysis of variance is to help the investigator understand his data. As such, it may need to be used more than once on the same data. As such, it deserves guidance from graphs and other devices for seeking understanding. It should not be an end in itself.
>
> The use of the technique, related graphs and study of the interacting effects of the experimental variables provides the experimenter with a valuable tool to assist in understanding the relationship between the variables involved in the industrial process. In consonance with the above discussion, it is believed necessary to study the combined or interacting effects of all variables in order to appreciate fully the experimental data and enhance the understanding of what actually transpires during an industrial process.

As a result of reviewing the available literature, it is believed that this investigation will be useful in determining the usefulness of the technique in the area of metal cutting.

A description of the experimental design and procedure is presented in Chapter III. Chapter IV consists of the analysis of the results of the data. Chapter V is devoted to the Summary and Conclusions.

CHAPTER III

METHODS AND PROCEDURES

The discussion of the methods and procedures will be divided into five sections. The first section will provide a description of the physical equipment, second section describes the material, third section is a description of the experimental procedure, fourth section explains and shows the experimental design used, and the fifth section explains the data processing.

Physical Equipment

The equipment utilized and the use made of the equipment is shown in Table I. Below and following Table I is a detailed description of each piece of equipment.

A 36-inch Do All band saw was used to cut the material, which came in 20 foot lengths, into pieces approximately eight inches in length. The eight inch piece was desirable because eight, three-fourths inch cuts were to be made on each piece leaving two inches in the center of the piece to hold the material in the collet for the final cut.

A model HLV-H Hardinge High Speed Precision Tool Room Lathe fully equipped, including a Jacobs Spindle Nose Lathe Chuck and a complete set of Jacobs Rubber Flex Collets, was used in the study. The lathe had an independent power feed which was calibrated to provide the desired feed in inches per revolution. This calibration was accomplished by using a standard stop watch and the carriage handwheel scale provided to determine longitudinal movement. The lathe was also equipped with a variable spindle drive up to 3000 RPM. The speed was controlled with a tachometer.

TABLE I

EQUIPMENT AND USE

Equipment	Use
Band saw	Cut material to length
Lathe	Cutting operation
Lathe collet	Hold test specimen for cutting operation
Cutting tools	Cutting operation
Tachometer	Setting spindle speed
Wattmeter	Recording power
Tool grinder	Maintain tool geometry
Profilometer	Measurement of surface finish

The cutting tools were ground from three-eights inch square Rex 95 tool steel. This tool steel is manufactured by the Crucible Steel Company of America. The chemical composition of the tool steel was as follows: Carbon - 0.80%; Tungsten - 14.00%; Vanadium - 2.00%; Molybdenum - 0.75%; Chromium - 4.00%; and Cobalt - 5.25%.

A Meylan model 3200 Tachometer was used to set the spindle speed of the lathe.

A model 164A Rustrak recording wattmeter was wired into the system just in front of the lathe to record the entire power used in the cutting operation.

A Delta-Milwaukee Toolmaker Grinder was used to keep the tools sharp and to maintain all parts of the tool geometry except nose radius, within ± 1° of the desired configuration. The nose radius was maintained within the limits by hand sharpening by the operator.

The Profilometer used was made by the Micrometrical Division of the Bendix Corporation and consisted of a type QB Amplimeter, a type VB Mototrace, and a type LK Tracer.

Material

The material used was SAE 1018 cold drawn carbon steel. This material was selected primarily because of its wide use in industry. The chemical composition of the material was as follows: Carbon - 0.15% - 0.20%; Manganese - 0.60% - 0.90%; Phosphorous - 0.04% maximum; and Sulphur - 0.05% maximum.

Experimental Procedure

The experimental procedure became routine after the first few cuts were made. The steps used in the procedure were as follows:

1. Cutting material to length.

2. Sharpening of the tool bits.

3. Placing a piece of material in the lathe.

4. Setting the speed and feed for the desired cutting.

5. Adjusting the correct tool bit for cutting and determining if the tool was sharp; if not sharpening as needed.

6. Starting the recording wattmeter.

7. Engage the longitudinal feed for the cutting.

8. Disengaging and retracting the cutting tool.

9. Stopping the spindle.

10. Stopping the wattmeter.

11. Recording the power consumed.

This procedure, which is described in detail in Appendix A, provides the first portion of the experimental procedure.

At the end of each day's cutting, the profilometer equipment was set up and the surface finish readings were taken for that day's cutting. The procedure used was as follows:

1. Place steel specimen in a vee block.

2. Place tracer stylus on specimen.

3. Observe amplimeter dial.

4. Record reading.

The chart reading on the recording wattmeter was checked as each roll of chart paper became full and the paper corresponding to each data sheet was stapled to the correct sheet.

A sample of the data sheet used to record the data is included in Appendix A along with a more detailed discussion of the experimental procedure used in this study.

Design of the Experiment

The literature review indicated that there were numerous variables that affect surface finish and power when using a lathe; therefore, the selection of the independent variables needed careful consideration. It was decided to select a few of the important variables and make every effort to hold all other variables constant, thereby nullifying their effects.

As previously stated, most authors consider speed to be the most important variable effecting power in this type of cutting operation.

The primary factors influencing surface finish are cutting speed, feed, and cutting tool geometry when turning metal on a lathe. From the Tool Engineers Handbook, the following statement is made concerning surface finish:

> Ordinarily, surface roughness improves with increased cutting speed. The change is rapid up to some critical speed because of a continuous reduction in size of the built-up edge.
>
> The size of the chip cross-sectional area (caused by feed and depth of cut) has a large effect on surface finish. With a large cut, the surface finish is poor; for a small cut, it is good.
>
> Tool design and form have a very marked effect on surface finish; a change in it is the means most often used to correct poor finish in practice. The general effect of the various quantities determining the tool form, stated in terms of single-point nomenclature, may be summarized for high speed tools as follows: An increase in the true rake angle improves the surface finish considerably; it reduces the size of the built-up edge. An increase in the side cutting edge angle will ordinarily improve the finish, but the degree of improvement is quite variable, depending on other variables. The reason for the improvement is that an increase in the side cutting edge angle decreases the actual chip thickness and thus the size of the built-up edge (8).

Figure 3 shows the nomenclature of a single pointed tool.

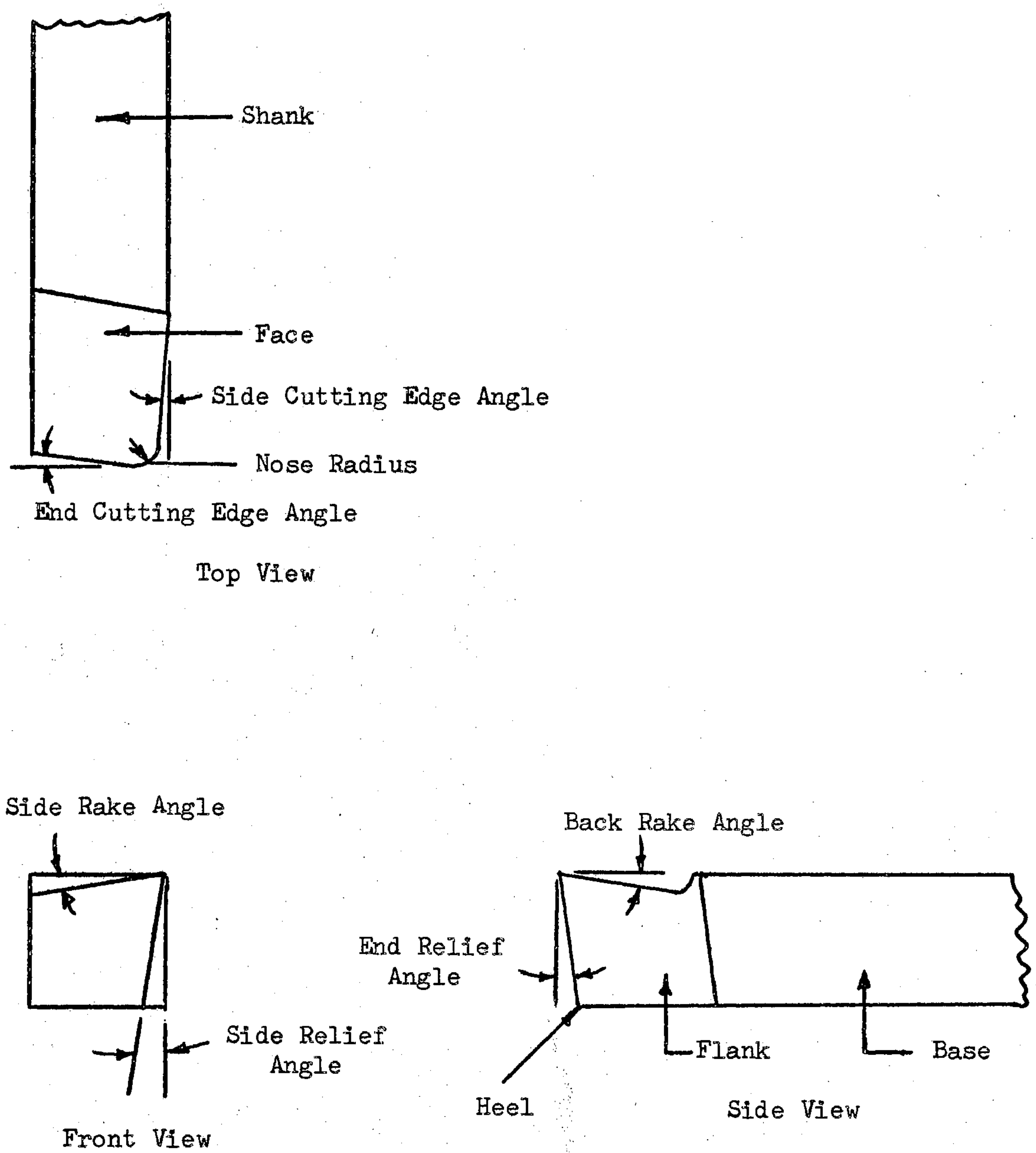

Figure 3. A Sketch Illustrating the Various Elements Associated With a Straight Shank, Right-Cut, Single-Point Tool

For economic reasons and in order to keep the study within reasonable size, such things as other materials, other types of tool material, and use of a cutting fluid were not considered in this study. Some incorporation of these variables will be discussed later in the thesis along with other suggestions about further research in this area.

A randomized factorial design was chosen as the design to be used in the study so that interactions between variables could be effectively studied. Regarding interactions, Cochran and Cox (13) stated:

> A factorial experiment may be suitable in investigations of the interaction among the effects of several factors. From their nature, interactions cannot be studied without testing some of the combinations formed from the different factors. Frequently, information is best obtained by testing all combinations.

Anderson and Bancroft (14) commented:

> The interaction is the important effect about which the factorial design can give information. Many experimenters still examine the performance of one set of treatments such as different fertilizers, for one standard variety and then different varieties for a standard fertilizer. Such an experiment tells little about the optimum fertilizer - variety combination which should be used, if the fertilizers do not respond in a similar manner for all varieties. Or if an engineer wants to know something about the relationship between the temperature of a process and the length of time the process is carried on, he needs to try out various combinations of the two variables - temperature and time. Similarly an animal feeder may want to know the optimum level of supplemental feeding and type of pasture or the optimum combination of concentrates and roughage in the ration. And the human nutritionist needs to know the best combination of various parts of the diet for healthy living. All of these experiments require some knowledge of how different amounts or kinds of one treatment interact with different amounts or kinds of another treatment. If the results are purely additive, that is, one treatment acts independently of the other treatment, the experiment can be divided into two simple experiments on the two treatments. However, the experimenter seldom is sure that there is no interaction and often is afraid that there will be some interaction, especially if the individual representatives of each treatment are widely different.

Hicks (15) makes the following observation about factorial experiments:

> Some of the advantages of factorial experiments are as follows:
>
> 1. They are more efficient than one factor at a time experiments.
> 2. All data are used in computing effects.
> 3. Some information is gleaned on possible interaction between factors.
>
> The advantages are even more pronounced as the number of levels of the factors are increased.

Seven factors, or independent variables, were selected for the factorial design. The dependent variables were first cut surface finish and power requirement. The factors and the level for each factor were as follows:

1. Depth of cut (inch) - the distance between the bottom of the cut and the uncut surface of the work, measured in a direction at right angles to the machined surface.
   (a) .0156 ± .0001 (1/64")
   (b) .0312 ± .0001 (1/32")
   (c) .0625 ± .0001 (1/16")
2. Tool feed (inch per revolution) - the relative amount of motion of the tool into the work for each revolution.
   (a) .002
   (b) .004
   (c) .006
3. Back-rake angle (degrees) - the angle between the face of a tool and a line parallel to the base of the shank or

holder measured in a plane parallel to the centerline of the point and at right angles to the base. The angle is positive if the face slopes downward from the point toward the shank and negative if the face slopes upward from the point toward the shank.

(a) zero back rake (0° ± 1 degree)

(b) positive back rake (+5° ± 1 degree)

(c) negative back rake (-5° ± 1 degree)

4. Side cutting edge angle (degrees) - the angle between the straight side cutting edge and the side of the tool shank.

(a) 15° ± 1 degree

(b) 30° ± 1 degree

(c) 45° ± 1 degree

5. Cutting speed fpm - the peripheral or surface speed of the work with respect to the tool.

(a) 80 (308 RPM)

(b) 160 (610 RPM)

(c) 240 (912 RPM)

(d) 320 (1212 RPM)

6. Trials - each combination of the treatment variables was accomplished twice for each replication.

7. Replications - the treatments were repeated twice; i.e., two different lots of SAE 1018 cold drawn carbon steel.

The remaining parts of the tool geometry were kept constant according to the following table:

1. Side-rake angle - 14 ± 1 degree

2. End-relief angle - 6 ± 1 degree

3. Side-relief angle - 6 ± 1 degree

4. End-cutting-edge angle - 8 ± 1 degree

5. Nose radius - 3/64 ± 1/64 inch.

This shape, in conjunction with the angles that are independent variables, was used in the investigation because it was described as a standard shape and used for various studies involving high speed cutting tools (7).

In light of the material discussed, the design used in the investigation was as follows. Table II is the Identification Table and Table III is the Analysis of Variance Table.

Significance tests of all main effects and higher order interactions were made at the five per cent significance level. Graphs showing the significant effects were constructed to aid in the analysis found in Chapter IV.

The randomization of the data collection was accomplished by punching IBM cards from 1 through 648 and completely shuffling the cards before listing the order on a 407 accounting machine. This order was used for the first replication. Then, cards were punched from 649 through 1296 and shuffled as before and listed to provide the order of processing for the second replication.

Due to physical limitations of part of the equipment, the .0625 level of the depth of cut was not used in part of the analysis. The Analysis of Variance Table then becomes as shown in Table IV.

TABLE II

IDENTIFICATION TABLE

Field	Factor	Level	Code	Sort Order	Identification
5	Depth of Cut	.0156 In.	1	A	D
		.0312	2		
		.0625	3		
10	Tool Feed	.002 In./Rev.	1	B	TF
		.004	2		
		.006	3		
15	Side-Cutting Edge Angle	15 Deg.	1	C	SC
		30	2		
		45	3		
20	Back-Rake Angle	0	1	D	BR
		+5	2		
		-5	3		
25	Cutting Velocity	80 FPM	1	E	S
		160	2		
		240	3		
		320	4		
30	Trial	1	1	F	T
		2	2		
35	Replication	1	1	R	R
		2	2		
37-40	Roughness				
42-45	Power				

TABLE III

ANALYSIS OF VARIANCE I

Source of Variation	df	SS	MS	F
A	2			
B	2			
C	2			
D	2			
E	3			
F	1			
AB	4			
AC	4			
AD	4			
AE	6			
AF	2			
BC	4			
BD	4			
BE	6			
BF	2			
CD	4			
CE	6			
CF	2			
DE	6			
DF	2			
EF	3			
ABC	8			

TABLE III (continued)

Source of Variation	df	SS	MS	F
ABD	8			
ABE	12			
ABF	4			
ACD	8			
ACE	12			
ACF	4			
ADE	12			
ADF	4			
AEF	6			
BCD	8			
BCE	12			
BCF	4			
BDE	12			
BDF	4			
BEF	6			
CDE	12			
CDF	4			
CEF	6			
DEF	6			
ABCD	16			
ABCE	24			
ABCF	8			
ABDE	24			

TABLE III (continued)

Source of Variation	df	SS	MS	F
ABDF	8			
ABEF	12			
ACDE	24			
ACDF	8			
ACEF	12			
ADEF	12			
BCDE	24			
BCDF	8			
BCEF	12			
BDEF	12			
CDEF	12			
ABCDE	48			
ABCDF	16			
ABCEF	24			
ABDEF	24			
ACDEF	24			
BCDEF	24			
ABCDEF	48			
ERROR	647			
TOTAL	1295			

TABLE IV

ANALYSIS OF VARIANCE II

Source of Variation	df	SS	MS	F
A	1			
B	2			
C	2			
D	2			
E	3			
F	1			
AB	2			
AC	2			
AD	2			
AE	3			
AF	1			
BC	4			
BD	4			
BE	6			
BF	2			
CD	4			
CE	6			
CF	2			
DE	6			
DF	2			
EF	3			
ABC	4			

TABLE IV (continued)

Source of Variation	df	SS	MS	F
ABD	4			
ABE	6			
ABF	2			
ACD	4			
ACE	6			
ACF	2			
ADE	6			
ADF	2			
AEF	3			
BCD	8			
BCE	12			
BCF	4			
BDE	12			
BDF	4			
BEF	6			
CDE	12			
CDF	4			
CEF	6			
DEF	6			
ABCD	8			
ABCE	12			
ABCF	4			
ABDE	12			

TABLE IV (continued)

Source of Variation	df	SS	MS	F
ABDF	4			
ABEF	6			
ACDE	12			
ACDF	4			
ACEF	6			
ADEF	6			
BCDE	24			
BCDF	8			
BCEF	12			
BDEF	12			
CDEF	12			
ABCDE	24			
ABCDF	8			
ABCEF	12			
ABDEF	12			
ACDEF	12			
BCDEF	24			
ABCDEF	24			
ERROR	431			
TOTAL	863			

Data Processing

Three separate passes were made on the IBM 1410 computer to obtain the mean squares necessary to calculate the F ratios. The first pass was with levels one and two of factor A using the surface roughness as the dependent variable. The second pass was with the same data cards using the power as the dependent variable. The third pass was with all three levels of factor A using the power requirement as the dependent variable. The data was punched into the cards with a keypunch according to the fields shown in Table II (page 23). The F ratio's were calculated on a desk calculator and the results along with the analysis of the results are shown in Chapter IV.

CHAPTER IV

ANALYSIS OF RESULTS

In accordance with the experimental design shown in Chapter III, three separate Analysis of Variances were performed on the collected data. The results of the surface finish analysis is shown in Table V. The results of the power requirement analysis with two levels of variable A is shown in Table VI. The results of the power requirement analysis with three levels of variable A is shown in Table VII. The discussion of the results will follow the same order as presented in Tables V, VI, and VII. All of the effects that are significant at the .05 level will be considered in the discussion.

The values used to plot the graphs are the mean values calculated by the computer for the conditions that are shown. These values are found in tabular form in Appendix B.

A significant effect is one that shows a greater difference than expected in the levels of the variable being considered. A significant interaction indicates that a variable, when considered with another variable, causes some change or difference in the other variable being considered.

A listing of the significant effects and their corresponding figures are shown:

1. Main Effects

    a. (B) Tool Feed — Figure 4

TABLE V

F-RATIO TABLE SURFACE FINISH

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
A (Depth of Cut)	250.26	1	250.26	.0979	NS
B (Tool Feed)	833,478.24	2	416,739.12	163.0683	.05
C (Side Cutting Edge Angle)	57,033.73	2	28,516.87	11.1585	.05
D (Back Rake Angle)	81,373.10	2	40,686.55	15.9204	.05
E (Cutting Speed)	1,587,120.90	3	529,040.30	207.0113	.05
F (Trials)	6,085.47	1	6,085.47	2.3812	NS
AB	1,347.55	2	673.78	.2636	NS
AC	1,215.86	2	607.93	.2378	NS
AD	3,602.80	2	1,801.40	.7048	NS
AE	40,490.36	3	13,496.79	5.2812	.05
AF	1,995.33	1	1,995.33	.7807	NS
BC	61,304.71	4	15,326.18	5.9970	.05
BD	9,173.53	4	2,293.38	.8973	NS
BE	663,494.79	6	110,582.47	43.2704	.05
BF	4,354.18	2	2,177.09	.8518	NS
CD	22,746.72	4	5,686.68	2.2251	NS
CE	27,002.66	6	4,500.44	1.7610	NS
CF	27,747.29	2	13,873.65	5.4287	.05
DE	80,369.79	6	13,394.97	5.2413	.05
DF	4,611.25	2	2,305.63	.9021	NS

TABLE V (continued)

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
EF	4,810.76	3	1,603.59	.6274	NS
ABC	21,780.63	4	5,445.16	2.1306	NS
ABD	3,302.92	4	825.73	.3231	NS
ABE	31,209.15	6	5,201.53	2.0353	NS
ABF	2,713.20	2	1,356.60	.5308	NS
ACD	5,326.38	4	1,331.60	.5210	NS
ACE	10,610.36	6	1,768.39	.6919	NS
ACF	502.06	2	251.03	.0982	NS
ADE	1,637.03	6	272.84	.1067	NS
ADF	2,261.71	2	1,130.86	.4425	NS
AEF	10,239.70	3	3,413.23	1.3355	NS
BCD	4,336.95	8	542.12	.2121	NS
BCE	75,533.43	12	6,294.45	2.4629	.05
BCF	13,947.40	4	3,486.85	1.3643	NS
BDE	52,743.95	12	4,395.33	1.7198	NS
BDF	6,938.91	4	1,734.73	.6787	NS
BEF	7,281.12	6	1,213.52	.4748	NS
CDE	38,576.06	12	3,214.67	1.2578	NS
CDF	3,730.41	4	932.60	.3649	NS
CEF	21,106.27	6	3,517.71	1.3764	NS
DEF	5,712.80	6	952.13	.3725	NS
ABCD	13,798.31	8	1,724.79	.6749	NS
ABCE	18,181.62	12	1,515.14	.5928	NS

TABLE V (continued)

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
ABCF	13,443.04	4	3,360.76	1.3150	NS
ABDE	21,607.22	12	1,800.60	.7045	NS
ABDF	7,600.91	4	1,900.23	.7435	NS
ABEF	37,599.59	6	6,266.60	2.4520	.05
ACDE	10,461.40	12	871.78	.3411	NS
ACDF	1,141.98	4	285.50	.1117	NS
ACEF	13,531.25	6	2,255.21	.8824	NS
ADEF	6,233.22	6	1,038.87	.4065	NS
BCDE	27,462.58	24	1,144.27	.4477	NS
BCDF	27,865.17	8	3,483.15	1.3629	NS
BCEF	40,108.96	12	3,342.41	1.3078	NS
BDEF	31,012.11	12	2,584.34	1.0112	NS
CDEF	22,170.20	12	1,847.52	.7229	NS
ABCDE	57,919.27	24	2,413.30	.9443	NS
ABCDF	9,657.60	8	1,207.20	.4723	NS
ABCEF	61,518.95	12	5,126.58	2.0060	.05
ABDEF	31,411.97	12	2,617.66	1.0242	NS
ACDEF	17,768.37	12	1,480.70	.5793	NS
BCDEF	32,935.80	24	1,372.33	.5369	NS
ABCDEF	31,779.24	24	1,324.14	.5181	NS
ERROR	1,101,469.89	431	2,555.61		
TOTAL	5,489,103.00	863	6,360.49		

TABLE VI

F-RATIO TABLE POWER TWO LEVELS D. O. C.

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
A (Depth of Cut)	3,162,698.00	1	3,162,698.00	1156.5994	.05
B (Tool Feed)	3,221,918.45	2	1,610,959.23	589.1281	.05
C (Side Cutting Edge Angle)	32,445.59	2	16,222.80	5.9326	.05
D (Back Rake Angle)	12,683.79	2	6,341.90	2.3192	NS
E (Cutting Speed)	18,456,200.56	3	6,152,066.85	2249.8123	.05
F (Trials)	22,919.56	1	22,919.56	8.3816	.05
AB	197,761.85	2	98,880.93	36.1607	.05
AC	3,255.45	2	1,627.73	.5952	NS
AD	6,419.90	2	3,209.95	1.1738	NS
AE	893,731.84	3	297,910.61	108.9459	.05
AF	14,340.74	1	14,340.74	5.2444	.05
BC	8,080.16	4	2,020.04	.7387	NS
BD	8,866.75	4	2,216.69	.8106	NS
BE	569,628.86	6	94,938.14	34.7189	.05
BF	8,827.66	2	4,413.83	1.6141	NS
CD	26,508.13	4	6,627.03	2.4235	.05
CE	108,380.57	6	18,063.43	6.6058	.05
CF	779.40	2	389.70	.1425	NS
DE	18,061.96	6	3,010.33	1.1008	NS
DF	33,378.01	2	16,689.01	6.1031	.05

TABLE VI (continued)

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
EF	15,553.82	3	5,184.61	1.8960	NS
ABC	12,076.96	4	3,019.24	1.1041	NS
ABD	24,203.14	4	6,050.79	2.2127	NS
ABE	27,913.70	6	4,652.28	1.7013	NS
ABF	1,593.84	2	796.92	.2914	NS
ACD	12,119.52	4	3,029.88	1.1080	NS
ACE	89,425.34	6	14,904.22	5.4504	.05
ACF	2,539.12	2	1,269.56	.4642	NS
ADE	13,764.09	6	2,294.02	.8389	NS
ADF	5,444.68	2	2,722.34	.9955	NS
AEF	31,980.79	3	10,660.26	3.8984	.05
BCD	27,745.25	8	3,468.16	1.2683	NS
BCE	51,462.65	12	4,288.55	1.5683	NS
BCF	12,971.07	4	3,242.77	1.1858	NS
BDE	25,655.22	12	2,137.94	.7818	NS
BDF	5,597.46	4	1,399.37	.5117	NS
BEF	20,104.08	6	3,350.68	1.2253	NS
CDE	37,659.48	12	3,138.29	1.1476	NS
CDF	24,330.32	4	6,082.58	2.2244	NS
CEF	18,314.58	6	3,052.43	1.1162	NS
DEF	38,716.67	6	6,452.78	2.3597	.05
ABCD	6,620.11	8	827.51	.3026	NS
ABCE	61,072.60	12	5,089.38	1.8611	.05

TABLE VI (continued)

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
ABCF	2,071.91	4	517.98	.1894	NS
ABDE	46,457.81	12	3,871.48	1.4158	NS
ABDF	7,291.77	4	1,822.94	.6666	NS
ABEF	11,597.80	6	1,932.97	.7068	NS
ACDE	27,283.19	12	2,273.60	.8314	NS
ACDF	25,348.38	4	6,337.10	2.3183	NS
ACEF	5,456.71	6	909.45	.3325	NS
ADEF	18,706.02	6	3,117.67	1.1401	NS
BCDE	51,793.00	24	2,158.04	.7891	NS
BCDF	7,383.95	8	922.99	.3375	NS
BCEF	54,208.92	12	4,517.41	1.6520	NS
BDEF	38,609.75	12	3,217.48	1.1766	NS
CDEF	35,545.14	12	2,962.10	1.0832	NS
ABCDE	54,197.50	24	2,258.23	.8258	NS
ABCDF	32,770.76	8	4,096.35	1.4980	NS
ABCEF	23,698.18	12	1,974.85	.7222	NS
ABDEF	29,350.54	12	2,445.88	.8944	NS
ACDEF	22,329.40	12	1,860.78	.6804	NS
BCDEF	29,070.61	24	1,211.28	.4429	NS
ABCDEF	57,935.38	24	2,413.97	.8827	NS
ERROR	1,178,560.00	431			
TOTAL	29,133,432.43	863			

TABLE VII

F-RATIO TABLE POWER THREE LEVELS D. O. C.

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
A (Depth of Cut)	27,289,243.21	2	13,644,621.61	2444.8608	.05
B (Tool Feed)	10,456,451.01	2	5,228,225.51	936.8001	.05
C (Side Cutting Edge Angle)	61,962.77	2	30,981.39	5.5512	.05
D (Back Rake Angle)	35,598.32	2	17,799.16	3.1892	.05
E (Cutting Speed)	49,789,826.25	3	16,596,608.75	2973.8016	.05
F (Trials)	75,228.30	1	75,228.30	13.4795	.05
AB	2,348,152.27	4	587,038.07	105.1862	.05
AC	11,946.35	4	2,986.59	.5351	NS
AD	77,060.40	4	19,265.10	3.4519	.05
AE	7,400,194.48	6	1,233,365.75	220.9960	.05
AF	30,133.33	2	15,066.67	2.6996	NS
BC	56,064.31	4	14,016.08	2.5114	NS
BD	120,083.25	4	30,020.81	5.3791	.05
BE	1,635,688.50	6	272,614.75	48.8474	.05
BF	41,445.30	2	20,722.65	3.7131	.05
CD	56,970.36	4	14,242.59	2.5520	.05
CE	341,501.81	6	56,916.97	10.1984	.05
CF	16,919.82	2	8,459.91	1.5158	NS
DE	107,103.89	6	17,850.65	3.1985	.05
DF	58,311.68	2	29,155.84	5.2241	.05

TABLE VII (continued)

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
EF	44,698.83	3	14,899.61	2.6697	.05
ABC	51,907.72	8	6,488.47	1.1626	NS
ABD	147,092.15	8	18,386.52	3.2945	.05
ABE	347,722.86	12	28,976.91	5.1921	.05
ABF	29,128.45	4	7,282.11	1.3048	NS
ACD	22,153.72	8	2,769.22	.4961	NS
ACE	195,128.69	12	16,260.72	2.9136	.05
ACF	54,987.42	4	13,746.86	2.4631	.05
ADE	128,859.30	12	10,738.28	1.9240	.05
ADF	7,353.35	4	1,838.34	.3293	NS
AEF	38,948.89	6	6,491.48	1.1631	NS
BCD	32,062.96	8	4,007.87	.7181	NS
BCE	126,968.87	12	10,580.74	1.8958	.05
BCF	24,010.15	4	6,002.54	1.0755	NS
BDE	214,623.69	12	17,885.31	3.2047	.05
BDF	24,808.78	4	6,202.20	1.1113	NS
BEF	35,260.22	6	5,876.70	1.0529	NS
CDE	93,654.67	12	7,804.56	1.3984	NS
CDF	28,272.60	4	7,068.15	1.2664	NS
CEF	46,123.48	6	7,687.25	1.3774	NS
DEF	52,569.43	6	8,761.57	1.5699	NS
ABCD	24,747.47	16	1,546.72	.2771	NS
ABCE	226,004.75	24	9,416.86	1.6873	.05

TABLE VII (continued)

Source of Variation	Sum of Squares	df	Mean Square	F-Ratio	P
ABCF	24,136.93	8	3,017.12	.5406	NS
ABDE	333,465.29	24	13,894.39	2.4896	.05
ABDF	38,435.89	8	4,804.49	.8608	NS
ABEF	37,050.84	12	3,087.57	.5532	NS
ACDE	93,881.12	24	3,911.71	.7009	NS
ACDF	30,424.45	8	3,803.06	.6802	NS
ACEF	45,888.99	12	3,824.08	.6852	NS
ADEF	82,077.85	12	6,839.82	1.2255	NS
BCDE	120,715.36	24	5,029.81	.9012	NS
BCDF	37,779.83	8	4,722.48	.8461	NS
BCEF	175,144.35	12	14,595.36	2.6152	.05
BDEF	210,050.41	12	17,504.20	3.1364	.05
CDEF	69,547.08	12	5,795.59	1.0384	NS
ABCDE	336,428.23	48	7,008.92	1.2558	NS
ABCDF	91,190.47	16	5,699.40	1.0212	NS
ABCEF	136,533.70	24	5,688.90	1.0193	NS
ABDEF	183,201.11	24	7,633.38	1.3677	NS
ACDEF	47,250.67	24	1,968.78	.3527	NS
BCDEF	70,298.24	24	2,929.09	.5248	NS
ABCDEF	181,421.66	48	3,779.62	.6772	NS
ERROR	3,610,865.92	647	5,580.94		
TOTAL	107,963,476.52	1295	83,369.48		

b. (C) Side Cutting Edge Angle — Figure 5

c. (D) Back Rake Angle — Figure 6

d. (E) Cutting Speed — Figure 7

2. First Order Interactions

a. (AE) Depth of Cut by Cutting Speed — Figure 8

b. (BC) Tool Feed by Side Cutting Edge Angle — Figure 9

c. (BE) Tool Feed by Cutting Speed — Figure 10

d. (CF) Side Cutting Edge Angle by Trials — Figure 11

e. (DE) Back Rake Angle by Cutting Speed — Figure 12

3. Second Order Interaction

a. (BCE) Tool Feed by Side Cutting Edge Angle by Cutting Speed — Figure 13

4. Third Order Interaction

a. (ABEF) Depth of Cut by Tool Feed by Cutting Speed by Trials — Figure 14

5. Fourth Order Interaction

a. (ABCEF) Depth of Cut by Tool Feed by Side Cutting Edge Angle by Cutting Speed by Trials — Figure 15

Figure 4 shows that the surface finish is adversely affected as there is an increase in feed. This was the expected result.

Figure 5 indicates that the smaller side cutting edge angle produces the best finish and that there is a trend toward an improved surface finish with the 45° angle as compared to the 30° angle.

Figure 6 shows, as expected, that the surface finish becomes better as one moves from a negative to positive back rake for the High Speed Steel tool bits used in this investigation. This was expected according to the literature search.

Figure 7 shows, as expected, that there is a marked improvement in surface finish as the speed increases. This pronounced effect will carry its influence into the interactions that follow.

Figure 8 verifies the result shown in Table V that the depth of cut alone does not have a significant affect on the surface finish. A comparison of Figure 8 with Figure 7 shows almost no change in cutting speed indicating that the depth of cut at the slower feeds has some affect, but almost no affect as the speed increases.

Figure 9 shows that the side cutting edge angle shown in Figure 5 has very little affect on the feed shown in Figure 4 indicating that feed will probably play an important part in the final analysis of surface finish.

Figure 10 indicates that there is less variability at the slower feeds. A comparison of Figure 10 with Figure 7 bears out the fact that the better surface finish comes from the faster speeds.

Figure 11 indicates that the trials have an affect on surface finish. The reason for significance could be assigned to material variability,

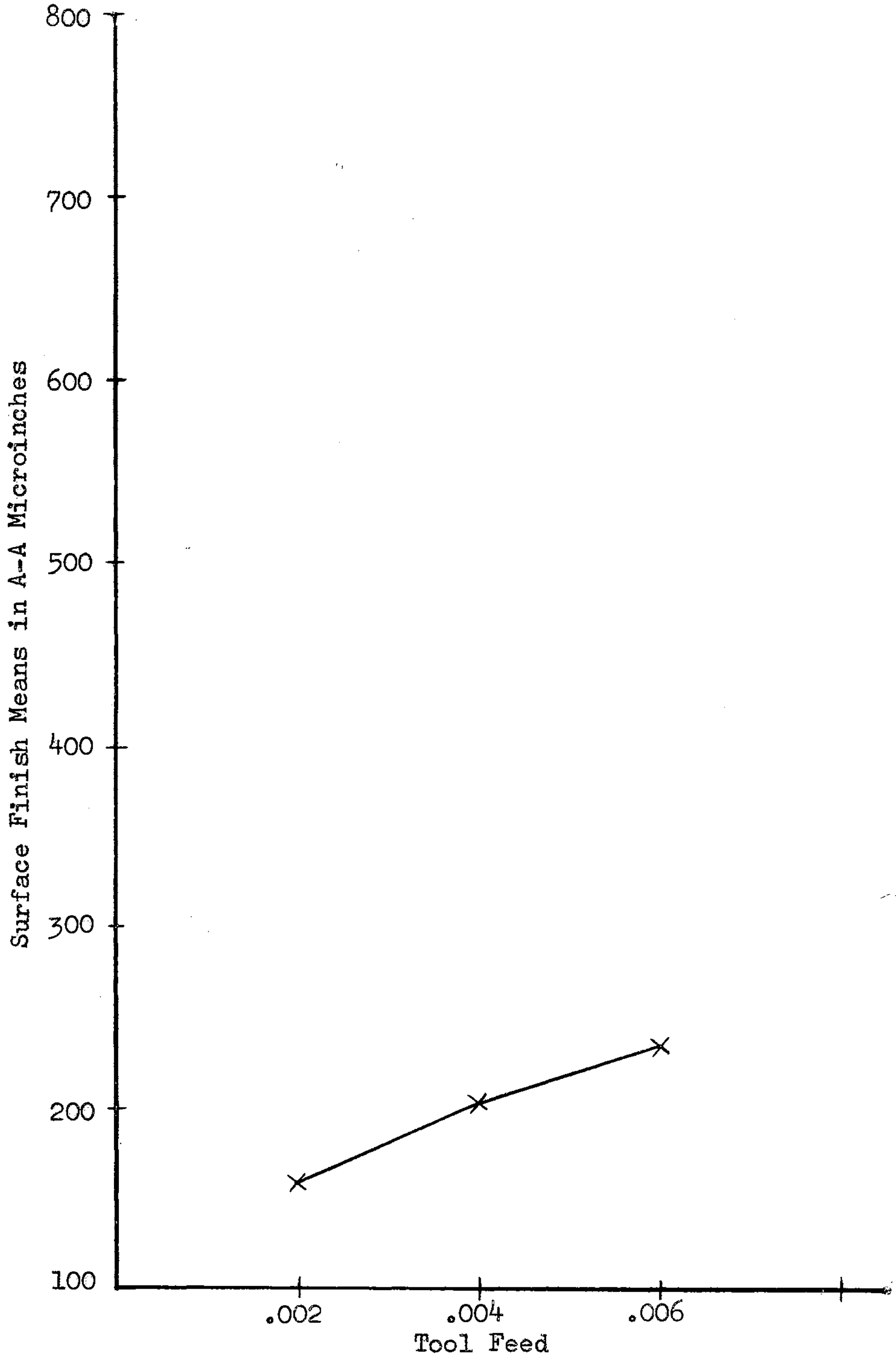

Figure 4. Main Effect Tool Feed I

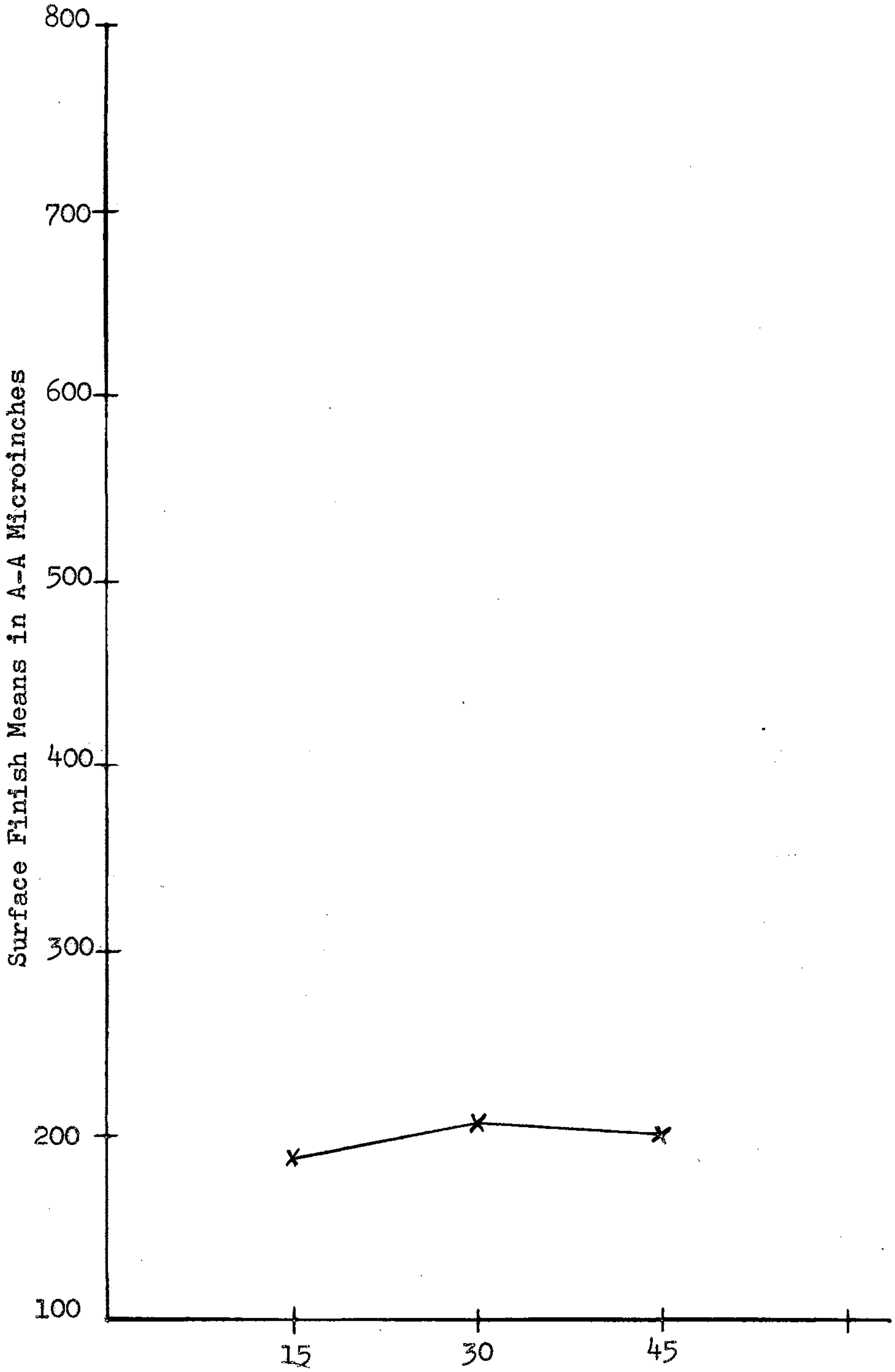

Figure 5. Main Effect Side Cutting Edge Angle I

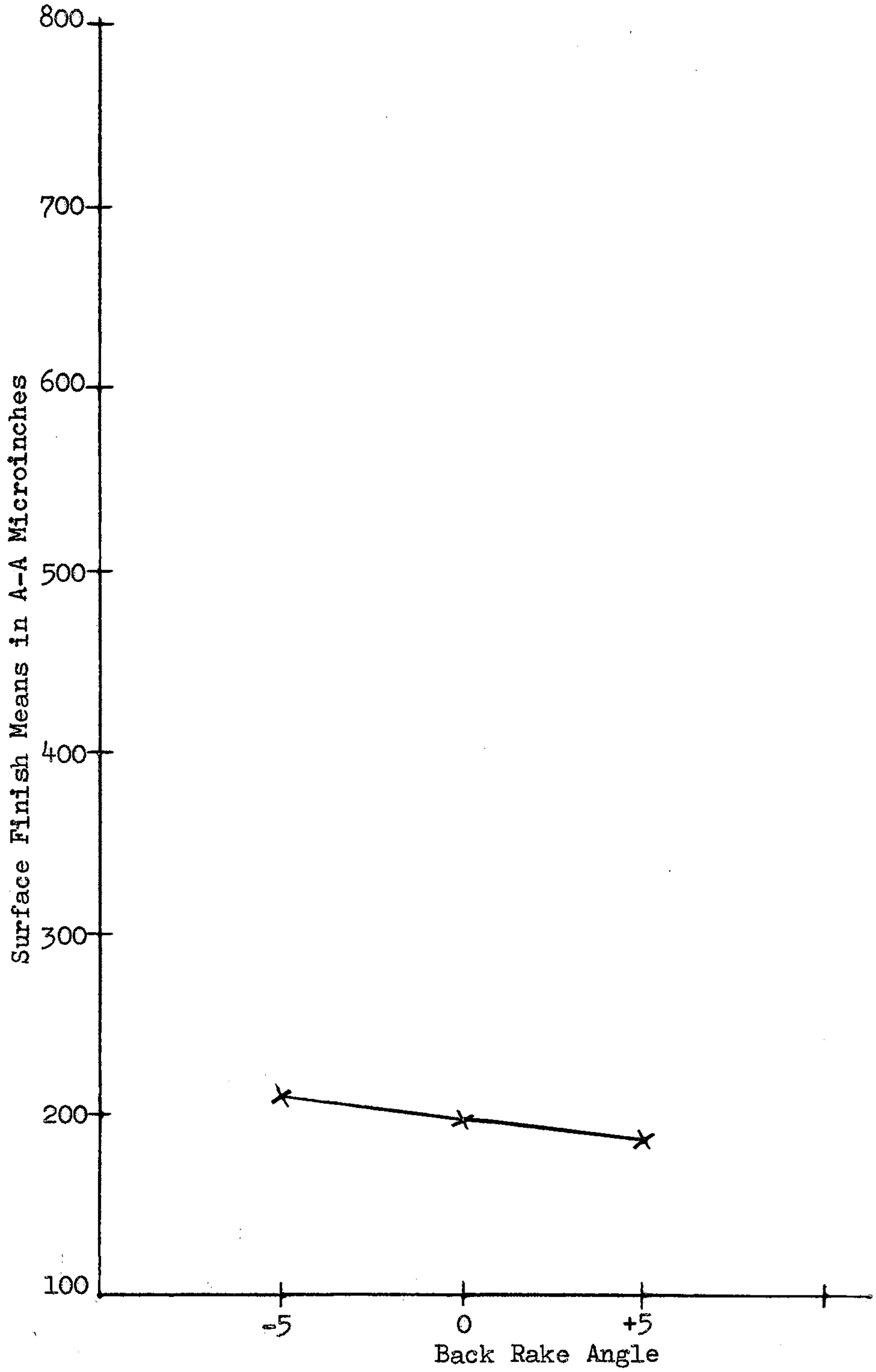

Figure 6. Main Effect Back Rake Angle I

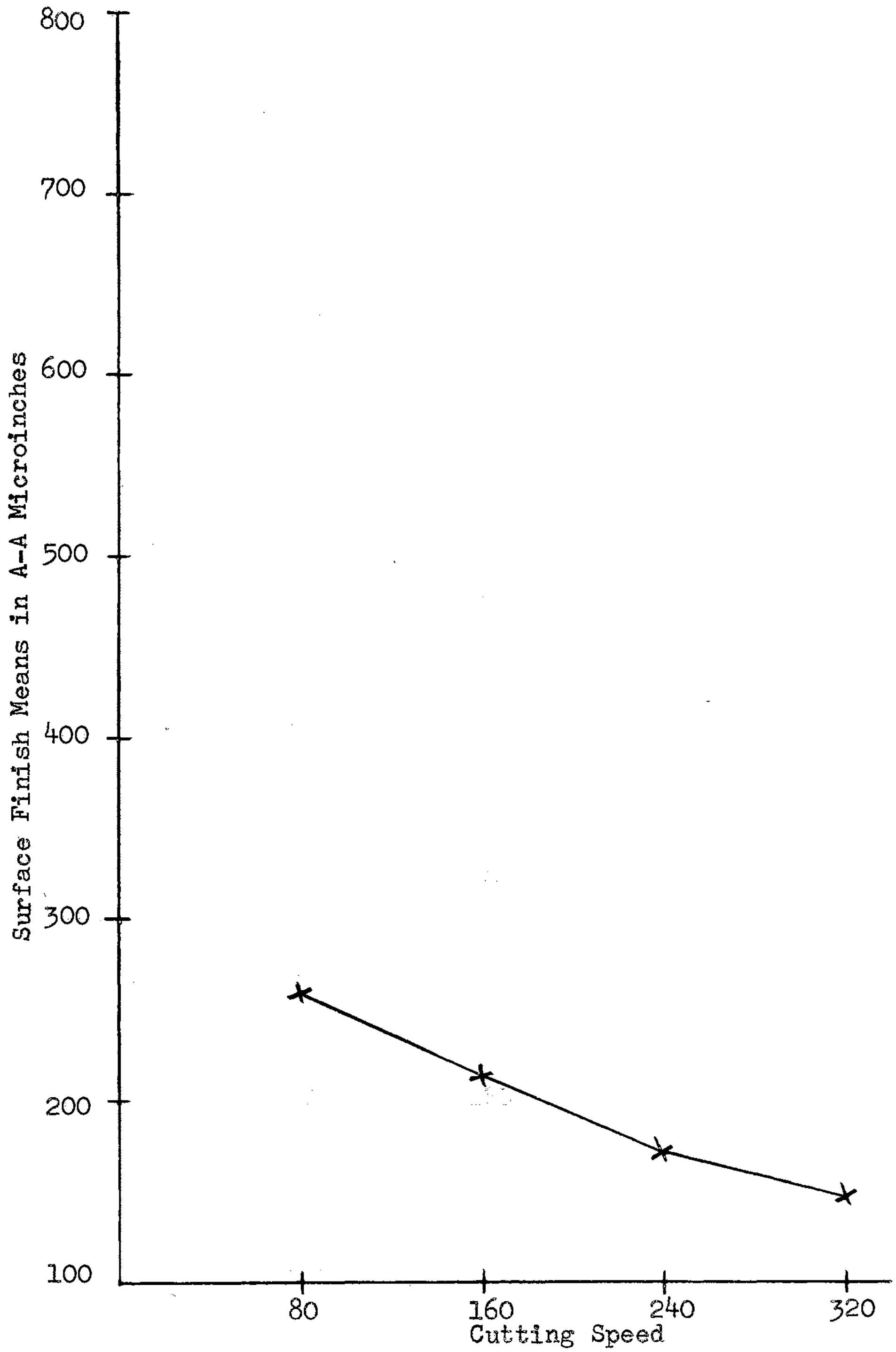

Figure 7. Main Effect Cutting Speed I

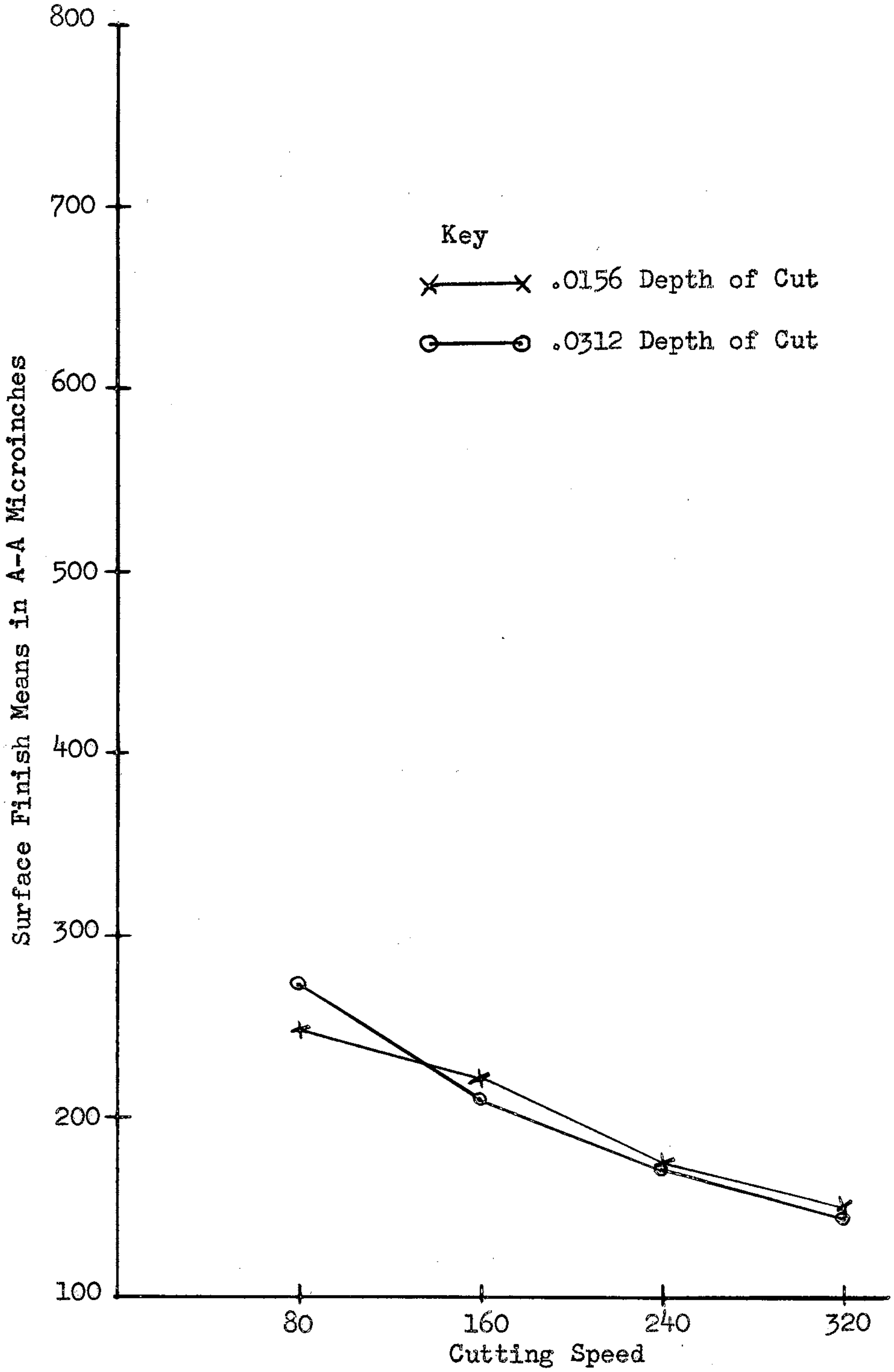

Figure 8. Interaction Depth of Cut by Cutting Speed I

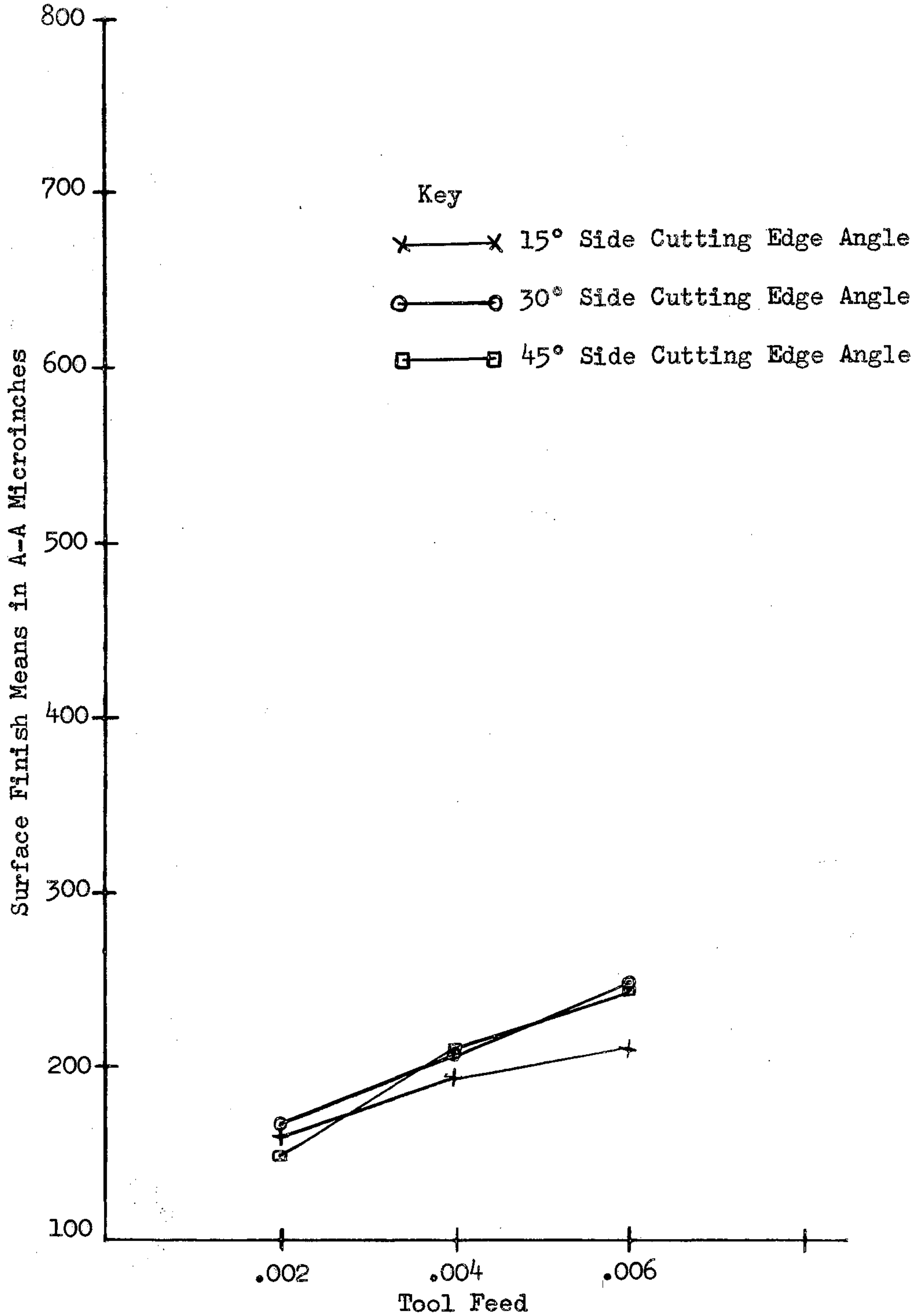

Figure 9. Interaction Tool Feed by Side Cutting Edge Angle I

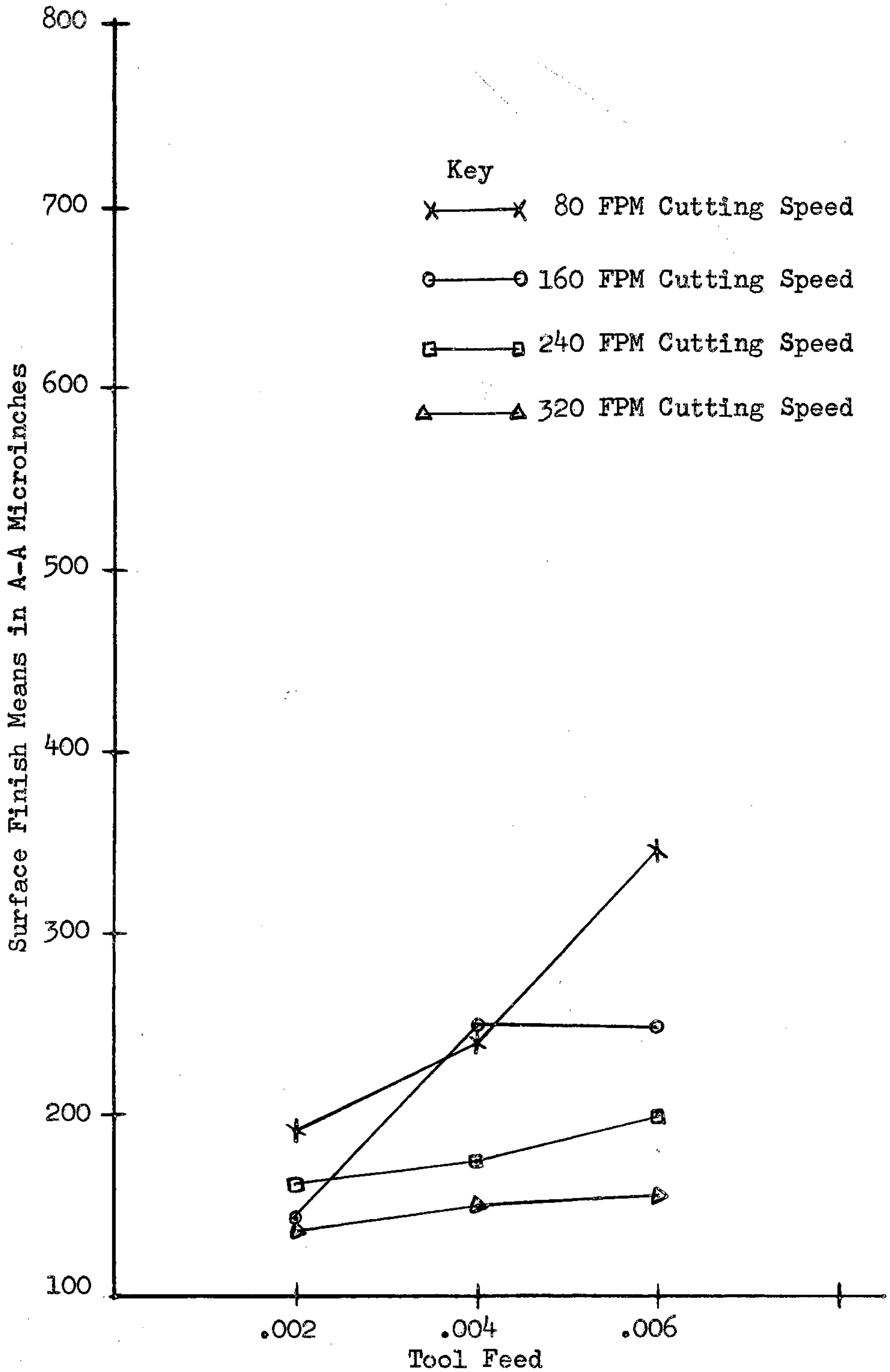

Figure 10. Interaction Tool Feed by Cutting Speed I

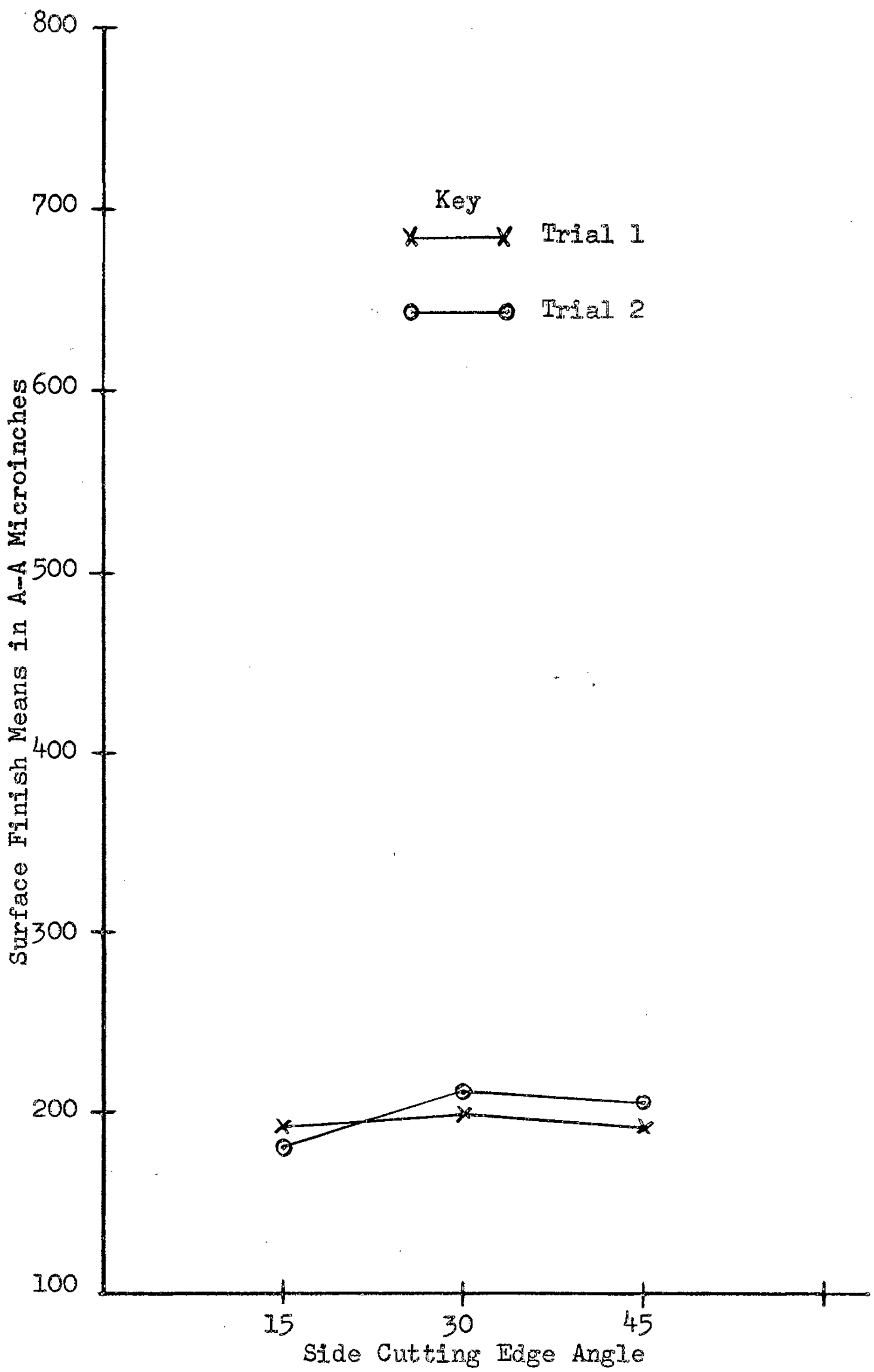

Figure 11. Interaction Side Cutting Edge Angle by Trials I

operator error, or possibly machine failure.

Figure 12 shows that the back rake angle changes the surface finish at the faster speeds along the same pattern as shown in Figure 6. At the slower speeds, there is apparently little effect.

Figure 13 indicates again that as the speed increases it is the dominant factor. In general, the trend from slower to faster feed, as shown in Figure 9, is still maintained. The effect of the side cutting edge angle in this interaction is not evident. It does not follow that pattern established in Figure 5 giving additional support to the overriding effects of feed and speed.

In Figure 14, the predominance of the increasing speed bringing about the better surface finish can again be seen. The depth of cut shows no trend, but the feed again indicates that the slower feed produces the better surface finish. Trials have no apparent effect.

From Figure 15 comes a possible reason why trials interact in some effects, even though every effort was made to keep this out of the significant effects. It can be seen that there is considerable variability in some of the trials. From the figure there is also the indication again that speed and feed have the most affect on surface finish with the higher speeds and slower feeds producing the most desirable values. The figure also indicates that the 15° and 45° side cutting edge angle appear to produce better surface finish than does the 30° angle confirming the evidence of Figure 5 (page 44). Depth of cut which was not a significant main effect appears to show some significance here with the smaller depth of cut producing the better finish.

In reviewing Figures 4 through 15, speed is the most important factor

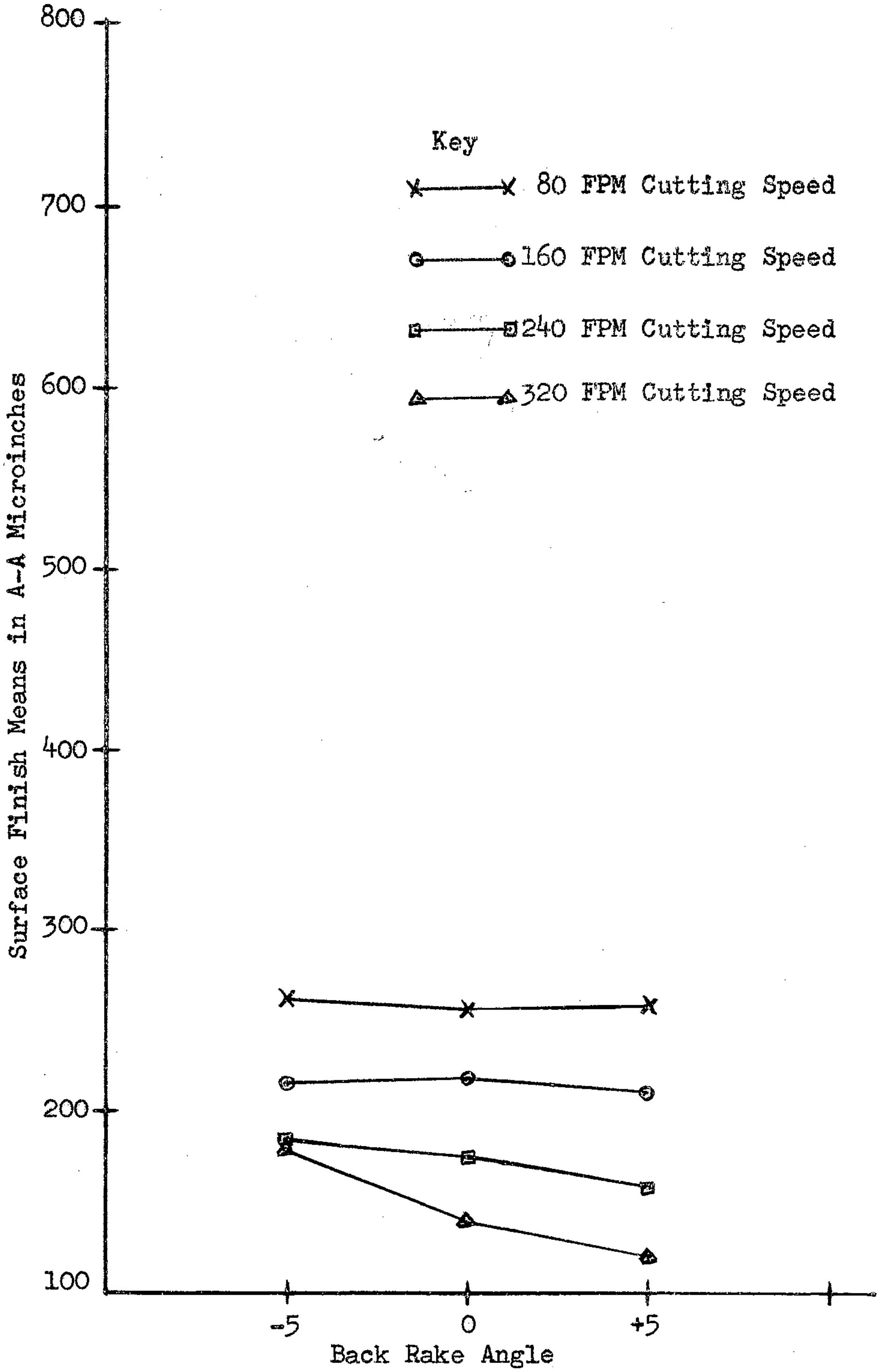

Figure 12. Interaction Back Rake Angle by Cutting Speed I

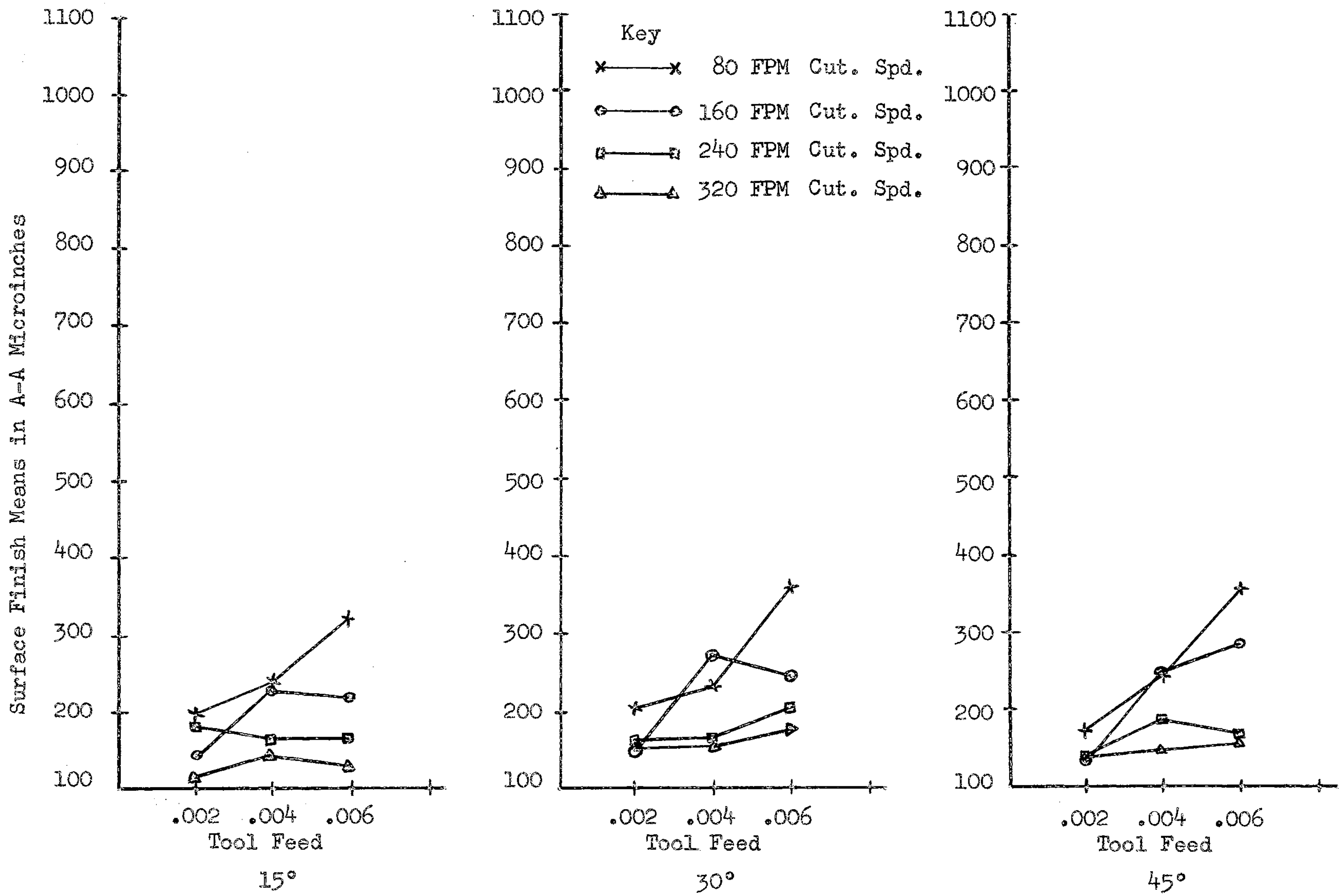

Figure 13. Interaction Tool Feed by Side Cutting Edge Angle by Cutting Speed I

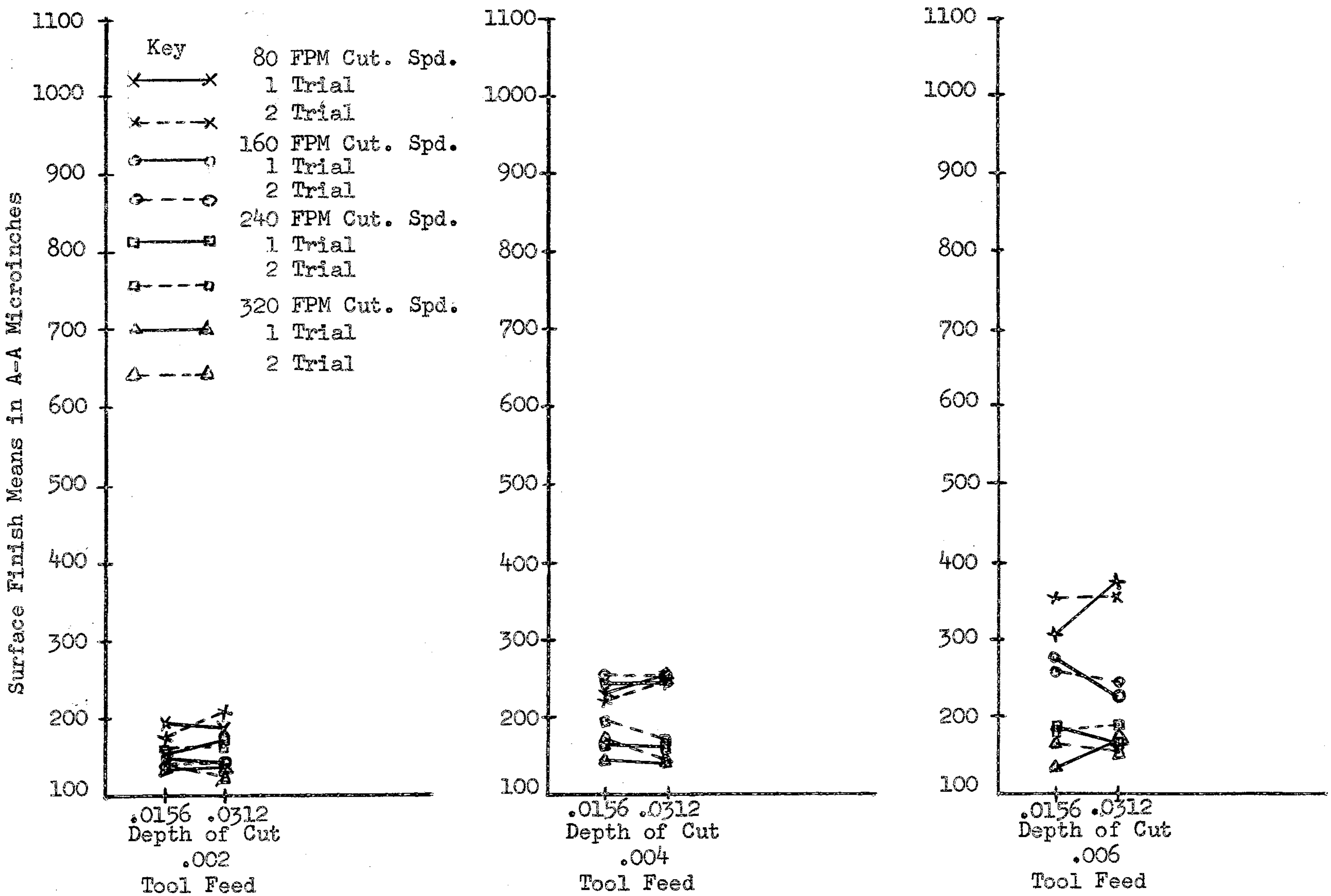

Figure 14. Interaction Depth of Cut by Tool Feed by Cutting Speed by Trials - I

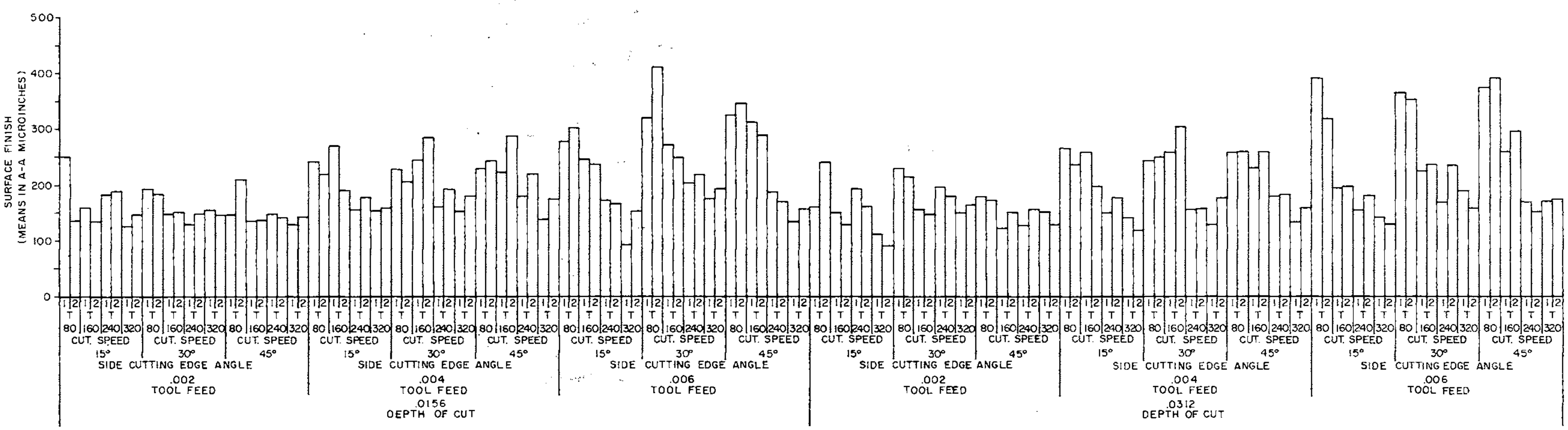

Figure 15. Interaction Depth of Cut by Tool Feed by Side Cutting Edge Angle by Cutting Speed by Trials - I

in surface finish with feed being the next most important factor. This analysis substantiates the statements about surface finish by Boston (2) made in Chapter II.

From Table VI the following effects are significant for power requirements:

1. Main Effects
    a. (A) Depth of Cut — Figure 16
    b. (B) Tool Feed — Figure 17
    c. (C) Side Cutting Edge Angle — Figure 18
    d. (E) Cutting Speed — Figure 19
    e. (F) Trials — Figure 20
2. First Order Interactions
    a. (AB) Depth of Cut by Tool Feed — Figure 21
    b. (AE) Depth of Cut by Cutting Speed — Figure 22
    c. (AF) Depth of Cut by Trials — Figure 23
    d. (BE) Tool Feed by Cutting Speed — Figure 24
    e. (CD) Side Cutting Edge Angle by Back Rake Angle — Figure 25
    f. (CE) Side Cutting Edge Angle by Cutting Speed — Figure 26
    g. (DF) Back Rake Angle by Trials — Figure 27
3. Second Order Interactions

a. (ACE) Depth of Cut by Side Cutting Edge Angle by Cutting Speed — Figure 28

b. (AEF) Depth of Cut by Cutting Speed by Trials — Figure 29

c. (DEF) Back Rake Angle by Cutting Speed by Trials — Figure 30

4. Third Order Interaction

a. (ABCE) Depth of Cut by Tool Feed by Side Cutting Edge Angle by Cutting Speed — Figure 31.

From Figure 16 it is apparent, as expected, that power is affected by depth of cut. This variable will prove to be important in the interactions that follow.

Figure 17 indicates an increase in power consumption with an increase in feed. This increase was also expected.

Figure 18 shows that the side cutting edge angle has very little affect on power at the 30° and 45° angle, but the 15° appears to reduce the power enough to be significant.

Figure 19 shows that speed has a great influence on power. As stated in Chapter II, this variable is consistently the most important one in power consumption. In the figures that follow, it is apparent just how much influence it has on power consumption.

Figure 20 shows that trials are significant. There is no real reason for this, although it could probably be one of several things. Material

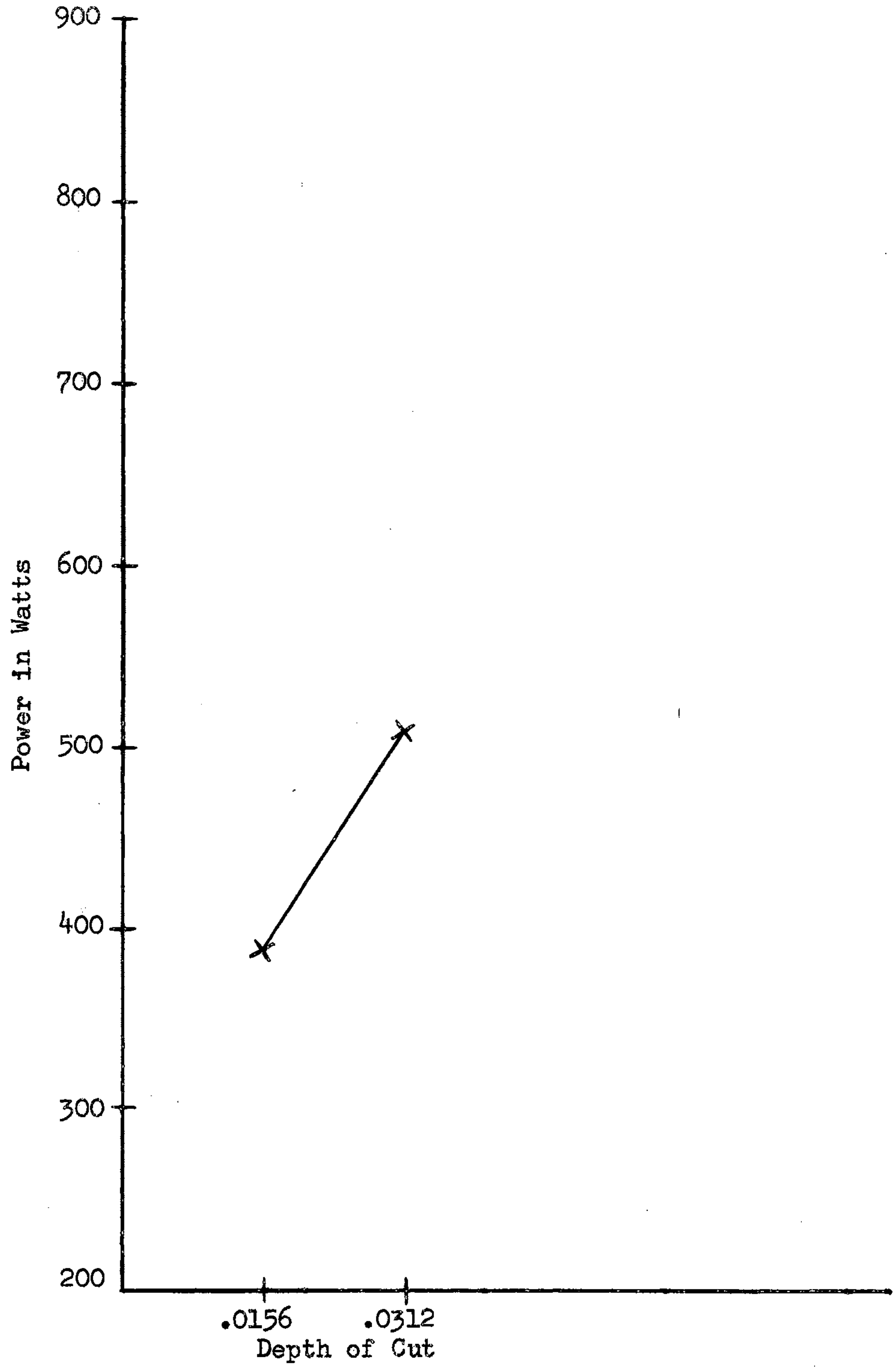

Figure 16. Main Effect Depth of Cut II

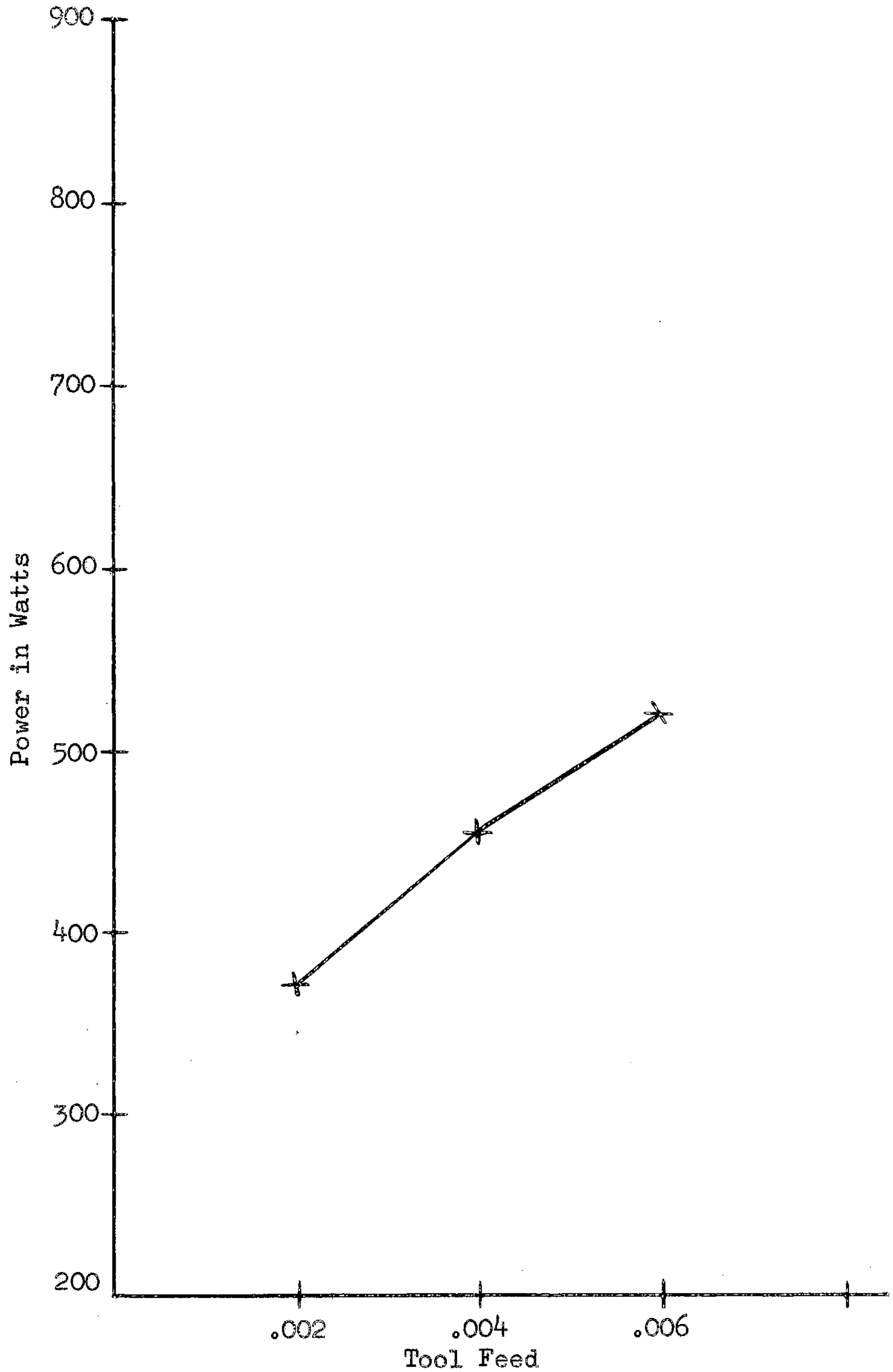

Figure 17. Main Effect Tool Feed II

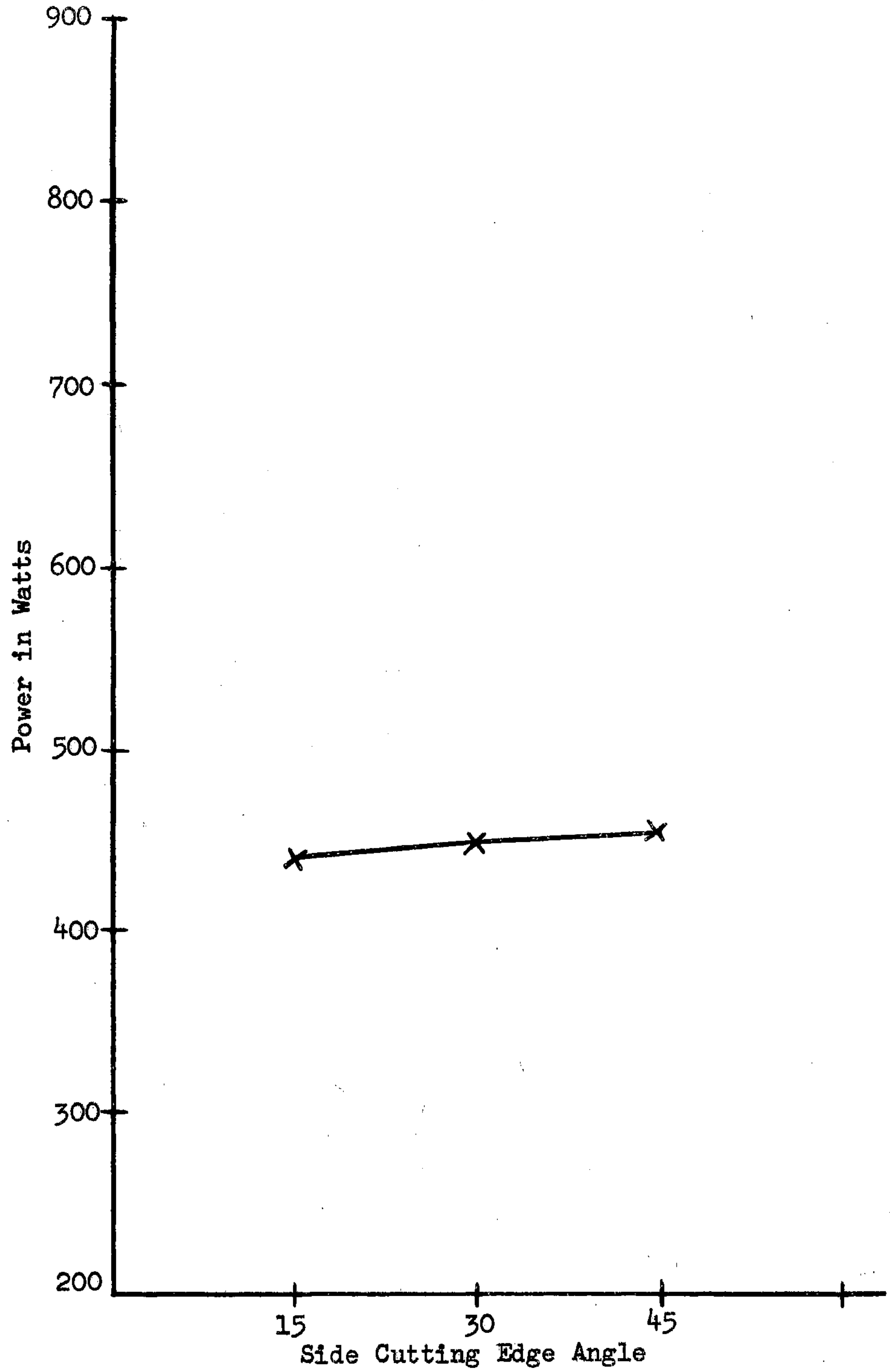

Figure 18. Main Effect Side Cutting Edge Angle II

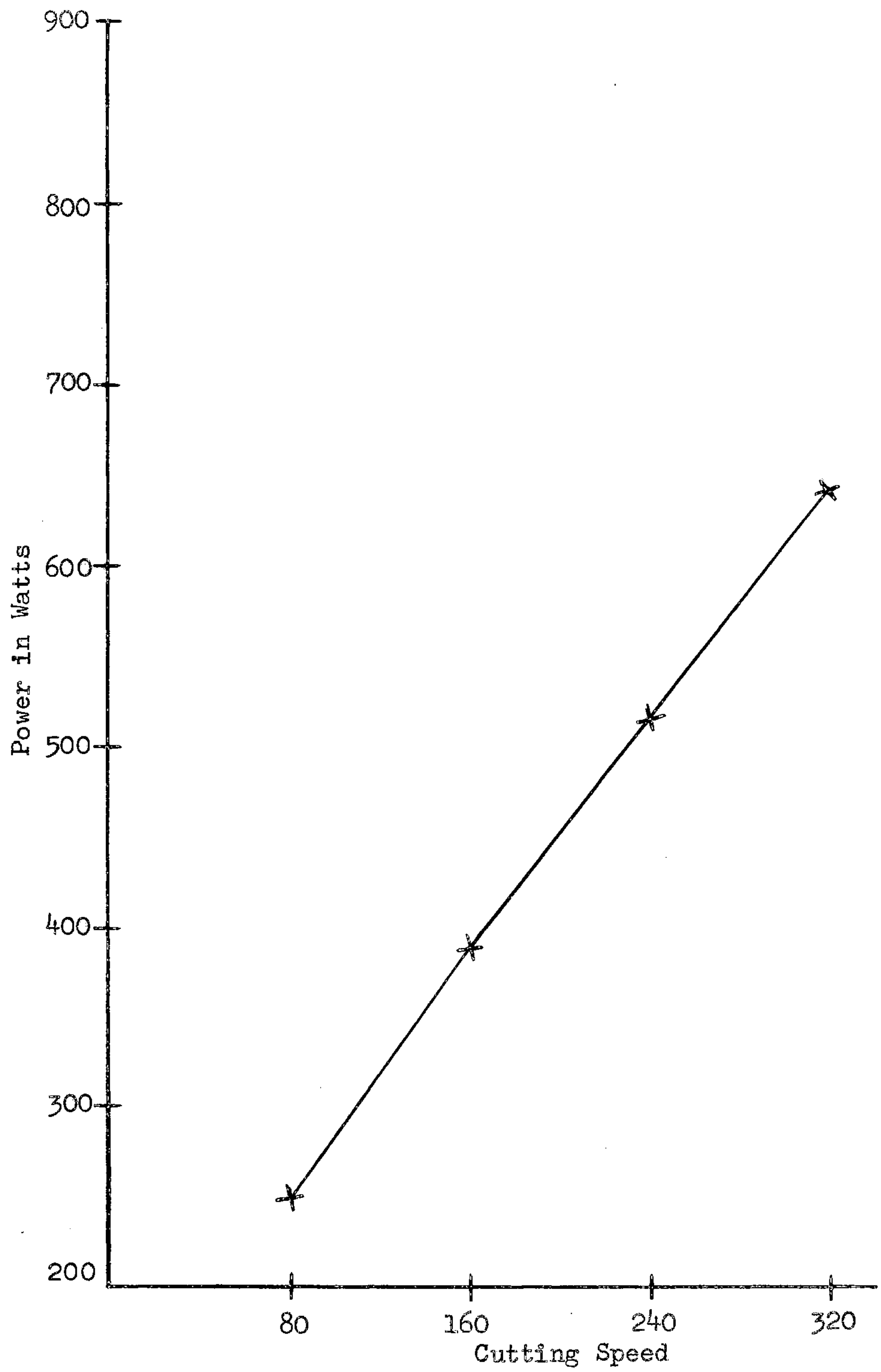

Figure 19. Main Effect Cutting Speed II

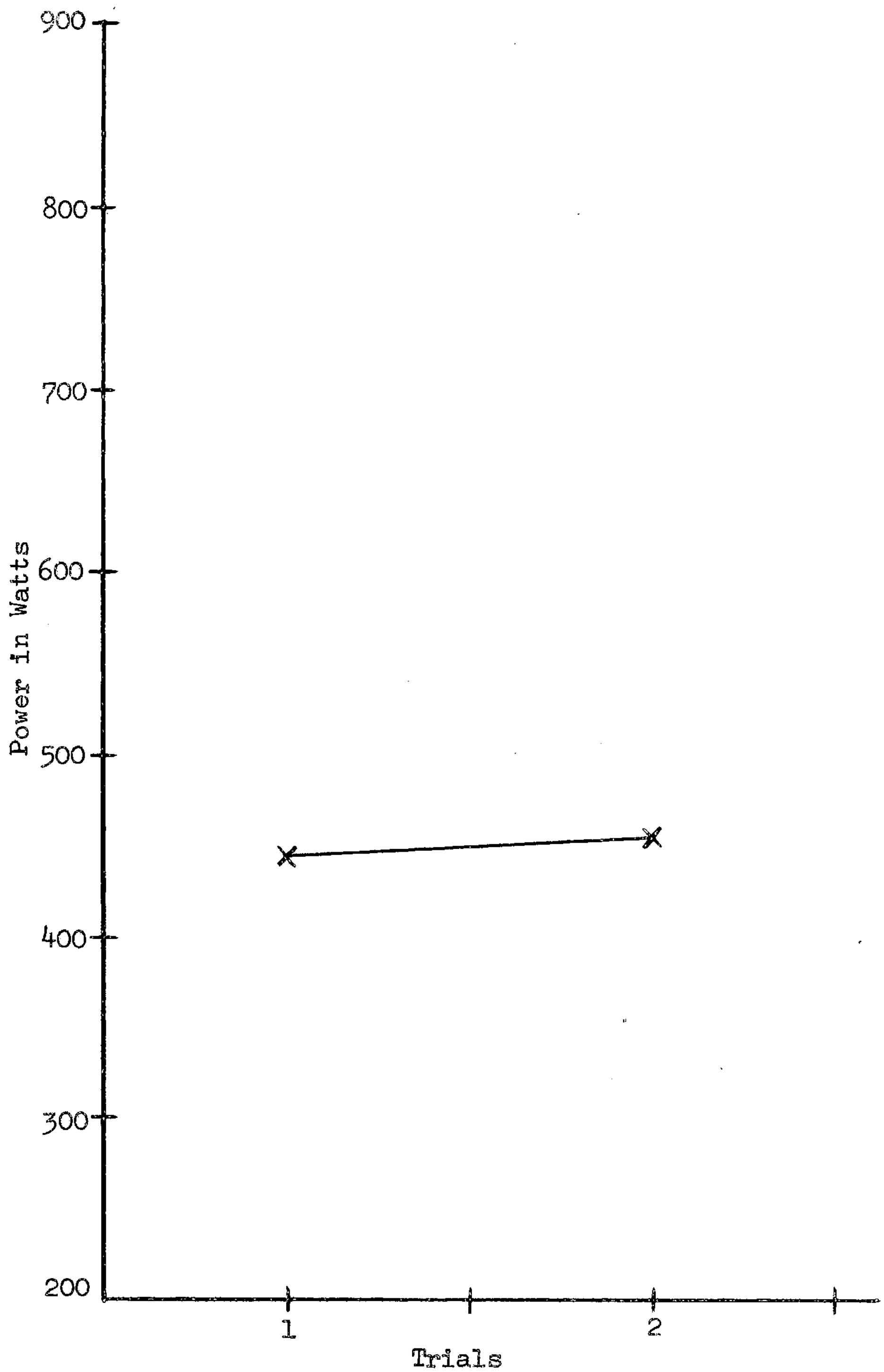

Figure 20. Main Effect Trials II

difference may have been the reason. Operator errors in experimental procedure or in the judgment factors that were involved. Although it is not likely, since all equipment used was new, there may have been some equipment malfunction that caused trials to be significant.

Figure 21 indicates that when the depth of cut and feed are combined there is a greater variability than when considered singly. The slower feed smaller depth of cut reduces the power some, while the higher feed larger depth of cut increases the power requirement. The increase in power with the combined effect of feed and depth of cut was expected.

Figure 22 shows that depth of cut and speed combined to give an increase in power. This was expected because of the significant affects of the individual main effects.

As indicated before, there is no real reason for the trials to be significant as is shown in Figure 23, but there appears to be some difference at the .0312 depth of cut.

Figure 24 indicates the strong influence of speed because in examining Figure 19 there is very little effect on the power required. The slower feed speed combination shows a slight decrease where the faster speed combination shows only an approximate 100 watt increase in the power.

Figure 25 shows that the smaller the side cutting angle, the more affect the back rake has. It shows a considerable reduction for the +5 and -5 degree angles. For the zero degree back rake angle, the effect appears to be the reverse; that is, decreasing the power as the side cutting angle gets larger.

Figure 26 indicates that the side cutting edge angle, in general,

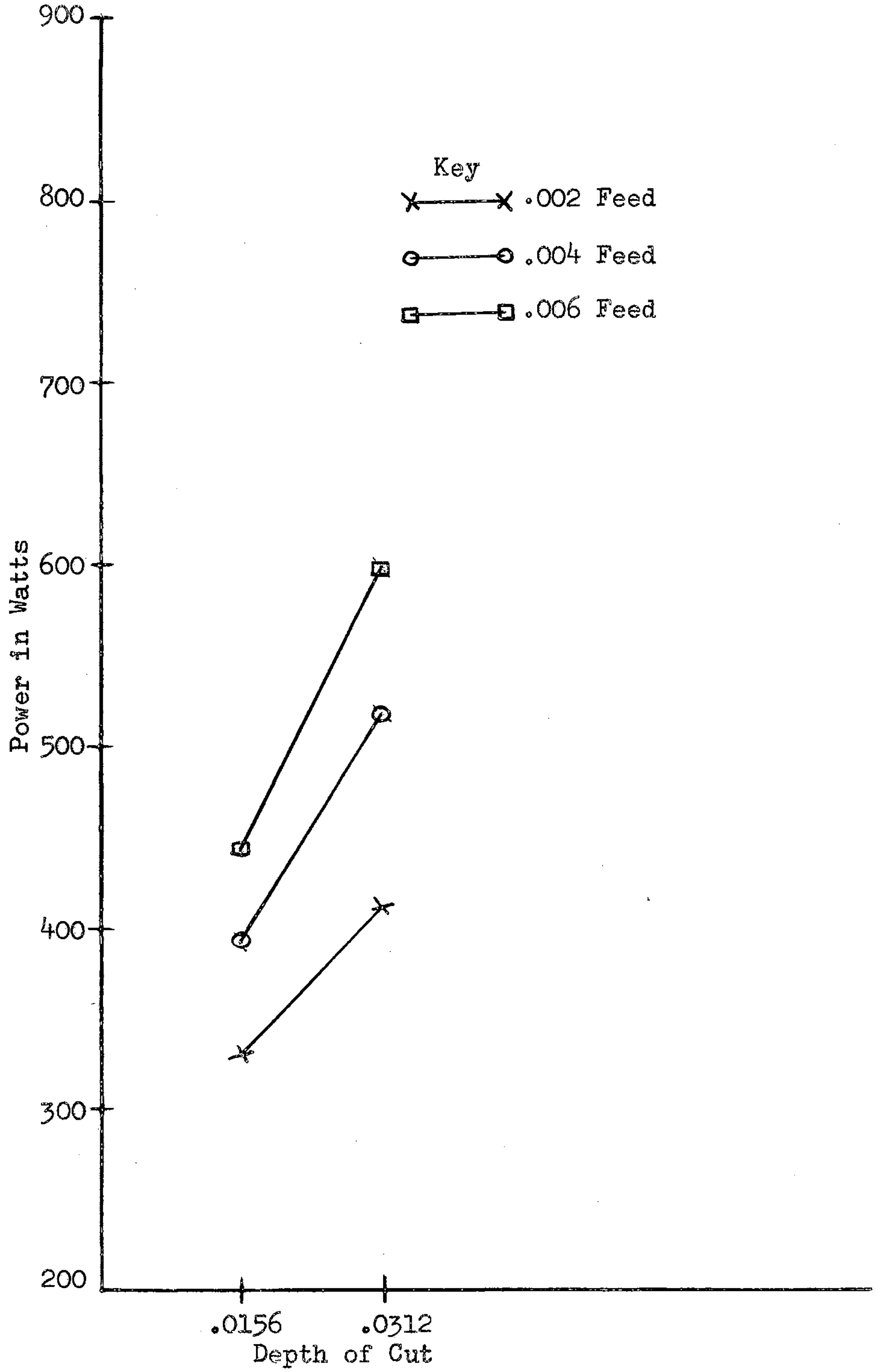

Figure 21. Interaction Depth of Cut by Tool Feed II

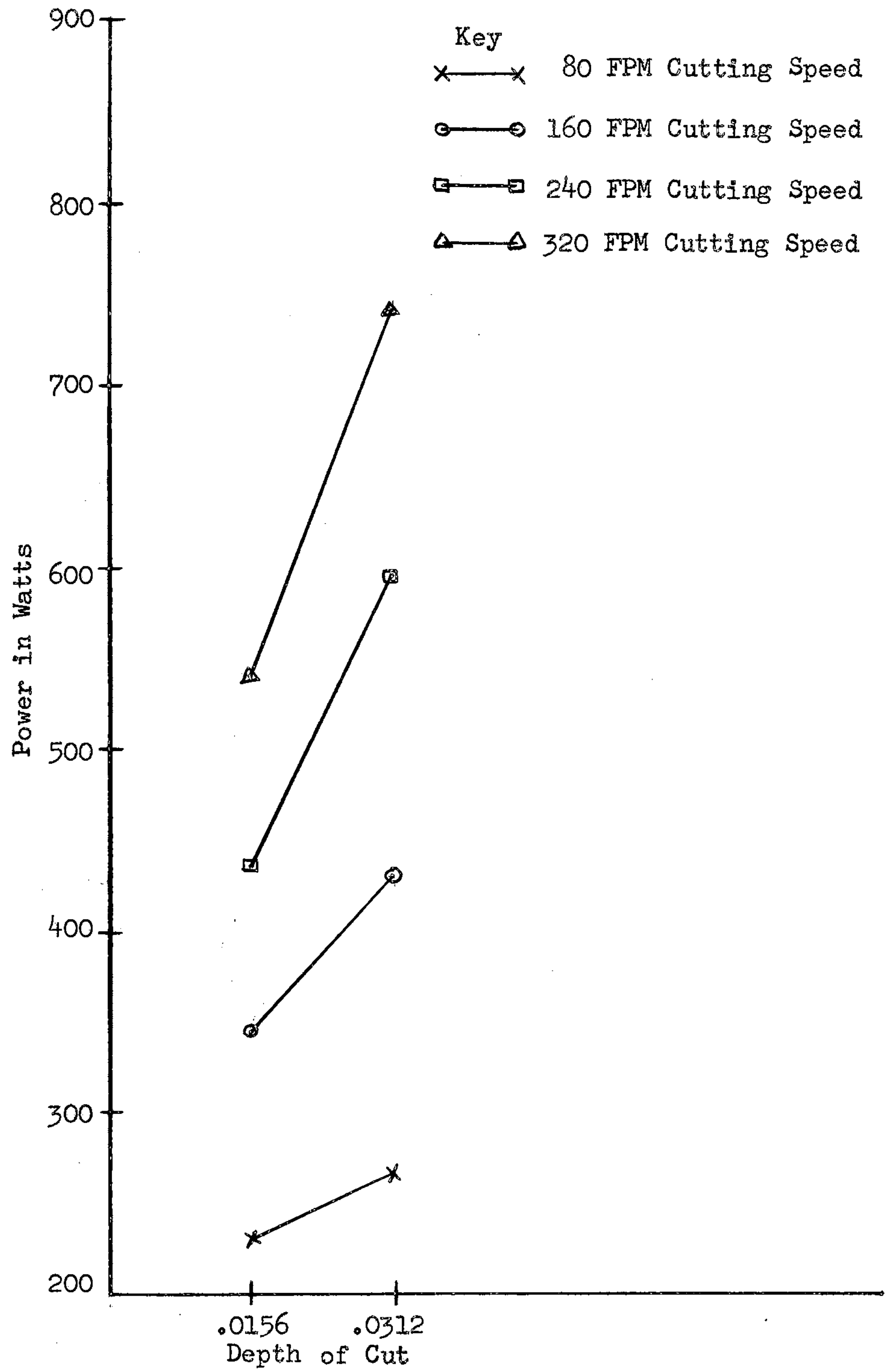

Figure 22. Interaction Depth of Cut by Cutting Speed II

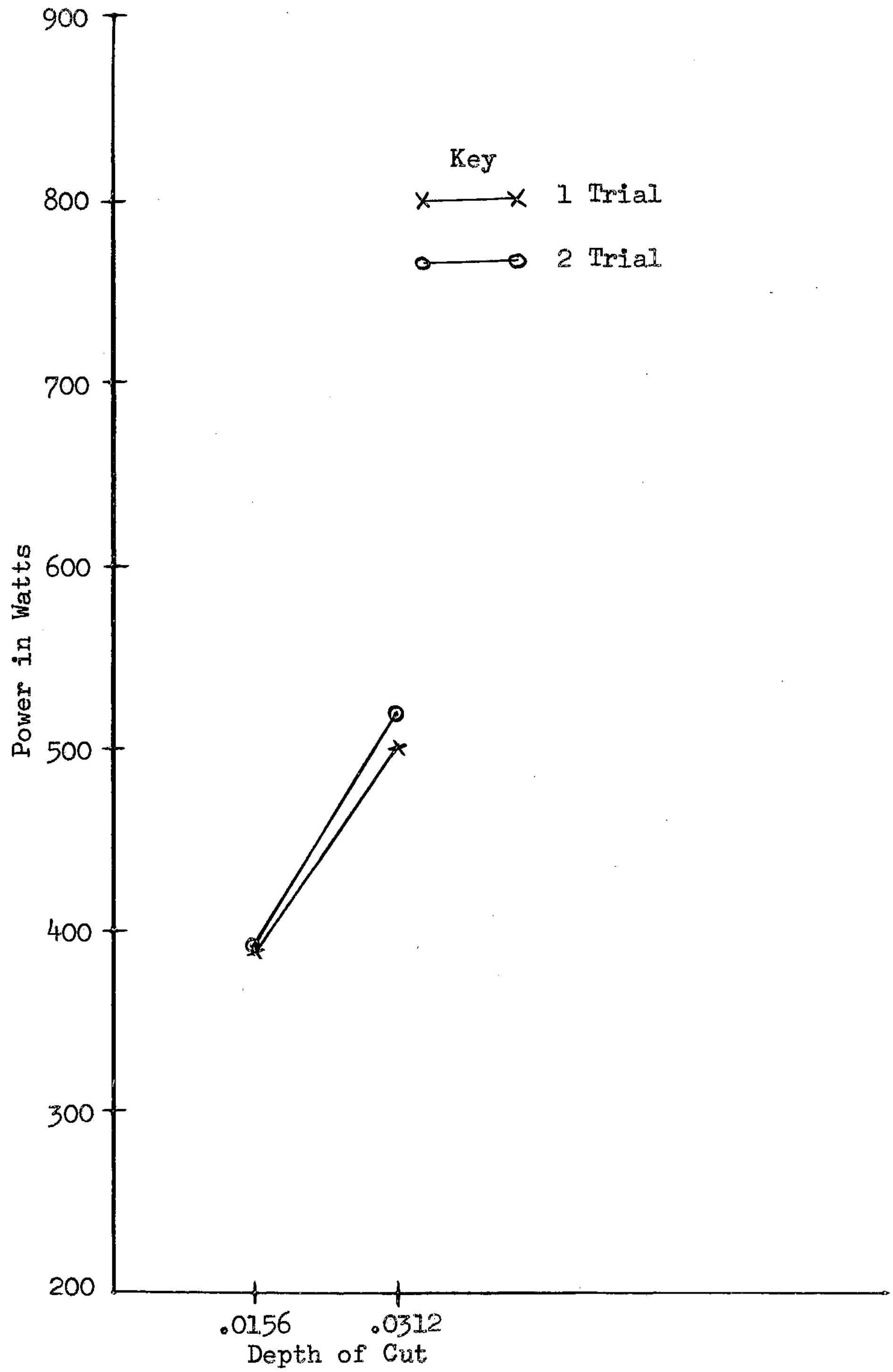

Figure 23. Interaction Depth of Cut by Trials II

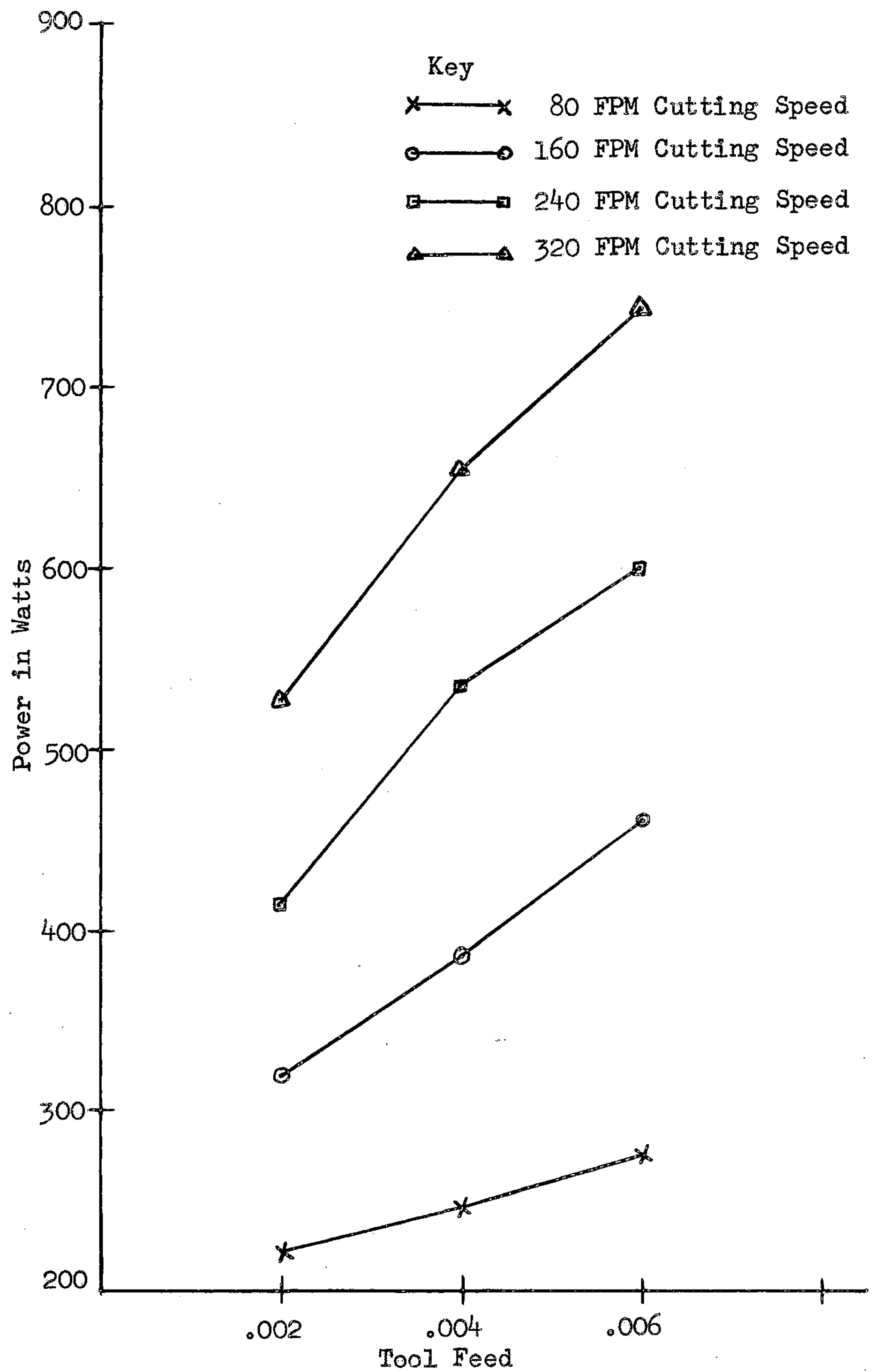

Figure 24. Interaction Tool Feed by Cutting Speed II

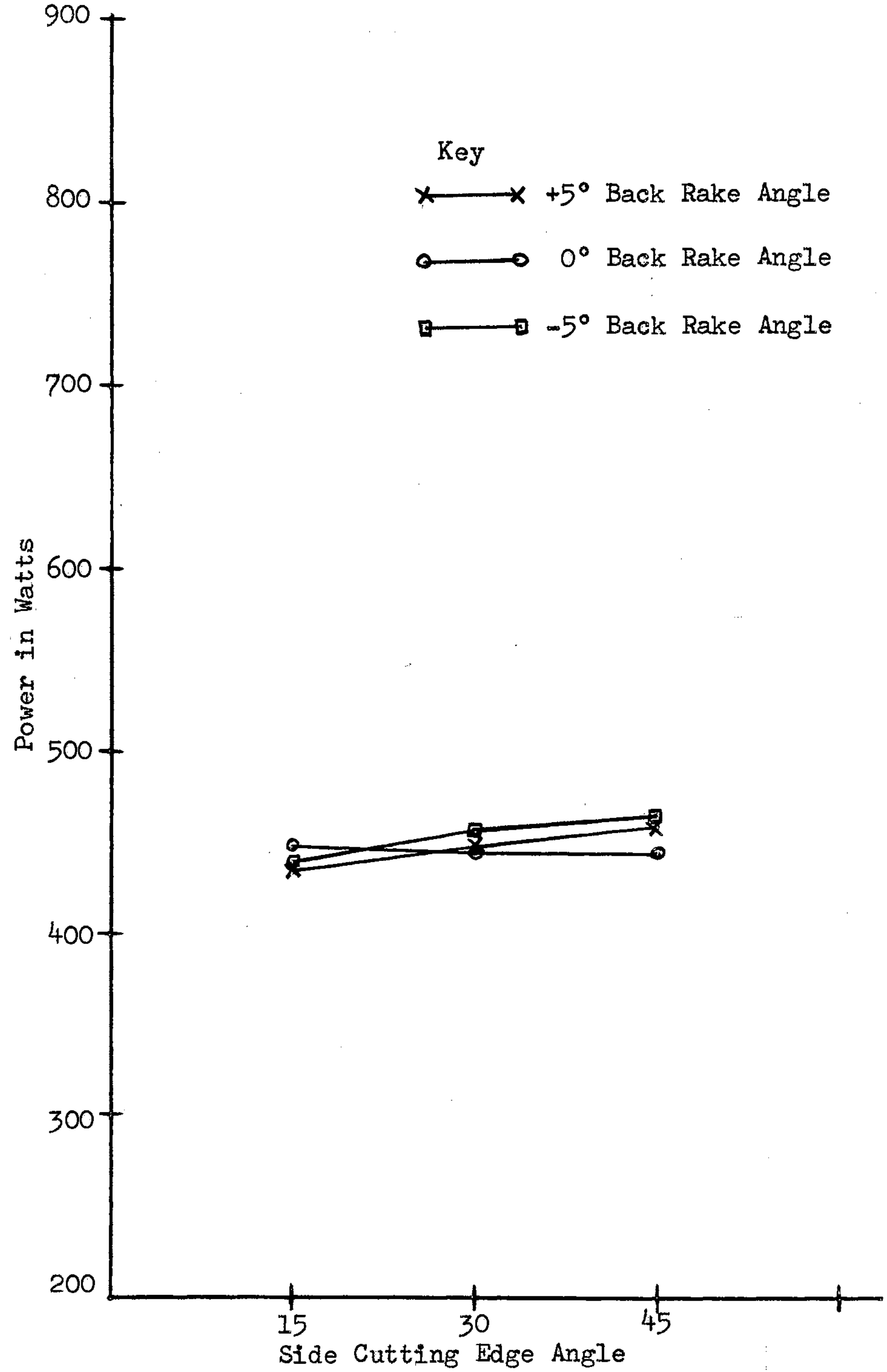

Figure 25. Interaction Side Cutting Edge Angle by Back Rake Angle II

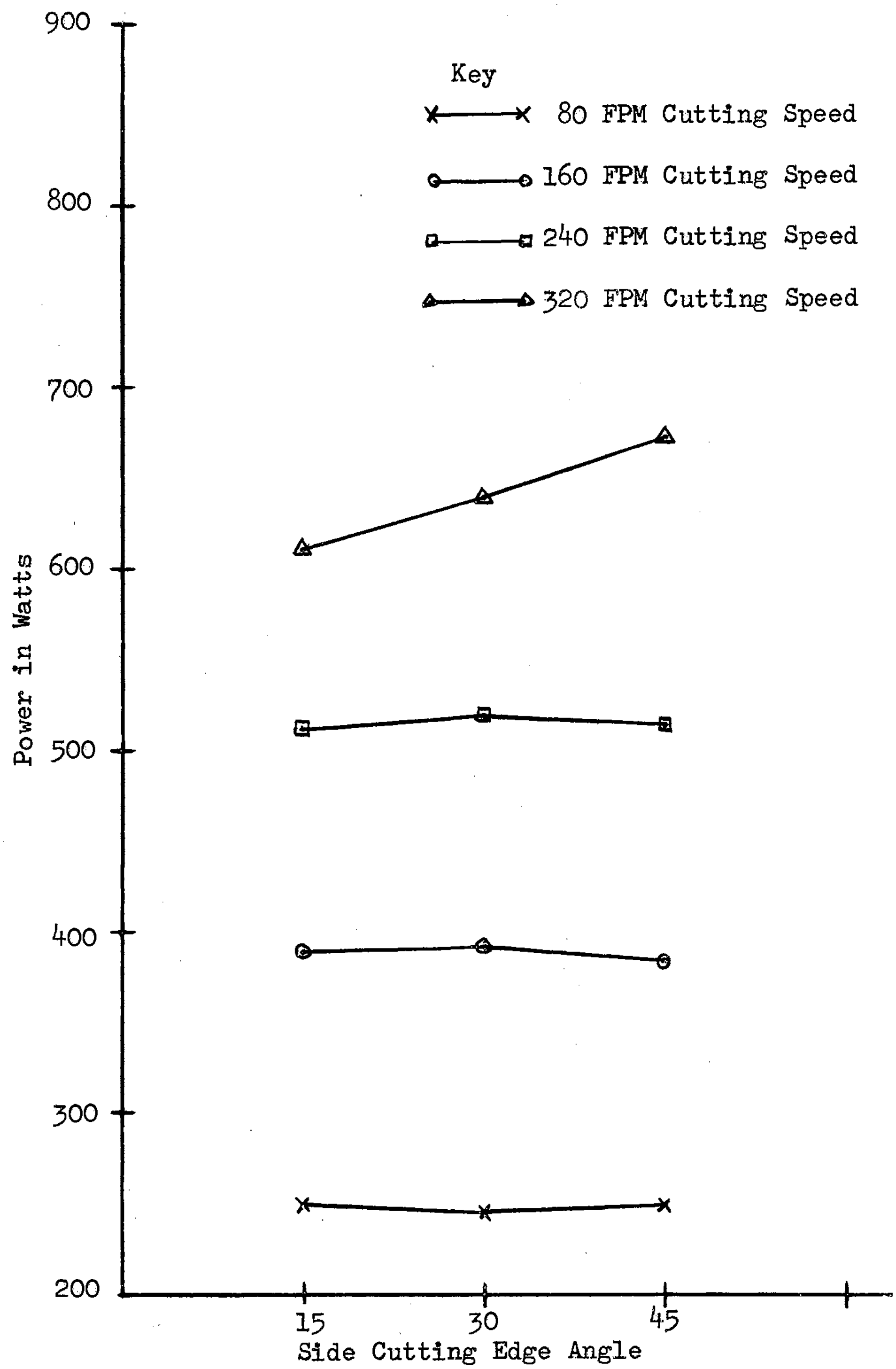

Figure 26. Interaction Side Cutting Edge Angle by Cutting Speed II

has little or no affect on power requirements at the slower speeds, but as the speed increases the effect begins to appear. In comparing Figure 19 with Figure 26, this statement can be substantiated.

Figure 27 does not show any trend except that neither of these factors are very important to power consumption, but that there is enough difference to cause significance.

Figure 28 again indicates the predominance of the speed effect and that the smaller side cutting edge angle does reduce power requirements some at the higher speeds. As seen before, the effect of depth of cut is evident but makes very little change in the over-all interaction as compared to Figure 22 where only depth of cut and speed were involved. This figure shows a marked difference between the 15° and the 45° side cutting edge angle that is significant in the interaction.

Figure 29 shows quite effectively that the trials are not a significant variable, but is carried into the interaction by other effects. A comparison with Figure 22 clearly shows not much difference in the AE and AEF interactions. The speed and depth of cut effects are the same as those stated for Figure 22.

Figure 30 shows that at the slower speeds back rake has very little effect, but as the speed increases it begins to show some effect. Again it shows generally that trials are not a very important factor, but does show some difference as the speed increases.

Figure 31 summarizes Figure 16 through 30 indicating that speed, depth of cut, feed and side cutting edge angle effect power requirements in that order. Within the limits of this study, the speed is predominant and causes the significant difference in this interaction.

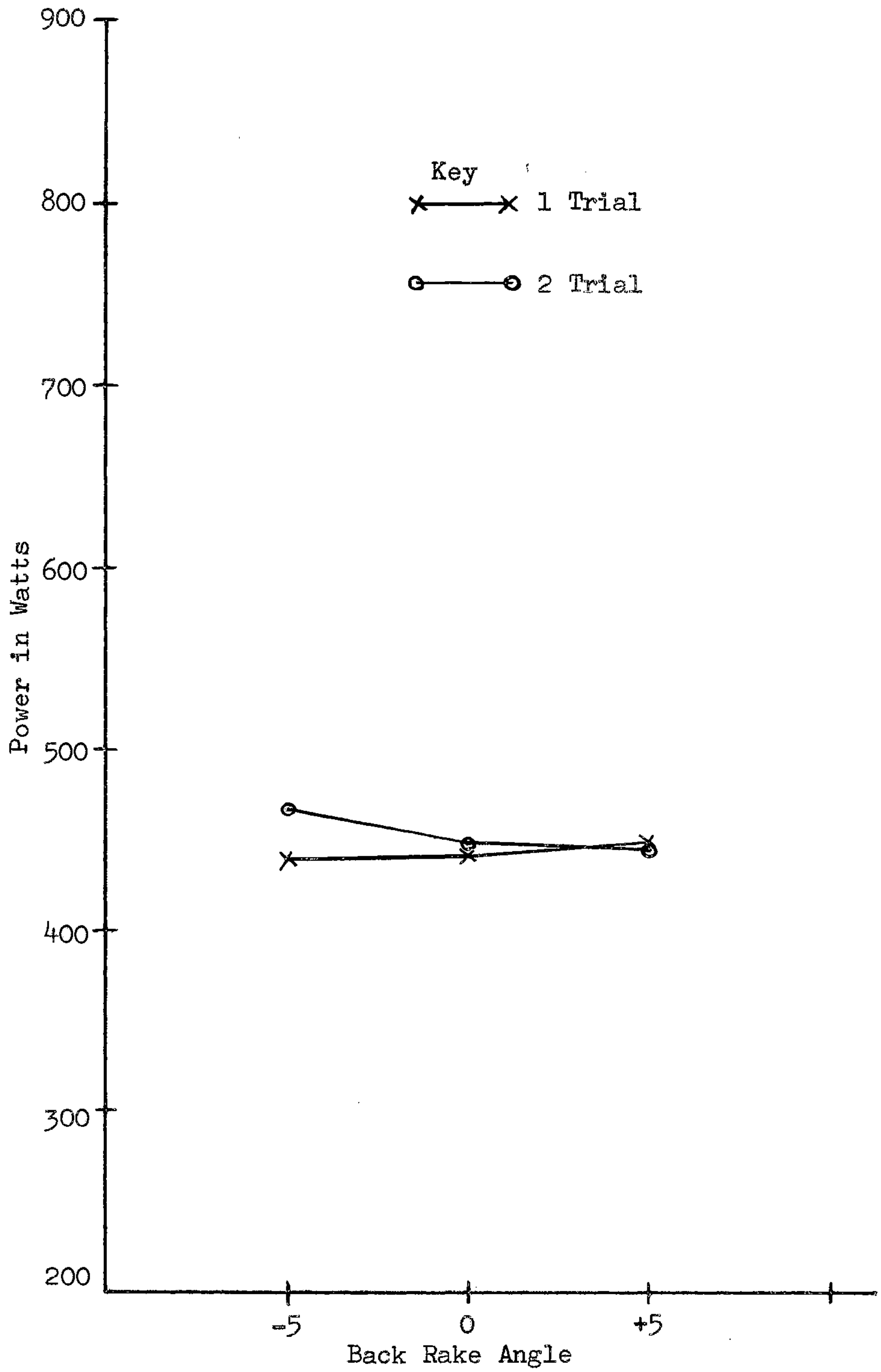

Figure 27. Interaction Back Rake Angle by Trials - II

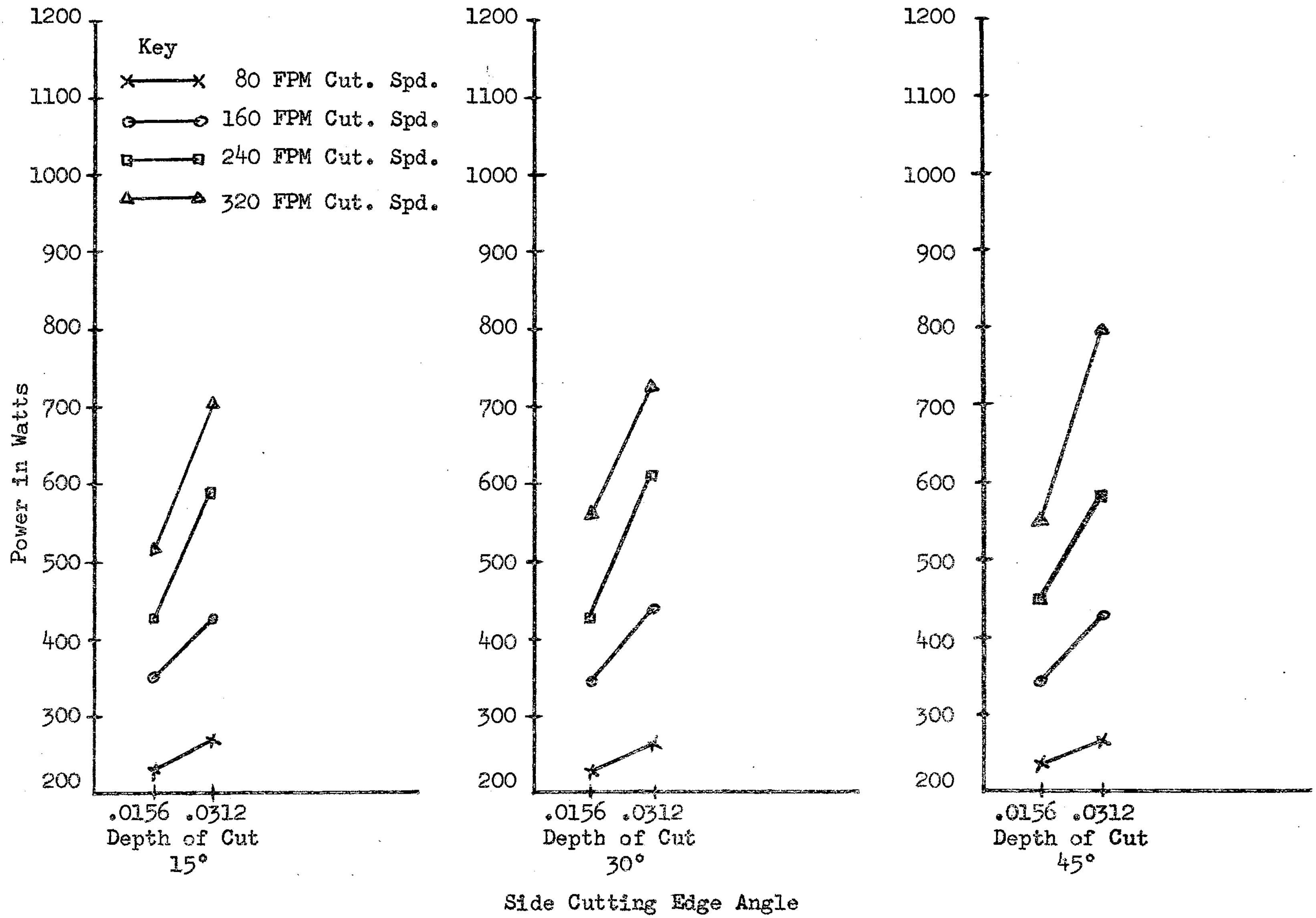

Figure 28. Interaction Depth of Cut by Side Cutting Edge Angle by Cutting Speed - II

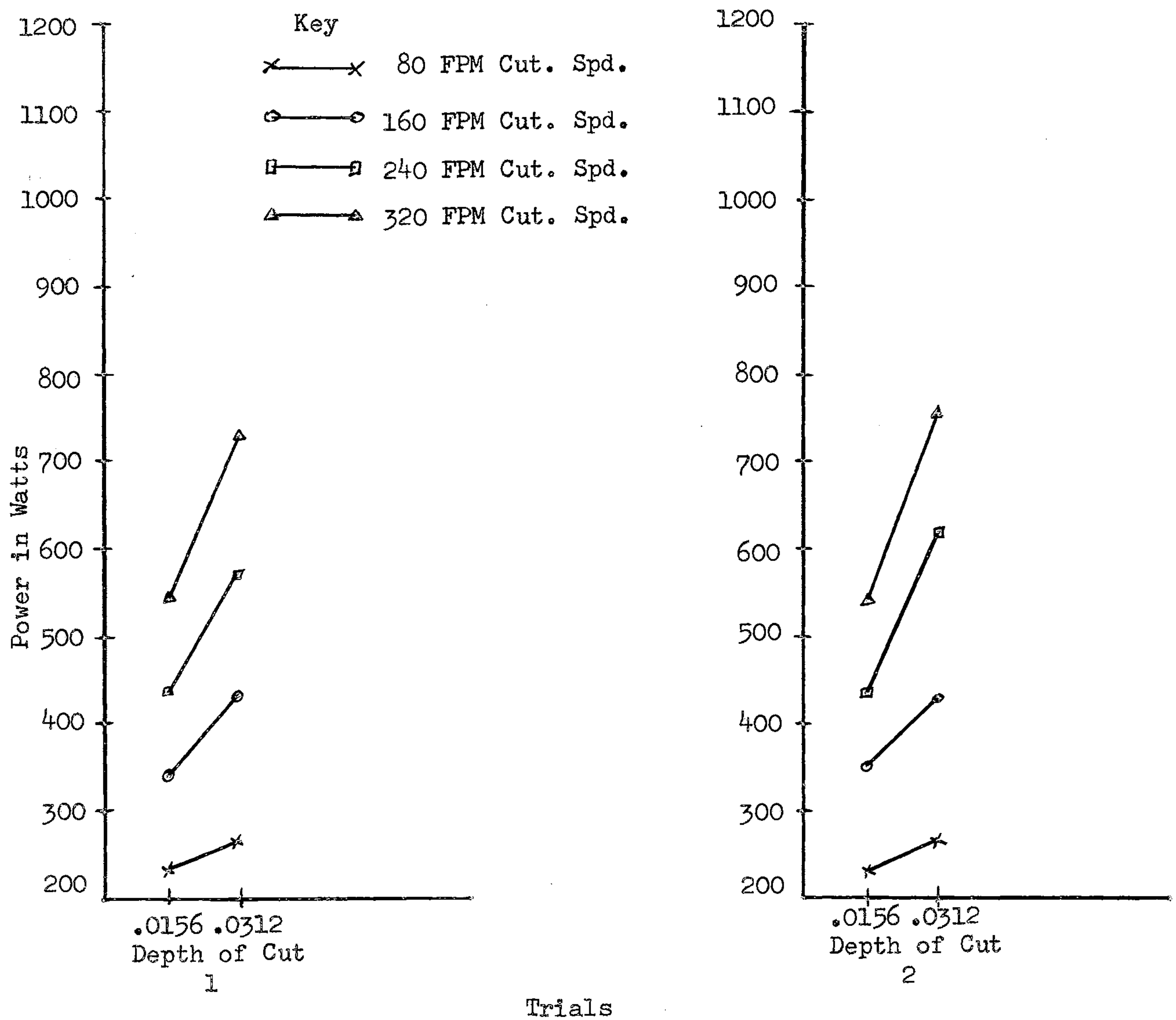

Figure 29. Interaction Depth of Cut by Cutting Speed by Trials II

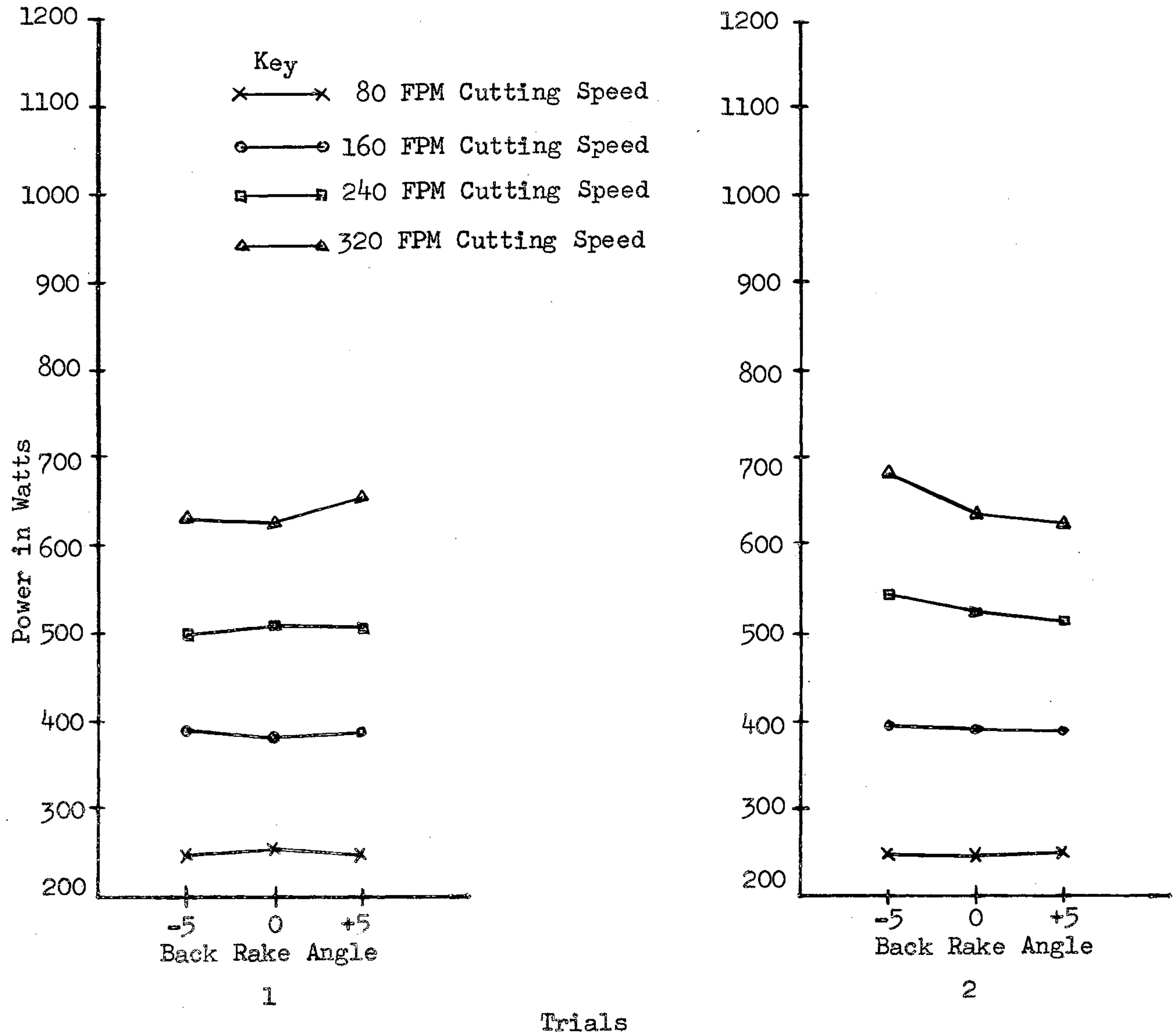

Figure 30. Interaction Back Rake Angle by Cutting Speed by Trials - II

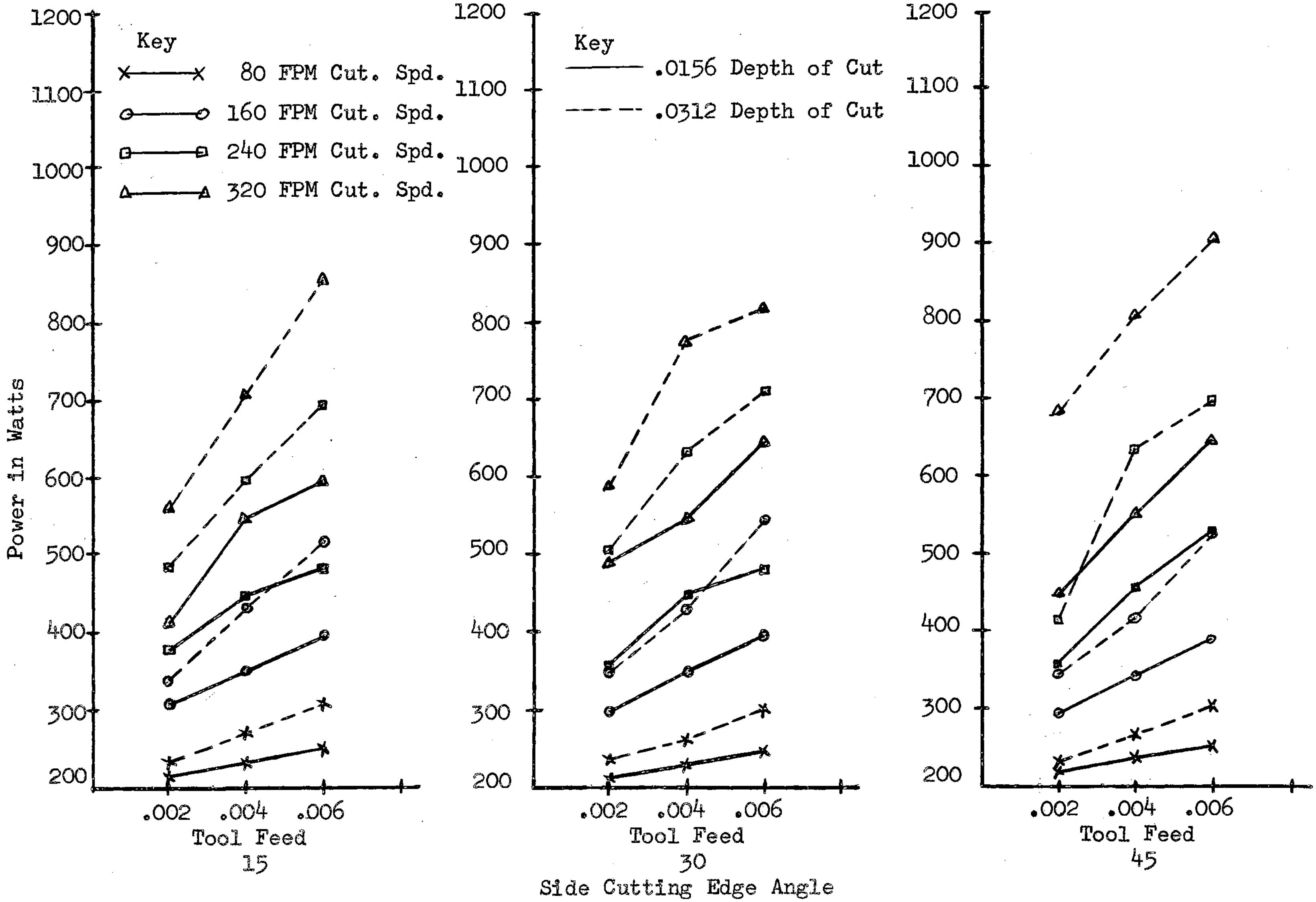

Figure 31. Interaction Depth of Cut by Tool Feed by Side Cutting Edge Angle by Cutting Speed - II

From Table VII the following effects are significant:

1. Main Effects

a.	(A)	Depth of Cut	Figure 32
b.	(B)	Tool Feed	Figure 33
c.	(C)	Side Cutting Edge Angle	Figure 34
d.	(D)	Back Rake Angle	Figure 35
e.	(E)	Cutting Speed	Figure 36
f.	(F)	Trials	Figure 37

2. First Order Interactions

a.	(AB)	Depth of Cut by Tool Feed	Figure 38
b.	(AD)	Depth of Cut by Back Rake Angle	Figure 39
c.	(AE)	Depth of Cut by Cutting Speed	Figure 40
d.	(BD)	Tool Feed by Back Rake Angle	Figure 41
e.	(BE)	Tool Feed by Cutting Speed	Figure 42
f.	(BF)	Tool Feed by Trials	Figure 43
g.	(CD)	Side Cutting Edge Angle by Back Rake Angle	Figure 44
h.	(CE)	Side Cutting Edge Angle by Cutting Speed	Figure 45
i.	(DE)	Back Rake Angle by Cutting Speed	Figure 46
j.	(DF)	Back Rake Angle by Trials	Figure 47
k.	(EF)	Cutting Speed by Trials	Figure 48

3. Second Order Interactions

a. (ABD) Depth of Cut by Tool Feed by Back Rake Angle — Figure 49

b. (ABE) Depth of Cut by Tool Feed by Cutting Speed — Figure 50

c. (ACE) Depth of Cut by Side Cutting Edge Angle by Cutting Speed — Figure 51

d. (ACF) Depth of Cut by Side Cutting Edge Angle by Trials — Figure 52

e. (ADE) Depth of Cut by Back Rake Angle by Cutting Speed — Figure 53

f. (BCE) Tool Feed by Side Cutting Edge Angle by Cutting Speed — Figure 54

g. (BDE) Tool Feed by Back Rake Angle by Cutting Speed — Figure 55

4. Third Order Interactions

a. (ABCE) Depth of Cut by Tool Feed by Side Cutting Edge Angle by Cutting Speed — Figure 56

b. (ABDE) Depth of Cut by Tool Feed by Back Rake Angle by Cutting Speed — Figure 57

c. (BCEF) Tool Feed by Side Cutting Edge Angle by Cutting Speed — Figure 58

d. (BDEF) Tool Feed by Back Rake Angle by Cutting Speed by Trials — Figure 59

Figure 32 indicates that the depth of cut has a definite effect on the power. A comparison with Figure 19 indicates the same rate of climb of the power requirements is carried from the two levels of depth of cut into the three levels of depth of cut.

Figure 33 shows the same general slope as that of Figure 17, but shows considerable increase in the power requirement pointing out the affect of the depth of cut on the power since Figure 17 considers only two levels of depth of cut as Figure 33 considers three levels of depth of cut.

Figure 34 indicates an increase in power of about the same magnitude as does Figure 18 for the three side cutting edge angles, but again shows the increase in total power because of the consideration of the third level of depth of cut.

Figure 35 shows that as the back rake angle moves from negative to positive there is a slight decrease in the power requirements. This appears to indicate that the zero degree back rake should be given more careful consideration.

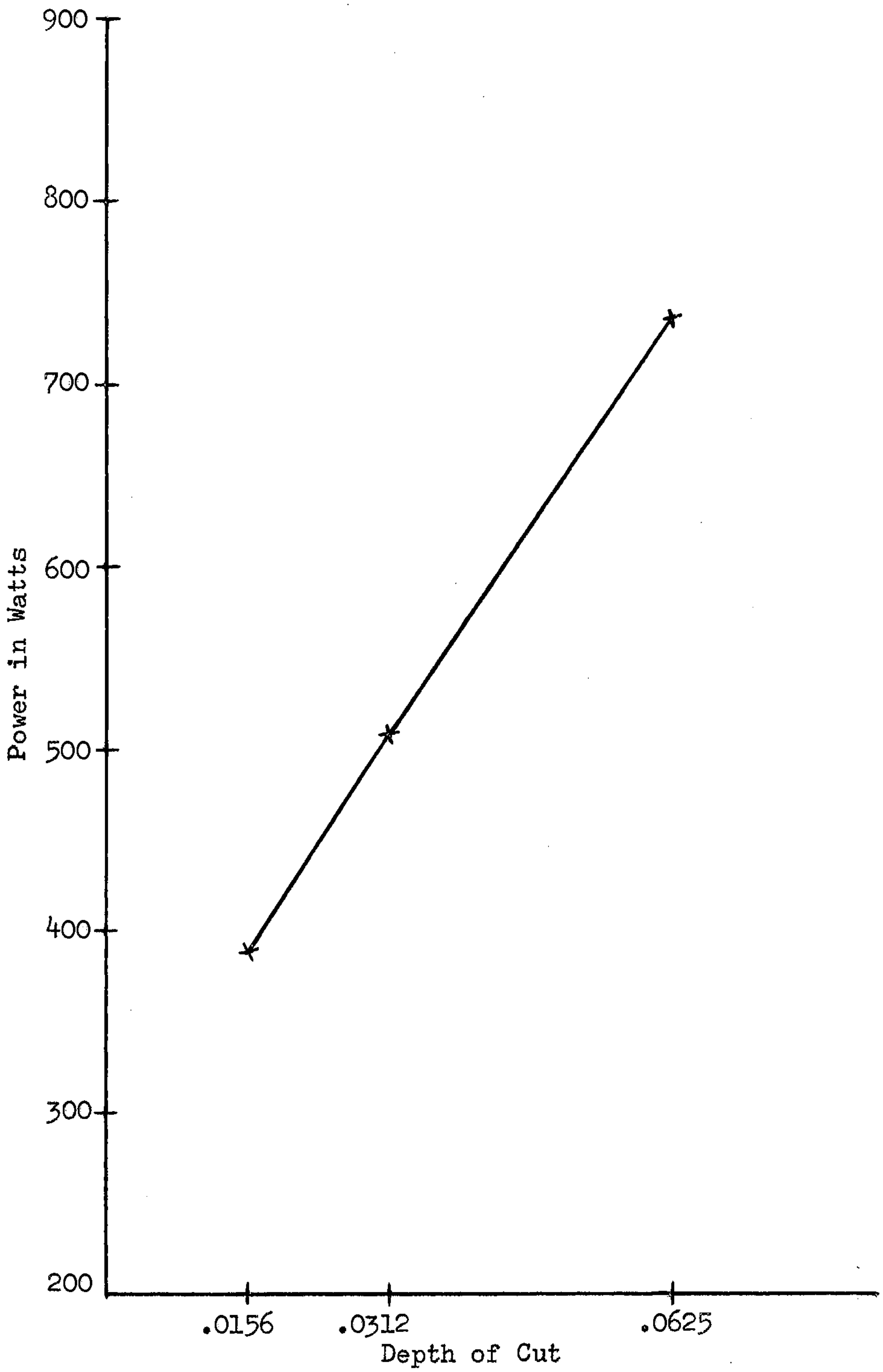

Figure 32. Main Effect Depth of Cut - III

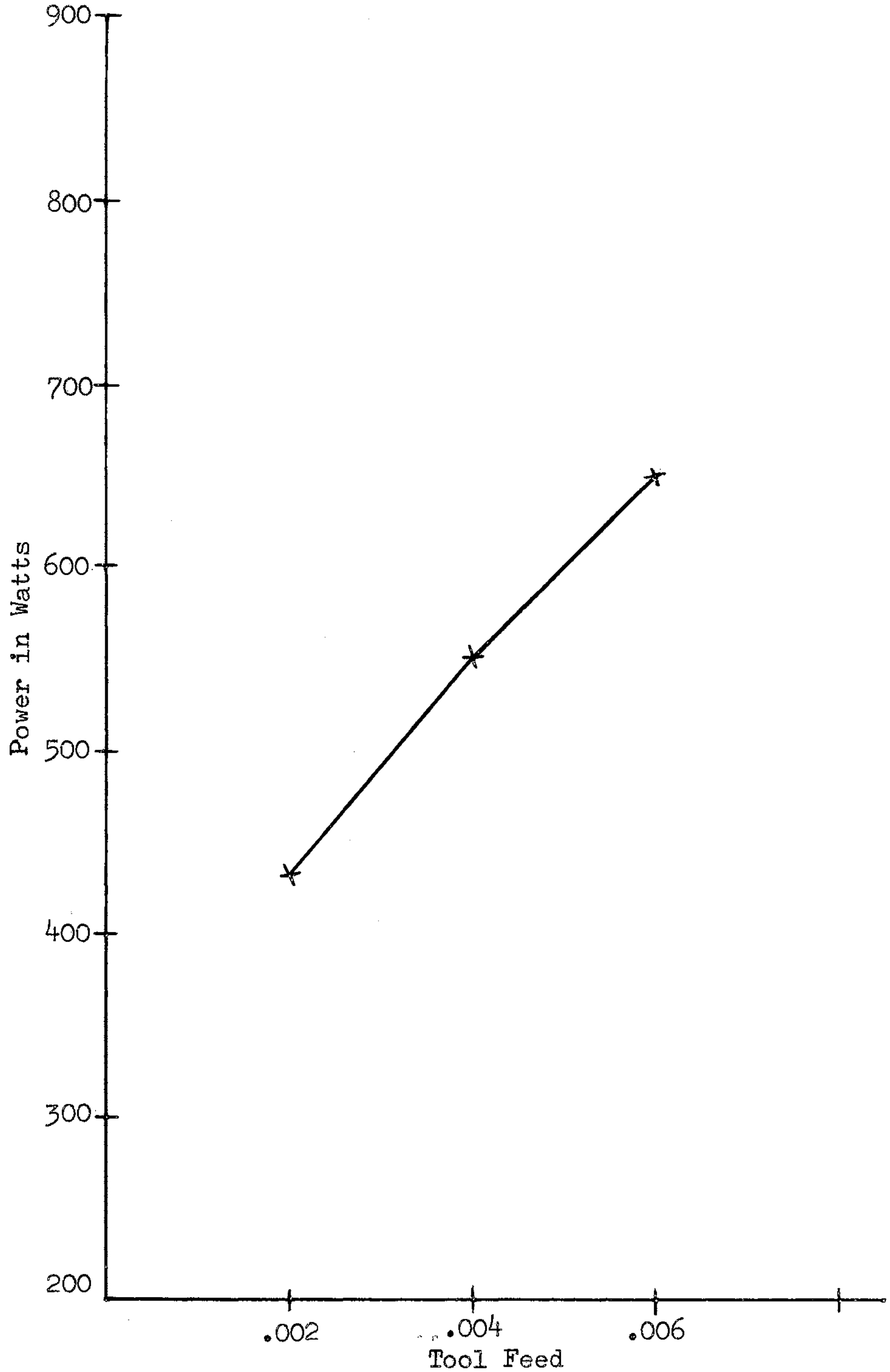

Figure 33. Main Effect Tool Feed - III

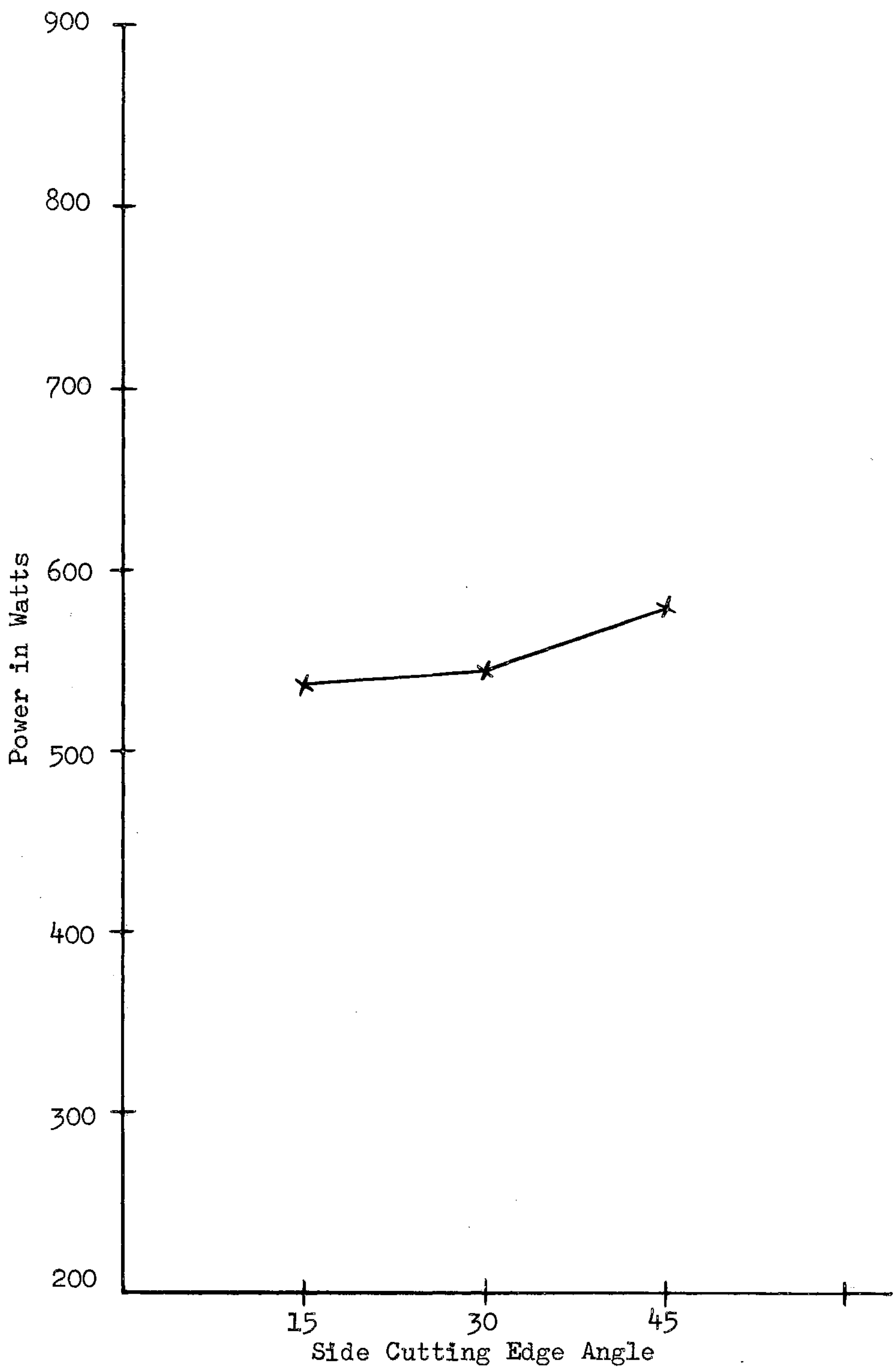

Figure 34. Main Effect Side Cutting Edge Angle - III

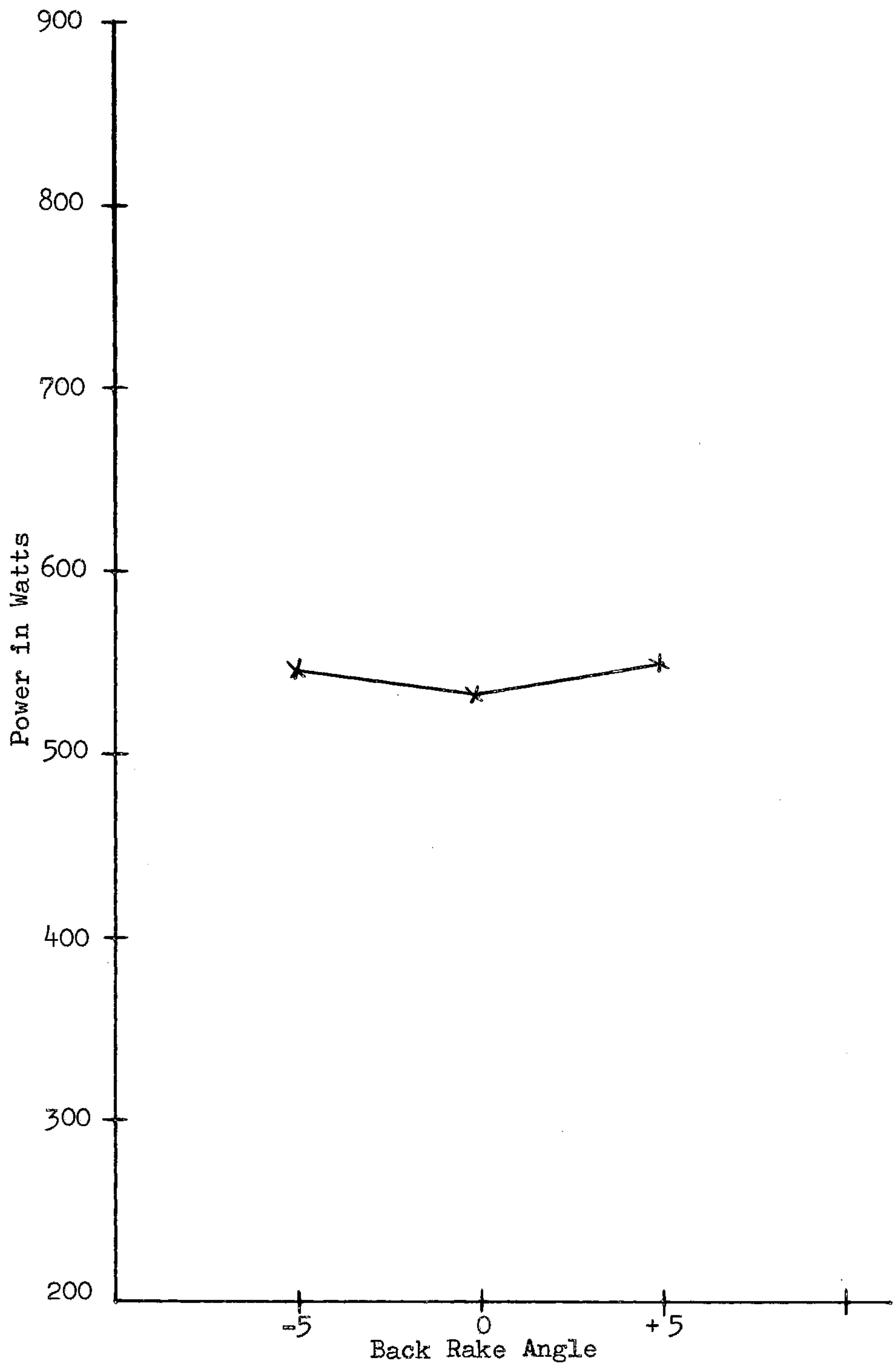

Figure 35. Main Effect Back Rake Angle - III

Figure 36 shows the affect of speed to have the same general slope as that of Figure 19 where only two levels of depth of cut were considered. The over-all increase in the power requirements can again be attributed to the effect of considering the third level of depth of cut.

Figure 37 shows trials significant as it was with the two factors depth of cut analysis. The reason for significance here would be the same as stated on page 63.

Figure 38 shows the same general trend as that of Figure 21 indicating that the depth of cut does have considerable affect on the power requirements. As stated in Chapter III, Boston (2) considers this combination to have a significant effect on power.

From Figure 39 one would have to conclude that the back rake angle has little affect on the power consumption. Depth of cut again appears as the predominant factor and has prevailed in this interaction making it significant.

Figure 40 extends the trends established in Figure 22 in a linear fashion. This was expected since depth of cut and speed played an important part in the analysis at the two level depth of cut.

Figure 41 appears to contradict the feed effect shown in Figure 33, but at the same time does not completely follow the back rake angle effect of Figure 35. The -5° back rake angle which is supposed to have the most affect on reducing power for the cutting tool steel involved does not appear to have this effect indicating that either back rake needs to be investigated more or that it has very little effect in total power consumption.

Figure 42 indicates the same general trend as shown in Figure 24.

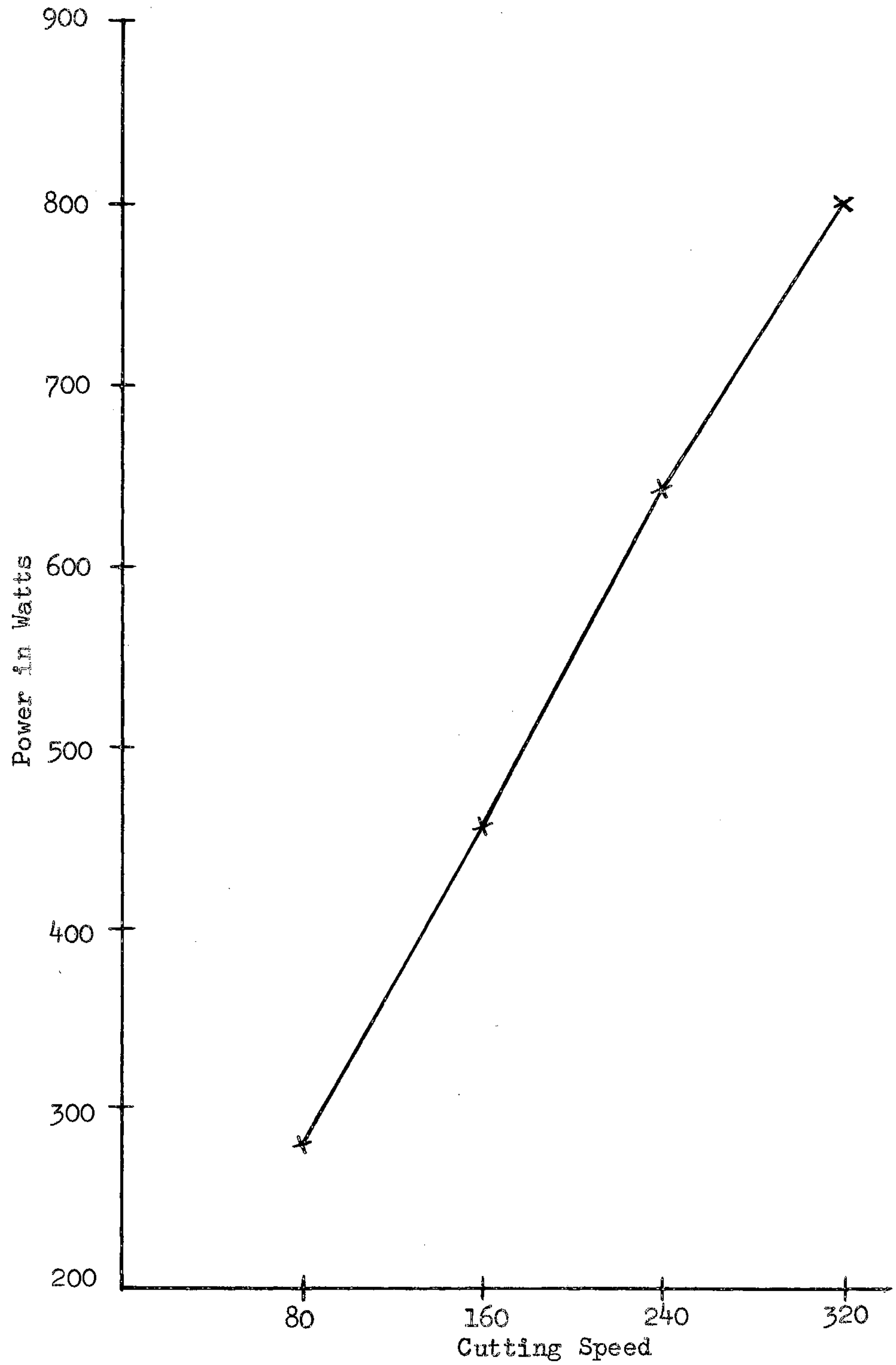

Figure 36. Main Effect Cutting Speed - III

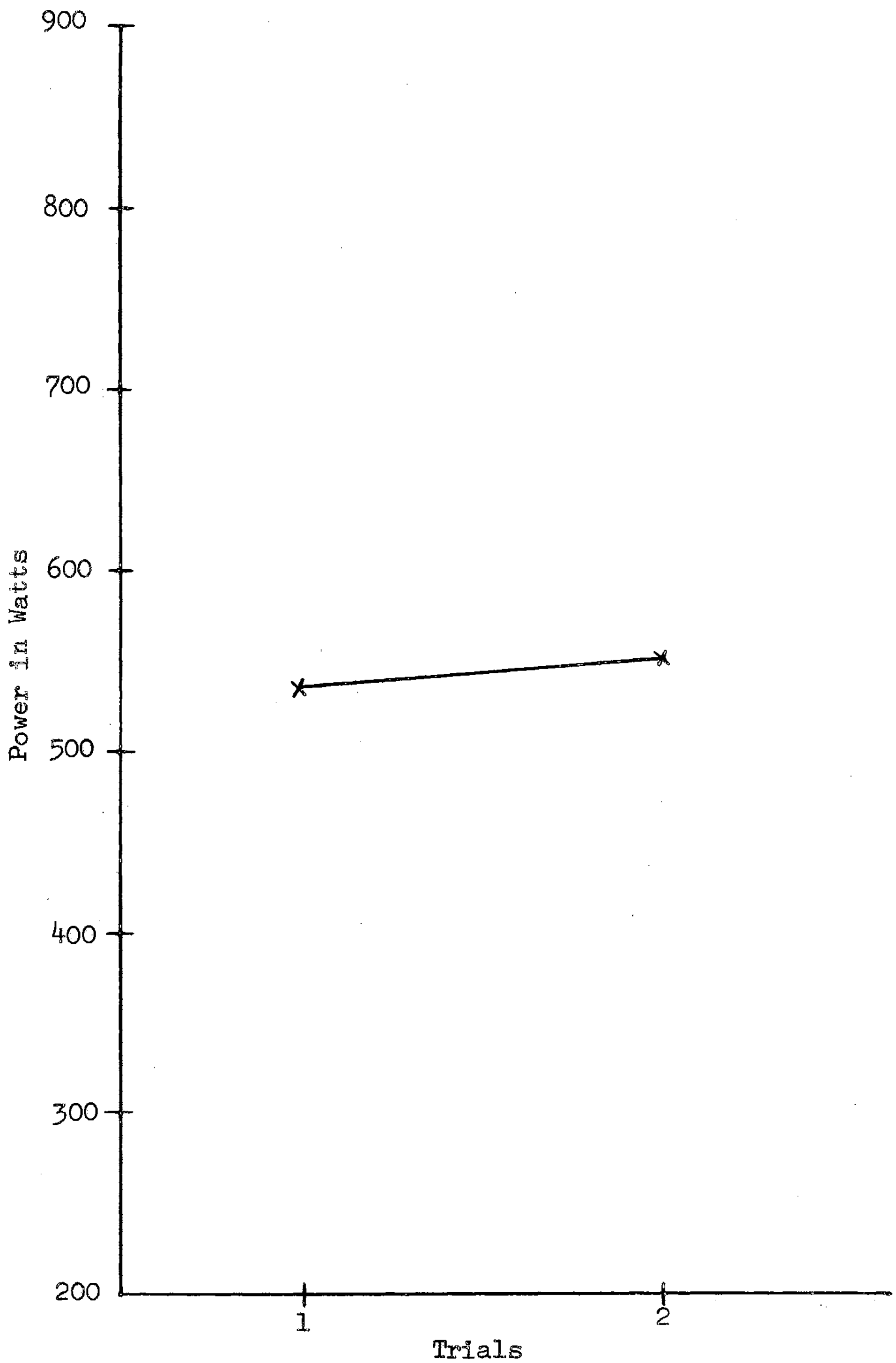

Figure 37. Main Effect Trials - III

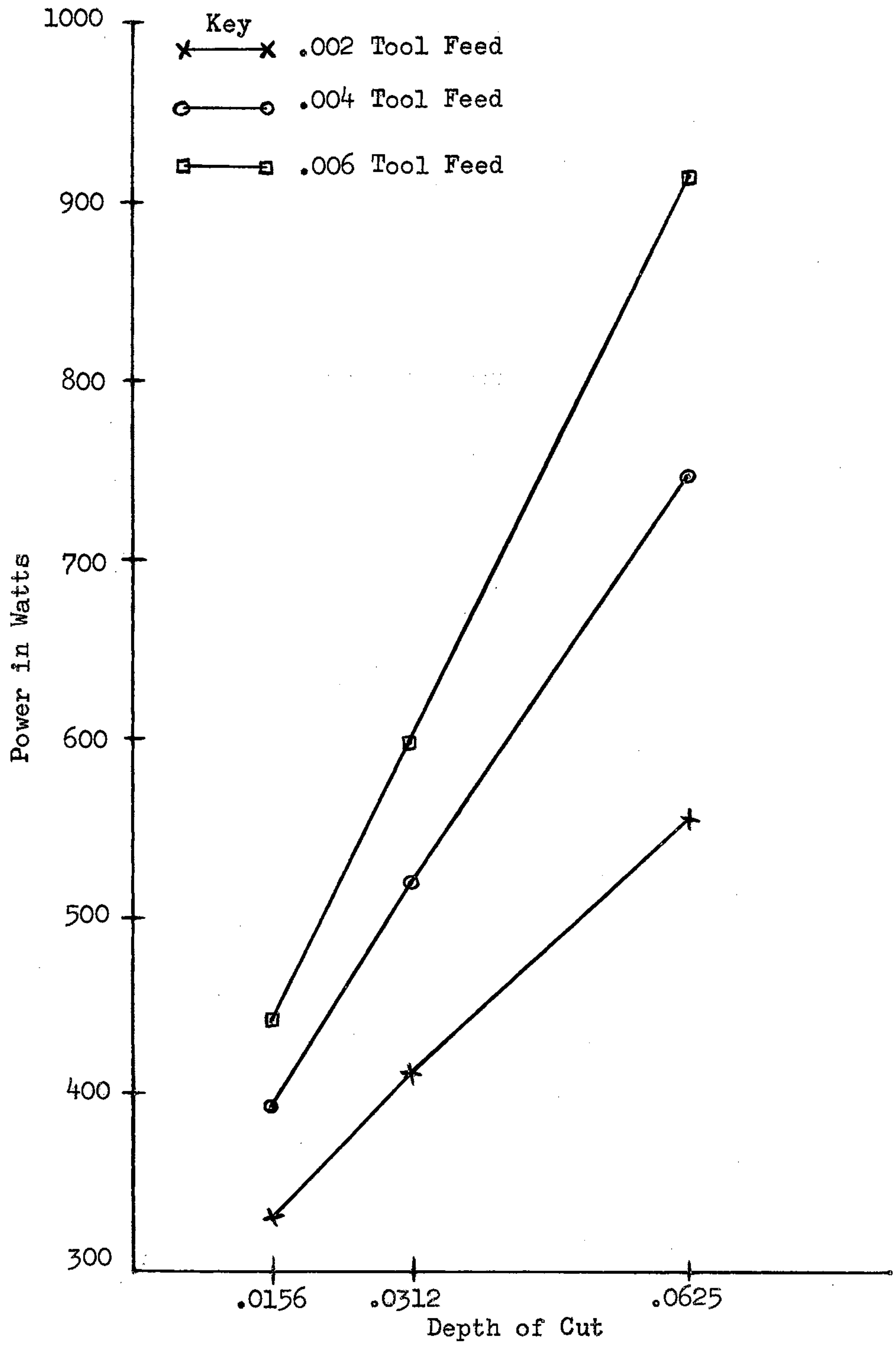

Figure 38. Interaction Depth of Cut by Tool Feed - III

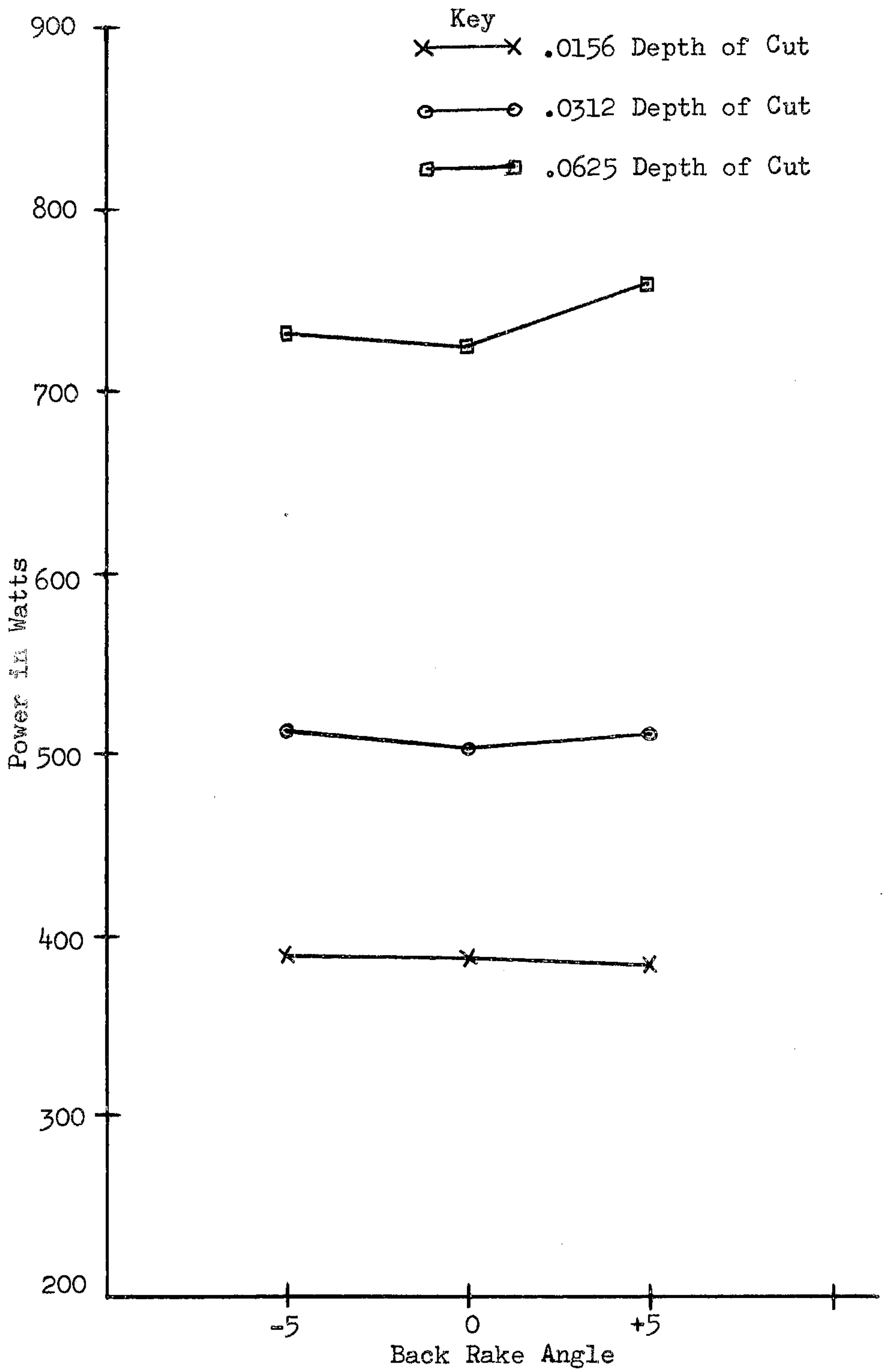

Figure 39. Interaction Back Rake Angle by Depth of Cut - III

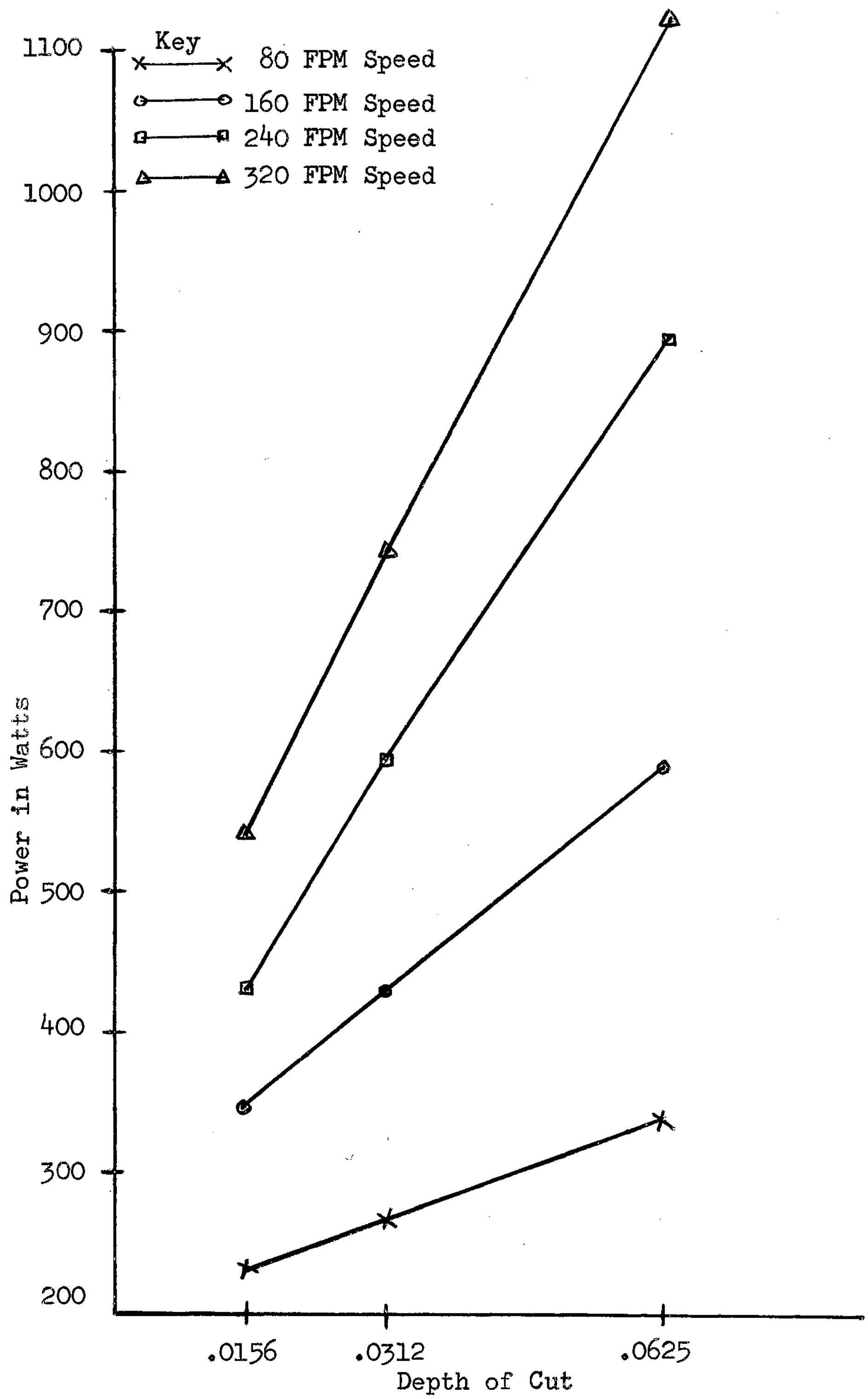

Figure 40. Interaction Depth of Cut by Cutting Speed - III

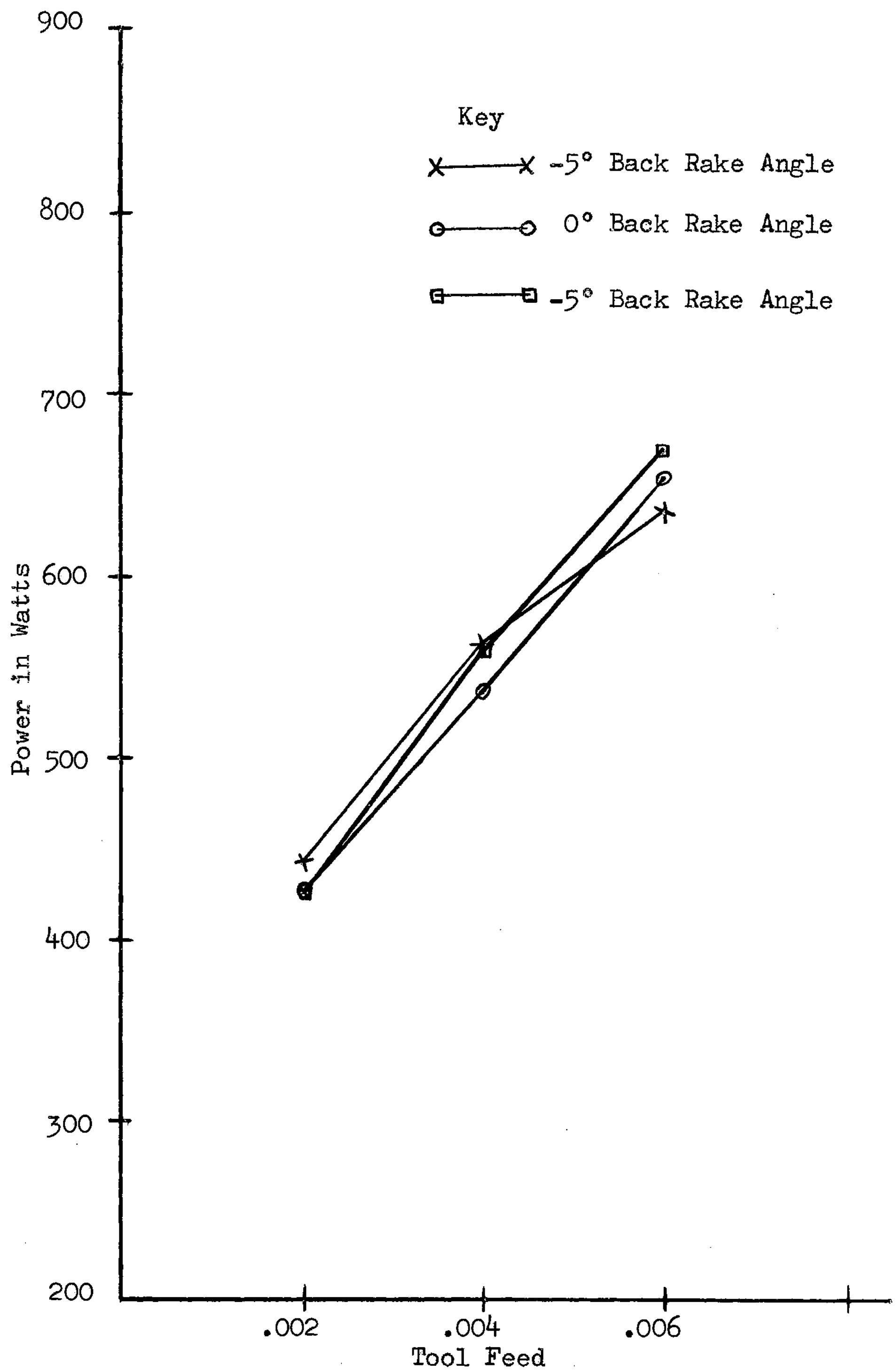

Figure 41. Interaction Tool Feed by Back Rake Angle - III

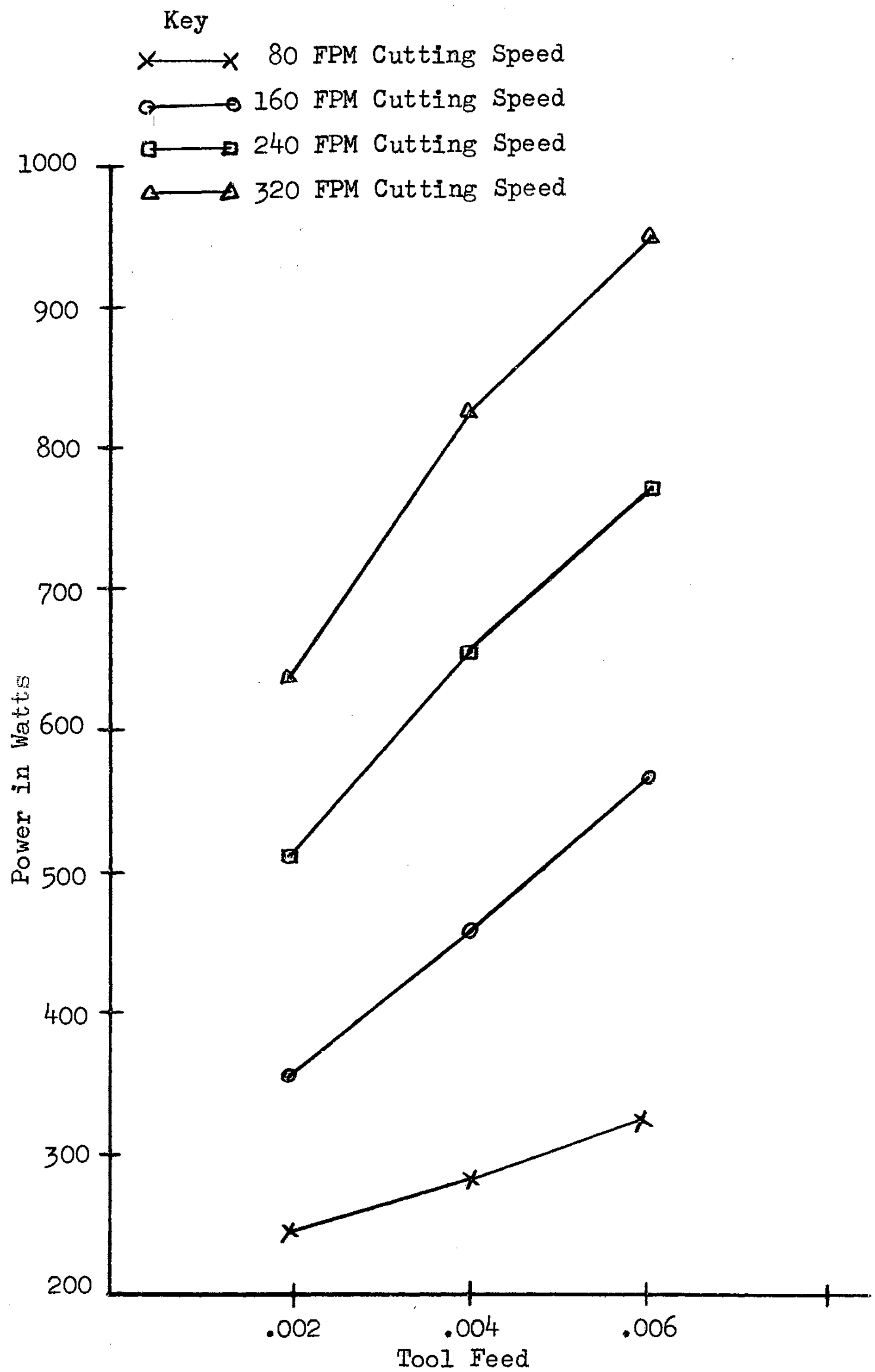

Figure 42. Interaction Tool Feed by Cutting Speed - III

Again the increase in power requirements can be attributed to the additional level of the variable depth of cut.

Figure 43 indicates an interaction between feed and trials, but an examination of Figure 33 indicates very little change in the feed effect; therefore, it appears that trials have enough difference to cause the effect to be significant, but that they have little affect on the total power requirement.

The side cutting edge angle by back rake effect shown in Figure 44 indicates the same general pattern as that shown in Figure 25. It is at the higher power requirements because of the effect of the additional depth of cut.

Figure 45 indicates just as was shown by Figure 26 that at slower speed the side cutting edge angle has little or no effect on the power requirements. It also shows, that at the higher speed, there is some change indicating some further study in this area.

The DE interaction shown in Figure 46 did not appear significant in the two-level of depth of cut analysis; therefore, it has been plotted with speed as a coordinate and, as can be seen from this type of graph, back rake angle has almost no effect on the speed when comparing it with Figure 36.

The DF interaction of Figure 47 indicates the same trend as the DF interaction of Figure 27 but at a higher power level due to the additional depth of cut being considered. This effect will become negligible in the higher order interaction analysis.

The speed effect in Figure 48 is the same as that of Figure 36 indicating that the trials, although significant in the interaction, do not have much of an affect except at the higher speeds used in this study.

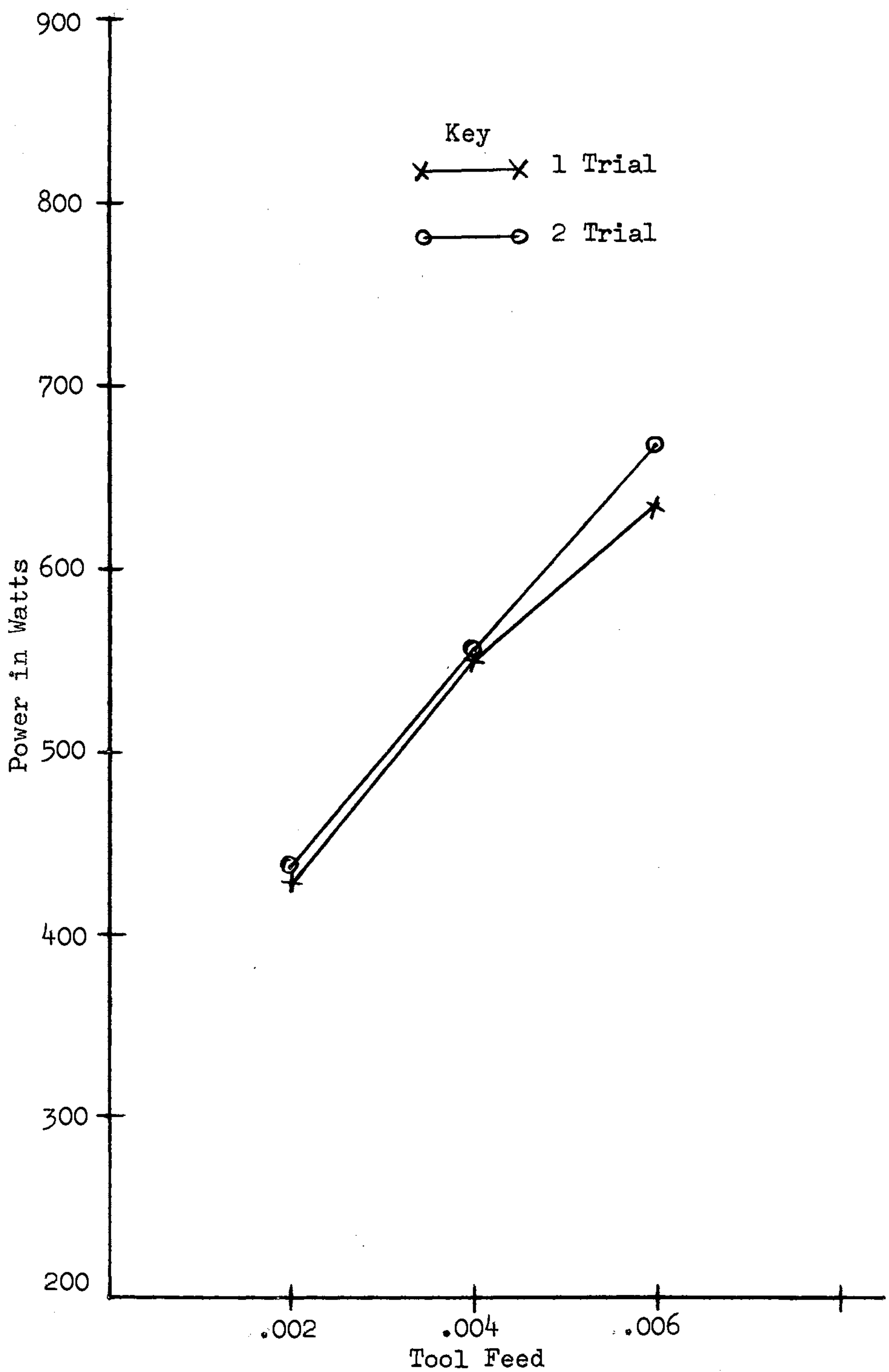

Figure 43. Interaction Tool Feed by Trials - III

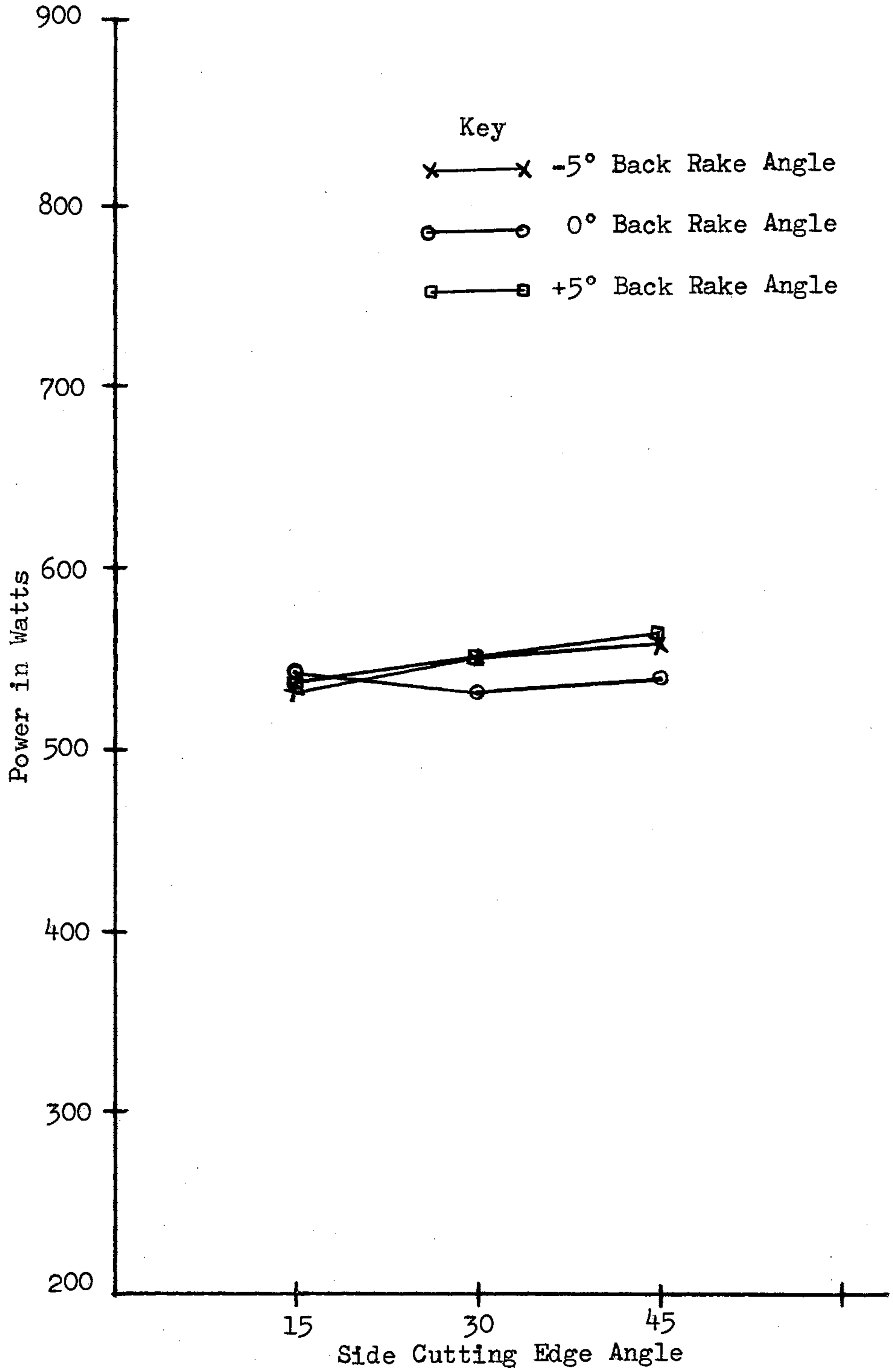

Figure 44. Interaction Side Cutting Edge Angle by Back Rake Angle - III

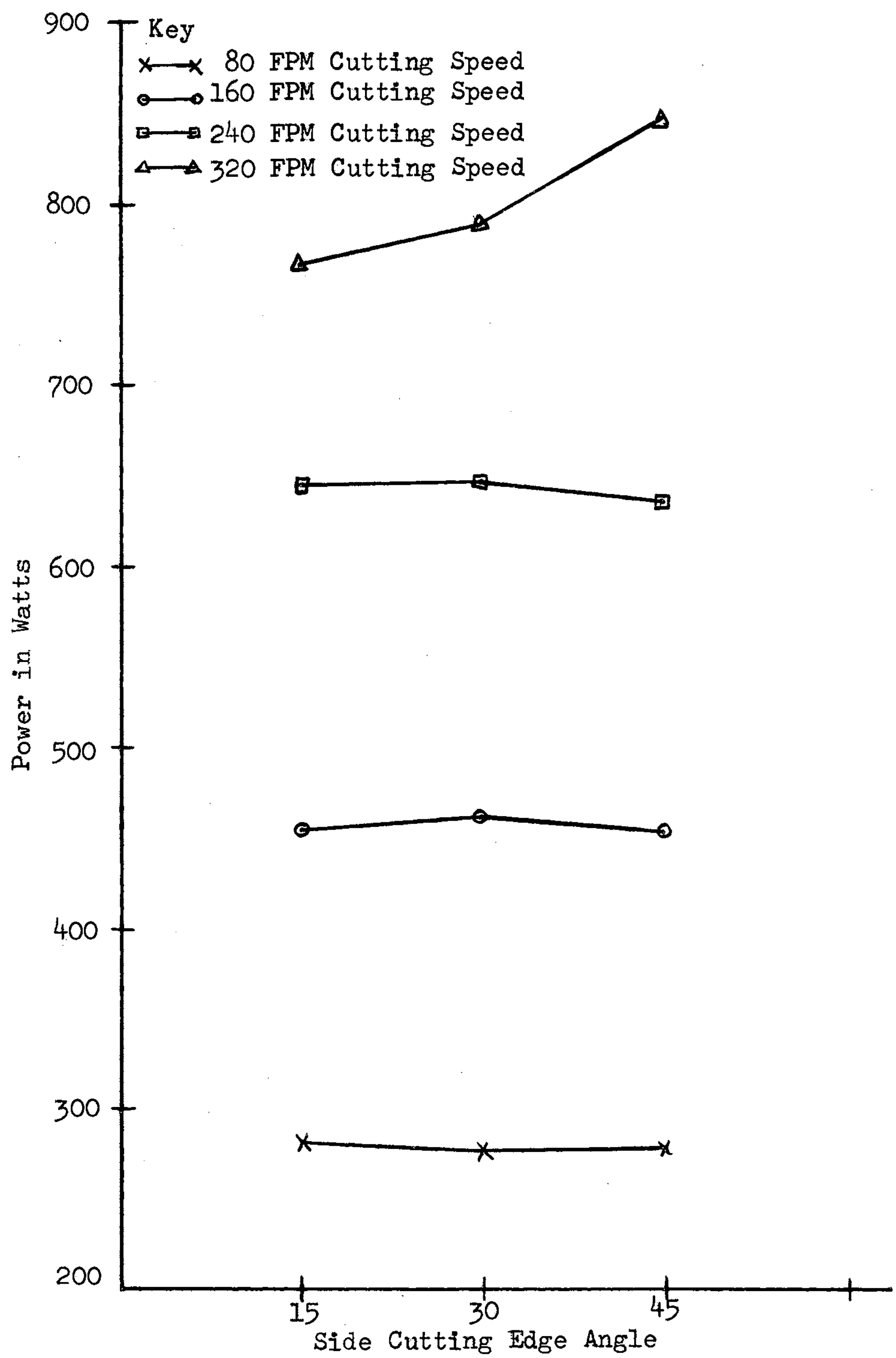

Figure 45. Interaction Side Cutting Edge Angle by Cutting Speed - III

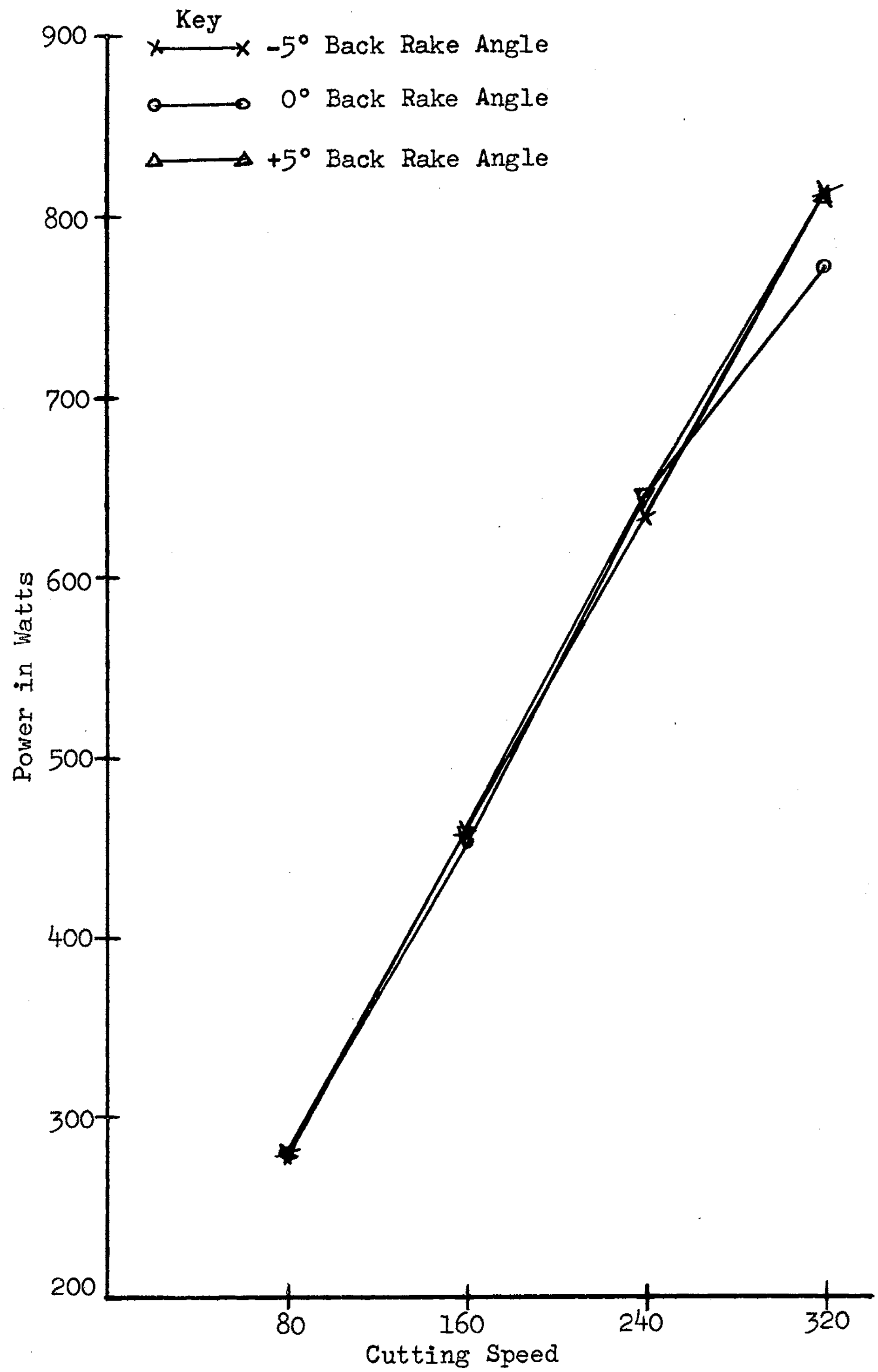

Figure 46. Interaction Cutting Speed by Back Rake Angle - III

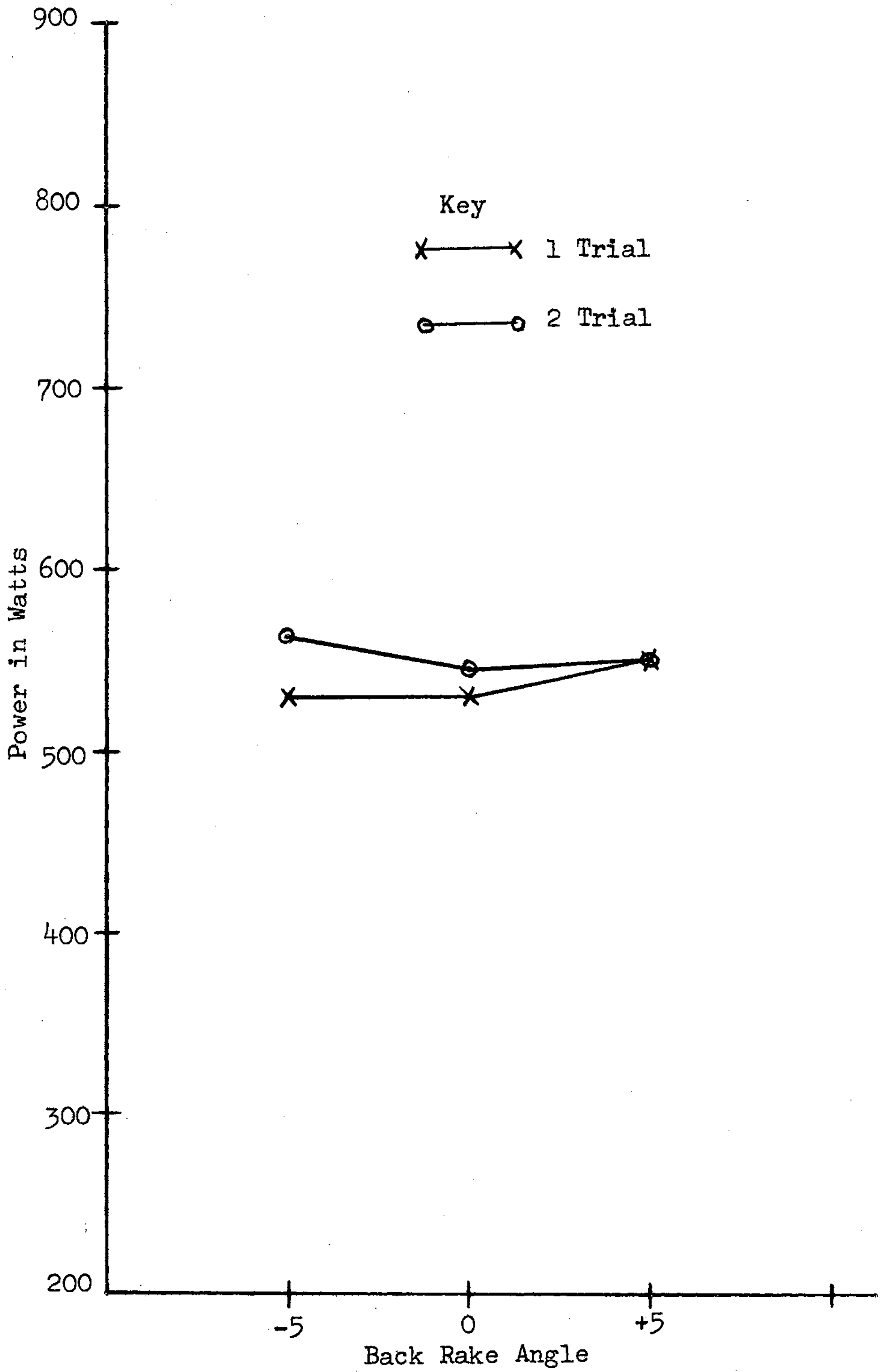

Figure 47. Interaction Back Rake Angle by Trials - III

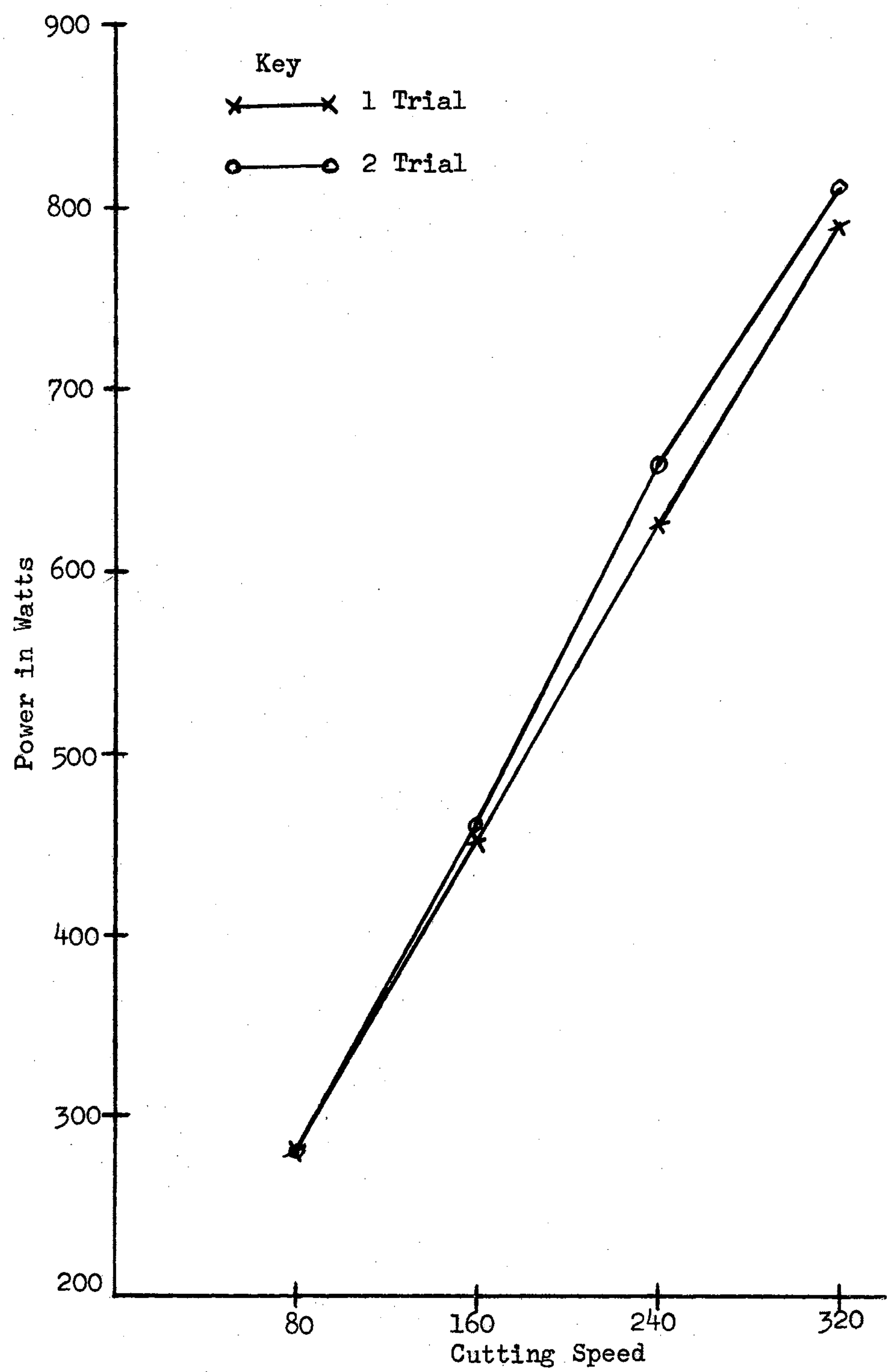

Figure 48. Interaction Cutting Speed by Trials - III

Figure 49 indicates still further that back rake has little effect since a comparison of Figure 49 with the AB interaction of Figure 38 indicates the same general pattern, that the increase in feed with depth of cut increases the power slightly.

The significance of the ABE interaction shown in Figure 50 was expected since these are the three most dominant factors in affecting power requirements. This effect was not significant in the two-level depth of cut analysis which can only be explained by the fact that the additional level of the depth of cut factor had enough influence on the interaction to cause it to be significant.

Figure 51 continues the trend shown in Figure 28, that the increase in the side cutting edge angle at the higher cutting speed causes an increase in the power requirements. The speed increase is also very evident as is the difference in the depth of cut.

An examination of Figure 52 indicates that trials have little effect on variable speed and since the AC interaction was not significant it can be concluded that the side cutting edge angle does not have any great effect on cutting speeds' influence of the power requirements.

Figure 53 again shows the effect of the interaction of depth of cut and speed, and also indicates again that the back rake has very little influence at the slower speeds and only a slight influence at the higher speeds. Comparing this to Figure 39 shows the same general trends as that of the previous analysis.

By comparing Figure 54 with Figure 42, one can see that the side cutting does not have a prominent effect on the power. The feed and speed produce in general the same pattern as was shown in Figure 42.

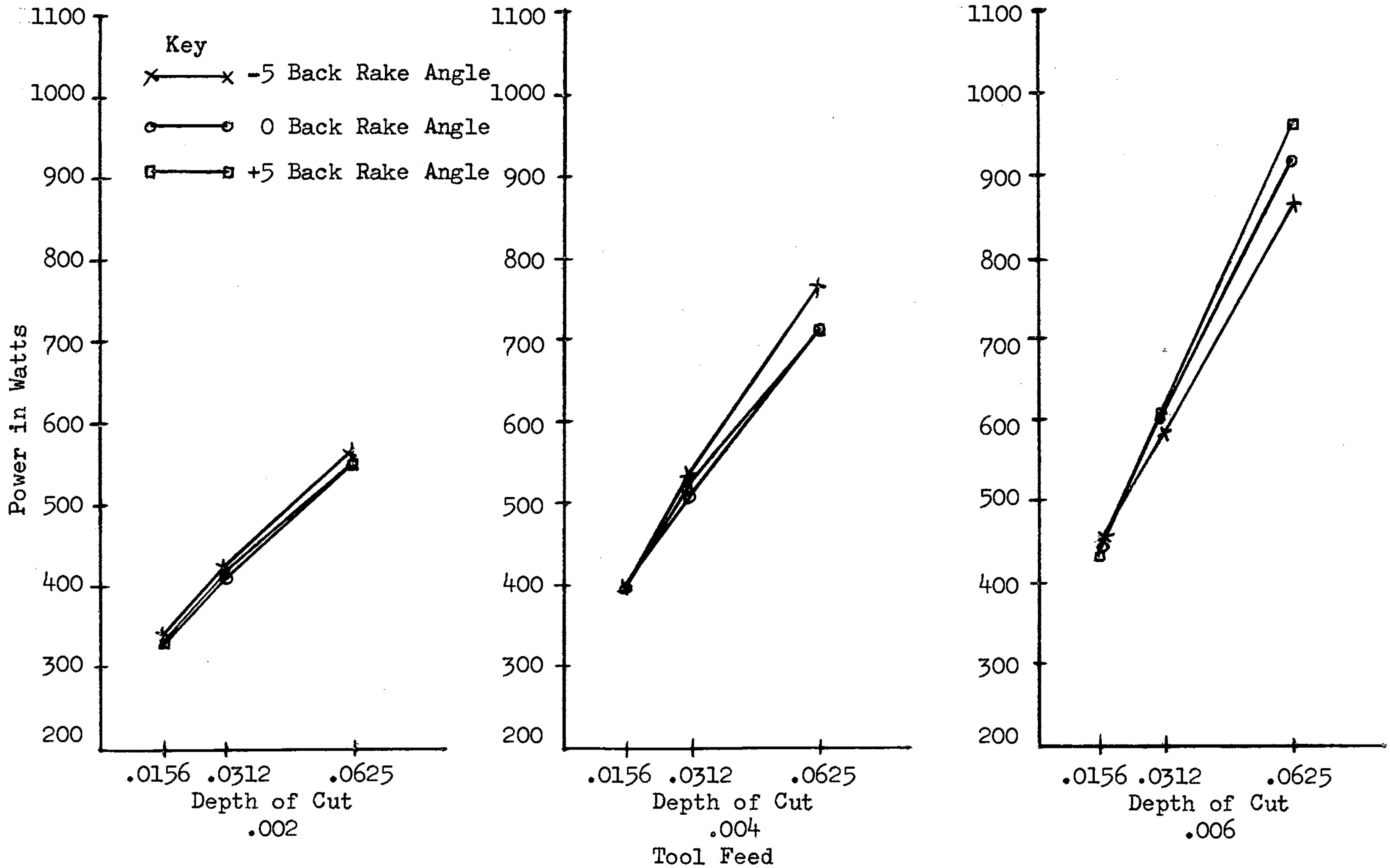

Figure 49. Interaction Depth of Cut by Tool Feed by Back Rake Angle - III

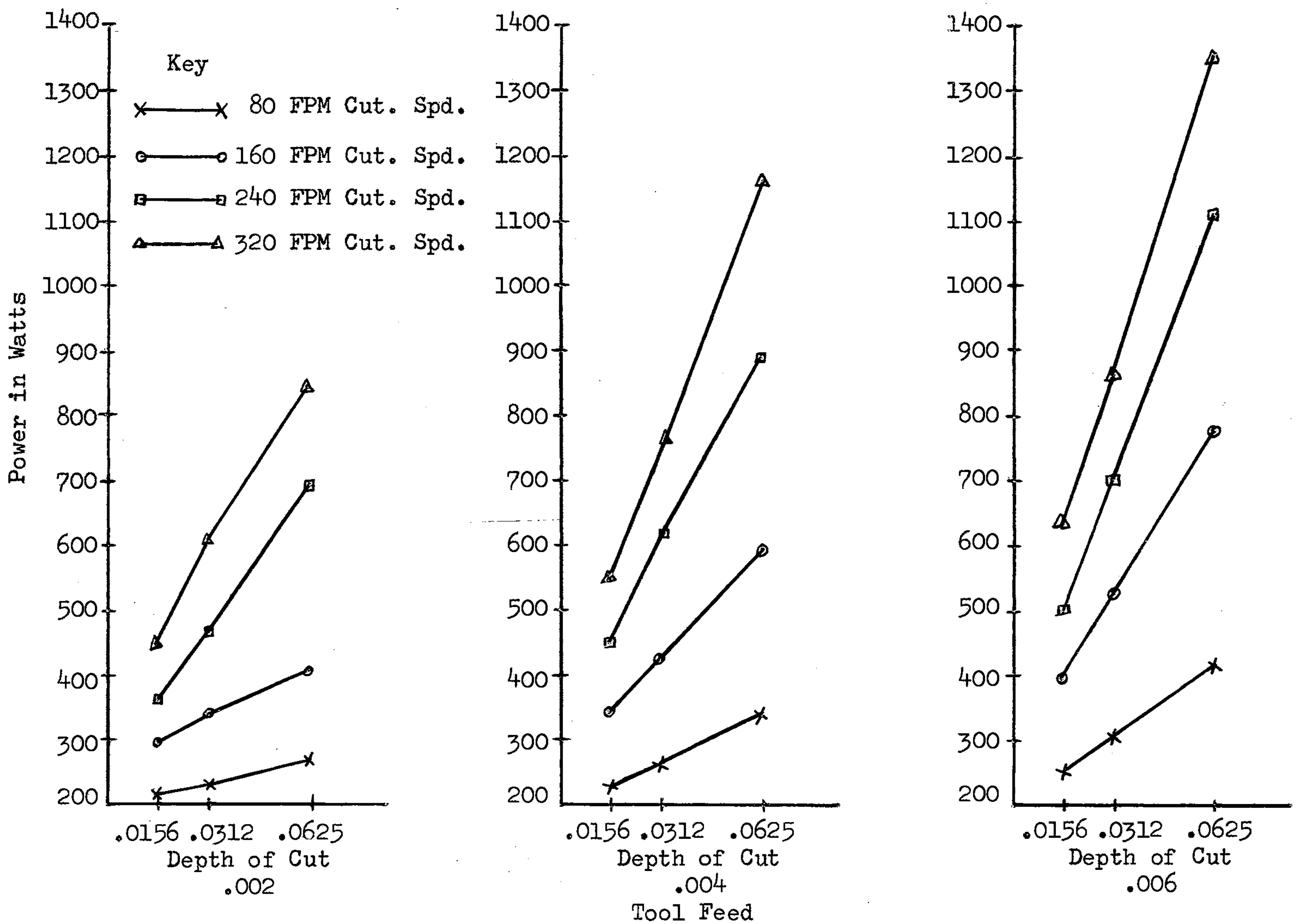

Figure 50. Interaction Depth of Cut by Tool Feed by Cutting Speed - III

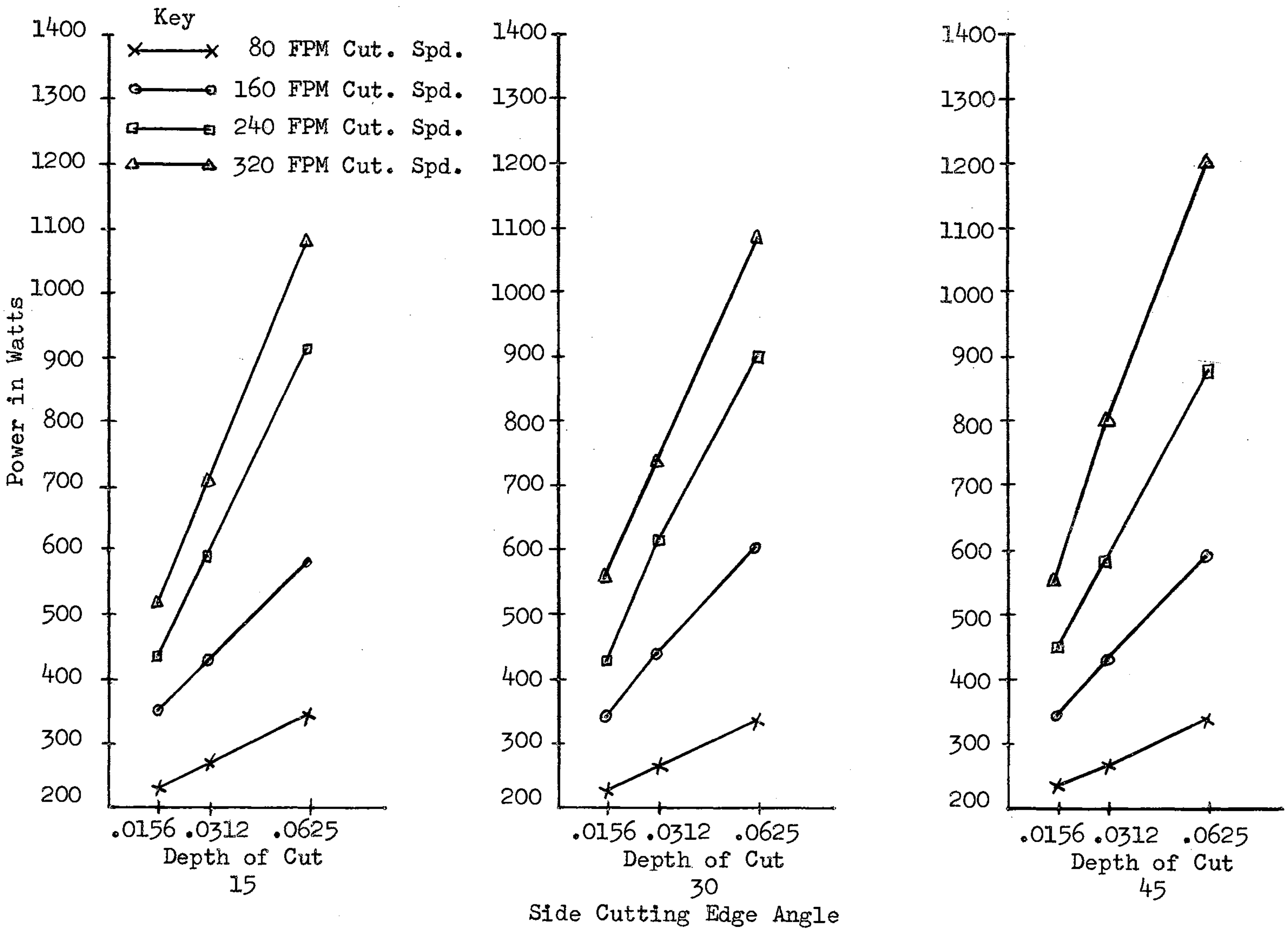

Figure 51. Interaction Depth of Cut by Side Cutting Edge Angle by Cutting Speed - III

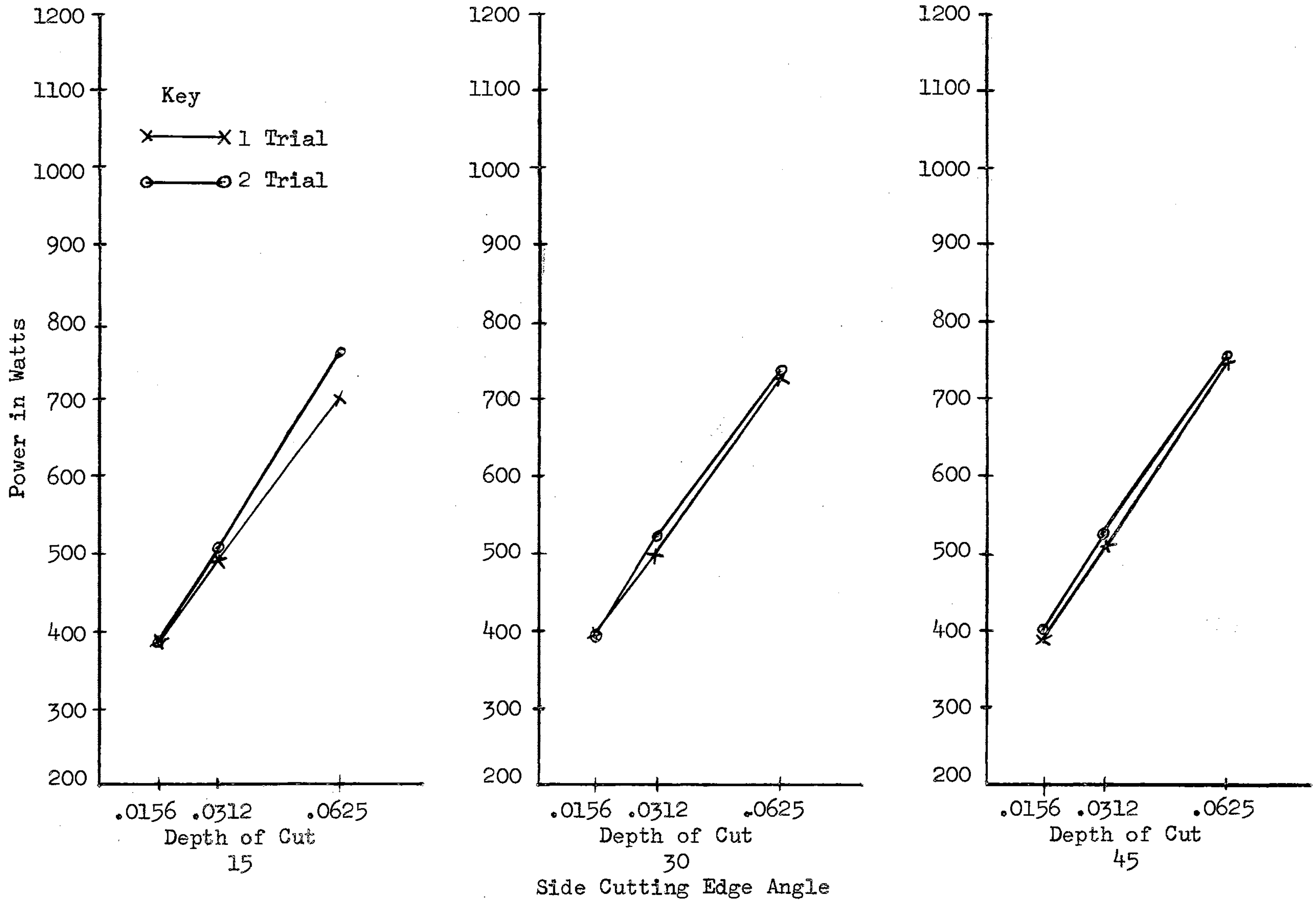

Figure 52. Interaction Depth Cut by Side Cutting Edge Angle by Trials - III

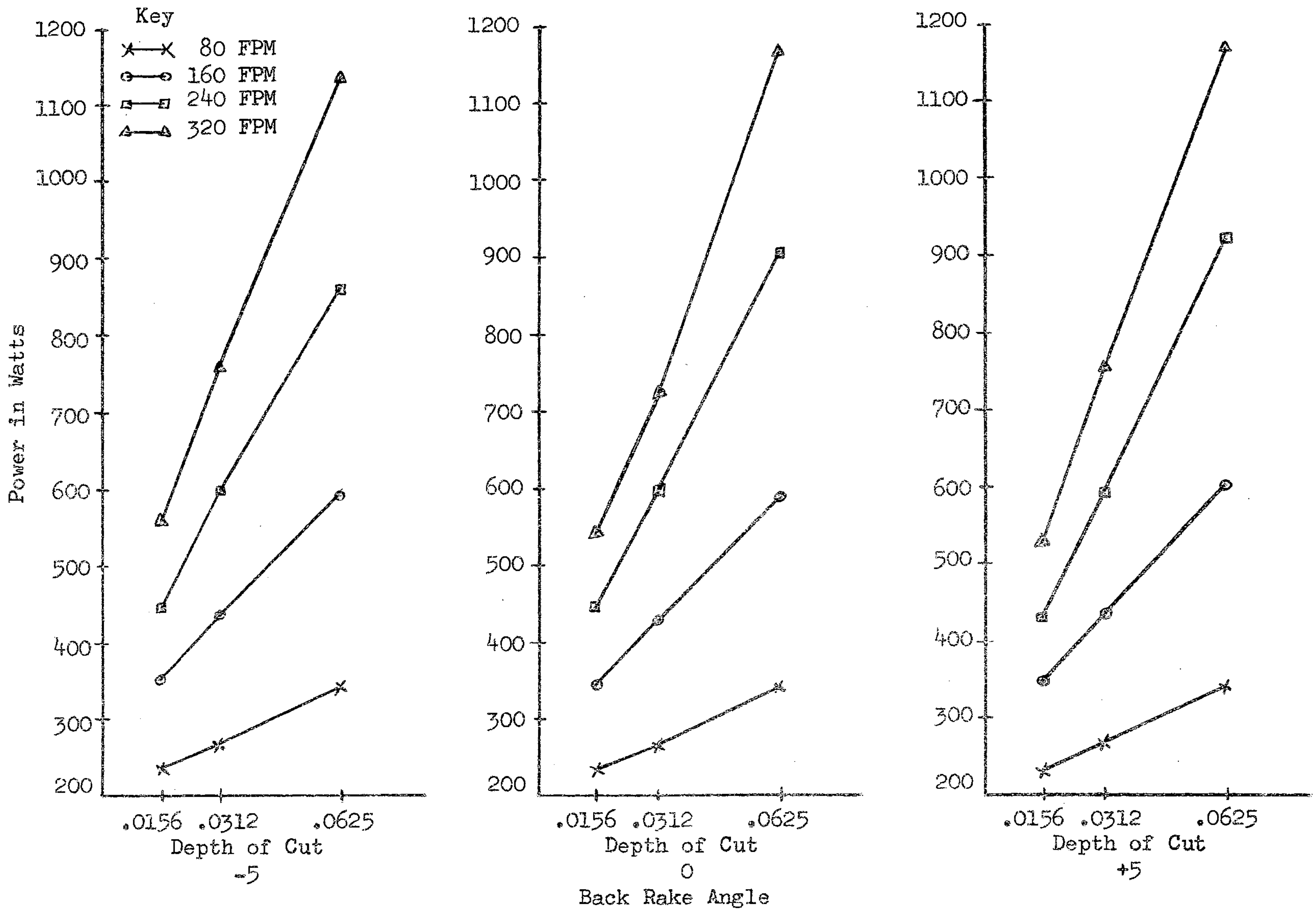

Figure 53. Interaction Depth of Cut by Back Rake Angle by Cutting Speed - III

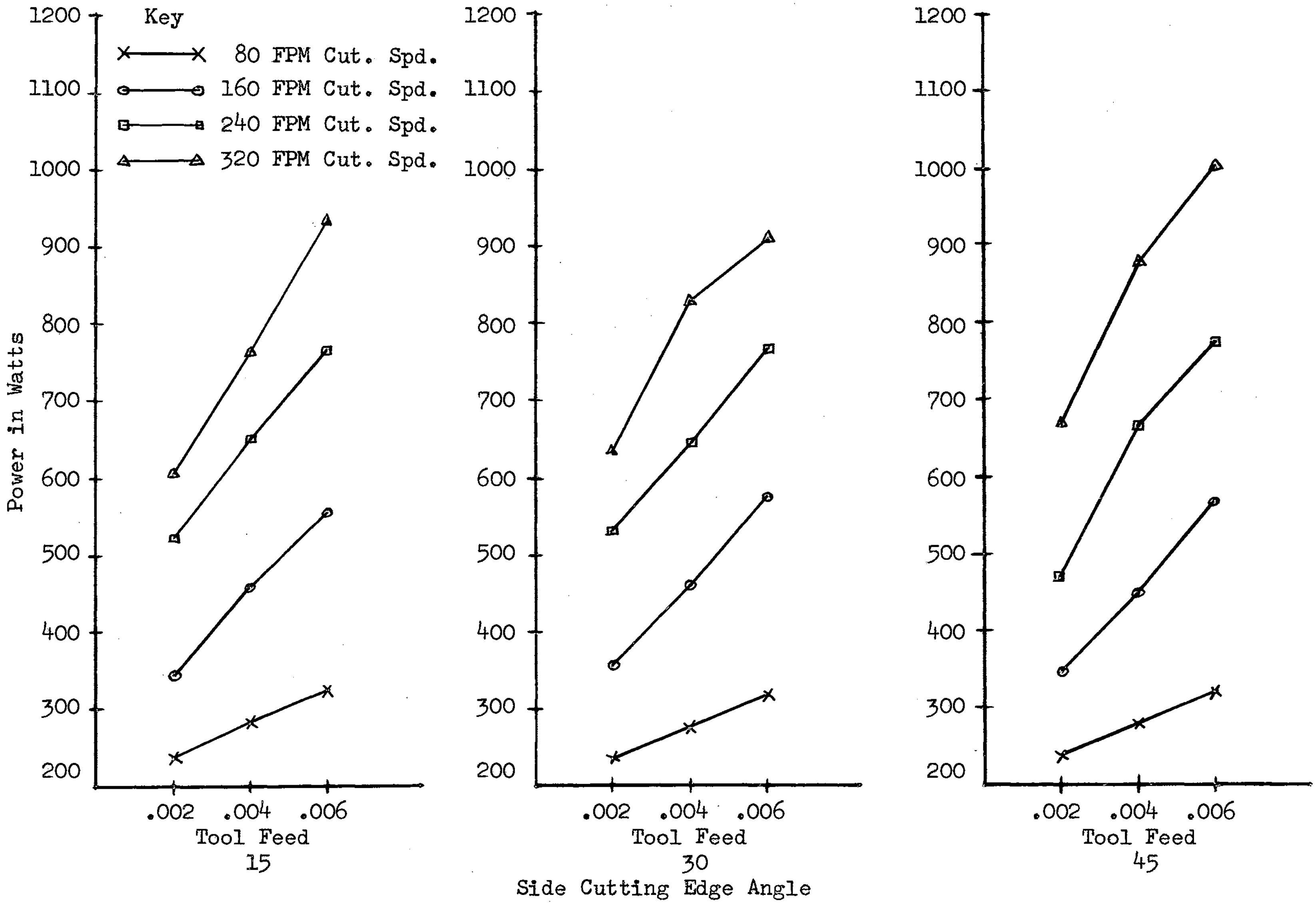

Figure 54. Interaction Tool Feed by Side Cutting Edge Angle by Cutting Speed - III

Figure 55 also indicates the same general pattern as that of Figure 42 indicating that the back rake has very little effect on the power requirement but that the speed and feed do have a considerable effect.

Figure 56 extends the trends established in Figure 31 giving further evidence of the interaction of A, B, and E, and showing the nonsignificance of the variable C. The ABE interaction of Figure 50 is repeated with little change giving further support to the lack of significance of side cutting edge angle.

Figure 57 again is almost the same as Figure 50 indicating speed, depth of cut, and feed have the greatest affect and back rake when combined with other variables does not play a very important part in power requirements.

Figure 58 shows almost the same results as Figure 54 indicating that trials really are not important and only brought into the interaction by the difference at the higher speeds. It shows speed and feed to be the most prevailing variables and that there is little or no significance from the side cutting edge angle.

From Figure 59 it can be seen that the speed does have an affect on the power required. The effects of C, D, and F as shown in the lower order interactions have almost completely been eliminated indicating the speed is again the most predominant factor in the study.

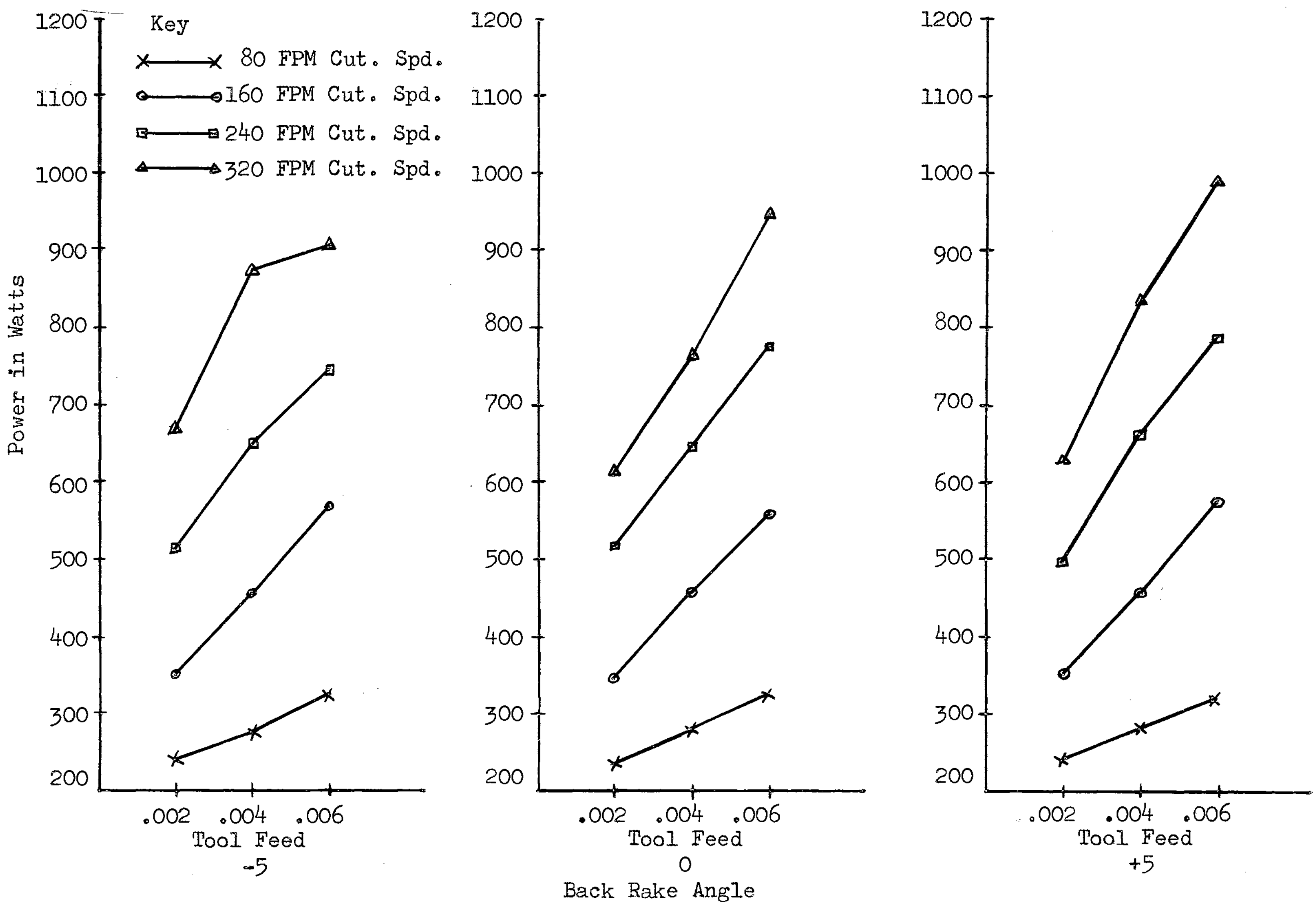

Figure 55. Interaction Tool Feed by Back Rake Angle by Cutting Speed - III

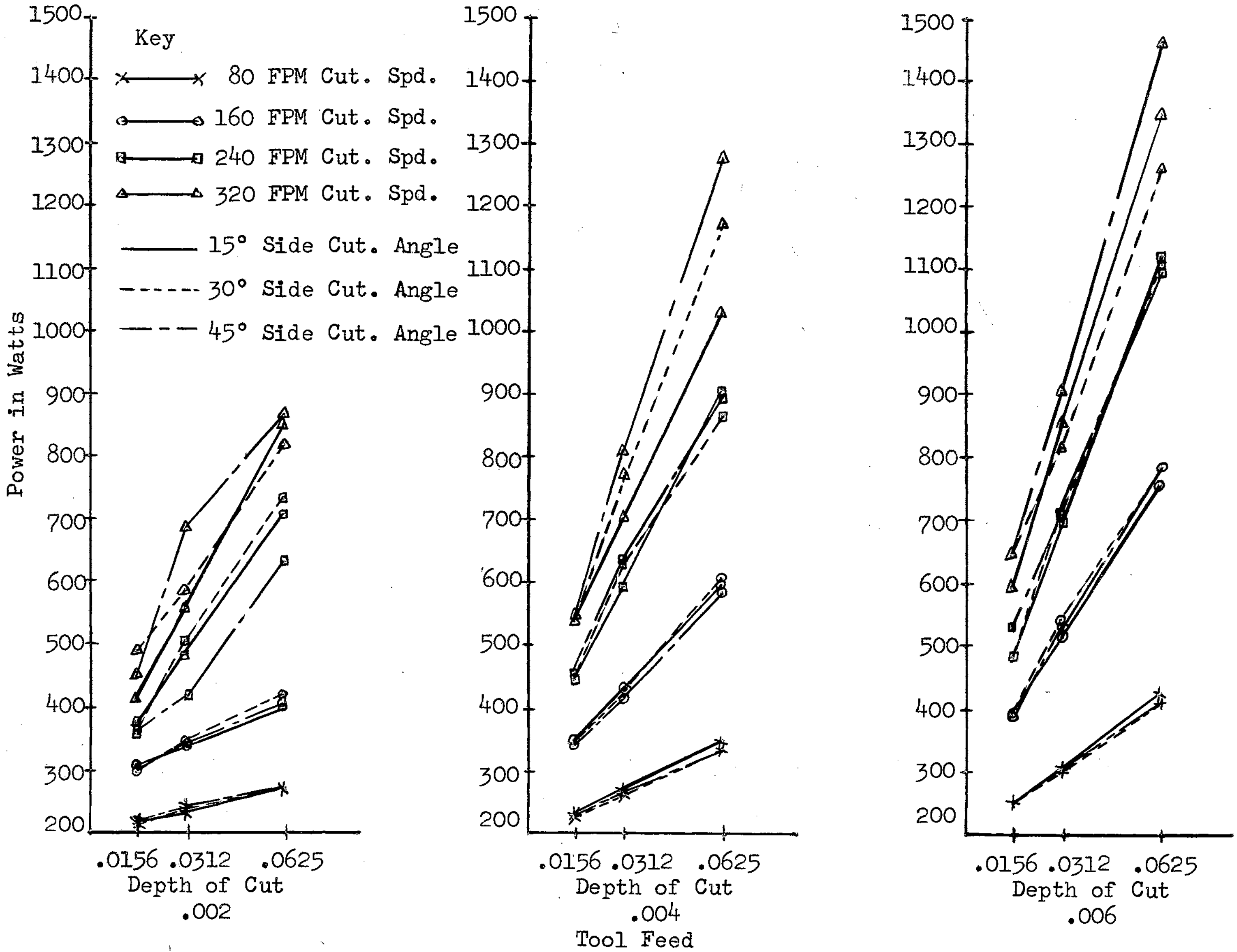

Figure 56. Interaction Depth of Cut by Tool Feed by Side Cutting Edge Angle by Cutting Speed - III

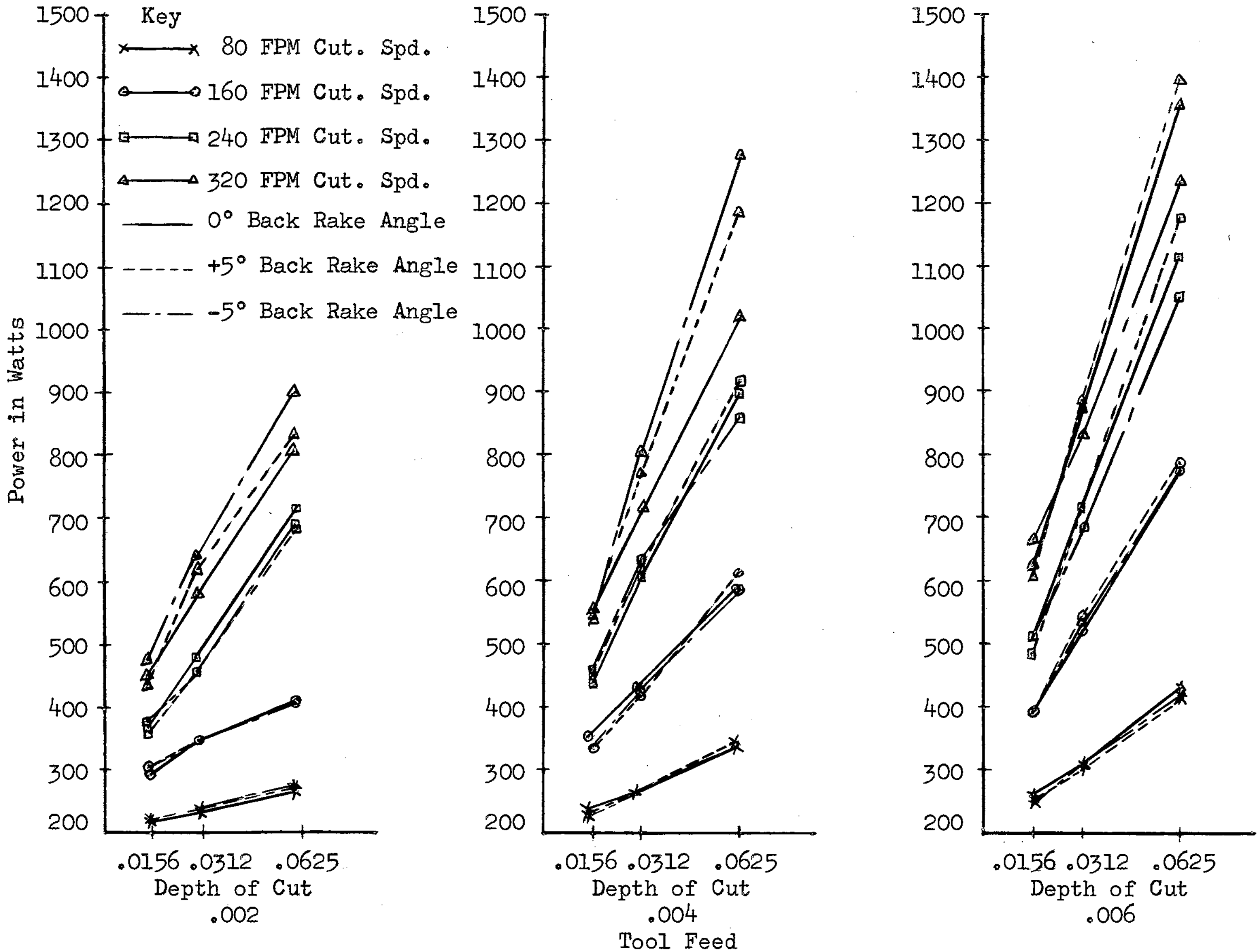

Figure 57. Interaction Depth of Cut by Tool Feed by Back Rake Angle by Cutting Speed - III

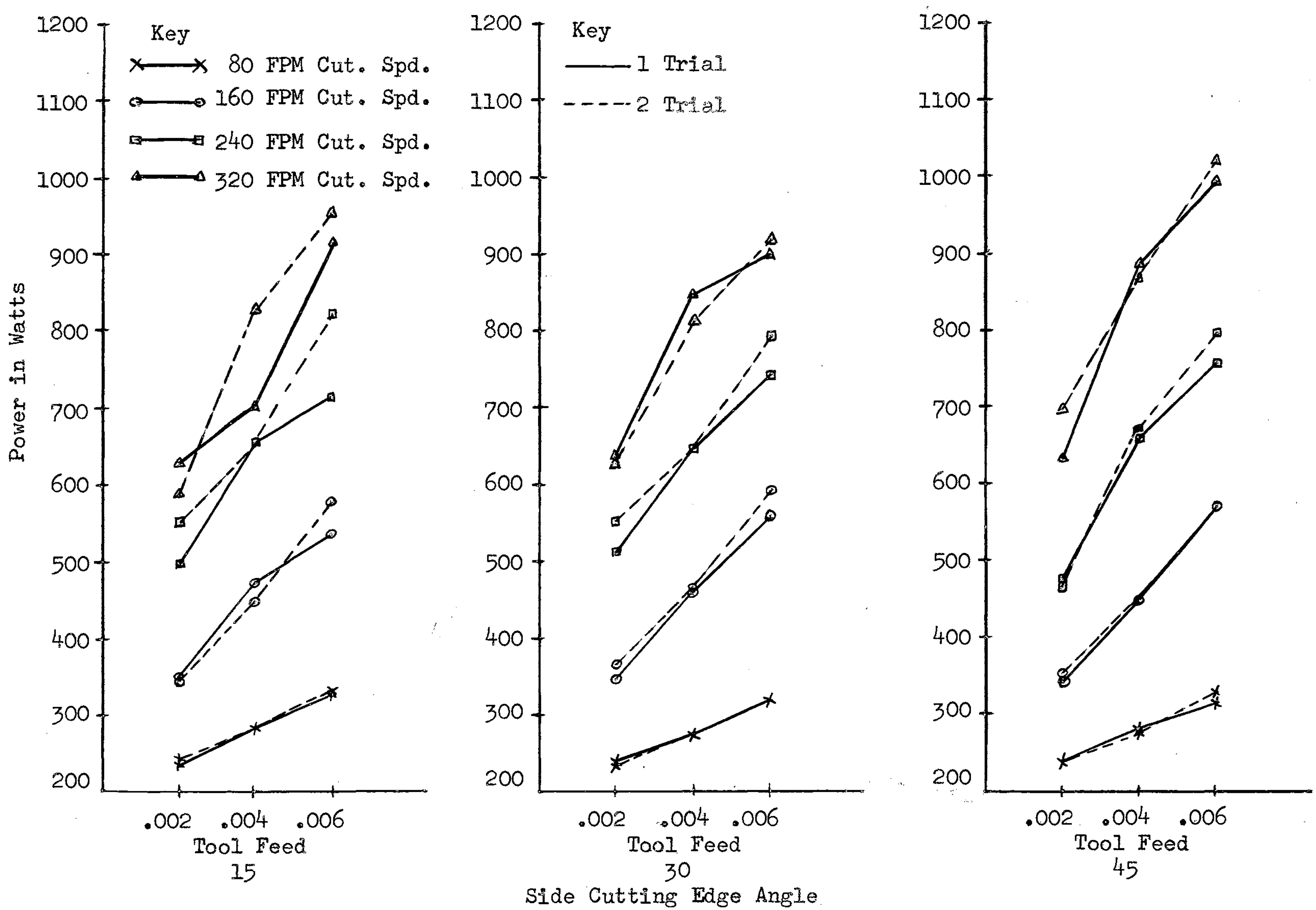

Figure 58. Interaction Tool Feed by Side Cutting Edge Angle by Cutting Speed by Trials - III

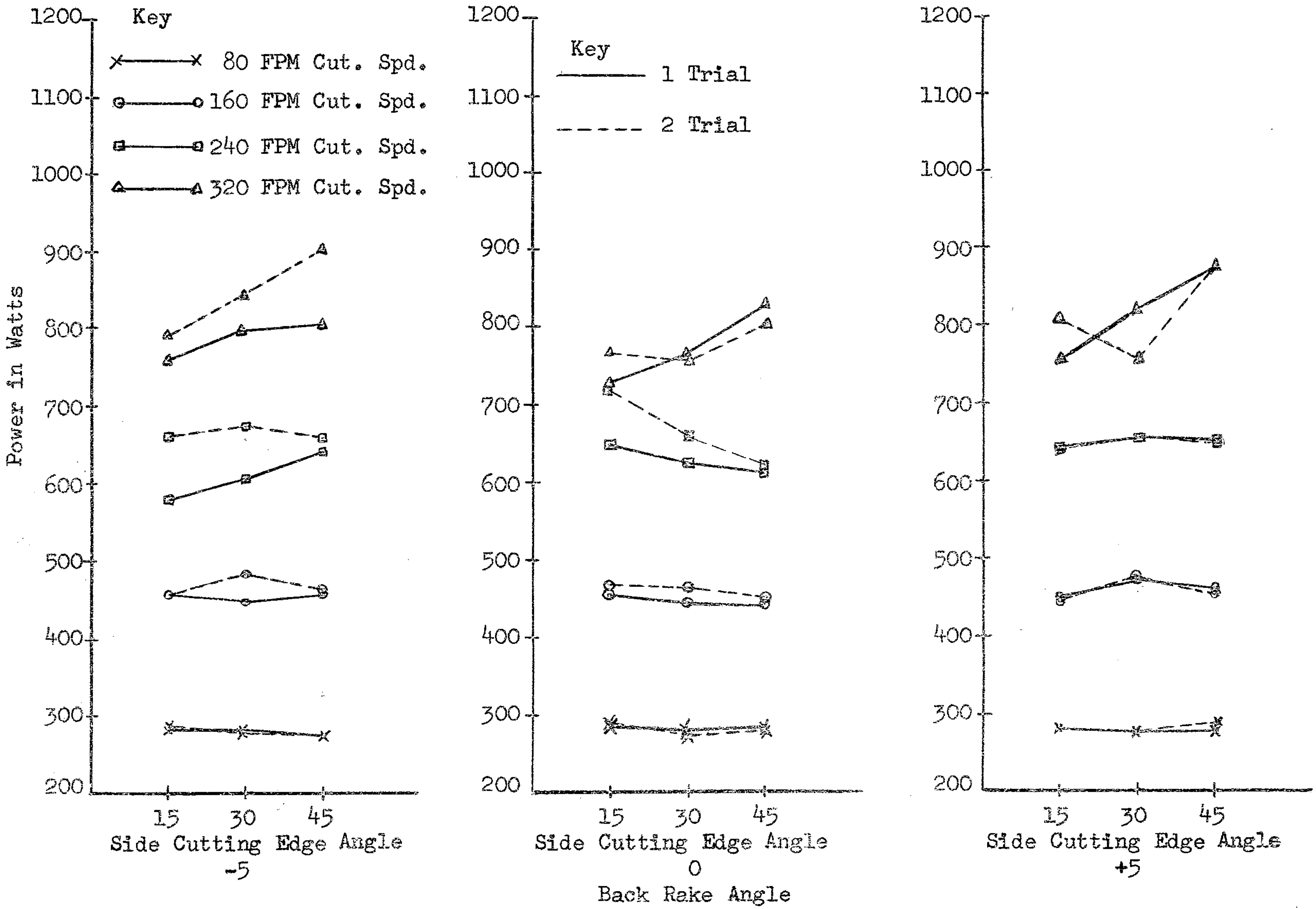

Figure 59. Interaction Side Cutting Edge Angle by Back Rake Angle by Cutting Speed by Trials - III

CHAPTER V

SUMMARY AND CONCLUSIONS

As stated in Chapter I the primary objective of this investigation was to determine by physical experimentation and subsequent statistical analysis, the interdependence of various machining variables and their interacting effect on first cut surface roughness and power requirements. It was also stated that the investigation would be used to try to determine which of the dependent variables should be used in further investigations of this type should it prove to be of real value.

In this chapter, an effort will be made to summarize the results of the study and draw conclusions and make recommendations that result from the study. Since the analysis was broken into three parts, the summary will follow the same general plan. In order to bring the reader up to date and make it easier to follow, the variables, significant effects, and interactions for each analysis will be listed in a table according to the order shown in the design of the experiment. Following each table will be the summary statements about the variables and the significant effects.

TABLE VIII

EFFECTS GROUPED BY VARIABLES FOR FIRST ANALYSIS

Variable	Significant Effects	Figure Number
A (Depth of Cut)	AE	8
	ABEF	14
	ABCEF	15
B (Tool Feed)	B	4
	BC	9
	BE	10
	BCE	13
	ABEF	14
	ABCEF	15
C (Side Cutting Edge Angle)	C	5
	BC	9
	CF	11
	BCE	13
	ABCEF	15
D (Back Rake Angle)	D	6
	DE	12
E (Cutting Speed)	E	7
	AE	8
	BE	10
	DE	12
	BCE	13
	ABEF	14

TABLE VIII (continued)

Variable	Significant Effects	Figure Number
	ABCEF	15
F (Trials)	ABEF	14
	ABCEF	15

Depth of Cut I

This variable by itself does not appear to have a significant affect on surface finish. By examining the Figures 8, 14, and 15 where depth of cut occurs as an interaction, there is no evidence to deny the main effect conclusion. This investigation does not uphold the statement of the Tool Engineers Handbook that greater depths of cut have an adverse affect on the surface finish (8). It may be that additional depths of cut should be analyzed before any conclusive evidence can be obtained.

Tool Feed I

The tool feed is a significant variable when studying surface finish. This is in accord with the literature in this area. It is most prominent in the interactions of Figures 10, 13, 14, and 15 when it is combined with the cutting speed. As expected, it becomes more significant as the cutting speed increases and feed remains constant, but less significant when the feed itself is increased.

Side Cutting Edge Angle I

The side cutting edge angle appears significant as a main effect which agrees with what was expected from the literature search. It is apparent as the higher order interactions of Figures 13 and 15 are examined it does not have as great an affect. It, therefore, appears to be less significant in producing good surface finish than the published literature leads one to believe. This observation agrees with one made in a somewhat similar study by Kirk (11).

Back Rake Angle I

The back rake angle also appears significant as a main effect. This was expected from the literature search, but the absence of this variable in the higher order interactions appears to indicate that its significance is not too important when looking at surface finish. From Figure 6, it can be seen that the positive 5° back rake angle produced the best surface finish. It appears then that further study needs to be made with a greater positive back rake angle to see if the 5° angle is the best to use for surface finish considerations under the restrictions of this investigation.

Cutting Speed I

Cutting speed is by far the most important variable that affects the surface finish. It is the most significant main effect of the variables studied. Each interaction shown indicates the predominance of the cutting speed. The BE interaction of Figure 10 indicates the greatest improvement in the surface finish, providing more evidence to the importance of the cutting speed. Figure 15 which summarizes the over-all effect on surface finish indicates in almost every combination that cutting speed is a very important variable to consider when good surface finish is desired.

Trials I

Trials, although appearing as significant in the higher order interactions, really are not a factor of importance to surface finish.

TABLE IX

EFFECTS GROUPED BY VARIABLES FOR SECOND ANALYSIS

Variable	Significant Effects	Figure Number
A (Depth of Cut)	A	16
	AB	22
	AE	23
	AF	24
	ACE	28
	AEF	29
	ABCE	31
B (Tool Feed)	B	17
	AB	22
	BE	24
	ABCE	31
C (Side Cutting Edge Angle)	C	18

TABLE IX (continued)

Variable	Significant Effects	Figure Number
	CD	25
	CE	26
	ACE	28
	ABCE	31
D (Back Rake Angle)	CD	25
	DF	27
	DEF	30
E (Cutting Speed)	E	19
	AE	22
	BE	24
	CE	26
	ACE	28
	AEF	29
	DEF	30
	ABCE	31
F (Trials)	F	20
	AF	23
	DF	27
	AEF	29
	DEF	30

Depth of Cut II

Depth of cut is a significant variable in power consumption. Figures 22, 23, and 31 indicate it is most significant when combined with feed than speed and the feed speed combination. The combination effect was expected since most writers consider power directly proportional to the metal removal rate, of which depth of cut plays an important part.

Tool Feed II

The tool feed is also a significant main effect. Figures 22, 24, and 31 indicate that the effect, when combined with depth of cut and cutting speed, plays an important part in power requirements. This was expected because it is also a function of the metal removal rate.

Side Cutting Edge Angle II

The side cutting edge angle is a significant main effect because it is a function of the metal removal rate. It does not, however, appear to play as significant a part in the higher order interactions. Figures 28 and 31 appear to indicate that the side cutting edge angle is not as important as the main effects make it appear. Even the examination of Table VII clearly points out that it is not nearly as significant as are depth of cut, feed, or speed.

Back Rake Angle II

It appears that the back rake angle has little effect on power requirements. Figure 30 indicates that maybe at higher speeds it will have some affect. This may need investigation to verify this statement.

Cutting Speed II

The cutting speed is the most significant variable affecting power. The interactions of Figures 22, 24, 26, 28, 29, 30, and 31 clearly show the influence speed has on the power requirements. It was expected that the interactions with depth of cut and feed shown in Figures 22, 24, 28, 29, and 31 would be significant because speed is an important factor in the metal removal rate.

Trials II

Trials although significant as a main effect do not become important as the analysis becomes more complex and it does not appear in the higher order interaction of Figure 31.

TABLE X

EFFECTS GROUPED BY VARIABLES FOR THIRD ANALYSIS

Variable	Significant Effects	Figure Number
A (Depth of Cut)	A	32
	AB	38
	AD	39
	AE	40
	ABD	49
	ABE	50
	ACE	51
	ACF	52

TABLE X (continued)

Variable	Significant Effects	Figure Number
	ADE	53
	ABCE	56
	ABDE	57
B (Tool Feed)	B	33
	AB	38
	BD	41
	BE	42
	BF	43
	ABD	49
	ABE	50
	BCE	54
	BDE	55
	ABCE	56
	ABDE	57
	BCEF	58
	BDEF	59
C (Side Cutting Edge Angle)	C	34
	CD	44
	CE	45
	ACE	51
	ACF	52
	BCE	54
	ABCE	56

TABLE X (continued)

Variable	Significant Effects	Figure Number
	BCEF	58
D (Back Rake Angle)	D	35
	AD	39
	BD	41
	CD	44
	DE	46
	DF	47
	ABD	49
	ADE	53
	BDE	55
	ABDE	57
	BDEF	59
E (Cutting Speed)	E	36
	AE	40
	BE	42
	CE	45
	DE	46
	EF	48
	ABE	50
	ACE	51
	ADE	53
	BCE	54
	BDE	55

TABLE X (continued)

Variable	Significant Effects	Figure Number
	ABCE	56
	ABDE	57
	BCEF	58
	BDEF	59
F (Trials)	F	37
	BF	43
	DF	47
	EF	48
	ACF	52
	BCEF	58
	BDEF	59

Depth of Cut III

As in the second analysis, depth of cut is a significant variable. It is more significant than in the second analysis leading to the observation that it is real important to power consumption. Figures 38, 40, 50, and 56 show particularly that the depth of cut is important. The other figures include one of the lesser significant variables carried into the interaction by the strong influence of the depth of cut. Figure 40 shows more strongly than does some of the other figures that depth of cut does affect the power requirements.

Tool Feed III

The significance of tool feed in this analysis becomes real important. Figures 38, 42, and 50 show the real significance of the depth of cut, feed, and speed combination on the metal removal rate. Tool feed is significant in more interactions than in the previous analysis, indicating that as depth of cut increases the feed becomes more important.

Side Cutting Edge Angle III

The interactions of Figures 51, 54, and 56 show that even though the side cutting edge angle is significant it is not a real important factor to be considered. If the depth of cut were increased considerably, it might be more significant.

Back Rake Angle III

The back rake angle which is significant as a main effect here and was not in the previous analysis diminishes in importance in the higher order interactions. It is carried into the interaction by depth of cut, feed, or speed in all figures except 44, but this figure does not show any real pattern and, therefore, it is concluded that the back rake angle does not have a very important influence on power.

Cutting Speed III

Cutting speed is the most significant effect of the variables considered in this part of the investigation. In examining the Figures 36, 40, 42, 45, 46, 48, 50, 51, 53, 54, 55, 56, 57, 58, and 59, it is evident that the effect of speed prevails in all cases. It is, therefore, concluded that this is the most singly important variable that effects power consumption.

Trials III

Even though trials is a significant factor, it does not appear to be an important factor.

In conclusion, it is believed that the study has achieved its objective. The technique applied can be used to determine which variables have significant effect on metal cutting. Since the depth of cut, feed, and speed are so much more significant than the other factors considered in power consumption, it may be that the average metal cutting operation can use what is considered standard material (SAE 1018) and cut giving consideration to the highly significant variables and not so much consideration to the other variables. It may be that an economic study in light of this type of conclusion would prove to be useful. This author feels the difference between the significant effects should be considered in future research in this area and in metal cutting in general. To state which of the dependent variables should be used in future studies seems inappropriate at this time because they are measuring two different dependent variables. It would appear that since speed was the predominant factor in all three analysis that maybe a study should be made to determine the relationship of the two dependent variables and speed.

This study brings to light then the following areas of possible future research:

1. Investigation of the relationship of cutting speed and the two dependent variables, first cut, surface finish, and power requirements.

2. A study of the same type using a greater number and larger depths of cut to see if the trends established in this study will continue.

3. Investigation of the influence of a back rake angle greater than +5°.

4. Investigation of the effect of the back rake at higher speeds.

5. The study points out that more work is needed in the area to find a better way of measuring surface finish.

6. This type of study should be expanded to other types of tool bits and other materials.

7. Design the experiment using a fractional factorial analysis to see if the conclusions are the same providing a shorter test to get the same information.

8. An economic study to determine if there is economic justification to verify the significance found in the research.

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APPENDIX A

DESCRIPTION OF PROCEDURE

The material which came in 20 foot lengths had to be cut into eight inch pieces. This was done on a 36 inch Do All band saw. The tool bits were sharpened to the predetermined angles on a Delta-Milwaukee Toolmaker Grinder. With these two preliminary steps completed, the actual cutting operation could be started.

The piece of material was picked at random from the stack of eight inch pieces. The piece was placed in the Jacobs Spindle Nose Lathe Chuck allowing approximately two and one-half inches of material to protrude from the chuck allowing two cuts to be made before the material was extended further so that two more cuts could be made.

The proper feed was set on the independent power feed and the spindle speed was adjusted on the headstock of the lathe and verified with the tachometer.

The proper tool was selected from the nine tools and placed in the tool holder and adjusted for correct height and the correct depth of cut.

The wattmeter was started and allowed to run for a few seconds to establish the unloaded conditions.

The longitudinal feed was engaged and the metal cutting started. It was allowed to move three-fourths inch, according to the operator's visual opinion, then disengaged and retracted from the cutting position. The spindle rotation was then stopped.

The wattmeter was stopped and a visual reading of the power was made and recorded.

The process was then repeated until the eight cuts were made on a piece, then another piece was placed in the lathe and cutting continued.

At the end of each day, the surface finish readings were made. A piece of material was placed into a vee block and the tracer placed on the section of the material where the surface finish was to be ascertained. The tracer was allowed to move back and forth several times and the high and low value was noted. The piece was rotated and the values noted again. This procedure was done at least three times for any one section of the cut and the lowest and highest values were recorded on the data sheet shown as Figure A-1. The middle value of this range was then calculated and recorded and this was the value used in the analysis. The procedure was repeated until all the cuts made that day were checked and the surface finish recorded.

When a roll of chart paper on the wattmeter was full it was removed from the meter and all readings were checked against those recorded during the cutting procedure. The chart paper was then cut into pieces and placed with the data sheet that had the readings corresponding to the reading on the chart paper. This procedure was repeated each time the roll of chart paper was full.

The steps described above were repeated until the total of 1296 cuts were made.

Depth-Cut ____ Feed ____ Back Rake ____ Side Cut Edge ____ Speed ____ Trial ____ Replication ____ Surface Finish ____ Power ____ CARD ____	Depth-Cut ____ Feed ____ Back Rake ____ Side Cut Edge ____ Speed ____ Trial ____ Replication ____ Surface Finish ____ Power ____ CARD ____
Depth-Cut ____ Feed ____ Back Rake ____ Side Cut Edge ____ Speed ____ Trial ____ Replication ____ Surface Finish ____ Power ____ CARD ____	Depth-Cut ____ Feed ____ Back Rake ____ Side Cut Edge ____ Speed ____ Trial ____ Replication ____ Surface Finish ____ Power ____ CARD ____
Depth-Cut ____ Feed ____ Back Rake ____ Side Cut Edge ____ Speed ____ Trial ____ Replication ____ Surface Finish ____ Power ____ CARD ____	Depth-Cut ____ Feed ____ Back Rake ____ Side Cut Edge ____ Speed ____ Trial ____ Replication ____ Surface Finish ____ Power ____ CARD ____
Depth-Cut ____ Feed ____ Back Rake ____ Side Cut Edge ____ Speed ____ Trial ____ Replication ____ Surface Finish ____ Power ____ CARD ____	Depth-Cut ____ Feed ____ Back Rake ____ Side Cut Edge ____ Speed ____ Trial ____ Replication ____ Surface Finish ____ Power ____ CARD ____

Figure A-1. Data Sheet

APPENDIX B

MEAN VALUES USED TO PLOT THE GRAPHS IN CHAPTER IV

CODE USED IN COLUMN HEADINGS

D. O. C.--Depth of Cut

Feed--Tool Feed

S. C. E. A.--Side Cutting Edge Angle

B. R.--Back Rake Angle

Speed--Cutting Speed

Trials--Trials

Mean--Mean Value

SURFACE FINISH ANALYSIS

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
			B EFFECT			
	.002					158.64
	.004					203.51
	.006					234.28
			C EFFECT			
		15				188.07
		30				207.72
		45				200.65
			D EFFECT			
			-5			211.07
			0			198.03
			+5			187.34
			E EFFECT			
				80		260.20
				160		214.89
				240		172.75
				320		147.41
			AE INTERACTION			
.0156				80		248.10
.0156				160		220.60
.0156				240		174.29
.0156				320		150.11
.0312				80		272.30
.0312				160		209.18
.0312				240		171.22
.0312				320		144.71
			BC INTERACTION			
	.002	15				160.10
	.002	30				167.78
	.002	45				148.04
	.004	15				194.27
	.004	30				206.93
	.004	45				209.34
	.006	15				209.84
	.006	30				248.45
	.006	45				244.56
			BE INTERACTION			
	.002			80		192.92
	.002			160		143.03
	.002			240		162.18
	.002			320		136.44
	.004			80		239.72
	.004			160		250.35

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
	.004			240		174.24
	.004			320		149.75
	.006			80		347.96
	.006			160		251.29
	.006			240		181.85
	.006			320		156.04
		CF INTERACTION				
		15			1	193.38
		15			2	182.76
		30			1	201.87
		30			2	213.57
		45			1	193.23
		45			2	208.07
		DE INTERACTION				
			-5	80		263.65
			-5	160		215.04
			-5	240		185.60
			-5	320		180.00
			0	80		257.22
			0	160		218.75
			0	240		174.56
			0	320		141.56
			+5	80		259.72
			+5	160		210.88
			+5	240		158.08
			+5	320		120.68
		BCE INTERACTION				
	.002	15		80		197.29
	.002	15		160		143.46
	.002	15		240		181.42
	.002	15		320		118.42
	.004	15		80		240.00
	.004	15		160		228.33
	.004	15		240		165.63
	.004	15		320		143.13
	.006	15		80		322.29
	.006	15		160		218.54
	.006	15		240		168.75
	.006	15		320		129.79
	.002	30		80		205.21
	.002	30		160		150.00
	.002	30		240		163.00
	.002	30		320		152.71
	.004	30		80		232.29
	.004	30		160		273.13
	.004	30		240		167.08
	.004	30		320		155.21
	.006	30		80		362.21

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
	.006	30		160		245.63
	.006	30		240		206.58
	.006	30		320		179.38
	.002	45		80		176.25
	.002	45		160		135.42
	.002	45		240		142.29
	.002	45		320		138.21
	.004	45		80		246.88
	.004	45		160		249.58
	.004	45		240		190.00
	.004	45		320		150.92
	.006	45		80		359.38
	.006	45		160		289.71
	.006	45		240		170.21
	.006	45		320		158.96

ABEF INTERACTION

.0156	.002			80	1	196.94
.0156	.002			80	2	176.39
.0156	.002			160	1	147.50
.0156	.002			160	2	140.39
.0156	.002			240	1	152.17
.0156	.002			240	2	159.06
.0156	.002			320	1	135.39
.0156	.002			320	2	144.72
.0156	.004			80	1	232.78
.0156	.004			80	2	221.94
.0156	.004			160	1	246.39
.0156	.004			160	2	253.89
.0156	.004			240	1	165.00
.0156	.004			240	2	197.11
.0156	.004			320	1	147.50
.0156	.004			320	2	171.39
.0156	.006			80	1	307.78
.0156	.006			80	2	352.78
.0156	.006			160	1	276.39
.0156	.006			160	2	259.06
.0156	.006			240	1	187.50
.0156	.006			240	2	184.89
.0156	.006			320	1	133.89
.0156	.006			320	2	167.78
.0312	.002			80	1	188.61
.0312	.002			80	2	209.72
.0312	.002			160	1	142.67
.0312	.002			160	2	141.56
.0312	.002			240	1	171.94
.0312	.002			240	2	165.56
.0312	.002			320	1	138.06
.0312	.002			320	2	127.61
.0312	.004			80	1	256.11
.0312	.004			80	2	248.06

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0312	.004			160	1	248.61
.0312	.004			160	2	252.50
.0312	.004			240	1	162.50
.0312	.004			240	2	172.33
.0312	.004			320	1	134.28
.0312	.004			320	2	145.83
.0312	.006			80	1	376.94
.0312	.006			80	2	354.33
.0312	.006			160	1	226.11
.0312	.006			160	2	243.61
.0312	.006			240	1	165.28
.0312	.006			240	2	189.72
.0312	.006			320	1	167.50
.0312	.006			320	2	155.00

ABCEF INTERACTION

.0156	.002	15		80	1	251.67
.0156	.002	15		80	2	136.67
.0156	.002	15		160	1	160.83
.0156	.002	15		160	2	135.00
.0156	.002	15		240	1	183.33
.0156	.002	15		240	2	187.50
.0156	.002	15		320	1	124.50
.0156	.002	15		320	2	146.67
.0156	.002	30		80	1	192.50
.0156	.002	30		80	2	183.33
.0156	.002	30		160	1	147.50
.0156	.002	30		160	2	150.83
.0156	.002	30		240	1	128.17
.0156	.002	30		240	2	148.53
.0156	.002	30		320	1	153.33
.0156	.002	30		320	2	145.00
.0156	.002	45		80	1	146.67
.0156	.002	45		80	2	209.17
.0156	.002	45		160	1	134.17
.0156	.002	45		160	2	135.33
.0156	.002	45		240	1	145.00
.0156	.002	45		240	2	140.83
.0156	.002	45		320	1	128.33
.0156	.002	45		320	2	142.50
.0156	.004	15		80	1	240.83
.0156	.004	15		80	2	218.33
.0156	.004	15		160	1	270.00
.0156	.004	15		160	2	190.00
.0156	.004	15		240	1	154.17
.0156	.004	15		240	2	178.83
.0156	.004	15		320	1	152.50
.0156	.004	15		320	2	159.17
.0156	.004	30		80	1	227.50
.0156	.004	30		80	2	205.00
.0156	.004	30		160	1	245.03

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0156	.004	30		160	2	285.00
.0156	.004	30		240	1	161.67
.0156	.004	30		240	2	192.50
.0156	.004	30		320	1	152.50
.0156	.004	30		320	2	180.83
.0156	.004	45		80	1	230.00
.0156	.004	45		80	2	242.50
.0156	.004	45		160	1	223.33
.0156	.004	45		160	2	286.67
.0156	.004	45		240	1	179.17
.0156	.004	45		240	2	220.00
.0156	.004	45		320	1	137.50
.0156	.004	45		320	2	174.17
.0156	.006	15		80	1	277.50
.0156	.006	15		80	2	302.50
.0156	.006	15		160	1	246.67
.0156	.006	15		160	2	237.50
.0156	.006	15		240	1	172.50
.0156	.006	15		240	2	165.83
.0156	.006	15		320	1	93.33
.0156	.006	15		320	2	153.33
.0156	.006	30		80	1	320.83
.0156	.006	30		80	2	410.00
.0156	.006	30		160	1	270.00
.0156	.006	30		160	2	250.83
.0156	.006	30		240	1	203.33
.0156	.006	30		240	2	218.83
.0156	.006	30		320	1	175.00
.0156	.006	30		320	2	193.33
.0156	.006	45		80	1	325.00
.0156	.006	45		80	2	345.83
.0156	.006	45		160	1	312.50
.0156	.006	45		160	2	288.83
.0156	.006	45		240	1	186.67
.0156	.006	45		240	2	170.00
.0156	.006	45		320	1	133.33
.0156	.006	45		320	2	156.67
.0312	.002	15		80	1	159.17
.0312	.002	15		80	2	241.67
.0312	.002	15		160	1	150.00
.0312	.002	15		160	2	128.00
.0312	.002	15		240	1	192.50
.0312	.002	15		240	2	161.67
.0312	.002	15		320	1	111.67
.0312	.002	15		320	2	90.83
.0312	.002	30		80	1	229.17
.0312	.002	30		80	2	215.83
.0312	.002	30		160	1	155.83
.0312	.002	30		160	2	146.67
.0312	.002	30		240	1	195.83
.0312	.002	30		240	2	179.17

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0312	.002	30		320	1	149.17
.0312	.002	30		320	2	163.33
.0312	.002	45		80	1	177.50
.0312	.002	45		80	2	171.67
.0312	.002	45		160	1	122.17
.0312	.002	45		160	2	150.00
.0312	.002	45		240	1	127.50
.0312	.002	45		240	2	155.83
.0312	.002	45		320	1	153.33
.0312	.002	45		320	2	128.67
.0312	.004	15		80	1	265.00
.0312	.004	15		80	2	235.83
.0312	.004	15		160	1	257.50
.0312	.004	15		160	2	195.83
.0312	.004	15		240	1	151.67
.0312	.004	15		240	2	177.83
.0312	.004	15		320	1	142.50
.0312	.004	15		320	2	118.33
.0312	.004	30		80	1	245.83
.0312	.004	30		80	2	250.83
.0312	.004	30		160	1	258.33
.0312	.004	30		160	2	303.73
.0312	.004	30		240	1	156.67
.0312	.004	30		240	2	157.50
.0312	.004	30		320	1	128.33
.0312	.004	30		320	2	159.17
.0312	.004	45		80	1	257.50
.0312	.004	45		80	2	257.58
.0312	.004	45		160	1	230.00
.0312	.004	45		160	2	258.33
.0312	.004	45		240	1	179.17
.0312	.004	45		240	2	181.67
.0312	.004	45		320	1	132.00
.0312	.004	45		320	2	160.00
.0312	.006	15		80	1	391.67
.0312	.006	15		80	2	317.50
.0312	.006	15		160	1	193.33
.0312	.006	15		160	2	196.67
.0312	.006	15		240	1	153.83
.0312	.006	15		240	2	180.83
.0312	.006	15		320	1	142.50
.0312	.006	15		320	2	130.00
.0312	.006	30		80	1	364.17
.0312	.006	30		80	2	353.83
.0312	.006	30		160	1	225.00
.0312	.006	30		160	2	236.67
.0312	.006	30		240	1	168.33
.0312	.006	30		240	2	235.83
.0312	.006	30		320	1	142.50
.0312	.006	30		320	2	159.17
.0312	.006	45		80	1	375.00

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0312	.006	45		80	2	391.67
.0312	.006	45		160	1	260.00
.0312	.006	45		160	2	297.50
.0312	.006	45		240	1	171.67
.0312	.006	45		240	2	152.50
.0312	.006	45		320	1	170.00
.0312	.006	45		320	2	175.83

POWER REQUIREMENTS (2 D.O.C.)

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
			A EFFECT			
.0156						388.61
.0312						509.62
			B EFFECT			
	.002					371.17
	.004					455.88
	.006					520.30
			C EFFECT			
		15				441.10
		30				450.28
		45				455.97
			E EFFECT			
				80		249.50
				160		388.94
				240		516.25
				320		642.22
			F EFFECT			
					1	443.97
					2	454.27
			AB INTERACTION			
.0156	.002					330.06
.0156	.004					393.53
.0156	.006					442.26
.0312	.002					412.29
.0312	.004					518.23
.0312	.006					598.33
			AE INTERACTION			
.0156				80		231.06
.0156				160		345.88
.0156				240		436.44
.0156				320		541.06
.0312				80		267.04
.0312				160		431.99
.0312				240		596.06
.0312				320		743.38

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
		AF INTERACTION				
.0156					1	387.54
.0156					2	389.54
.0312					1	500.39
.0312					2	518.84
		BE INTERACTION				
	.002			80		222.57
	.002			160		319.51
	.002			240		414.63
	.002			320		527.99
	.004			80		247.92
	.004			160		386.04
	.004			240		535.04
	.004			320		654.51
	.006			80		276.67
	.006			160		461.25
	.006			240		599.10
	.006			320		744.17
		CD INTERACTION				
		15	-5			440.53
		15	0			448.02
		15	+5			434.74
		30	-5			457.34
		30	0			445.00
		30	+5			448.49
		45	-5			465.52
		45	0			444.06
		45	+5			458.33
		CE INTERACTION				
		15		80		250.35
		15		160		389.24
		15		240		513.14
		15		320		611.67
		30		80		246.60
		30		160		392.50
		30		240		520.21
		30		320		641.81
		45		80		250.21
		45		160		385.07
		45		240		515.42
		45		320		673.19
		DF INTERACTION				
			-5		1	440.96
			-5		2	467.97
			0		1	442.36
			0		2	449.03
			+5		1	448.58
			+5		2	445.80

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
		ACE INTERACTION				
.0156		15		80		230.97
.0156		15		160		350.28
.0156		15		240		434.61
.0156		15		320		516.39
.0156		30		80		227.64
.0156		30		160		345.69
.0156		30		240		426.67
.0156		30		320		558.33
.0156		45		80		234.58
.0156		45		160		341.67
.0156		45		240		448.06
.0156		45		320		548.47
.0312		15		80		269.72
.0312		15		160		428.19
.0312		15		240		591.69
.0312		15		320		706.94
.0312		30		80		265.56
.0312		30		160		439.31
.0312		30		240		613.75
.0312		30		320		725.28
.0312		45		80		265.83
.0312		45		160		428.47
.0312		45		240		582.78
.0312		45		320		797.92
		AEF INTERACTION				
.0156				80	1	231.20
.0156				80	2	230.93
.0156				160	1	339.81
.0156				160	2	351.94
.0156				240	1	437.65
.0156				240	2	435.24
.0156				320	1	541.48
.0156				320	2	540.65
.0312				80	1	266.85
.0312				80	2	267.22
.0312				160	1	432.31
.0312				160	2	431.67
.0312				240	1	572.04
.0312				240	2	620.09
.0312				320	1	730.37
.0312				320	2	756.39
		DEF INTERACTION				
			-5	80	1	245.83
			-5	80	2	249.44
			-5	160	1	389.58
			-5	160	2	394.58
			-5	240	1	498.56
			-5	240	2	545.22

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
			-5	320	1	629.64
			-5	320	2	682.64
			0	80	1	253.61
			0	80	2	247.36
			0	160	1	380.69
			0	160	2	390.83
			0	240	1	509.86
			0	240	2	522.36
			0	320	1	625.28
			0	320	2	635.56
			+5	80	1	247.64
			+5	80	2	250.42
			+5	160	1	387.92
			+5	160	2	390.00
			+5	240	1	506.11
			+5	240	2	515.42
			+5	320	1	652.64
			+5	320	2	627.36

ABCE INTERACTION

.0156	.002	15		80		213.33
.0156	.002	15		160		305.00
.0156	.002	15		240		374.00
.0156	.002	15		320		409.58
.0156	.002	30		80		209.17
.0156	.002	30		160		294.17
.0156	.002	30		240		354.17
.0156	.002	30		320		487.50
.0156	.002	45		80		217.50
.0156	.002	45		160		292.08
.0156	.002	45		240		358.33
.0156	.002	45		320		445.83
.0156	.004	15		80		230.00
.0156	.004	15		160		350.00
.0156	.004	15		240		446.92
.0156	.004	15		320		547.50
.0156	.004	30		80		227.08
.0156	.004	30		160		347.08
.0156	.004	30		240		445.42
.0156	.004	30		320		542.50
.0156	.004	45		80		234.58
.0156	.004	45		160		342.92
.0156	.004	45		240		456.67
.0156	.004	45		320		551.67
.0156	.006	15		80		249.58
.0156	.006	15		160		395.83
.0156	.006	15		240		482.92
.0156	.006	15		320		592.08
.0156	.006	30		80		246.67
.0156	.006	30		160		395.83
.0156	.006	30		240		480.42

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0156	.006	30		320		645.00
.0156	.006	45		80		251.67
.0156	.006	45		160		390.00
.0156	.006	45		240		529.17
.0156	.006	45		320		647.92
.0312	.002	15		80		231.67
.0312	.002	15		160		336.67
.0312	.002	15		240		483.33
.0312	.002	15		320		557.08
.0312	.002	30		80		234.17
.0312	.002	30		160		346.67
.0312	.002	30		240		502.92
.0312	.002	30		320		586.25
.0312	.002	45		80		229.58
.0312	.002	45		160		342.50
.0312	.002	45		240		415.00
.0312	.002	45		320		681.67
.0312	.004	15		80		269.17
.0312	.004	15		160		431.25
.0312	.004	15		240		596.25
.0312	.004	15		320		706.67
.0312	.004	30		80		260.83
.0312	.004	30		160		428.33
.0312	.004	30		240		629.17
.0312	.004	30		320		772.50
.0312	.004	45		80		265.83
.0312	.004	45		160		416.67
.0312	.004	45		240		635.83
.0312	.004	45		320		806.25
.0312	.006	15		80		308.33
.0312	.006	15		160		516.67
.0312	.006	15		240		695.42
.0312	.006	15		320		857.08
.0312	.006	30		80		301.67
.0312	.006	30		160		542.92
.0312	.006	30		240		709.17
.0312	.006	30		320		817.08
.0312	.006	45		80		302.08
.0312	.006	45		160		526.25
.0312	.006	45		240		697.50
.0312	.006	45		320		905.83

POWER REQUIREMENTS (3 D.O.C.)

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
			A EFFECT			
.0156						388.61
.0312						509.62
.0625						738.55

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
			B EFFECT			
	.002					432.18
	.004					552.76
	.006					651.85
			C EFFECT			
		15				537.77
		30				544.42
		45				554.59
			D EFFECT			
			-5			547.21
			0			538.52
			+5			551.05
			E EFFECT			
				80		279.84
				160		457.22
				240		643.52
				320		801.81
			F EFFECT			
					1	537.98
					2	553.21
			AB INTERACTION			
.0156	.002					330.06
.0156	.004					393.53
.0156	.006					442.26
.0312	.002					412.29
.0312	.004					518.23
.0312	.006					598.33
.0625	.002					554.18
.0625	.004					746.22
.0625	.006					914.95
			AD INTERACTION			
.0156			-5			388.90
.0156			0			387.64
.0156			+5			384.30
.0312			-5			513.61
.0312			0			503.75
.0312			+5			511.49
.0625			-5			732.71
.0625			0			724.17
.0625			+5			758.77
			AE INTERACTION			
.0156				80		231.06
.0156				160		345.88
.0156				240		436.44

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0156				320		541.06
.0312				80		267.04
.0312				160		431.99
.0312				240		596.06
.0312				320		743.38
.0625				80		341.41
.0625				160		593.78
.0625				240		898.04
.0625				320		1120.98

BD INTERACTION

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
	.002		-5			442.38
	.002		0			426.88
	.002		+5			427.38
	.004		-5			563.60
	.004		0			536.47
	.004		+5			558.21
	.006		-5			635.66
	.006		0			652.22
	.006		+5			667.66

BE INTERACTION

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
	.002			80		238.41
	.002			160		349.38
	.002			240		507.20
	.002			320		633.21
	.004			80		278.37
	.004			160		455.81
	.004			240		653.80
	.004			320		823.06
	.006			80		322.73
	.006			160		566.46
	.006			240		769.55
	.006			320		948.65

BF INTERACTION

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
	.002				1	427.13
	.002				2	437.22
	.004				1	550.41
	.004				2	555.11
	.006				1	636.38
	.006				2	667.31

CD INTERACTION

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
		15	-5			532.26
		15	0			543.66
		15	+5			537.40
		30	-5			550.59
		30	0			532.13
		30	+5			550.45

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
		45	-5			558.69
		45	0			539.78
		45	+5			565.30
		CE INTERACTION				
		15		80		282.80
		15		160		454.38
		15		240		646.81
		15		320		767.10
		30		80		277.31
		30		160		463.33
		30		240		647.66
		30		320		789.38
		45		80		279.40
		45		160		453.94
		45		240		636.07
		45		320		848.94
		DE INTERACTION				
			-5	80		280.91
			-5	160		453.35
			-5	240		646.38
			-5	320		773.44
			0	80		279.64
			0	160		459.82
			0	240		648.27
			0	320		816.46
			+5	80		278.96
			+5	160		458.47
			+5	240		635.90
			+5	320		815.52
		DF INTERACTION				
			-5		1	530.95
			-5		2	563.48
			0		1	531.84
			0		2	545.20
			+5		1	551.13
			+5		2	550.96
		EF INTERACTION				
				80	1	279.30
				80	2	280.38
				160	1	452.92
				160	2	461.46
				240	1	627.36
				240	2	659.67
				320	1	792.27
				320	2	811.35

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
			ABD INTERACTION			
.0156	.002		-5			339.44
.0156	.002		0			325.94
.0156	.002		+5			431.88
.0156	.004		-5			394.02
.0156	.004		0			394.08
.0156	.004		+5			391.98
.0156	.006		-5			452.50
.0156	.006		0			442.40
.0156	.006		+5			431.88
.0312	.002		-5			421.15
.0312	.002		0			406.15
.0312	.002		+5			409.58
.0312	.004		-5			532.71
.0312	.004		0			504.58
.0312	.004		+5			517.40
.0312	.006		-5			586.98
.0312	.006		0			600.52
.0312	.006		+5			607.50
.0625	.002		-5			566.54
.0625	.002		0			548.54
.0625	.002		+5			547.46
.0625	.004		-5			764.08
.0625	.004		0			710.23
.0625	.004		+5			765.25
.0625	.006		-5			867.50
.0625	.006		0			913.75
.0625	.006		+5			963.60
			ABE INTERACTION			
.0156	.002			80		213.33
.0156	.002			160		297.08
.0156	.002			240		362.17
.0156	.002			320		447.64
.0156	.004			80		230.56
.0156	.004			160		346.67
.0156	.004			240		449.67
.0156	.004			320		547.22
.0156	.006			80		249.31
.0156	.006			160		393.89
.0156	.006			240		497.50
.0156	.006			320		628.33
.0312	.002			80		231.81
.0312	.002			160		341.94
.0312	.002			240		467.08
.0312	.002			320		608.33
.0312	.004			80		265.28
.0312	.004			160		425.42
.0312	.004			240		620.42
.0312	.004			320		761.81
.0312	.006			80		304.03

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0312	.006			160		528.61
.0312	.006			240		700.69
.0312	.006			320		860.00
.0625	.002			80		270.08
.0625	.002			160		409.11
.0625	.002			240		692.36
.0625	.002			320		845.17
.0625	.004			80		339.28
.0625	.004			160		595.33
.0625	.004			240		891.31
.0625	.004			320		1160.17
.0625	.006			80		414.86
.0625	.006			160		776.89
.0625	.006			240		1110.44
.0625	.006			320		1357.61

ACE INTERACTION

.0156		15		80		230.97
.0156		15		160		350.28
.0156		15		240		434.61
.0156		15		320		516.39
.0156		30		80		227.64
.0156		30		160		345.69
.0156		30		240		426.67
.0156		30		320		558.33
.0156		45		80		234.58
.0156		45		160		341.67
.0156		45		240		448.06
.0156		45		320		548.47
.0312		15		80		269.72
.0312		15		160		428.19
.0312		15		240		591.67
.0312		15		320		706.94
.0312		30		80		265.56
.0312		30		160		439.31
.0312		30		240		613.75
.0312		30		320		725.28
.0312		45		80		265.83
.0312		45		160		428.47
.0312		45		240		582.78
.0312		45		320		797.92
.0625		15		80		347.69
.0625		15		160		584.67
.0625		15		240		914.17
.0625		15		320		1077.97
.0625		30		80		338.75
.0625		30		160		605.00
.0625		30		240		902.56
.0625		30		320		1084.53
.0625		45		80		337.78
.0625		45		160		591.67

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0625		45		240		877.39
.0625		45		320		1200.44

ACF INTERACTION

.0156		15			1	383.86
.0156		15			2	382.75
.0156		30			1	390.00
.0156		30			2	389.17
.0156		45			1	388.75
.0156		45			2	397.64
.0312		15			1	490.56
.0312		15			2	507.71
.0312		30			1	499.79
.0312		30			2	522.15
.0312		45			1	510.83
.0312		45			2	526.67
.0625		15			1	700.75
.0625		15			2	761.50
.0625		30			1	729.14
.0625		30			2	736.28
.0625		45			1	748.10
.0625		45			2	755.54

ADE INTERACTION

.0156			-5	80		227.78
.0156			-5	160		350.83
.0156			-5	240		445.31
.0156			-5	320		557.36
.0156			0	80		234.58
.0156			0	160		342.22
.0156			0	240		434.58
.0156			0	320		539.17
.0156			+5	80		230.83
.0156			+5	160		344.58
.0156			+5	240		429.44
.0156			+5	320		526.67
.0312			-5	80		267.50
.0312			-5	160		433.33
.0312			-5	240		598.14
.0312			-5	320		755.14
.0312			0	80		266.39
.0312			0	160		429.31
.0312			0	240		597.64
.0312			0	320		721.67
.0312			+5	80		267.22
.0312			+5	160		433.33
.0312			+5	240		592.08
.0312			+5	320		753.33
.0625			-5	80		341.61
.0625			-5	160		591.25
.0625			-5	240		863.92

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0625			-5	320		1134.06
.0625			0	80		341.75
.0625			0	160		588.53
.0625			0	240		906.92
.0625			0	320		1059.50
.0625			+5	80		340.86
.0625			+5	160		601.56
.0625			+5	240		923.28
.0625			+5	320		1169.39
		BCE INTERACTION				
	.002	15		80		238.00
	.002	15		160		347.17
	.002	15		240		522.72
	.002	15		320		606.08
	.002	30		80		238.33
	.002	30		160		354.17
	.002	30		240		530.00
	.002	30		320		631.17
	.002	45		80		238.89
	.002	45		160		346.81
	.002	45		240		468.89
	.002	45		320		663.89
	.004	15		80		282.61
	.004	15		160		459.08
	.004	15		240		651.06
	.004	15		320		762.36
	.004	30		80		274.31
	.004	30		160		460.97
	.004	30		240		646.75
	.004	30		320		828.78
	.004	45		80		278.19
	.004	45		160		447.26
	.004	45		240		663.58
	.004	45		320		878.06
	.006	15		80		327.78
	.006	15		160		556.89
	.006	15		240		766.67
	.006	15		320		932.86
	.006	30		80		319.31
	.006	30		160		574.86
	.006	30		240		766.22
	.006	30		320		908.19
	.006	45		80		321.11
	.006	45		160		567.64
	.006	45		240		775.75
	.006	45		320		1004.89
		BDE INTERACTION				
	.002		-5	80		239.69
	.002		-5	160		350.42

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
	.002		-5	240		511.08
	.002		-5	320		668.31
	.002		0	80		236.39
	.002		0	160		345.97
	.002		0	240		575.67
	.002		0	320		609.47
	.002		+5	80		239.14
	.002		+5	160		351.75
	.002		+5	240		494.86
	.002		+5	320		623.36
	.004		-5	80		274.94
	.004		-5	160		455.75
	.004		-5	240		651.53
	.004		-5	320		872.19
	.004		0	80		280.28
	.004		0	160		456.17
	.004		0	240		646.94
	.004		0	320		762.47
	.004		+5	80		279.89
	.004		+5	160		455.50
	.004		+5	240		662.92
	.004		+5	320		834.53
	.006		-5	80		322.25
	.006		-5	160		569.25
	.006		-5	240		745.08
	.006		-5	320		906.06
	.006		0	80		326.06
	.006		0	160		557.92
	.006		0	240		776.53
	.006		0	320		948.39
	.006		+5	80		319.89
	.006		+5	160		572.22
	.006		+5	240		787.03
	.006		+5	320		991.50

ABCE INTERACTION

.0156	.002	15		80		213.33
.0156	.002	15		160		305.00
.0156	.002	15		240		374.00
.0156	.002	15		320		409.58
.0156	.002	30		80		209.17
.0156	.002	30		160		294.17
.0156	.002	30		240		354.17
.0156	.002	30		320		487.50
.0156	.002	45		80		217.50
.0156	.002	45		160		292.08
.0156	.002	45		240		358.33
.0156	.002	45		320		445.83
.0156	.004	15		80		230.00
.0156	.004	15		160		350.00
.0156	.004	15		240		446.92

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0156	.004	15		320		547.50
.0156	.004	30		80		227.08
.0156	.004	30		160		347.08
.0156	.004	30		240		445.42
.0156	.004	30		320		542.50
.0156	.004	45		80		234.58
.0156	.004	45		160		342.92
.0156	.004	45		240		456.67
.0156	.004	45		320		551.67
.0156	.006	15		80		249.58
.0156	.006	15		160		395.83
.0156	.006	15		240		482.92
.0156	.006	15		320		592.08
.0156	.006	30		80		246.67
.0156	.006	30		160		395.83
.0156	.006	30		240		480.42
.0156	.006	30		320		645.00
.0156	.006	45		80		251.67
.0156	.006	45		160		390.00
.0156	.006	45		240		529.17
.0156	.006	45		320		647.92
.0312	.002	15		80		231.67
.0312	.002	15		160		336.67
.0312	.002	15		240		483.33
.0312	.002	15		320		557.08
.0312	.002	30		80		234.17
.0312	.002	30		160		346.67
.0312	.002	30		240		502.92
.0312	.002	30		320		586.25
.0312	.002	45		80		229.58
.0312	.002	45		160		342.50
.0312	.002	45		240		415.00
.0312	.002	45		320		681.67
.0312	.004	15		80		269.17
.0312	.004	15		160		431.25
.0312	.004	15		240		596.25
.0312	.004	15		320		706.67
.0312	.004	30		80		260.83
.0312	.004	30		160		428.33
.0312	.004	30		240		629.17
.0312	.004	30		320		772.50
.0312	.004	45		80		265.83
.0312	.004	45		160		416.67
.0312	.004	45		240		635.83
.0312	.004	45		320		806.25
.0312	.006	15		80		308.33
.0312	.006	15		160		516.67
.0312	.006	15		240		695.42
.0312	.006	15		320		857.08
.0312	.006	30		80		301.67
.0312	.006	30		160		542.92

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0312	.006	30		240		709.17
.0312	.006	30		320		817.08
.0312	.006	45		80		302.08
.0312	.006	45		160		526.25
.0312	.006	45		240		697.50
.0312	.006	45		320		905.83
.0625	.002	15		80		269.00
.0625	.002	15		160		399.83
.0625	.002	15		240		710.83
.0625	.002	15		320		851.58
.0625	.002	30		80		271.67
.0625	.002	30		160		421.67
.0625	.002	30		240		732.92
.0625	.002	30		320		819.75
.0625	.002	45		80		269.58
.0625	.002	45		160		405.83
.0625	.002	45		240		633.33
.0625	.002	45		320		864.17
.0625	.004	15		80		348.67
.0625	.004	15		160		596.00
.0625	.004	15		240		910.00
.0625	.004	15		320		1032.00
.0625	.004	30		80		335.00
.0625	.004	30		160		607.50
.0625	.004	30		240		865.67
.0625	.004	30		320		1171.33
.0625	.004	45		80		334.17
.0625	.004	45		160		582.50
.0625	.004	45		240		898.25
.0625	.004	45		320		1276.25
.0625	.006	15		80		425.42
.0625	.006	15		160		758.17
.0625	.006	15		240		1121.67
.0625	.006	15		320		1349.42
.0625	.006	30		80		409.58
.0625	.006	30		160		785.83
.0625	.006	30		240		1109.08
.0625	.006	30		320		1262.50
.0625	.006	45		80		409.58
.0625	.006	45		160		786.67
.0625	.006	45		240		1100.58
.0625	.006	45		320		1460.92

ABDE INTERACTION

.0156	.002		-5	80		214.17
.0156	.002		-5	160		302.50
.0156	.002		-5	240		372.33
.0156	.002		-5	320		468.75
.0156	.002		0	80		211.67
.0156	.002		0	160		287.50
.0156	.002		0	240		360.00

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0156	.002		0	320		444.58
.0156	.002		+5	80		214.17
.0156	.002		+5	160		301.25
.0156	.002		+5	240		354.17
.0156	.002		+5	320		429.58
.0156	.004		-5	80		225.42
.0156	.004		-5	160		353.33
.0156	.004		-5	240		455.67
.0156	.004		-5	320		541.67
.0156	.004		0	80		237.92
.0156	.004		0	160		350.00
.0156	.004		0	240		438.33
.0156	.004		0	320		552.08
.0156	.004		+5	80		228.33
.0156	.004		+5	160		336.67
.0156	.004		+5	240		445.00
.0156	.004		+5	320		547.92
.0156	.006		-5	80		243.75
.0156	.006		-5	160		396.67
.0156	.006		-5	240		507.92
.0156	.006		-5	320		661.67
.0156	.006		0	80		254.17
.0156	.006		0	160		389.17
.0156	.006		0	240		505.42
.0156	.006		0	320		620.83
.0156	.006		+5	80		250.00
.0156	.006		+5	160		395.83
.0156	.006		+5	240		479.17
.0156	.006		+5	320		602.50
.0312	.002		-5	80		232.92
.0312	.002		-5	160		339.17
.0312	.002		-5	240		475.00
.0312	.002		-5	320		637.50
.0312	.002		0	80		229.58
.0312	.002		0	160		342.92
.0312	.002		0	240		475.00
.0312	.002		0	320		577.08
.0312	.002		+5	80		232.92
.0312	.002		+5	160		343.75
.0312	.002		+5	240		451.25
.0312	.002		+5	320		610.42
.0312	.004		-5	80		262.92
.0312	.004		-5	160		429.17
.0312	.004		-5	240		638.75
.0312	.004		-5	320		800.00
.0312	.004		0	80		265.42
.0312	.004		0	160		430.42
.0312	.004		0	240		606.67
.0312	.004		0	320		715.83
.0312	.004		+5	80		267.50
.0312	.004		+5	160		416.67

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
.0312	.004		+5	240		615.83
.0312	.004		+5	320		769.58
.0312	.006		-5	80		306.67
.0312	.006		-5	160		531.67
.0312	.006		-5	240		681.67
.0312	.006		-5	320		827.92
.0312	.006		0	80		304.17
.0312	.006		0	160		514.58
.0312	.006		0	240		711.25
.0312	.006		0	320		872.08
.0312	.006		+5	80		301.25
.0312	.006		+5	160		539.58
.0312	.006		+5	240		709.17
.0312	.006		+5	320		880.00
.0625	.002		-5	80		272.00
.0625	.002		-5	160		409.58
.0625	.002		-5	240		685.92
.0625	.002		-5	320		898.67
.0625	.002		0	80		767.92
.0625	.002		0	160		407.50
.0625	.002		0	240		712.00
.0625	.002		0	320		806.75
.0625	.002		+5	80		270.33
.0625	.002		+5	160		410.25
.0625	.002		+5	240		679.17
.0625	.002		+5	320		830.08
.0625	.004		-5	80		336.50
.0625	.004		-5	160		584.75
.0625	.004		-5	240		860.17
.0625	.004		-5	320		1274.92
.0625	.004		0	80		337.50
.0625	.004		0	160		588.08
.0625	.004		0	240		895.83
.0625	.004		0	320		1019.50
.0625	.004		+5	80		343.83
.0625	.004		+5	160		613.17
.0625	.004		+5	240		917.92
.0625	.004		+5	320		1186.08
.0625	.006		-5	80		416.33
.0625	.006		-5	160		779.42
.0625	.006		-5	240		1045.67
.0625	.006		-5	320		1228.58
.0625	.006		0	80		419.83
.0625	.006		0	160		770.00
.0625	.006		0	240		1112.92
.0625	.006		0	320		1352.25
.0625	.006		+5	80		408.42
.0625	.006		+5	160		781.25
.0625	.006		+5	240		1172.75
.0625	.006		+5	320		1492.00

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
			BCEF INTERACTION			
	.002	15		80	1	236.61
	.002	15		80	2	239.39
	.002	15		160	1	349.17
	.002	15		160	2	345.17
	.002	15		240	1	494.72
	.002	15		240	2	550.72
	.002	15		320	1	626.44
	.002	15		320	2	585.72
	.002	30		80	1	241.39
	.002	30		80	2	235.28
	.002	30		160	1	345.28
	.002	30		160	2	363.06
	.002	30		240	1	510.56
	.002	30		240	2	549.44
	.002	30		320	1	635.00
	.002	30		320	2	627.33
	.002	45		80	1	238.89
	.002	45		80	2	238.89
	.002	45		160	1	341.67
	.002	45		160	2	351.94
	.002	45		240	1	475.00
	.002	45		240	2	462.78
	.002	45		320	1	630.83
	.002	45		320	2	696.94
	.004	15		80	1	282.33
	.004	15		80	2	282.89
	.004	15		160	1	472.61
	.004	15		160	2	445.56
	.004	15		240	1	652.33
	.004	15		240	2	649.28
	.004	15		320	1	699.94
	.004	15		320	2	824.78
	.004	30		80	1	273.33
	.004	30		80	2	275.28
	.004	30		160	1	457.78
	.004	30		160	2	464.17
	.004	30		240	1	646.56
	.004	30		240	2	646.94
	.004	30		320	1	846.50
	.004	30		320	2	811.50
	.004	45		80	1	280.83
	.004	45		80	2	275.56
	.004	45		160	1	448.06
	.004	45		160	2	446.67
	.004	45		240	1	657.89
	.004	45		240	2	669.28
	.004	45		320	1	886.78
	.004	45		320	2	869.33
	.006	15		80	1	325.83
	.006	15		80	2	329.72

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
	.006	15		160	1	536.06
	.006	15		160	2	577.72
	.006	15		240	1	712.28
	.006	15		240	2	821.06
	.006	15		320	1	912.33
	.006	15		320	2	953.39
	.006	30		80	1	319.44
	.006	30		80	2	319.17
	.006	30		160	1	557.78
	.006	30		160	2	591.94
	.006	30		240	1	742.28
	.006	30		240	2	790.17
	.006	30		320	1	899.83
	.006	30		320	2	916.56
	.006	45		80	1	315.00
	.006	45		80	2	327.22
	.006	45		160	1	568.33
	.006	45		160	2	566.94
	.006	45		240	1	754.67
	.006	45		240	2	796.83
	.006	45		320	1	992.78
	.006	45		320	2	1017.00

CDEF INTERACTION

15	-5	80	1	280.22
15	-5	80	2	283.83
15	-5	160	1	454.33
15	-5	160	2	453.44
15	-5	240	1	577.06
15	-5	240	2	660.94
15	-5	320	1	758.89
15	-5	320	2	789.39
15	0	80	1	283.17
15	0	80	2	287.83
15	0	160	1	453.89
15	0	160	2	467.61
15	0	240	1	648.50
15	0	240	2	717.39
15	0	320	1	725.56
15	0	320	2	765.33
15	+5	80	1	281.39
15	+5	80	2	280.33
15	+5	160	1	449.61
15	+5	160	2	447.39
15	+5	240	1	633.78
15	+5	240	2	643.22
15	+5	320	1	754.28
15	+5	320	2	809.17
30	-5	80	1	280.00
30	-5	80	2	278.06
30	-5	160	1	446.11

D.O.C.	Feed	S.C.E.A.	B.R.	Speed	Trials	Mean
		30	-5	160	2	482.22
		30	-5	240	1	605.28
		30	-5	240	2	673.61
		30	-5	320	1	797.22
		30	-5	320	2	843.00
		30	0	80	1	279.17
		30	0	80	2	272.78
		30	0	160	1	443.06
		30	0	160	2	463.33
		30	0	240	1	621.06
		30	0	240	2	658.72
		30	0	320	1	763.28
		30	0	320	2	755.61
		30	+5	80	1	275.00
		30	+5	80	2	278.89
		30	+5	160	1	471.67
		30	+5	160	2	473.61
		30	+5	240	1	673.06
		30	+5	240	2	654.22
		30	+5	320	1	820.83
		30	+5	320	2	756.33
		45	-5	80	1	273.61
		45	-5	80	2	278.06
		45	-5	160	1	455.00
		45	-5	160	2	459.72
		45	-5	240	1	640.78
		45	-5	240	2	657.72
		45	-5	320	1	802.89
		45	-5	320	2	901.72
		45	0	80	1	283.06
		45	0	80	2	279.44
		45	0	160	1	441.39
		45	0	160	2	450.83
		45	0	240	1	610.67
		45	0	240	2	621.94
		45	0	320	1	829.33
		45	0	320	2	801.56
		45	+5	80	1	278.06
		45	+5	80	2	284.17
		45	+5	160	1	461.67
		45	+5	160	2	455.00
		45	+5	240	1	636.11
		45	+5	240	2	649.22
		45	+5	320	1	878.17
		45	+5	320	2	880.00

VITA

Morris Henry Schneider

Candidate for the Degree of

Doctor of Philosophy

Thesis: A STATISTICAL INVESTIGATION OF SOME MACHINING VARIABLES

Major Field: Engineering

Biographical:

Personal Data: Born November 26, 1923 in Sutton, Nebraska, the son of Peter and Eva Schneider of Sutton, Nebraska.

Education: Attended High School in Sutton, Nebraska, and graduated in 1941. Entered the University of Nebraska in June 1946 and received a Bachelor of Science degree in Education in January 1951. Re-entered the University of Nebraska in September 1954 and received a Bachelor of Science degree in Mechanical Engineering in June 1959. Entered Kansas State University in June 1960 and received a Master of Science degree in Industrial Engineering in August 1961. Entered Oklahoma State University in June 1964 and completed requirements for the degree of Doctor of Philosophy in August 1965.

Professional Experience: Employed by the Capital Office Supply Company as Office Manager January 1951 to August 1954. Employed by the University of Nebraska as Instructor of Mechanical Engineering September 1954 to June 1960. Employed concurrently and during summers as Design Engineer for Nebraska Boiler Company. Employed September 1960 by Kansas State University as Instructor of Industrial Engineering and in September 1961 as Assistant Professor of Industrial Engineering until May 1962. Employed June 1962 to May 1964 as Assistant Professor of Industrial Engineering at Texas Technological College. June 1964 to August 1965, National Science Foundation Faculty Fellow at Oklahoma State University. Employed as Associate Professor of Mechanical Engineering by the University of Nebraska September 1965.

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