# INVESTIGATION OF THE GRINDING PROCESS

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# NOMENCLATURE

AA = Arithmetic Average

Ave. = Average

C.F. = Cross Feed

Cu. in. = Cubic Inch

d.f. = Degrees of Freedom

Dia. = Diameter

D.O.C. = Depth of Cut

FPM = Feet per Minute

G.S. = Grain Size

G.Wh. = Grinding Wheel

In. = Inch

in./str. = Inch per Stroke

K.W. = Kilowatt

M.S. = Mean Square

NS = Not Significant

P = Probability

P.C. = Power Consumption

R = Number of Replication

RC = Rockwell C

RMS = Root Mean Square

R.O.M.R. = Rate of Metal Removal

RPM = Revolution per Minute

# NOMENCLATURE (Continued)

SS = Sum of Squares

S.F. = Surface Finish

Sq. in. = Square Inch

S.R. = Surface Roughness

T.S. = Table Speed

# CHAPTER I

## INTRODUCTION

This research project presents quantitative information about surface grinding. Part one investigates tool life. Part two quantitatively studies the effect of sparkout on surface finish. Part three identifies the individual as well as the combined effects of different factors on surface finish and power requirements.

Grinding, as applied to the machining processes, describes the removal of metal by means of rotating abrasive wheels. It is a metal cutting process similar in many ways to other commonly employed methods of metal removal such as milling, turning and shaping. In fact, a grainding wheel may be described as a multi-toothed milling cutter, each tooth consisting of a small abrasive particle (1).

On the other hand, there are many fundamental differences between the grinding process and the other machining methods. In most metal cutting processes, the tools have known geometry and orientation, but in grinding there are randomly oriented cutting teeth. In most grinding processes, depths of cut taken by the abrasive grains are very small compared with cuts taken in other machining processes. Also, surface speeds at which the grinding process is carried out are very high relative to the others.

As a result of the random grit geometry, small depth of cut, and high cutting speed, mechanisms of the grinding process are difficult to observe and evaluate.

There are increasing requirements for the grinding process in modern industry as a result of the many advantages it offers. Properly controlled, the grinding operation gives very accurate dimensions and a surface with a high quality finish. As the grinding process employs a cutter with very hard teeth, the abrasive grains, machining ultra-hard materials can be easily achieved.

There are many types of grinding operations: surface grinding, cylindrical grinding, internal grinding, etc. This research project is limited to the semi-finishing, horizontal spindle, surface grinding operation (see Figure 1).

Vidosic (2) defines machinability as the ease with which metal can be removed. Improved machinability in a surface grinding operation indicates that a better surface finish and satisfactory tool life have been obtained, and less power was consumed. All these variables must be achieved while maintaining the quality of the surface structure of the metal being ground. Surface finish and tool life are the most important factors that influence the economics of the grinding process. However, power measurements give a very reliable indication of the

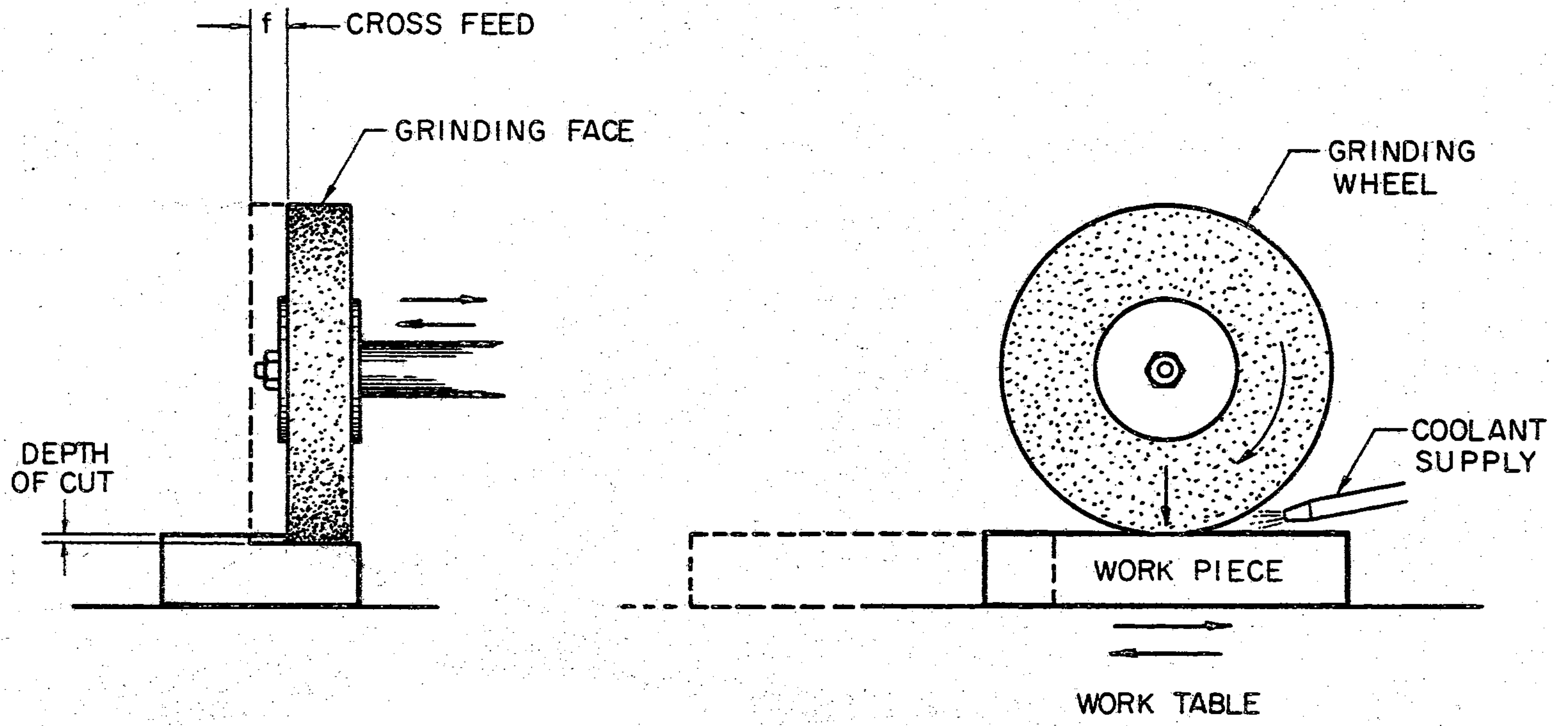


Figure 1. Surface Grinding - Horizontal Spindle

severity of the operation as well as other parameters.

The desired results of the grinding process, like many other machining processes, are influenced by many factors such as: type of grinding operation, kind of grinding wheel, properties of the metal being ground, cutting speed, depth of cut, feed, coolant, etc. There is no single, conclusive criterion to indicate the machinability rating of all grinding process conditions. Schneider (3) states:

> Many times one or more objectives may be sacrified; 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.

Surface quality is of great importance as it ensures optimum service, life, appearance, performance, and other desired properties. Surface finish is considered to be one of the most important criteria for specifying surface quality.

Surface finish should be specified very carefully due to the ever increasing cost of machining operations as well as the increasing use of surface finish as a manufacturing specification. Excessively refined finish quality cannot be overlooked on the assuption that it does not increase the cost. One automotive manufacturer estimated that each microinch of overfinish increased part costs by an average of 1 % (4).

Tool life as well as surface finish greatly influence the economics of metal removal. Prior and accurate knowledge of tool life, in terms of its value and behavior has a considerable practical value in the design of an efficient machining process. Tool life in this study is defined in terms of the amount of metal removed, the area machined, and/or the time between two sharpenings of the grinding wheel, considering the limits of surface quality to be achieved. In other words, tool life is the useful service between the sharpening of the grinding wheel and the time it fails to perform in accordance with some specified criterion.

Despite the broad progress and the considerable amount of research studying metal cutting operations, the grinding operation continues to lack systematic description and understanding.

Mueller (5); in April 1968, stated:

> Abrasive intelligence is sadly lacking in industry today. Because of this lack of information, industry is confused and this confusion is compounded too often because of inadequate or erroneous information.
>
> Laboratory testing techniques need to be expanded to include documentation of factual data and the dissemination of these data in logical, orderly, and simple manner.
>
> We are plagued with the established tradition that the use of abrasives is complex, mysterious, and confusing. Laboratory testing could have for one of its purposes, programs to dispel this concept by generating simple rules of practice that would be acceptable to all. Then, instead of compounded confusion, a harmonious habit of abrasive usage would be instilled.

The main objective of this research project is to obtain quantitative information about the surface grinding operation. The first part is a study of the volume of material that can be removed between wheel dressings while operating on a continuous production basis. Various depths of cut were produced while maintaining the surface finish within some specified tolerances. The wheel, coolant, feed and table speed used in this first part were specified at the most practical levels based on experience (6-7). The wheel is allowed to sparkout for a specified number of runs before recording the surface finish. The life of the wheel is terminated when the surface finish does not meet the specified tolerances or when cracking starts to appear on the finished surface. Frequent microscopic inspection of the material is employed to detect the initiation of cracking. This part presents factual, quantitative data about tool life to aid in planning the grinding operations and stimulating further investigations.

Sparkout is a normal practice in grinding operations. Part Two quantitatively studies its effect on surface finish. Furthermore, the results of part one and part two are used in planning the ranges of experimentation in Part Three.

Part Three will be a quantitative analysis concerned with the effect of the wheel, the coolant, the depth of cut, the table speed and the cross feed on the first cut surface roughness and the power requirement.

The use of coolant is believed by many to be of unquestionalbe value in the grinding operations; others feel this factor is open to investigation. The coolant is definitely effective in reducing the temperature of the surface cut, thus preventing undesirable burns, and reducing the power consumed. On the other hand, the effect of coolant use on surface finish and tool life must be further studied. Lamber (8) states:

> For a number of years, cutting fluids have been used with carbon steel and high-speed steel tools for cooling so that higher operating speeds could be used or longer tool life realized for a certain cutting speed.
>
> In some cases, cutting fluids do not improve tool life, especially when cemented tungsten carbide tools are used.

Dry grinding is not unusual in industry. Therefore, in the preliminary experiments of this project, some surfaces were ground employing a coolant; other experiments did not utilize a coolant. The two sets of finished surfaces showed no significant difference. Therefore, the coolant is included as a variable to be studied in Part Three.

The other variables were varied over the whole range that was possible on the available machine. Portions of the studied ranges are not normally used in practical applications; however, the purpose of this study is to quantitatively reveal the interrelationships among the factors studied and to stimulate further interest.

Power consumption is of secondary effect on the economics of machining. However, accurate knowledge of its levels and effects helps in efficient production planning. In grinding operations, involving high speed rotating abrasive wheels, overloaded conditions create potential hazards, not only to the finished surface but also to the machine and the operator (7, 9).

Due to the wide range of the various internal and external factors that influence any machining operation, grinding has a statistical, probabilistic character (3). The combined effect of all these factors acting together is observed on the final results. Individual contributions are not immediately evident. With systematic variation of controllable factors, statistical methods are powerful in identifying the individual effects as well as the combinatorial effects (3, 10-12).

Knowing the quantitative effects, mathematical models were developed to estimate the quality of surface finish and power requirement for the first cut during the useful life of the grinding wheel. Twelve representative treatments were chosen in such a manner as to encompass the entire range of treatments performed. Predictions of the mathematical models of the surface roughness were compared to the experimental results of these twelve treatments. Furthermore, ten more treatments, representing the highest ten rates of metal removal, were used to check the accuracy of power consumption.

Graphs and tables were developed relating the surface finish and power consumption to the rate of metal removal. These graphs and tables facilitate effecient and satisfactory grinding.

# CHAPTER II

## REVIEW OF THE LITERATURE

### Surface Grinding

The surface grinding operation is employed when a fine surface finish is desired or when a metal part is manufactured to close tolerances. The elements of surface grinding are shown in Figure (1). The tool used in the operation, the grinding wheel, is composed of carefully sized abrasive grains held together by a bonding material. There is a great variety of grinding wheels. When selecting a wheel for a specific application, there are five factors that must be considered (13):

1. The abrasive - the cutting agent used in the wheel;
2. The grain size - the particle size or mesh of the abrasive grains;
3. The bond - the bonding material that holds the abrasive grains together;
4. The grade - the strength of the bonding of the grinding wheel frequently referred to as its hardness, and

5. The structure - the proportion and arrangement of the abrasive grains and bond in the grinding wheel.

Figure 2 shows the standard abrasive designations.

The widely used abrasives today are silicon carbide (SiC) and aluminum oxide ($AL_2O_3$). The penetration hardness and fracture characteristics of aluminum oxide, whereby it constantly exposes new sharp cutting edges, make it better suited for grinding relatively tough, high-tensile-strength materials.

According to Shaw (1) and other (13, 14) the grain size and the structure are the elements that affect the surface finish of the work-piece most. Course and medium sizes are normally used for roughing and semifinishing operations, while fine sizes are used for finishing.

The bond must hold the abrasive grains together in the wheel with just the right strength to permit each grain on the cutting face to perform effectively. A wheel is said to be hard if its bond is very strong and capable of holding the abrasive grains against the forces tending to pry them loose. If only a small force is needed to release the grains, the wheel is said to be soft. Letters from D to Z refer to the increasing hardness of wheels. Hard wheels are recommended for soft materials, and medium and soft wheels for hard materials (13).

The structure of a grinding wheel is designated by a number ranging from 0 to 15, the lower numbers designating

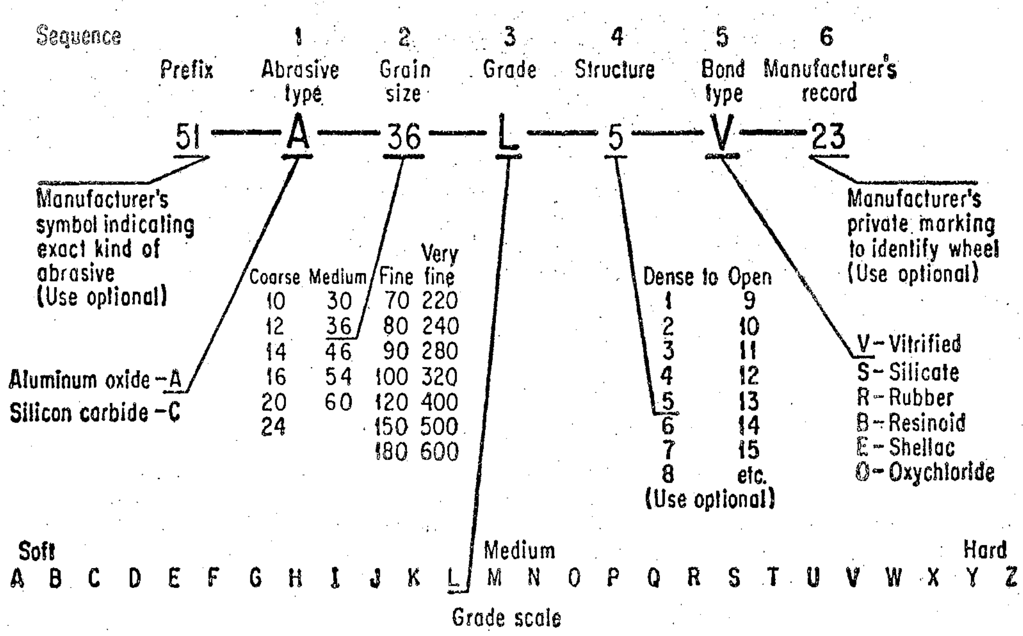


Figure 2. Standard Bonded-Abrasive Wheel-Marking System (American Standard Association)

denser structures or a closer grain spacing. Soft, ductile materials require a wide spacing. A fine finish requires a wheel with abrasive particles closely spaced.

## Surface Finish

The surface of a solid object defines it and separates it from other materials. The qualities of a machined surface depend on its geometry, microscopic structure and chemical composition. Standards of surface quality now deal particularly with the geometry of the surface deviations from the nominal surface (3). The deviations of the actual surface from the moninal are called roughness, waviness and flaws (Figure 3).

Surface roughness is defined as the deviation from the nominal in the form of finely spaced irregularities. These are produced by cutting edges and tool feed.

Waviness is comprised of the recurrent irregularities in the form of waves with the roughness superimposed on it. They may be caused by deflection, vibrations or warping. Flaws are any irregularities occuring at infrequent intervals. A scratch, a crack, a ridge, or a peak are classified as flaws. The direction of the surface pattern defines lay. It results from tool marks, or grain orientation (2). Figure 4 depicts the analysis of surface roughness.

Surface roughness is considered one of the most important manufacturing specifications. Precise dimensions,

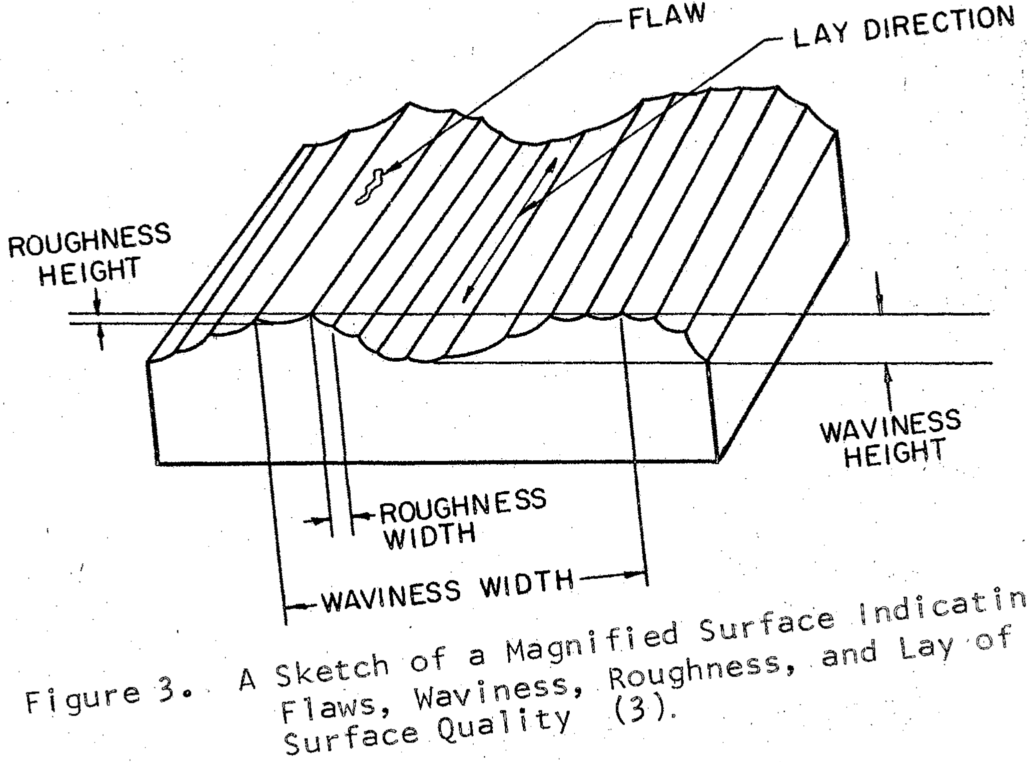
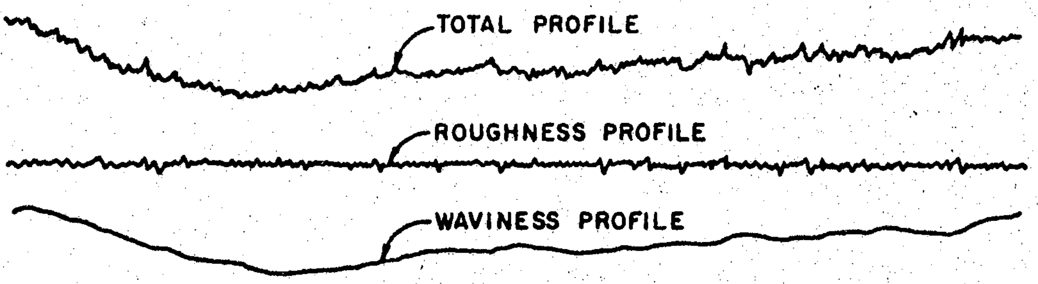
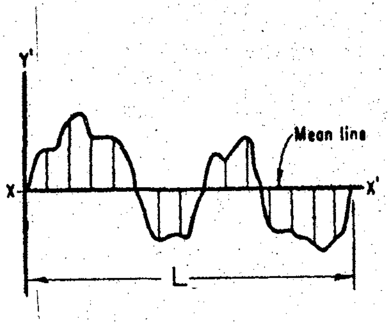


Figure 3. A Sketch of a Magnified Surface Indicating Flaws, Waviness, Roughness, and Lay of Surface Quality (3).





ENLARGEMENT OF ROUGHNESS PROFILE

Figure 4. Surface Roughness

friction, fatigue, hardness, lubrication, and heat transfer properties of the workpiece are some of the variables affected by surface roughness (3). This study is concerned with surface roughness; waviness and surface defects, arizing from the material or its manufacture, are not considered.

The surface roughness is identified by the average of the deviations from the mean line. The mean line should be located such that the algebraic sum of the areas above and below it equals zero (see Figure 4). Roughness height is measured in microinches. There are two ways of measuring the average height.

1. The arithmetic average (AA)

$$AA = \frac{1}{L} \int_o^L |y| dx = \frac{\sum |y|}{n}$$

where y represents deviations, and n is the number of such values, and L is the length over which y is averaged, and

2. The root-mean square (rms).

$$rms = \left[ \frac{1}{L} \int_o^L y^2 dx \right]^{\frac{1}{2}} = \left[ \frac{\sum y^2}{n} \right]^{\frac{1}{2}}$$

Of the two, AA is prefered having been officially accepted as the U.S. standard measurement and it is used in this research (15).

The accurate consideration of surface finish has become an important goal in the field of production design. This is described by Miller (4):

> 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 %.

## Tool Life

Tool life studies have become a well established necessity in any industry engaged in machining. The useful life of a cutting tool has a large influence on the economics of production. Considerable research has been carried out to establish the fact that tool life studies can save much time and money in the design of efficient machining processes (8)

Much of researchers attention has been devoted to single and multi-tool cutting in order to develop specific tool life correlations for different tool-workpiece combinations. At the same time no quantitative analysis has been reported in the literature on the useful life of grinding wheels. Therefore, this study attempts to provide quantitative information about tool life and behavior of a grinding wheel under different conditions during its useful life.

Different definitions may be given to what is meant by tool life. Tool life is terminated based on many factors such as the required surface finish, dimensional stability, surface structure of finished workpiece. In this study tool failure will be determined by any of the following:

1. Finish failure - occurrence of a sudden or gradual pronounced change in the finish of a workpiece.
2. Surface structure failure - the appearance of coloured bands indicating rubbing and execessive heat which causes cracking of the surface metal.
3. Complete failure - grinding wheel is completely unable to cut or is starting to break.

The useful life of the grinding wheel is given in terms of the amount of metal removed, area machined and machining time.

## Sparkout

Sparkout means allowing the grinding wheel to repeatedly pass over the surface after it has been ground without infeeding any more depth of cut. Sparkout is commonly used in almost all grinding operations. It is reported to greatly improve surface finish particularly in plunge grinding (5). The quantitative imporvement by, and the economical justification for sparkout were not reported for semifinishing operations. Based on pilot experiments in this project, better results may be obtained, in less time, by properly adjusting other factors such as grain size, feed, speed, etc., and without employing sparkout. The results of Part Two are evaluated in light of the later results of Part Three.

## Power

Power consumption is considered secondary to tool life and surface finish in its effect on the economics of machining. However, power is used as a measuring criterion because it indicates the level of severity and other parameters involved in the operation. The design capabilities of the wheels, the machines, and the workpiece to stand certain severity of operations must be known carefuly and taken into consideration to avoid damaging consequences (7, 9).

There are four measures used in specifying the power consumed in machining: the gross power, the net power, the specific power consumption, and the volume of metal removal per unit of net power. The net power, which is used in this study, is the power actually supplied to the grinding wheel and consumed in removing the metal in the grinding operation.

## Statistical Analysis

Because of multiplicity of internal and external factors influencing the grinding process, as well as any other machining process, it lends itself to statistical, probablistic analysis. Shaw (1) writes:

> Of all metal cutting processes grinding is undoubtedly least understood. The laws and equations governing the grinding operation are obtainable only through the application of statistical averages.

The lacking understanding of abrasive operations at the present leads to confusion often compounded by erroneous information. Documentation and dessimination of testing data must be standardized and expanded in order to meet the growing industrial needs (5)

Pollock (16-20), Ratterman (21), and others (22-30), in their research of the grinding operations varied one parameter or variable at a time. This sort of study can reveal much desirable information without the utilizing of statistical techniques. But there is no doubt that many other valuable results can be obtained by using statistical analysis to study the effect and significance of the interrelation and interaction of the multitude of factors involved in the grinding process.

The surveyed literature does not indicate an attempt to apply physical experimentation coupled with subsequent statistical analysis of the data to further the

the understanding of this process.

According to Schneider (3), Katsev (10), Tayler (11), and Green (12) the use of mathematical statistics in machinging process, especially the factorial experimentation technique, results in the following:

1. It increases the possibility of studying and understanding the process.
2. It establishes relationships that evaluate the effects of variations in a single variable as well as the combined effect of several parameters varying simultaneously.
3. It establishes quantitatively the effect of unknown or unnoticed factors on the process.
4. It improves the analytical efficiency as compared to varying one factor at a time by using all available data in computing the individual contribution of each factor.

In conclusion, Green and Tucky (12) gave the following comment on the usefulness of the analysis of variance, factorial experimentation techniques:

> 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.

# CHAPTER III

# TOOL LIFE STUDY

## Experimental Design

Surface grinding operation was selected for investigation in this work. This process was chosen for several reasons. Surface grinding is the most common grinding operation and has long been used to evaluate the effect of different factors on the surface finish. An available horizontal spindle surface grinding machine was used. Also, as the semifinishing grinding operation has a wide application this study was limited to that area.

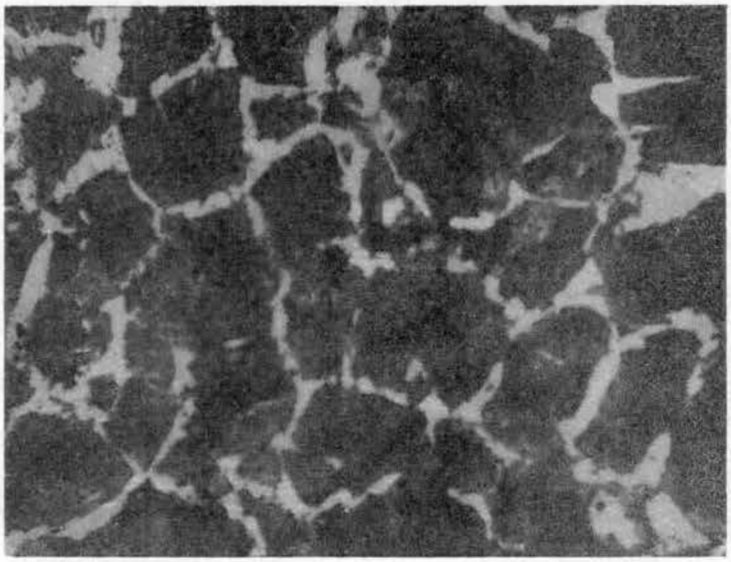
The material selected was SAE 1045 hot-rolled steel with the following chemical composition (31):

| | | |
|---|---|---|
| 1. | Carbon | .43 to .50% |
| 2. | Manganese | .60 to .90% |
| 3. | Phosphourus | .04 % maximum. |
| 4. | Sulpher | .05 % maximum. |

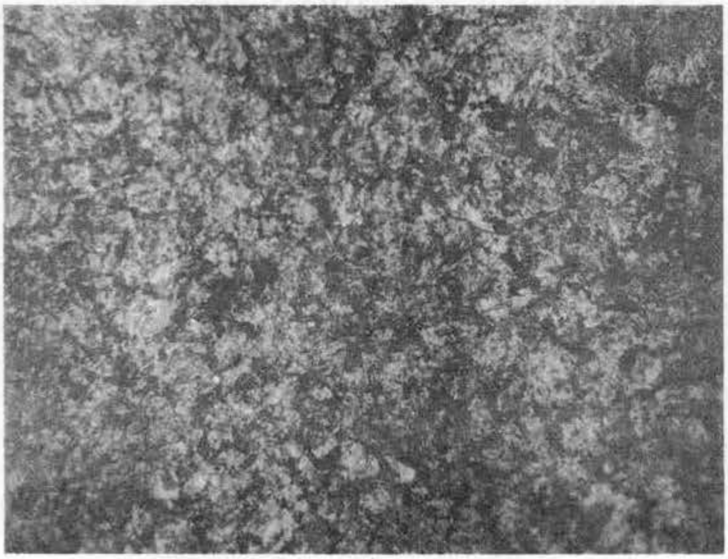
The selection of this steel for use as the workpiece material was based on two main considerations: First, SAE 1045 steel is widely used industrially in machinery parts, forming dies, racks, slides, etc. Second, it is easy to harden up to the specified limits of practical application. The steel was hardened to 45 ± 2 Rockwell C. Figure five shows the microscopic structure of that metal before and after hardening. The dimensions of the workpiece was 2 x 4 x 10 inches, giving a work surface of 40 square inches. Several small specimens of 3/4 inches diameter from the same material and hardness were used to facilitate microscopic inspection.

The grinding wheel used was Carborundum AA 46 H8 V40 of size 12 x 1 x 5 inches. The specification of the wheel is given as follows (13):

1. Abrasive A, aluminum oxide, suitable for grinding relatively high-tensile-strength materials.
2. Grain size 46, medium, used for semi-finishing.
3. Grade H, medium, used for relatively hard materials.
4. Structure 8, medium, suitable for simi-finishing.
5. Bond V, vitrified, suitable for high stock-removal rates.
6. Diameter, 12 inches.
7. Thickness, 1 inch.
8. Rotation speed, with no cutting, was 1800 RPM, giving surface speed of 5650 feet per minute.



A. Before Hardening X 400



B. After Hardening X 400

Figure 5. Microscopic Structure of SAE 1045

While cutting the speed was reduced as low as 1770 RPM, a surface speed of 5558 feet per minute. Truing and sharpening of the wheel was accomplished by the use of a diamond tool. This wheel was chosen because it fits the conditions set for the experiment.

The grinding operation was conducted under wet conditions, that is, with the use of coolant. Coolant used was water miscible and it was applied continuously.

## Experimental Equipment

A Thompson horizontal spindle, surface grinding machine was used for the study. The work table motor was of 1.5 H.P. The grinding wheel attachments were equiped with a motor of 3 H.P. The machine was equiped with automatic controlled cross feed and table speed devices. The range on the cross feed was .057-.286 inches per stroke. The range on table speed varied from 0 to 55 feet per minute. The division on the infeed depth of cut device was equal to .0005 inches and could be controlled to one half a division making it possible to take cuts of .00025 inches. A magnetic chuck held the workpiece in place.

The surface finish measuring device was a Bendix profilometer capable of measuring surface finish from 0.1 to 3000 microinches either in arithmatic or root mean square average. A Weston Industrial Analyzer was used to measure power consumption.

A Unitrom microscope equiped with polaride camera with magnification up to X 800 was used to detect surface deformities. A complete list of the equipment used in the experiment is given in Table 1.

## Design of the Experiment

The independent variable in this experiment was the depth of cut. The kind of wheel, cross feed, table speed and coolant were kept constant. As the width of the grinding wheel used was one inch, the cross feed used was .286 inches per stroke, the maximum crossfeed available on the machine, to meet the recommended specifications (6, 9). The table speed used was 40 feet per minute as the recommended one was between 35 and 45 feet per minute. Six levels of depth of cut were selected to cover the range of depth of cut used in this kind of operations. The six were: .00025, .0005 , .00075, .001, .00125 and .0015 inches. For each depth of cut the test was started with a sharp wheel. After removing a specified amount of material, the wheel was allowed to sparkout by crossing the workpiece five times before measuring the surface finish. The amount of metal removed each time was .200 cubic inches for depthes of cut .00025, .0005, .001, and .00125 inches; and .240 cubic inches for depthes of cut .00075, and .0015 inches. The increments of metal removed were specified in that order to obtain a reasonabley complete number of passes over the 40 square inches

# TABLE I

## EQUIPMENT AND USE

| Equipment | Use |
|---|---|
| Grinding Machine | Grinding operation |
| Magnetic chuck | Hold test specimen for grinding |
| Grinding wheel | Grinding operation |
| Diamond tool | Truing and dressing |
| Wattmeter | Measurement of power |
| Microscope | Inspect surface deformities |
| Strobotac | Measurement of r.p.m. of grinding wheel |
| Profilometer | Measurement of surface finish |

surface (Figure 6).

The range of surface finish was measured over a length of 0.750 inches. The surface structure was inspected to detect the development of any cracking. The 3/4 inch diameter specimens were used for the microscopic inspection. If the measured surface finish range was within the tolerances set for each depth of cut and there was no cracking, the test was continued removing each time the same amount of metal without resharpening the wheel. The life of the wheel was considered terminated when the measured surface finish range went out of the set tolerances or when cracking developed. The measured surface finish ranges were recorded and plotted against total metal removed (Figure 7). Figure 15 in Appendix A shows a data sheet used for recording the data. The number of cuts, n, is the number of cutting passes with the specified depth of cut, d, to remove the amount of metal specified. For example, in case of d= .001 inches, and a surface area, A, of 40 square inches:

$$n = \frac{.200}{A \times d} = \frac{.200}{40 \times .001} = 5$$

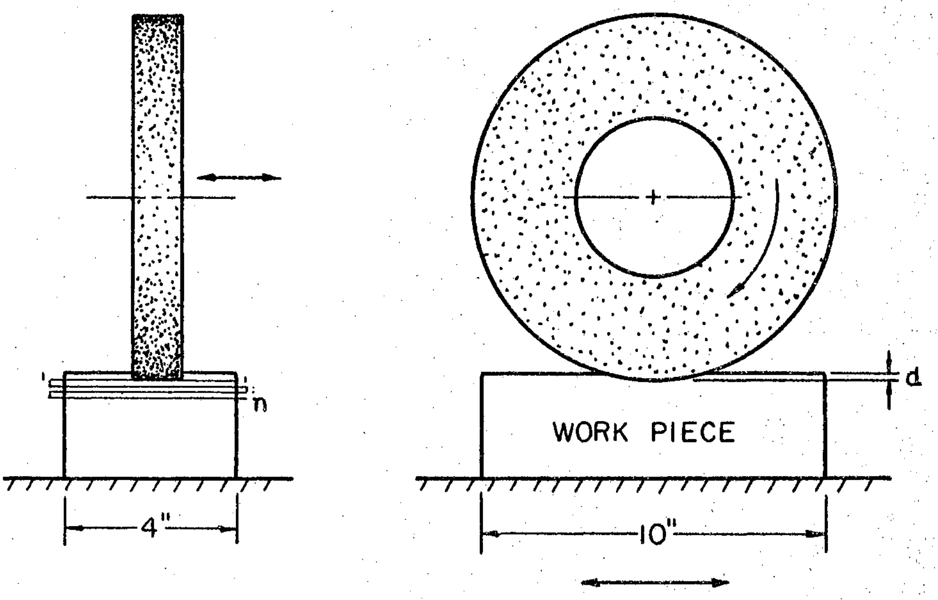


Figure 6. Grinding Procedure

## Experimental Procedure

The steps followed in every test were:

1. Truing and sharpening the grinding wheel.
2. Placing the workpiece, 2 x 4 x 10 inches, and the small specimens, .75 inches diameter, on the magnetic chuck and energizing the chuck.
3. Setting the feed and speed.
4. Adjusting the grinding wheel to start cutting.
5. Infeeding the depth of cut used.
6. After grinding one area, infeed the depth of cut again to grind the second area and so on untill the specified amount of metal was removed.
7. Sparking out five times without infeeding any more depth of cut.
8. Stopping the machine.
9. Removing workpiece to measure surface finish range.
10. Recording surface finish range.
11. Removing the 3/4 inch diameter specimen frequently to be polished, etched, and inspected under the microscope for cracking.

12. Measuring the net power consumption at different intervals during the test.
13. Stopping the test when the surface finish range exceeded the specified tolerances or when cracking was detected.
14. Starting another test for another depth of cut.

## Analysis of Results

Experimental results are plotted as a function of the total metal removed. Figures 7, 9, 11, 13, 15, and 17 show the results of the tests for depths of cut of .0015, .00125, .001, .00075, .0005, and .00025 inches respectively. Figures 8, 10, and 12 show the microscopic structure for the greatest three depths of cut after removing 1.2 cubic inches of metal and at the end of tool life in each case. Figures 14, 16, and 18 show the microscopic structure for the other three depths of cut at the end of tool life. From the microscopic inspection and the detailed study of pictures taken, it was clear that no cracks developed during the useful life of the grinding wheel. The untolerable increase in the surface roughness was the criterion used to indicate the termination of the grinding wheel useful life. The tolerance limit is taken to be 120 % of the stabilized upper level of measured surface finish. Table 2 gives the tolerance limits used to indicate the termination of tool life for the different depths of cut.

Table 3 lists the tool life for all depths of cut used with respect to the volume of metal removed, the area machined, the machining time, and the rate of metal removed. Table 3 shows that the area machined and machining time increase with the decrease of the depth of cut. Figure 19 relates the depth of cut to tool life in terms of both the metal removed and the area machined. Inspection of Figure 19 reveals that a depth of cut of .001 inches maximizes the amount of metal removed.

Table 4 presents the net power consumed by a recently sharpened wheel as well as the maximum levels reached during the useful life of the wheel. The results shows that the maximum increase was 26 % at D.O.C., .00075 and .0015 in.

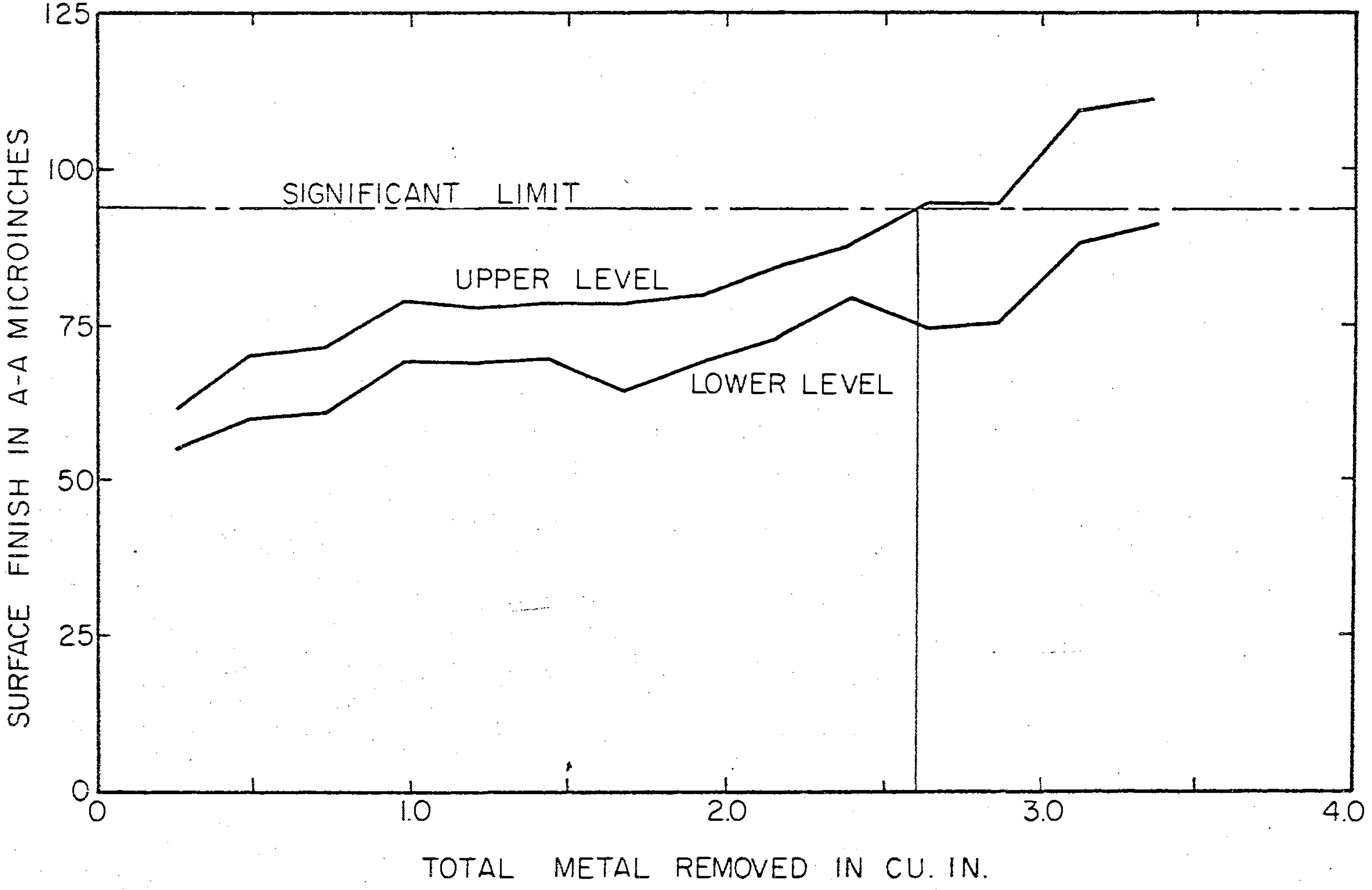
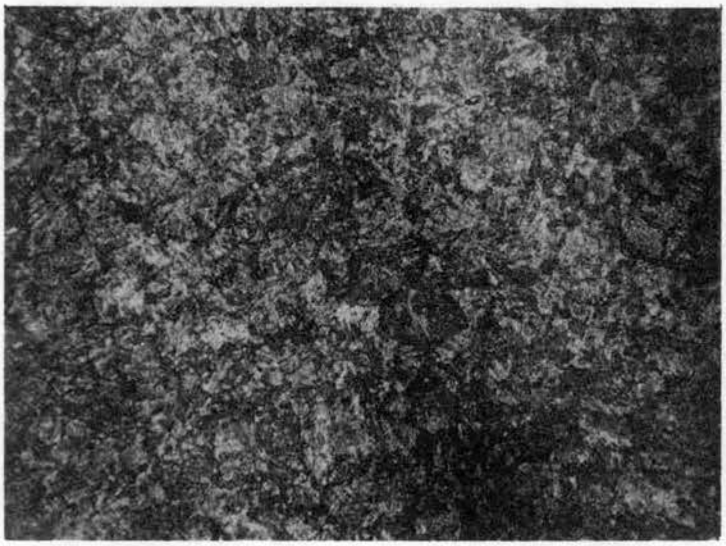
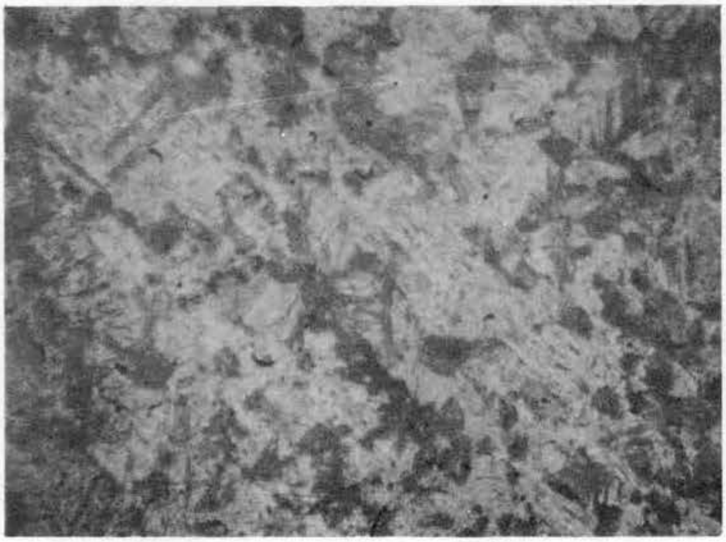


Figure 7. Tool Life (D.O.C. .0015 in.)



A. After Removing 1.2 Cu. In. X 400



B. At the End of Tool Life

Figure 8. Microscopic Structure at .0015 Inches D.O.C.

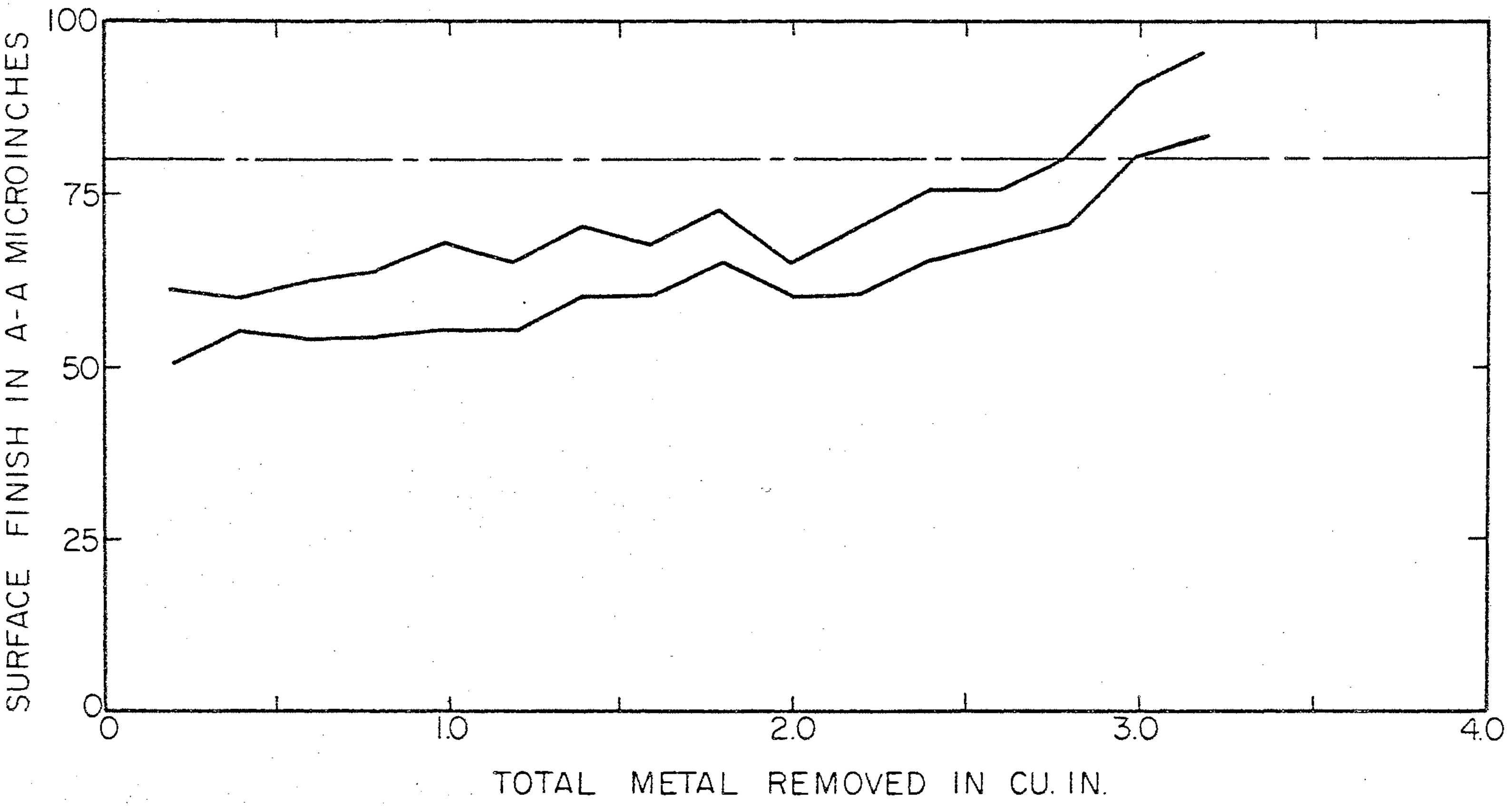
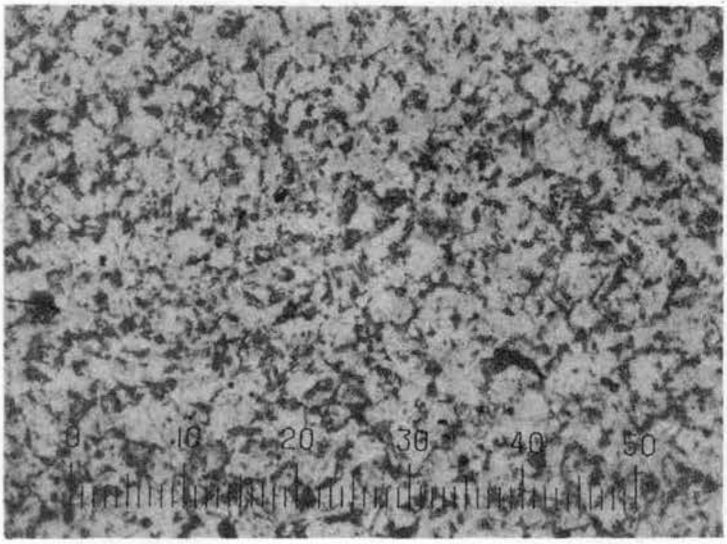
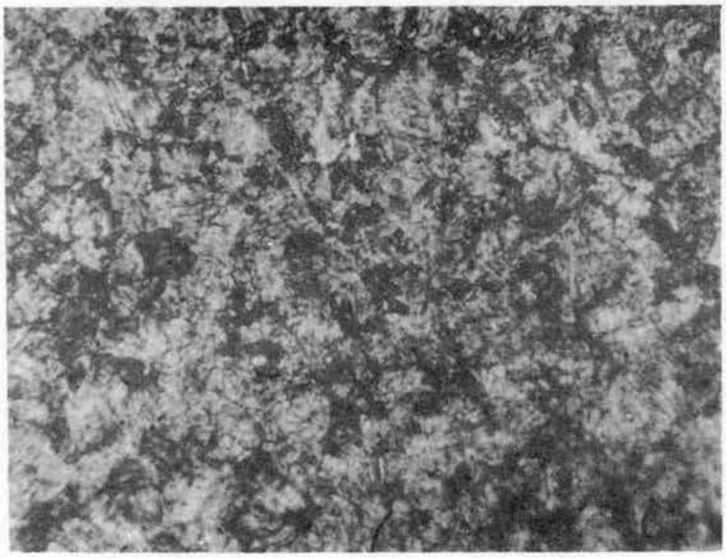


Figure 9. Tool Life. (D.O.C. .00125. in.)



A. After Removing 1.2. Cu. In. X 300



B. At the End of Tool Life X 800

Figure 10. Microscopic Structure at .00125 Inches D.O.C.

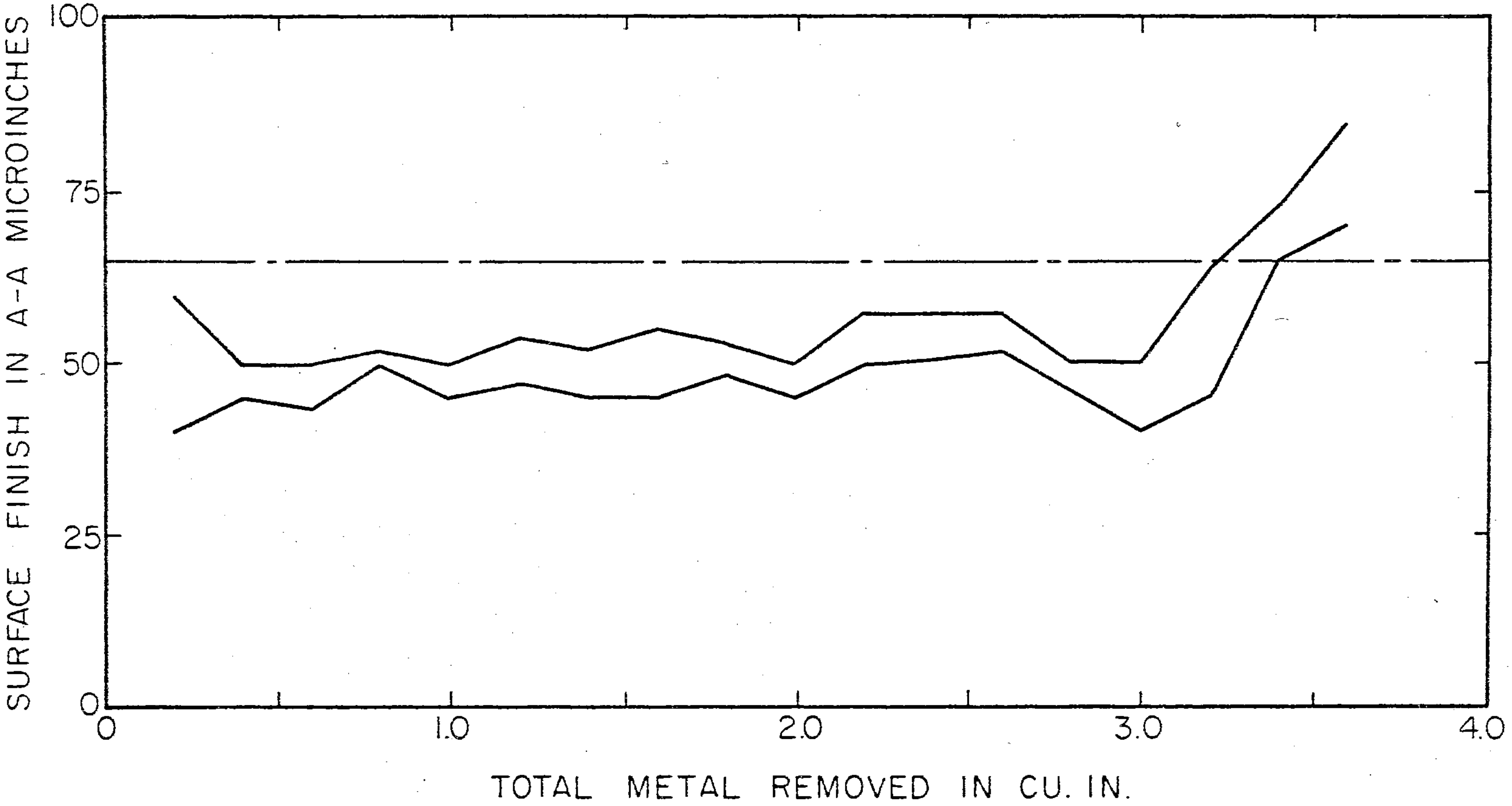
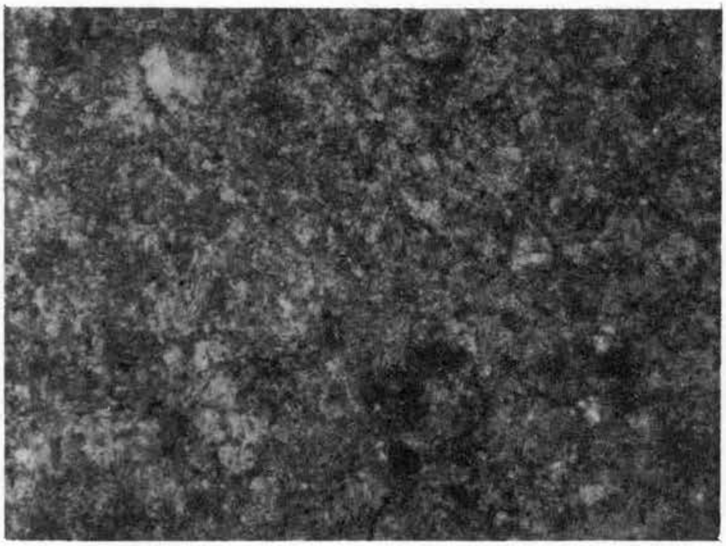
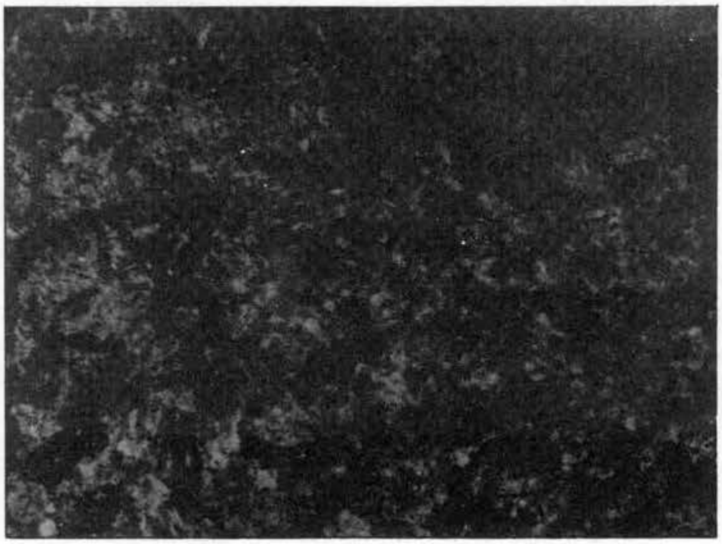


Figure 11. Tool Life. (D.O.C. .001.in.)



A. After Removing 1.2 Cu. In. X 300



B. At the End of Tool Life X 800

Figure 12. Microscopic Structure at .0010 in. D.O.C.

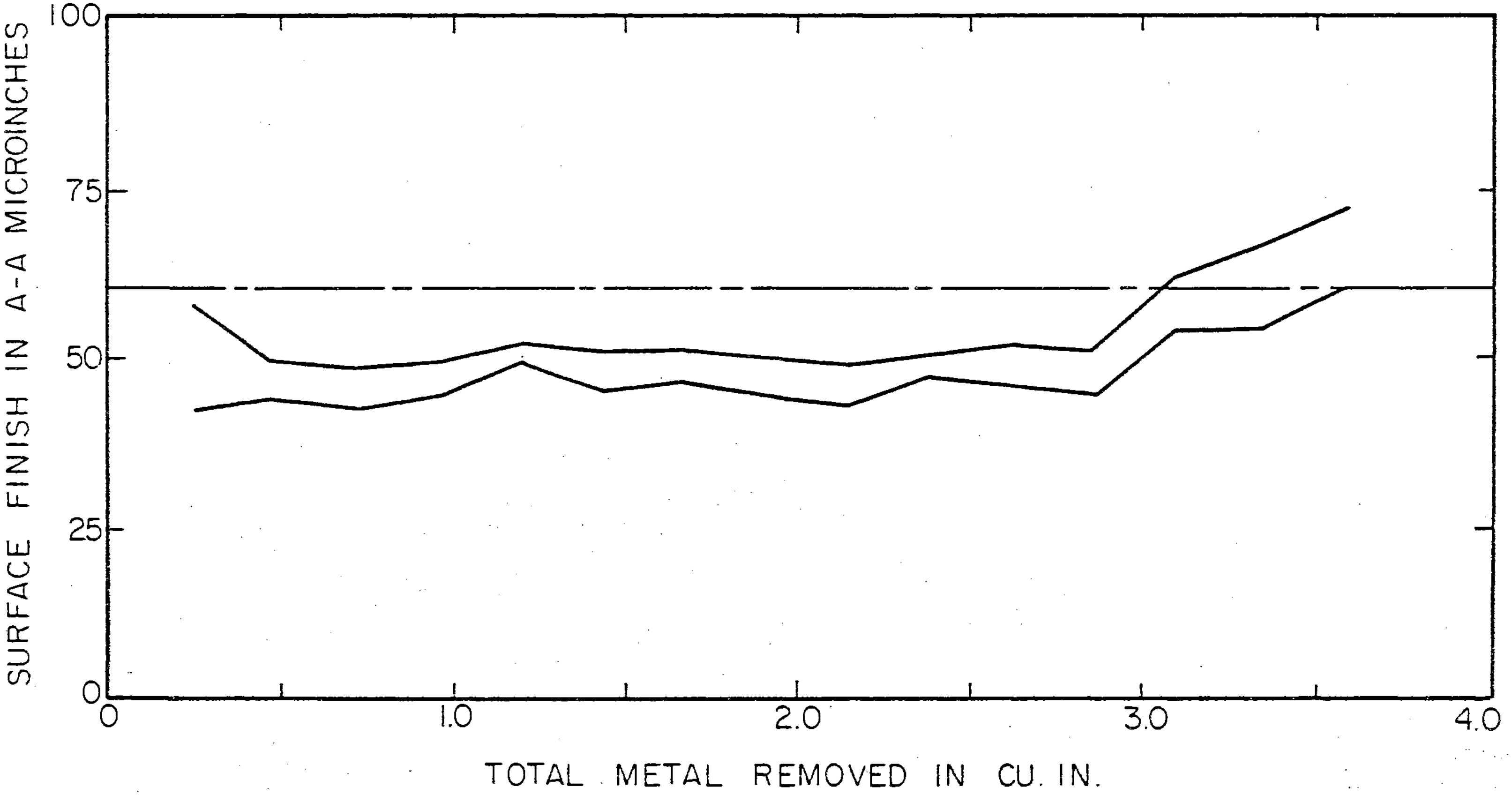


Figure 13. Tool Life (D.O.C. .00075 in.)

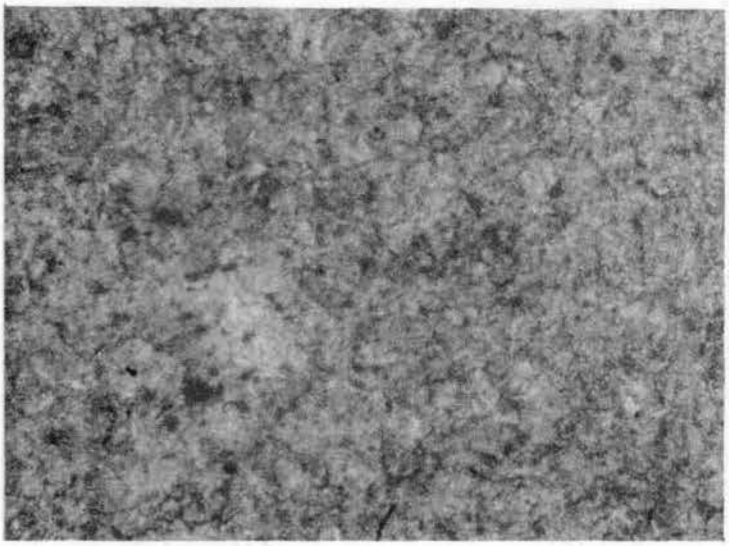


Figure 14. Microscopic Structure at
.00075 Inches D.O.C.
at the End of Tool Life
X 400

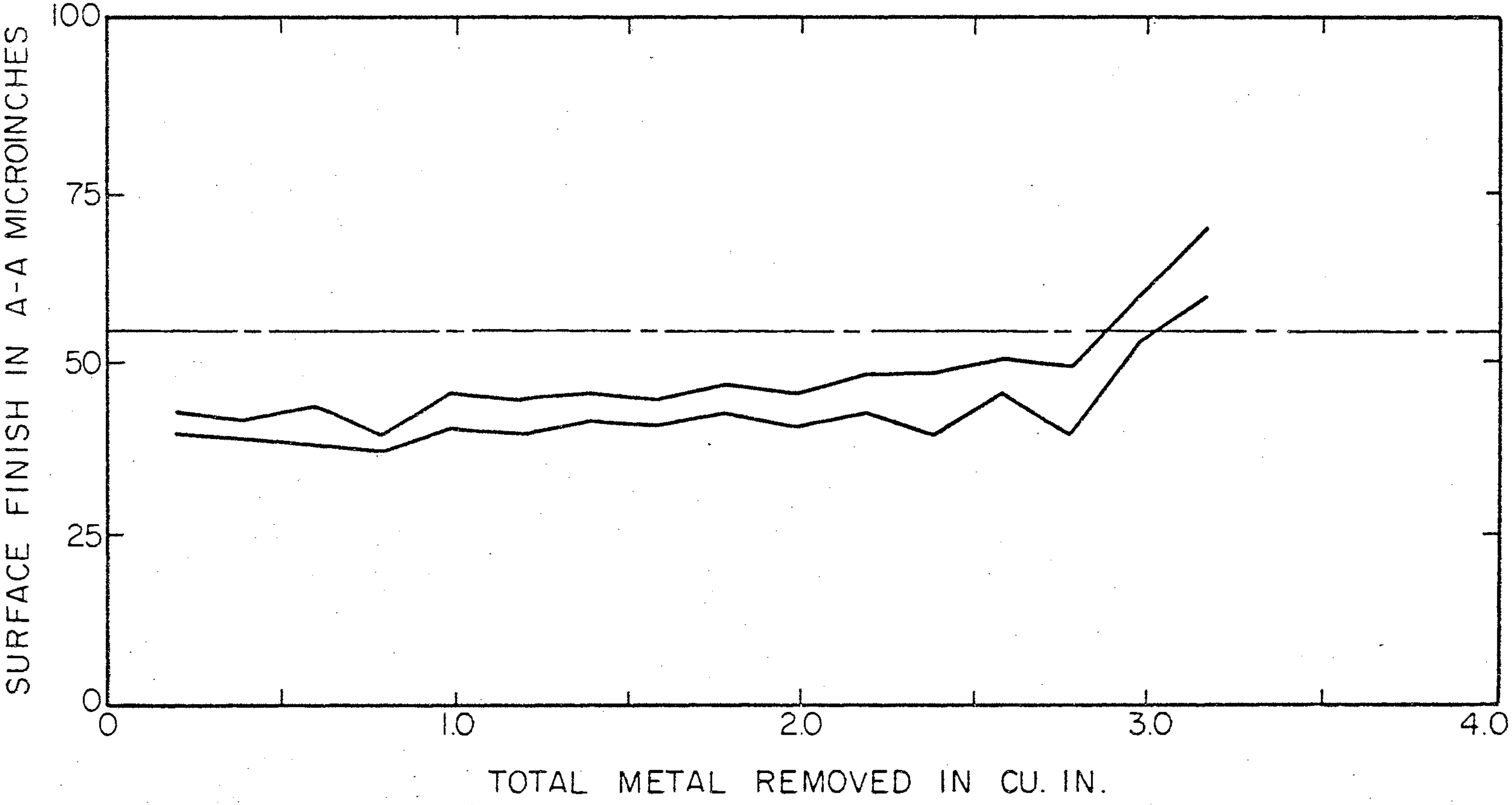


Figure 15. Tool Life (D.O.C .0005 in.)

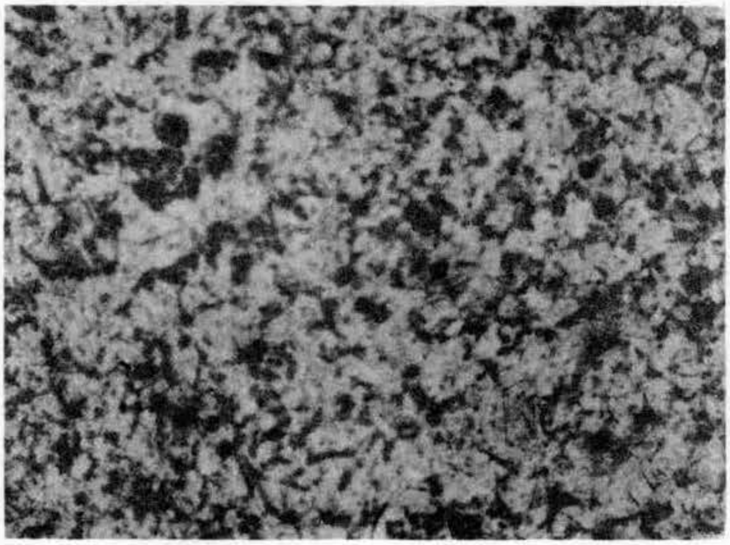


Figure 16. Microscopic Structure at .0005 Inches D.O.C. at the End of Tool Life X 400

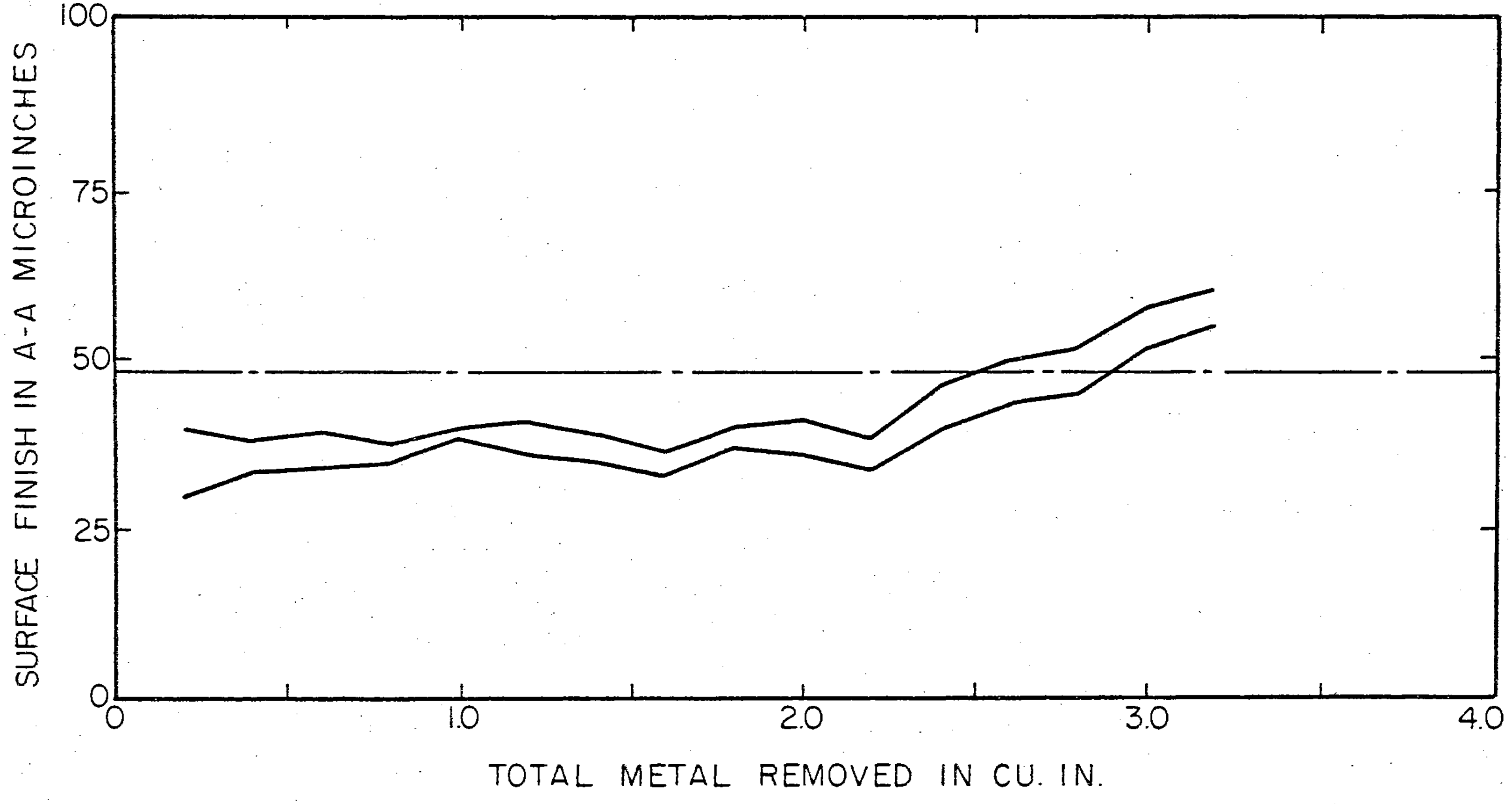


Figure 17. Tool Life.(D.O.C. ..00025 in.)

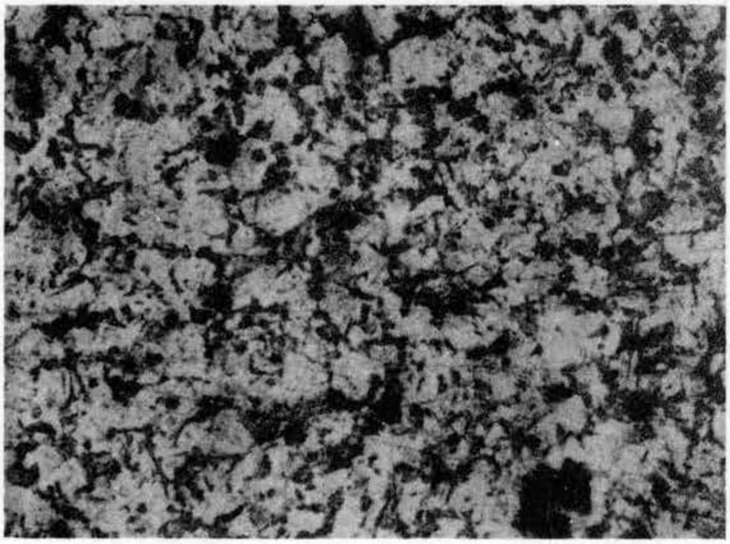


Figure 18. Microscopic Structure at .00025 Inches D.O.C. at the end of Tool Life X 400

## TABLE II

## TOLERANCE LIMITS OF SURFACE FINISH

| Depth of cut Inches | Stabilized upper level Microinches | Tolerance limit Microinches |
|---|---|---|
| .0015 | 77 | 94 |
| .00125 | 66 | 80 |
| .0010 | 54 | 65 |
| .00075 | 51 | 61 |
| .0005 | 46 | 55 |
| .00025 | 40 | 48 |

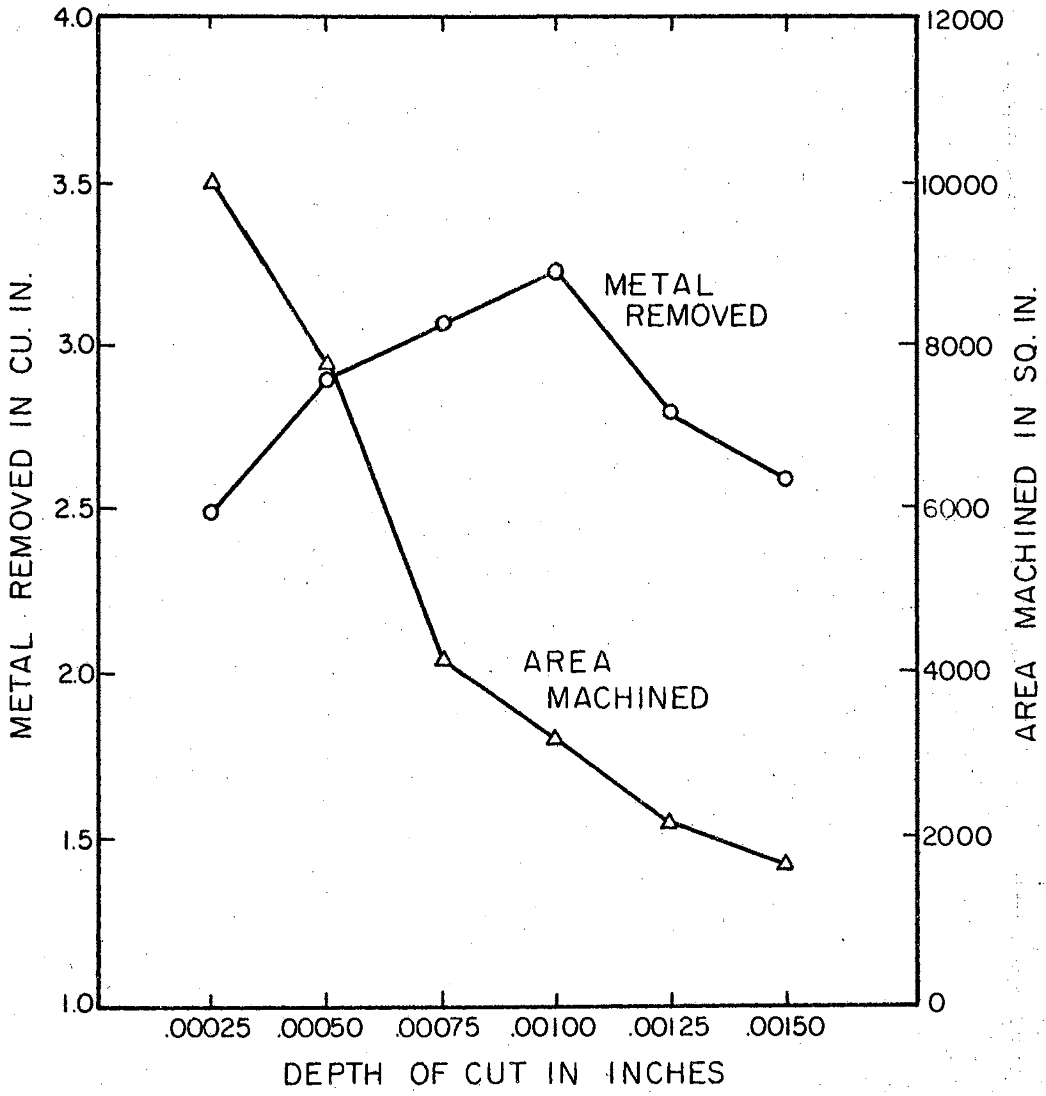


Figure 19. Tool Life Values

## TABLE III

## TOOL LIFE VALUES

| Depth of cut in. | Metal Removed cu. in. | Area Machined sq. in. | Machining time min. | Rate of Metal Removal cu. in./min. |
|---|---|---|---|---|
| .0015 | 2.6 | 1733 | 12.7 | .205 |
| .00125 | 2.8 | 2240 | 16.4 | .171 |
| .001 | 3.23 | 3230 | 23.6 | .137 |
| .00075 | 3.08 | 4106 | 29.9 | .103 |
| .0005 | 2.9 | 5800 | 42.6 | .068 |
| .00025 | 2.5 | 10000 | 73.5 | .034 |

## TABLE IV

## POWER CONSUMPTION

| D.O.C. in. | P.C. at start of grinding Watts | Maximum P.C. Watts | Maximum Increase % |
|---|---|---|---|
| .00025 | 650 | 800 | 23% |
| .0005 | 1200 | 1500 | 25% |
| .00075 | 1350 | 1700 | 26% |
| .0010 | 1650 | 2000 | 21% |
| .00125 | 2000 | 2500 | 25% |
| .0015 | 2300 | 2900 | 26% |

# CHAPTER IV

# SPARKOUT EFFECT

## Experimental Design

The effect of sparkout is presented in this chapter. As in Chapter Three, the experiment consisted of:

1. Workpiece material SAE 1045, hardness 45 RC, and size 2x 4x 10 in.
2. G. Wh. AA 46 H8 V40
3. C.F. .286 in. per stroke.
4. Table speed 40 FPM.
5. Coolant, Water Miscible.

The adjustable variable was the depth of cut. Six depths of cut were used: .00025, .0005, .00075, .001, .00125 and .0015 in. For each depth of cut the test was started with a recently sharpened wheel.

Initial grinding with a freshly sharpened wheel yielded a greater surface roughness than that obtained, and maintained during the useful life of the wheel, after removing a small amount of metal. The prelimenary study showed that removing an average amount of .02 cu. in. of metal with the freshly sharpened wheel was sufficient to stabilize the wheel. Therefore, to stabilize the wheel the workpiece surface, 40 sq. in., was ground with a depth of cut of .0005 in. To assure the removal of this amount, the wheel was allowed to sparkout for five passes without infeeding any depth of cut before starting the test.

The first run of each test consisted of grinding the surface area with the specified level of depth of cut for the test and then the surface finish was measured without allowing any sparkout. For the second run the wheel was allowed to sparkout for one pass only after grinding the surface area with the same depth of cut before measuring the surface finish. The test was continued increasing one sparkout pass each time until five sparkout passes were reached before measuring the surface finish range. After each run the wheel was allowed to sparkout for a number of passes to relieve any strained conditions before starting the next run. This number of passes plus the sparkout passes used in the previous run should add to five passes to make the starting conditions similar for each of the six runs of the test.

It was found from chapter three that the minimum amount of metal removed was 2.5 cu. in. before it was necessary to resharpen the wheel. This amount is larger than the amount removed in any test. Therefore, the wheel was sharpened only once at the start of every test.

Table 5 shows the measured surface finish ranges for the six tests. The measured surface finish ranges were plotted against the number of sparkout passes for each depth of cut (Figures 20, 22-26).

To detect the development of any cracking, the 3/4 in. dia. specimens were ground under the same conditions and frequently inspected. Figure 21 shows the microscopic structure for the greatest two depths of cut after the grinding pass without any sparkout.

## Experimental Procedure

The steps followed in every test were:

1. Truing and sharpening the grinding wheel.
2. Placing the workpiece, 2x 4x 10 in., and the 3/4 in. pieces on the magnetic chuck and energizing the chuck.
3. Setting the feed and speed.
4. Adjusting the grinding wheel to start cutting.
5. Infeeding .0005 in. depth of cut so that the wheel removes the specified amount of metal, .02 cu. in., to adjust itself after sharpening.
6. Allowing the wheel to sparkout for five passes to remove any metal left.
7. Infeeding the depth of cut specified for the test.
8. Grinding one area without any sparkout.
9. Stopping the machine, removing the workpiece, and measuring the surface finish.

10. Removing the 3/4 inch diameter specimen to be polished, etched, and inspected under the microscope for cracking.
11. Replacing the rorkpiece on the magnetic chuck and allowing the wheel to pass over the workpiece for five times.
12. Repeating steps 7 to 11 while increasing the number of sparkout passes by one each time before measuring the surface finish; and reducing the number of passes before infeeding the depth of cut for the next run by one.
13. Stopping the test when the number of sparkout passe reached five.
14. Starting another test for another depth of cut.

## Analysis of the Results

Experimental results are plotted as a function of the number of sparkout passes. Figures 20, and 22-26 show the test results for depths of cut of .0015, .00125, .001, .00075, .0005, and .00025 in. respectively. Figure 21 shows the microscopic structure for the greatest two depths of cut after the grinding pass, without any sparkout.

Inspection of Figure 21 shows that no cracks had developed. Compared to the time consumed in the sparkout passes, the sparkout effect on the surface finish is

## TABLE V

## SPARKOUT EFFECT ON SURFACE FINISH FOR AA-46-H8-V40 WHEEL

| D.O.C. | Number of Sparkout Passes | | | | | |
|---|---|---|---|---|---|---|
| in. | 0 | 1 | 2 | 3 | 4 | 5 |
| .00025 | 27-30 | 24-30 | 30-35 | 25-27 | 28-29 | 26-28 |
| .0005 | 35-37 | 34-36 | 34-38 | 28-34 | 27-30 | 26-28 |
| .00075 | 35-39 | 36-38 | 35-37 | 34-36 | 31-33 | 28-30 |
| .0010 | 38-41 | 39-41 | 39-43 | 38-40 | 38-40 | 35-40 |
| .00125 | 39-44 | 40-43 | 38-45 | 38-42 | 40-43 | 37-42 |
| .0015 | 40-45 | 40-46 | 39-43 | 39-45 | 40-43 | 40-43 |

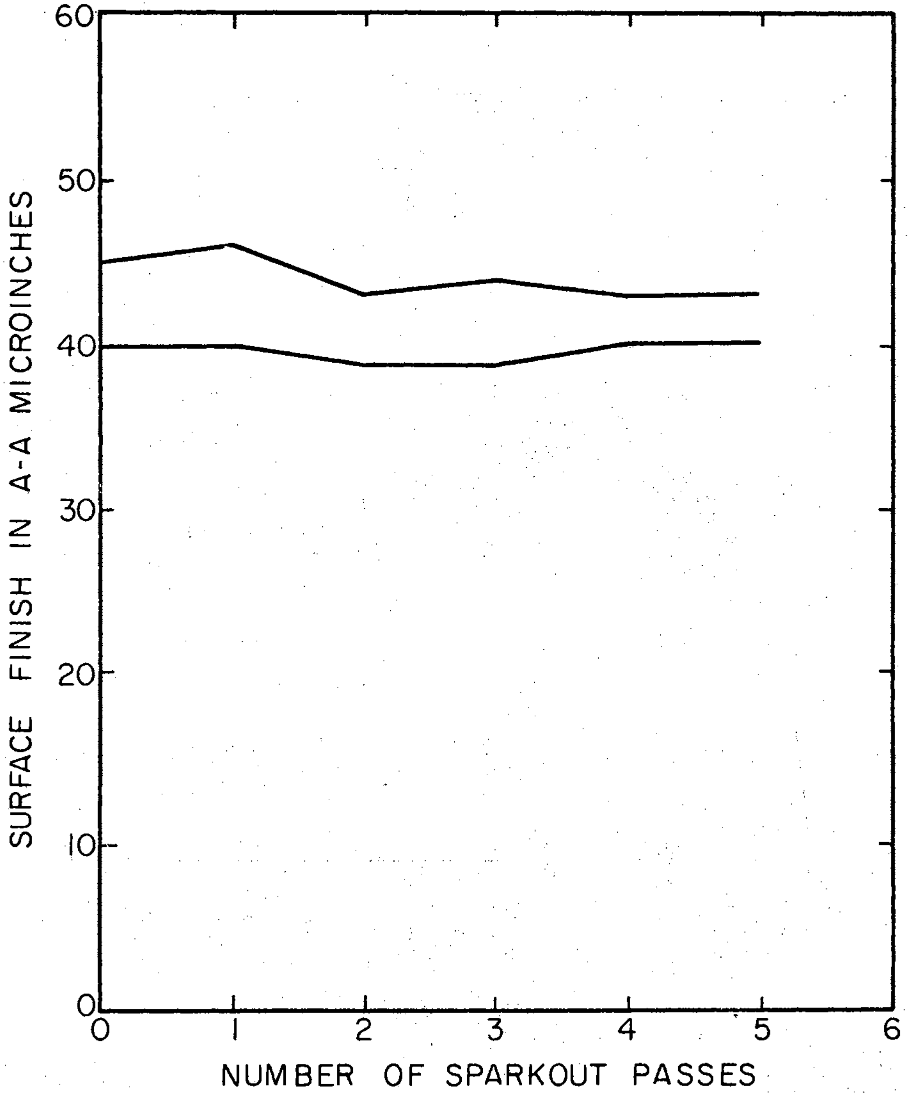
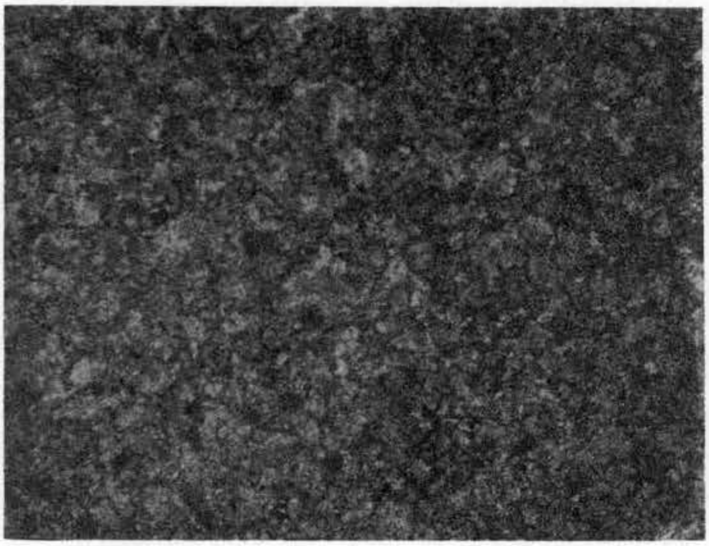
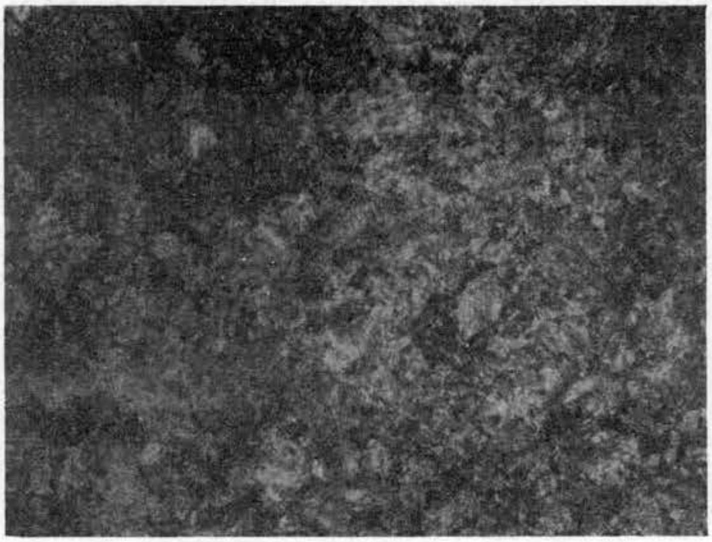


Figure 20. Sparkout Effect (D.O.C. .0015 In.)



A. Depth of Cut .00125 in. X 250



B. Depth of Cut .0015 in. X 500

Figure 21. Microscopic Structure
Using A A46 H8 V
Grinding Wheel

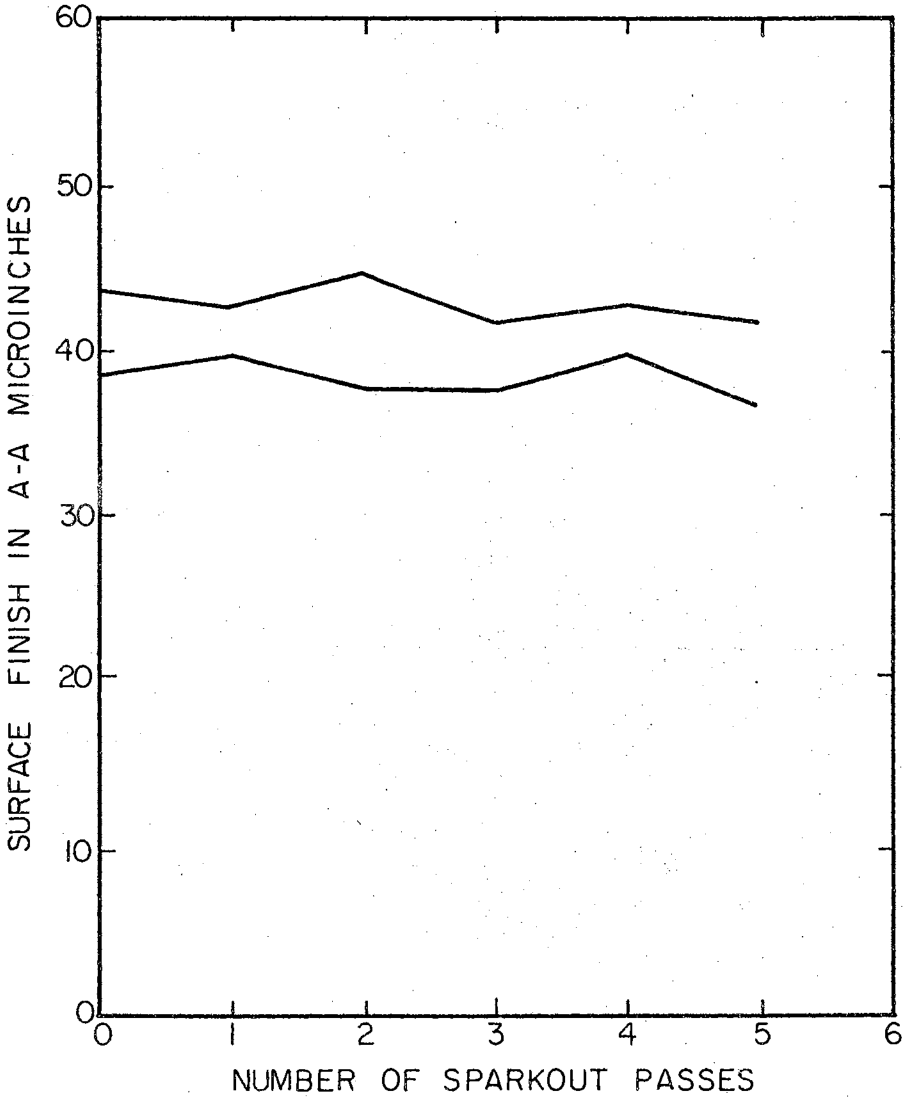


Figure 22. Sparkout Effect (D.O.C. .00125 In.)

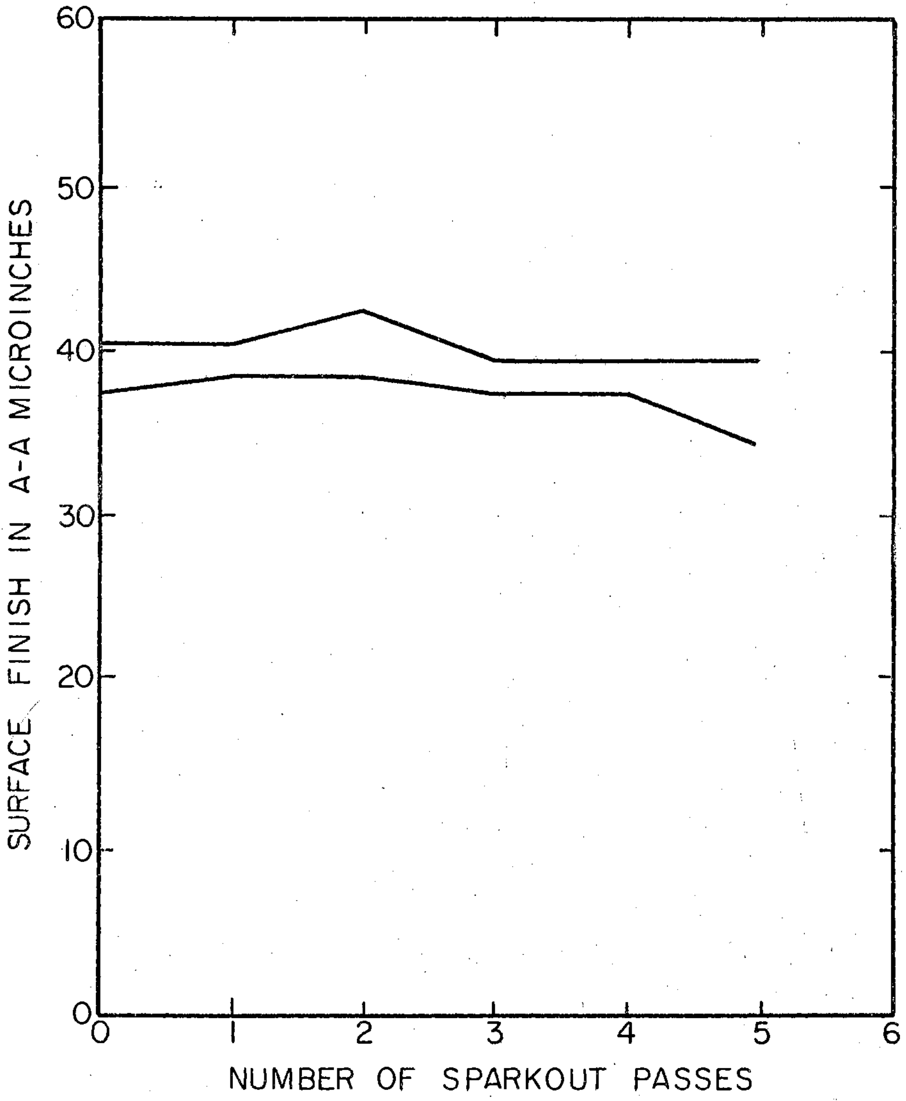


Figure 23. Sparkout Effect (D.O.C. .001 In.)

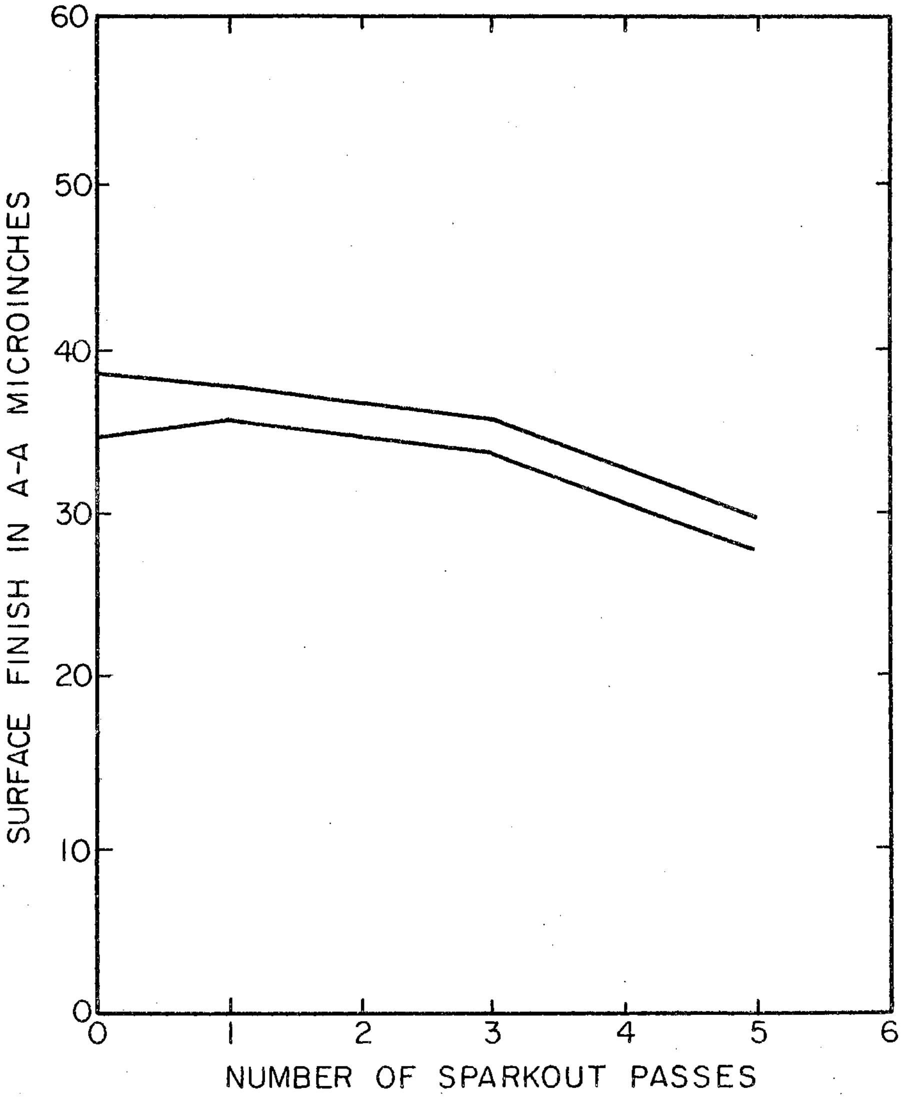


Figure 24. Sparkout Effect (D.O.C. .00075 In.)

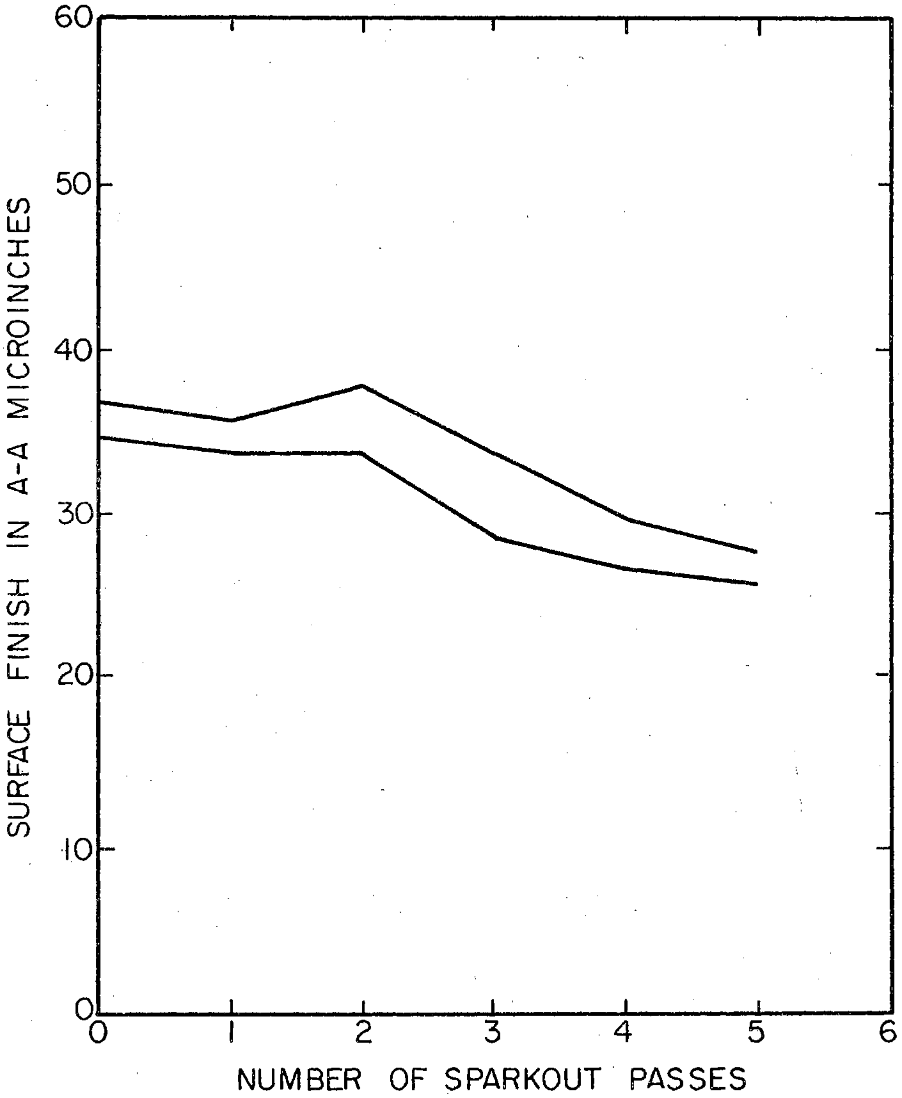


Figure 25. Sparkout Effect (D.O.C. .0005 In.)

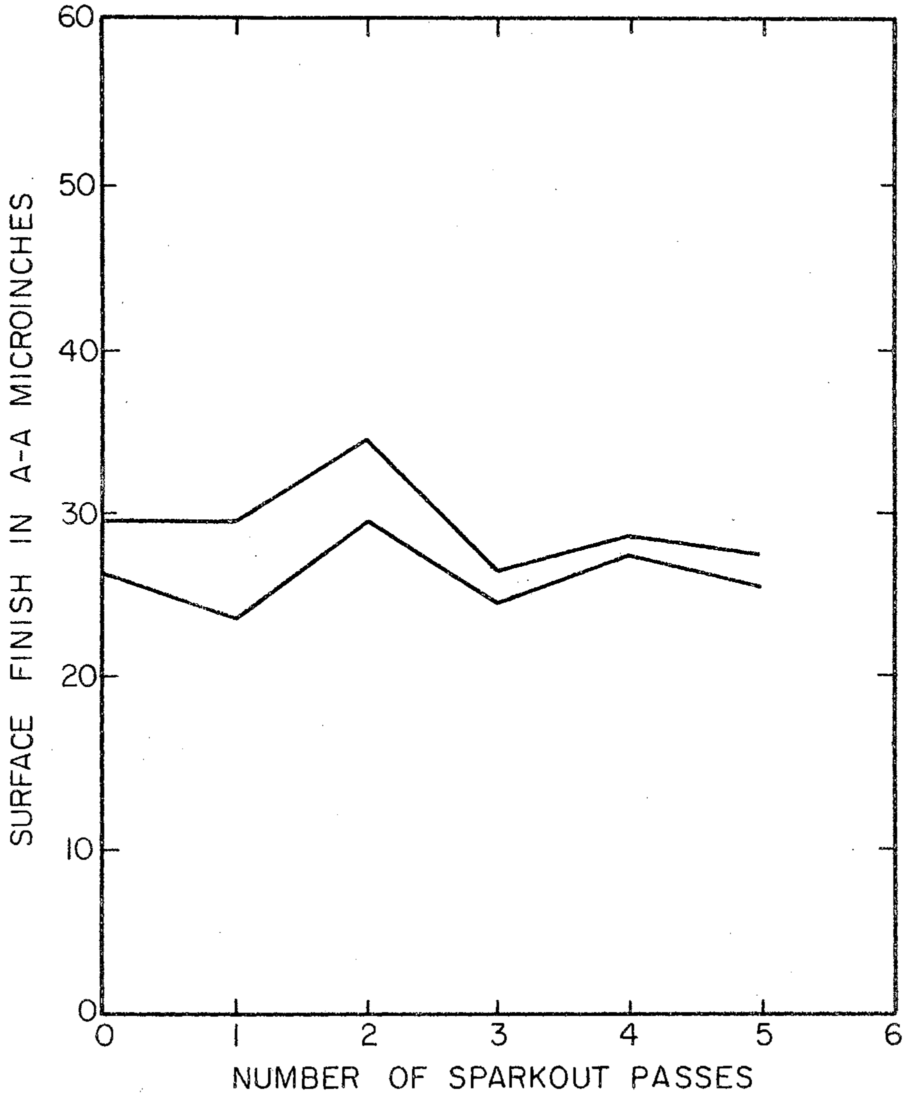


Figure 26. Sparkout Effect (D.O.C. .00025 In.)

insignificant as may be seen from Table 5 and Figures 20, and 22-26.

## Effect of Grain Size

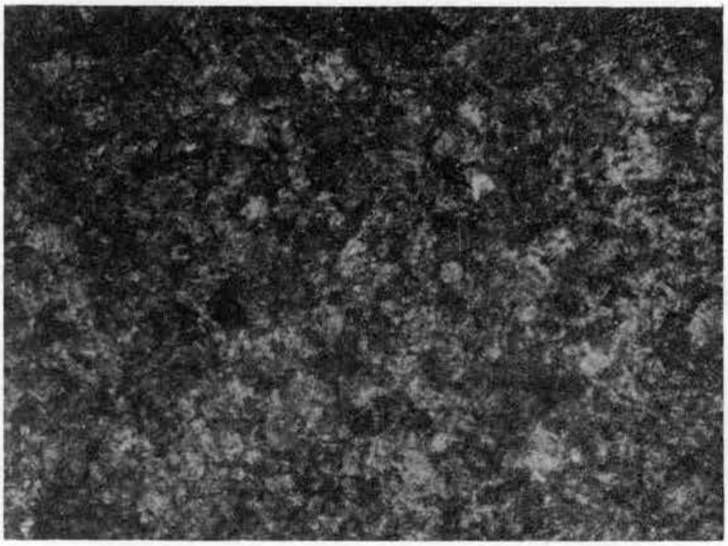
Next, the effect of a finer, 60 grain size wheel was investigated and compared to the findings of earlier work with the 46 grain size wheel in an attempt to improve the surface finish while saving the sparkout time. Similar experiments were carried out employing an AA 60-H8-V40 grinding wheel. Thus, the only factor changed was the grain size, i.e. 60 instead of 46. Table 6 presents the results of the experiment without any sparkout and with five sparkout passes. Figure 27 shows the microscopic structure for the greatest two depths of cut after grinding without any sparkout while using the 60 grain size wheel.

There was some doubt that cracks might develop when using the 60 grit size wheel at the highest specified levels of depths of cut. A Tool life test was conducted at the highest depth of cut, i.e., .0015 in. The results indicated that the surface finish exceeded the tolerance set of 74 microinches after removing 1.96 cu. in. Figure 28 shows the results of the test and the tolerance limit. Inspection of the 3/4 in dia. pieces revealed no cracking development during the useful life of the wheel. Figure 29 shows the microscopic structure of the metal after removing 1.2 cu. in. and at the end of tool life.

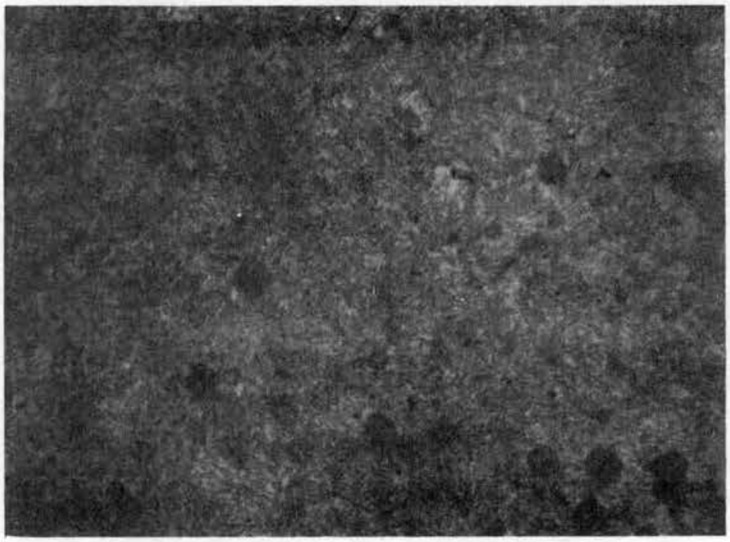
## TABLE VI

## SPARKOUT EFFECT ON SURFACE FINISH FOR AA-60-H8-V40

| D.O.C. in. | S.F. without any sparkout | S.F. after 5 sparkout passes |
|---|---|---|
| .00025 | 22-24 | 18-20 |
| .0005 | 24-28 | 19-22 |
| .00075 | 26-30 | 21-23 |
| .0010 | 28-31 | 22-25 |
| .00125 | 29-34 | 25-28 |
| .00150 | 30-35 | 26-28 |



A. Depth of Cut .00125 in. X 400



B. Depth of Cut .0015 in. X 800

Figure 2. Microscopic Structure Using
A A60 H8 V40 Gr. Wh.
Without Sparkout

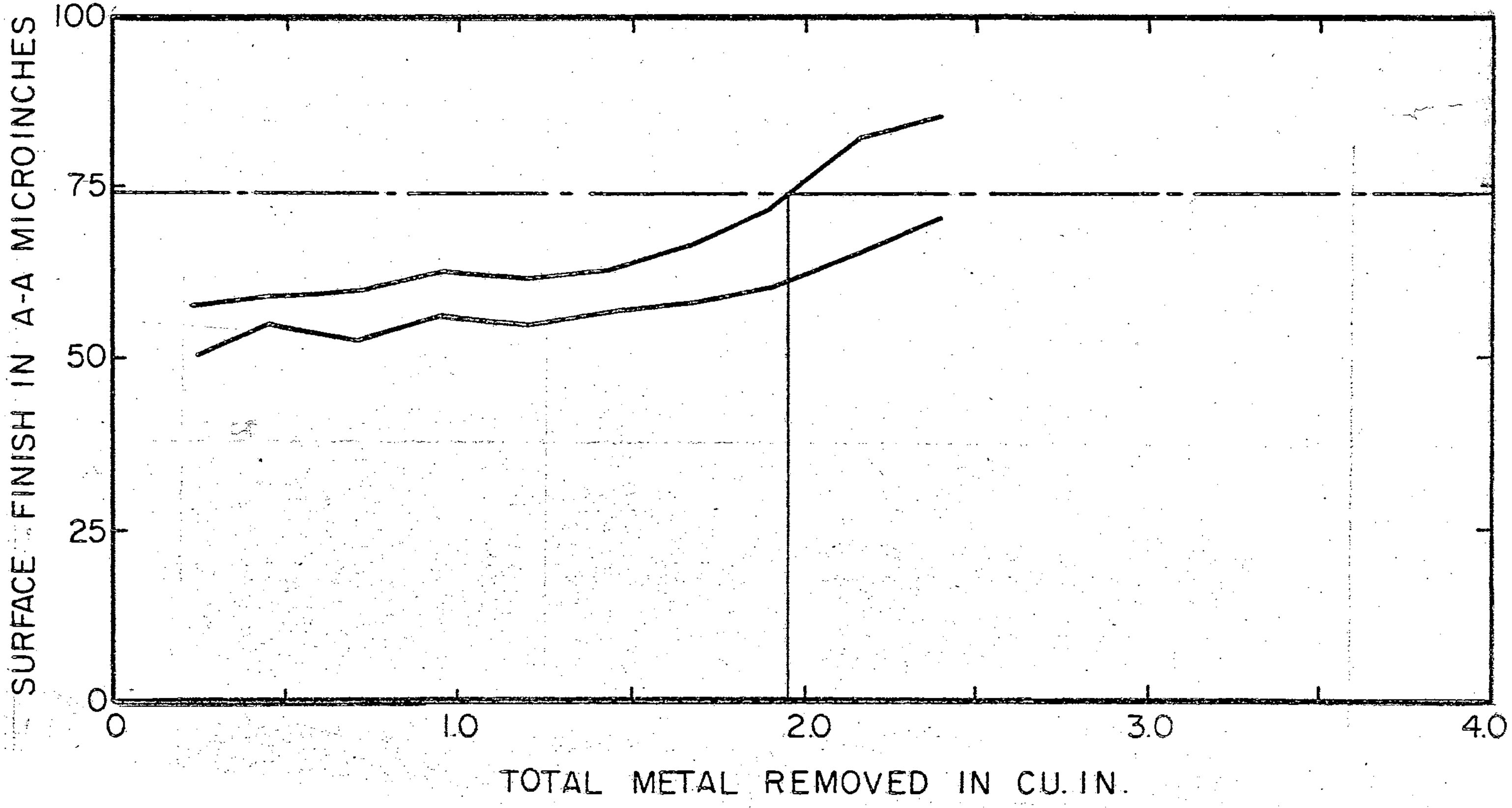
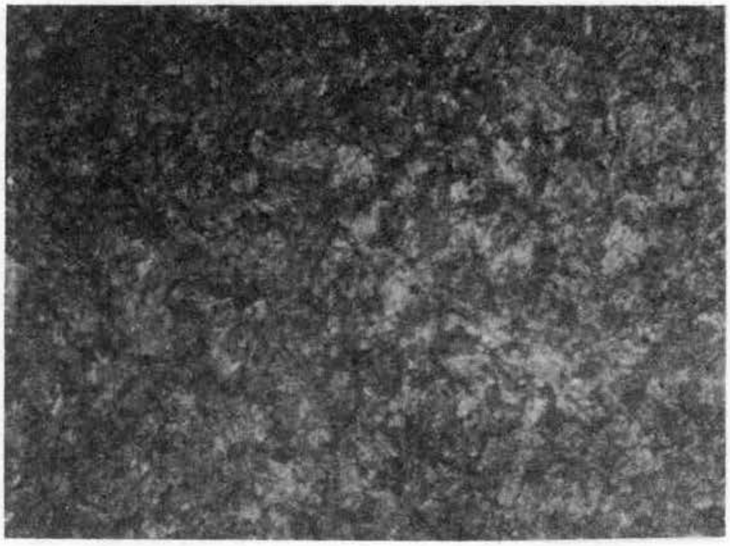
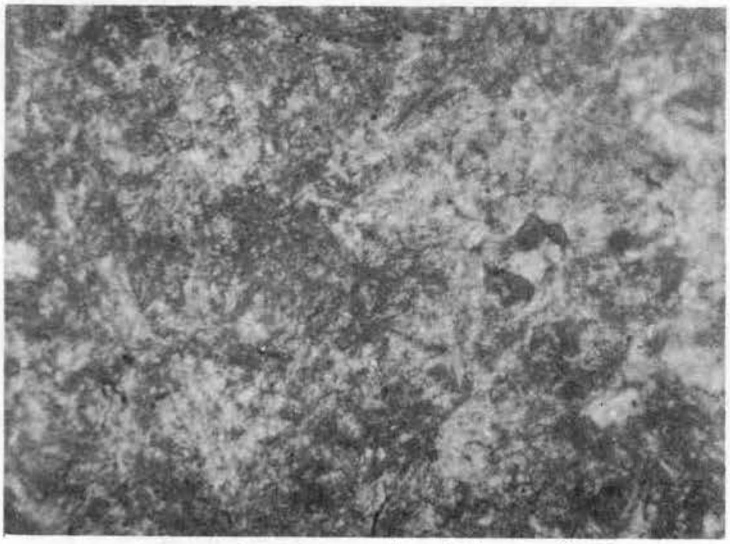


Figure 28. Tool Life (Depth of Cut .0015 inches), Wheel AA60 H8 V40



A. After Removing 1.2 Cub. In. X 400



B. At the End of Tool Life X 800

Figure 29. Microscopic Structure at .0015 in. D.O.C. Using AA60 H8 V40 Gr. Wh.

The effect of using a wheel with a finer grit size is shown in figure 30 which compares the averages of surface finish of the two wheels after grinding without any sparkout. Comparison indices A and B, defined as follows were calculated:

$$\text{Index A} = \frac{\sum \text{S.F. ave after 5 sparkout passes}}{\sum \text{S.F. ave without sparkout}}$$

$$\text{Index B} = \frac{\sum \text{S.F. ave without sparkout for AA 60 G.Wh.}}{\sum \text{S.F. ave without sparkout for AA 46 G.Wh.}}$$

$$\text{Index A for the 46 grain size wheel} = \frac{201}{227} = 88.5\%$$

$$\text{Index A for the 60 grain size wheel} = \frac{139}{172} = 80.8\%$$

$$\text{Index B} = \frac{172}{227} = 75.8\%$$

The results reveal the following:

1. The reduction in surface roughness after five sparkout passes is only 11.5 % for the 46 grain size wheel.
2. The reduction due to sparkout increased to 19.2 % for the 60 grain size wheel.
3. The reduction due to the use of the 60 grain size wheel compared to the 46 grain size wheel was 24.2 %.

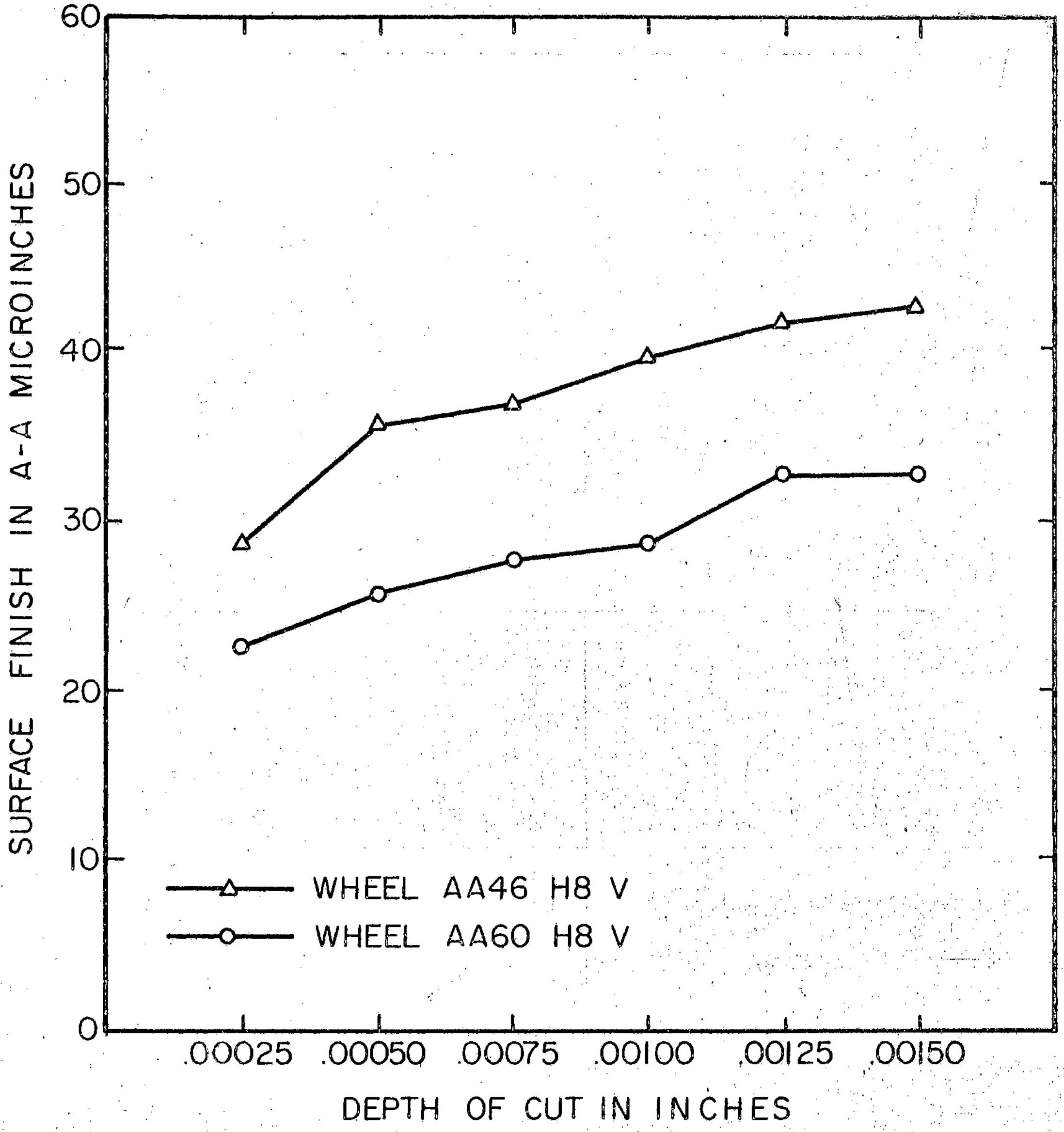


Figure 30. Effect of Grain Size on Surface Finish

4. The ratio of the two grain sizes

$$= \frac{46}{60} = 76.7\%$$

Which approximately equals index B.

# CHAPTER V

# EFFECT OF GRAIN SIZE, COOLANT, DEPTH OF CUT, TABLE SPEED, AND CROSS FEED ON SURFACE FINISH AND POWER CONSUMPTION

The primary objective of this chapter is to quantitatively determine, by physical experimentation and subsequent statistical analysis, the interdependence and interaction of the various grinding variables on the first cut surface finish (S.F.) and power consumption (P.C.).

Chapter four results showed that the commonly used method of sparkout has no significant effect on the semifinishing grinding process. Changing one variable, the grain size (G.S.), improved S.F. Ratterman (21) changed the table speed and reported a significant effect on S.F. Others (16-20, 22-30) changed other variables one at a time and reported different effects on S.F. and power consumption. In this chapter the five variables, grain size, coolant, depth of cut (D.O.C), table speed (T.S.), and cross feed (C.F.) were changed at the same time and their effects on S.F. and P.C. were studied and evaluated. Review of the available literature indicated that those five factors have the most significant effect on S.F. and P.C.

As stated in Chapter 1, the grinding process has a statistical, probabilistic character. The factorial experimentation method was used to reveal the individual effect as well as the interaction of the multitude of factors involved in the process. Anderson and Bancraft (32) stated:

> 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 indivdual representatives of each treatment are widely different.

## Experimental Design

The material selected for this part was S A E 1045 hot-rolled steel, hardened up to 45 ± 2 Rockwell C, the same material used in Chapters Three and Four.

Five factors, or independent variables, were selected for the factorial design. The dependent variables were the first cut surface finish without any sparkout and the power consumption. The factors and the levels for each factor were as follows:

1. The grain size (G.S.)- the particle size or mesh of the abrasive grains of the grinding wheel:
   (a) 46
   (b) 60
2. Coolant - water miscible:
   (a) Wet grinding; grinding with coolant
   (b) Dry grinding; grinding without coolant
3. Depth of cut (D.O.C.) - the distance between the bottom of the cut and the uncut surface of the workpiece:
   (a) .00025 in.
   (b) .0005 in.
   (c) .00075 in.
   (d) .0010 in.
   (e) .00125 in.

4. Table speed (T.S.) - the speed of the table carrying the chuck which held the workpiece:
    - (a) 17 FPM
    - (b) 37 FPM
    - (c) 55 FPM
5. Cross feed (C.F.) - the distance the wheel was moved at the end of each stroke perpendicular to the direction of table speed:
    - (a) .057 in. per stroke
    - (b) .133 in. per stroke
    - (c) .286 in. per stroke

The treatments were repeated three times; i.e. the number of replications, R, was three. In order to keep the study within reasonable size and for economical reasons, the other factors such as material hardness, structure and hardness of the wheel that could affect the grinding process were kept constant. Due to physical limitations of the machine and wheels used, the .0015 in. D.O.C. was not used in this part. Table 7 indentifies the factors used and their levels.

All combinations of the five factors were used. The total number of the different treatments is equal to the product of all the levels of the five factors giving 180 different treatments. For example, a treatment 21432 means that wheel number 2, with coolant, D.O.C., .001 in., T.S., 55 FPM., and C.F., .133 in. per stroke were used. As

## TABLE VII

## IDENTIFICATION TABLE

| Factor | Level | Code | Sort |
|---|---|---|---|
| Grain Size | 46 | 1 | A |
| | 60 | 2 | |
| Coolant | Wet | 1 | B |
| | Dry | 2 | |
| Depth of Cut | .00025 in. | 1 | C |
| | .0005 | 2 | |
| | .00075 | 3 | |
| | .00100 | 4 | |
| | .00125 | 5 | |
| Table Speed | 17 FPM | 1 | D |
| | 37 | 2 | |
| | 55 | 3 | |
| Cross Feed | .057 in./stroke | 1 | E |
| | .133 | 2 | |
| | .286 | 3 | |
| Replications | 1 | 1 | R |
| | 2 | 2 | |
| | 3 | 3 | |

the total experiment was replicated three times, the total numbers of treatments were 540 treatments.

In factorial experiments, a randomized complete-block design means that all treatment combinations are applied randomly. The different 180 treatments would be equally likely applied in any possible sequence in each replication. The levels of the factors are changed according to the treatments sequence resulting from the randomization procedure. However, the continuous change of the grinding wheel is not recommended and is time consuming. Thus, another factorial experimentation design, the split-plot design, was applied. The main plot, the wheels, were arranged in a randomized block design. The subplot treatments consisted of a factorial arrangement of the other four factors, giving 90 different treatments. These 90 different treatments, may appear in any possible sequence. However, all these 90 different treatments will be applied without changing the wheel. Thus, the wheel is changed and another randomized sequence is performed with the second type of wheel. The whole experiment was repeated three times. The wheel was randomly chosen. In this way the number of wheel changes was reduced to a maximum of six times for the three replications.

The randomization of the data collection was accomplished as follows:

The 90 different treatments were punched on computer cards, and five similar sets were produced. The first set, representing the 90 different treatments, was shuffled before listing the order. To choose the first wheel for the first replicate, a coin was tossed. If it was a head, wheel AA46 H8V was used first and wheel AA60 H8V was the second for the first replicate, and vice versa. Before using the second wheel the second set of the 90 different treatments was shuffled before listing the experimental order. The same randomization procedures were applied before starting the second and third replication.

From the results of Chapter Three it was clear that grinding, with a sharpened wheel, any ten of the indicated treatments will remove an amount of metal far less than the tool life amount. Therefore, the wheel was sharpened only every ten treatments. From Chapter Four, the sparkout had very little effect on surface finish; therefore, the analysis was done on the first cut surface finish and the net power consumption without any sparkout.

Preliminary tests were carried out to detect the development of any cracks at the highest levels of D.O.C. and T.S. Figures 31 and 32 show the tool life and behaviour for A 46 and A 60 grinding wheels at a D.O.C. of .00125 in., T.S. of 55 FPM, and C.F. of .133 in. per stroke while grinding without coolant. Figure 33 shows the microscopic structure at the end of tool life for the two wheels. Even though a rise in the temperature of the workpiece and the appearance of some dark bands were observed while grinding without coolant, microscopic

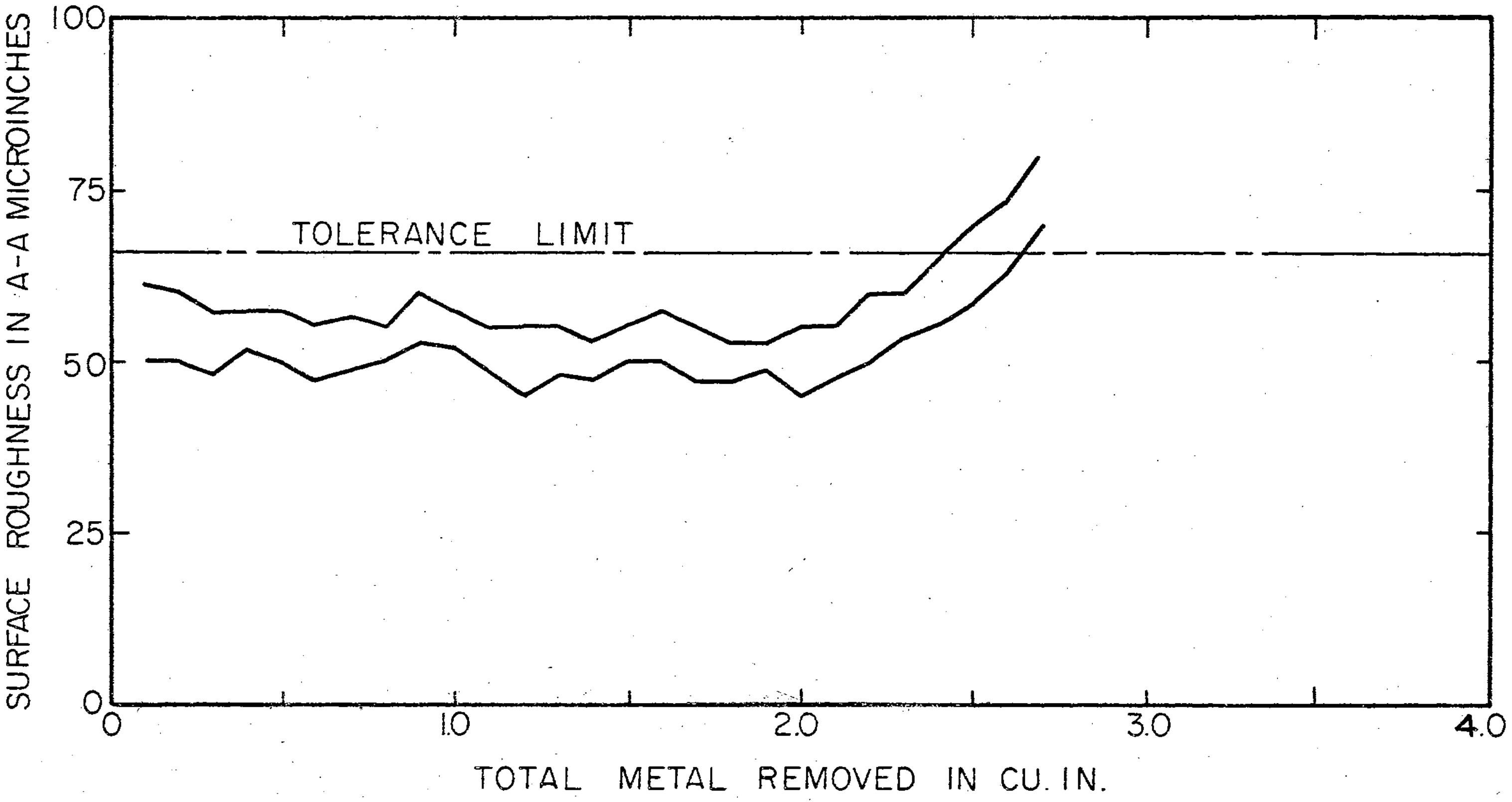


Figure 31. Tool Life (Dry Grinding, G. Wh. A46, D.O.C. .00125 in.)

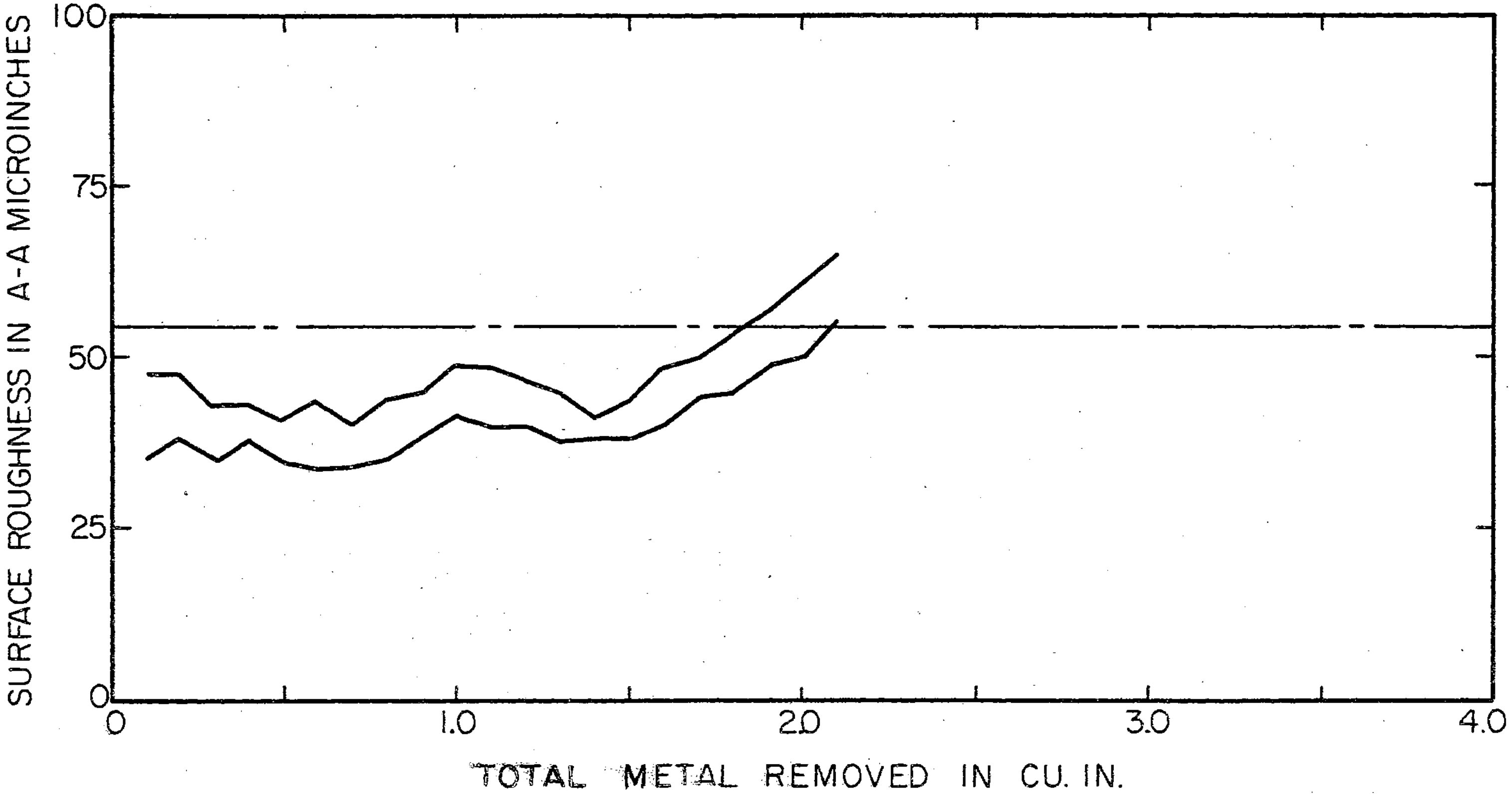
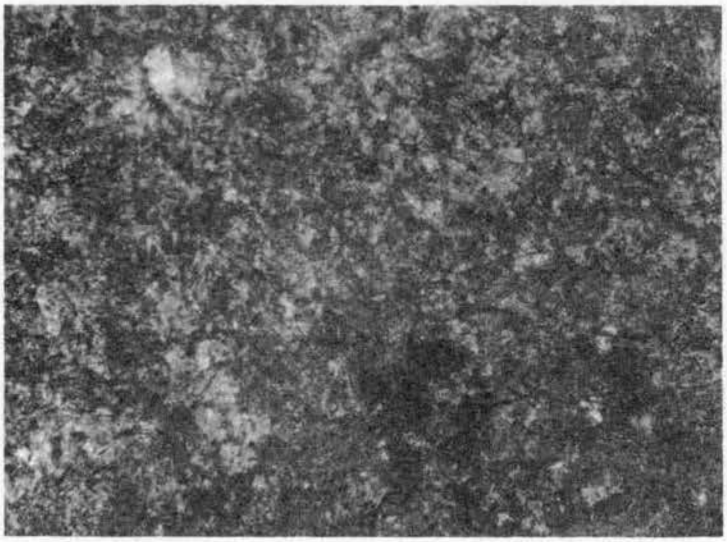
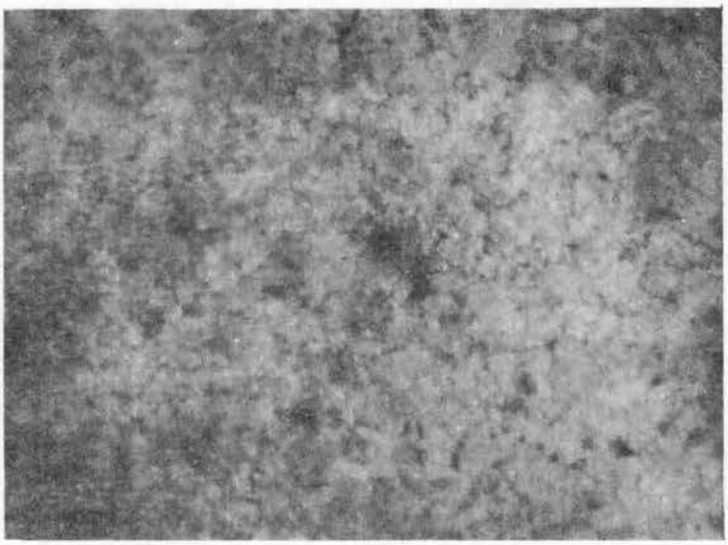


Figure 32. Tool Life (Dry Grinding, G. Wh. A 60, D.O.C. .00125 in.)



A. Grinding Wheel AA46 H8 V40 X 400



B. Grinding Wheel AA60 H8 V40 X 400

Figure 33. Microscopic Structure, Grinding Without Coolant at D.O.C., .00125 in., T.S. 55 FPM., at the End of Tool Life

inspection detected no cracks. Therefore, microscopic inspection was not applied during the experiments of this chapter.

## Experimental Procedure

The steps followed in every complete experiment or replicate were:

1. Replacing the grinding wheel according to the result of tossing a coin. If it turned up a head, wheel AA 46 H8 was used for the first set and wheel AA 60 H8 for the second set, and vice versa.
2. Truing, sharpening, and adjusting the grinding wheel.
3. Placing the workpiece, 2x 4x 10 in. on the magnetic chuck.
4. Adjusting the grinding wheel to start cutting.
5. Following the arrangement of the 90 different treatments, resulted from the randomization of the set of cards, the levels of the coolant, D.O.C., T.S., and C.F. were set according to the first treatment in the sequence.
6. Grinding the surface area, 40 sq. in., and recording the net power consumed while cutting.

7. Stopping the machine, removing the workpiece, and measuring the surface finished.
8. Replacing the workpiece and removing any strained conditions by allowing the wheel to pass over the workpiece for five passes, without infeeding any D.O.C.
9. Setting the machine to grind with the levels specified for the next treatment according to the randomized sequence.
10. Sharpening and adjusting the wheel every ten treatments.
11. Replacing the second grain size wheel after the 90 different treatments were completed.
12. Repeating steps 2 to 9 using the second randomized set of the 90 different treatments.
13. The second and the third replicates were performed in the order specified by the randomization technique.

## Data Processing

Two separate runs of the IBM system 360 computer program were made to obtain the degrees of freedom (d.f.), the sum of squares (SS), and the mean squares (MS) necessary to calculate the F ratios. The means of the dependent variables for each combination were calculated by the computer program. The first pass used surface finish as the dependent variable. The second pass was made with the same data cards using power consumption as the dependent variable.

The F ratios were calculated by dividing the mean square for each combination, source of variation, by the error mean square. Knowing the degrees of freedom of the source of variation and the error, the probability (P) associated with the F ratio was figured from the statistical F-tables. For the same d.f., a larger value of F indicates higher level of significance, and leads to a lower value of P. The source of variation was considered significant if P was less than 0.1. The F ratios were calculated on a Wang desk calculator.

## Analysis of Results

### Surface Finish

The results of surface finish analysis are shown in Table 8. The levels of statistical significance for the main effects as well as all interactions appear in the table. A significant effect is one that leads to considerable change in the levels of the variable under consideration. A significant interaction indicates that a variable, when considered with another variable or variables, causes a measurable difference at the different levels.

## TABLE VIII

## ANALYSIS OF VARIANCE I SURFACE FINISH

| Source of variation | d.f. | SS | MS | F-Ratio | P |
|---|---|---|---|---|---|
| Total | 539 | 47,305.65 | | | |
| Main Plots | | | | | |
| (R) | 2 | 25.20 | 12.60 | | |
| (A) | 1 | 17,035.35 | 17,035.35 | 884.0348 | .005 |
| (RA) Error(a) | 2 | 38.53 | 19.27 | | |
| Subplot Treatments | | | | | |
| B | 1 | 134.00 | 134.00 | 47.9462 | .005 |
| C | 4 | 3,079.09 | 769.77 | 275.4294 | .005 |
| D | 2 | 10,329.74 | 5,164.87 | 1848.0285 | .005 |
| E | 2 | 10,195.74 | 5,097.87 | 1824.0554 | .005 |
| A B | 1 | 15.34 | 15.34 | 5.4888 | .025 |
| A C | 4 | 288.16 | 72.04 | 25.7764 | .005 |
| A D | 2 | 552.43 | 276.22 | 98.8335 | .005 |
| A E | 2 | 1,090.68 | 545.34 | 195.1266 | .005 |
| B C | 4 | 124.51 | 31.13 | 11.1385 | .005 |
| B D | 2 | 65.83 | 32.91 | 11.7754 | .005 |
| B E | 2 | 0.38 | 0.19 | .0679 | NS |
| C D | 8 | 744.07 | 93.01 | 33.2796 | .005 |
| C E | 8 | 301.13 | 37.64 | 13.4678 | .005 |
| D E | 4 | 640.31 | 160.08 | 21.4971 | .005 |
| A B C | 4 | 87.43 | 21.86 | 7.8217 | .005 |
| A B D | 2 | 51.27 | 25.64 | 9.1742 | .005 |
| A B E | 2 | 6.25 | 3.12 | 1.1164 | NS |

# TABLE VIII (CONTINUED)

| Source of variation | d.f. | SS | MS | F-Ratio | P |
|---|---|---|---|---|---|
| A C D | 8 | 219.09 | 27.39 | 9.8003 | .005 |
| A C E | 8 | 92.56 | 11.57 | 4.1398 | .005 |
| A D E | 4 | 60.09 | 15.02 | 5.3743 | .005 |
| B C D | 8 | 158.80 | 19.85 | 7.1023 | .005 |
| B C E | 8 | 77.97 | 9.75 | 3.4886 | .005 |
| B D E | 4 | 51.01 | 12.75 | 4.5620 | .005 |
| C D E | 16 | 344.32 | 21.52 | 7.7000 | .005 |
| A B C D | 8 | 150.77 | 18.85 | 6.7447 | .005 |
| A B C E | 8 | 38.40 | 4.80 | 1.7174 | NS |
| A B D E | 4 | 73.90 | 18.47 | 6.6087 | .005 |
| A C D E | 16 | 171.06 | 10.69 | 3.8249 | .005 |
| B C D E | 16 | 38.59 | 2.41 | .8623 | NS |
| A B C D E | 16 | 28.73 | 1.80 | .6441 | NS |
| ERROR (b) | 356 | 994.95 | 2.7948 | | |

Mean values calculated by the computer for the different condions were used to plot graphs. For practical reasons the statistically significant main effects and the first order interactions only, were considered. Their list and corresponding figures are:

| | |
|---|---|
| 1. Main Effects | |
| a. Grinding Wheel Grain Size, A | Figure 34 |
| b. Coolant, B | Figure 35 |
| c. Depth of Cut, C | Figure 36 |
| d. Table Speed, D | Figure 37 |
| e. Cross Feed, E | Figure 38 |
| 2. First Order Interactions | |
| a. Grain Size by Coolant, AB | Figure 39 |
| b. Grain Size by Depth of Cut, AC | Figure 40 |
| c. Grain Size by Table Speed, AD | Figure 41 |
| d. Grain Size by Cross Feed, AE | Figure 42 |
| e. Coolant by Depth of Cut, BC | Figure 43 |
| f. Coolant by Table Speed, BD | Figure 44 |
| g. Depth of Cut by Table Speed,CD | Figure 45 |
| h. Depth of Cut by Cross Feed,CE | Figure 46 |
| k. Table Speed by Cross Feed, DE | Figure 47 |

The mean values used to plot the main effects and the first order interactions are shown in Table 17, Appendix B.

Figure 34 shows that the surface finish is improved by using a finer grain size wheel. The reduction in S.R. could be indicated by the ratio of S.R. means.

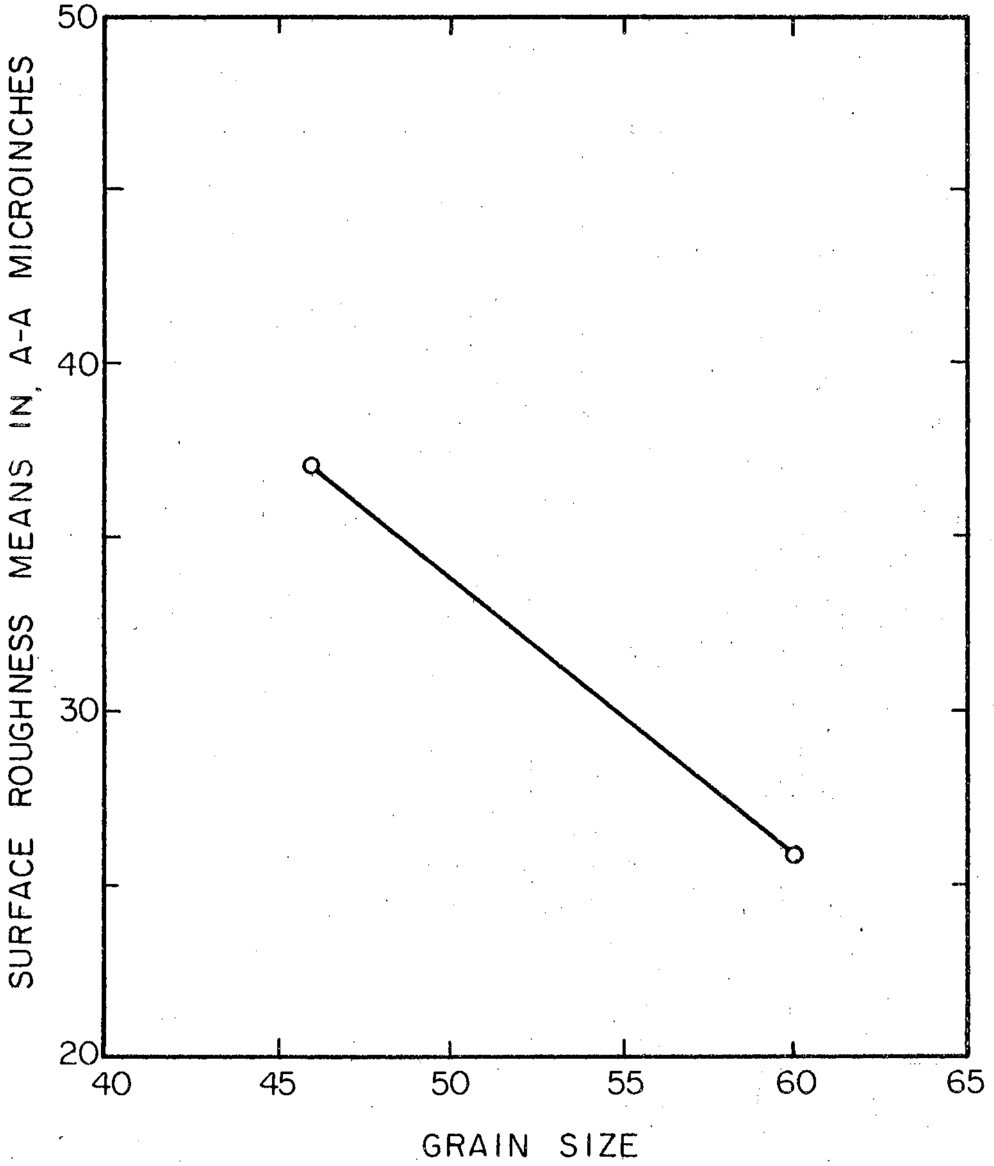


Figure 34. Main Effect Grain Size I (A)

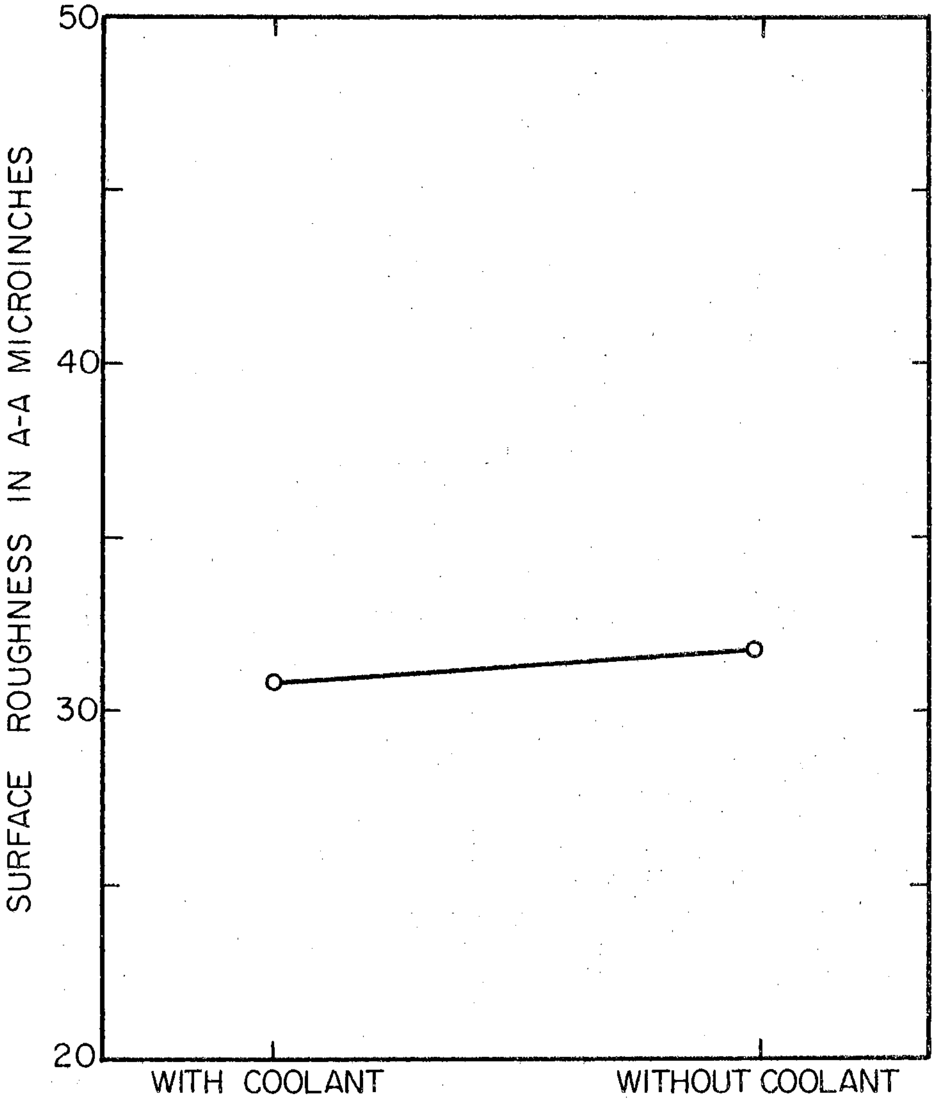


Figure 35. Main Effect Coolant I (B)

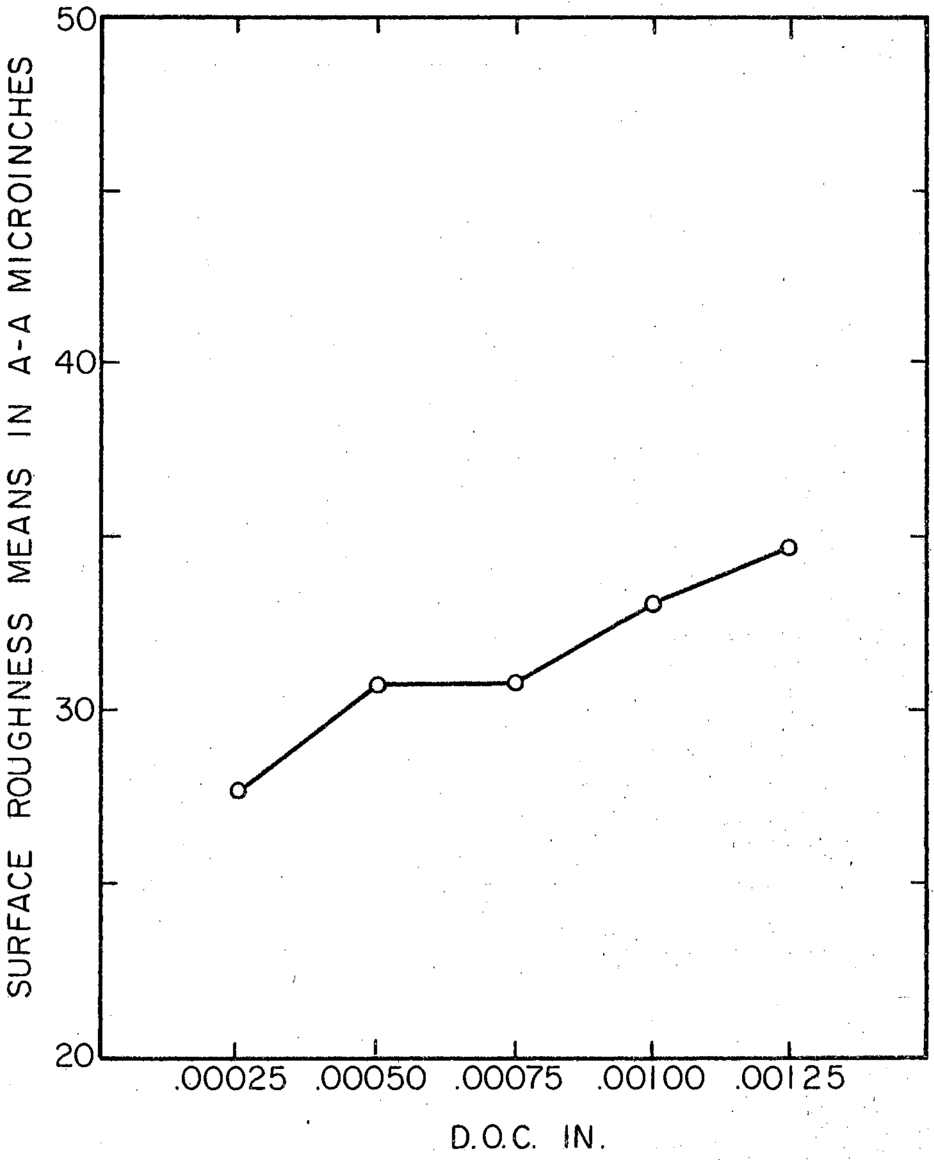


Figure 36. Main Effect Depth of Cut I (C)

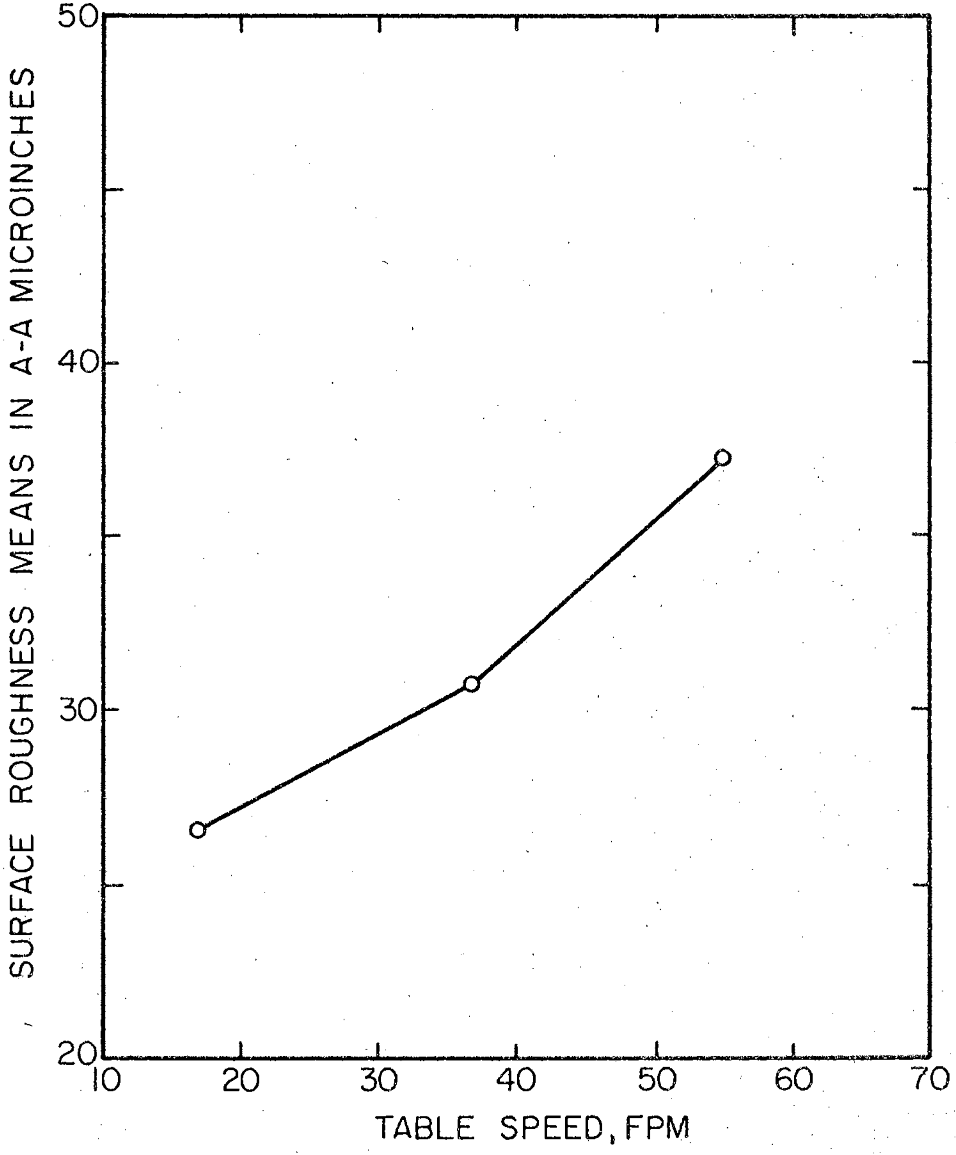


Figure 37. Main Effect Table Speed I (D)

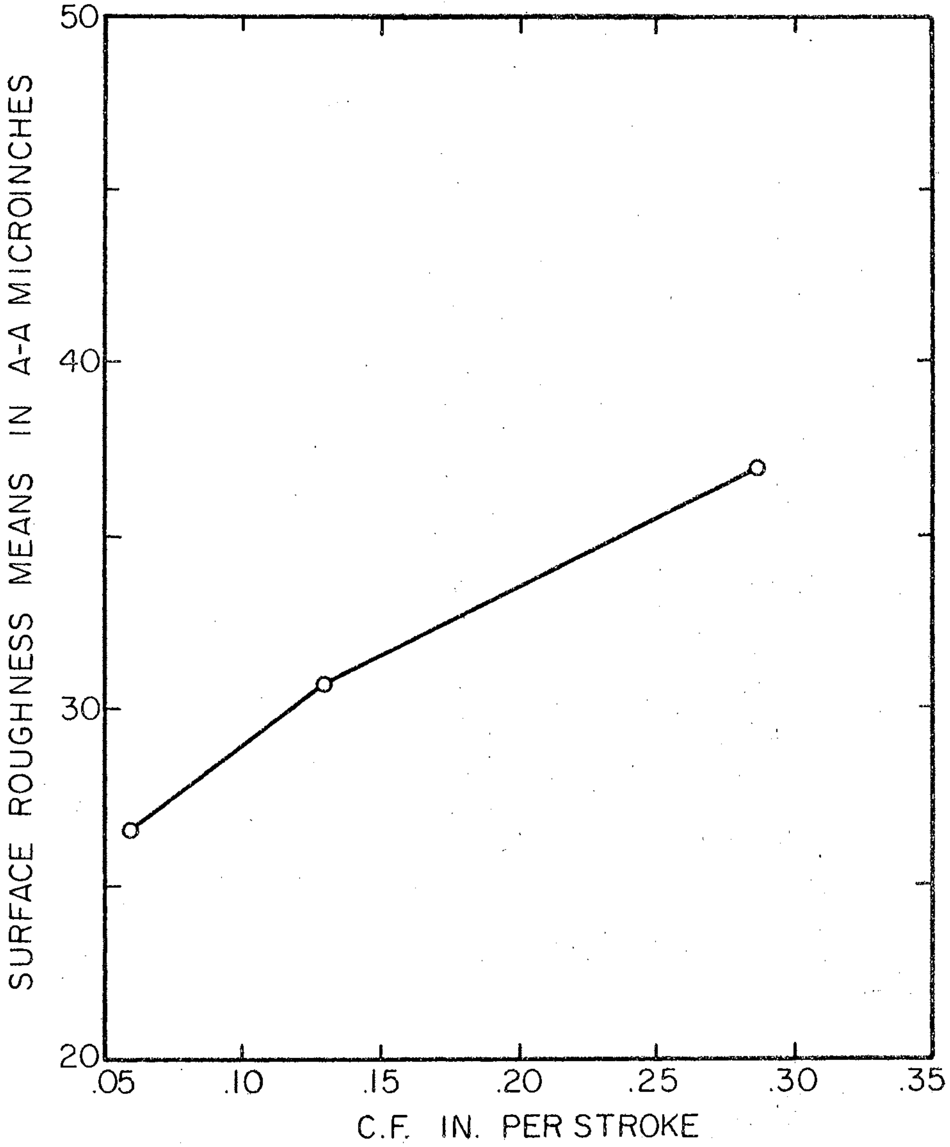


Figure 38. Main Effect Cross Feed I (E)

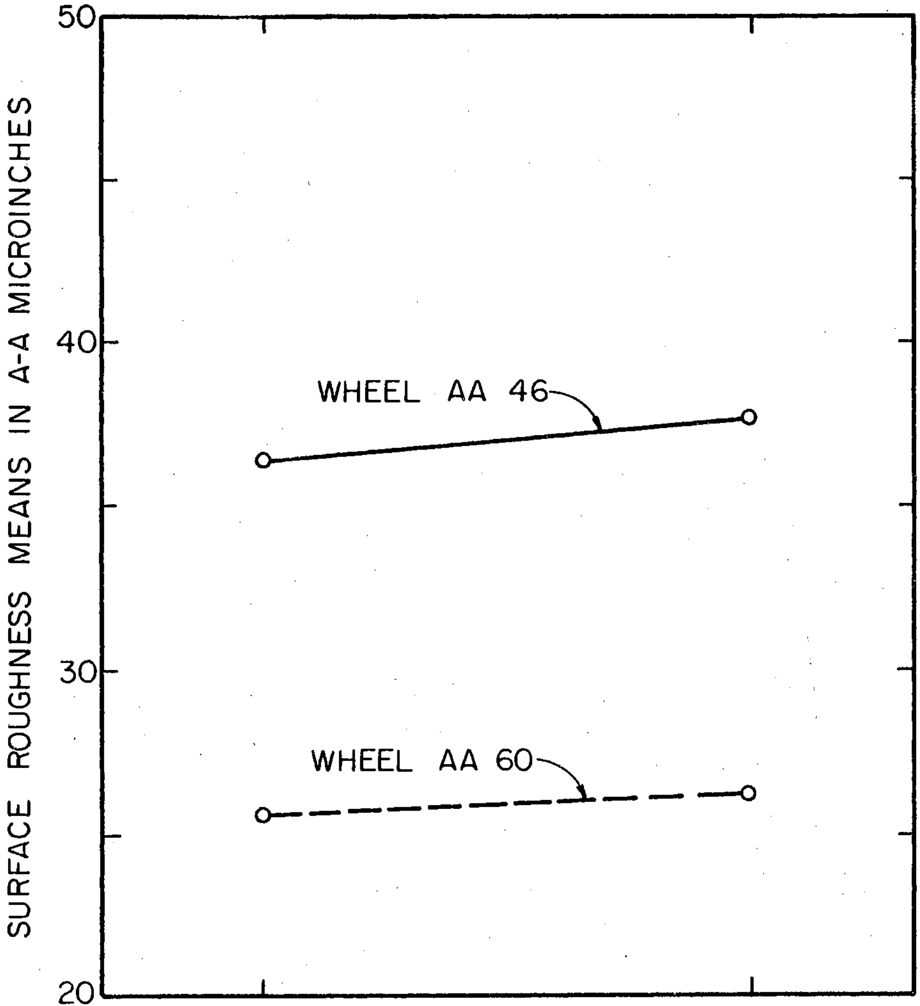


Figure 39. Interaction G.S. by Coolant I (AB)

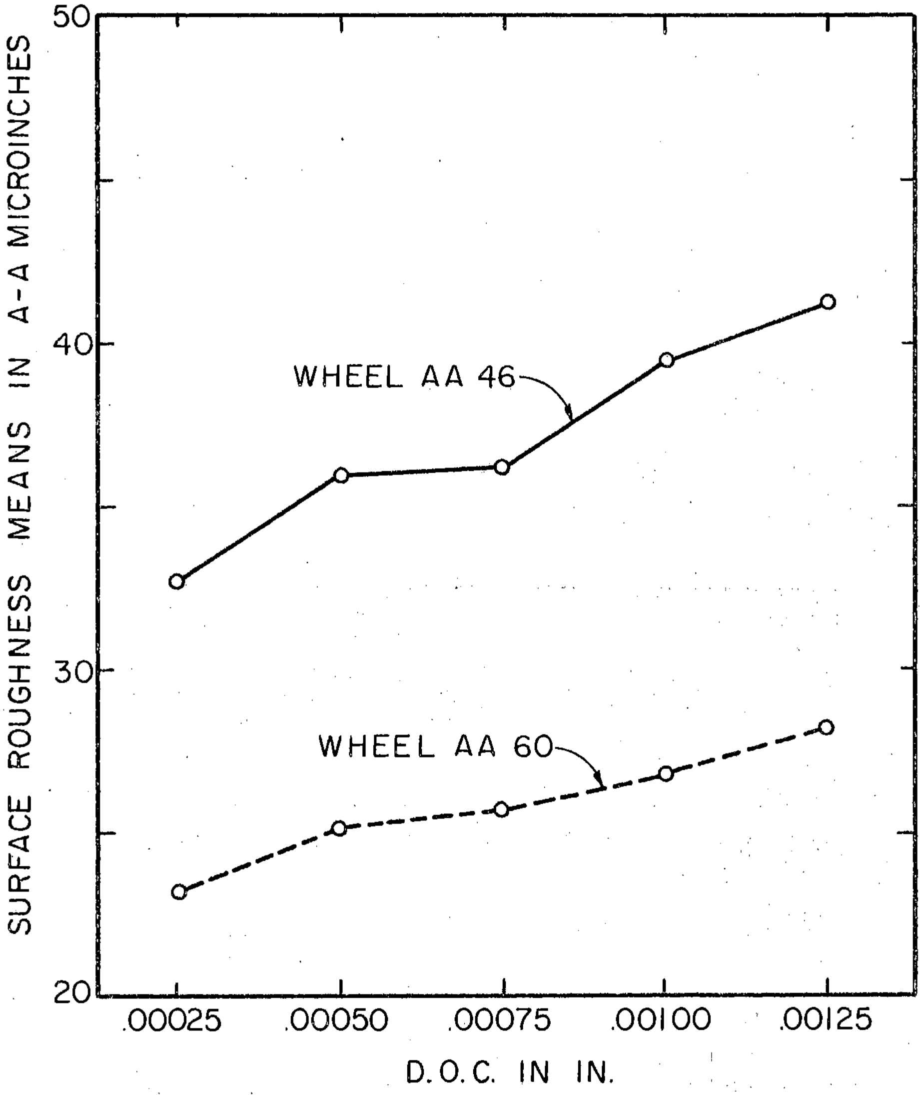


Figure 40. Interaction G.S. by D.O.C.
I (AC)

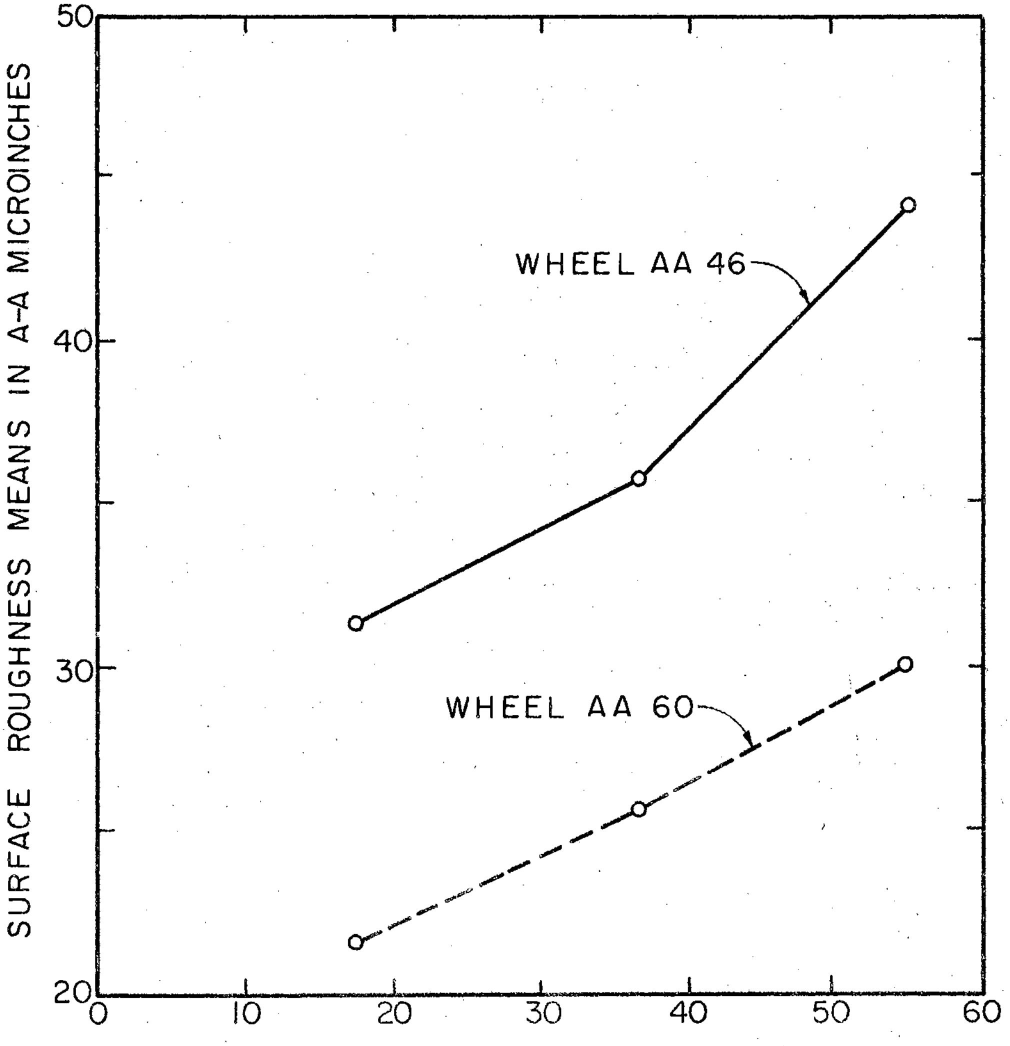


Figure 41. Interaction G.S. by T.S.
(AD)

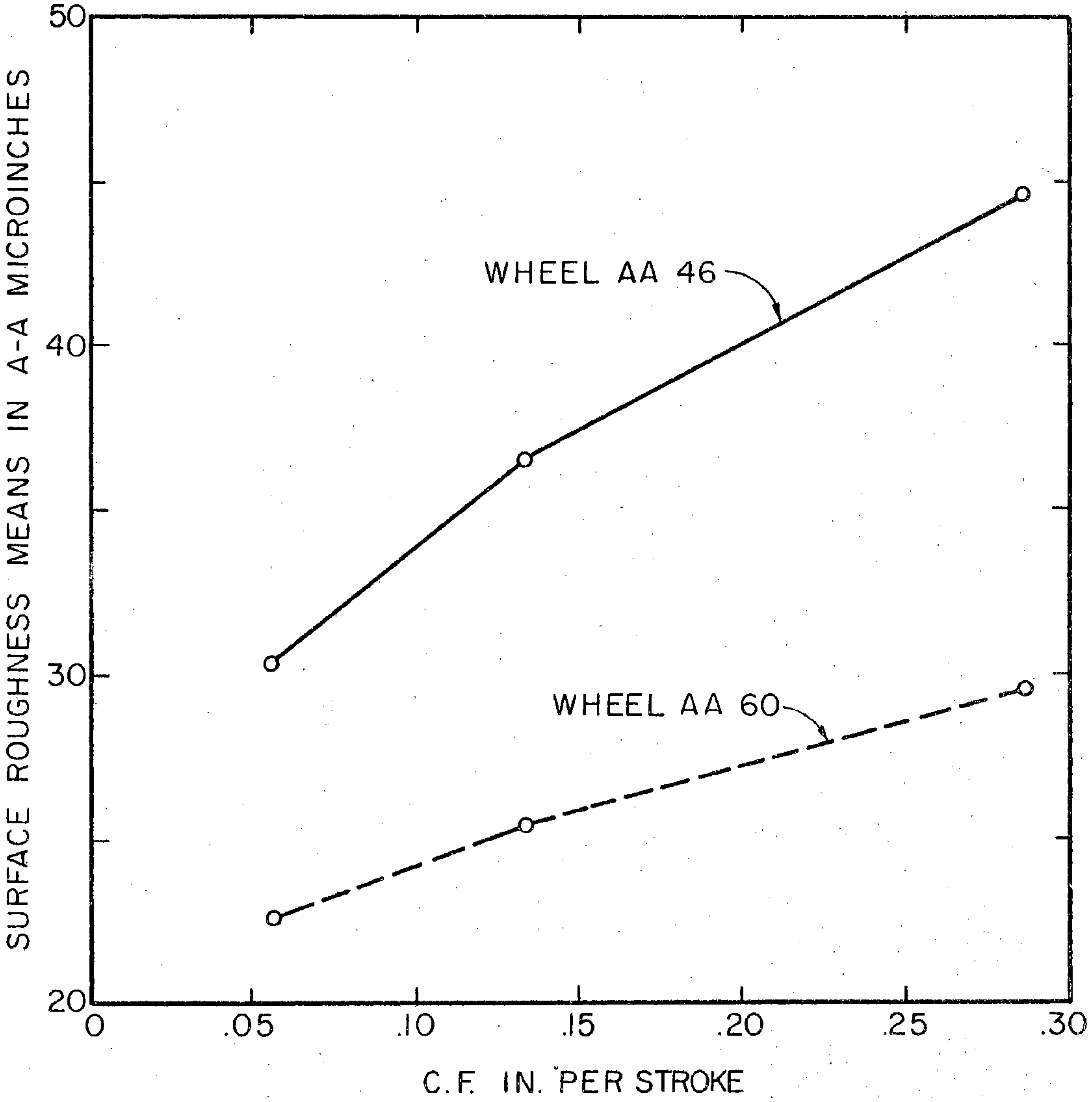


Figure 42. Interaction Grain Size by Cross Feed I (AE)

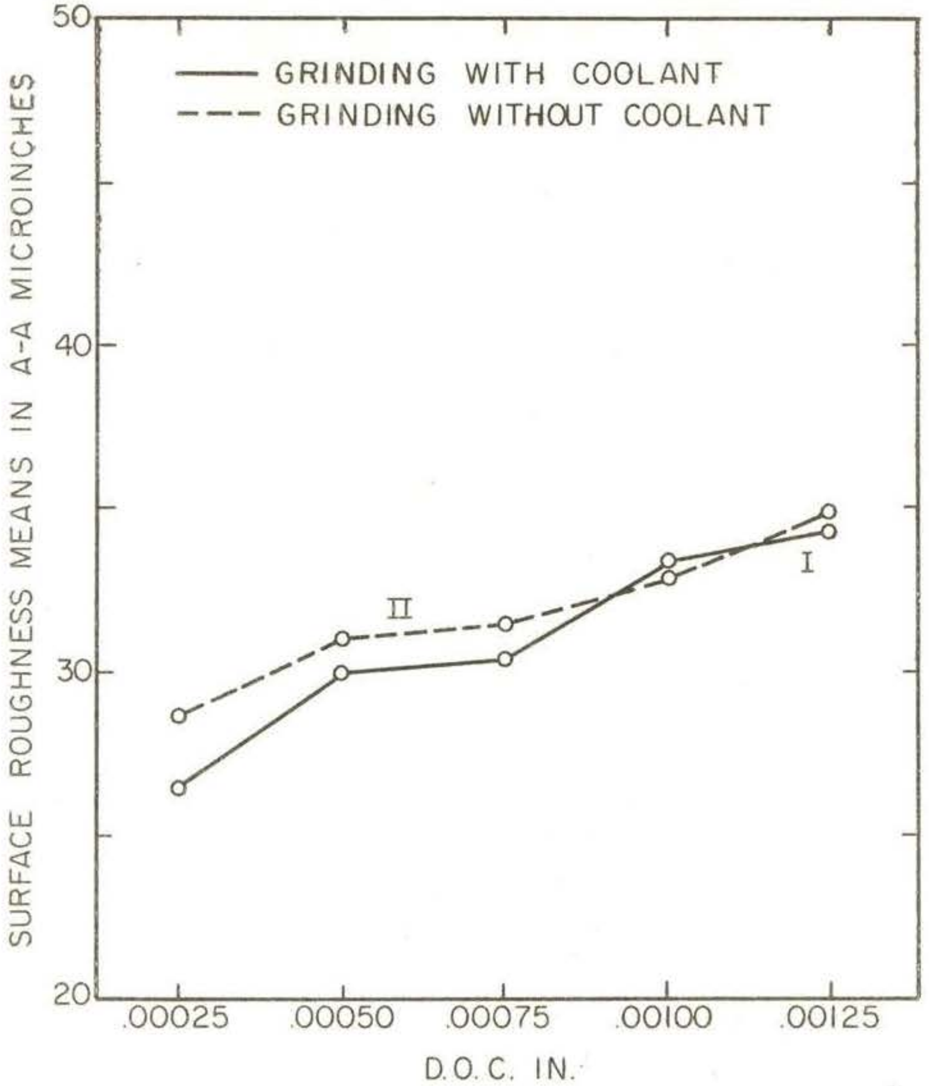


Figure 43. Interaction Coolant by D.O.C. I (BC)

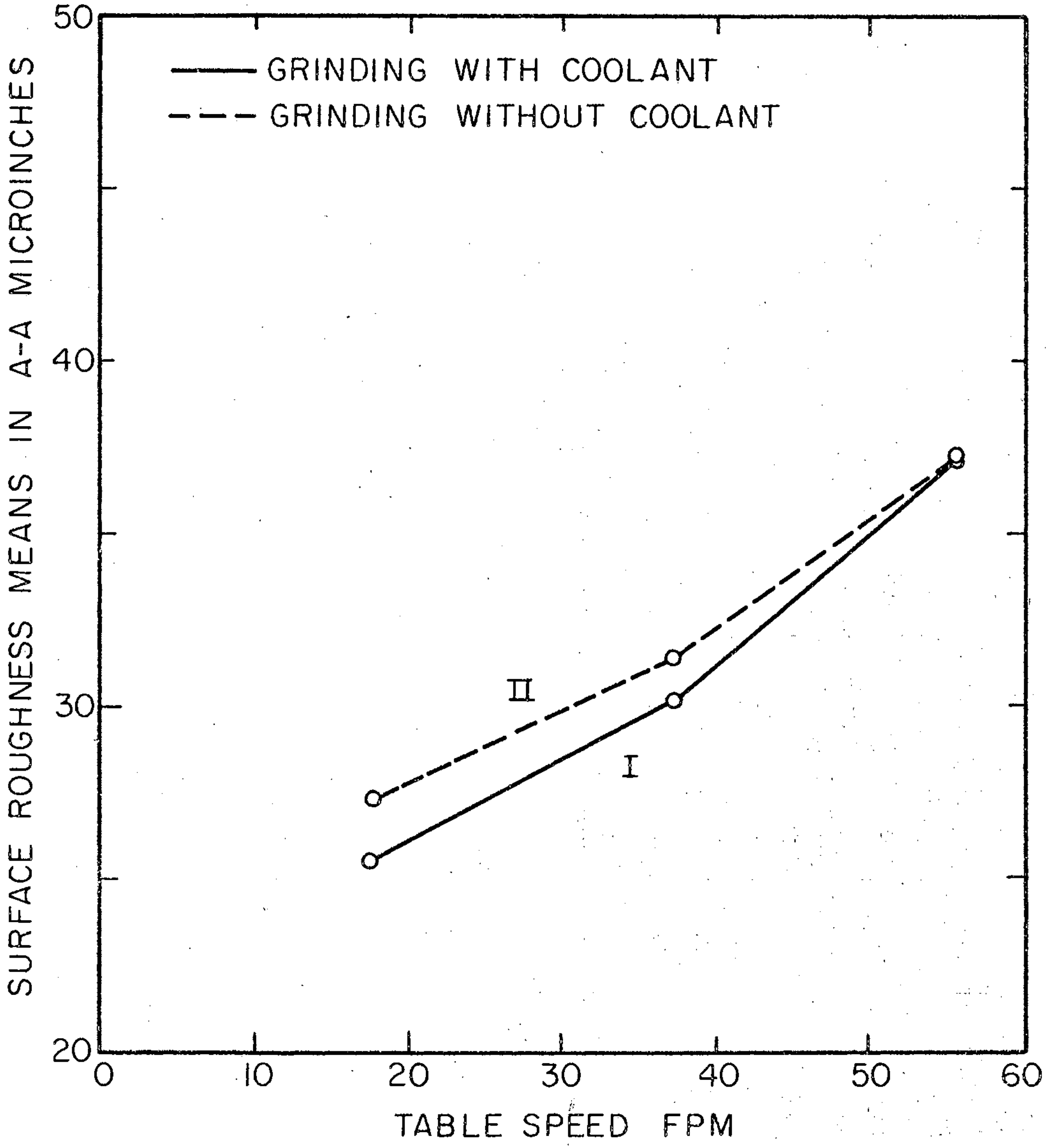


Figure 44. Interaction Coolant by Table Speed I (BD)

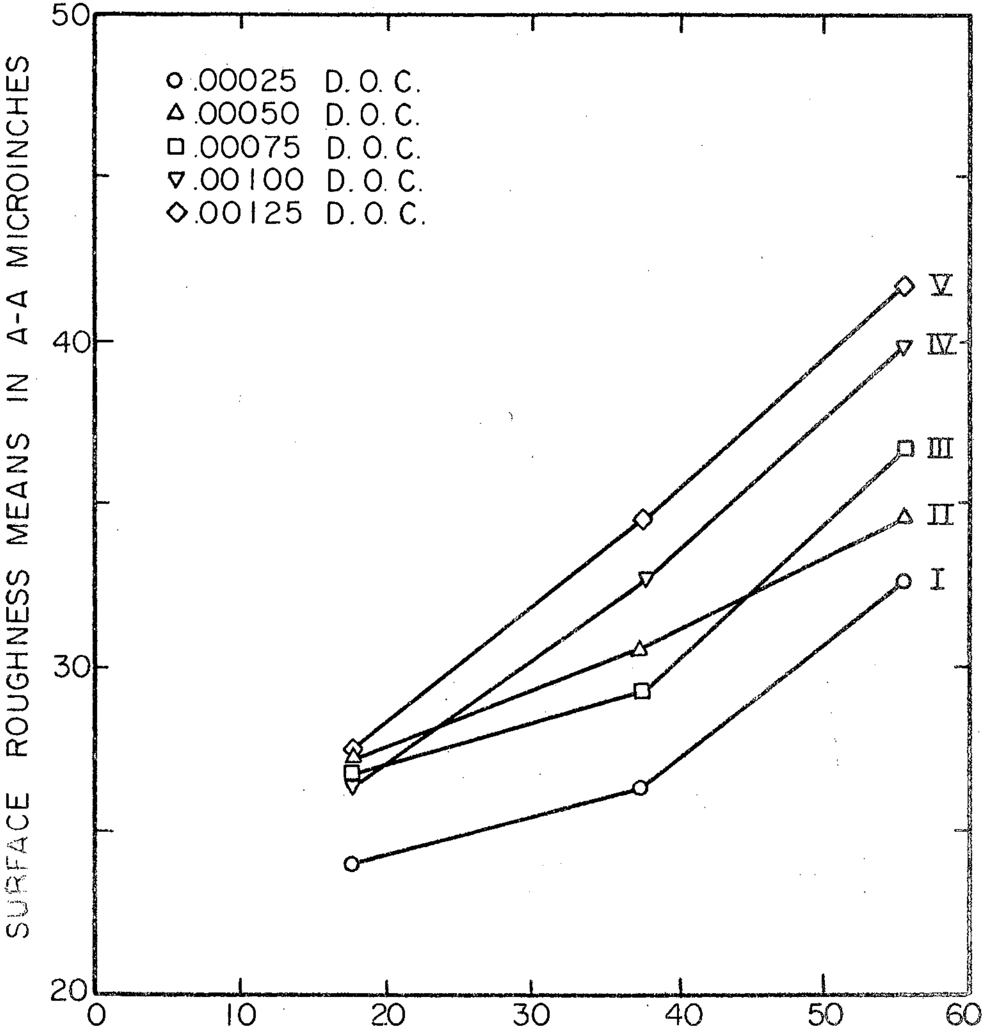


Figure 45. Interaction D.O.C. by T.S.
I (CD)

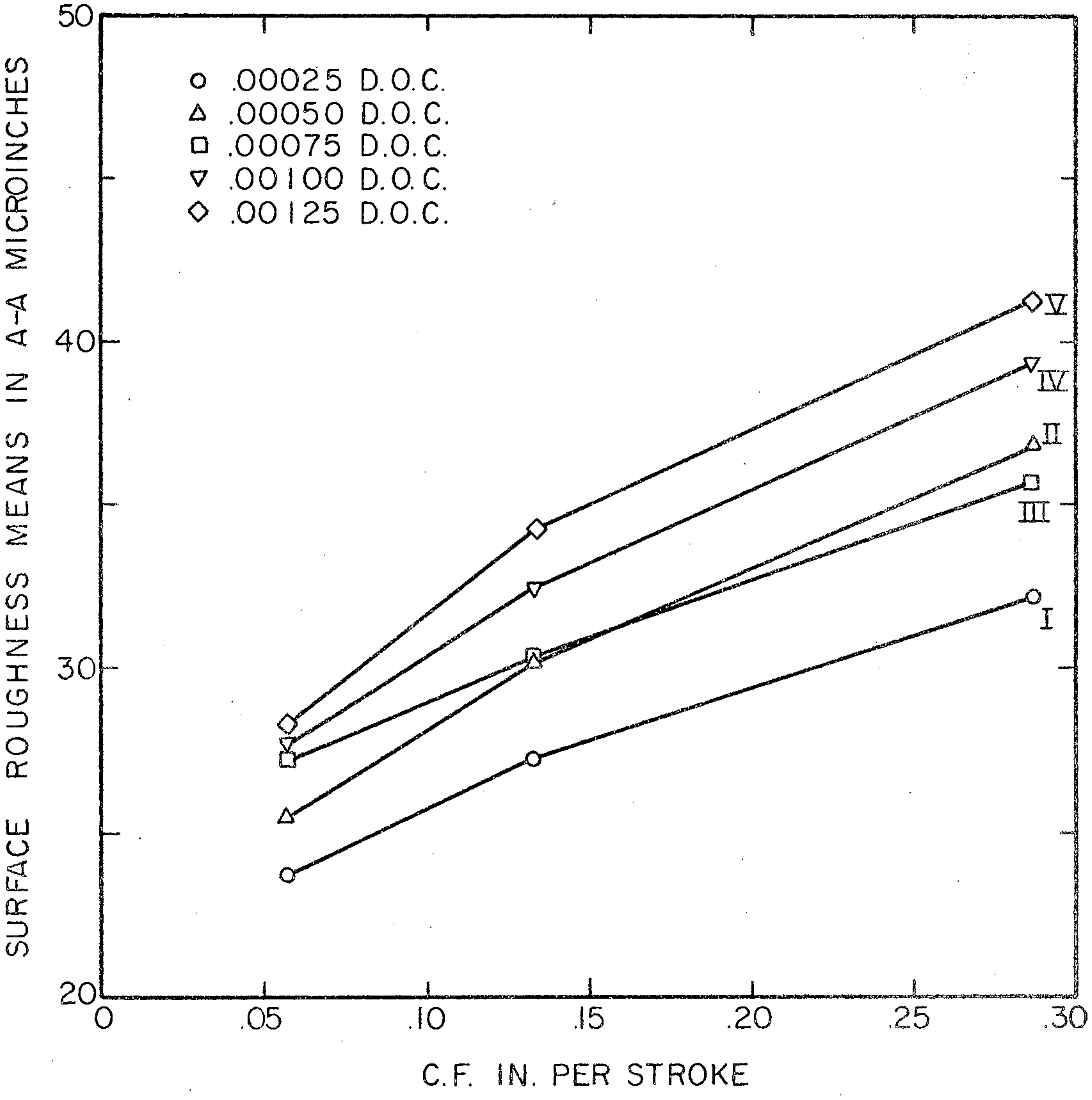


Figure 46. Interaction D.O.C. by C.F. I
(CE)

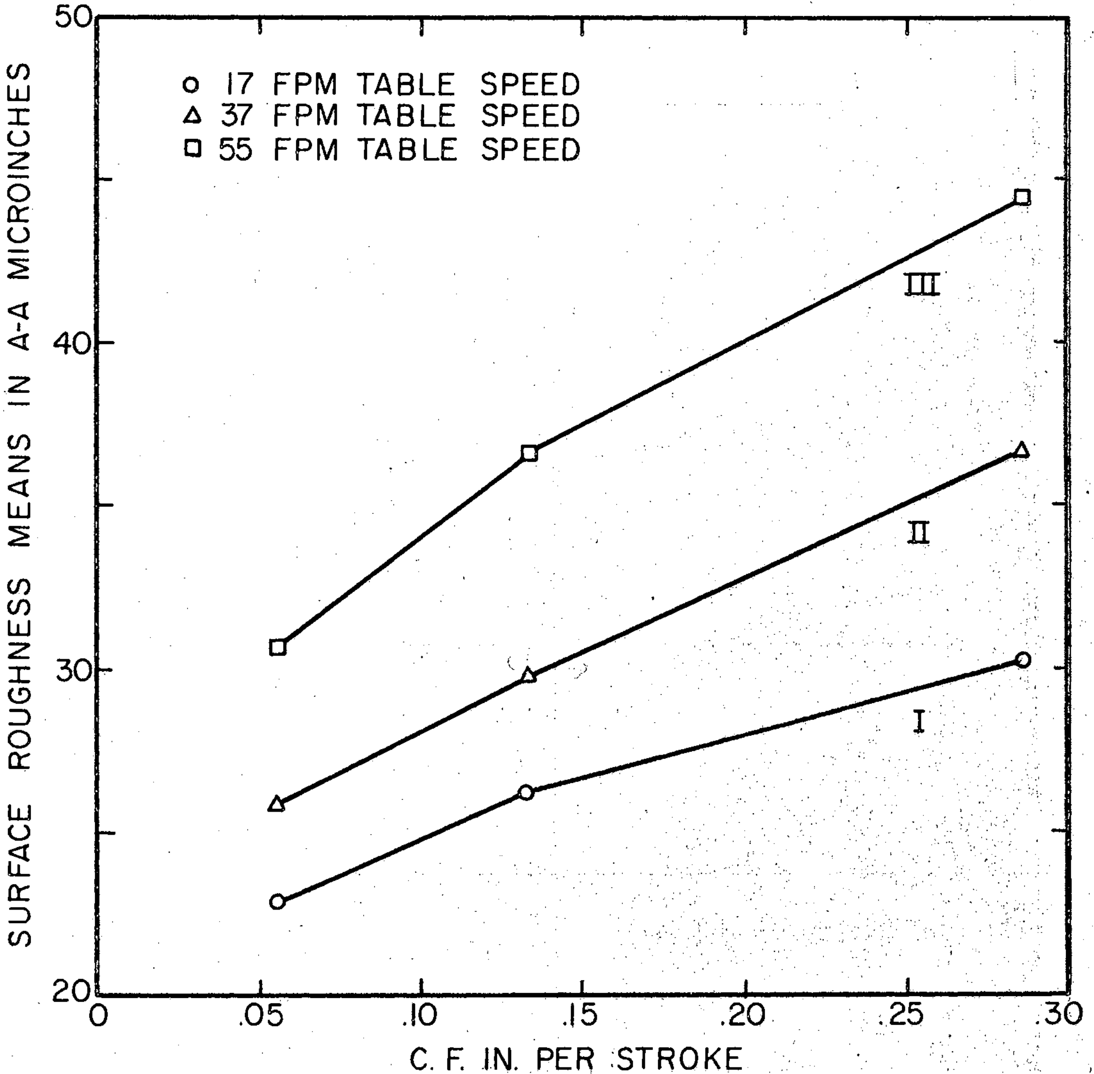


Figure 47. Interaction Table Speed by Cross Feed I (DE)

$$\text{S.R. ratio} = \frac{25.83}{37.07} = 69.7\ \%$$

which indicates an improvement of 30.3 %
This ratio is approximately equal to the reduction ratio in Chapter Four of 75.8 %, and the ratio of the grain sizes, 76.7 %.
Increasing the mesh number by 14 reduced S.R. by 11.24 microinches. This could be related as follows:
Decrease in S.R. = (.803) increase in mesh number.

Figure 35 indicates the small effect of the use of coolant on the first cut surface finish. The ratio of S.R. is:

$$\frac{30.95}{31.95} = 96.9\ \%$$

which indicates an improvement of 3.1 %. Although the main effect of coolant, is statistically significant according to Table 8, the study of the related graphs showed that it has no practical significance on first cut S.R.

Figure 36 shows that S.R. increases with the increase of D.O.C. With an increase of .001 in., the S.R. increased 7.02 microinches. This could be related on the average as follows:

$$\Delta\ \text{S.R. (microinches)} = 7.02 \times \Delta\ \text{(D.O.C.)}$$

where $\Delta$ (D.O.C.) is in thousands of an inch.

Figure 37 shows that S.R. increases with the increase of T.S. The rate of increase is smaller in the range from 17 FPM to 37 FPM than the rate of increase in the range from 37 FPM to 55 FPM. With an increase in T.S. of 38 FPM, S.R. increased 10.66 microinches. This could be related as:

$\Delta$ S.R. in microinches = .280 x $\Delta$ (T.S.)

where $\Delta$ (T.S.) is in FPM.

Figure 38 shows that S.R. increases with the increase of the C.F. The rate of increase is higher in the range of .057 to .133 in per stroke, than in the range of .133 to .286 in. per stroke. With an increase of .229 in. per stroke, S.R. increased 10.59 microinches. This could be related as follows:

$\Delta$ S.R. in microinches = 46.24 x $\Delta$ (C.F.)

where $\Delta$ (C.F.) is in in. per stroke.

Figure 39 shows that use of coolant with the 46 grain size wheel slightly reduced S.R. over the 60 grain size wheel. The reduction in the case of the 46 grain size wheel was 1.33 microinches while for 60 grain size wheel it was .66 microinches.

Figure 40 shows that the increase in D.O.C. increased S.R. with a higher rate in case of the 46 G.S. wheel than in the case of the 60 G.S. wheel. The average rate for the 46 wheel was 9.06 microinches per .001 in., and 4.98 microinches per .001 in. for the A 60 wheel.

Figure 41 shows that the increase in T.S. increased S.R. at a higher rate in the case of the A 46 wheel than the A 60 wheel. The first rate was .338 while the second was .222 microinches per F.P.M.

Figure 42 shows that for the given increase in C.F., the 46 G.S. wheel leads to a greater increase in S.R. than the 60 G.S. wheel; 61.44 vs. 31.09 microinches per in. per stroke.

Figure 43 shows that the increase in D.O.C. increased the S.R. in case of grinding with or without coolant. The average rate of change of S.R. between the limits of .00025 and .00125 in. varied slightly. However, the rates of change over the four incremental ranges showed a significant variation.

Figure 44 shows that grinding without coolant had greater effect at lower table speeds than at higher speeds.

Figure 45, 46, and 47 verify the results found in the previous analysis that S.R. increased with the increase in D.O.C., T.S., and C.F. However, the rates of change from one level to another in each factor were not the same. This was shown also in Table 8 due to the statistical significance of the first interaction of these factors.

## The Relation Between Surface Roughness and D.O.C., T.S., and C.F.

The previous analysis showed the effect of each factor on S.R. The smallest effect on the first cut surface roughness was due to the coolant, 3.1 % reduction. However, grinding with coolant is in common use, unless conditions oblige the other case, as temperature of workpiece and power consumed are reduced by the coolant. Therefore, the mathematical relations presented in this section were mainly developed for grinding with coolant. However, due to the small difference, i.e. 3.1 %, these relations could be used satisfactorily to estimate S.R. while grinding without coolant.

The independent variables used in these relations were: D.O.C., T.S., and C.F. From the study of the graphs discussed in the previous section, it is seen that the responses could be linearly estimated. The response equation considered for each wheel was in the following multiple Linear regression from:

$$S.R. = B_o + B_1 X_1 + B_2 X_2 + B_3 X_3 \qquad (5-1)$$

where:

$B_o$, $B_1$, $B_2$ and $B_3$ are constants

S.R. = Surface roughness in microinches.

$X_1$ = Depth of Cut in thousands of an inch.

$X_2$ = Table Speed in FPM.

$X_3$ = Cross feed in in. per stroke.

Table 9 shows the means of S.R. for each wheel from the experiments while grinding with coolant at the different levels of D.O.C., T.S., and C.F. The results are presented according to the increasing order of the rate of metal removal (R.O.M.R.). These means and levels were used to calculate the constants for each equation. These constants were actually determined by a computer program, run on the

# TABLE IX

## RATE OF METAL REMOVED W.R.T.,S.R., D.O.C., T.S., AND C.F.

| R.O.M.R. cu.in./min. | S.R. Microinches | | $X_1$ D.O.C. .001 in. | $X_2$ T.S. FPM | $X_3$ C.F. in./str. |
|---|---|---|---|---|---|
| | A46 G.Wh. | A60 G.Wh. | | | |
| .0029 | 20.33 | 17.33 | 0.25 | 17 | .057 |
| .0058 | 25.67 | 18.67 | 0.50 | 17 | .057 |
| .0063 | 24.0 | 20.0 | 0.25 | 37 | .057 |
| .0068 | 25.33 | 20.0 | 0.25 | 17 | .133 |
| .0087 | 27.00 | 18.67 | 0.75 | 17 | .057 |
| .0094 | 31.33 | 23.33 | 0.25 | 55 | .057 |
| .0116* | 27.00 | 18.67 | 1.00 | 17 | .057 |
| .0127 | 27.67 | 21.33 | 0.50 | 37 | .057 |
| .0136 | 30.33 | 21.33 | 0.50 | 17 | .133 |
| .0145 | 28.0 | 20.0 | 1.25 | 17 | .057 |
| .0146 | 30.00 | 23.0 | 0.25 | 17 | .286 |
| .0148 | 27.33 | 21.67 | 0.25 | 37 | .133 |
| .0188 | 30.0 | 25.67 | 0.50 | 55 | .057 |
| .0190 | 28.00 | 23.33 | 0.75 | 37 | .057 |
| .0204 | 30.0 | 21.33 | 0.75 | 17 | .133 |
| .022 | 37.33 | 25.33 | 0.25 | 55 | .133 |
| .0253 | 31.33 | 24.33 | 1.00 | 37 | .057 |
| .0272* | 29.0 | 21.67 | 1.00 | 17 | .133 |
| .0282 | 35.0 | 25.33 | 0.75 | 55 | .057 |
| .0292 | 34.67 | 24.00 | 0.50 | 17 | .286 |
| .0296 | 31.00 | 23.00 | 0.50 | 37 | .133 |
| .0316 | 31.67 | 24.33 | 1.25 | 37 | .057 |

TABLE IX (CONTINUED)

| R.O.M.R.<br>cu.in./min | S.R. Microinches |  | $X_1$<br>D.O.C.<br>.001 in. | $X_2$<br>T.S.<br>FPM | $X_3$<br>C.F.<br>in./str. |
|---|---|---|---|---|---|
|  | A46 G.Wh. | A60 G.Wh. |  |  |  |
| .0317 | 31.33 | 16.00 | 0.25 | 37 | .286 |
| .0340 | 33.00 | 22.00 | 1.25 | 17 | .133 |
| .0376 | 39.00 | 26.33 | 1.00 | 55 | .057 |
| .0438 | 35.33 | 23.67 | 0.75 | 17 | .286 |
| .0440 | 41.00 | 27.00 | 0.50 | 55 | .133 |
| .0444* | 35.67 | 25.0 | 0.75 | 37 | .133 |
| .0470 | 38.00 | 27.33 | 1.25 | 55 | .057 |
| .0472 | 44.33 | 29.00 | 0.25 | 55 | .286 |
| .0583* | 37.33 | 23.67 | 1.00 | 17 | .286 |
| .0592 | 37.33 | 26.33 | 1.00 | 37 | .133 |
| .0635 | 39.33 | 28.33 | 0.50 | 37 | .286 |
| .0660 | 40.00 | 28.00 | 0.75 | 55 | .133 |
| .0729* | 38.00 | 24.33 | 1.25 | 17 | .286 |
| .0740 | 38.67 | 27.00 | 1.25 | 37 | .133 |
| .0880 | 48.67 | 32.33 | 1.00 | 55 | .133 |
| .0944 | 46.67 | 32.67 | 0.50 | 55 | .286 |
| .0952* | 46.33 | 28.67 | 0.75 | 37 | .286 |
| .1100 | 50.67 | 34.00 | 1.25 | 55 | .133 |
| .1270 | 48.00 | 31.00 | 1.00 | 37 | .286 |
| .1416 | 53.67 | 34.33 | 0.75 | 55 | .286 |
| .1587* | 43.00 | 32.33 | 1.25 | 37 | .286 |
| .1888 | 64.00 | 37.00 | 1.00 | 55 | .286 |
| .2360 | 66.67 | 39.33 | 1.25 | 55 | .286 |

IBM 1620. The multiple linear regression equation for AA 46 H8 V40 grinding wheel was:

$$S.R. = 6.132 + 10.51\ X_1 + .375\ X_2 + 61.3\ X_3 \quad \ldots \quad (5\text{-}2)$$

The multiple linear regression equation for the AA 60 H8 V40 grinding wheel was:

$$S.R. = 9 + 4.8\ X_1 + .225\ X_2 + 29.5\ X_3 \quad \ldots\ldots\ldots\ldots (5\text{-}3)$$

It is noticed that the constants obtained from the linear regression analysis match closely the rates calculated from the previous graphs. To check the accuracy of the regression equations developed above, Index C, defined below, was calculated for 12 different treatments covering the full variables ranges on the available machine.

$$\text{Index C} = \frac{\text{Estimated S.R.}}{\text{Average Experimental S.R.}} \times 100\ \%$$

Values of Index C for the two wheels are shown in Table 10. For the A 46 wheel, the estimated S.R. varied between $\pm$ 9 % for 11 treatments out of the 12 considered. The other difference was -13.9 %. For the A 60 wheel, the differences for 10 treatments out of the 12 were between $\pm$ 9 %. The maximum of the other two was 12.6 %

The estimated values were plotted against the actual experimental results. Figures 48 and 49 shows these points for the A 46 and A 60 grinding wheels, respectively. Linear regression lines relating the estimated value (Y) to the actual value (X) were developed. The linear regression line for the A 46 wheel is:

## TABLE X

## INDEX C VALUES

| D.O.C. .001 in. | T.S. FPM | C.F. in. /stroke | A46.H8.V40.G.Wh. |  |  | A60.H8.V40.G.Wh. |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  | Ave. S.R. | Est. S.R. | Index C | Ave. S.R. | Est. S.R. | Index C |
| .25 | 17 | .057 | 20.33 | 18.631 | 91.6% | 17.33 | 16.216 | 93.6% |
| .25 | 55 | .286 | 44.33 | 46.917 | 105.8% | 29.00 | 32.662 | 112.6% |
| .50 | 37 | .057 | 27.67 | 28.756 | 103.9% | 21.33 | 22.516 | 105.6% |
| .50 | 55 | .133 | 41.00 | 40.165 | 98 % | 27.00 | 29.348 | 108.7% |
| .75 | 17 | .133 | 30.00 | 28.542 | 95.1% | 21.33 | 20.858 | 97.8% |
| .75 | 37 | .133 | 35.67 | 36.042 | 101.0% | 25.00 | 25.958 | 103.8% |
| .75 | 55 | .286 | 53.67 | 52.169 | 97.2% | 34.33 | 35.062 | 102.1% |
| 1.00 | 17 | .286 | 37.33 | 40.547 | 108.6% | 23.67 | 26.572 | 112.2% |
| 1.00 | 37 | .286 | 48.00 | 48.047 | 100.1% | 31.00 | 31.672 | 102.1% |
| 1.00 | 55 | .133 | 48.67 | 45.420 | 93.3% | 32.33 | 31.748 | 98.2% |
| 1.25 | 37 | .133 | 38.67 | 41.297 | 106.8% | 27.00 | 28.358 | 105 % |
| 1.25 | 55 | .286 | 66.67 | 57.424 | 86.1% | 39.33 | 37.462 | 95.3% |

$Y = 5.2 + .85689\ X$

and for the A 60 wheel is:

$Y = 2.131\ X\ .95215\ X$ , where ,

$Y$ = the estimated value of S.R. in microinches, and

$X$ = the actual value of S.R. in microinches. These lines were drawn and compared to the ideal line, $Y = X$.

The comparison of the ideal line and the regression lines shown in figures 48 and 49, and the relatively small variations found in Table 10 prove the multiple linear regression model (5-1) to be satisfactory for this type of operation.

The study of the tool life and behavior for grinding with coolant, Chapter Three, showed that the resulting surface finish was within small tolerances for the first 90% of tool life as seen in Figures (7-17); during the final 10 % of the wheel life, it gradually deteriorated and led to unacceptable tolerances. Figures 31 and 32 show the same results while grinding without coolant. Figure 35 shows that the reduction in S.R. due to the use of coolant was only 3.1 %. Therefore, it is concluded that equations (5-2) and (5-3) could be used not only to estimate the S.R. yielded by a recently sharpened wheel, but also for the estimation of S.R. expected during the entire useful life of the wheel while grinding with or without coolant.

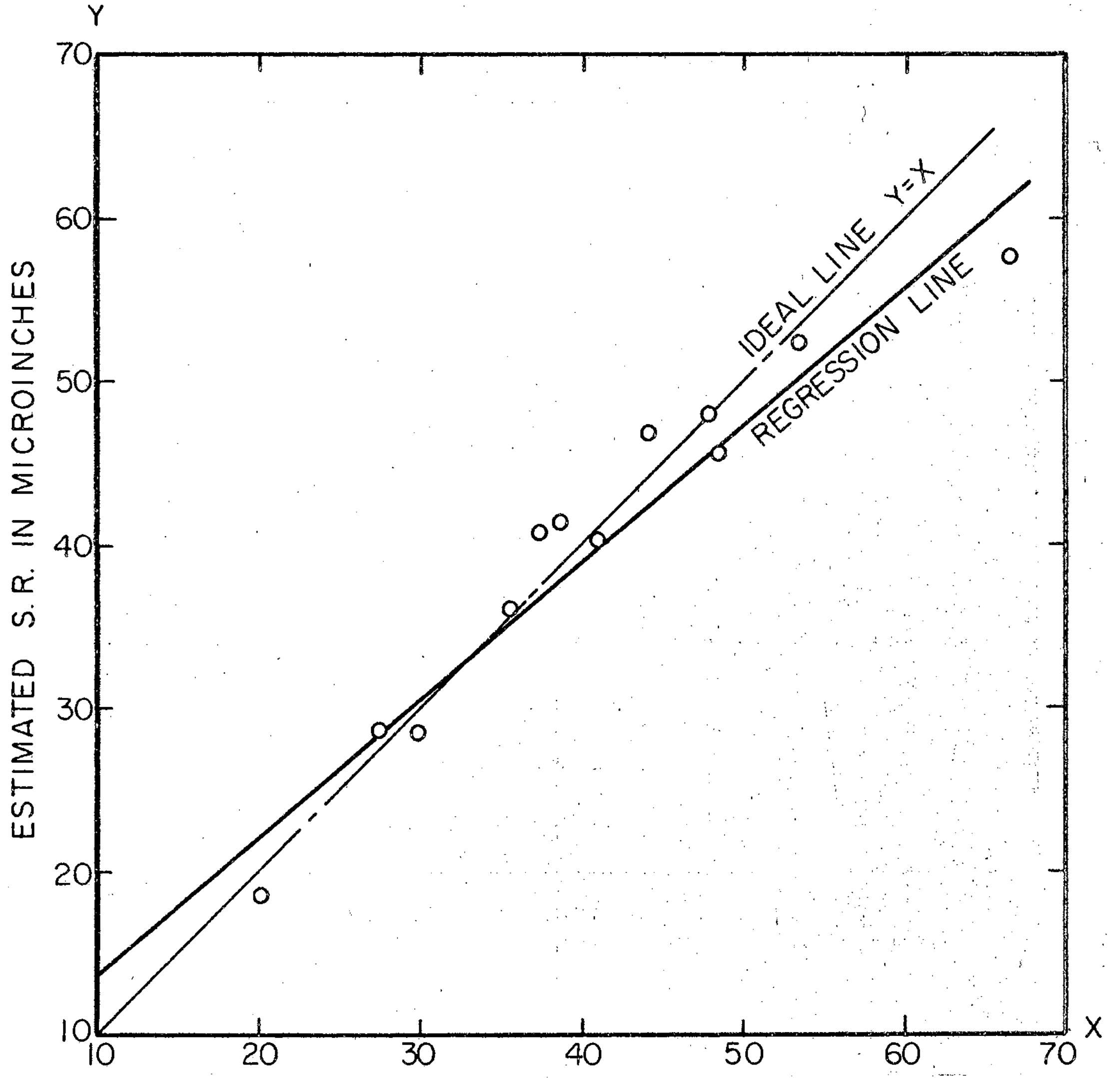


Figure 48. Actual S.R. vs. Estimated S.R. for AA46 Grinding Wheel

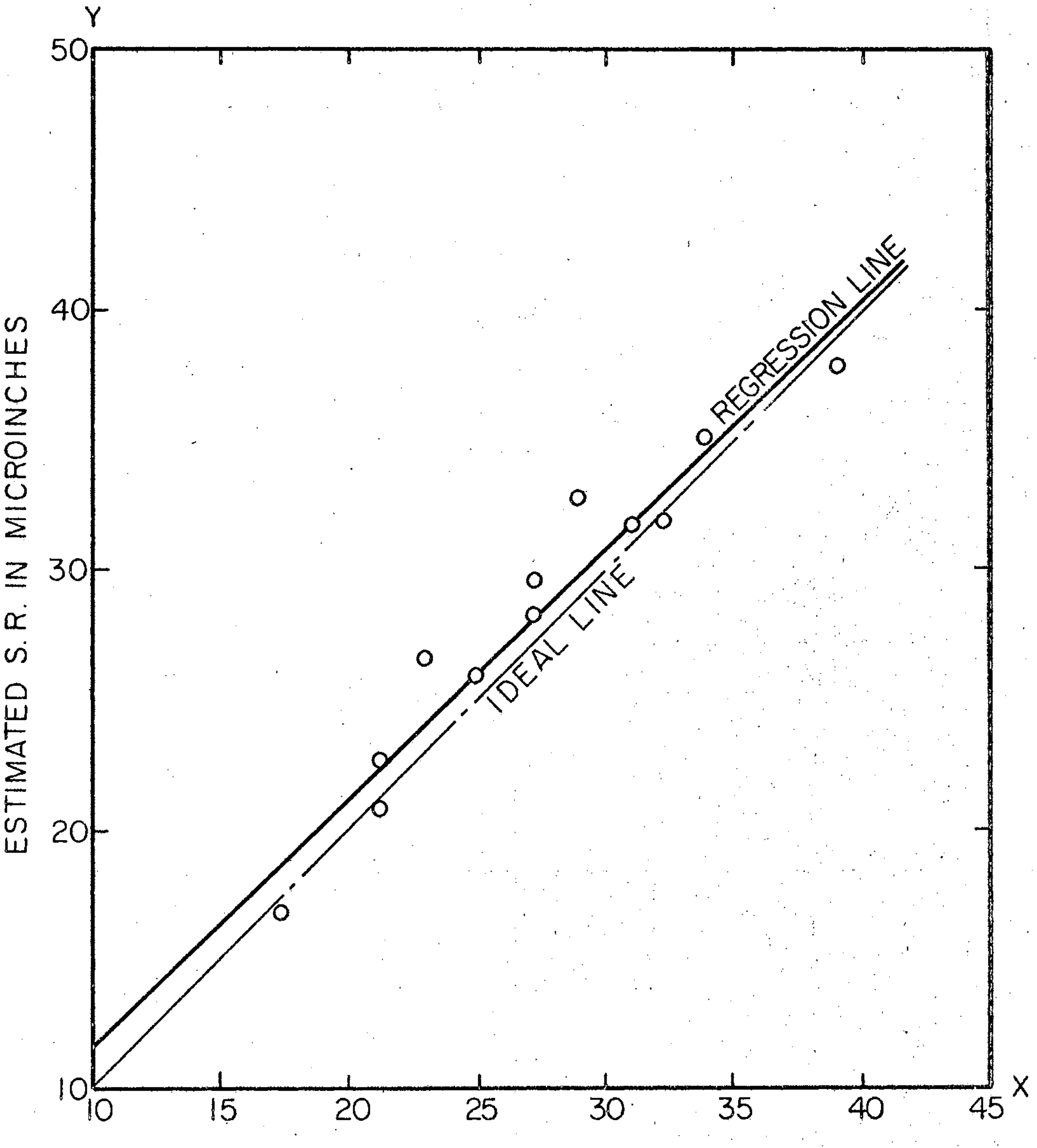


Figure 49. Actual S.R. vs. Estimated S.R. for AA60 Grinding Wheel

## Relation Between Surface Roughness and Rate of Metal Removal

The rate of metal removal was calculated for each case and presented in an increasing order as shown in Table 9. These quantities were calculated as follows:

$$\begin{aligned} \text{R.O.M.R.} &= \text{D.O.C. (in)} \times \text{T.S. (Ft./min)} \times 12 \times \\ &\quad \text{C.F. (in./Str.)}. \\ &= (.001\ X_1) \times (12\ X_2) \times (X_3) \\ &= .012\ X_1\ X_2\ X_3 \text{ cu. in. per min.} \end{aligned} \qquad (5\text{-}4)$$

These values were plotted against S.R. for each of the two grinding wheels in figure 50. From points 1, 2, 3, 4, 5, 6, and 7 on the graph, it is clear that by proper adjustment of the variables levels, a higher rate of metal removal could be achieved while maintaining a lower surface roughness. For example, point 7 shows a reduction of 20 % in S.R. while increasing R.O.M.R. by .017 cu in. per min. The study of these points indicates that the best conditions, for a specified R.O.M.R., could be reached by increasing the D.O.C. to the maximum allowable level, and then consecutively increasing the C.F. and T.S.

What is ultimately desired is a systematic method for specifying these independent variables such that equation 5-4 is maximized while, at the same time, equation 5-1 is minimized.

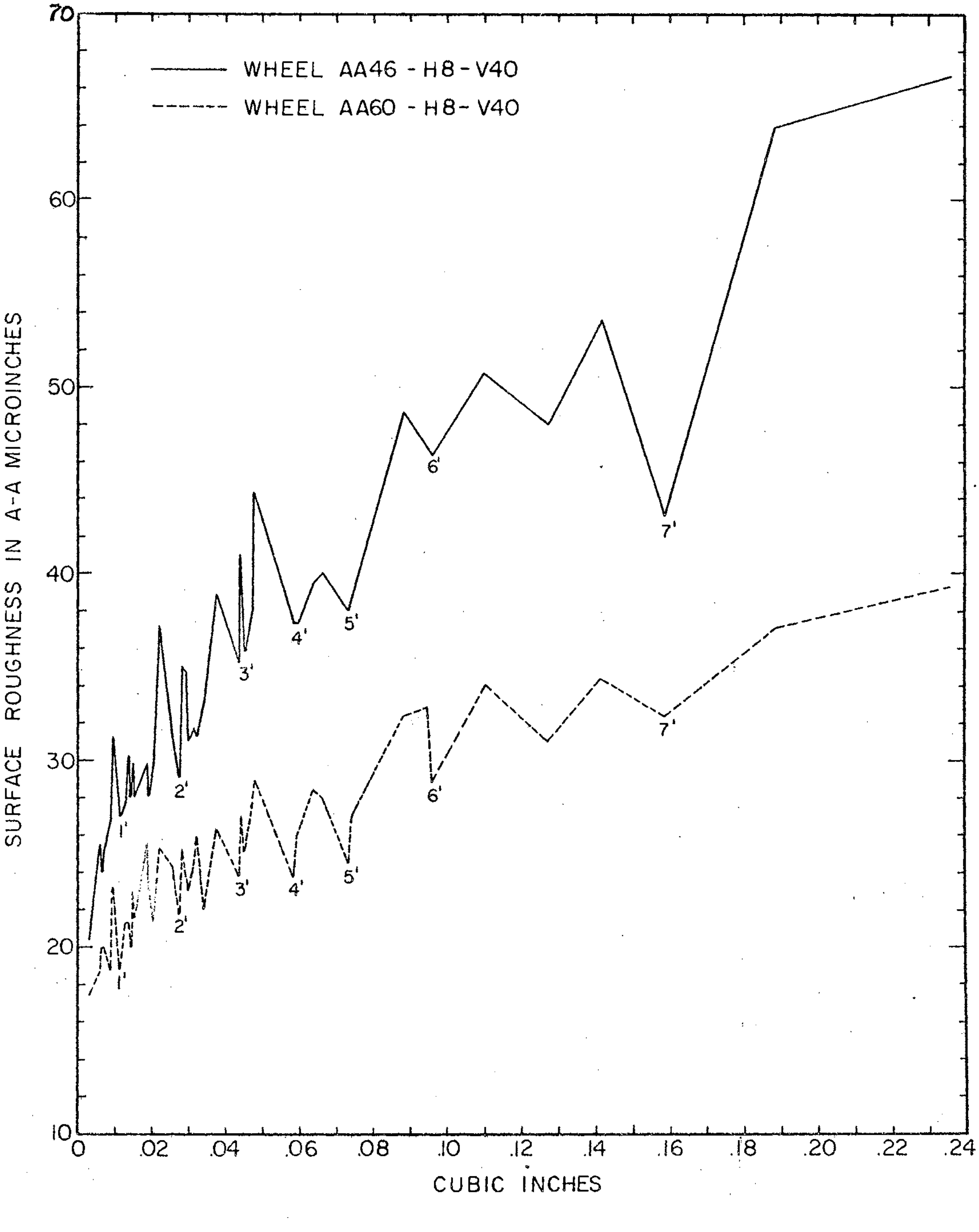


Figure 50. Rate of Metal Removal vs. S.F.

## Power Consumption

Results of statistical analysis with P.C. as the dependent variable are presented in Table 11. The levels of statistical significance for the main effects as well as all interactions are shown. Grain size of the wheel appears to have no significant effect on P.C. To keep the analysis within a practical size, only the statistically significant main effects and their statistically significant first order interactions were considered. Those are :

| | |
|---|---|
| 1. Main Effects | |
| a. Coolant, B, | Figure 51 |
| b. Depth of Cut, C, | Figure 52 |
| c. Table Speed, D, | Figure 53 |
| d. Cross Feed, E | Figure 54 |
| 2. First Order Interaction | |
| a. Coolant by Cross Feed, BE, | Figure 55 |
| b. Depth of Cut by Table Speed, CD, | Figure 56 |
| c. Depth of Cut by Cross Feed, CE | Figure 57 |
| d. Table Speed by Cross Feed, DE | Figure 58 |

The mean values used to plot these figures are listed in Table 18, Appendix B.

Figure 51 indicates that the use of coolant reduced P.C. as indicated by the ratio of P.C. means:

$$\text{P.C. ratio} = \frac{896.69}{956.46} \times 100 = 93.7\ \%$$

or a reduction of 6.3 %.

## TABLE XI

## ANALYSIS OF VARIANCE II NET POWER CONSUMPTION

| Source of variation | d.f. | SS | MS | F-Ratio | P |
|---|---|---|---|---|---|
| Total | 539 | 218,212,262.04 | | | |
| Main Plots | | | | | |
| R | 2 | 25,377.87 | 12,688.94 | | |
| A | 1 | 98,145.19 | 98,145.19 | 14.08 | NS |
| RA(Error-a-) | 2 | 13,940.09 | 6,970.05 | | |
| Subplot Treatments | | | | | |
| B | 1 | 482,406.67 | 482,406.67 | 42.2975 | .005 |
| C | 4 | 40,862,390.74 | 10,215,597.69 | 895.7061 | .005 |
| D | 2 | 87,470,898.15 | 43,735,449.07 | 3,834.7350 | .005 |
| E | 2 | 59,181,753.43 | 29,590,876.71 | 2,594.5354 | .005 |
| A B | 1 | 163,977.96 | 163,977.96 | 14.3776 | .005 |
| A C | 4 | 496,141.85 | 124,035.46 | 10.8754 | .005 |
| A D | 2 | 1,311,312.59 | 655,656.30 | 57.4881 | .005 |
| A E | 2 | 263,190.65 | 131,595.32 | 11.5383 | .005 |
| B C | 4 | 13,685.93 | 3,421.48 | .3000 | NS |
| B D | 2 | 45,813.33 | 22,906.67 | 2.0084 | NS |
| B E | 2 | 259,200.28 | 129,600.14 | 11.3634 | .005 |
| C D | 8 | 7,477,087.04 | 934,635.88 | 81.9491 | .005 |
| C E | 8 | 3,695,610.93 | 461,951.37 | 40.5040 | .005 |
| D E | 4 | 6,258,826.30 | 1,564,706.57 | 137.1938 | .005 |

TABLE XI (CONTINUED)

| Source of variation | d.f. | SS | MS | F-Ratio | P |
|---|---|---|---|---|---|
| A B C | 4 | 24,265.56 | 6,066.39 | .5319 | NS |
| A B D | 2 | 42,044.81 | 21,022.41 | 1.8432 | NS |
| A B E | 2 | 172,626.76 | 86,313.38 | 7.5680 | .005 |
| A C D | 8 | 1,139,511.48 | 142,438.94 | 12.4890 | .005 |
| A C E | 8 | 773,887.59 | 96,735.95 | 8.4818 | .005 |
| A D E | 4 | 1,349,517.41 | 337,379.35 | 29.5815 | .005 |
| B C D | 8 | 155,677.41 | 19,459.68 | 1.7062 | NS |
| B C E | 8 | 211,730.74 | 26,466.34 | 2.3205 | .025 |
| B D E | 4 | 44,658.89 | 11,164.72 | .9788 | NS |
| C D E | 16 | 959,707.96 | 59,981.75 | 5.2591 | .005 |
| A B C D | 8 | 104,803.33 | 13,100.42 | 1.1486 | NS |
| A B C E | 8 | 124,953.33 | 15,619.17 | 1.3695 | NS |
| A B D E | 4 | 32,606.30 | 8,151.57 | .7147 | NS |
| A C D E | 16 | 499,889.07 | 31,243.07 | 2.7394 | .005 |
| B C D E | 16 | 220,314.26 | 13,769.64 | 1.2073 | NS |
| ABCDE | 16 | 176,109.44 | 11,006.84 | .9650 | NS |
| Error(b) | 356 | 4,060,207.55 | 11,405.08 | | |

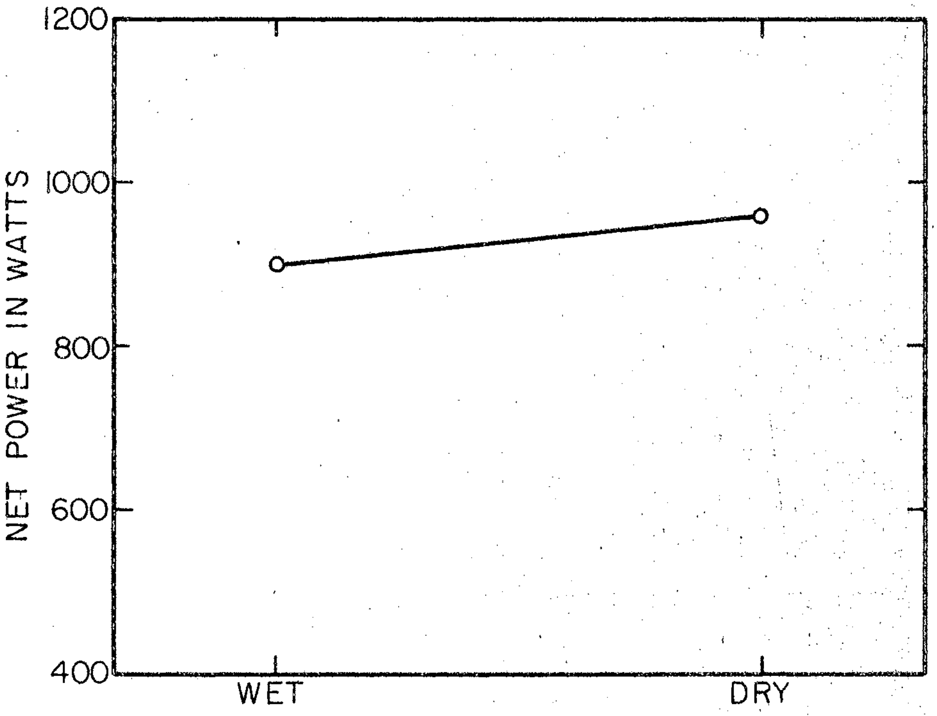


Figure 51 - Main Effect Coolant II (b)

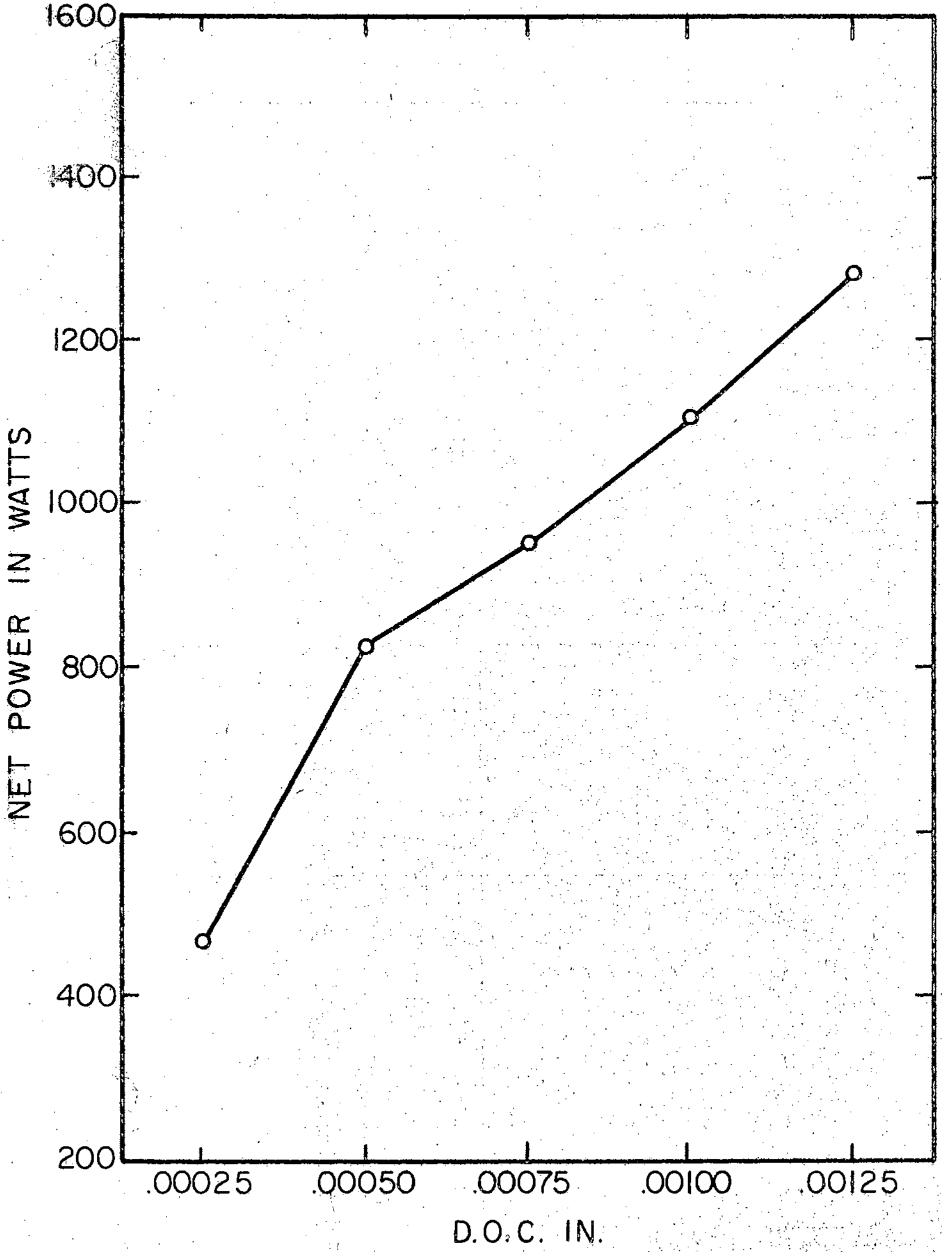


Figure 52. Main Effect Depth of Cut II (C).

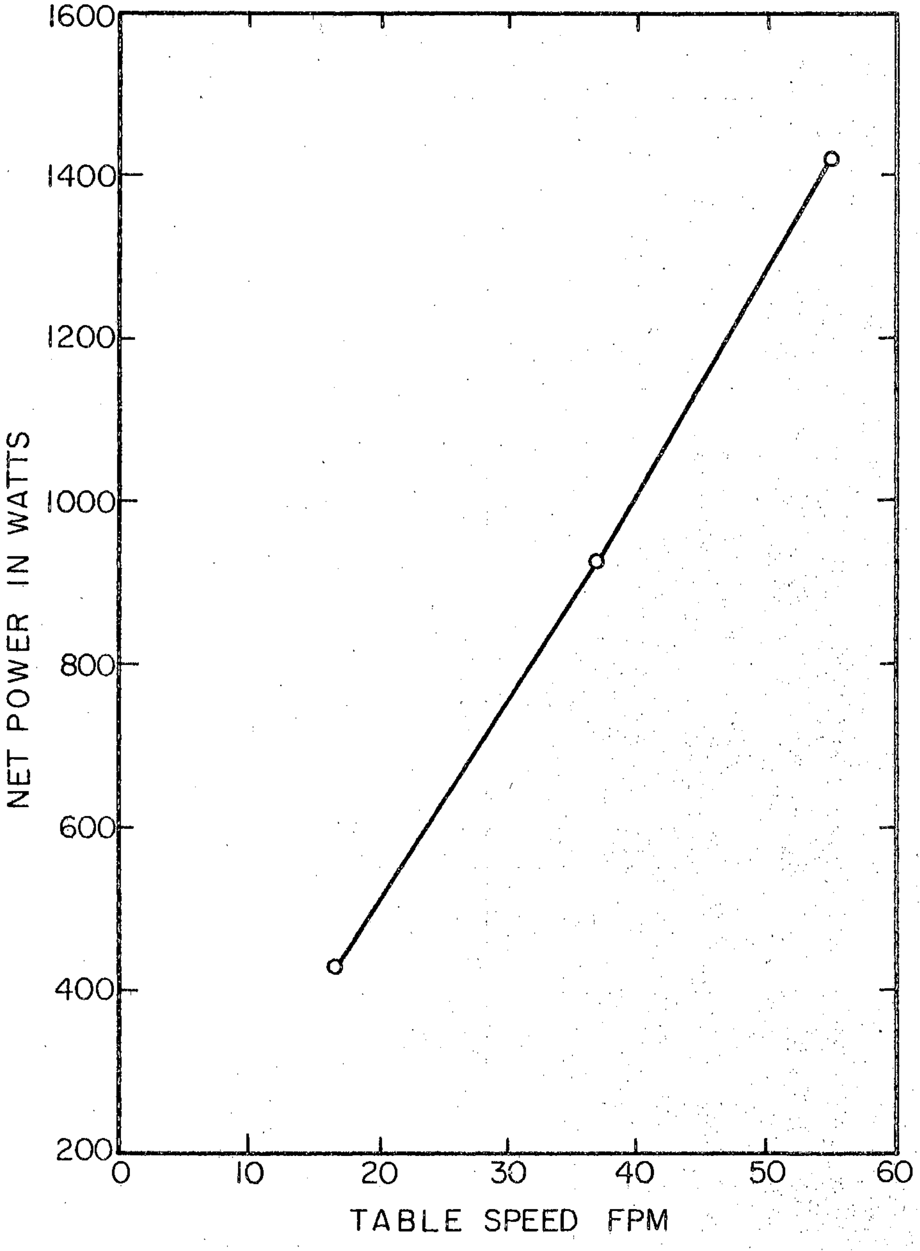


Figure 53. Main Effect Table Speed II (D)

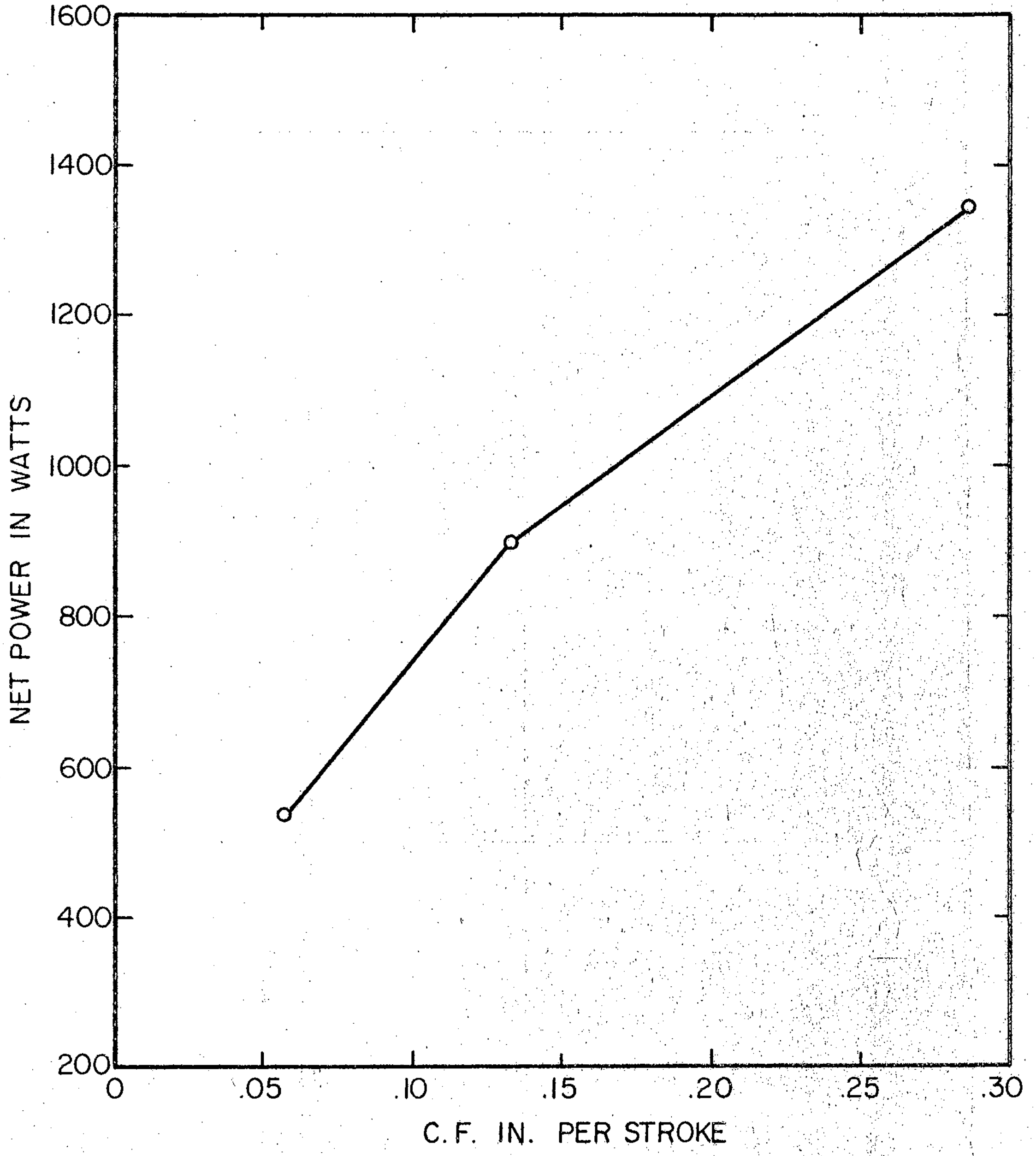


Figure 54. Main Effect Cross Feed II (E)

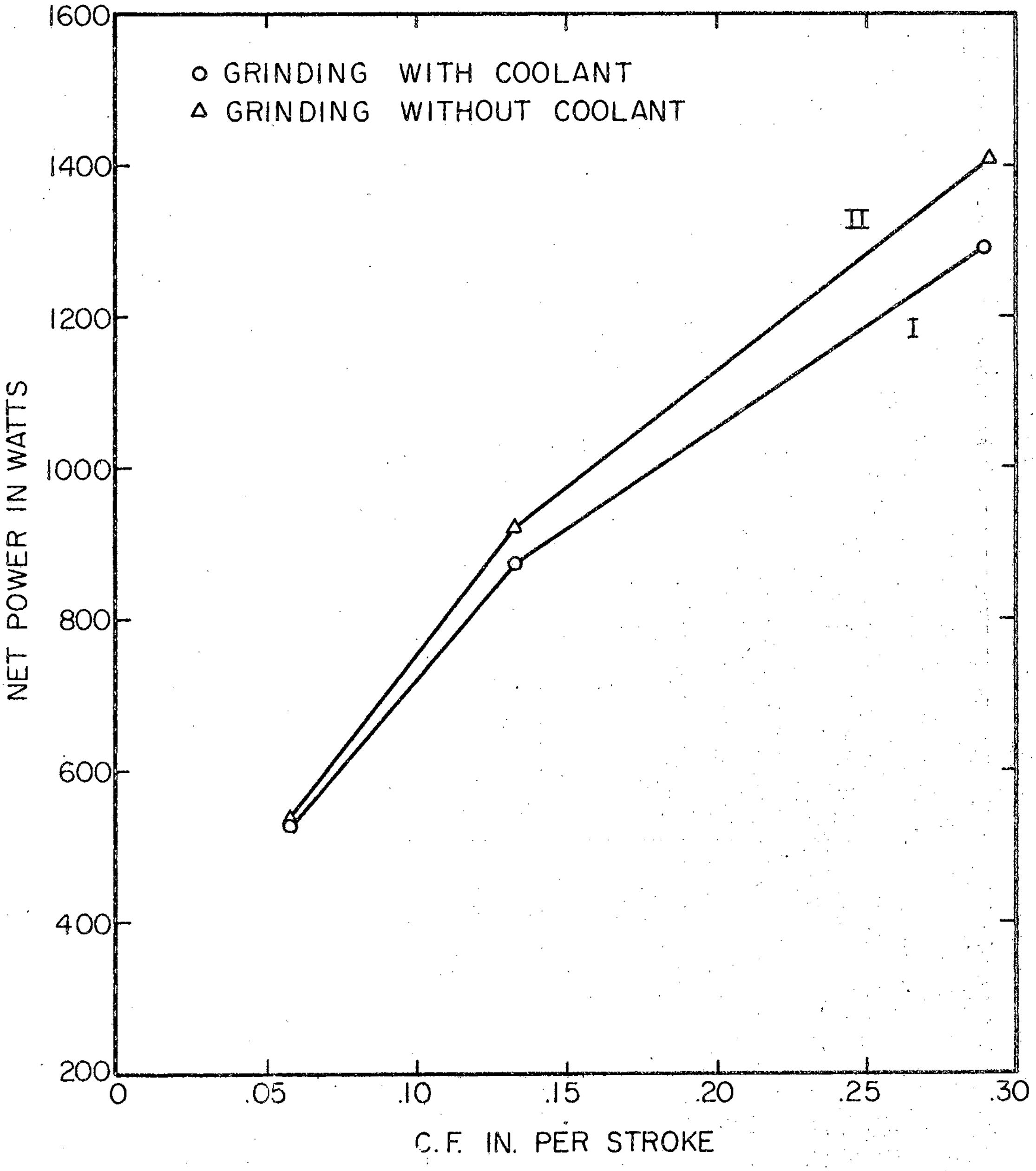


Figure 55. Interaction Coolant by Cross Feed II (BE)

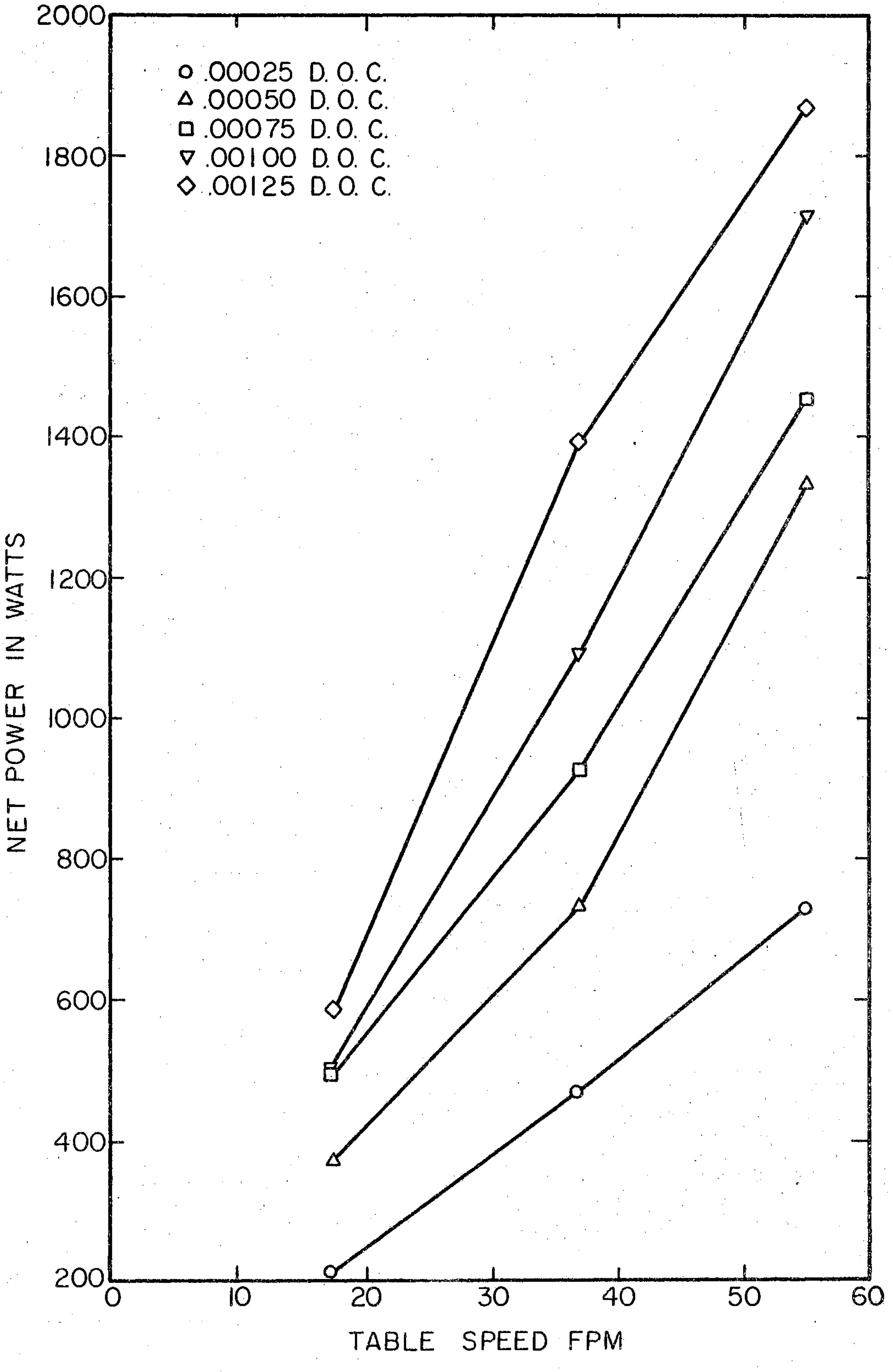


Figure 56. Interaction D.O.C. by T.S. II (CD)

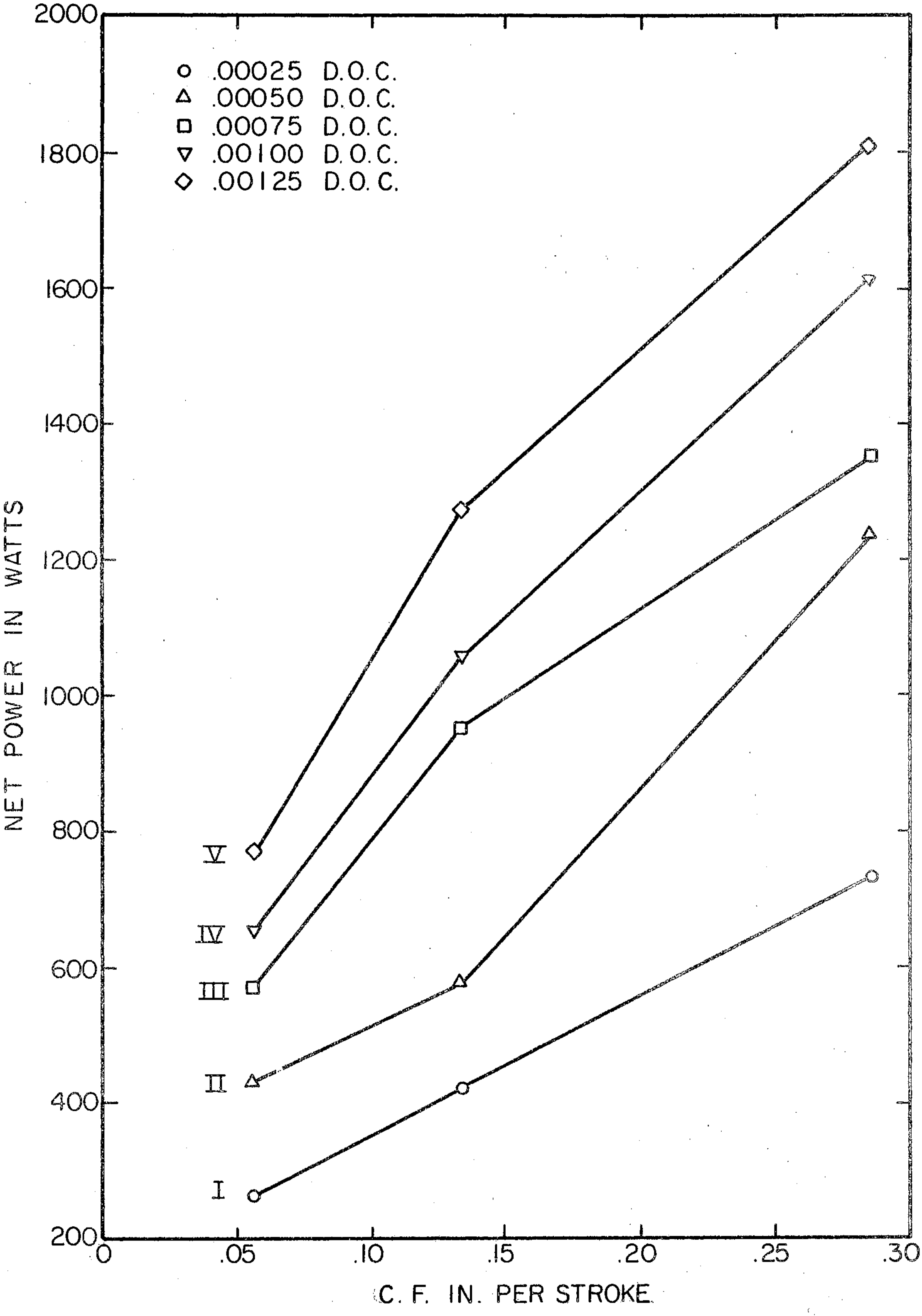


Figure 56. Interaction D.O.C. by C.F
II (CE)

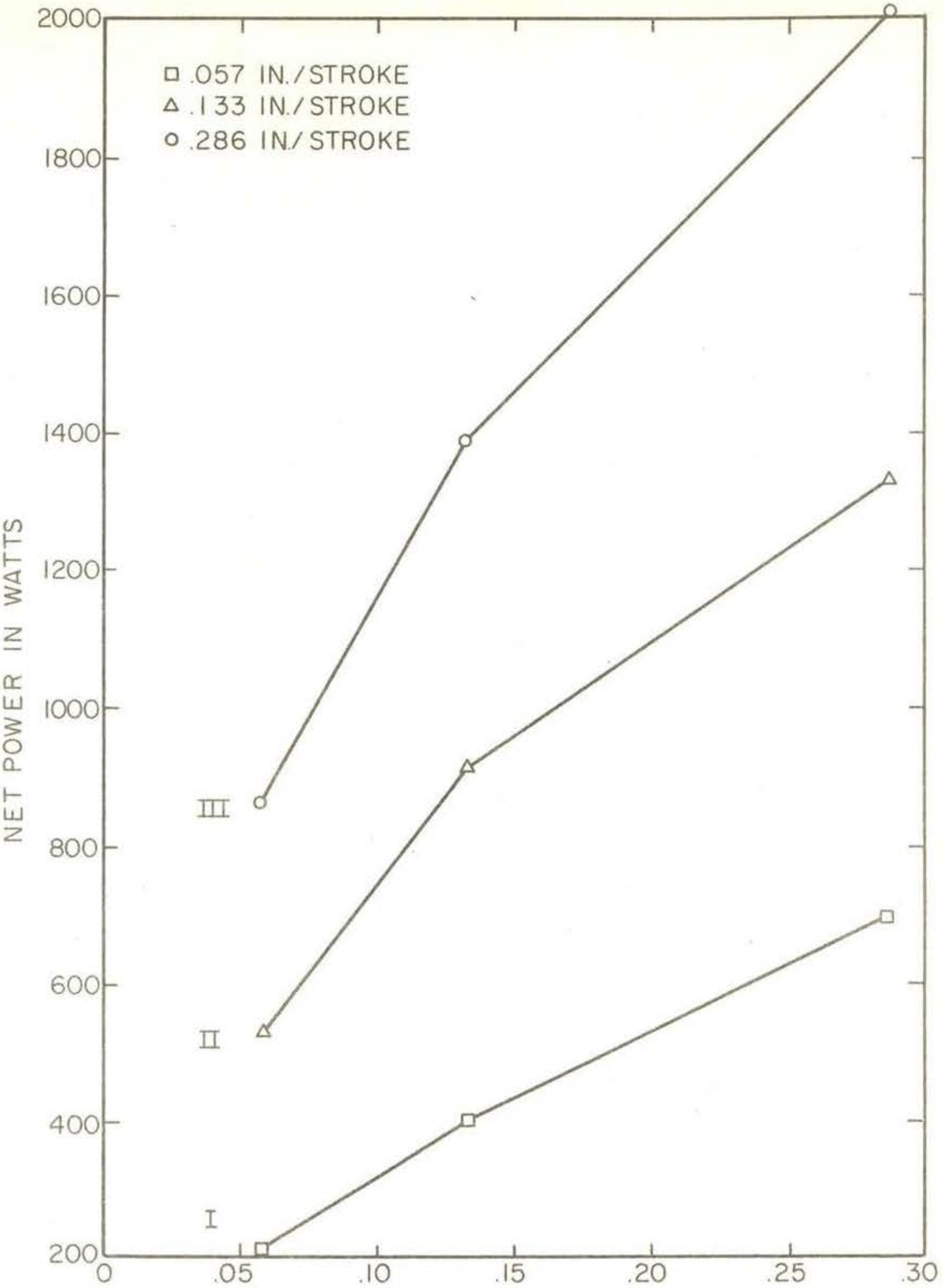


Figure 58. Interaction T.S. by C.F.
II (DE)

Figure 52 indicates that P.C. increased as D.O.C. is increased. The rate of increase is higher in the range of .00025 to .0005 in. than in the range of .0005 to .00125 in. The average rate is 810.56 watts per .001 in.

$$\Delta \text{ P.C.} = 810.56 \times \Delta \text{ (D.O.C.) Watts}$$

where $\Delta$ (D.O.C.) is expressed in thousands of an inch.

It is seen from Figure 53 that P.C. increases as T.S. is increased, at an average rate of:

$$\text{Rate} = \frac{985.83}{38} = 25.94$$

$$\Delta \text{ P.C.} = 25.94 \times \Delta \text{ (T.S.) watts}$$

where $\Delta$ T.S. has units of FPM.

It is seen from Figure 54 that P.C. increases with increasing C.F., at an average rate of:

$$\text{Rate} = \frac{809.52}{.223} = 3630.1$$

$$\Delta \text{ P.C.} = 3630 \times \Delta \text{ (C.F.) watts}$$

with $\Delta$ (C.F.) expressed in in. per stroke.

It is seen from Figure 55 that the use of coolant is more effective in reducing power consumption at higher levels of C.F.

Figures 54, 55 and 56 verify the conclusions of the previous paragraphs; namely that P.C. increases with the increase of D.O.C., T.S. and C.F. The rates of increase are different, from one factor to another, and from one level to another for the same factor.

## Relation Between Power Consumption
## and D.O.C., T.S., and C.F.

Mathematical relations are developed in this section to estimate P.C. while grinding with or without coolant. The independent variables used in these relations are D.O.C., T.S., C.F., Table 12. The previous analysis showed that grain size of the wheel has no effect on P.C. It was found from the study of graphs (51-58) that the responses could be linearly related. The response equation considered for each wheel was in the following multiple linear regression form:

$$\text{P.C.} = B_o + B_1 X_1 + B_2 X_2 + B_3 X_3 \ldots \quad (5\text{-}5)$$

where $B_o$, $B_1$, $B_2$, $B_3$ are constants

P.C. = Power consumption in watts,

$X_1$ = D.O.C. in .001 in.,

$X_2$ = T.S. in FPM., and

$X_3$ = C.F. in in./stroke.

Since the higher levels of P.C. concern this study most, the multiple linear regression equations were calculated using the highest 20 rates of metal removal. The equations for grinding with and without coolant, respectively, are as follows:

$$\text{P.C.} = -1226.2 + 853.2\ X_1 + 27.8\ X_2 + 2528\ X_3 \quad (5\text{-}6)$$

and

$$\text{P.C.} = -1268.3 + 829.1\ X_1 + 29.2\ X_2 + 4032\ X_3 \quad (5\text{-}7)$$

# TABLE XII

## RATE OF METAL REMOVED w.r.t., P.C. D.O.C., T.S., AND C.F.

| R.O.M.R. Cu.in/min | P.C. in Watts | | $X_1$ D.O.C. .001 in. | $X_2$ T.S. FPM | $X_3$ C.F. in./str. |
|---|---|---|---|---|---|
| | Wet | Dry | | | |
| .0029 | 54.17 | 78.33 | 0.25 | 17 | .057 |
| .0058 | 169.17 | 212.50 | 0.50 | 17 | .057 |
| .0063 | 350.00 | 266.67 | 0.25 | 37 | .057 |
| .0068 | 177.50 | 200.00 | 0.25 | 17 | .133 |
| .0087 | 258.33 | 257.00 | 0.75 | 17 | .057 |
| .0094 | 375.00 | 450.00 | 0.25 | 55 | .057 |
| .0116 | 208.33 | 258.33 | 1.00 | 17 | .057 |
| .0127 | 333.33 | 350.00 | 0.50 | 37 | .057 |
| .0136 | 316.67 | 341.67 | 0.50 | 17 | .133 |
| .0145 | 308.33 | 241.67 | 1.25 | 17 | .057 |
| .0146 | 350.00 | 441.67 | 0.25 | 17 | .286 |
| .0148 | 408.33 | 491.67 | 0.25 | 37 | .133 |
| .0188 | 741.67 | 783.33 | 0.50 | 55 | .057 |
| .0190 | 508.33 | 458.33 | 0.75 | 37 | .057 |
| .0204 | 425.00 | 491.67 | 0.75 | 17 | .133 |
| .022 | 600.00 | 691.67 | 0.25 | 55 | .133 |
| .0253 | 658.33 | 700.00 | 1.00 | 37 | .057 |
| .0272 | 416.67 | 433.33 | 1.00 | 17 | .133 |
| .0282 | 1016.67 | 916.67 | 0.75 | 55 | .057 |
| .0292 | 650.00 | 533.33 | 0.50 | 17 | .286 |
| .0296 | 600.00 | 750.00 | 0.50 | 37 | .133 |
| .0316 | 791.67 | 883.33 | 1.25 | 37 | .057 |

## TABLE XII (CONTINUED)

| R.O.M.R. Cu.in/min | P.C. in Watts | | $X_1$ D.O.C. .001 in. | $X_2$ T.S. FPM | $X_3$ C.F. in./str. |
|---|---|---|---|---|---|
| | Wet | Dry | | | |
| .0317 | 525.00 | 775.00 | 0.25 | 37 | .286 |
| .0340 | 600.00 | 616.67 | 1.25 | 17 | .133 |
| .0376 | 1016.67 | 1050.00 | 1.00 | 55 | .057 |
| .0438 | 616.67* | 908.33 | 0.75 | 17 | .286 |
| .0440 | 1266.67 | 1400.00 | 0.50 | 55 | .133 |
| .0444 | 950.00 | 983.33 | 0.75 | 37 | .133 |
| .0470 | 1166.67 | 1183.33 | 1.25 | 55 | .057 |
| .0472 | 1100.00 | 1183.33 | 0.25 | 55 | .286 |
| .0583* | 850.00* | 858.33 | 1.00 | 17 | .286 |
| .0582 | 1050.00 | 1083.33 | 1.00 | 37 | .133 |
| .0635 | 1166.67 | 1216.67 | 0.50 | 37 | .286 |
| .0660 | 1416.67 | 1483.33 | 0.75 | 55 | .133 |
| .0729 | 866.67* | 900.00 | 1.25 | 17 | .286 |
| .0740 | 1366.67 | 1400.00 | 1.25 | 37 | .133 |
| .0880 | 1650.00 | 1683.33 | 1.00 | 55 | .133 |
| .0944 | 1808.33 | 2000.00 | 0.50 | 55 | .286 |
| .0952 | 1266.67* | 1400.00 | 0.75 | 37 | .286 |
| .1100 | 1850.00 | 1850.00 | 1.25 | 55 | .133 |
| .127 | 1516.67* | 1550.00 | 1.00 | 37 | .286 |
| .1416 | 1850.00 | 2033.33 | 0.75 | 55 | .286 |
| .1587 | 1866.67 | 2033.33 | 1.25 | 37 | .286 |
| .1888 | 2350.00 | 2533.33 | 1.00 | 55 | .286 |
| .2360 | 2516.67 | 2683.33 | 1.25 | 55 | .286 |

To check the accuracy of the predicted values by these equations, Index D was calculated for the ten treatments of the maximum rates of metal removal, where Index D is defined as:

$$\text{Index D} = \frac{\text{Estimated P.C.}}{\text{Average experimental P.C.}} \times 100\ \%$$

It is seen from Table 13 that the maximum over-estimation was 14 %, and the maximum under-estimation was 8.6 %.

The estimated values were plotted against the actual experimental results. Figures 59 and 60 show these points for grinding with and without coolant, respectively. Linear regression lines relating the estimated value (Y) to the actual value (X) were developed. The linear regression line for grinding with coolant is,

$$Y = 401 + .768\ X$$

and for grinding without coolant is,

$Y = 462 + .7566\ X$ where

$Y$ = the estimated value of P.C. in watts, and

$X$ = the actual value of P.C. in watts.

These lines were drawn and compared to the ideal line

$$Y = X.$$

The relatively small variations found in Table 13, and the comparison of the ideal line and the regression lines shown in figures 59 and 60 prove the multiple linear regression model (5-5) to be satisfactory for this type of operation.

## TABLE XIII

## INDEX D VALUES

| $X_1$ | $X_2$ | $X_3$ | Grinding with coolant | | | Grinding w/o coolant | | |
|---|---|---|---|---|---|---|---|---|
| D.O.C. .001 in | T.S. FPM | C.F. in/str. | Avg. P.C. | Est. P.C. | Index D | Avg. P.C. | Est. P.C. | Index D |
| 1.25 | 37 | .133 | 1366 | 1325 | 97 % | 1400 | 1361 | 97.2% |
| 1.00 | 55 | .133 | 1650 | 1597 | 96.8% | 1683 | 1698 | 101 % |
| .50 | 55 | .286 | 1808 | 1721 | 95.2% | 2000 | 1901 | 95 % |
| .75 | 37 | .286 | 1267 | 1440 | 113.7% | 1400 | 1564 | 111.7% |
| 1.25 | 55 | .133 | 1850 | 1820 | 98.4% | 1850 | 1905 | 103 % |
| 1.00 | 37 | .286 | 1516 | 1653 | 109 % | 1550 | 1771 | 114 % |
| .75 | 55 | .286 | 1850 | 1935 | 104.6% | 2033 | 2109 | 103.7% |
| 1.25 | 37 | .286 | 1866 | 1866 | 100 % | 2033 | 1978 | 97.3% |
| 1.00 | 55 | .286 | 2350 | 2148 | 91.4% | 2533 | 2316 | 91.4% |
| 1.25 | 55 | .286 | 2516 | 2361 | 93.8% | 2683 | 2522 | 94 % |

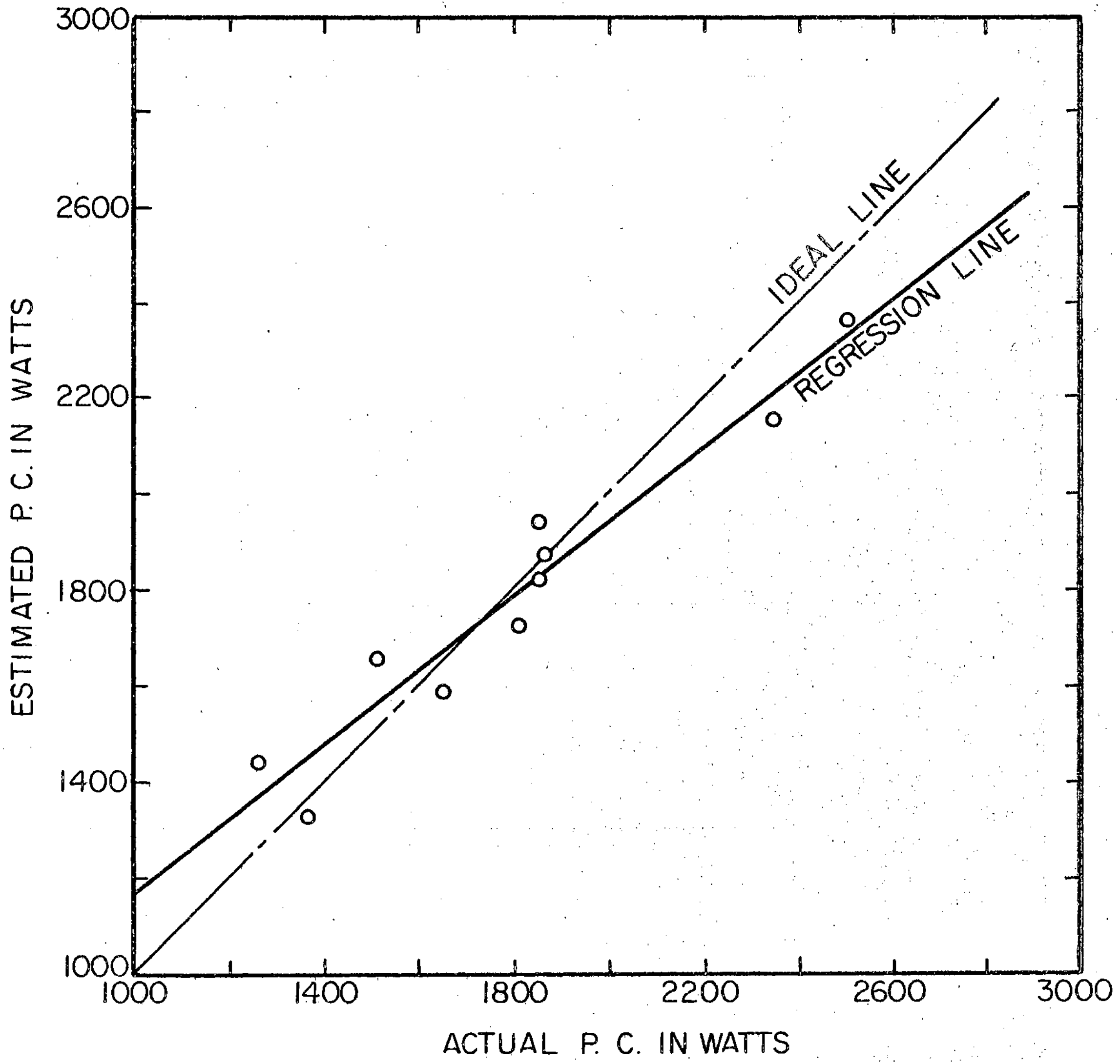


Figure 59. Actual P.C. vs. Estimated P.C. While Grinding with Coolant

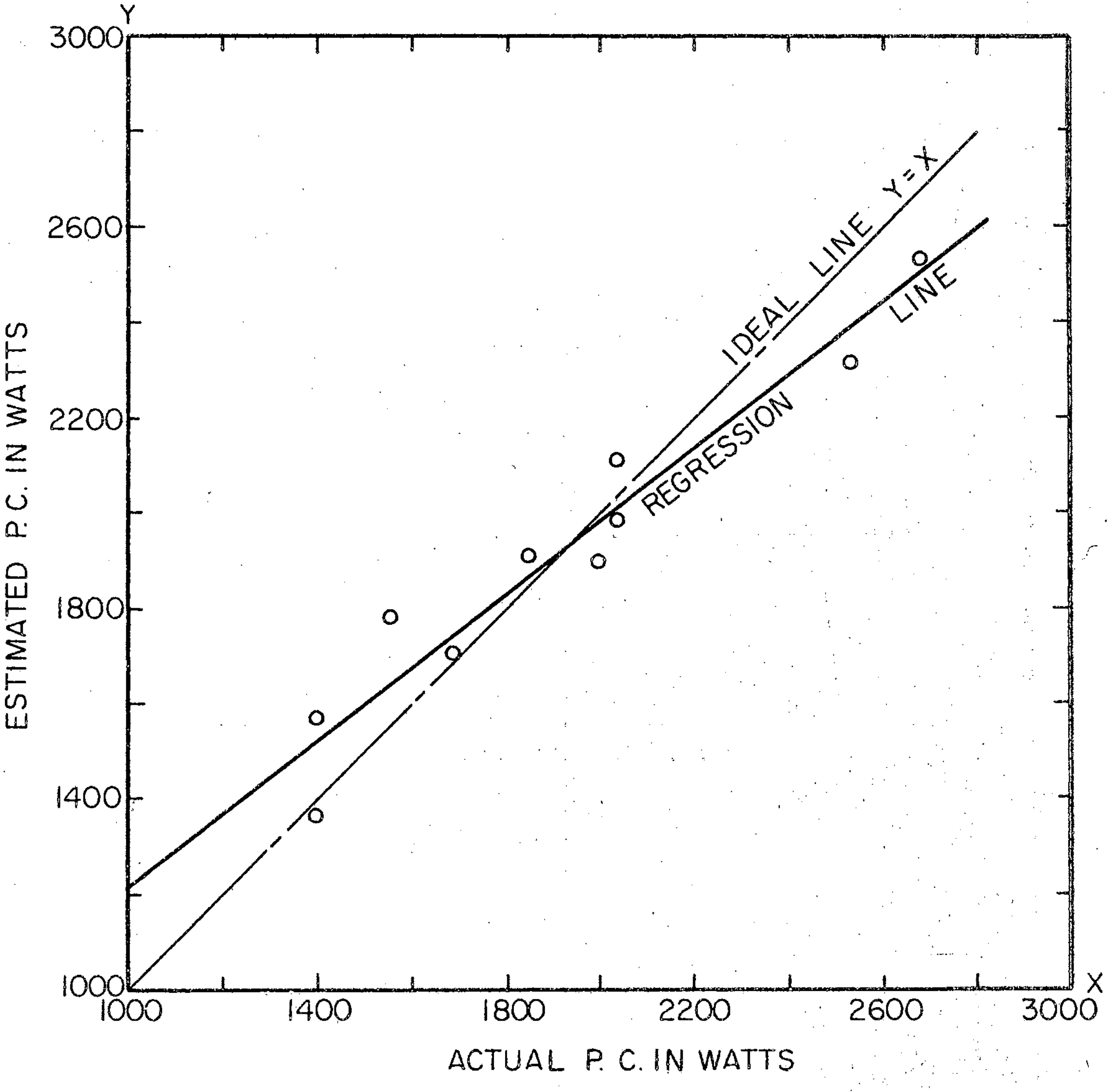


Figure 60. Actual P.C. Vs. Estimated P.C. While Grinding Without Coolant

According to Chapter Three, a maximum increase of 26 % in P.C. was reached due to wheel deterioration. For safety considerations it is recommended here that the estimated P.C. be multiplied by a safety factor of 1.35. This 35 % increase compensates for the under-estimation and deterioration of the wheel.

## Relation Between Power Consumption and R.O.M.R.

Rates of metal removal were calculated according to equation 5-4 for each treatment. Table 12 indicates the rate of metal removal and the corresponding P.C. while grinding with and without coolant at the different levels of D.O.C., T.S., and C.F. In Figure 61 the average values of P.C. are plotted against R.O.M.R. It is seen that with proper adjustment of the variable factors levels, larger R.O.M.R. could be achieved while maintaining lower P.C. as seen at points 1, 2, 3, 4, and 5. For example, point 3 shows a reduction of 39 % in P.C. while increasing R.O.M.R. by .006 cu. in. per min. The study of these points reveals that these points were achieved by using the highest allowable level of C.F., and the lowest level of T.S., while increasing the D.O.C. gradually to the maximum allowable level; i.e. the least factor to be increased is the T.S. to reach the R.O.M.R. desired.

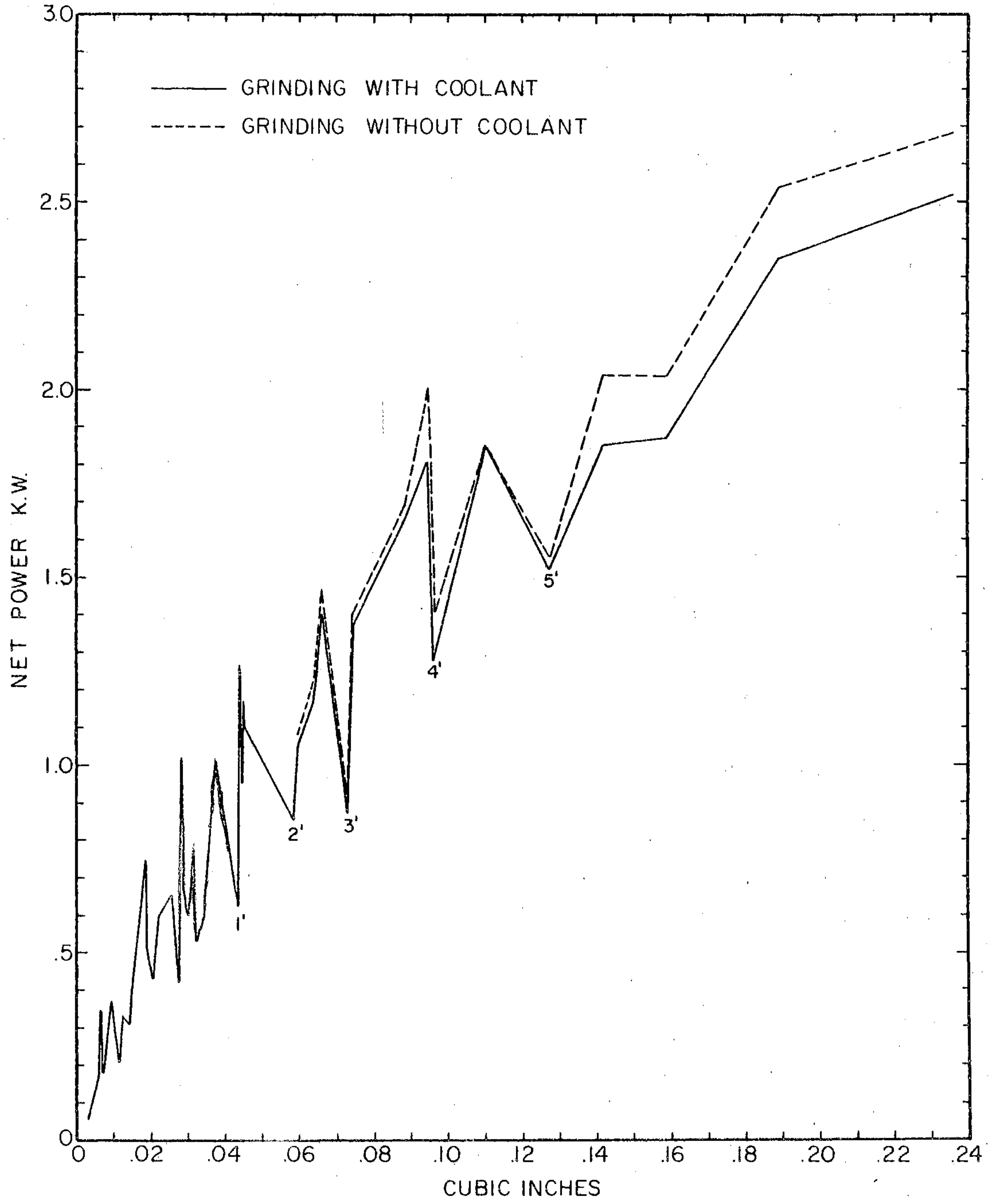


Figure 61. Rate of Metal Removal vs. P.C.

# CHAPTER VI

## SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This research project was primarily concerned with the presentation of quantitative information about the semi-finishing surface grinding process. It was felt that this machining process is lacking documented factual data. Part One investigated tool life. Part Two studied the effect of sparkout on S.R. Part Three determined, by physical experimentation and subsequent statistical analysis, the interdependence of various grinding variables and their interacting effect on first cut S.R. and P.C. Since the study was broken into three parts, the summary will follow the same general plan.

### Tool Life

Tool life was studied in terms of both total metal removed and area machined for various depths. The two depths of cut that gave the largest amount of metal removed, 3.2 and 3.08 cu. in., were .001 and .00075 in. The minimum amount of metal removed, 2.5 cu. in., was reported at .00025 in. D.O.C., but at the same time it gave the maximum area machined, 10000 sq. in. The use of a finer grain size wheel, 60 instead of 46, reduced tool life by a ratio of .755 at D.O.C., .0015 in. The microscopic inspection revealed the development of no cracking during the tool life period.

The depths of cut that give the maximum tool life, and the effect of grain size on this amount should be studied with other kind of wheels before the results of this part can be generalized for the total range of the semifinishing grinding process.

## Sparkout Effect

The presented results indicate that sparkout effect on S.R. is insignificant compared to the time consumed in it. Five sparkout passes reduced S.R. 11.5 % for the AA46 H8 V40 grinding wheel, and 19.2 % for the AA60 H8 V40 grinding wheel. Proper adjustment of the independent variables, D.O.C, T.S., and C.F. reduced S.R. 20 % while increasing R.O.M.R. Using a finer grain size wheel, 60 instead of 46, reduced S.R. 30.3 % without any sparkout. Literature reviewed reports that courser grain size wheels are more efficient in removing relatively large amount of materials.

It is indicated, here, in order to achieve a better quality surface finish, that at the last cut of the workpiece, the levels of D.O.C., T.S., and C.F. should be adjusted to give the lowest S.R. at a reasonable R.O.M.R. This should be done without removing the workpiece or applying any sparkout. This is desired as to save the time of readjusting the workpiece on finer grain size wheel or consuming a relatively long time in sparkout. If the R.O.M.R. is very low or the S.R. resulted does not meet the specified limit, the workpiece should be removed and finished on a finer grain size wheel.

The sparkout effect should be studied with other kinds of wheels before the statements presented can be generalized for other grinding processes.

## Effect of Grain Size, Coolant, D.O.C., T.S., and C.F. on Surface Roughness and Power Consumption

### Grain Size

Grain size has a considerable effect on S.R. and an insignificant effect on P.C. The ratio of the average surface roughness values was approximately equal to the inverse of the mesh number of the abrasive grains. Using the 60 grain size wheel instead of the 46 wheel reduced S.R. by a ratio of 0.697. The incremental rates of change, when considered with the other independent variables, were more uniform for the A60 wheel than for the A46 wheel.

### Coolant

The use of coolant reduced S.R. by 3.1 % and P.C. by 6.3 %. The use of coolant has a greater effect at lower levels of D.O.C., and T.S. than the higher ones. Its use also considerably reduced the temperature of the workpiece and affected the polish of the surface finished. Although microscopic inspection revealed the development of no cracks while grinding without coolant, it was reported in the literature reviewed that the surface integrity of the material ground was greatly affected.

It is recommended here to use coolant unless conditions oblige the other case. In such case, small depths of cut and table speeds should be applied.

### Depth of Cut, Table Speed, and Cross Feed

The rates of change in S.R. and P.C. due to the incremental increase in each of the independent variables, D.O.C., T.S., and C.F. are given in Table 14.

Table -14- Rates of Change in S.R. and P.C.

| Source of Variation | Rates of Change | |
|---|---|---|
| | S.R. microinches/unit | P.C. Watts/unit |
| D.O.C. (.001 inc.) | 7.020 | 810.56 |
| T.S. (FPM) | .280 | 25.94 |
| C.F. (in./stroke) | 46.240 | 3630.10 |

Mathematical relations were developed relating S.R. and P.C. to D.O.C., T.S, and C.F. The multiple linear regression form proved to be satisfactory for this type of operation. The S.R. equations for the AA46 H8 V40 and AA60 H8 V40 grinding wheels are given respectively:

$$S.R. = 6.132 + 10.51 X_1 + .375 X_2 + 61.3 X_3 \qquad (5\text{-}2)$$

$$S.R. = 9 + 4.8 X_1 + .225 X_2 + 29.5 X_3 \qquad (5\text{-}3)$$

The P.C. equation for grinding with and without coolant are:

$$P.C. = -1226.2 + 853.2 X_1 + 27.8 X_2 + 2528 X_3 \qquad (5\text{-}6)$$

$$P.C. = -1268.3 + 829.1 X_1 + 29.2 X_2 + 4032.6 X_3 \qquad (5\text{-}7)$$

where

P.C. in watts

S.R. in microinches

$X_1$ = D.O.C. in .001 in.

$X_2$ = T.S. in FPM.

$X_3$ = C.F. in in./stroke

Rates of metal removal were calculated for the different combinations of the independent variables.

$$R.O.M.R. = .012 X_1 X_2 X_3 \text{ cu. in./min.} \qquad (5\text{-}4)$$

The ultimate desire would be to maximize the R.O.M.R. while minimizing S.R. and P.C.

It was found that the first case could be achieved by increasing the D.O.C. to the maximum allowable level, and then consecutively increasing the C.F. and T.S. The best conditions for P.C. could be achieved by using the highest allowable level of C.F., and the lowest level of T.S., while increasing the D.O.C. gradually to the maximum allowable level; i.e., the least factor to be increased is the T.S. to reach the R.O.M.R. desired.

## Areas for Further Research

Further investigations pointed out by this research are:

1. The study of the effect of grain size, hardness and structure of the wheel, and hardness of metal machined on tool life.
2. Relating tool life to D.O.C., T.S., C.F., and, consequently, R.O.M.R.
3. The effect on tool life resulting from intermittent and continuous grinding.
4. The possibility of using P.C. measurements to indicate tool life for certain wheel-workpiece combinations.
5. The effect of sparkout on S.R. with respect to grain size, hardness, and structure of the wheel.
6. Effect of sparkout on dimensional tolerances of workpiece.

7. Studies which will yield further knowledge about the effect of grain size, structure of the wheel, and hardness of metal machined on S.R. This should lead to the development of mathematical relations relating S.R. to grain size, structure hardness of metal machined, as well as the other independent variables that effect the grinding process.
8. Although microscopic inspection revealed the development of no cracking at the levels used in this research, further investigation is needed to ascertain the effect on the surface integrity of the machined metal.
9. The effect of P.C. on the surface integrity of the workpiece.
10. The development of a mathematical algorithm to determine the best combination of the independent variables levels such that the R.O.M.R. is maximized while maintaining S.R. and P.C. at the minimum possible levels.

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# APPENDIX A

# DATA RECORDING

## TABLE XV

## DATA SHEET
(Tool Life)

Depth of cut = .001 inches

| No. | Number of cuts = 5 | Number of sparkout = 5 | Surface finish range |
|---|---|---|---|
| 1 | IIIII | IIIII | 40 - 60 |
| 2 | IIIII | IIIII | 45 - 50 |
| 3 | IIIII | IIIII | 43 - 50 |
| 4 | IIIII | IIIII | 50 - 52 |
| 5 | IIIII | IIIII | 45 - 50 |
| 6 | IIIII | IIIII | 47 - 54 |
| 7 | IIIII | IIIII | 45 - 52 |
| 8 | IIIII | IIIII | 45 - 55 |
| 9 | IIIII | IIIII | 48 - 53 |
| 10 | IIIII | IIIII | 45 - 50 |
| 11 | IIIII | IIIII | 50 - 57 |
| 12 | IIIII | IIIII | 51 - 57 |
| 13 | IIIII | IIIII | 52 - 57 |
| 14 | IIIII | IIIII | 46 - 50 |
| 15 | IIIII | IIIII | 40 - 50 |
| 16 | IIIII | IIIII | 45 - 64 |
| 17 | IIIII | IIIII | 65 - 73 |
| 18 | IIIII | IIIII | 70 - 85 |

## TABLE XVI

S.R. and P.C.

Replication No. :1 Set No. :2 G.Wh. :AA46H8V40

| No. | Treatments Sequence | Surface Roughness microinches | Power Consumption Watts |
|---|---|---|---|
| 1 | 2432 | | |
| 2 | 2321 | | |
| 3 | 1222 | | |
| 4 | 2112 | | |
| 5 | 1511 | | |
| 6 | 1533 | | |
| 7 | 2431 | | |
| . | .... | | |
| . | .... | | |
| . | .... | | |
| . | .... | | |
| . | .... | | |
| 90 | .... | | |

# APPENDIX B

# MEAN VALUES USED TO PLOT THE GRAPHS IN CHAPTER V

## TABLE XVII

## SURFACE FINISH ANALYSIS

| G.S. | Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|---|
| | | A Effect | | | |
| 46 | . | . | . | . | 37.07 |
| 60 | . | . | . | . | 25.83 |
| | | B Effect | | | |
| . | wet | . | . | . | 30.95 |
| . | dry | . | . | . | 31.95 |
| | | C Effect | | | |
| . | . | .00025 | . | . | 27.63 |
| . | . | .0005 | . | . | 30.81 |
| . | . | .00075 | . | . | 30.97 |
| . | . | .00100 | . | . | 33.19 |
| . | . | .00125 | . | . | 34.65 |
| | | D Effect | | | |
| . | . | . | 17 | . | 26.49 |
| . | . | . | 37 | . | 30.72 |
| . | . | . | 55 | . | 37.13 |
| | | E Effect | | | |
| . | . | . | . | .057 | 26.47 |
| . | . | . | . | .133 | 30.83 |
| . | . | . | . | .286 | 37.06 |

TABLE XVII (CONTINUED)

| G.S. | Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|---|
| | | A B Interaction | | | |
| 46 | wet | . | . | . | 36.40 |
| 46 | dry | . | . | . | 37.73 |
| 60 | wet | . | . | . | 25.50 |
| 60 | dry | . | . | . | 26.16 |
| | | A C Interaction | | | |
| 46 | . | .00025 | . | . | 32.07 |
| 46 | . | .00050 | . | . | 36.24 |
| 46 | . | .00075 | . | . | 36.43 |
| 46 | . | .0010 | . | . | 39.46 |
| 46 | . | .00125 | . | . | 41.13 |
| 60 | . | .00025 | . | . | 23.19 |
| 60 | . | .00050 | . | . | 25.19 |
| 60 | . | .00075 | . | . | 25.70 |
| 60 | . | .001 | . | . | 26.93 |
| 60 | . | .00125 | . | . | 28.17 |
| | | A D Interaction | | | |
| 46 | . | . | 17 | . | 31.32 |
| 46 | . | . | 37 | . | 35.70 |
| 46 | . | . | 55 | . | 44.18 |
| 60 | . | . | 17 | . | 21.67 |
| 60 | . | . | 37 | . | 25.74 |
| 60 | . | . | 55 | . | 30.09 |

TABLE XVII (CONTINUED)

| G.S. | Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|---|
| | | A E Interaction | | | |
| 46 | . | . | . | .057 | 30.39 |
| 46 | . | . | . | .133 | 36.36 |
| 46 | . | . | . | .286 | 44.46 |
| 60 | . | . | . | .057 | 22.54 |
| 60 | . | . | . | .133 | 25.30 |
| 60 | . | . | . | .286 | 29.66 |
| | | B C Interaction | | | |
| . | wet | .00025 | . | . | 26.50 |
| . | wet | .0005 | . | . | 30.00 |
| . | wet | .00075 | . | . | 30.43 |
| . | wet | .001 | . | . | 33.48 |
| . | wet | .00125 | . | . | 34.35 |
| . | dry | .00025 | . | . | 28.76 |
| . | dry | .0005 | . | . | 31.61 |
| . | dry | .00075 | . | . | 31.52 |
| . | dry | .001 | . | . | 32.91 |
| . | dry | .00125 | . | . | 34.94 |
| | | B D Interaction | | | |
| . | wet | . | 17 | . | 25.64 |
| . | wet | . | 37 | . | 30.10 |
| . | wet | . | 55 | . | 37.11 |
| . | dry | . | 17 | . | 27.34 |

TABLE XVII (CONTINUED)

| G.S. | Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|---|
| . | dry | . | 37 | . | 31.34 |
| . | dry | . | 55 | . | 37.16 |
| | | C D Interaction | | | |
| . | . | .00025 | 17 | . | 24.00 |
| . | . | .00025 | 37 | . | 26.19 |
| . | . | .00025 | 55 | . | 32.69 |
| . | . | .0005 | 17 | . | 27.25 |
| . | . | .0005 | 37 | . | 30.61 |
| . | . | .0005 | 55 | . | 34.56 |
| . | . | .00075 | 17 | . | 26.89 |
| . | . | .00075 | 37 | . | 29.36 |
| . | . | .00075 | 55 | . | 36.67 |
| . | . | .00100 | 17 | . | 26.72 |
| . | . | .001 | 37 | . | 32.89 |
| . | . | .001 | 55 | . | 39.97 |
| . | . | .00125 | 17 | . | 27.61 |
| . | . | .00125 | 37 | . | 34.56 |
| . | . | .00125 | 55 | . | 41.78 |
| | | C E Interaction | | | |
| . | . | .00025 | . | .057 | 23.69 |
| . | . | .00025 | . | .133 | 27.14 |
| . | . | .00025 | . | .286 | 32.06 |
| . | . | .0005 | . | .057 | 25.44 |

# TABLE XVII (CONTINUED)

| G.S. | Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|---|
| . | . | .0005 | . | .133 | 30.03 |
| . | . | .0005 | . | .286 | 36.94 |
| . | . | .00075 | . | .057 | 27.11 |
| . | . | .00075 | . | .133 | 30.11 |
| . | . | .00075 | . | .286 | 35.69 |
| . | . | .001 | . | .057 | 27.72 |
| . | . | .001 | . | .133 | 32.50 |
| . | . | .001 | . | .286 | 39.36 |
| . | . | .00125 | . | .057 | 28.36 |
| . | . | .00125 | . | .133 | 34.36 |
| . | . | .00125 | . | .286 | 41.22 |
| | | D E Interaction | | | |
| . | . | . | 17 | .057 | 22.97 |
| . | . | . | 17 | .133 | 26.22 |
| . | . | . | 17 | .286 | 30.30 |
| . | . | . | 37 | .057 | 25.88 |
| . | . | . | 37 | .133 | 29.70 |
| . | . | . | 37 | .286 | 36.58 |
| . | . | . | 55 | .057 | 30.55 |
| . | . | . | 55 | .133 | 36.57 |
| . | . | . | 55 | .286 | 44.28 |

## TABLE XVIII

## POWER CONSUMPTION ANALYSIS

| Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|
| B Effect | | | | |
| wet | . | . | . | 896.69 |
| dry | . | . | . | 956.46 |
| C Effect | | | | |
| . | .00025 | . | . | 473.24 |
| . | .0005 | . | . | 813.33 |
| . | .00075 | . | . | 958.80 |
| . | .001 | . | . | 1103.70 |
| . | .00125 | . | . | 1283.80 |
| D Effect | | | | |
| . | . | 17 | . | 435.28 |
| . | . | 37 | . | 923.33 |
| . | . | 55 | . | 1421.11 |
| E Effect | | | | |
| . | . | . | .057 | 535.47 |
| . | . | . | .133 | 899.25 |
| . | . | . | .286 | 1345.00 |

TABLE XVIII (CONTINUED)

| Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|
| | | BE Interaction | | |
| wet | . | . | .057 | 530.44 |
| wet | . | . | .133 | 872.94 |
| wet | . | . | .286 | 1286.67 |
| dry | . | . | .057 | 540.50 |
| dry | . | . | .133 | 925.56 |
| dry | . | . | .286 | 1403.33 |
| | | CD Interaction | | |
| . | .00025 | 17 | . | 216.94 |
| . | .00025 | 37 | . | 469.44 |
| . | .00025 | 55 | . | 733.33 |
| . | .00050 | 17 | . | 370.56 |
| . | .00050 | 37 | . | 736.11 |
| . | .00050 | 55 | . | 1333.33 |
| . | .00075 | 17 | . | 495.83 |
| . | .00075 | 37 | . | 927.78 |
| . | .00075 | 55 | . | 1452.78 |
| . | .0010 | 17 | . | 504.17 |
| . | .0010 | 37 | . | 1093.06 |
| . | .0010 | 55 | . | 1713.89 |
| . | .00125 | 17 | . | 588.89 |
| . | .00125 | 37 | . | 1390.28 |
| . | .00125 | 55 | . | 1872.22 |

TABLE XVIII (CONTINUED)

| Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|
| | | CE Interaction | | |
| . | .00025 | . | .057 | 262.36 |
| . | .00025 | . | .133 | 428.19 |
| . | .00025 | . | .286 | 729.17 |
| . | .0005 | . | .057 | 431.67 |
| . | .0005 | . | .133 | 779.17 |
| . | .0005 | . | .286 | 1229.17 |
| . | .00075 | . | .057 | 572.22 |
| . | .00075 | . | .133 | 958.33 |
| . | .00075 | . | .286 | 1345.83 |
| . | .001 | . | .057 | 648.61 |
| . | .001 | . | .133 | 1052.78 |
| . | .001 | . | .286 | 1609.72 |
| . | .00125 | . | .057 | 762.50 |
| . | .00125 | . | .133 | 1277.78 |
| . | .00125 | . | .286 | 1811.11 |
| | | DE Interaction | | |
| . | . | 17 | .057 | 206.42 |
| . | . | 17 | .133 | 401.92 |
| . | . | 17 | .286 | 697.50 |
| . | . | 37 | .057 | 530.00 |
| . | . | 37 | .133 | 908.33 |
| . | . | 37 | .286 | 1331.67 |

TABLE XVIII (CONTINUED)

| Coolant | D.O.C. | T.S. | C.F. | Mean |
|---|---|---|---|---|
| . | . | 55 | .057 | 870.00 |
| . | . | 55 | .133 | 1387.50 |
| . | . | 55 | .286 | 2005.83 |

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