# THE MACHINING OF INCONEL X-750 STEEL, USING COPPER SULPHATE ELECTROLYTE AS A CUTTING FLUID



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by

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## ABSTRACT

The cutting forces, tooth wear, surface finish, and cutting power were observed for 3/8" x 3" side and face milling cutters at two levels of cutting feed (2.1 and 7.7 in./min.) and depth of cut (.005" and .010") while cutting Inconel X-750.

The investigation briefly traces the development of metal cutting science, pointing out some of the fallacies which have persisted to the present day. It proposes that metal to metal contact, and hence wear, be reduced by using a soft metal as a solid lubricant. Copper was eventually selected because of its electro-negative nature when compared to high speed steel. Copper is deposited continuously on the face and flank of milling cutter teeth by an electrolyte solution of copper sulphate and sulphuric acid.

The experiment consisted of three phases, the first being of a preliminary nature to evaluate the feasibility of depositing copper by this process. Measurements of cutting power for various depths of cut, using a mild steel work piece, were compared to those obtained using a soluble oil, with favourable results for the copper sulphate electrolyte.

Evaluation of the electrolyte cutting fluid to determine its optimum composition by measuring cutter wear, cutting forces, cutting power, and the surface finish of the work piece, follows. Observations of surface finish and cutting power produced no positive result. However, the other variables indicated a preference for a copper sulphate concentration of 11.1 grams per litre of solution and a sulphuric acid concentration of 5 millilitres of concentrated acid per litre of solution.

The determination of the optimum composition of the copper based electrolyte was achieved using Inconel X-750 as the work piece material. This grade of Inconel was also used in the third and final phase of the experiment, which was to compare the electrolyte cutting fluid with a conventional sulphurized cutting oil. Results of this comparison indicate that the conventional cutting oil, Veedol AFTON #8 containing 1.8 to 2 per cent sulphur, produces less wear at a lower wear rate than the copper sulphate solution.

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Of the many people who contributed to the study, two require special mention, my brother, John, for his advice and assistance during the initial stages of the experiment, and my wife, Lorraine, for her part in the typing of this Thesis.

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# CHAPTER 1

# INTRODUCTION

## 1.10 GENERAL

Metal cutting, the shaping of metals and metal alloys by gouging, chipping, tearing, or other mechanical means of parting one molecule from another, has been an integral part of the development of industrialized society from its beginnings in the Industrial Revolution through to the present day. Now, as then, the problem of finding a metal cutting tool hard enough and/or tough enough to cut other metals without displaying excessive wear is still with us. The use of carbon steels during the 1800's has largely given way to the use of medium alloy steels and high speed steels, depending on the character of the metal to be cut.

The study or science of metal cutting has, since the 19th century, followed two main paths, one analytical, the other experimental. One of the earliest analytical studies was made in 1877 by THIME in ERNST (1951) who analyzed the geometry of chip formation, pointing out that the chip was formed by a process of displacement of the metal ahead of the tool on a plane running from the cutting edge to the work surface.

ZVORYKIN (1893) in ERNST (1951) and BRIKS (1896) in ERNST (1951), made investigations into the geometry of the metal cutting process and its accompanying plastic deformation. However, they failed to provide an analysis that could be used in the investigation of the tool/work piece in terms of cutting forces, cutting speeds, etc. Contempories of ZVORYKIN, BRIKS and HERMANN in ERNST (1951) and again, in 1907, LINDNER in ERNST (1951) made similar analyses of the cutting process, but again they were concerned mainly with mechanical factors controlling chip size and shape.

It appears that the approach taken by these researchers was all but abandoned until recent years and that metal cutting research began to develop along practical and empirical lines. The lack of proper instrumentation and techniques lead to many false conclusions which, for some reason, have persisted to the present time. One individual of particular note is MALLOCK in ERNST (1951) who in 1881 discovered in his observations of chip formation that the application of a cutting fluid considerably reduced the rubbing friction between chip and tool. However, his interpretation that the shear angle was practically constant was in error. Another error of a more serious nature was made by REULEAUX in ERNST (1951) in 1900 when he reported the presence of a crack preceding the cutting tool tip from which he concluded that the cutting process was similar to the splitting of wood by an axe.

In 1901 KICK in ERNST (1951) pointed out the fallacy of this model and used the work of THIME to prove his point. However, the relative stature of REULEAUX discounted this criticism and the fallacy has persisted until quite recently.

In 1906 ROSENHAIN in ERNST (1951), with the aid of a microscope, showed that plastic deformation and not fracture was the main mechanism of chip formation. Further work by this researcher combined with that of STURNEY in ERNST (1951) in 1925 reinforced these early observations. The latter studies were performed by the sectioning of chips. The presence of plastic flow was further confirmed by HERBERT in ERNST (1951) with a study of the hardness of partially formed chips in which he showed the presence of severe work hardening.

One other early researcher of note is BOSTON in ERNST (1951) who reported in 1930 on photographs of the actual process of chip formation. His report contained many observations of what actually occurs at the cutting edge of the tool.

Unfortunately for the science of metal cutting, these early researchers failed to correlate their findings with careful analytical studies, so that most of the current knowledge that is used in selecting the proper cutting tool for the job in hand has been developed during and subsequent to the Second World War.

Carbon, and in some cases high speed tool steels, are no match for today's space age materials with yield strengths as high as 200,000 psi, as displayed by some maraging steels. This has resulted in the invention of a variety of tool materials during the past two or three decades.

SHAW (1958) proposes five factors which a tool material should possess: hot hardness, wear resistance, toughness, low friction and last but by no means least, favourable cost. Unfortunately, the perfect tool, exhibiting all of these characteristics in sufficient degree, has not been invented so that, at the present level of technology, tool material is selected on the basis of the type of material to be cut and the nature of the cutting process i.e., rough cut, finish cut or surface grinding. Carbon steels, low alloy steels and high carbon steels of various grade and composition are still extensively used, but to these have been added cemented carbides, silicon carbides, cermet, and the hardest substance of all, diamond. The last four are generally costly but are noted for their wear resistance. In some cases one has no choice but to use these tools as cutting fluids have not yet been developed to the point where the cheaper high speed and low alloy tool steels can be used instead.

This immediately leads one to ask, "What cutting fluids?" and "How can an improvement result in a cost saving?" To answer this it is first necessary to ascertain the common denominator which can be used as a criterion for rating all tool materials. There are of course several, but in the final analysis the cost per unit time or per unit volume of metal removed has to be the most important. Not only must we consider the volume of metal removed but also the way in which it is removed. If excessive heat is generated tool failure may occur with the result that excessive cutting power is required to give a poorer surface finish. This leads to the conclusion that to improve the technology of metal cutting is to decrease the cost per cubic inch of metal removed and, by so doing, all other factors being equal, we must increase the life of the cutting tool.

## 1.20 TOOL LIFE CRITERIA AND WEAR

The question now arises, how do we measure tool life and, by life, do we mean the point at which the tool, because of power limitation, simply refuses to cut, or do we mean some arbitrary condition which, when reached, renders the cutting tool inoperative?

Before we can properly answer this question it is necessary to consider the various types of tool failure which can occur. First, there is failure caused by too high a temperature at the cutting tip, making this part of the cutting tool softer than the metal being cut and resulting in tool failure. The second type of failure is obvious in that it is concerned with physical breakage of the cutter tip which sometimes occurs with the harder and more brittle cutting materials. The third and most common type of tool failure is the gradual wearing away of the cutting surfaces of the tool. Current theories of metal cutting action suggest that tool wear is accomplished by the action of the work piece chip rubbing against the face of the tool to form crater wear and the rubbing of the clearance face against the work piece itself. This concept is further clarified by Figure 1.1 which more adequately defines the wear land on the tool flank and crater wear on the tool face.

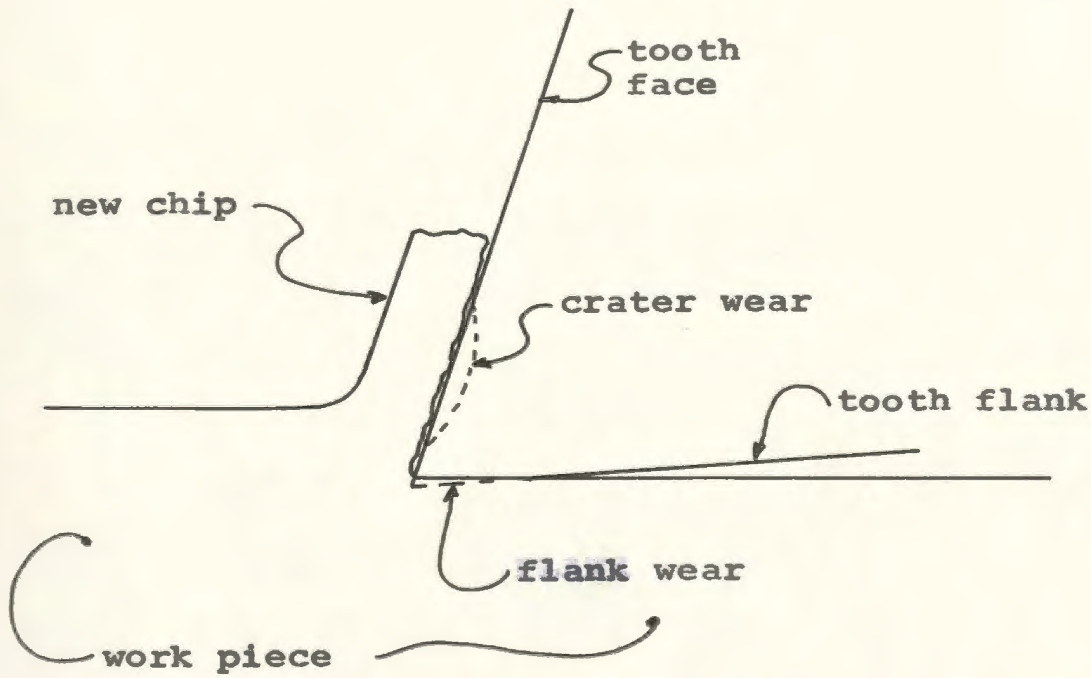


FIG. 1.1 ILLUSTRATION OF TYPICAL TOOL WEAR

Measurement of wear varies from one researcher to another. Certainly the absolute measurement of wear would include the total volume removed from the cutting tool at any given time. However, difficulty in making this measurement has prompted most researchers to measure the wear land only, either by width or area.

This, then, leads us to a tool life criterion based on tool wear. Various methods are used. BRAITHWAITE (1970), for example, suggests that tool flank wear up to .030" could have been used to illustrate his statistical technique instead of the measurement of cutting force. ZLATIN AND KAHLES (1967) mention, "a reasonable cutter life of 200 to 250 inches of work travel". BHATTACHARYYA ET AL (1970) compares tool life results on the basis of .2 m.m. of flank wear.

## 1.30 THE THEORY OF WEAR

We have seen from Figure 1.1 the location of wear on a cutting tool but have not considered the mechanism or mechanisms that create this wear. ARCHARD (1959) based his discussion of the temperatures of rubbing surfaces on the welding together of the asperities present on the surfaces of two metals rubbing together and showed a relationship between rubbing velocity and temperature, and rubbing speed and wear rate with the result that wear rates increase as temperatures increase. WELSH (1964) performed considerable work on wear rates of the rubbing of dry steels under varying load conditions showing that as load increases wear rate increases. He states in his discussion of Part 11, "There can be little doubt that the hardness and state of oxidation of the surfaces are the principal factors controlling the wear rate pattern." Both of these authors have one thing in common. They dealt with conditions where metal to metal contact was present.

Figure 1.2 is a model of the type of welding contact referred to by ARCHARD (1959).

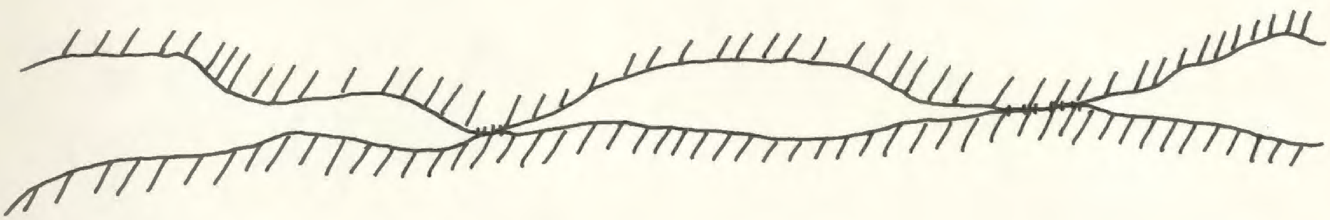

FIG. 1.2 WELDING OF ASPERITIES

Wear occurs where one asperity shears off the softer of the two as illustrated in Figure 1.3.

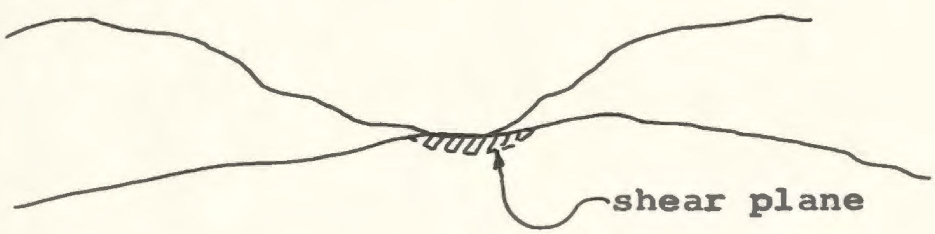


FIG. 1.3 FORMATION OF WEAR PARTICLE

The shaded portion of this illustration eventually becomes loose and forms a wear particle.

A second wear mechanism as discussed by RABINOWICZ (1966), and one that is applicable to the metal cutting process, is the gouging or plowing of large asperities of the harder of the two surfaces creating a wear scar and hence, wear debris.

There is a third wear mechanism which, although not present in cutting operations, is nevertheless worthy of mention. That is "three particle wear", consisting of the formation of iron oxide spheroids between the rubbing surfaces. Formation and existence of these particles is dependent on the surface loading, greatly reducing wear when they are present.

Regardless of the mechanism by which wear takes place, and each is present in most cases, it cannot occur unless and until there is metal-to-metal contact of the cutting tool and the work piece. Therefore, if one is to reduce or eliminate wear, it is necessary to reduce or prevent metal-to-metal contact.

## 1.40 CUTTING FLUIDS AND THEIR APPLICATION

The prime objective of any cutting fluid has to be the prevention of wear which, as we have seen, is synonymous with the prevention of metal to metal contact. Unfortunately, in the cutting process, no method of which the author is aware is available to eliminate metal to metal contact. The best that can be done with existing cutting fluids is to reduce the amount of contact.

In addition to reducing wear, a cutting fluid or lubricant must perform other tasks such as flushing away the chips generated by the cutting process, cooling the tool, etc. MATTHIJSEN and BREKEL (1967) list five requirements for a cutting fluid. These are:-

1. The liquid should be inexpensive.
2. It should not evaporate too quickly.
3. It should be non-toxic.
4. It should be thin-flowing and be a good cutting agent.
5. It should not be harmful either to the human skin or to machines.

Other authors, notably CROXON (1970) and SHAW (1958) list some of the same and other requirements that must be met.[1]

The development of new cutting fluids has been approached from many angles. ACKERMAN (1969) in his classification of metal working fluids, states that since the Second World War there has been a major development in the field of cutting fluid technology, principally in the use of chemical solutions. He goes on to report on a proposed classification consisting of oils, oil base fluids, aqueous emulsions and dispersions, chemical solutions, solid lubricants and miscellaneous.

Aqueous emulsions i.e., oil in water or water in oil cutting fluids are mainly cooling agents. However some fluids listed under this category contain extreme pressure additives. In any event, cooling agents are required to conduct heat away as quickly as possible with the lubrication function, if any, as a secondary effect. This type of cutting fluid

[1]These publications have been cited to illustrate the non-uniformity and, to a certain extent, the complexity, of the subject.

is quite acceptable in that it meets most of the requirements of a cutting fluid. However, as cutting pressures and forces increase and hence tool temperature, a point is reached where this type of fluid breaks down. Failure occurs when the amount of heat generated is sufficient to maintain a layer of steam between the fluid and the tool. This greatly reduces the cooling action and inhibits any lubricating action which may be present in the cutting process, resulting in complete metal-to-metal contact.

A second classification, and one in which considerable work seems to have been done, is in the area of cutting oils, with or without additives, which the author shall discuss together with chemical solutions.

Cutting oils are not designed primarily for their cooling action, but to penetrate to the point of the cutting tool during the process of chip formation,[1] and/or to adhere to the surface of the tool before and during the cutting action in an effort to reduce metal to metal contact and hence friction and wear. How well the cutting oil achieves this aim will depend on whether or not the oil is squeezed out or if it can, in fact, penetrate the labyrinth of fine capillaries present during chip formation. The success or failure will of course depend on the machinability of the metal to be cut. A cutting oil which is successful in one application may be a failure in another.

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1 SHAW (1958)

In an attempt to make cutting oils more effective, several additives have been used to increase their lubrication properties. These additives, usually referred to as "Extreme Pressure" or "EP additives", usually take the form of sulphur, chlorine and phosphorous compounds which produce a chemically formed layer between the tool and work piece, so-called boundary layer lubrication. The OWENS and ROBERTS (1967) investigation into the chemical nature of the freshly generated metal surface of the cutting process shows that the selection of additives is greatly enhanced by an understanding of its chemical activity. They also report on the use of iodine as an additive in the cutting of stainless and titanium steels.

Finally, there are the solid lubricants and miscellaneous. Unlike coolants and oils, solid lubricants, whether sprayed on or attached by chemical or electro-chemical means, reduce friction, and hence wear, by presenting to the chip tool interface a soft layer of metal so that the harder of the two surfaces will wear away the softer material leaving the tool material relatively intact and without wear.

OWENS and ROBERTS (1967) and SHAW (1958) report on the use of solid chemicals such as lead sulphide, molybdenum disulphide, graphite, etc. The problem however with solid lubricants, again according to OWENS and ROBERTS (1967), is how to apply them to the normal cutting process in an effective manner.

## 1.50 THE MACHINING OF DIFFICULT-TO-CUT METALS

The machining of difficult-to-cut materials such as titanium and stainless steels has, to a large extent, been approached by the use of cutting oils using EP additives. The selection of these additives depends not only on the tool life but the speeds and feeds attainable for a given depth of cut and the surface finish.

CATT and MILWAIN (1967) state that titanium steels (Inconel X-750) can be cut successfully with high speed steel using EP cutting fluids and that phosphates used as additives showed great promise. However, because of corrosion problems, their experience with milling as reported in this paper was attained using a synthetic soluble fluid at a cutting speed of thirty feet per minute and a feed of one inch per minute. It seems that the low tool/chip contact area combined with the low thermal conductivity of titanium alloys, and the tendency for galling and welding of the metal, result in poor tool life. To prevent this, ZLATIN (1970) recommends the use of active chlorinated oils but warns that this particular additive is suspected of causing chloride embrittlement of the machined surface. Other researchers, notably ZIEGELMEIER (1970) have used chlorine base additives. ZIEGELMEIER refrigerated the coolant with reportedly good experience in cutting Inconel X-750.

One of the drawbacks of chlorinated oils has already been cited. Another is the effect on human skin which makes this additive a hazard to some people. Other additives such as sulphur have been used and, in some cases, a combination of sulphur and chlorine. The use of iodine has already been mentioned. It seems that this additive has the effect of forming a solid lubricant on the surface of the work tool.

SHAW (1958) in his discussion of EP additives, gives the following chemical reactions with respect to cutting oils:

(a) For chlorine

$$R_aCl_b + Fe \qquad FeCl_2 + R_aCl_{b-2}$$

(b) For sulphur

$$R_cS_d + Fe \qquad FeS + R_cS_{d-1}$$

To summarize, at this point it can briefly be said that the importance of the chemical nature of the cutting fluid at the tool work interface cannot be over stressed in the selection of a cutting fluid, and that the use of solid lubricants should overcome some of the problems that cannot be solved by EP additives. One suspected problem is that EP additives may not be sufficient to prevent metal-to-metal contact at the higher pressures and temperature encountered in cutting titanium alloy steels.

With this in mind it is proposed that a soft metal, specifically copper,[1] be used as a solid lubricant in the

[1]Copper was selected over other soft metals such as lead, tin and zinc because of its ease of application.

milling of Inconel X-750 and that this effort be compared with experience gained from the cutting of the same material under the same conditions using a sulphurized cutting oil.[1]

## 1.60 PREVIOUS WORK

The use of copper in the form of copper sulphate is not new to the machine shop experience, being used extensively for fine layout work and in the lubrication of cutting dies as a solid lubricant. "IRON AGE" (1969) reports the use of an applied layer of titanium carbide to the cutter tip. Tool life was reportedly increased by as much as 500%. However, the thin layer had to be applied before the cutting process commenced. This reference is cited to illustrate the use of applied films to tooth cutting surfaces and should not be construed to mean that the cutting mechanism is the same as for soft metals. In the case of copper, the thin coating wears off quickly. The Japanese[2] solved this problem by continuously adding soft metals such as aluminum, tin and white metal to the teeth of a milling cutter by means of the metal spray technique as illustrated in Figure 1.4.

Other solid lubricants include the use of iodine as already mentioned and the use of lead sulphide, molybdenum disulphide and graphite as reported by ROWE AND WETTON (1969).

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[1] Appendic C page 179

[2] Publication abstract, "MACHINING", describing work being carried out at Toyo University, Japan.

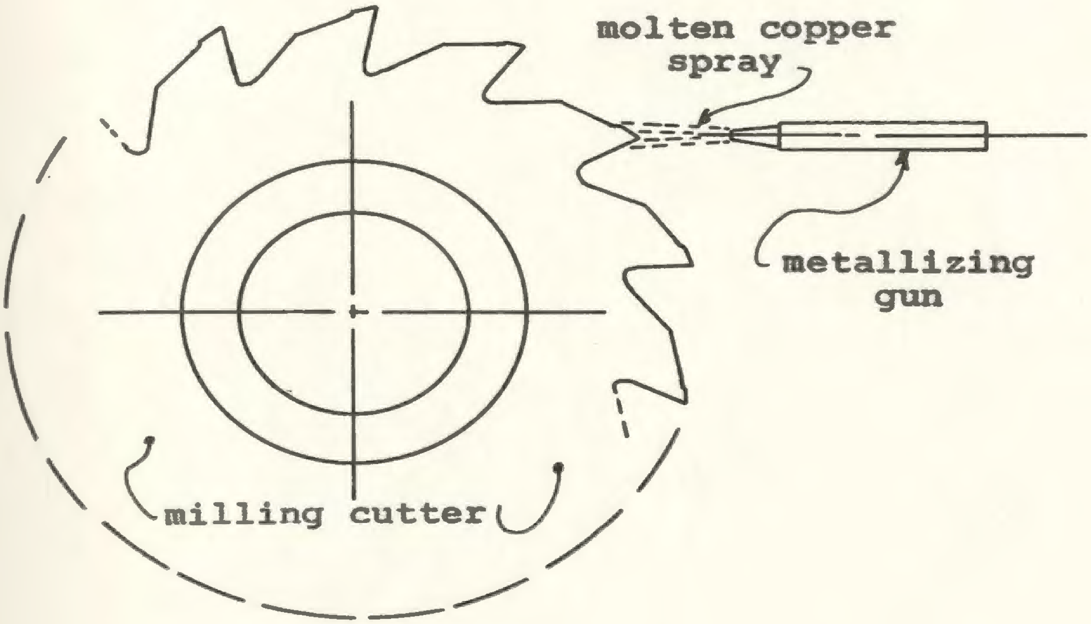


FIG. 1.4 JAPANESE METALLIZING PROCESS

## 1.70 THE DEPOSITION OF COPPER

In the present investigation, it is proposed to take advantage of the chemical nature of the cutting tool steel, copper sulphate, and the clean surface generated at the tool chip interface.

It was at first thought that copper would have to be electroplated on the milling cutter which, in turn, would have to be energized as a cathode with a piece of solid copper mounted close to the tool, both of which would be joined by a continuously flowing copper plating solution which would have the secondary effect of acting as a coolant and a flushing agent. Based on papers by BENNETT (1912) and BENNETT AND BROWN (1913), it was concluded that such an approach was feasible and should produce a strong, adhesive layer of copper. This prompted the search for a suitable plating solution. The literature cites the following:

1. The use of copper sulphate with sodium oxalate and triethanolamine. BROCKMAN AND BREWER (1936).

2. A copper oxalate plating solution. RAMA CHAR AND SHIVARAMAN (1953).

3. Copper sulphate and sulphuric acid. BENNETT (1913).

4. Finally, there is the most efficient of all plating solutions, the copper cyanide solution. BRENNER (1963).

Each plating solution was considered in turn. The first to be eliminated was the copper cyanide bath because of its toxic characteristics. In their turn, all except the copper sulphate and acid solution were eliminated, mainly on the basis of their inefficiency as plating baths.

Further consideration of the problem revealed that it would not be necessary to have a very thick layer of copper on the tooth surfaces; just enough to cover the asperities so that shear in the copper could take place. Shearing, it was estimated, could occur with the presence of a layer a few molecules thick. PAULING (1953) indicates that the electro chemical nature of the copper and iron is such[1] that

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[1]The oxidation potential for solid copper is -0.337 volts, and for solid iron is +.44 volts.

the copper deposits on the cutter teeth as the electrolyte solution flows over the cutter according to the following reaction:

$$CuSO_4 \qquad Cu^{++} + SO_4^{--}$$

$$Cu^{++} + 2e \qquad Cu$$

In addition, the electrolyte acts as a flushing agent and coolant. See Appendix C, page 182

1.80 PILOT STUDY

It was, of course, expected that the copper would very quickly wear off but would just as quickly be reapplied by the continuous flow of copper sulphate solution. To verify this proposition and to form the basis for further investigation, an electrolyte cutting fluid of roughly the same composition as suggested by BENNETT (1913) consisting of 16 per cent copper sulphate, 4 per cent sulphuric acid and 80 per cent water by weight was tried out.

The test was conducted using a 3/8" x 3" milling cutter to mill a mild steel work piece 1/4" x 6" long at 144 feet per minute cutting speed and at a feed of 7.7 inches per minute at varying depths of cut. The results of this test can be seen in Figure 1.5.

This figure is a comparison of cutting power for the electrolyte bath compared to a standard soluble cutting oil with a definite advantage for the copper sulphate-sulphuric acid cutting fluid.

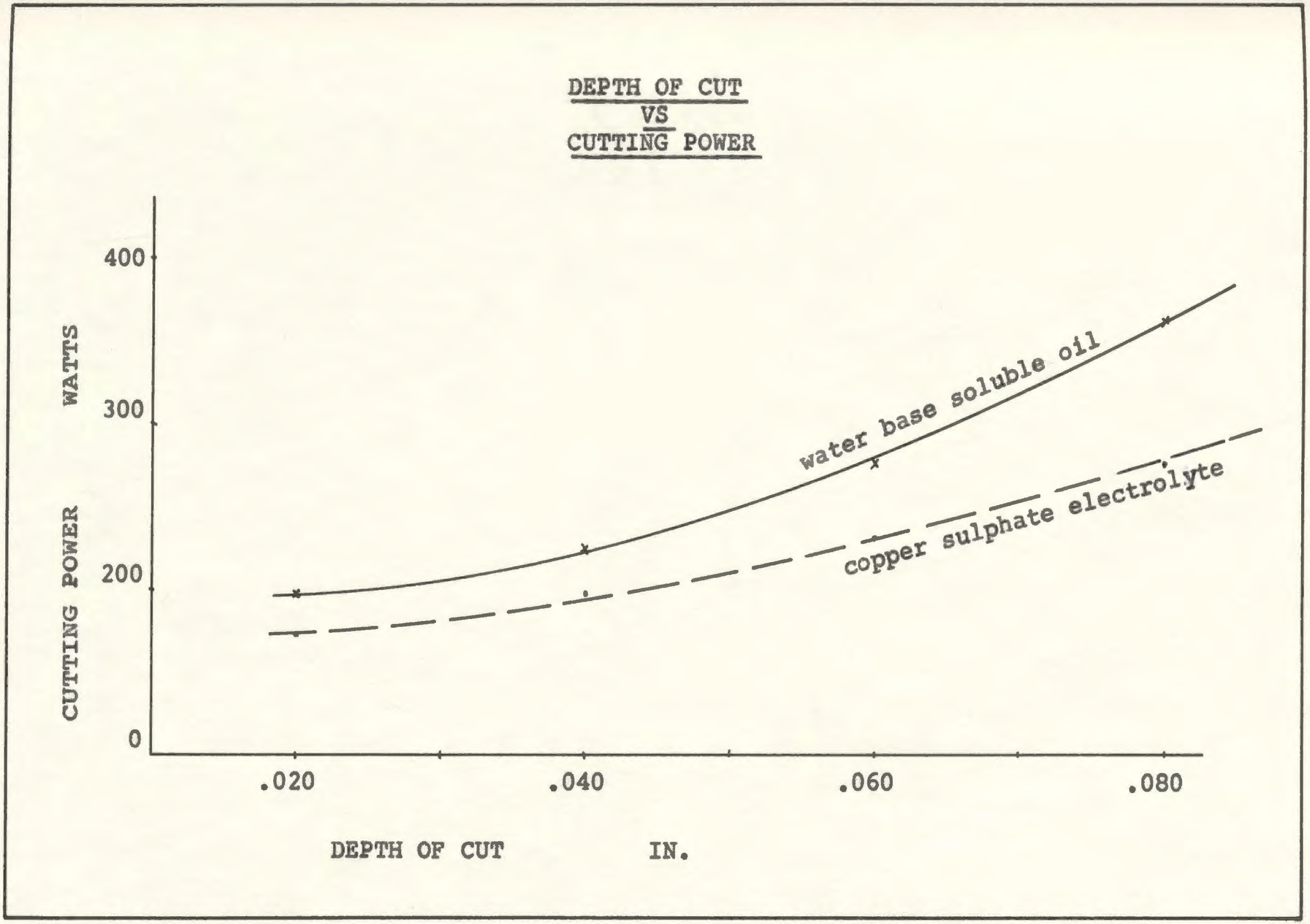


FIG. 1.5 COMPARISON OF POWER CONSUMED WHEN USING WATER BASE SOLUBLE OIL AND COPPER SULPHATE ELECTROLYTE AS CUTTING FLUID

# CHAPTER 2

# OBJECTIVES OF THE STUDY

## 2.10 PURPOSE OF THE STUDY

Recommended methods of studying the metal cutting problem involve the combination of practical experimentation and analytical analysis with the objective of further understanding the cutting process. Other research is directed at understanding the cutting process on a micro level by the study of chip formation. RAMALINGHAM (1968).

Regardless of the type or scope of investigation, the end result is directed either towards the advancement of metal cutting knowledge and/or the selection of cutting tools, cutting fluids and other parameters which will result in the most economical use of the tool.

The purpose of the current study is to observe cutting forces and tool wear using copper sulphate electrolyte as a cutting fluid, and to compare the results, by analytical analysis, with a conventional sulphurized cutting oil when milling Inconel X-750.

## 2.20 DESIRED RESULTS

By taking measurements of all the relevant parameters, within the limitations of the equipment used, of cutting forces, depth of cut, cutting speed, cutting feed and surface finish, to determine the actual relationship between these variables using copper sulphate electrolyte and to compare them with comparable data obtained using a sulphurized cutting oil.

# CHAPTER 3

# EXPERIMENTAL PROCEDURE

## 3.10 STATISTICAL CONTROL

The planning of the experiment necessarily revolves around the method to be used for the statistical evaluation of results. The testing, because of the nature of the experiment, will be divided into three parts.

The initial phase of the experiment will consist of a pilot study which will not be subject to any statistical analysis. Part 1 of the experiment will be concerned with the establishment of the optimum concentration of copper sulphate and sulphuric acid in the cutting fluid. Based on preliminary tests of cutting power versus depth of cut, it was decided that because of the slightly polynomial nature of the curve, a Curvilinear Regression Control and analysis of this part would be sufficient for the determination of these parameters.

The control of Part 11 presented a different problem as its objective was to compare the optimized copper sulphate solution with the results obtained using a sulphurized cutting oil.[1] The controlled variables consisted of depth of

[1] Cutting oil used was Veedol AFTON #8 sulphurized fatty oil containing 1.8 to 2% sulphur.

cut, cutting feed rate and cutting time. Testing at five levels of each variable was considered too time-consuming so that consideration was given to the use of a screening experiment with the aim of eliminating extraneous parameters. After considerable examination, this approach was abandoned as BRAITHWAITE AND HAGUE (1970), indicated that each of the above-mentioned variables was necessary to the experiment. In an effort to reduce the amount of actual testing without compromising the validity of the results, it was decided to conduct tests at two levels for feed rate and depth of cut and at five levels for time, and use a linear regression analysis to evaluate the results.

## 3.20 THE PILOT STUDY

A mild steel work piece was set up in the vice of a #00 Elliott Milling Machine as shown in Figure 3.1, and five cuts at the same depth of cut were made.

The mild steel test piece was 1/4" thick x 6" long and cut by a 3/8" x 3" milling cutter using copper sulphate electrolyte solution as a cutting fluid. The arbor speed was set at 183 RPM for a cutting speed of 144 feet per minute and a feed rate of 7.7 inches per minute.

As this part of the investigation was of a preliminary nature, cutting power only was measured by means of a three phase wattmeter for depths of cut of .020", .040", .060" and .080".

On completion of the testing, the results were compared by plotting a graph of cutting power versus depth of cut.

## 3.30 PART 1 OF THE EXPERIMENT

The determination of optimum values of sulphuric acid and copper sulphate was conducted at 96.4 feet per minute cutting speed, 4.1 inches per minute feed and a depth of cut of .005". Experimentation was carried out on a No. 00 Elliott Milling Machine as shown in Figure 3.1.

FIG. 3.1 ELLIOTT #00 MILLING MACHINE

Figure 3.1 is a photograph of the machine used showing the copper sulphate solution pails on top with hoses feeding electrolyte to the cutting tool. The cutting fluid deposits its copper, cools the cutter, flushes away the chips and is itself carried away through the protective plastic guard surrounding the work piece.[1]

Test specimens were held in the vice and a facing cut taken to establish a surface from which the depth of cut could be measured. A depth of cut of .005" was then set using a .0001" dial gauge and a cut was made at a feed rate of 4.1 inches per minute. This process was repeated five times with readings of cutting power and cutting forces in the x and y directions being taken during each cut. Cutting power was measured at the beginning, the middle and end of each cut by wattmeters, using the two wattmeter method. Forces were recorded automatically. Subsequently, chart recordings were analyzed and averages of three readings for each cut determined. After every five cuts wear on each tooth was measured and recorded as was the surface finish of the test piece.

The cutting fluid used in this phase of experimentation was copper sulphate and sulphuric acid in various concentrations selected more or less at random in the reasonable proximity of standard plating baths. Copper sulphate

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[1]This and other details can be seen in Fig. 4.1

concentration was determined by titration of a standard supply, and sulphuric acid in millilitres of concentrated acid.

The first series of tests was numbered 1 to 20 inclusive. The results were examined and a further series of twenty-three tests, numbered 101 to 123 inclusive, was made. A second evaluation resulted in several of these tests being abandoned because of recorder problems. Other test runs were made using concentrations selected to verify the results of the first two series of tests.

The optimum concentration of copper sulphate and sulphuric acid was determined following a statistical analysis of the results.

## 3.40 PART 11 OF THE EXPERIMENT

The optimum concentrations of copper sulphate and sulphuric acid were established by an analysis of the data collected in Part 1 of the experiment. This solution was used in this part of the experiment as a cutting fluid.

The experiment proceeded by placing the test piece in the vice and taking a facing cut with a cutting tool especially reserved for the purpose. The test cutter was installed and the work raised so as to just touch the rotating cutter. The depth of cut was set using a .0001" dial gauge at either .005" or .010" depending on the test run. This process was repeated for five cuts. Feed rate at two levels, 2.1 inches per minute and 7.7 inches per minute were used with a constant cutting speed of 96.4 feet per minute.

As in Part 1, cutting power was measured by the two wattmeter method and cutting forces were measured on a dual channel strip chart recorder. After every five cuts, wear on each tooth of the cutter was measured as was the surface roughness of the work piece. The above process, using the same cutter, was repeated for a total of five cycles (twenty-five cuts) to form one test. A total of eight tests were made, four using the optimized copper sulphate and sulphuric acid cutting fluid, and four using a sulphurized cutting oil. Cutting forces were measured as in Part 1.

The results of Part 11 were analyzed using statistical techniques and the relative merits of each discussed. The experiment concluded with an examination of the wear land on a typical tooth used with each type of cutting fluid.

## 3.50 TITRATION OF THE COPPER SULPHATE CUTTING FLUID

Tests 1 through 20 were undertaken using a standard solution of copper sulphate. This solution was made as strong as practicable and diluted for the various tests.

Test 5, for example, was performed using a copper sulphate and sulphuric acid solution containing eighty millilitres of the standard solution and zero millilitres of sulphuric acid diluted with water to four litres of solution i.e., a dilution of one part copper sulphate to fifty parts of solution, or 1.50. Other dilutions of 1:40, 1:30, etc., are as shown in Table 3.2.

Before the completion of this series of tests, a representative sample of the standard solution was obtained and titrated with .05N sodium thiosulphate to obtain the true concentration of elemental copper in the solution.

A typical test proceeded as follows: To a five millilitre sample of copper sulphate solution was added ten millilitres of iodide and an excess of starch solution. Thiosulphate was added from a standard laboratory burette in amounts shown in Table 3.1.

TABLE 3.1

VOLUME OF SODIUM THIOSULPHATE REQUIRED FOR TITRATION OF COPPER SULPHATE SOLUTION

| Test No. | Volume (ml) |
|---|---|
| 1 | 69.6 |
| 2 | 69.3 |
| 3 | 69.1 |
| 4 | 69.8 |
| 5 | 69.7 |
| AVE. | 69.5 |

Calculation of the concentration was performed by multiplying this amount by the concentration of the thiosulphate solution and dividing by the volume of copper sulphate solution to obtain the number of equivalents of copper. Hence, number of equivalents = $\frac{69.5 \times .05}{5}$ = .695 giving a copper concentration of 63.549 x .695 = 44.14 grams per litre or 111.0 grams of copper sulphate per litre of solution.

This means that the dilution figures expressed as ratios can now be expressed as grams of copper sulphate per litre of solution as shown in Table 3.2.

TABLE 3.2

COPPER SULPHATE CONCENTRATION IN GRAMS PER LITRE OF SOLUTION

| Dilution Ratio | $CuSO_4$ (gm/l of solution) | Test Nos. |
|---|---|---|
| 1: 2.5 | 43.4 | 37, 120, 39 |
| 1: 5 | 22.22 | 31, 119, 40 |
| 1: 7.5 | 14.80 | 101, 102, 103, 104, 105, 106 |
| 1:10 | 11.11 | 1, 6, 11, 16, 117, 21 |
| 1:15 | 7.40 | 108, 111, 112 |
| 1:20 | 5.22 | 2, 7, 12, 17, 122 |
| 1:30 | 3.70 | 3, 8, 13, 18, 113 |
| 1:40 | 2.61 | 4, 9, 14, 19, 114 |
| 1:50 | 2.222 | 5, 10, 15, 20, 115 |

Sample calculation:

For Test #5 1:50

(80 to 4000) means that one litre of the cutting solution contains $\frac{111.0}{50}$ = 2.222 grams of copper sulphate per litre of solution.

# CHAPTER 4

# INDEPENDENT VARIABLES

## 4.10 INTRODUCTION

In the planning of an experiment in metal cutting or any field, either to prove a point or disprove as the case may be, or simply to add to the knowledge in that field, it is first necessary to specify the scope of the analysis and define its parameters.

The evaluation of a new cutting fluid, which is the problem in this case, should consist of a comparison of the new process with a commonly accepted fluid on a parameter by parameter basis but, which parameters?

Literature available on the subject is based on variables varying from surface chemistry and chip formation to the machine variables of cutting speeds, feeds and depths of cut. Measurement of cutter wear and cutting forces are commonly used to evaluate performance. The visual qualitative evaluation has not been neglected either as evidenced by RAMALINGAM (1968) and LUK (1964).

The following discussion of the independent variables will be applicable to Part 1 and Part 11 of the investigation.

Variables for the pilot study have already been defined in Chapter 1.[1]

## 4.20 WORK PIECE MATERIAL

To be consistant with the aims of the investigation i.e., to develop a process for reducing milling cutter wear while machining difficult to cut materials, consideration was given to three materials: AISI 3430 alloy steel, Inconel X-750 and maraging steel. There was no particular reason to use any of these particular materials other than supply and delivery problems which opted for Inconel X-750. The material, in the "as supplied" condition, consisted of a 4' 0" x 1" square piece which was subsequently cut into twenty-one specimens 6" long x 1/4" wide x 1" deep. The initial cut was performed on a standard bandsaw using a high speed steel blade followed by a grinding process to reduce them to the desired size. Average dimensions and hardness of material are as specified in Table 4.1[2] from which the statistics shown in Table 4.2 were derived.

In view of the low standard deviations, it was decided that subsequent calculations would be made using a length of six inches and a thickness of one-quarter inch. These values are well within the confidence interval for the 98 per cent level of confidence.

---

[1]See Section 1.80

[2]Actual measurements are listed in Appendix A

TABLE 4.1

AVERAGE DIMENSIONS AND HARDNESS OF TEST PIECES

| Test Piece No. | Width (in.) | Length (in.) | Thickness (in.) | Hardness (Rockwell-C) |
|---|---|---|---|---|
| 1 | 1.013 | 6.026 | .251 | 34.0 |
| 2 | 1.013 | 6.030 | .250 | 37.0 |
| 3 | 1.011 | 6.007 | .250 | 35.0 |
| 4 | 1.010 | 6.000 | .251 | 35.5 |
| 5 | 1.005 | 6.014 | .250 | 35.6 |
| 6 | 1.012 | 6.024 | .251 | 36.1 |
| 7 | 1.015 | 6.020 | .251 | 36.0 |
| 8 | 1.008 | 5.994 | .251 | 34.8 |
| 9 | 1.011 | 5.991 | .251 | 35.8 |
| 10 | 1.012 | 6.001 | .250 | 35.1 |
| 11 | 1.012 | 5.991 | .250 | 34.6 |
| 12 | 1.010 | 6.002 | .250 | 34.8 |
| 13 | 1.009 | 5.995 | .251 | 34.5 |
| 14 | 1.012 | 5.994 | .251 | 35.8 |
| 15 | 1.010 | 6.004 | .250 | 36.0 |
| 16 | 1.012 | 6.004 | .251 | 34.5 |
| 17 | 1.012 | 6.036 | .251 | 35.6 |
| 18 | 1.014 | 6.017 | .251 | 35.1 |
| 19 | 1.013 | 6.023 | .251 | 34.3 |
| 20 | 1.012 | 6.010 | .249 | 34.8 |
| 21 | 1.013 | 6.016 | .250 | 35.0 |

TABLE 4.2

OVERALL AVERAGE SIZE AND HARDNESS
OF TEST PIECES

| | VALUE - (INCHES) | | | ROCKWELL-C |
|---|---|---|---|---|
| STATISTIC | WIDTH | DEPTH | THICKNESS | HARDNESS |
| Avg. | 1.011 | 6.009 | .250 | 35.23 |
| Std. Dev. | .0285 | .078 | .016 | .728 |
| Confidence Interval | | | | |
| 98% | ±.0157 | ±.043 | ±.008 | ±.401 |
| 95% | ±.0129 | ±.035 | ±.007 | ±.331 |

Note:
A Rockwell C Hardness of 35.23 is approximately equal to 331 Brinnel Hardness number

The metallurgical content of the material used consisted of 73% Ni, .04% C, 6.75% Fe, 15% Cr, 2.5 Ti.

4.30 MILLING CUTTERS AND CUTTING SPEED

It is proposed in the experiment to study the process of metal cutting using a 3/8" x 3" diameter milling cutter, up milling using copper as a solid lubricant and compare with sulphurized oil. Controlled variables will consist of cutting feed, depth of cut and cutting fluids to establish various levels of cutting power, cutting forces, cutter wear and surface finish of the work piece.

Consideration was given to the variation of cutting speed but was discarded for several reasons:

1. The machine used cannot supply a cutting speed lower than 96.4 feet per minute without extensive alteration, and

2. It was felt that in cutting Inconel X-750 it should be at levels higher than those recommended.

Two classes of cutter were considered: high speed steel and carbide tip. The criterion for selection was that any material would be sufficient provided a uniform material was used throughout. A side and face high speed steel cutter (18 per cent tungsten), having a rake angle of $14^{\circ}$ was eventually selected as it was the most readily available.

It was realized that the cutting speed should be as low as possible. Therefore the smallest size cutters (three inch in diameter), having a face width of three-eighths inch and fourteen teeth, were purchased. The three-eighths inch width in combination with the one-quarter inch wide test piece was used to provide a reference point from which to measure the flank wear on the teeth of the cutter.

4.40 DEPTH OF CUT

A conventional approach was used in selecting the depth(s) of cut. The level for Part 1 was taken as .005" as this appeared to give the best cutting conditions for the cutting speed and feed used. For Part 11, the two levels selected were .005" and .010".

After preliminary examination, it was discovered that the vertical feed screw on the milling machine was not sufficiently accurate for the results required. To overcome this problem a dial indicator capable of measuring to the nearest .0001" was used to set the depth of cut. The dial gauge was mounted as shown in Figure 4.1.

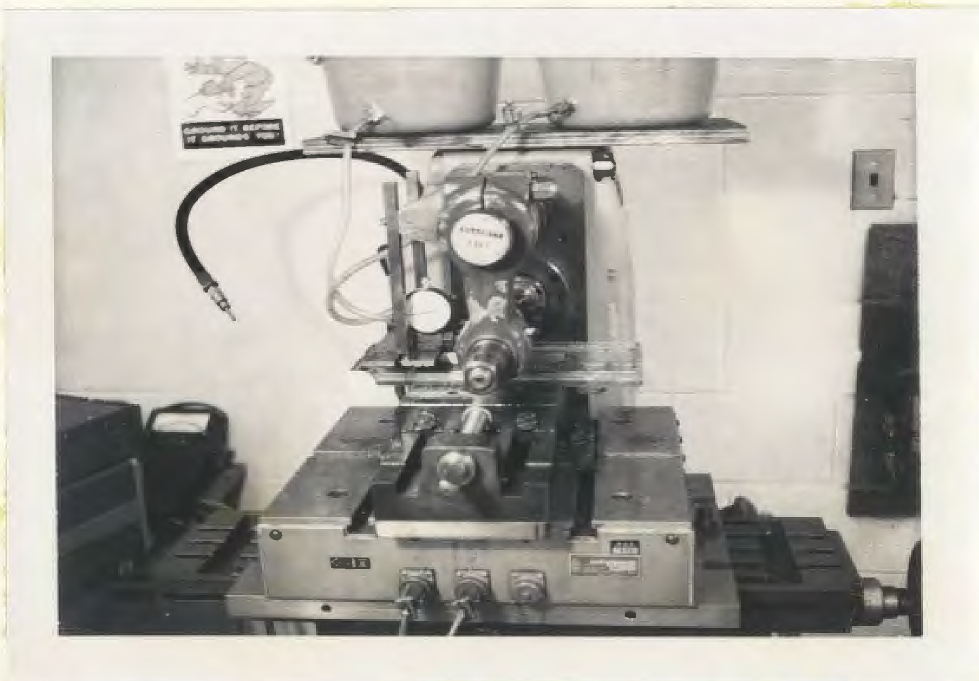


FIG. 4.1 DIAL GAUGE AND MOUNTING BRACKET

## 4.50 FEED RATE

Feed rates were selected at random from those available on the machine. Part 1 of the testing was performed using a medium low feed rate of 4.4 inches per minute. For Part 11, a low level of 2.1 inches per minute and a high level of 7.7 inches per minute were selected.

Conversion to feed per tooth at a cutting speed of

96.4 feet per minute (which was constant throughout the experiment) is as follows:

1. For a feed of 2.1 inches per minute
   .0012 inches

2. For a feed of 4.4 inches per minute
   .0025 inches

3. For a feed of 7.7 inches per minute
   .0045 inches

It should be noted at this point that tachometer readings of actual arbor speed were taken and a discrepancy found at the lowest operating RPM of 2.7 RPM so that 122.7 RPM was used to calculate the cutting speed of the cutter.

# CHAPTER 5

# EXPERIMENTAL MEASUREMENTS

## 5.10 CUTTER WEAR

Considerable thought was given to the measurement of tooth wear. Three basic questions immediately presented themselves:

1. What should be measured?
2. How should it be measured?
3. How much should be measured?

At the beginning of Part 1 of the investigation it was thought that a statistical sample of the cutter tooth wear (four at random of the fourteen teeth) could be obtained as representative of cutter wear. However, examination of the tooth wear distribution made it necessary to measure the wear on all teeth.

Wear on milling cutter teeth according to SHAW (1958) occurs at two places; on the face of the tooth where it appears as crater wear and on the flank of the tooth, generally referred to as flank wear. The best measure of wear is, of course, the total wear measured, either by surface replica or by total weight loss. Both of these had to be ruled out in this case for the following reasons:

1. The use of surface replicas is time consuming and placed too great a strain on the research facilities considering the number of teeth involved (about 1800 measurements).

2. Because of the adhesion of copper to the exposed area of the cutter, which varied from cutter to cutter, total weight difference was meaningless.

EIGOMAYEL AND ZAKARIA (1973) claim in their paper entitled "STATISTICAL CORRELATION OF TOOL WEAR PARAMETERS", that the flank wear is proportional to crater wear for high speed steel lathe tools cutting various materials. Extrapolating to the present process with its small depth of cut which is expected to produce little crater wear, it was decided to measure the wear land on the tooth flank using the original tooth face as a reference. This can be further justified by the scope of the experiment which is to establish the difference in the performance of two cutting fluids. (A comparison will be valid regardless of the method used as long as measurements are consistent.

This then leads to the problem of how to measure the flank wear. Figure 5.1 shows the plan and profile of a typical cutter tooth.

The nature of the wear ruled out the use of mechanical measuring equipment as it was felt that the variation in the readings would be greater than the wear, which in some cases was zero and extremely difficult to see. This meant that the use of optical equipment had to be investigated. The main criteria being that the measuring instrument be sufficiently accurate and display enough of the tooth so that the original tooth edge could be seen and used as a reference.

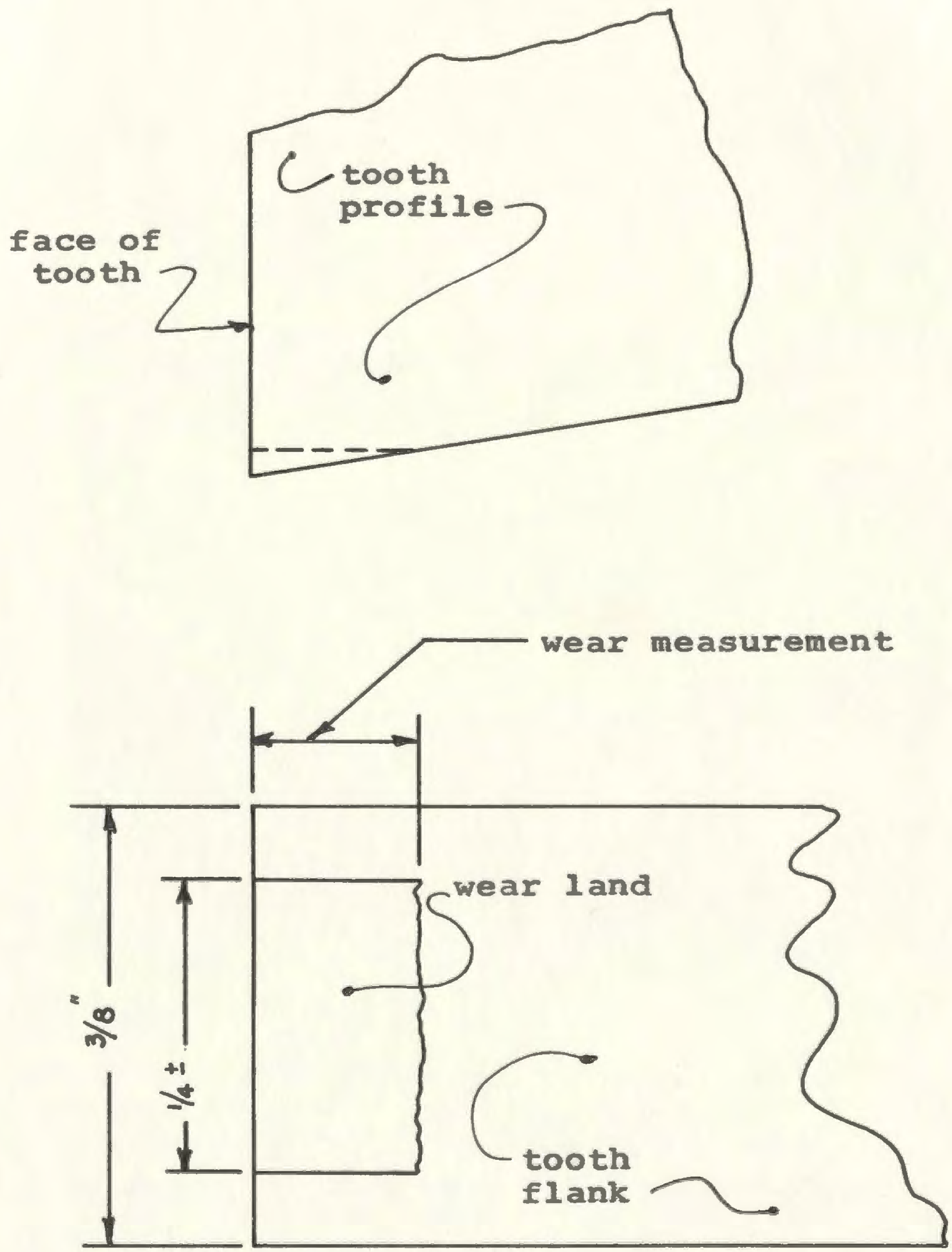



FIG. 5.1 MEASUREMENT OF WEAR LAND

Two approaches were considered:

1. The use of a metallurgical microscope.

2. The use of a travelling microscope.

To use the first of the two, although sufficiently accurate, is time consuming and was ruled out in favour of the travelling microscope (as shown in Figure 5.2) which has an accuracy of .001 centimetre and a magnification of fifty times which was sufficient to establish the reference line for the measurement.

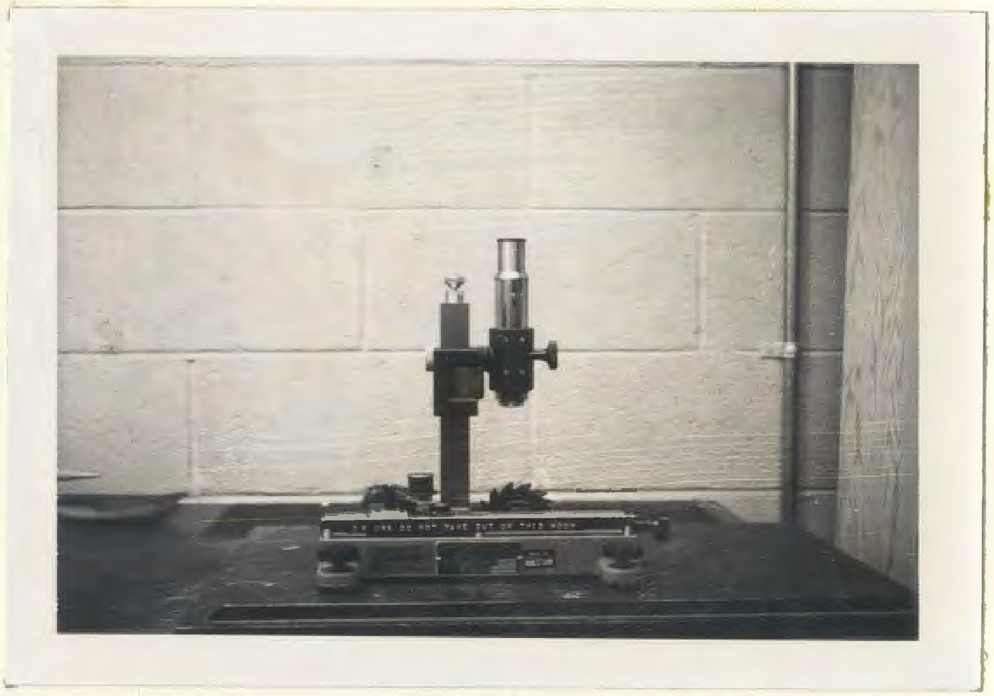


FIG. 5.2 TRAVELLING MICROSCOPE

Two methods of mounting the cutter for measurement were considered. First, mounting the cutter on an arbor or, the method which was selected, that of placing the cutter as shown in Figure 5.2. Although the latter was considered to be slightly less accurate than the arbor mounted cutter, it was estimated that the cutter could be placed by hand with very little error. A schematic of the method of measurement is presented in Figure 5.3.

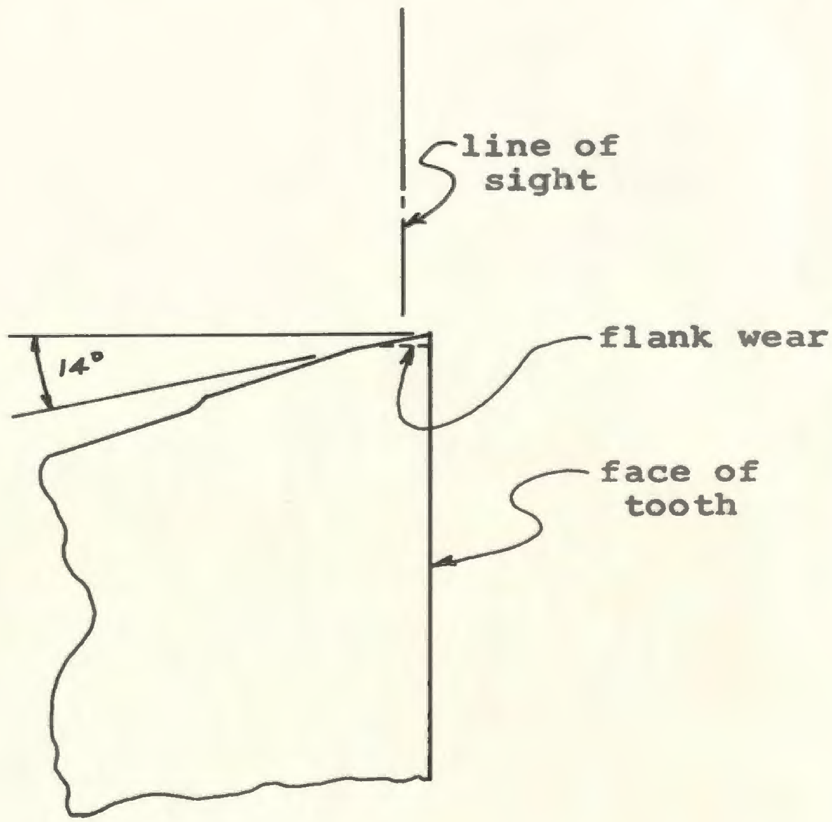



FIG. 5.3 GEOMETRY OF TOOTH PROFILE

Wear on cutters used with sulphurized oil was measured in a straightforward manner. That of the copper sulphate solution presented the problem of how to remove the copper from the wear land before measurements could be taken. This was readily solved by dipping each cutter tooth in a solution of concentrated nitric acid to dissolve the copper and washing in water immediately afterward. In some cases the cutters were put aside before measurement, in which case they were dipped in alcohol to remove the water and thus prevent corrosion of the surface.

## 5.20 CUTTING POWER

To keep the first and second phases of the experiment consistent with the pilot study, measurements of cutting power were recorded. Unfortunately, the same equipment was not available and power had to be measured using two kilowatt meters by the two wattmeter method as shown in Figure 5.4. Figure 5.5 shows the actual set up.

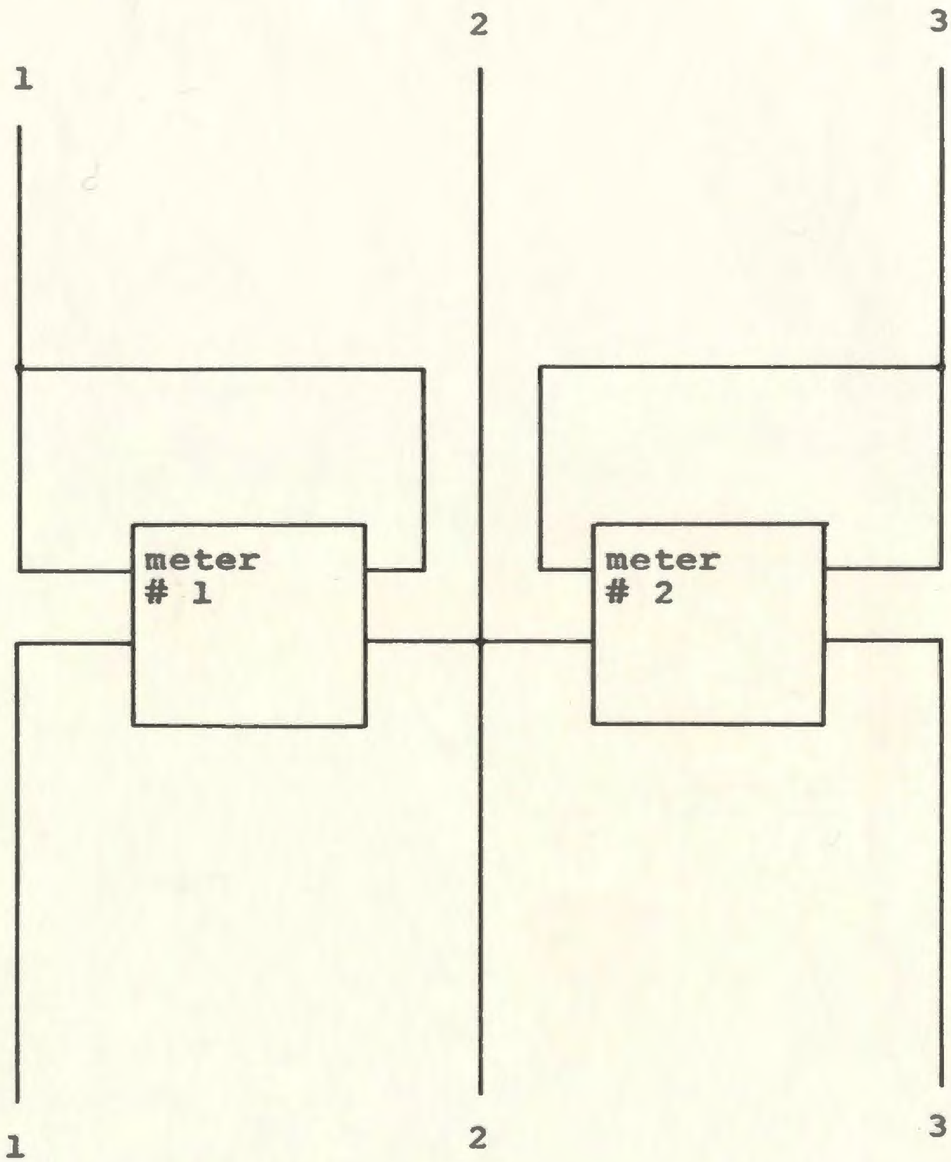
## 5.30 CUTTING FORCES

Of considerably more importance than the cutting power are the cutting forces, which brings us to the consideration of which forces to measure and how to measure them.

Because the reduction of wear is the main objective of the experiment, it was felt that, if cutting forces were to be measured, then these forces should, if possible, be those acting on the cutting faces of the cutter tooth i.e., the tooth face and flank.

SHAW (1958) devotes one chapter to the topic of dynamometry, describing the basic principles of design and the various types of transducers available. He spends considerable time on the bonded strain gauge instrument and eventually states that three dimensional strain gauge

3 PHASE 60 - POWER SUPPLY




Note:

If power factor angle of the circuit is greater than 60° subtract readings; if less than 60° add.

FIG. 5.4 SCHEMATIC DIAGRAM OF WATTMETER INSTALLATION

FIG. 5.5 WATTMETER INSTALLATION

dynamometers are available to measure milling cutter forces. With this in mind, the following criteria for a milling cutter dynamometer were established:

1. That it be of the octagonal ring type using bonded strain gauges.

2. That it be capable of measuring forces on the face and flank of the tooth i.e., forces in the x and y positions. Additionally, to facilitate further research it should also be capable of measuring forces in the z direction.

3. That the instrument be large and rugged.

4. To further facilitate future research, the dynamometer should be capable of measuring

forces up to and including 3,000 pounds on each axis.

A dynamometer known to meet all these requirements was found to be manufactured by Lebow Associates Incorporated, Model 6423-3K. This instrument contains four load cells corrected for moment loading and is factory calibrated. Method of installation is described in Figures 5.6, 5.7 and 5.8.

FIG. 5.6 LEBOW FORCE DYNAMOMETER

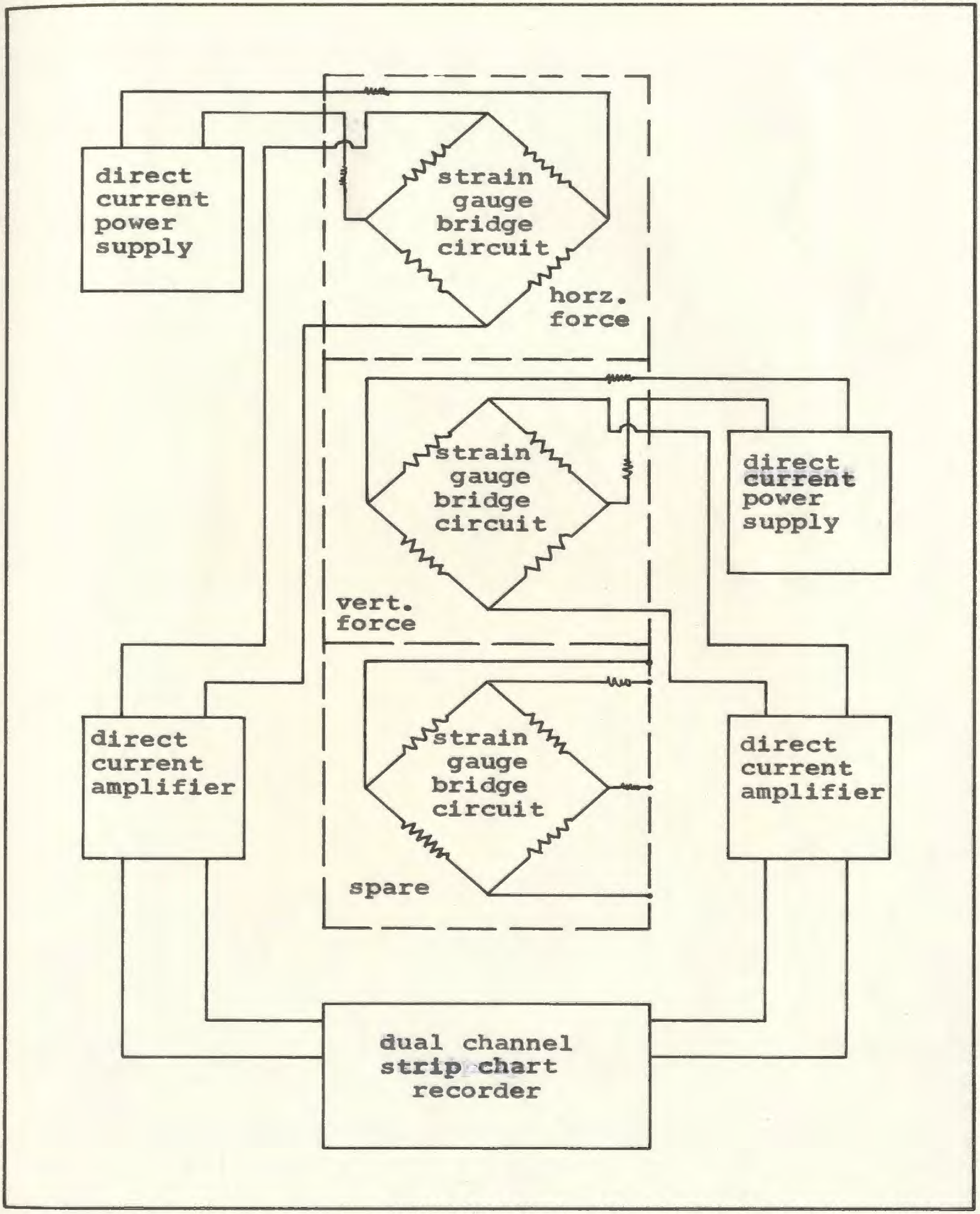



FIG. 5.7 SCHEMATIC DIAGRAM OF DYNAMOMETER INSTALLATION

FIG. 5.8 HEWLETT PACKARD TWO CHANNEL STRIP CHART RECORDER

Preliminary testing of the dynamometer indicated an extremely small displacement on the recorder. This necessitated the use of output signal amplifiers prior to input to the recorder. Power input to the dynamometer was provided by a Hewlett Packard direct current power supply.

Calibration to adapt the dynamometer to this application was carried out using the apparatus shown in Figure 5.9.

A convenient scale of one inch equals 2.5 kilograms on each channel was used in most cases except that other scales of one inch equals 2.08 kilograms, and one inch equals 2.0 kilograms were used for exceptionally high cutting forces. A sample of a chart recording taken during calibration proceedings is shown in Figure 5.10.

FIG. 5.9 DYNAMOMETER CALIBRATION APPARATUS


FIG. 5.10 DYNAMOMETER CALIBRATION RECORDING

## 5.40 SURFACE FINISH

It was realized early in the planning stages that some attempt would have to be made to measure the surface finish of the work. A total of three measurements of CLA in micro inches were taken on each sample and the values averaged. The equipment used for this purpose was a Taylor Hobson Talysurf 4 as shown in Figure 5.11.


FIG. 5.11 TAYLOR HOBSON TALYSURF 4

# CHAPTER 6

# ANALYSIS OF RESULTS

## 6.10 GENERAL

To be consistent with the experimental design, all test measurements were made changing one parameter at a time over a series of tests, and observed values of the dependent variables were noted and recorded. The test results in this section will be considered in three phases: first, the results of the pilot study; second, examination of the recorded values obtained for the tests made on the various compositions of the copper sulphate cutting fluid; and third, examination of the effects of the optimum concentration of copper sulphate and sulphuric acid versus sulphurized oil with respect to wear, cutting forces, etc., with an attempt being made, by means of the observation of the nature of the cutter wear, to explain some of the results.

## 6.20 PILOT STUDY

Table 6.1 contains the results of measurements made in accordance with the experimental procedure. These tests were of a preliminary nature and have been plotted as presented in Figure 6.1. It will be noted that the power required for cutting increases as the depth of cut increases

TABLE 6.1

CUTTING POWER AND DEPTH OF CUT
PILOT STUDY

| DEPTH OF CUT | POWER CONSUMED (WATTS) | | |
|---|---|---|---|
| (INCHES) | $CuSO_4/H_2SO_4$ | SOLUBLE OIL | DIFFERENCE |
| .020" | 70 | 90 | |
| | 72 | 94 | |
| | 80 | 94 | |
| | 80 | 90 | |
| | 70 | 90 | |
| AVG. | 74.4 | 91.6 | 17.2 |
| .040" | 100 | 126 | |
| | 94 | 126 | |
| | 100 | 120 | |
| | 94 | 130 | |
| | 94 | 124 | |
| AVG. | 96.4 | 125.2 | 28.8 |
| .060" | 128 | 184 | |
| | 124 | 168 | |
| | 140 | 174 | |
| | 120 | 170 | |
| | 134 | 174 | |
| AVG. | 129.2 | 174 | 44.8 |
| .080" | 180 | 280 | |
| | 180 | 280 | |
| | 180 | 260 | |
| | 170 | 254 | |
| | 170 | 260 | |
| AVG. | 176 | 266.8 | 90.8 |

Note:

All values were obtained using a 3/8" x 3" diameter high speed milling cutter having a rake angle of 14° arbor speed 183 RPM, feed 7.7" per minute. Test piece 1/4" x 6" long mild steel.

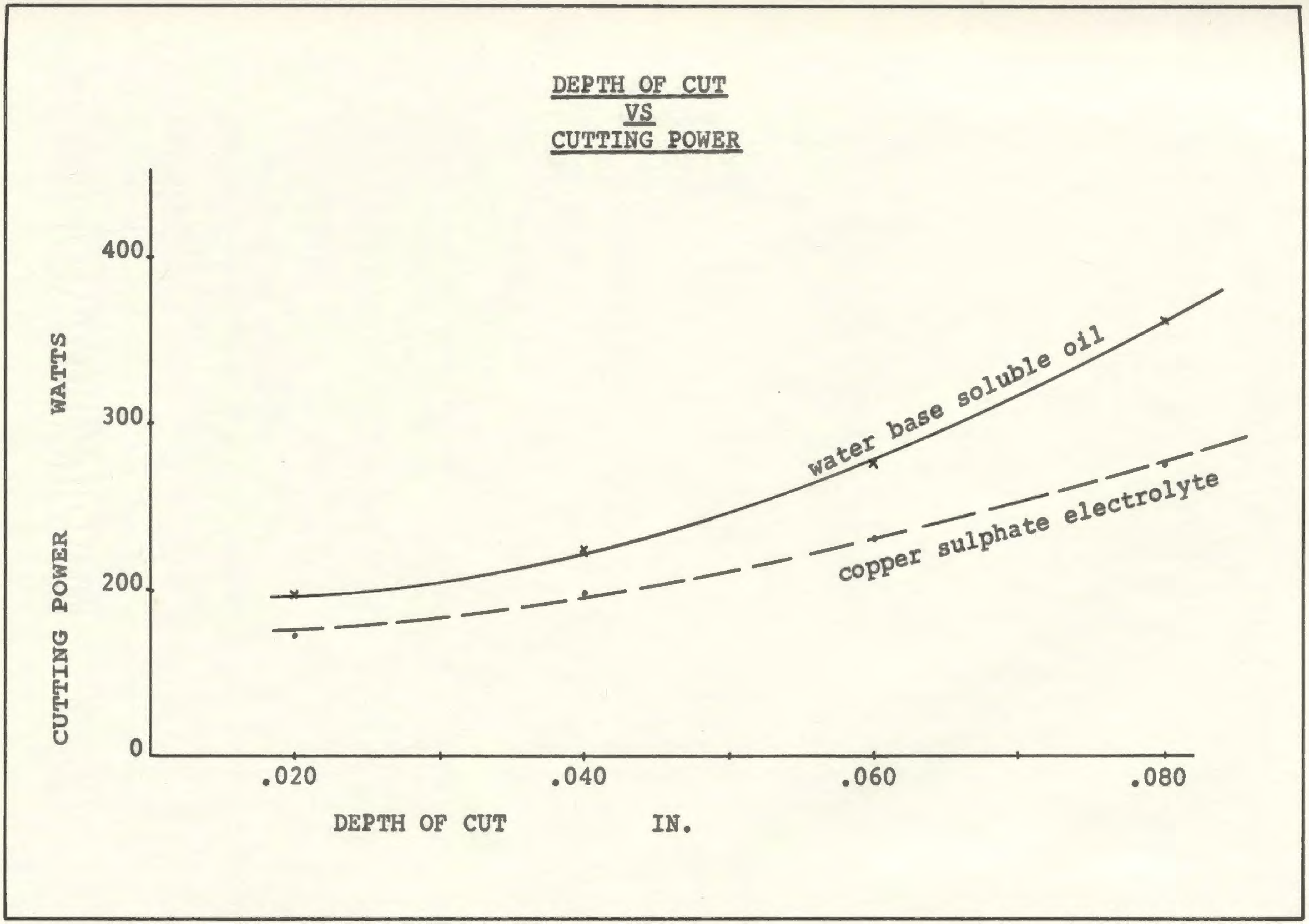



FIG. 6.1 COMPARISON OF POWER CONSUMED WHEN USING WATER BASE SOLUBLE OIL AND COPPER SULPHATE ELECTROLYTE AS CUTTING FLUID

for both cutting fluids, which is to be expected. However, the cutting power required for every depth of cut used is lower for the copper sulphate solution and the average percentage decrease in power consumption increases as the depth of cut increases. By actual measurement, the percentage decrease at .020" depth of cut is 21 per cent compared to 34 per cent at a depth of cut of .080".

## 6.21 CORRELATION OF RESULTS

The relationship between cutting power and cutting force can be seen as follows:

$$HP = \frac{F \times r \times N \times \pi \times 2}{33{,}000}$$

F = Cutting force

r = Diameter of the cutter divided by 2

N = Revolutions per minute of the milling machine arbor

HP = Horse power required which can be easily converted into watts

or Power = Constant x cutting force.

Hence any conclusions which we make based on cutting power must also be valid for cutting forces. To carry the argument a step further, one could argue that any conclusion based on cutting forces would probably be valid for cutter wear.

## 6.30 PART 1 -- OPTIMUM CONCENTRATION OF SULPHURIC ACID AND COPPER SULPHATE

The result of the pilot study was encouraging enough to prompt an investigation of the feasibility of cutting harder materials under more stringent conditions. However, instead of using a fixed concentration of copper sulphate and sulphuric acid, the amounts were varied to facilitate the deposition of copper on the cutter teeth. It was also necessary to measure other values such as wear, cutting forces, and surface finish in an attempt to determine, if possible, the optimum concentration of acid and copper sulphate in the cutting fluid.

## 6.31 METHOD OF ANALYSIS

After the performance of this phase of the experiment, it was realized that the large volume of data could only be handled with the aid of electronic data processing. This meant that the first step was to collate all the raw data and transfer it to data cards.

Two basic data cards were devised. Data Card A contained values of wear, copper sulphate and acid concentration, surface finish, and the test number. Data Card B contained readings of cutting power, cutting forces, and the test number. Input format was in accordance with the processing program.[1]

---

[1] See Appendix B.

Because of the nature of the measurements (14 for cutter wear and 5 for cutting forces, etc.) the first step in the analysis was to reduce the raw data to average values accompanied by their standard deviations. This can be seen in Table 6.2.

Examination of Table 6.2 indicates that for tests selected at random, the 95 per cent confidence levels for wear on Tests 39 and 5 are $.0091 \pm .003$ centimetres and $.0096 \pm .0005$ centimetres respectively. For cutting forces, only the resultant forces have been examined as they reflect the trends of the horizontal and vertical forces. For the same tests, the confidence intervals, again at 95 per cent, are $6.490 \pm 1.01$ kilograms and $6.246 \pm .682$ kilograms for Tests 5 and 39 respectively.

These errors are somewhat higher than expected and will have to be considered when determining the optimum values of acid and copper sulphate. This means that the selection will have to be based more on visual observation of the plotted results than on a statistical analysis.

It does not mean, however, that a polynomial regression analysis is invalid; but it does mean that any conclusions drawn from the results should be carefully examined. With this in mind, the values in Table 6.2 were subjected to a polynomial regression analysis. This was done for several degrees of polynomial starting at 2, 3 and what has been

TABLE 6.2

AVERAGE VALUES AND STANDARD DEVIATIONS. PART 1 DATA

| TEST | TOOTH WEAR | | HZ FORCE | | V FORCE | | R FORCE | | POWER | | CUSO4 | ACID | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO | AV | SD | AV | SD | AV | SD | AV | SD | AV | SD | CONC | CONC | CLA |
| 1 | 0.0060 | 0.003 | 4.677 | 0.505 | 4.925 | 0.415 | 6.794 | 0.636 | 0.021 | 0.006 | 11.109 | 0.0 | 27. |
| 2 | 0.0066 | 0.004 | 4.097 | 1.078 | 4.519 | 1.177 | 6.101 | 1.594 | 0.017 | 0.004 | 5.568 | 0.0 | 85. |
| 3 | 0.0073 | 0.004 | 3.984 | 0.633 | 4.529 | 0.735 | 6.040 | 0.902 | 0.022 | 0.002 | 3.698 | 0.0 | 86. |
| 4 | 0.0095 | 0.002 | 4.040 | 1.296 | 4.745 | 1.198 | 6.238 | 1.734 | 0.023 | 0.010 | 2.798 | 0.0 | 56. |
| 5 | 0.0096 | 0.001 | 4.377 | 0.845 | 4.790 | 1.080 | 6.490 | 1.364 | 0.023 | 0.005 | 2.216 | 0.0 | 36. |
| 6 | 0.0066 | 0.000 | 3.895 | 0.291 | 4.100 | 0.297 | 5.655 | 0.411 | 0.022 | 0.005 | 11.109 | 1.0 | 41. |
| 7 | 0.0079 | 0.001 | 3.460 | 0.585 | 3.745 | 0.678 | 5.121 | 0.716 | 0.026 | 0.010 | 5.568 | 1.0 | 48. |
| 8 | 0.0084 | 0.001 | 3.640 | 0.360 | 3.885 | 0.276 | 5.327 | 0.397 | 0.020 | 0.003 | 3.823 | 1.0 | 126. |
| 9 | 0.0091 | 0.003 | 3.875 | 0.536 | 4.151 | 0.701 | 5.679 | 0.876 | 0.019 | 0.001 | 2.798 | 1.0 | 42. |
| 10 | 0.0092 | 0.002 | 4.162 | 0.576 | 4.380 | 0.738 | 6.043 | 0.924 | 0.021 | 0.006 | 2.216 | 1.0 | 34. |
| 11 | 0.0044 | 0.004 | 2.862 | 0.224 | 3.069 | 0.224 | 4.196 | 0.314 | 0.018 | 0.004 | 11.109 | 2.5 | 17. |
| 12 | 0.0054 | 0.004 | 3.231 | 0.209 | 3.459 | 0.249 | 4.734 | 0.305 | 0.016 | 0.006 | 5.568 | 2.5 | 24. |
| 13 | 0.0058 | 0.001 | 3.660 | 0.238 | 3.739 | 0.324 | 5.233 | 0.393 | 0.018 | 0.004 | 3.698 | 2.5 | 43. |
| 14 | 0.0070 | 0.000 | 4.007 | 0.778 | 3.939 | 0.644 | 5.620 | 1.004 | 0.015 | 0.006 | 2.798 | 2.5 | 27. |
| 15 | 0.0079 | 0.000 | 4.761 | 0.279 | 4.662 | 0.479 | 6.666 | 0.510 | 0.028 | 0.008 | 2.216 | 2.5 | 28. |
| 16 | 0.0040 | 0.003 | 2.527 | 0.247 | 2.580 | 0.346 | 3.613 | 0.406 | 0.010 | 0.007 | 11.109 | 5.0 | 24. |
| 17 | 0.0046 | 0.001 | 2.780 | 0.342 | 3.010 | 0.220 | 4.098 | 0.394 | 0.012 | 0.006 | 5.568 | 5.0 | 25. |
| 18 | 0.0050 | 0.000 | 3.063 | 0.330 | 3.197 | 0.475 | 4.429 | 0.567 | 0.026 | 0.006 | 3.698 | 5.0 | 15. |
| 19 | 0.0054 | 0.001 | 3.509 | 0.399 | 3.583 | 0.270 | 5.016 | 0.468 | 0.016 | 0.003 | 2.798 | 5.0 | 19. |
| 20 | 0.0060 | 0.000 | 3.760 | 0.469 | 3.835 | 0.551 | 5.371 | 0.721 | 0.015 | 0.006 | 2.216 | 5.0 | 20. |
| 21 | 0.0055 | 0.004 | 2.266 | 0.346 | 2.209 | 0.324 | 3.164 | 0.472 | 0.016 | 0.005 | 11.109 | 10.0 | 24. |
| 31 | 0.0048 | 0.000 | 3.236 | 0.612 | 3.164 | 0.561 | 4.527 | 0.821 | 0.018 | 0.003 | 22.219 | 5.0 | 30. |
| 37 | 0.0076 | 0.001 | 4.127 | 1.033 | 4.240 | 0.879 | 5.918 | 1.347 | 0.017 | 0.004 | 44.384 | 5.0 | 19. |
| 39 | 0.0091 | 0.006 | 4.174 | 0.630 | 4.646 | 0.681 | 6.246 | 0.920 | 0.024 | 0.008 | 44.384 | 10.0 | 24. |
| 40 | 0.0065 | 0.003 | 3.199 | 0.262 | 3.109 | 0.253 | 4.463 | 0.333 | 0.017 | 0.005 | 22.219 | 10.0 | 24. |
| 101 | 0.0096 | 0.001 | 5.221 | 0.887 | 6.566 | 1.537 | 8.394 | 1.746 | 0.025 | 0.005 | 14.822 | 0.0 | 35. |
| 102 | 0.0071 | 0.004 | 4.500 | 0.352 | 4.400 | 0.312 | 6.295 | 0.434 | 0.017 | 0.004 | 14.822 | 1.0 | 29. |
| 103 | 0.0060 | 0.004 | 3.306 | 0.474 | 3.917 | 0.327 | 5.129 | 0.539 | 0.015 | 0.003 | 14.822 | 2.5 | 21. |
| 104 | 0.0043 | 0.002 | 2.774 | 0.235 | 2.801 | 0.271 | 3.943 | 0.349 | 0.017 | 0.006 | 14.822 | 5.0 | 27. |
| 105 | 0.0055 | 0.004 | 2.916 | 0.376 | 2.966 | 0.335 | 4.164 | 0.458 | 0.013 | 0.002 | 14.822 | 7.5 | 32. |

TABLE 6.2 (Continued)

| TEST NO | TOOTH WEAR AV | TOOTH WEAR SD | HZ FORCE AV | HZ FORCE SD | V FORCE AV | V FORCE SD | R FORCE AV | R FORCE SD | POWER AV | POWER SD | CUSO4 CONC | ACID CONC | CLA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 106 | 0.0059 | 0.004 | 2.791 | 0.789 | 2.340 | 0.278 | 3.655 | 0.761 | 0.015 | 0.006 | 14.822 | 10.0 | 33. |
| 108 | 0.0073 | 0.000 | 3.763 | 0.527 | 3.818 | 0.665 | 5.364 | 0.827 | -0.455 | 0.123 | 7.397 | 1.0 | 29. |
| 111 | 0.0053 | 0.004 | 3.200 | 0.557 | 3.142 | 0.675 | 4.485 | 0.870 | 0.017 | 0.007 | 7.397 | 7.5 | 34. |
| 112 | 0.0056 | 0.002 | 2.346 | 0.198 | 2.725 | 0.334 | 3.597 | 0.370 | 0.021 | 0.006 | 7.397 | 10.0 | 33. |
| 113 | 0.0059 | 0.001 | 4.700 | 0.335 | 3.982 | 0.427 | 6.161 | 0.529 | 0.019 | 0.001 | 3.698 | 7.5 | 22. |
| 114 | 0.0062 | 0.003 | 5.166 | 0.399 | 4.575 | 0.207 | 6.903 | 0.402 | 0.021 | 0.001 | 2.798 | 7.5 | 15. |
| 115 | 0.0066 | 0.002 | 5.766 | 0.105 | 4.950 | 0.161 | 7.599 | 0.168 | 0.023 | 0.002 | 2.216 | 7.5 | 26. |
| 117 | 0.0051 | 0.004 | 2.741 | 0.671 | 2.900 | 0.462 | 4.002 | 0.737 | 0.015 | 0.006 | 11.109 | 7.5 | 25. |
| 119 | 0.0065 | 0.005 | 3.433 | 0.490 | 3.366 | 0.303 | 4.819 | 0.437 | 0.021 | 0.003 | 22.219 | 7.5 | 25. |
| 120 | 0.0108 | 0.001 | 4.833 | 0.451 | 4.382 | 0.418 | 6.524 | 0.612 | 0.022 | 0.002 | 44.384 | 7.5 | 16. |
| 122 | 0.0055 | 0.001 | 4.132 | 0.283 | 3.599 | 0.271 | 5.481 | 0.364 | 0.000 | 0.045 | 5.568 | 7.5 | 29. |

referred to as 3+, which, in fact, represents the best fit polynomial. This approach was found necessary after a visual inspection of the 3+ curves revealed unexpected bumps which it was felt were not a true representation of the maximum likelihood estimates of the parameter being studied. Analysis of this data using tables and graphs then followed to determine the acid and copper sulphate concentration to be used in Part 11 of the investigation.

## 6.32 COMPUTER PROGRAMS USED

A number of programs were used in this phase of the experiment. Most were written specifically for the tasks required with one, Program PLORG and its accompanying sub programs, being borrowed from the IBM 370 Library.

Programs are as listed in Appendix B and are briefly described as follows: PROGRAM B1 was designed to accept raw data, calculate the average values and standard deviation of the various parameters, perform an internal sort using disk storage files and print and punch the output as presented in Table 6.2.

The punched output formed the input to another program, PROGRAM B3, which performed an internal sort with an output in punch card form in a format suitable for the regression analysis program.

PROGRAM B4 was an IBM packaged program which was modified to accept the output from Program B3. This data, together with the appropriate header cards, was accepted and processed to provide a printed output in terms of the coefficients of the best fit polynomial for the degree specified. The analysis of variance for two and three degree polynomials and the best fit polynomial was computed and a table of x, y and y estimate values together with a plot of these values was produced. In addition, the program was changed to output x, y and y estimate values in card form.

A fourth program, PROGRAM B5, was written to perform a straight line regression analysis. This program was modified at various times to accept the data which required processing. Output was arranged to be by system printer and punch card.

All programs were written in FORTRAN 1V. Programs B1, B3 and B5 were written by the author for the IBM 1130, 8K configuration using a 1402 printer and 1627 drum plotter. Various sorting and printing programs were devised as an aid in preparing this thesis. Listings of these programs are also found in Appendix B.

### 6.33 REGRESSION ANALYSIS

Using the above mentioned programs, an extremely large volume of data was generated (12,000 -- 13,000 lines) by Program B4. Regression analysis was performed on wear, horizontal cutting force, vertical cutting force, resultant cutting force, cutting power and surface finish against copper sulphate concentration for various levels of sulphuric acid concentration as shown in Table 6.2. A sample computer output for wear at five millilitres of sulphuric acid can be seen in Table 6.3, Figure 6.2 and Table 6.4.

This particular sample output was produced for a three degree polynomial having the equation

$$y = .00657 - .000453X + .0000233X^2 - .284X10^{-6}X^3$$

The analysis of variance indicates that this curve will estimate the most likely degree of curve to fit the data at the two per cent level of confidence. Table 6.3 is a print-out of the observed values, the regression estimates and the residual values (i.e., difference between the two). A visual representation can be found in Figure 6.2. This Figure and Tables 6.2 and 6.4 are representative only of the many tables and charts produced but not presented. Data for Tables 6.5 and 6.6 were generated from this print out.

6.34 ANALYSIS OF DATA

The first step in the analysis of data is to present a summary of the polynomial regression program output. This can be seen in Table 6.5. A quick look at this Table indicates a fairly good fit for curves of wear, vertical and horizontal cutting forces and the resultant force, but a poor fit for the cutting power and surface finish. This is deduced from a comparison of the F values with the F distribution statistic

TABLE 6.3

POLYNOMIAL REGRESSION OF DEGREE 3

# POLYNOMIAL REGRESSION - TABLE OF RESIDUALS

TABLE OF RESIDUALS

| OBSERVATION NO. | X VALUE | Y VALUE | Y ESTIMATE | RESIDUAL |
|---|---|---|---|---|
| 1 | 14,82240 | 0,00430 | 0,00406 | 0,00024 |
| 2 | 22,21980 | 0,00480 | 0,00491 | -0,00011 |
| 3 | 44,38429 | 0,00760 | 0,00760 | 0,00000 |
| 4 | 11,10990 | 0,00400 | 0,00403 | -0,00003 |
| 5 | 5,56880 | 0,00460 | 0,00473 | -0,00013 |
| 6 | 3,69860 | 0,00500 | 0,00521 | -0,00021 |
| 7 | 2,79820 | 0,00540 | 0,00549 | -0,00009 |
| 8 | 2,21640 | 0,00600 | 0,00568 | 0,00032 |

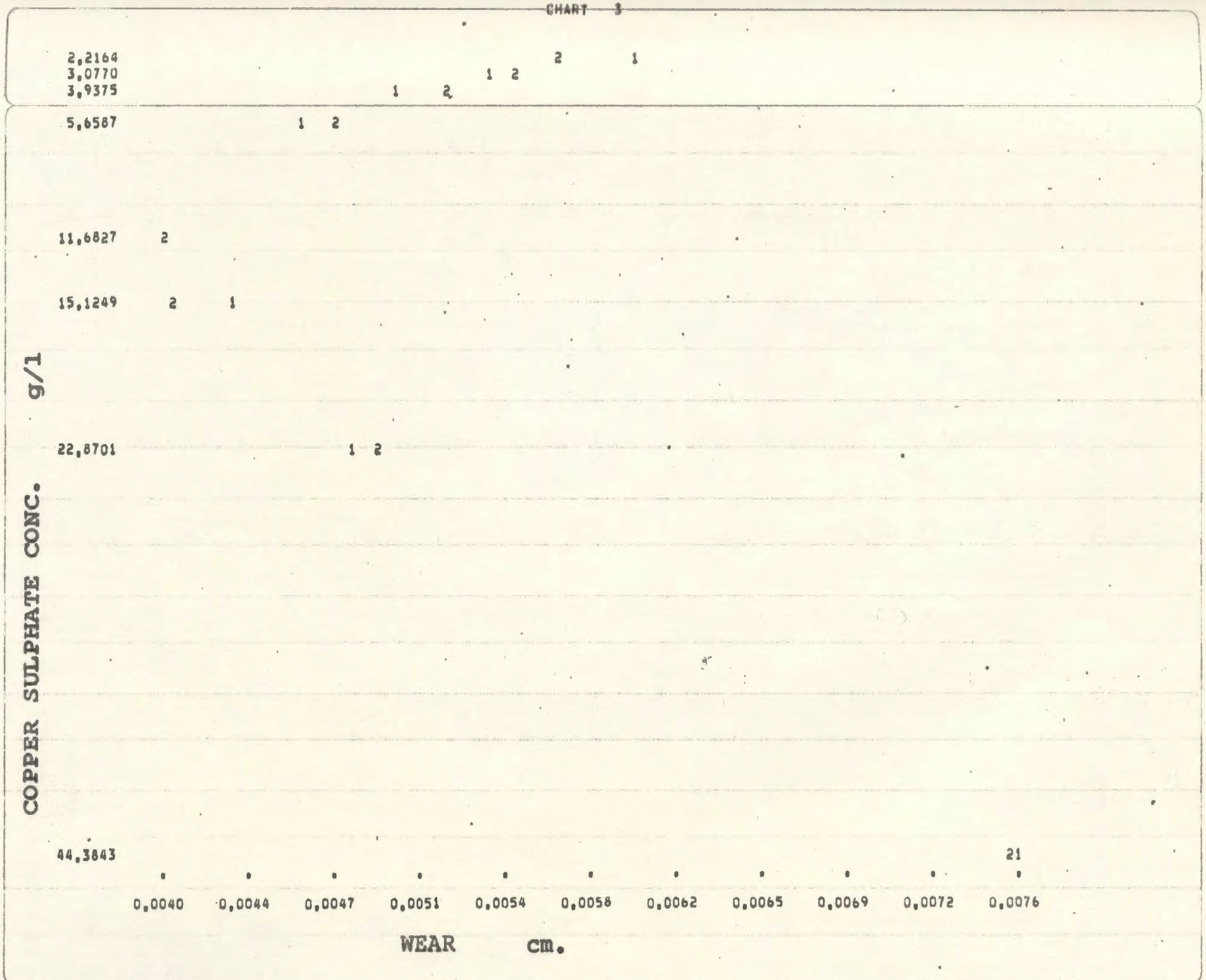



FIG. 6.2 SAMPLE OUTPUT POLYNOMIAL REGRESSION

POLYNOMIAL REGRESSION,....5

# TABLE 6.4

NUMBER OF OBSERVATIONS 8

## POLYNOMIAL REGRESSION - ANALYSIS OF VARIANCE

POLYNOMIAL REGRESSION OF DEGREE 1

INTERCEPT 0,4582211E-02

REGRESSION COEFFICIENTS
0,4720420E-04

ANALYSIS OF VARIANCE FOR 1 DEGREE POLYNOMIAL

| SOURCE OF VARIATION | DEGREE OF FREEDOM | SUM OF SQUARES | MEAN SQUARE | F VALUE | IMPROVEMENT IN TERMS OF SUM OF SQUARES |
|---|---|---|---|---|---|
| DUE TO REGRESSION | 1 | 0,00000 | 0,00000 | 3,18053 | 0,00000 |
| DEVIATION ABOUT REGRESSION | 6 | 0,00001 | 0,00000 | | |
| TOTAL | 7 | 0,00001 | | | |

POLYNOMIAL REGRESSION OF DEGREE 2

INTERCEPT 0,5761974E-02

REGRESSION COEFFICIENTS
-0,1697761E-03 0,4796847E-05

ANALYSIS OF VARIANCE FOR 2 DEGREE POLYNOMIAL

| SOURCE OF VARIATION | DEGREE OF FREEDOM | SUM OF SQUARES | MEAN SQUARE | F VALUE | IMPROVEMENT IN TERMS OF SUM OF SQUARES |
|---|---|---|---|---|---|
| DUE TO REGRESSION | 2 | 0,00001 | 0,00000 | 21,89250 | 0,00001 |
| DEVIATION ABOUT REGRESSION | 5 | 0,00000 | 0,00000 | | |
| TOTAL | 7 | 0,00001 | | | |

POLYNOMIAL REGRESSION OF DEGREE 3

INTERCEPT 0,6579258E-02

REGRESSION COEFFICIENTS
-0,4539345E-03 0,2337333E-04 -0,2845650E-06

ANALYSIS OF VARIANCE FOR 3 DEGREE POLYNOMIAL

| SOURCE OF VARIATION | DEGREE OF | SUM OF | MEAN | F | IMPROVEMENT IN TERMS |
|---|---|---|---|---|---|

TABLE 6.4 (Continued)

| | FREEDOM | SQUARES | SQUARE | VALUE | OF SUM OF SQUARES |
|---|---|---|---|---|---|
| DUE TO REGRESSION | 3 | 0,00001 | 0,00000 | 52,65565 | 0,00000 |
| DEVIATION ABOUT REGRESSION | 4 | 0,00000 | 0,00000 | | |
| TOTAL | 7 | 0,00001 | | | |

TABLE NO. 6.5

SUMMARY OF RESULTS - POLYNOMIAL REGRESSION

| ACID (Gm./l) | F VALUES | | | | | MINIMUM VALUES | | | | | COPPER SULPHATE CONC. (Gm./l) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DEGREE OF POLYNOMIAL | | | | | DEGREE OF POLYNOMIAL | | | | | DEGREE OF POLYNOMIAL | | | |
| | 2 | 3 | 3+ and Degree[3] | | Actual Value[1] | 2 | 3 | 3+ and Degree | | Actual Value[2] | 2 | 3 | 3+ and Degree[3] | |
| **Resultant cutting force (Kg.):** | | | | | | | | | | | | | | |
| 10.0 | 9.28 | 9.28 | 9.28 | 2 | 3.16 | 3.41 | 3.41 | 3.41 | 2 | 11.10 | 7.39 | 7.39 | 7.39 | 2 |
| 7.5 | 7.89 | 68.19 | 68.19 | 3 | 4.00 | 3.77 | 3.85 | 3.85 | 3 | 11.10 | 22.20 | 14.82 | 14.82 | 3 |
| 5.0 | 6.45 | 28.10 | 27.76 | 4 | 3.61 | 3.98 | 3.63 | 3.62 | 4 | 11.10 | 22.20 | 11.10 | 11.10 | 4 |
| 2.5 | 15.63 | 8.85 | 5.74 | 4 | 4.19 | 4.09 | 4.25 | 4.21 | 4 | 11.10 | 11.10 | 11.10 | 11.10 | 4 |
| 1.0 | 10.53 | 17.26 | 25.07 | 4 | 5.12 | 5.23 | 5.17 | 5.17 | 4 | 5.57 | 7.39 | 5.57 | 5.57 | 4 |
| 0.0 | 191.79 | 191.79 | 191.79 | 2 | 6.04 | 6.00 | 6.00 | 6.00 | 2 | 3.69 | 5.57 | 5.57 | 5.57 | 2 |
| **Cutting Power (Kw.):** | | | | | | | | | | | | | | |
| 10.0 | 4.79 | 70.80 | 70.80 | 3 | 1.50 | 1.54 | 1.46 | 1.46 | 3 | 14.80 | 22.20 | 14.80 | 14.80 | 3 |
| 7.5 | 0.39 | 1.02 | 1.03 | 4 | 0.00 | 1.50 | 1.09 | 1.02 | 4 | 5.50 | 14.80 | 11.10 | 5.56 | 4 |
| 5.0 | 0.07 | 0.29 | 0.29 | 3 | 1.00 | 1.53 | 1.32 | 1.32 | 3 | 11.10 | 22.20 | 11.10 | 11.10 | 3 |
| 2.5 | 0.54 | 0.79 | 0.53 | 4 | 1.50 | 1.49 | 1.43 | 1.49 | 4 | 14.80 | 11.10 | 5.56 | 3.69 | 4 |
| 1.0 | 0.83 | 0.44 | 1.15 | 5 | -45.60 | -16.90 | -17.50 | -39.60 | 5 | 7.30 | 7.30 | 7.40 | 7.40 | 4 |
| 0.0 | 5.66 | 4.08 | 7.62 | 4 | 1.70 | 1.90 | 1.82 | 1.71 | 4 | 5.56 | 5.56 | 5.56 | 5.56 | 4 |

1. Minimum value of variable actually recorded.
2. Concentration of copper sulphate corresponding to minimum value recorded.
3. 3+ Degree of polynomial represents the degree of the best fit curve.

TABLE NO. 6.5 (Continued)

| ACID (Gm./l) | F VALUES DEGREE OF POLYNOMIAL 2 | 3 | 3+ and Degree | | MINIMUM VALUES Actual Value | DEGREE OF POLYNOMIAL 2 | 3 | 3+ and Degree | | COPPER SULPHATE CONC. (Gm./l) Actual Value | DEGREE OF POLYNOMIAL 2 | 3 | 3+ and Degree | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CLA - Surface finish (Micro inch) | | | | | | | | | | | | | | |
| 10.0 | 0.59 | 0.20 | 0.20 | 3 | 24 | 23.90 | 23.90 | 23.90 | 3 | 11.10 | 44.30 | 44.30 | 44.30 | 3 |
| 7.5 | 2.23 | 2.12 | 2.12 | 3 | 15 | 15.33 | 16.00 | 16.00 | 3 | 2.79 | 44.30 | 44.30 | 44.30 | 3 |
| 5.0 | 7.95 | 4.36 | 4.36 | 3 | 15 | 19.10 | 18.47 | 18.47 | 3 | 3.69 | 44.30 | 2.21 | 2.21 | 3 |
| 2.5 | 1.01 | 0.81 | 0.61 | 4 | 17 | 19.30 | 15.60 | 17.33 | 4 | 11.10 | 14.80 | 11.10 | 11.10 | 4 |
| 1.0 | 0.30 | 0.30 | 1.18 | 5 | 29 | 40.90 | 22.55 | -2.20 | 5 | 7.30 | 11.10 | 11.10 | 14.80 | 5 |
| 0.0 | 0.89 | 19.15 | 19.15 | 3 | 27 | 23.20 | 25.73 | 25.73 | 3 | 11.10 | 14.80 | 11.10 | 11.10 | 3 |
| Wear (Cm. x $10^{-3}$) | | | | | | | | | | | | | | |
| 10.0 | 204.63 | 88.94 | 88.94 | 3 | 5.50 | 5.49 | 5.57 | 5.57 | 3 | 11.10 | 7.39 | 7.39 | 7.39 | 3 |
| 7.5 | 74.95 | 504.07 | 504.07 | 3 | 5.10 | 5.51 | 5.12 | 5.12 | 3 | 11.10 | 11.10 | 11.10 | 11.10 | 3 |
| 5.0 | 21.89 | 52.65 | 52.65 | 3 | 4.00 | 4.30 | 4.03 | 4.03 | 3 | 11.10 | 14.80 | 11.10 | 11.10 | 3 |
| 2.5 | 23.70 | 11.78 | 12.58 | 4 | 4.40 | 4.35 | 4.48 | 4.43 | 4 | 11.10 | 11.10 | 11.10 | 11.10 | 4 |
| 1.0 | 174.36 | 144.67 | 144.67 | 3 | 6.60 | 6.74 | 6.63 | 6.63 | 3 | 11.10 | 11.10 | 11.10 | 11.10 | 3 |
| 0.0 | 25.27 | 11.23 | 4.64 | 4 | 6.00 | 6.05 | 6.05 | 5.98 | 4 | 11.10 | 11.10 | 11.10 | 11.10 | 4 |

TABLE NO. 6.5 (Continued)

| ACID (Gm./1) | F VALUES DEGREE OF POLYNOMIAL 2 | 3 | 3+ and Degree | | MINIMUM VALUES Actual Value | DEGREE OF POLYNOMIAL 2 | 3 | 3+ and Degree | | COPPER SULPHATE CONC. (Gm./1) Actual Value | DEGREE OF POLYNOMIAL 2 | 3 | 3+ and Degree | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Vertical cutting force (Kg.)** | | | | | | | | | | | | | | |
| 10.0 | 4.39 | 1.48 | 1.48 | 3 | 2.21 | 2.58 | 2.53 | 2.53 | 3 | 11.10 | 7.40 | 7.40 | 7.40 | 3 |
| 7.5 | 6.99 | 43.61 | 43.61 | 3 | 2.90 | 2.76 | 2.78 | 2.78 | 3 | 11.10 | 22.20 | 14.80 | 14.80 | 3 |
| 5.0 | 8.34 | 34.98 | 81.57 | 4 | 2.58 | 2.83 | 2.61 | 2.60 | 4 | 11.10 | 14.80 | 11.10 | 11.10 | 4 |
| 2.5 | 13.13 | 6.05 | 6.46 | 4 | 3.07 | 3.06 | 3.11 | 3.07 | 4 | 11.10 | 11.10 | 11.10 | 11.10 | 4 |
| 1.0 | 7.87 | 49.04 | 32.39 | 4 | 3.74 | 3.79 | 3.74 | 3.74 | 4 | 5.50 | 7.40 | 5.50 | 5.50 | 4 |
| 0.0 | 102.69 | 142.37 | 142.37 | 3 | 4.51 | 4.37 | 4.46 | 4.46 | 3 | 5.50 | 5.50 | 5.50 | 5.50 | 3 |
| **Horizontal cutting force (Kg.)** | | | | | | | | | | | | | | |
| 10.0 | 35.29 | 14.45 | 14.45 | 3 | 2.27 | 2.22 | 2.29 | 2.29 | 3 | 11.10 | 7.40 | 7.39 | 7.39 | 3 |
| 7.5 | 8.48 | 75.97 | 159.06 | 4 | 2.74 | 2.57 | 2.66 | 2.84 | 4 | 11.10 | 22.20 | 14.82 | 11.10 | 4 |
| 5.0 | 4.98 | 21.57 | 21.57 | 3 | 2.53 | 2.82 | 2.51 | 2.51 | 3 | 11.10 | 14.80 | 11.10 | 11.10 | 3 |
| 2.5 | 16.57 | 13.85 | 6.40 | 4 | 2.86 | 2.72 | 2.90 | 2.87 | 4 | 11.10 | 11.10 | 11.10 | 11.10 | 4 |
| 1.0 | 10.68 | 9.27 | 8.11 | 4 | 3.46 | 3.59 | 3.55 | 3.55 | 4 | 5.56 | 7.39 | 5.57 | 5.57 | 4 |
| 0.0 | 19.11 | 17.52 | 17.52 | 3 | 3.98 | 4.11 | 4.00 | 4.00 | 3 | 3.69 | 5.56 | 5.57 | 5.57 | 3 |

TABLE 6.6

BEST FIT POLYNOMIAL COEFFICIENTS

| Acid Conc. (Gm./l) | Degree Best Fit | COEFFICIENTS $x^5$ | $x^4$ | $x^3$ | $x^2$ | X | Intercept |
|---|---|---|---|---|---|---|---|
| Wear: | | | | | | | |
| 10.0 | 3 | | | $-.987\times10^{-7}$ | $.870\times10^{-5}$ | $-.122\times10^{-3}$ | $.603\times10^{-2}$ |
| 7.5 | 3 | | | $-.285\times10^{-6}$ | $.240\times10^{-4}$ | $-.422\times10^{-3}$ | $.724\times10^{-2}$ |
| 5.0 | 3 | | | $-.284\times10^{-6}$ | $.233\times10^{-4}$ | $-.453\times10^{-3}$ | $.657\times10^{-2}$ |
| 2.5 | 4 | | $.301\times10^{-5}$ | $-.101\times10^{-3}$ | $.121\times10^{-2}$ | $-.613\times10^{-2}$ | $.165\times10^{-1}$ |
| 1.0 | 3 | | | $.134\times10^{-5}$ | $-.462\times10^{-5}$ | $-.437\times10^{-3}$ | $.102\times10^{-1}$ |
| 0.0 | 4 | | $.150\times10^{-5}$ | $-.499\times10^{-4}$ | $.658\times10^{-3}$ | $-.414\times10^{-2}$ | $.167\times10^{-1}$ |
| Horizontal cutting force: | | | | | | | |
| 10.0 | 3 | | | $-.868\times10^{-4}$ | $.586\times10^{-2}$ | $-.484\times10^{-1}$ | 2.365 |
| 7.5 | 4 | | $.320\times10^{-4}$ | $-.300\times10^{-2}$ | $.956\times10^{-1}$ | -1.200 | 8.00 |
| 5.0 | 3 | | | $-.255\times10^{-3}$ | $.187\times10^{-1}$ | - .332 | 4.235 |
| 2.5 | 4 | | $.137\times10^{-2}$ | $-.479\times10^{-1}$ | .593 | -3.119 | 9.165 |
| 1.0 | 4 | | $.769\times10^{-3}$ | $-.274\times10^{-1}$ | .348 | -1.791 | 6.724 |
| 0.0 | 3 | | | $-.167\times10^{-2}$ | $.542\times10^{-1}$ | - .417 | 4.937 |

TABLE 6.6 (Continued)

| Acid Conc. (Gm./l) | Degree Best Fit | COEFFICIENTS $x^5$ | $x^4$ | $x^3$ | $x^2$ | $x$ | Intercept |
|---|---|---|---|---|---|---|---|
| Vertical cutting force: | | | | | | | |
| 10.0 | 3 | | | $.722 \times 10^{-4}$ | $-.487 \times 10^{-2}$ | .139 | 1.742 |
| 7.5 | 3 | | | $-.335 \times 10^{-3}$ | $.255 \times 10^{-1}$ | - .504 | 5.740 |
| 5.0 | 4 | | $.379 \times 10^{-4}$ | $-.326 \times 10^{-2}$ | $.899 \times 10^{-1}$ | - .916 | 5.582 |
| 2.5 | 4 | | $.159 \times 10^{-2}$ | $-.535 \times 10^{-1}$ | .628 | -3.089 | 8.875 |
| 1.0 | 4 | | $.290 \times 10^{-3}$ | $-.119 \times 10^{-1}$ | .179 | -1.087 | 6.040 |
| 0.0 | 3 | | | $.145 \times 10^{-2}$ | $-.754 \times 10^{-2}$ | - .104 | 5.031 |
| Resultant cutting force: | | | | | | | |
| 10.0 | 2 | | | | $-.478 \times 10^{-4}$ | $.789 \times 10^{-1}$ | 2.833 |
| 7.5 | 3 | | | $-.566 \times 10^{-3}$ | $.434 \times 10^{-1}$ | .869 | 9.036 |
| 5.0 | 4 | | $.631 \times 10^{-4}$ | $-.540 \times 10^{-2}$ | .147 | -1.464 | 8.183 |
| 2.5 | 4 | | $.211 \times 10^{-2}$ | $-.722 \times 10^{-1}$ | .868 | -4.408 | 12.775 |
| 1.0 | 4 | | $.740 \times 10^{-3}$ | $-.274 \times 10^{-1}$ | .367 | -2.002 | 8.970 |
| 0.0 | 2 | | | | $.298 \times 10^{-1}$ | - .352 | 7.042 |

TABLE 6.6 (Continued)

| Acid Conc. (Gm./l) | Degree Best Fit | COEFFICIENTS $x^5$ | $x^4$ | $x^3$ | $x^2$ | X | INTERCEPT |
|---|---|---|---|---|---|---|---|
| Cutting power: | | | | | | | |
| 10.1 | 3 | | | $-.213\times10^{-5}$ | $.173\times10^{-3}$ | $-.387\times10^{-2}$ | $.409\times10^{-1}$ |
| 7.5 | 4 | | $.555\times10^{-6}$ | $-.472\times10^{-4}$ | $.125\times10^{-2}$ | $-.118\times10^{-1}$ | $.447\times10^{-1}$ |
| 5.0 | 3 | | | $-.164\times10^{-5}$ | $.111\times10^{-3}$ | $-.183\times10^{-2}$ | $.220\times10^{-1}$ |
| 2.5 | 4 | | $.219\times10^{-4}$ | $-.776\times10^{-3}$ | $.933\times10^{-2}$ | $-.441\times10^{-1}$ | $.855\times10^{-1}$ |
| 1.0 | 5 | $-.258\times10^{-3}$ | $.919\times10^{-2}$ | $-.114$ | $.607$ | $-1.375$ | 1.102 |
| 0.0 | 4 | | $-.112\times10^{-4}$ | $.359\times10^{-3}$ | $-.362\times10^{-2}$ | $.122\times10^{-1}$ | $.102\times10^{-1}$ |
| Surface finish (CLA) | | | | | | | |
| 10.0 | 3 | | | $.389\times10^{-3}$ | $-.192\times10^{-1}$ | $-.113$ | 32.806 |
| 7.5 | 3 | | | $.207\times10^{-2}$ | $-.157$ | 2.905 | 15.054 |
| 5.0 | 3 | | | $-.318\times10^{-3}$ | $-.309\times10^{-2}$ | .817 | 16.681 |
| 2.5 | 4 | | $-.479\times10^{-1}$ | 1.655 | $-19.074$ | 82.130 | 80.62 |
| 1.0 | 5 | $.912\times10^{-3}$ | $-.545$ | 11.613 | $-109.441$ | 441.285 | 520.873 |
| 0.0 | 3 | | | .365 | $-9.967$ | 75.492 | 83.853 |

i.e., any F value less than 4 has a significance level of less than Ninety per cent.

Table 6.6 contains the coefficients of the best fit polynomial curve for the recorded data. Unfortunately, no consistent relationship between the various variables and acid content of the cutting fluid can be established. For wear, a three degree curve seems to be a reasonable relationship but two of the six test runs indicate a fourth degree curve. The other parameters are worse in that half suggest one degree and the other half a different degree of curve. Surface finish and cutting power show no trend at all and will not be given further examination.

In summary, one can state the following conclusions based on the polynomial regression analysis:

1. That for wear, minimum values of the variable seem to be obtainable when the acid concentration is five millilitres per litre of sulphuric acid combined with eleven decimal one grams of copper sulphate per litre of solution.

2. That cutting power and surface finish do not provide any trend at all.

Figures 6.3, 6.4, 6.5 and 6.6 presented for visual inspection sustain these conclusions.

Figure 6.3 indicates that a copper sulphate concentration of Eleven decimal One grams per litre gives the minimum wear for all concentrations of sulphuric acid and that the curve of least wear occurs at a concentration of

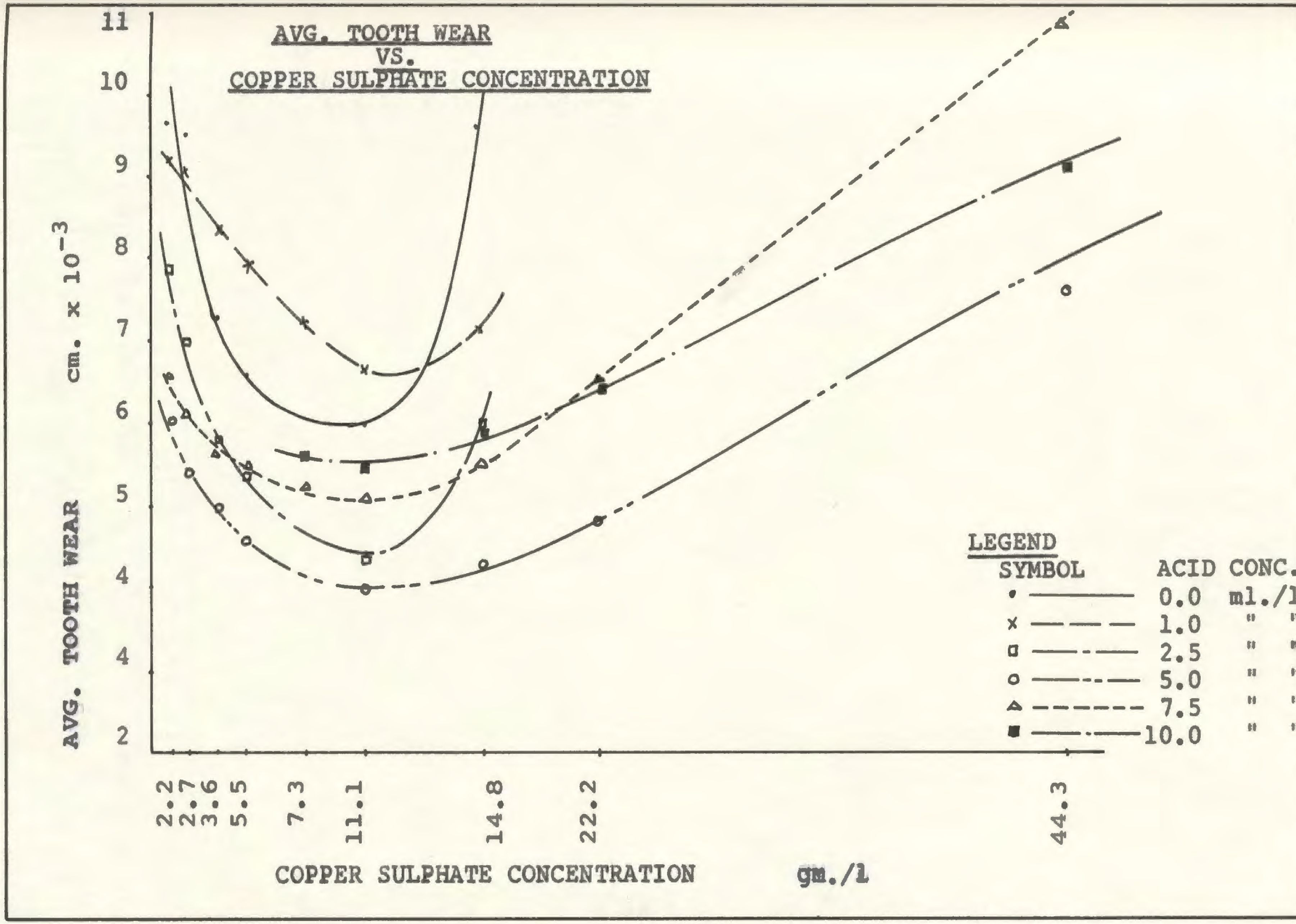



FIG. 6.3 AVERAGE TOOTH WEAR AGAINST COPPER SULPHATE CONCENTRATION

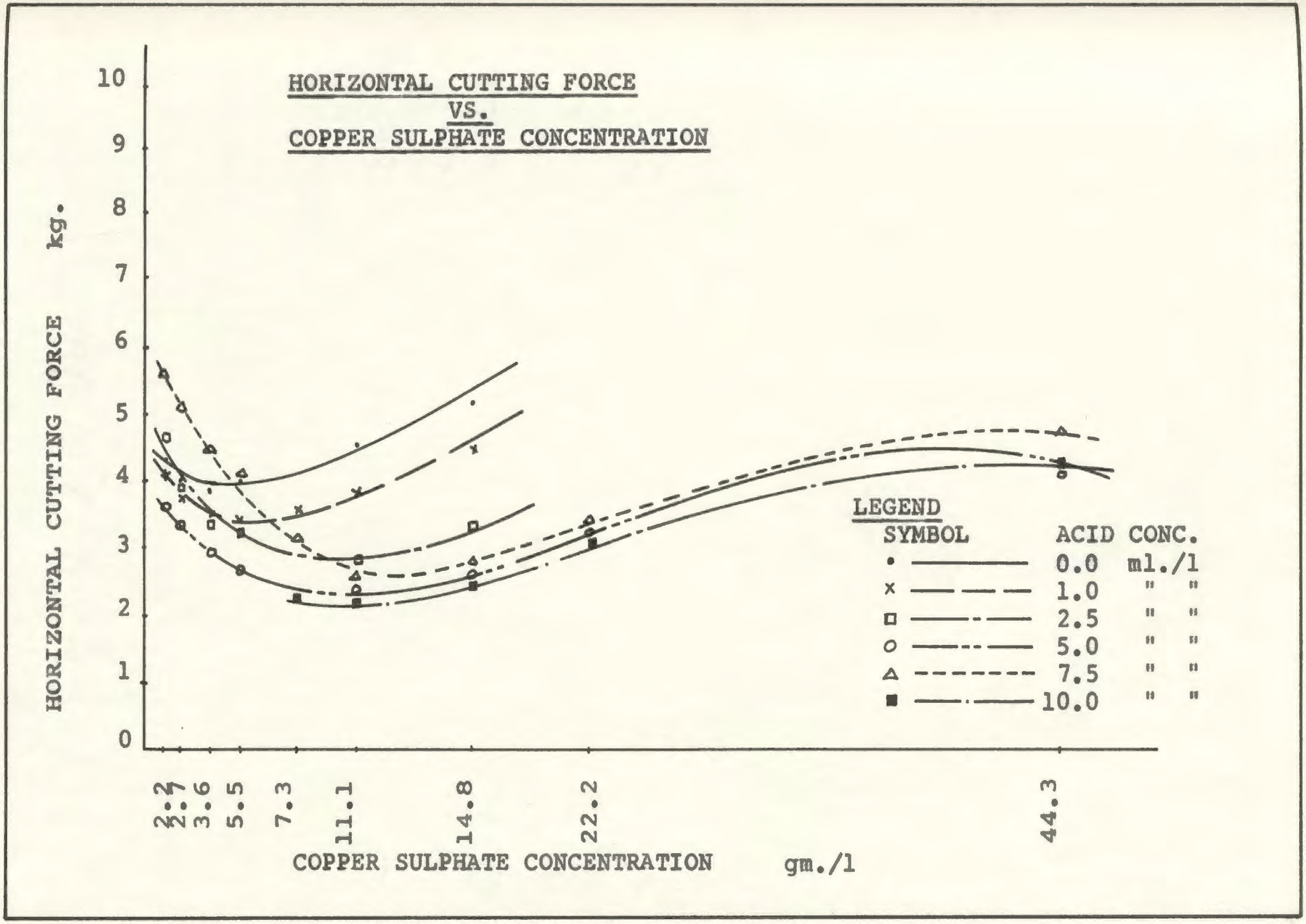



FIG. 6.4 HORIZONTAL CUTTING FORCE AGAINST COPPER SULPHATE CONCENTRATION

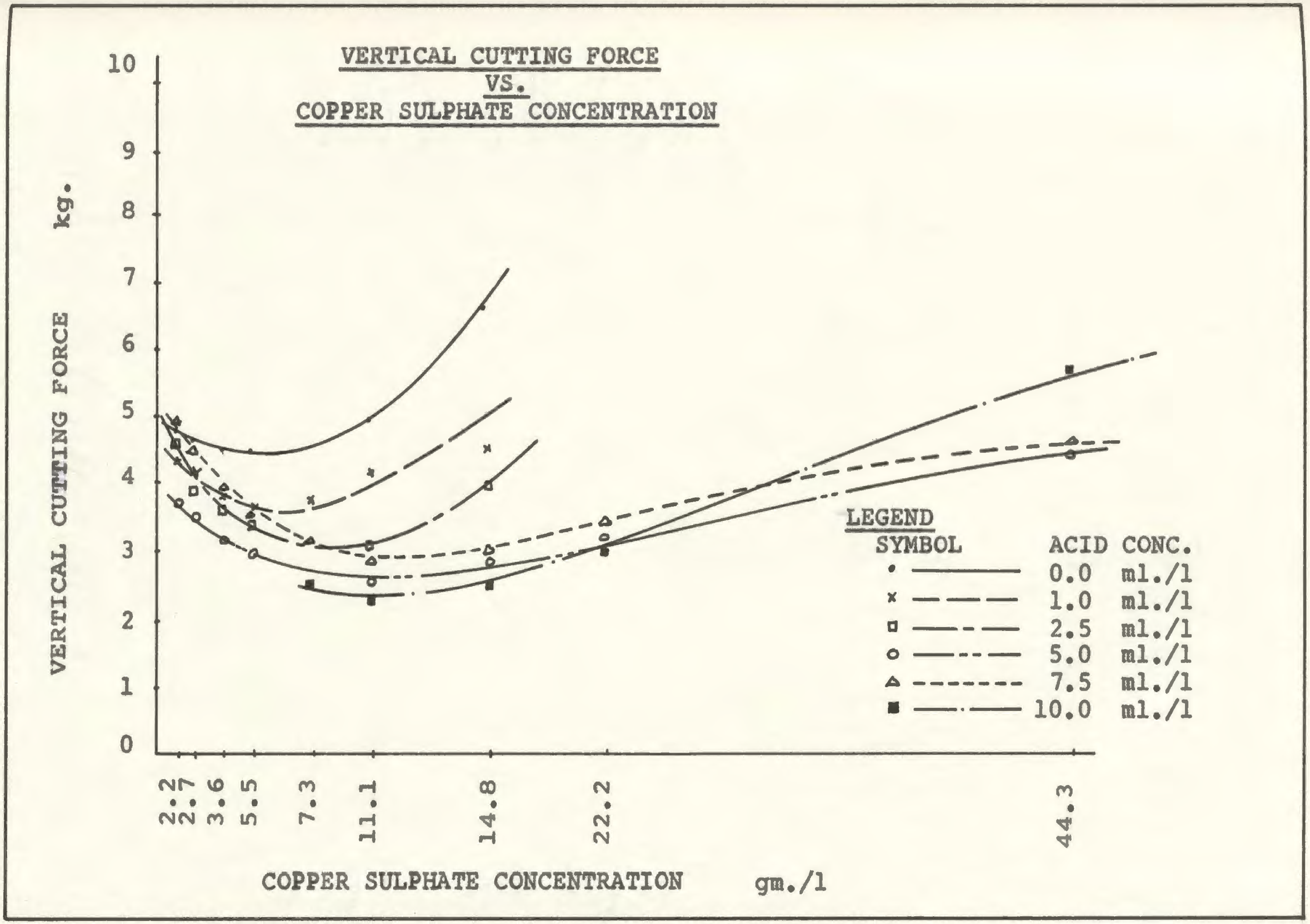



FIG. 6.5 VERTICAL CUTTING FORCE AGAINST COPPER SULPHATE CONCENTRATION

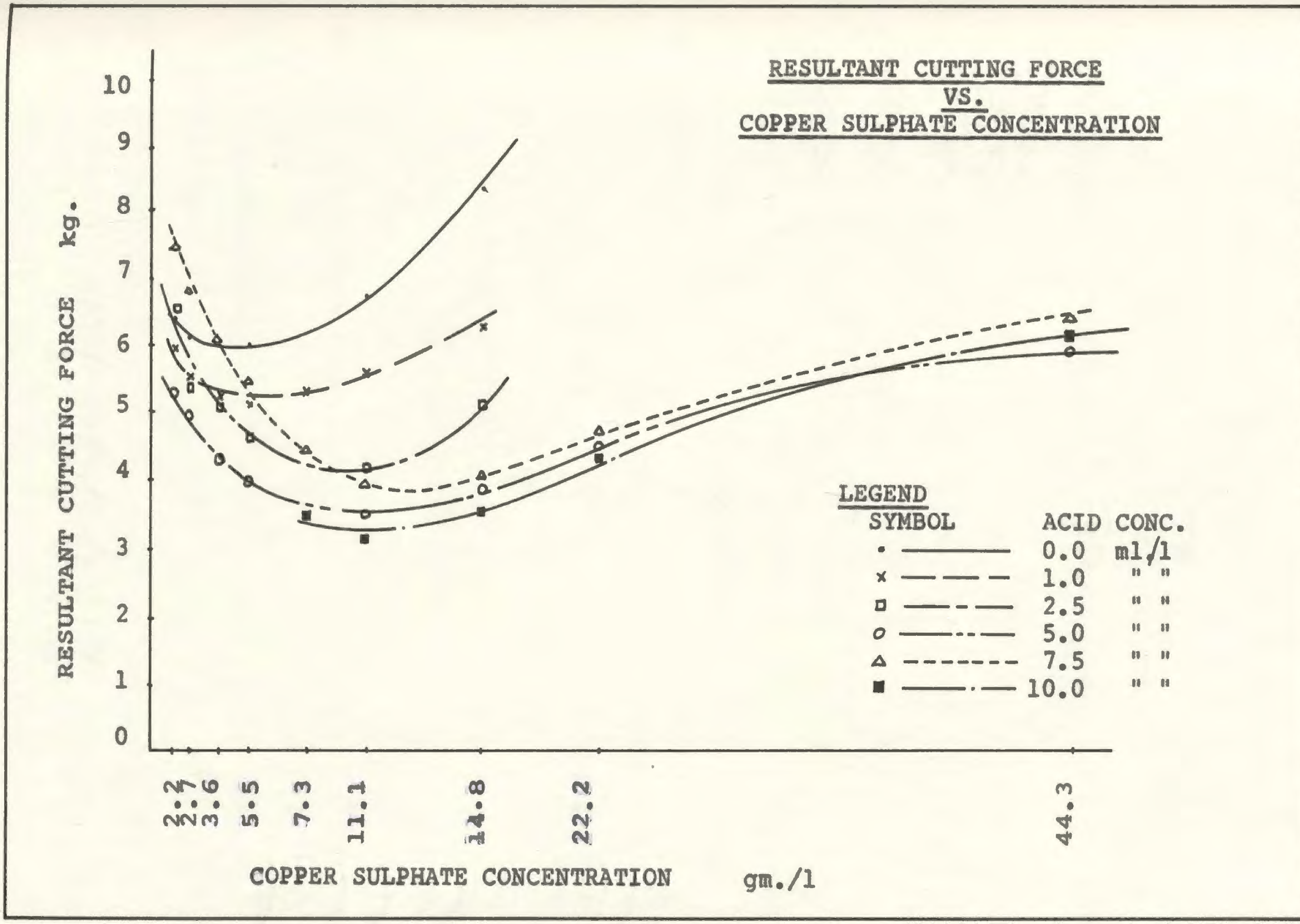



FIG. 6.6 RESULTANT CUTTING FORCE AGAINST COPPER SULPHATE CONCENTRATION

5 millilitres per litre of solution. Closer examination shows that the wear decreases as the acid content increases (up to 5 millilitres per litre) for all curves except the first i.e., the one with no acid at all. The only conclusion which can be put forward for this apparent anomaly is that the acid in the cutting fluid has an influence on the amount of wear experienced by the cutter and suggests the presence of a chemical action between acid and cutter.

Figures 6.4, 6.5 and 6.6 for horizontal, vertical and resultant cutting forces respectively, do not indicate such a clearly defined level of acid and copper sulphate. All three indicate basically the same trend in that the curves show an increase in copper sulphate concentration as the minimum cutting force for each curve decreases to a minimum at 11.1 grams of copper sulphate per litre of solution and a further absolute minimum at 11.1 grams of copper sulphate per litre of solution. Also, these minimum points occur for curves of 5 and 10 millilitres per litre of concentrated sulphuric acid respectively. This suggests that to obtain the lowest cutting forces, a copper sulphate concentration of 11.1 grams per litre of solution combined with 10 millilitres of sulphuric acid per litre is necessary. The copper sulphate concentration is obviously consistent with that obtained from the wear curves, but is at variance with them on the acid concentration.

To resolve this difference, it will be necessary to examine curves of cutting forces against wear. Earlier, it was suggested that there probably existed a relationship between these two variables. In an attempt to verify this, curves of cutting forces plotted against wear can be seen in Figures 6.7, 6.8 and 6.9.

A straight line regression analysis was performed on these data and the results summarized in Table 6.7.

TABLE 6.7

RESULTS OF STRAIGHT LINE REGRESSION ANALYSIS
CUTTING FORCE AGAINST WEAR
PART 1 DATA

| VARIABLE | SLOPE | INTERCEPT | CORR. COEFF. | NULL HYPOTHESIS STATISTIC |
|---|---|---|---|---|
| Horizontal Force | 293.5573 | 1.7805 | 0.5991 | 4.6738 |
| Vertical Force | 362.2131 | 1.4141 | 0.7065 | 6.2347 |
| Resultant Force | 460.7976 | 2.3070 | 0.6785 | 5.7696 |

Although the correlation coefficients are not overly high, the graphs themselves clearly indicate an upward trend; especially when one considers that the horizontal scale in these figures is twice the vertical scale. It should also be noted that the null hypothesis shows that the slope is significantly different from zero, at least at the 95 per cent level of confidence. Actual slopes are as shown.

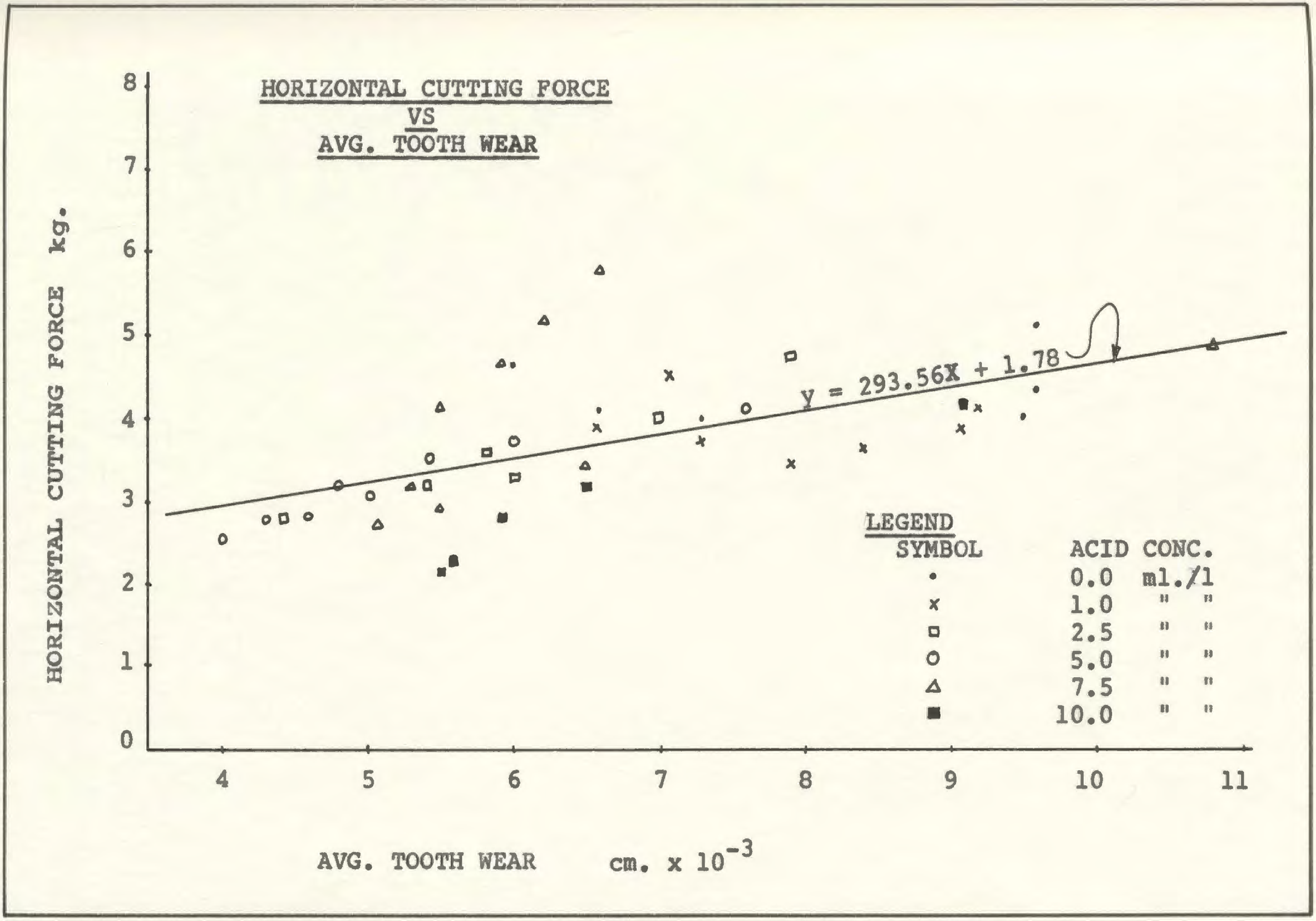



FIG. 6.7 HORIZONTAL CUTTING FORCE AGAINST AVERAGE TOOTH WEAR

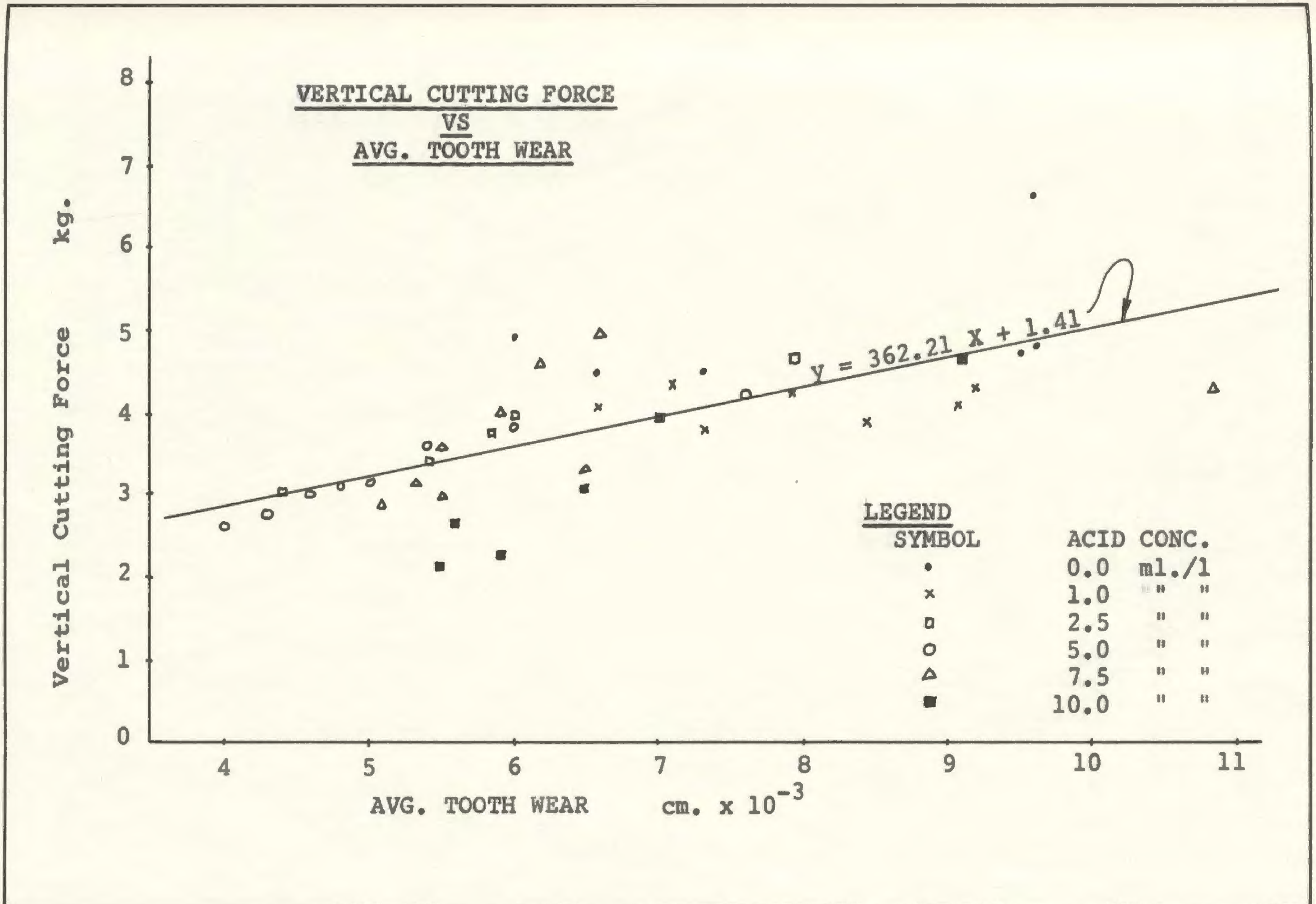



FIG. 6.8 VERTICAL CUTTING FORCE AGAINST AVERAGE TOOTH WEAR

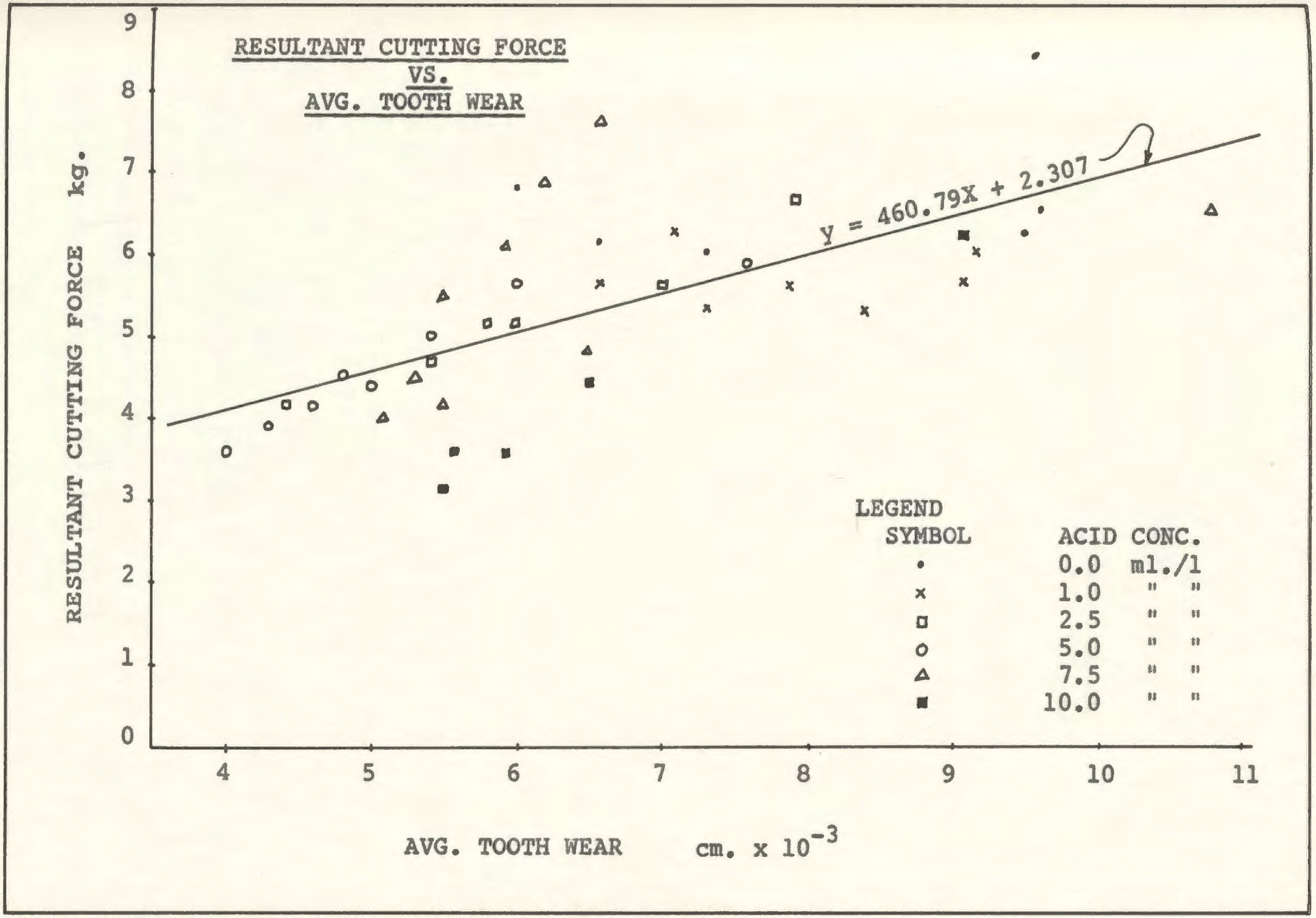



FIG. 6.9 RESULTANT CUTTING FORCE AGAINST AVERAGE TOOTH WEAR

A closer examination of this result can be seen in Figures 6.10, 6.11 and 6.12. These graphs show the way in which the slopes of the wear against cutting force curves change with increase in the acid content. It seems that small changes in acid content have little effect, but the overall trend is that, as the sulphuric acid concentration increases, the slope of the curve increases. This means that as the acid content increases, the cutting force required per unit wear increases.

This probably explains the reason for the low correlation coefficients obtained for Figures 6.8, 6.9 and 6.10. Finally, it should be noted that a straight line regression analysis was not made on these curves as it was desired to determine a trend, which has been found to be as explained. Values which were deemed to be out of line and were not used in drawing the curves have been circled.

With this in mind we refer to Figure 6.13 and consider the last point on the curve in the light of Figure 6.3. Because Figure 6.3 clearly indicates an increase in wear as acid content increases beyond 5 millilitres with that at 10 millilitres giving the maximum wear, one is lead to the conclusion that the curves for 10 millilitres in Figures 6.4, 6.5 and 6.6 are probably in error. In any case, if it were not in error, the 5 millilitre per litre curve should be selected as the optimum level for acid so that corrosive effects on the work piece and machinery, as well as the

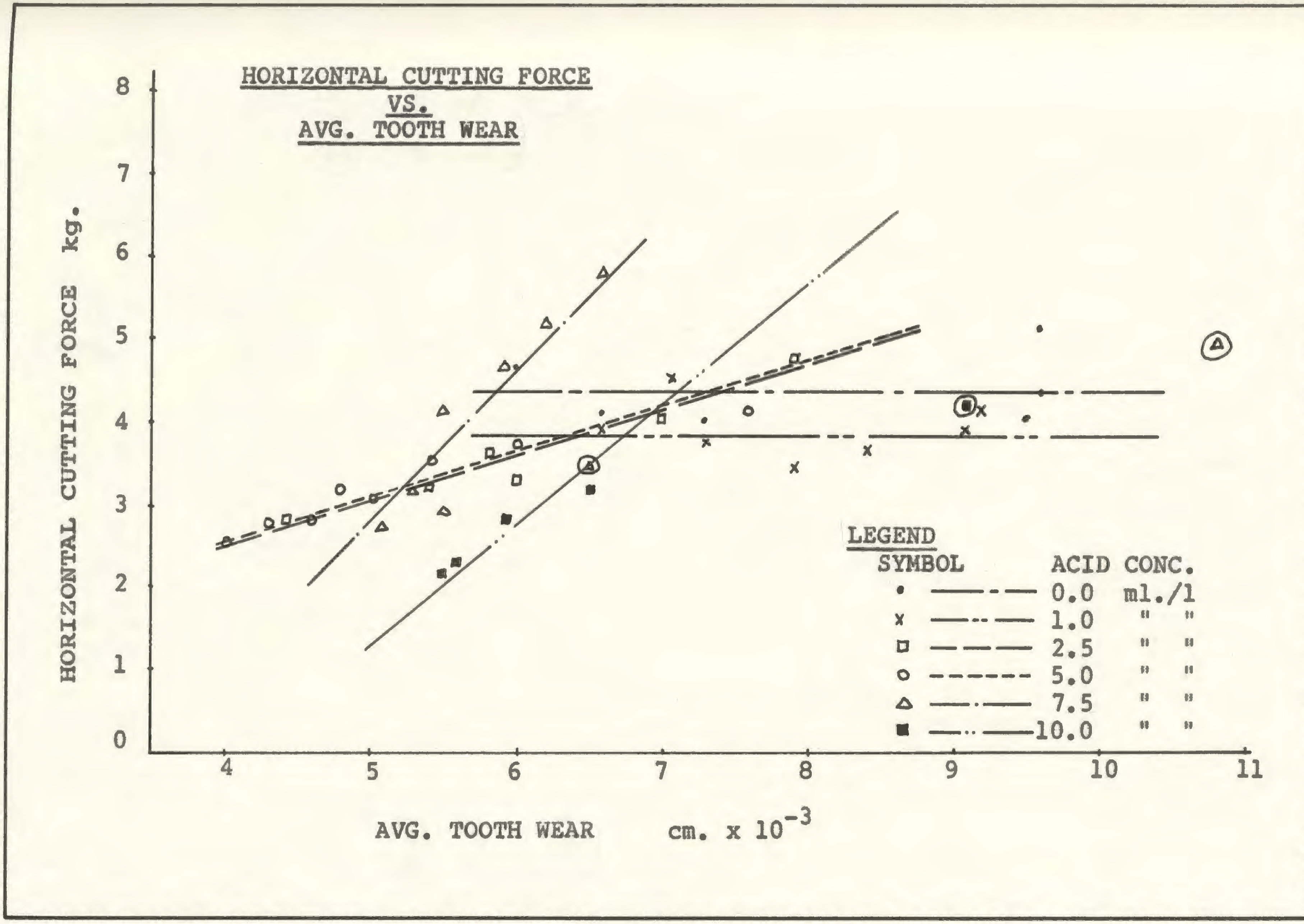



FIG. 6.10 HORIZONTAL CUTTING FORCE AGAINST AVERAGE TOOTH WEAR. COMPARISON OF SLOPES BY SULPHURIC ACID CONCENTRATION.

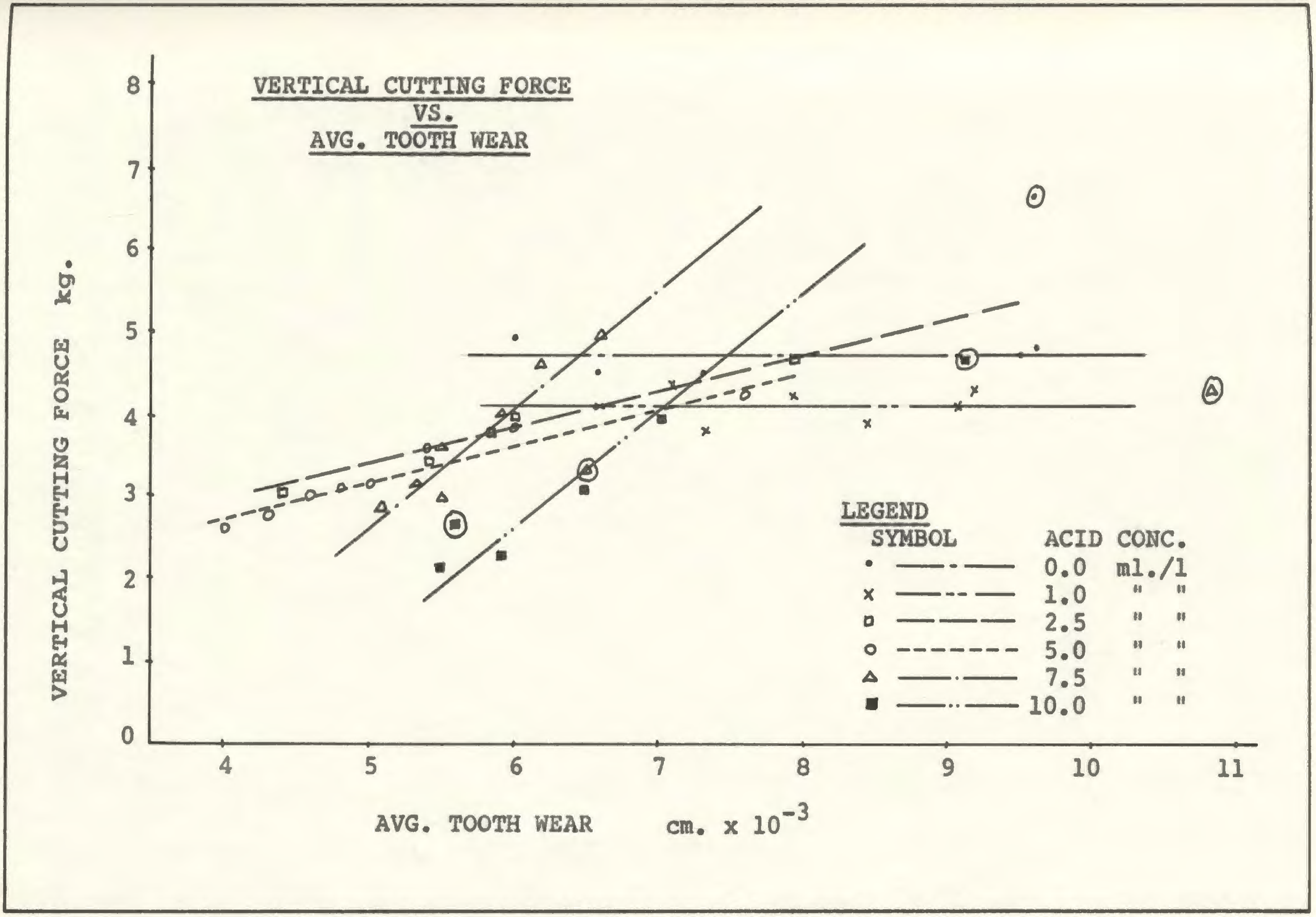



FIG. 6.11 VERTICAL CUTTING FORCE AGAINST AVERAGE TOOTH WEAR.
COMPARISON OF SLOPES BY SULPHURIC ACID CONCENTRATION.

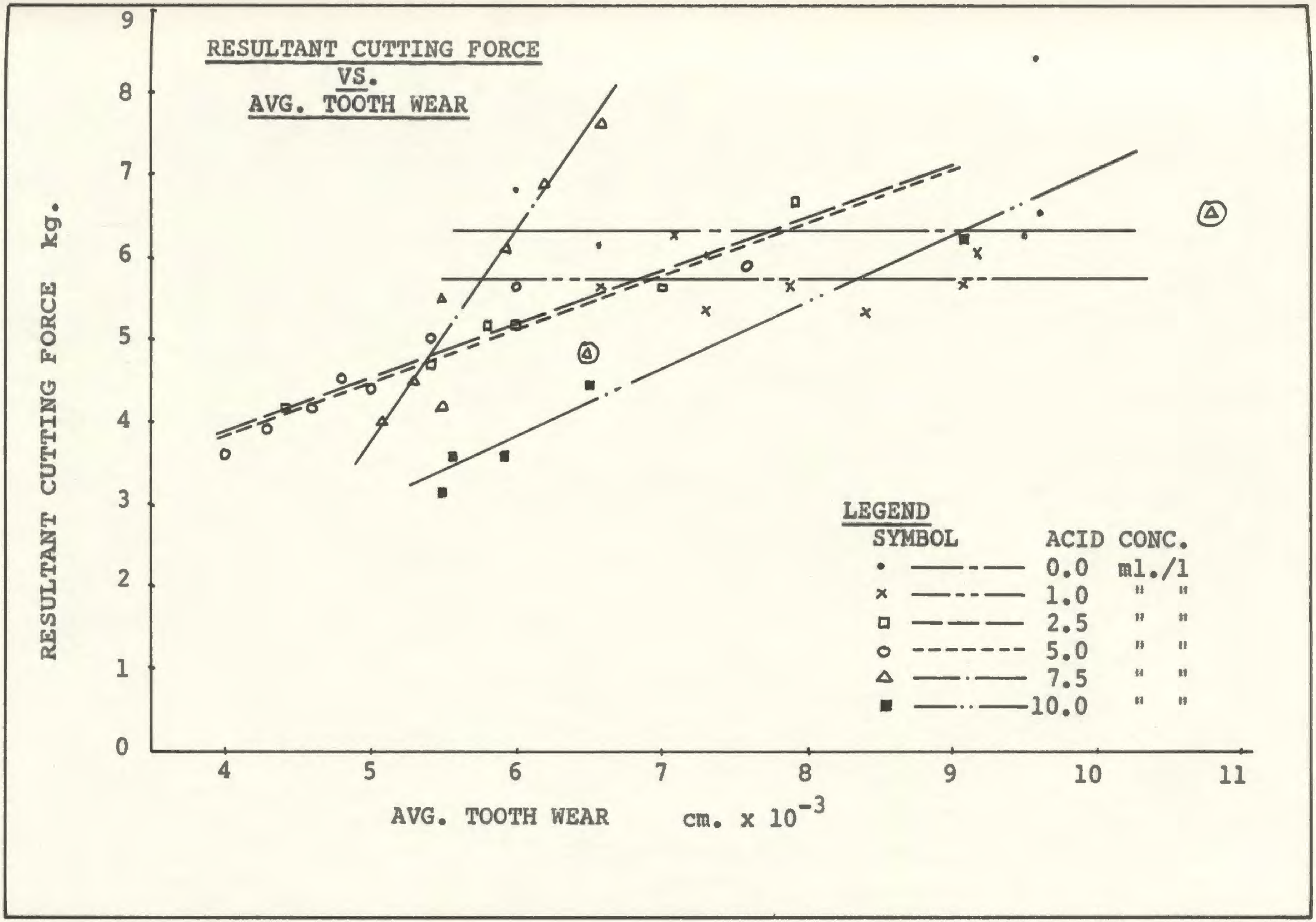



FIG. 6.12 RESULTANT CUTTING FORCE AGAINST AVERAGE TOOTH WEAR. COMPARISON OF SLOPES BY SULPHURIC ACID CONCENTRATION.

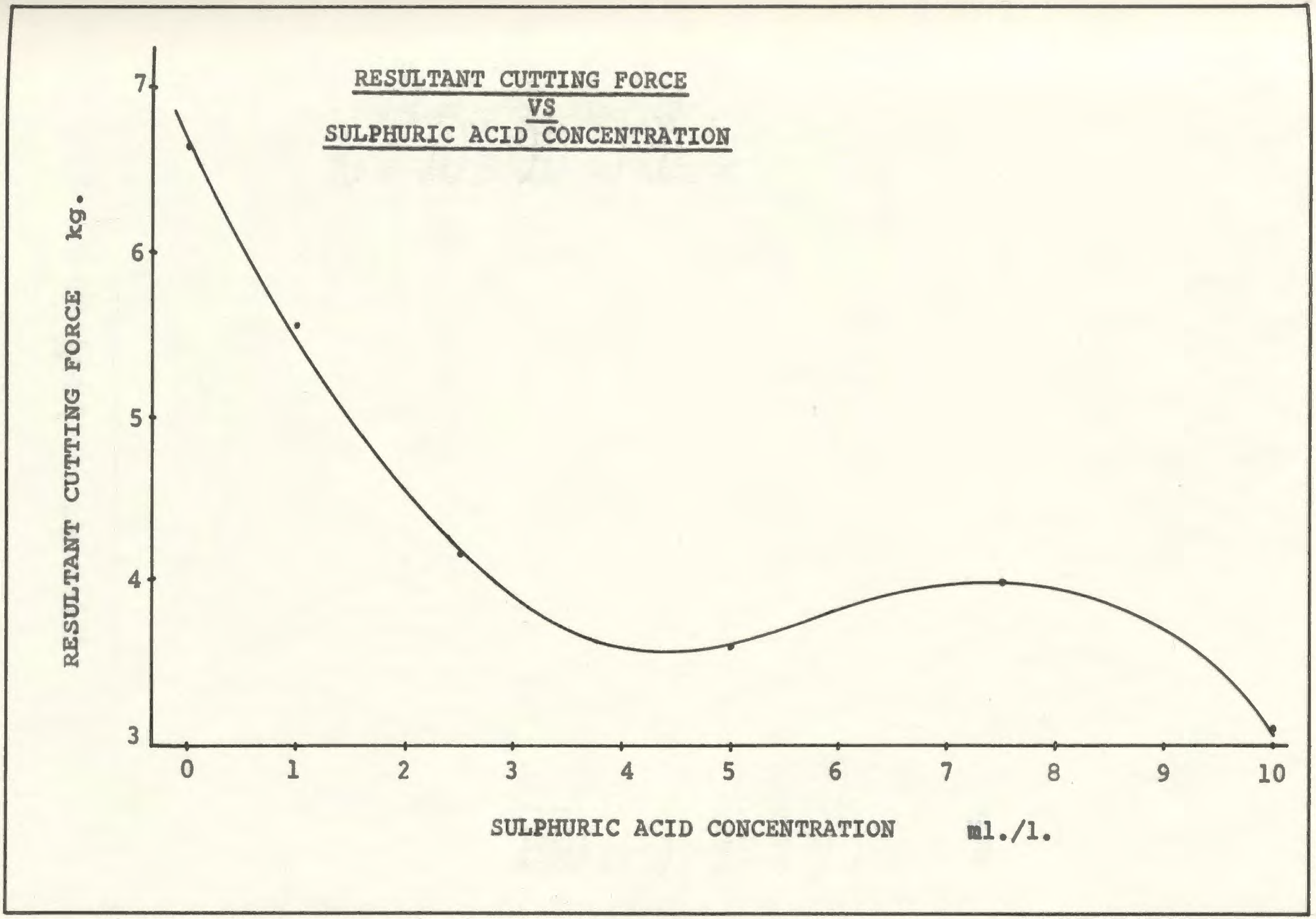



FIG. 6.13 CROSS SECTION OF FIGURE 6.6 AT 11.1 GRAMS OF COPPER SULPHATE PER LITRE OF SOLUTION

cutting tool, are kept to a minimum.

## 6.35 CONCLUSION

The conclusion to be drawn from the analysis of Part 1 data is that a concentration of 5 millilitres per litre of acid and 11.1 grams of copper sulphate per litre of solution, as suggested in paragraph 6.34, is in fact valid, and will be used as the cutting fluid for Part 11 of the investigation.

## 6.40 PART 11 -- COMPARISON OF SULPHURIZED OIL WITH OPTIMIZED COPPER SULPHATE CUTTING FLUID

Having proposed the use of an electrolyte plating solution to be used as a cutting fluid, and selecting its optimum composition, it now becomes necessary to compare this cutting fluid with a sulphurized oil recommended by the manufacturer for this particular application.[1]

## 6.41 METHOD OF ANALYSIS

The method of analysis of the data followed the same procedure as used in Part 1. The raw data was fed into a modified form of Program B1 to determine average values and standard deviations. The results of these calculations can be seen in Table 6.8.

Examination of Table 6.8 will be by means of a scatter diagram and straight line regression analysis using the various computer programs as described in paragraph 6.42.

---

[1]VEEDOL AFTON #8   1.2 to 2% sulphur

TABLE 6.8

AVERAGE VALUES AND STANDARD DEVIATIONS - PART 11 DATA

| TEST NO | TOOTH WEAR AV | TOOTH WEAR SD | HZ FORCE AV | HZ FORCE SD | V FORCE AV | V FORCE SD | R FORCE AV | R FORCE SD | POWER AV | POWER SD | FEED RATE | DEPTH OF CUT | CLA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A11 | 0.0070 | 0.002 | 3.466 | 0.517 | 5.216 | 1.270 | 6.278 | 1.282 | -0.009 | 0.008 | 2.1 | 0.005 | 9. |
| A12 | 0.0081 | 0.001 | 4.650 | 0.266 | 7.608 | 0.427 | 8.917 | 0.494 | -0.019 | 0.031 | 2.1 | 0.005 | 10. |
| A13 | 0.0094 | 0.002 | 5.366 | 0.277 | 8.566 | 0.302 | 10.109 | 0.402 | 0.017 | 0.016 | 2.1 | 0.005 | 12. |
| A14 | 0.0108 | 0.000 | 5.925 | 0.146 | 9.350 | 0.129 | 11.069 | 0.171 | 0.004 | 0.027 | 2.1 | 0.005 | 10. |
| A15 | 0.0113 | 0.000 | 6.091 | 0.257 | 9.816 | 0.378 | 11.553 | 0.453 | -0.014 | 0.012 | 2.1 | 0.005 | 11. |
| A21 | 0.0084 | 0.001 | 6.741 | 1.071 | 8.850 | 2.043 | 11.131 | 2.267 | -0.005 | 0.017 | 2.1 | 0.010 | 10. |
| A22 | 0.0098 | 0.002 | 8.166 | 0.077 | 11.875 | 0.228 | 14.413 | 0.168 | 0.004 | 0.009 | 2.1 | 0.010 | 12. |
| A23 | 0.0120 | 0.001 | 10.311 | 0.212 | 16.328 | 0.166 | 19.313 | 0.128 | 0.032 | 0.062 | 2.1 | 0.010 | 16. |
| A24 | 0.0137 | 0.001 | 11.275 | 0.439 | 17.533 | 0.640 | 20.845 | 0.775 | 0.012 | 0.012 | 2.1 | 0.010 | 20. |
| A25 | 0.0144 | 0.000 | 11.633 | 1.945 | 18.983 | 1.424 | 22.288 | 2.115 | -0.009 | 0.012 | 2.1 | 0.010 | 15. |
| A31 | 0.0100 | 0.001 | 9.920 | 1.030 | 10.586 | 2.237 | 14.527 | 2.315 | -0.003 | 0.010 | 7.7 | 0.010 | 16. |
| A32 | 0.0115 | 0.001 | 11.680 | 1.134 | 15.273 | 1.850 | 19.232 | 2.115 | 0.002 | 0.007 | 7.7 | 0.010 | 35. |
| A33 | 0.0131 | 0.002 | 12.540 | 1.150 | 17.233 | 1.198 | 21.315 | 1.620 | -0.005 | 0.009 | 7.7 | 0.010 | 28. |
| A34 | 0.0124 | 0.002 | 13.806 | 1.168 | 20.400 | 1.646 | 24.636 | 1.960 | -0.005 | 0.010 | 7.7 | 0.010 | 15. |
| A35 | 0.0140 | 0.000 | 15.654 | 1.197 | 22.731 | 1.438 | 27.600 | 1.855 | -0.003 | 0.006 | 7.7 | 0.010 | 23. |
| A41 | 0.0095 | 0.001 | 5.041 | 0.696 | 5.450 | 1.070 | 7.428 | 1.250 | -0.007 | 0.018 | 7.7 | 0.005 | 22. |
| A42 | 0.0099 | 0.001 | 6.050 | 0.748 | 7.625 | 1.162 | 9.737 | 1.345 | -0.004 | 0.011 | 7.7 | 0.005 | 17. |
| A43 | 0.0105 | 0.001 | 6.733 | 0.757 | 9.433 | 1.299 | 11.594 | 1.457 | 0.035 | 0.060 | 7.7 | 0.005 | 18. |
| A44 | 0.0114 | 0.000 | 7.266 | 1.194 | 11.550 | 2.060 | 13.646 | 2.380 | 0.010 | 0.020 | 7.7 | 0.005 | 20. |
| A45 | 0.0117 | 0.003 | 7.925 | 1.152 | 13.133 | 1.695 | 15.339 | 2.043 | 0.019 | 0.020 | 7.7 | 0.005 | 22. |
| A51 | 0.0052 | 0.003 | 4.758 | 0.364 | 4.075 | 0.344 | 6.265 | 0.497 | -0.000 | 0.009 | 7.7 | 0.005 | 47. |
| A52 | 0.0107 | 0.002 | 5.375 | 0.210 | 4.791 | 0.321 | 7.201 | 0.370 | 0.002 | 0.008 | 7.7 | 0.005 | 53. |
| A53 | 0.0124 | 0.003 | 5.291 | 0.653 | 5.725 | 0.745 | 7.796 | 0.989 | 0.028 | 0.046 | 7.7 | 0.005 | 29. |
| A54 | 0.0175 | 0.003 | 6.175 | 0.705 | 6.833 | 0.796 | 9.210 | 1.059 | -0.006 | 0.022 | 7.7 | 0.005 | 52. |
| A55 | 0.0180 | 0.000 | 6.166 | 0.933 | 7.283 | 1.202 | 9.543 | 1.517 | 0.004 | 0.031 | 7.7 | 0.005 | 46. |
| A61 | 0.0064 | 0.003 | 7.491 | 0.373 | 6.741 | 0.538 | 10.079 | 0.634 | -0.054 | 0.134 | 7.7 | 0.010 | 36. |
| A62 | 0.0129 | 0.003 | 8.883 | 0.814 | 8.333 | 0.850 | 12.180 | 1.170 | 0.038 | 0.045 | 7.7 | 0.010 | 74. |
| A63 | 0.0161 | 0.003 | 11.558 | 0.392 | 11.941 | 0.482 | 16.619 | 0.614 | -0.001 | 0.022 | 7.7 | 0.010 | 42. |
| A64 | 0.0193 | 0.004 | 11.850 | 0.637 | 12.208 | 0.991 | 17.016 | 1.130 | 0.004 | 0.034 | 7.7 | 0.010 | 47. |
| A65 | 0.0219 | 0.002 | 12.425 | 2.157 | 13.358 | 2.682 | 18.245 | 3.430 | -0.007 | 0.020 | 7.7 | 0.010 | 67. |

TABLE 6.8 (Continued)

| TEST NO | TOOTH WEAR AV | TOOTH WEAR SD | HZ FORCE AV | HZ FORCE SD | V FORCE AV | V FORCE SD | R FORCE AV | R FORCE SD | POWER AV | POWER SD | FEED RATE | DEPTH OF CUT | CLA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A71 | 0.0044 | 0.005 | 1.541 | 0.294 | 2.125 | 0.494 | 2.632 | 0.534 | 0.001 | 0.042 | 2.1 | 0.005 | 27. |
| A72 | 0.0075 | 0.004 | 2.433 | 0.226 | 3.108 | 0.377 | 3.952 | 0.386 | 0.006 | 0.036 | 2.1 | 0.005 | 12. |
| A73 | 0.0131 | 0.002 | 3.116 | 0.306 | 4.350 | 0.476 | 5.352 | 0.555 | -0.045 | 0.058 | 2.1 | 0.005 | 26. |
| A74 | 0.0233 | 0.003 | 3.791 | 0.929 | 5.433 | 1.447 | 6.626 | 1.717 | -0.001 | 0.008 | 2.1 | 0.005 | 57. |
| A75 | 0.0304 | 0.003 | 5.008 | 0.528 | 5.533 | 0.688 | 7.464 | 0.855 | -0.007 | 0.020 | 2.1 | 0.005 | 11. |
| A81 | 0.0086 | 0.003 | 4.183 | 0.736 | 4.341 | 0.900 | 6.030 | 1.155 | 0.000 | 0.007 | 2.1 | 0.010 | 67. |
| A82 | 0.0145 | 0.002 | 4.758 | 0.691 | 5.475 | 0.933 | 7.255 | 1.145 | -0.005 | 0.013 | 2.1 | 0.010 | 24. |
| A83 | 0.0262 | 0.003 | 7.616 | 0.680 | 9.383 | 1.510 | 12.094 | 1.575 | 0.006 | 0.018 | 2.1 | 0.010 | 32. |
| A84 | 0.0349 | 0.008 | 8.750 | 0.709 | 11.091 | 1.177 | 14.140 | 1.200 | 0.000 | 0.035 | 2.1 | 0.010 | 64. |
| A85 | 0.0446 | 0.010 | 10.625 | 0.417 | 14.391 | 1.046 | 17.892 | 1.057 | 0.004 | 0.015 | 2.1 | 0.010 | 49. |

The data for this section of the investigation seem to be more significant than for Part 1 in that the values of standard deviation for wear and resultant force are a little lower, although some results are poor.

Samples picked at random, test A24 and A63, give confidence levels of $0.0137 \pm .00057$ centimetres and $.0161 \pm .0017$ centimetres at 95 per cent for wear, and $20.845 \pm .574$ kilograms and $16.619 \pm .455$ kilograms respectively for resultant cutting force. The straight line regression analysis will be carried out by regressing wear, cutting forces, cutting power, and surface finish on volume of metal removed.

### 6.42 COMPUTER PROGRAMS USED

The first program to be used was a modified version of Program B1, which we shall call PROGRAM B2. The punch card output of this Program was used as input to Program B5 to perform a straight line regression analysis.

PROGRAM B6 was devised to read the card output of the straight line regression program and plot curves of wear, cutting forces, surface finish, and cutting power against volume of metal removed, on an IBM 1726 drum plotter. These plots, xerographically reduced, were then traced to form Figures 6.14, 6.15, 6.16, 6.17, 6.18, 6.19, 6.20, and 6.21. Listings of these and other programs can be seen in Appendix B.

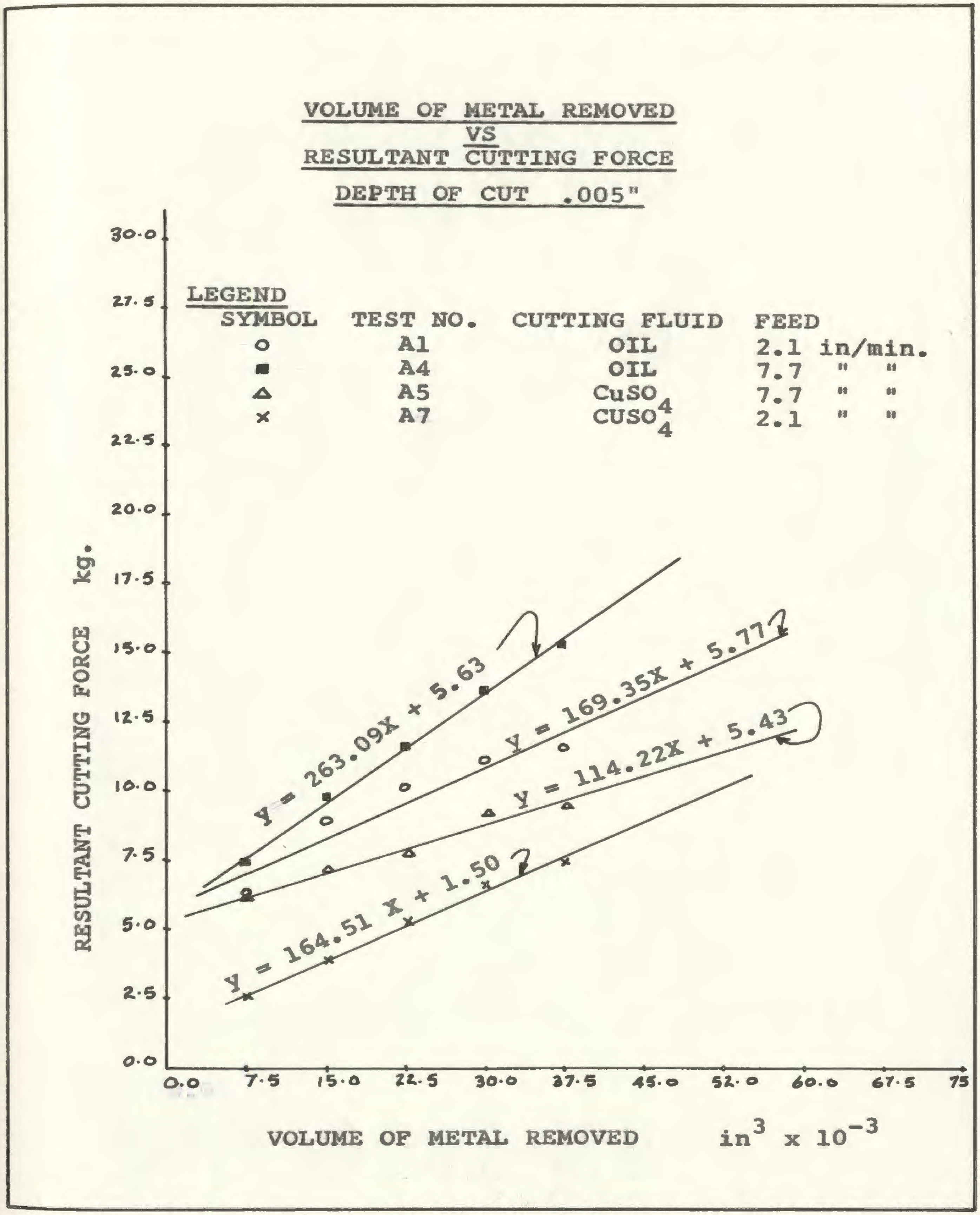



FIG. 6.14 VOLUME OF METAL REMOVED AGAINST RESULTANT CUTTING FORCE. DEPTH OF CUT .005"

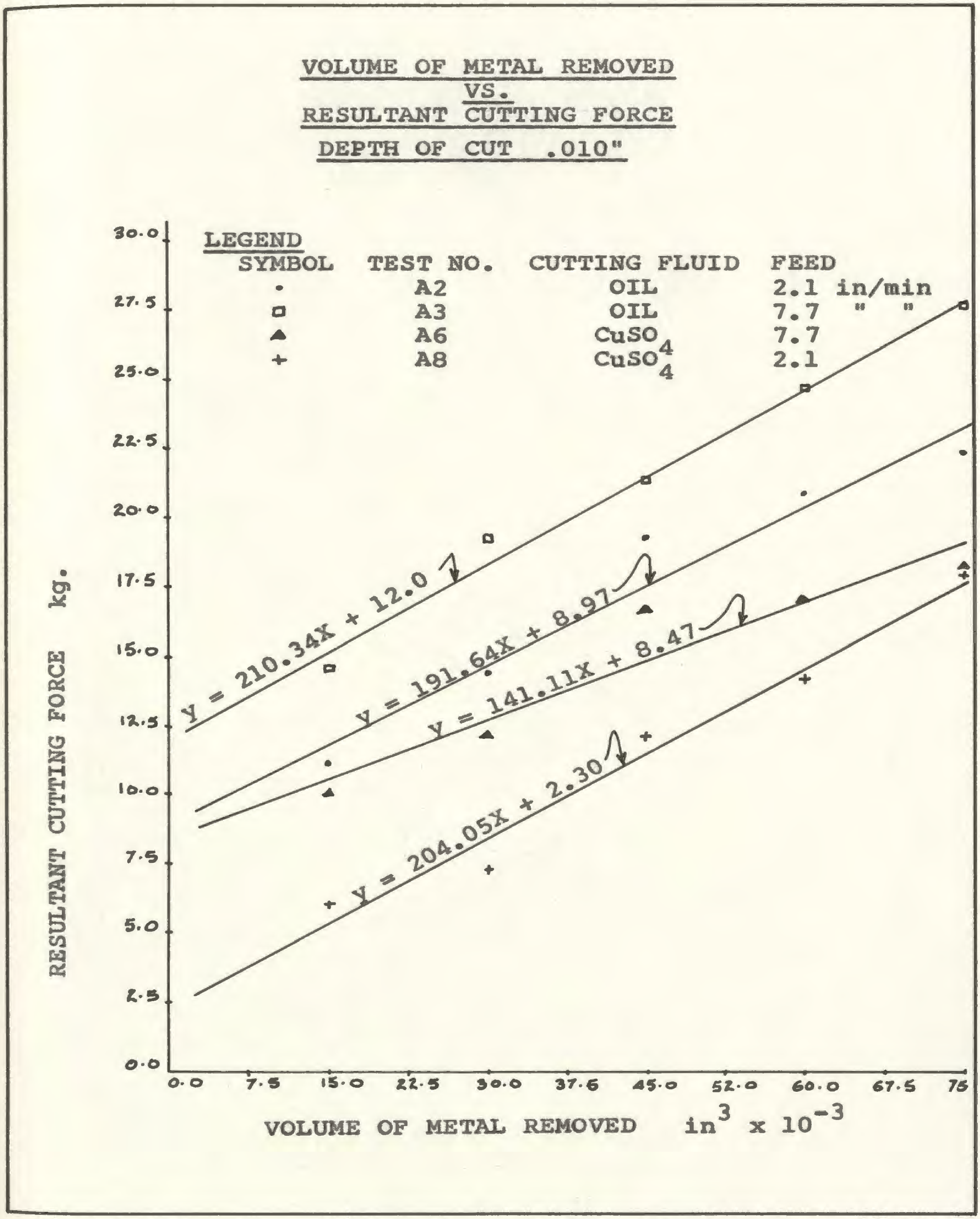



FIG. 6.15 VOLUME OF METAL REMOVED AGAINST RESULTANT CUTTING FORCE. DEPTH OF CUT .010"

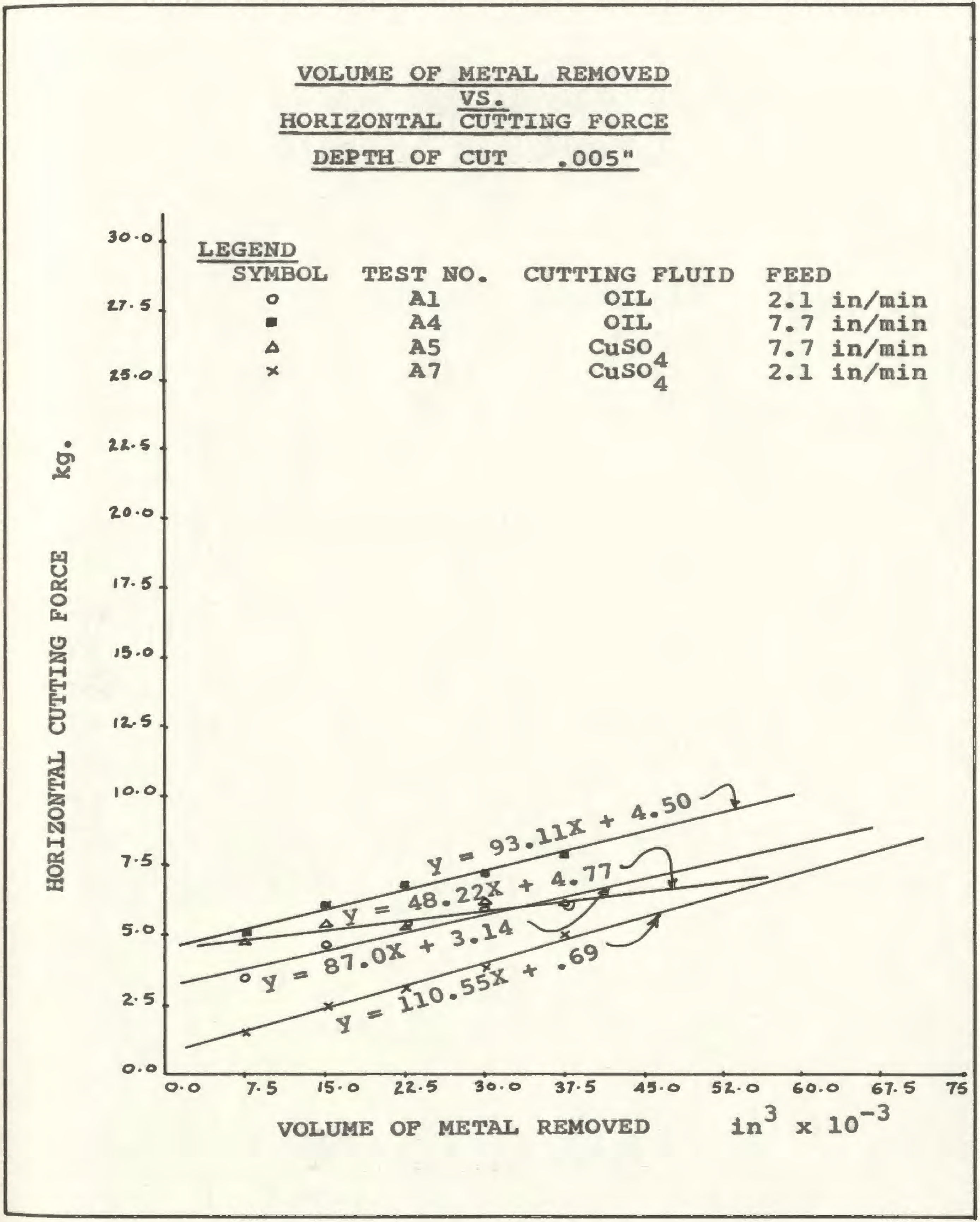



FIG. 6.16 VOLUME OF METAL REMOVED AGAINST HORIZONTAL CUTTING FORCE. DEPTH OF CUT .005"

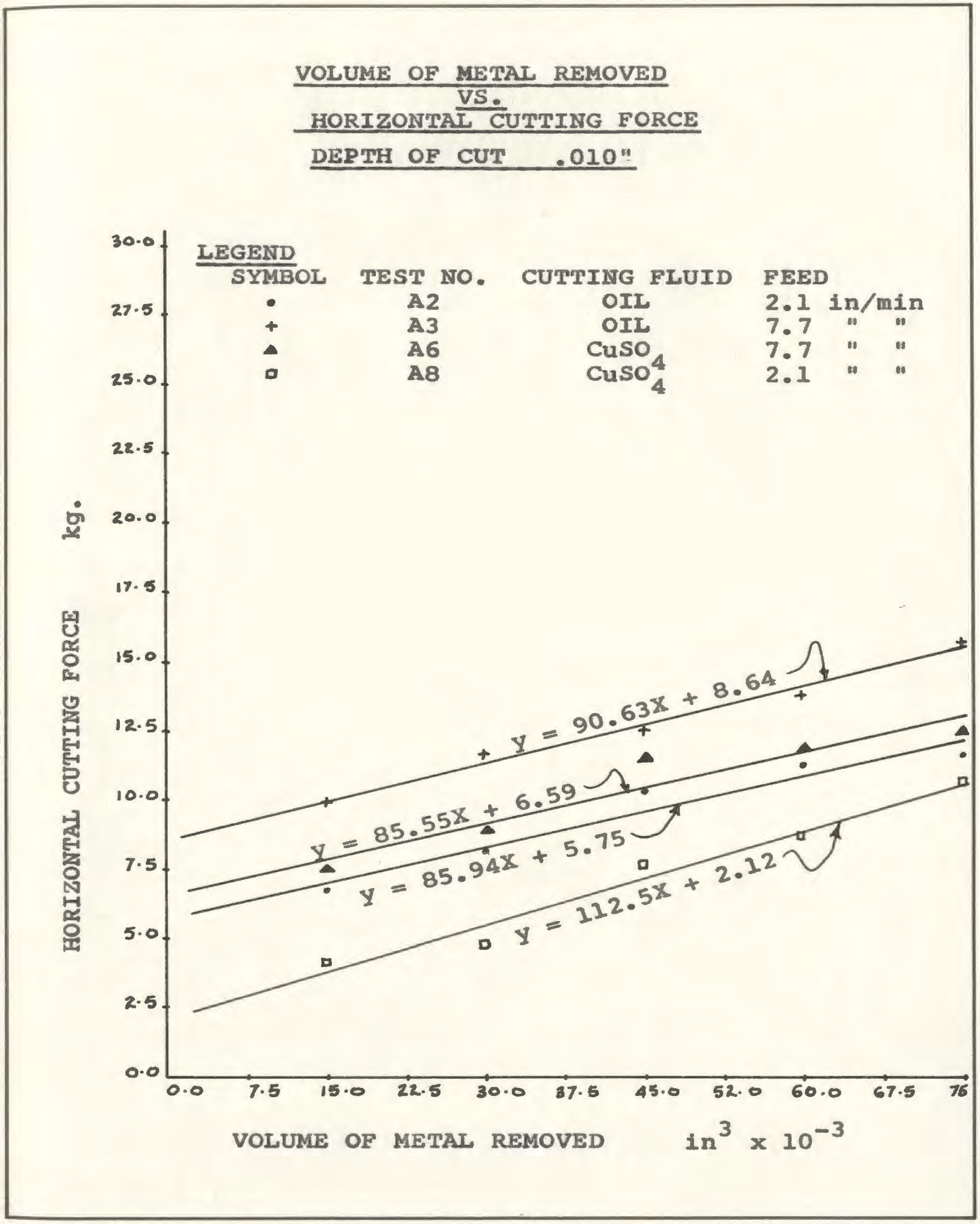



FIG. 6.17 VOLUME OF METAL REMOVED AGAINST HORIZONTAL CUTTING FORCE. DEPTH OF CUT .010"

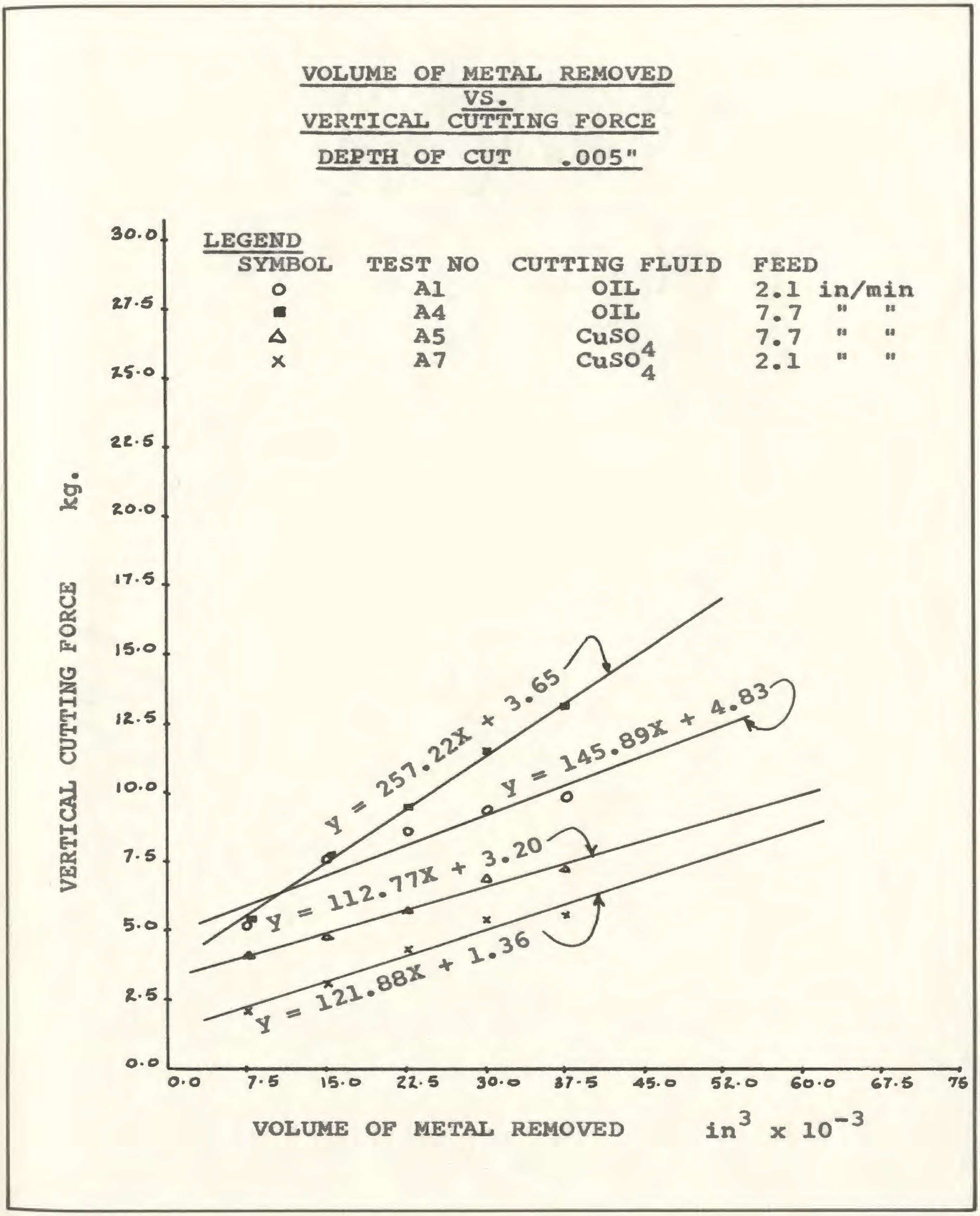



FIG. 6.18 VOLUME OF METAL REMOVED AGAINST VERTICAL CUTTING FORCE. DEPTH OF CUT .005"

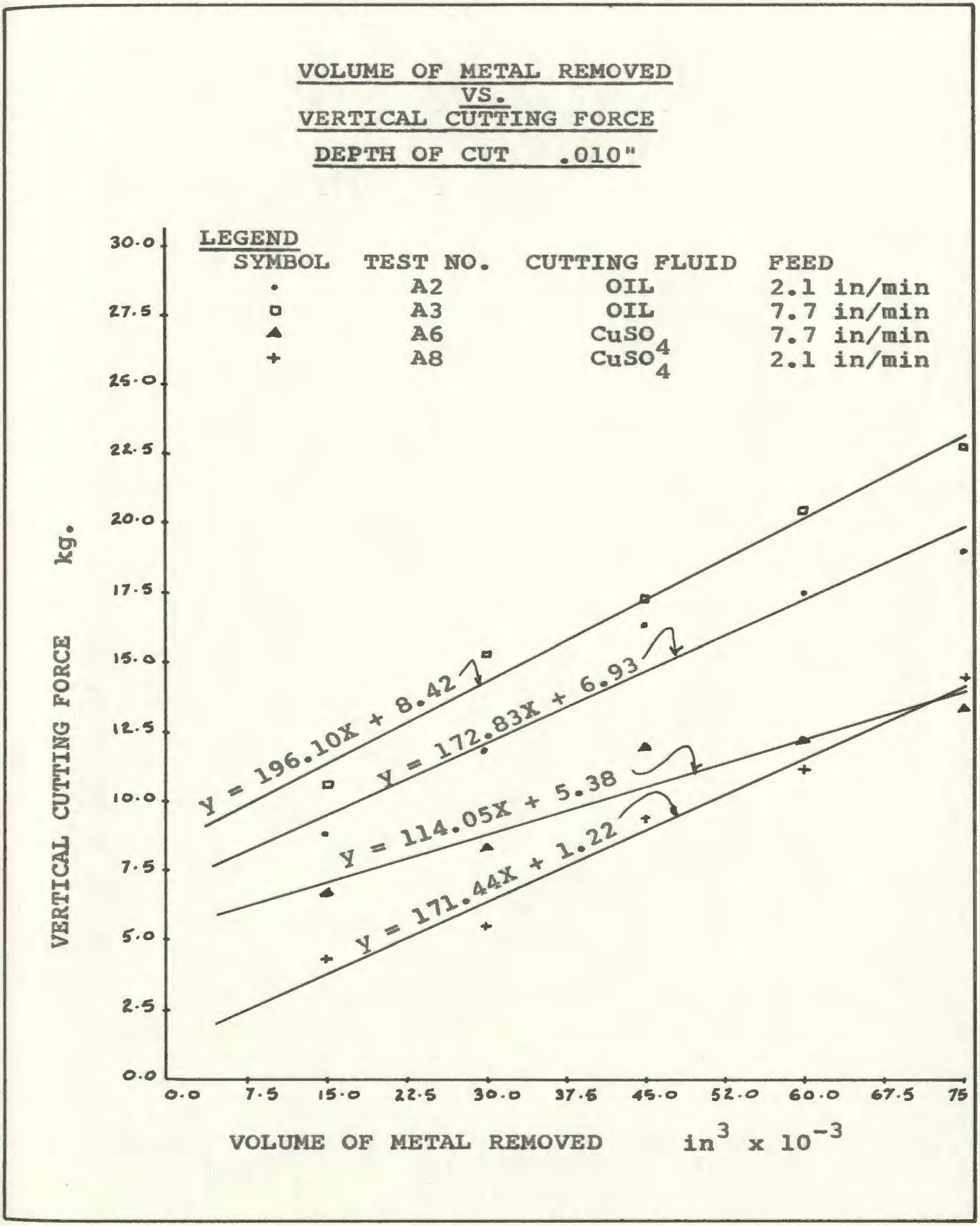



FIG. 6.19 VOLUME OF METAL REMOVED AGAINST VERTICAL CUTTING FORCE. DEPTH OF CUT .010"

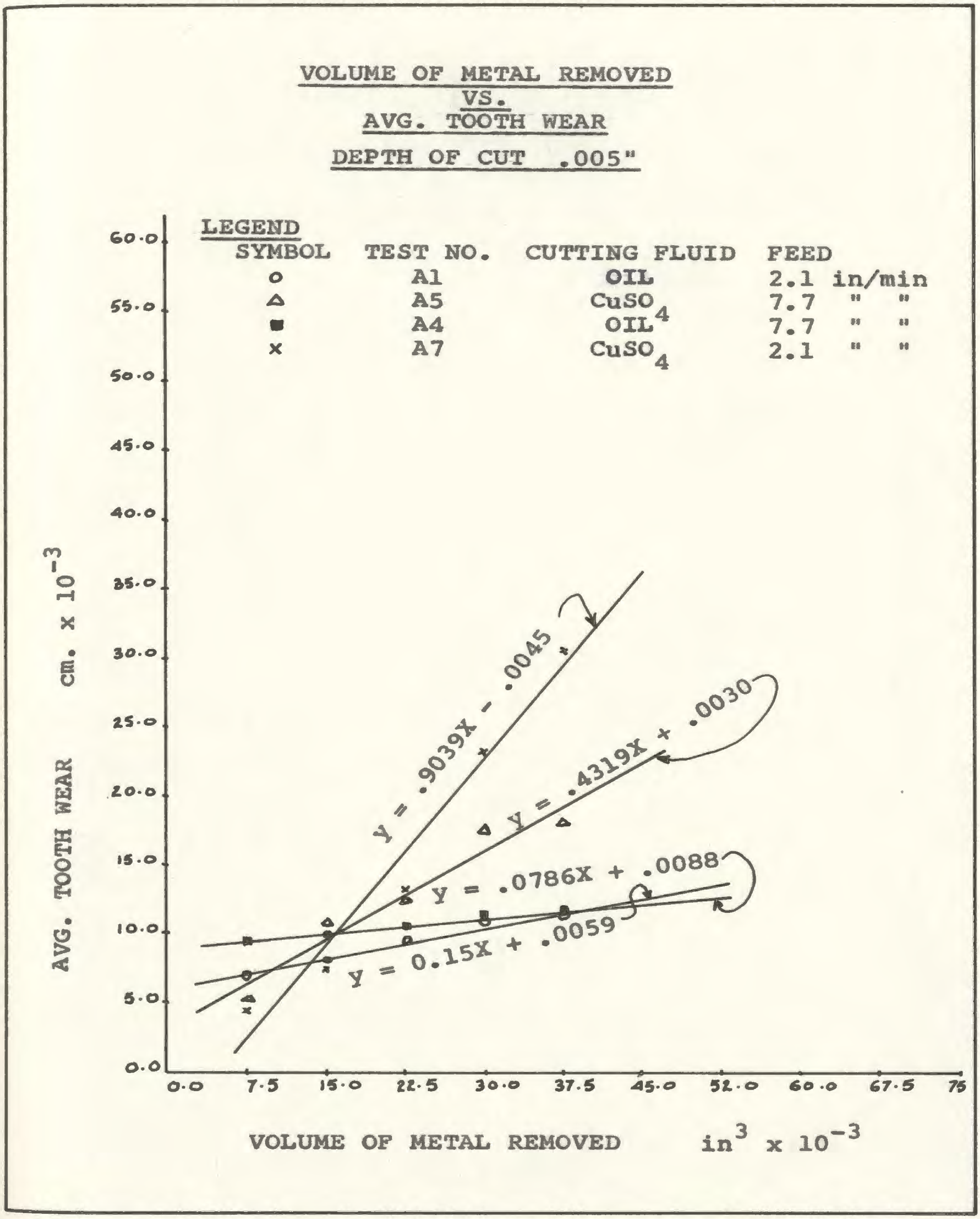



FIG. 6.20 VOLUME OF METAL REMOVED AGAINST AVERAGE TOOTH WEAR. DEPTH OF CUT .005"

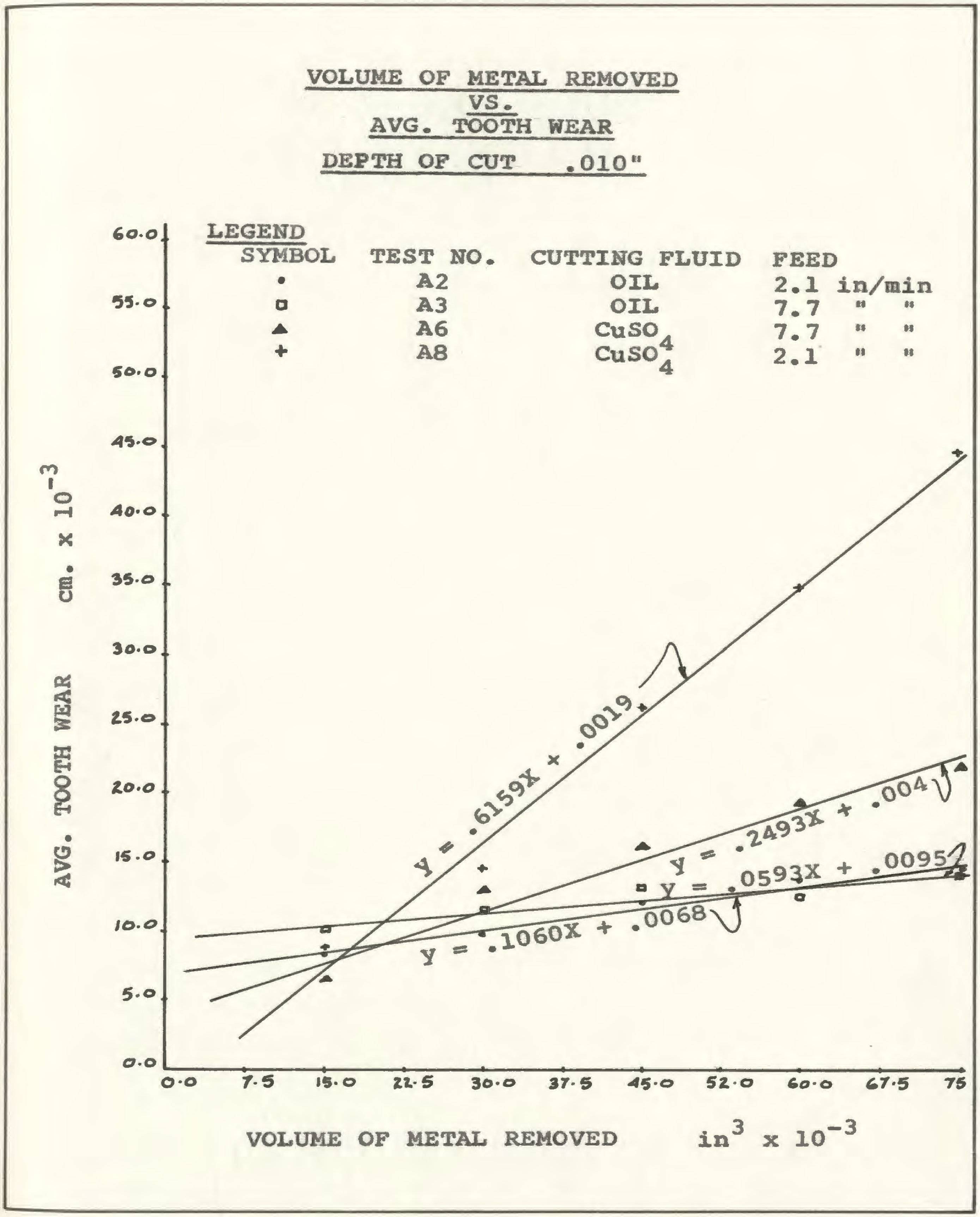



FIG. 6.21 VOLUME OF METAL REMOVED AGAINST AVERAGE TOOTH WEAR. DEPTH OF CUT .010"

## 6.43 ANALYSIS OF DATA

Using Program B5 and the data presented in Table 6.8, a straight line regression analysis was performed with the results as shown in Table 6.9. This table is arranged into six groupings: wear, horizontal cutting force, vertical cutting force, resultant cutting force, cutting power and surface finish. A quick appraisal will show that the last two variables can be neglected as the correlation coefficients are extremely low. Those of wear and cutting forces are quite high, requiring further investigation.

The slopes of the curves given for wear are rather low, so that a check to see if they are significantly different from Zero is in order. This may be seen from the null hypothesis statistic of Table 6.9. For N-2 degrees of freedom, any value greater than 2.179 has a slope that is significantly greater than Zero at the 95 per cent level of confidence. For cutting forces, the plus distribution indicates 3.182 as the critical value.

This means that the slope of these curves is a result of the relationship between the variables and is not due to random variation. It must, at this point, be noted that the null hypothesis statistic for cutting power and surface finish is less than the plus distribution value and, therefore, the slope of the regression line is a result of random variation and not the result of a relationship between

TABLE 6.9

STRAIGHT LINE REGRESSION COEFFICIENTS, PART 11

| TEST NO. | SLOPE | INTERCEPT | CORR. COEFF. | FEED RATE (IN/MIN) | DEPTH OF CUT (IN) | NULL HYP. STATISTIC |
|---|---|---|---|---|---|---|
| **Cutter tooth wear:** | | | | | | |
| A3 | 0.0593 | 0.0095 | 0.9169 | 7.7 | 0.010 | 3.9814 |
| A6 | 0.2493 | 0.0040 | 0.9816 | 7.7 | 0.010 | 8.9050 |
| A2 | 0.1060 | 0.0068 | 0.9885 | 2.1 | 0.010 | 11.3278 |
| A8 | 0.6159 | -0.0019 | 0.9964 | 2.1 | 0.010 | 20.3980 |
| A1 | 0.1506 | 0.0059 | 0.9915 | 2.1 | 0.005 | 13.2248 |
| A7 | 0.9039 | -0.0045 | 0.9831 | 2.1 | 0.005 | 9.3282 |
| A4 | 0.0786 | 0.0088 | 0.9888 | 7.7 | 0.005 | 11.4928 |
| A5 | 0.4319 | 0.0030 | 0.9705 | 7.7 | 0.005 | 6.9735 |
| **Vertical cutting force:** | | | | | | |
| A3 | 196.1033 | 8.4202 | 0.9900 | 7.7 | 0.010 | 12.1966 |
| A6 | 114.0545 | 5.3842 | 0.9566 | 7.7 | 0.010 | 5.6861 |
| A2 | 172.8324 | 6.9365 | 0.9713 | 2.1 | 0.010 | 7.0839 |
| A8 | 171.4446 | 1.2216 | 0.9883 | 2.1 | 0.010 | 11.2662 |
| A1 | 145.8889 | 4.8291 | 0.9494 | 2.1 | 0.005 | 5.2365 |
| A7 | 121.8879 | 1.3675 | 0.9757 | 2.1 | 0.005 | 7.7141 |
| A4 | 257.2210 | 3.6508 | 0.9987 | 7.7 | 0.005 | 35.1205 |
| A5 | 112.7760 | 3.2041 | 0.9934 | 7.7 | 0.005 | 15.0548 |
| **Horizontal cutting force:** | | | | | | |
| A3 | 90.6313 | 8.6417 | 0.9929 | 7.7 | 0.010 | 14.5506 |
| A6 | 85.5554 | 6.5916 | 0.9488 | 7.7 | 0.010 | 5.2027 |
| A2 | 85.9431 | 5.7582 | 0.9698 | 2.1 | 0.010 | 6.8960 |
| A8 | 112.5004 | 2.1241 | 0.9847 | 2.1 | 0.010 | 9.7898 |
| A1 | 86.9998 | 3.1425 | 0.9614 | 2.1 | 0.005 | 6.0597 |
| A7 | 110.5545 | 0.6908 | 0.9937 | 2.1 | 0.005 | 15.3626 |
| A4 | 93.1105 | 4.5083 | 0.9926 | 7.7 | 0.005 | 14.2508 |
| A5 | 48.2241 | 4.4682 | 0.9354 | 7.7 | 0.005 | 4.5819 |
| **Resultant cutting force:** | | | | | | |
| A3 | 210.3384 | 11.9973 | 0.9935 | 7.7 | 0.010 | 15.1687 |
| A6 | 141.1125 | 8.4782 | 0.9539 | 7.7 | 0.010 | 5.5100 |
| A2 | 191.6382 | 8.9746 | 0.9720 | 2.1 | 0.010 | 7.1773 |
| A8 | 204.0551 | 2.3000 | 0.9872 | 2.1 | 0.010 | 10.7613 |
| A1 | 169.3544 | 5.7751 | 0.9538 | 2.1 | 0.005 | 5.5043 |
| A7 | 164.5173 | 1.5037 | 0.9963 | 2.1 | 0.005 | 20.2358 |
| A4 | 263.0906 | 5.6297 | 0.9987 | 7.7 | 0.005 | 34.4834 |
| A5 | 114.2239 | 5.4333 | 0.9866 | 7.7 | 0.005 | 10.5123 |

TABLE 6.9 (Continued)

| TEST NO. | SLOPE | INTERCEPT | CORR. COEFF. | FEED RATE (IN/MIN) | DEPTH OF CUT (IN) | NULL HYP. STATISTIC |
|---|---|---|---|---|---|---|
| **Surface finish (CLA):** | | | | | | |
| A3 | -43.3323 | 25.9499 | -0.1219 | 7.7 | 0.010 | -0.2127 |
| A6 | 226.6677 | 43.5332 | 0.3274 | 7.7 | 0.010 | 0.6003 |
| A2 | 122.2224 | 9.5666 | 0.7427 | 2.1 | 0.010 | 1.9214 |
| A8 | 24.4433 | 46.3333 | 0.0305 | 2.1 | 0.010 | 0.0529 |
| A1 | 66.6654 | 9.2666 | 0.6378 | 2.1 | 0.005 | 1.4344 |
| A7 | 168.8891 | 23.2666 | 0.1081 | 2.1 | 0.005 | 0.1884 |
| A4 | 51.9991 | 19.1366 | 0.2990 | 7.7 | 0.005 | 0.5428 |
| A5 | -35.5568 | 46.6666 | -0.0426 | 7.7 | 0.005 | -0.0739 |
| **Cutting power:** | | | | | | |
| A3 | -0.0526 | -0.0011 | -0.3850 | 7.7 | 0.010 | -0.7227 |
| A6 | 0.4000 | -0.0225 | 0.2848 | 7.7 | 0.010 | 0.5146 |
| A2 | -0.0053 | 0.0067 | -0.0076 | 2.1 | 0.010 | -0.0132 |
| A8 | 0.0926 | -0.0033 | 0.4811 | 2.1 | 0.010 | 0.9507 |
| A1 | 0.1853 | -0.0089 | 0.1458 | 2.1 | 0.005 | 0.2552 |
| A7 | -0.3426 | -0.0020 | -0.1950 | 2.1 | 0.005 | -0.3445 |
| A4 | 0.9159 | -0.0103 | 0.6149 | 7.7 | 0.005 | 1.3506 |
| A5 | 0.0120 | 0.0049 | 0.0106 | 7.7 | 0.005 | 0.0184 |

cutting power, surface finish and the volume of metal removed.

Further examination of the data by means of scatter diagrams, as shown in Figures 6.14 to 6.21 inclusive, follows.

Figures 6.14 to 6.19 indicate that a greater cutting force is required by the sulphurized oil than for the copper sulphate solution, with greater forces required by the higher feed rate than for the lower feed rate in each case. Examination of Figures 6.14 and 6.15 together show that greater cutting forces are required for .010" depth of cut than for .005" depth of cut.

This trend is also valid for horizontal and vertical cutting forces as indicated in Figures 6.16, 6.17, 6.18 and 6.19 respectively, and is as one would expect.

Finally, it should be noted that the above curves show a tendency toward a uniform slope, especially in Figure 6.17. However, Figures 6.16, 6.18 and 6.19 have one odd slope each, which apparently appears at random, so that no particular trend can be established.

Based on the results of cutting force and the fair relationship between wear and cutting force established in Figures 6.7, 6.8 and 6.9 (Paragraph 6.35), it is reasonable to assume that the trends established for cutting forces would also be valid for wear.

Close examination of Figures 6.20 and 6.21 for volumes of 7.5 x $10^{-3}$ and 15 x $10^{-3}$ cubic inches removed respectively (i.e., the first test run), shows that this is partly true in that the wear for oil is greater than the wear experienced using copper sulphate for the same feed rates. Although this is true for a depth of cut of .005", it is less true for a depth of cut of .010". Beyond this point, however, the conclusions vary widely. First of all, the slope of the curves (the wear rate) shows clearly that in every case the rate of cutter tooth wear is greater using copper sulphate than using oil. Further, the greater the feed rate, the lower the wear rate, suggesting an optimum feed rate outside the range of the experiment. Last, but not least, the wear rate is greater for the lower depth of cut.

6.44 DISCUSSION OF RESULTS

In as much as the results as shown in Figures 6.20 and 6.21 are consistent for both oil and copper sulphate for feed and depth of cut, little comment will be made other than to state that these results indicate an optimum feed rate and an optimum depth of cut is present which was beyond the scope of this experiment.

The difference in wear and wear rate exhibited by the copper sulphate versus oil is another matter, as it is not consistent with the results of the pilot study and Part 1.

The pilot study indicated a preference for the copper sulphate solution based on power consumption. A relationship between power and cutting force was shown, as well as a fairly good relationship between cutting forces and wear (see Table 6.7). Therefore, we should have had less wear for the copper sulphate.

It was pointed out in paragraph 6.53 that wear for copper sulphate was in fact less if we considered one test only (recall, one test consists of five cuts). This is, in fact, consistent in all respects with former testing. However, what was not forseen was the effect of prolonged use of the cutter.

Table 6.10 is a summary of the slopes of the various curves shown in Figure 6.20 and 6.21.

TABLE 6.10

SLOPE OF CURVES FOR VOLUME OF METAL REMOVED AGAINST AVERAGE TOOTH WEAR

| DEPTH OF CUT | | | | | | | |
|---|---|---|---|---|---|---|---|
| .005" | | | | .010" | | | |
| FEED RATE | | | | FEED RATE | | | |
| 2.1 | | 7.7 | | 2.1 | | 7.7 | |
| $CuSO_4$ | OIL | $CuSO_4$ | OIL | $CuSO_4$ | OIL | $CuSO_4$ | OIL |
| .9039 | .15 | .4319 | .0786 | .6159 | .1060 | .2493 | .0593 |

It should be noted that the wear rate for low feed is about twice that for the high feed rate for both oil and copper sulphate for both depths of cut. This implies that there is no basic difference in the cutting action to account for the higher wear experienced by the copper sulphate condition, which means that we shall have to look elsewhere for the answer.

One approach is to consider the relationship of the copper sulphate wear and the sulphurized oil wear with respect to cutting forces. Table 6.11 shows the results of a straight line regression analysis of this type.

TABLE 6.11

STRAIGHT LINE REGRESSION COEFFICIENTS
WEAR AGAINST CUTTING FORCE

| VARIABLE | SLOPE | INTERCEPT | CORR. COEFF. | NULL HYPOTHESIS STATISTIC |
|---|---|---|---|---|
| OIL | .00029 | .0065 | .8771 | 7.7478 |
| $CuSO_4$ | .0013 | .0041 | .6095 | 3.2621 |

The straight line established for sulphurized cutting oil has a high correlation coefficient, which confirms our earlier assumption that wear is, in fact, proportioned to cutting force. The correlation coefficient for copper sulphate was observed to be .61. This can be seen more clearly on the scatter diagrams shown in Figures 6.22 and 6.23, which

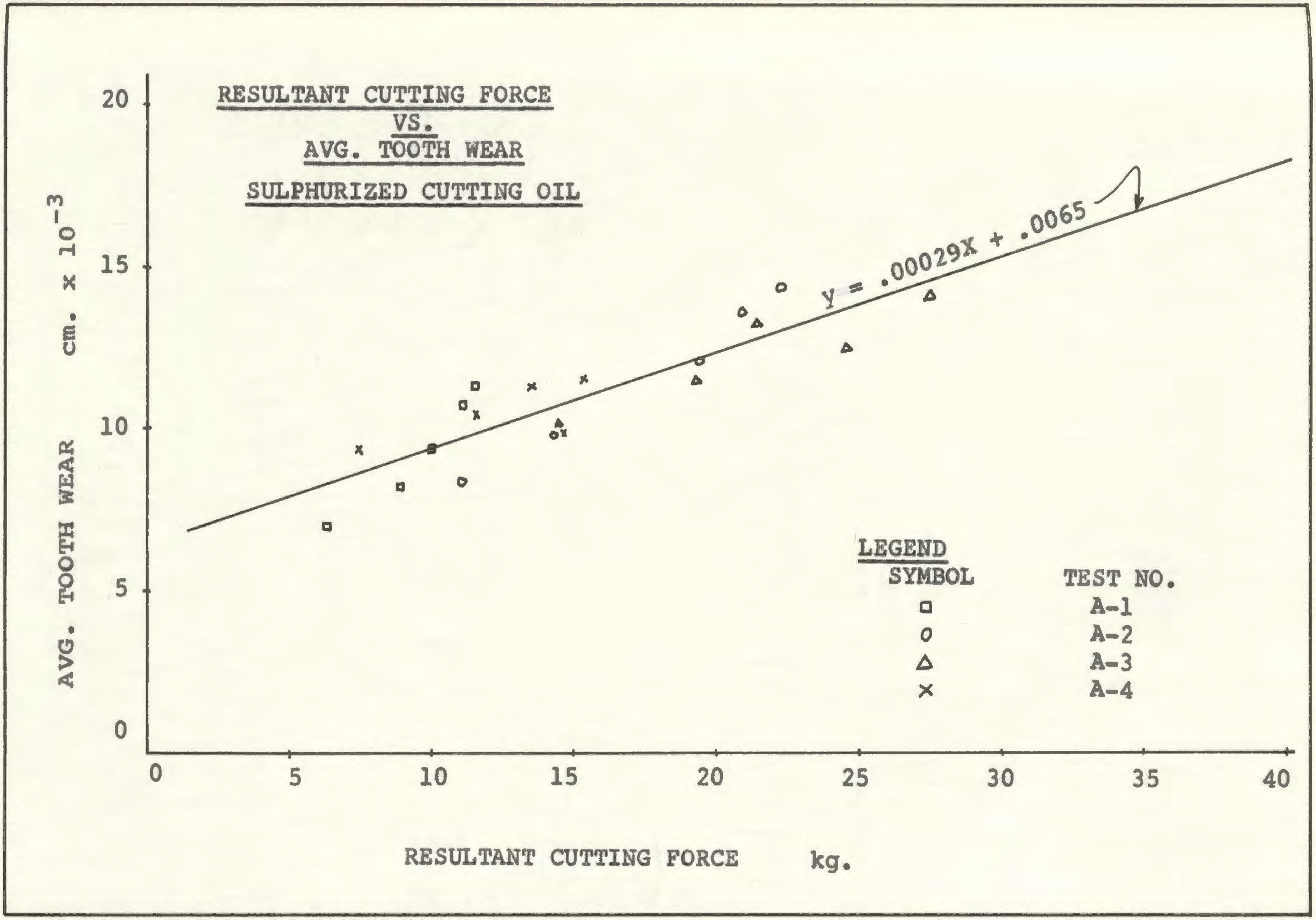



FIG. 6.22 RESULTANT CUTTING FORCE AGAINST AVERAGE TOOTH WEAR
SULPHURIZED CUTTING OIL

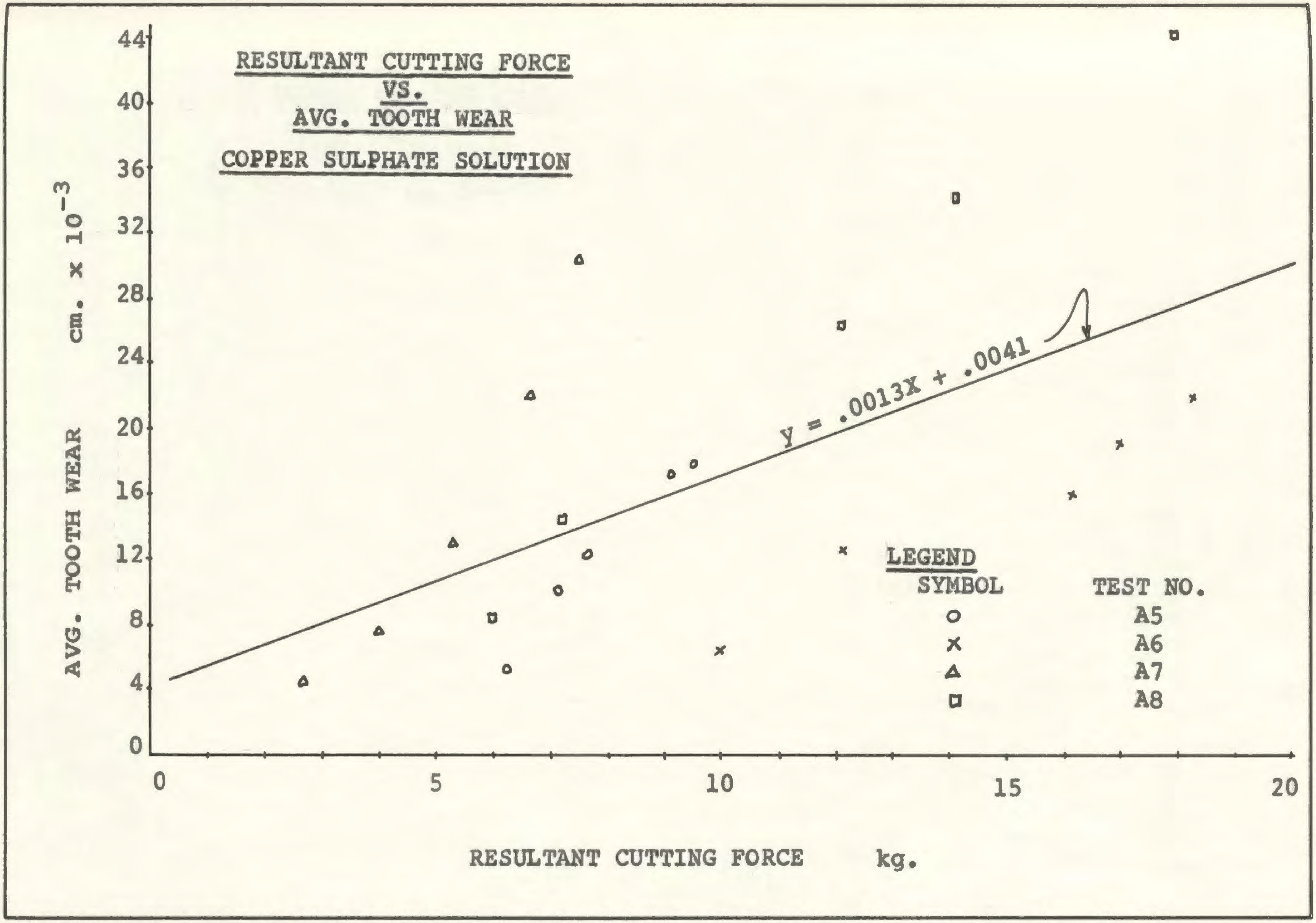



FIG. 6.23 RESULTANT CUTTING FORCE AGAINST AVERAGE TOOTH WEAR
COPPER SULPHATE SOLUTION

represent the wear versus resultant cutting force for oil and copper sulphate respectively.

The null hypothesis statistic shows that the equations derived from the regression are the most likely relationship for at least the 95 per cent level of confidence. Graphs for resultant force only have been presented, as similar plots for vertical and horizontal cutting forces would add little or nothing to the argument.

One interpretation of these results is that wear is occuring by means of a different mechanism for copper sulphate than for oil.

Earlier, fear was expressed that the acid in the electrolyte solution would attack the cutter and work piece causing excessive wear and corrosion. Examination of cutter teeth, selected at random, under an optical microscope is presented in Figures 6.26 and 6.27.

Figure 6.24 is a photograph of a typical tooth, taken after twenty-five cuts, using copper sulphate as a cutting fluid. Figure 6.25 is an enlargement of the same tooth. In addition to wear scars, both of these photographs clearly define the effects of the sulphuric acid on the high speed steel.

Pictures of a typical cutter tooth using sulphurized oil as a cutting fluid are presented so that a comparison of flank wear can be made. These figures, Figure 6.26 and 6.27

respectively, are of photographs of the same tooth taken at two different magnifications. Both show the presence of wear scars on the wear land with little or no evidence of corrosive action except on the tip of the tooth as shown in Figure 6.27. The jagged edge shown could have been caused by the chipping during the cutting process, or it may be the result of chipping and acid attack by the formation of sulphuric acid by the sulphur in the cutting oil.

FIG. 6.24 FLANK WEAR ON A CUTTER TOOTH SELECTED AT RANDOM. TWENTY-FIVE CUTS USING COPPER SULPHATE ELECTROLYTE AS A CUTTING FLUID

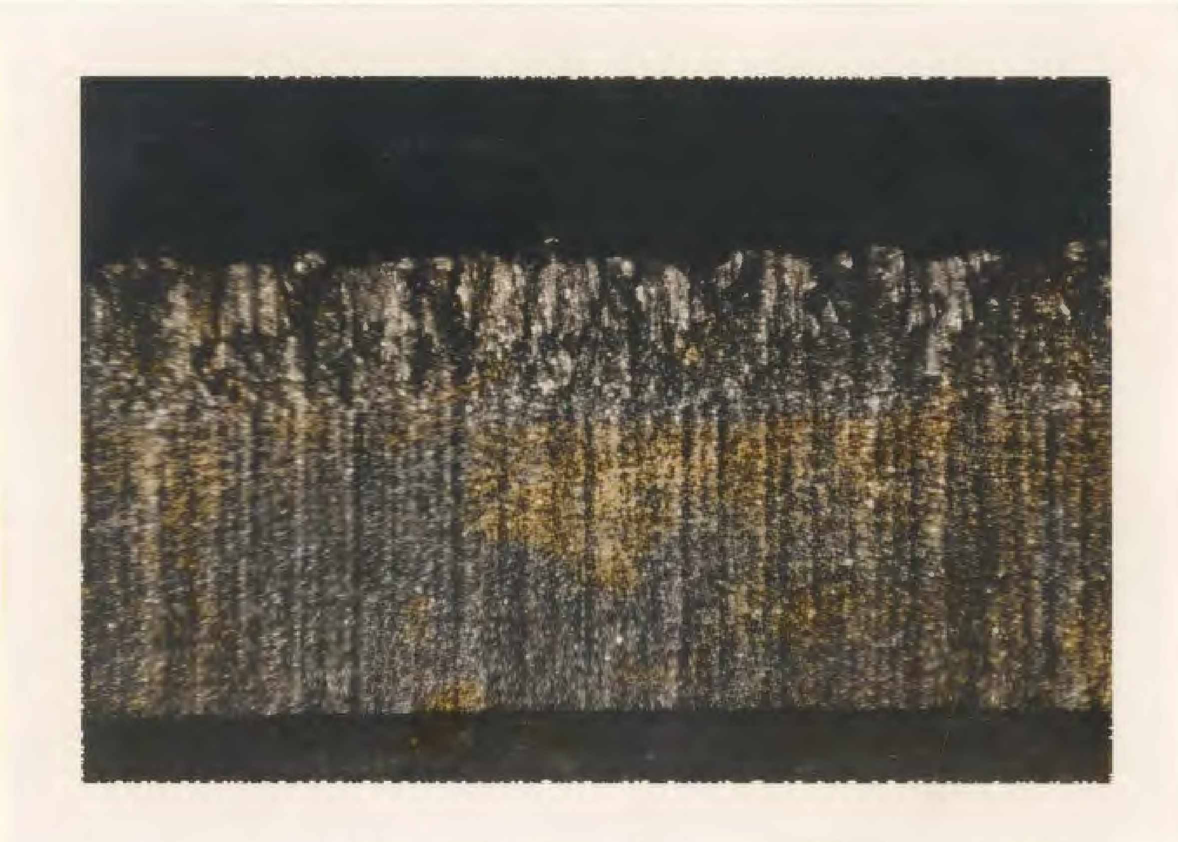


FIG. 6.25 FLANK WEAR ON A CUTTER TOOTH SELECTED AT RANDOM. TWENTY-FIVE CUTS USING COPPER SULPHATE ELECTROLYTE AS A CUTTING FLUID. SAME TOOTH AS SHOWN IN FIGURE 6.24 AT A GREATER MAGNIFICATION.

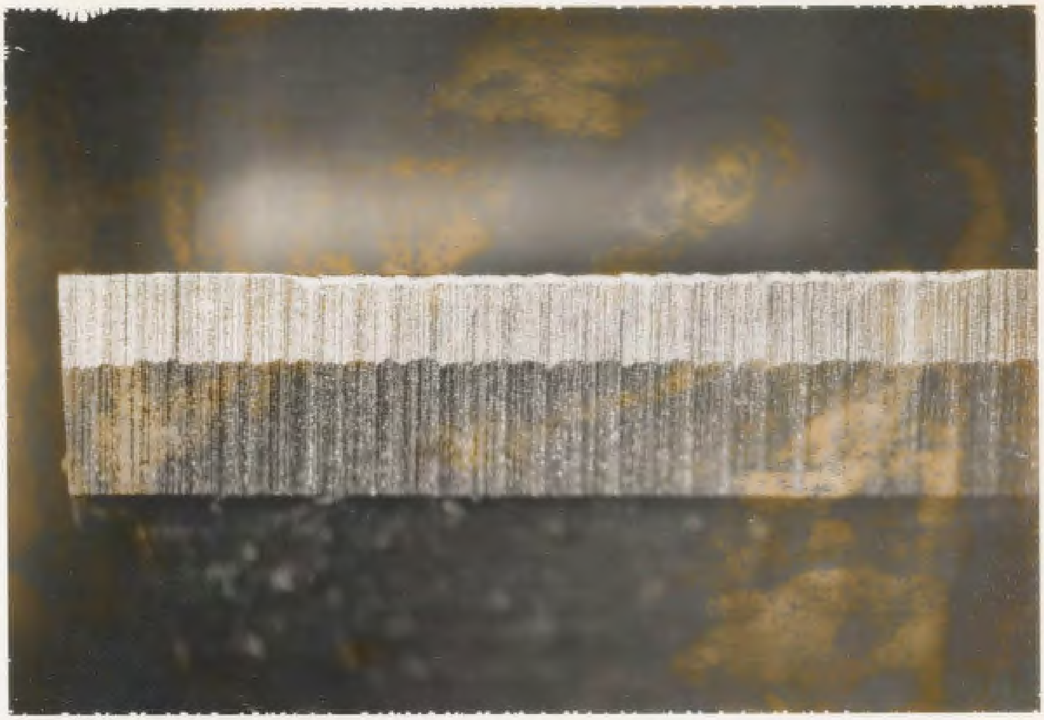


FIG. 6.26 FLANK WEAR ON A CUTTER TOOTH SELECTED AT RANDOM. TWENTY-FIVE CUTS USING SULPHURIZED OIL AS A CUTTING FLUID

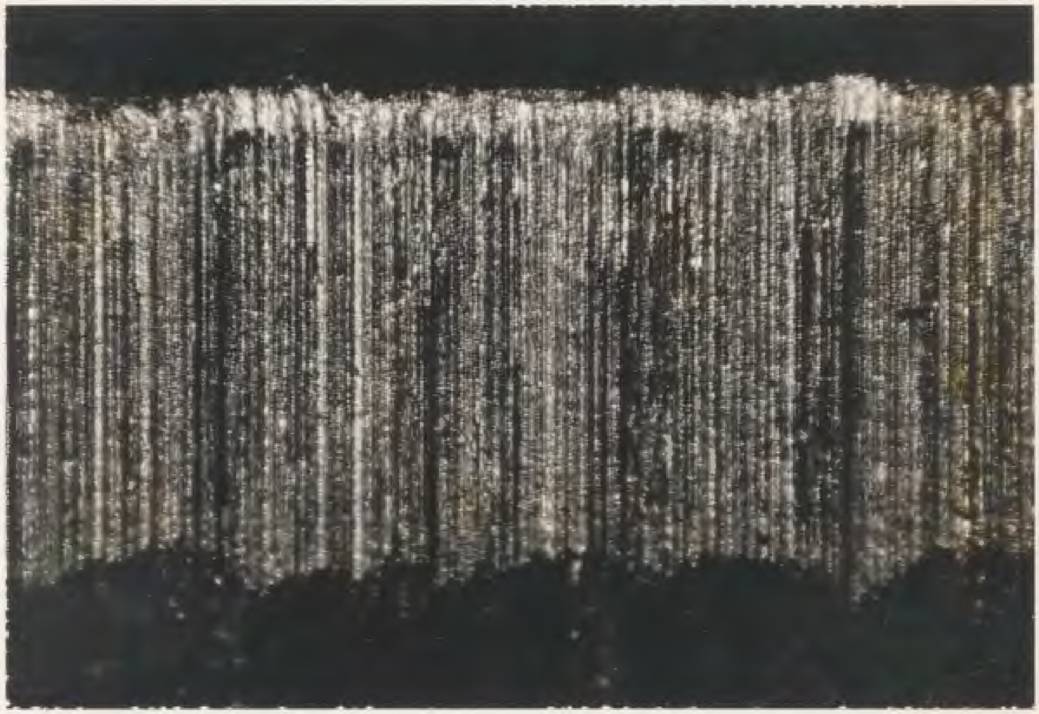


FIG. 6.27 FLANK WEAR ON A CUTTER TOOTH SELECTED AT RANDOM. TWENTY-FIVE CUTS USING SULPHURIZED OIL AS A CUTTING FLUID. SAME TOOTH AS SHOWN IN FIGURE 6.26 AT A GREATER MAGNIFICATION

# CHAPTER 7

# SUMMARY AND CONCLUSIONS

## 7.10 SUMMARY

The development of metal cutting science, for a long time, neglected the analytic aspects of the field in favour of empirical studies that in many cases led to false conclusions. The present study, the object of which was, "to observe cutting forces and tool wear using copper sulphate electrolyte as a cutting fluid and compare the results with those obtained with a conventional sulphurized oil when cutting INCONEL X-750", proceeded in three parts: A Pilot Study, Part 1 and Part 11.

The pilot study was a simple test measuring cutting power for various depths of cut on mild steel, using a soluble oil and a copper sulphate electrolyte as cutting fluids. The results were favourable for the copper sulphate solution requiring some 34 per cent less power operating at a depth of cut of .080".

Using this result as an encouragement, Part 1 of the experiment commenced, with the objective of determining the concentration of copper sulphate and concentrated sulphuric acid, in grams and millilitres per litre of solution respectively, which would result in the least cutting tool wear.

In addition to the measurement of cutting power, cutting forces exerted by the milling cutter were also measured and, because of their relationship to wear, were also used as a criteria for the determination of the optimum concentration of copper sulphate and sulphuric acid. The results of a series of tests using various concentrations of acid and copper sulphate were examined by plotting curves, performing a polynomial regression analysis, and by visual examination. This examination showed that a concentration of 11.1 grams of copper sulphate per litre of solution combined with 5 millilitres per litre of solution of sulphuric acid (the remainder being water) were determined to be the optimum concentrations.

Having established that there was indeed an optimum electrolyte solution, the next step was to compare its performance with that of a standard cutting oil. VEEDOL AFTON #8 containing 1.2 to 2 percent sulphur was used for this purpose.

This series of tests, referred to as Part 11 of the experiment, proceeded with the measurement of cutting power, cutting forces, cutter wear and surface finish. As in Part 1, the analysis of results showed no trend for either cutting fluids on the basis of cutting power and surface finish. The results of equivalent tests for wear and cutting forces, taken at two levels of depth of cut and two levels of cutting feed, were examined by plotting and straight line regression analysis. Reasonably good straight line curves were obtained, resulting in correlation coefficients of .97 and greater.

It was expected from the results of the first two phases of the study that the copper sulphate cutting fluid would have an advantage over the sulphurized oil with respect to cutter tooth wear and cutting forces. Unfortunately, the result was somewhat confusing. Measurements of cutting force indicated that the electrolyte cutting fluid reduced the cutting forces with respect to those required by sulphurized oil, but the amount of wear and the wear rates were higher for the copper sulphate solution.

Closer examination of this result by means of a straight line regression analysis of tooth wear regressed on cutting force, for each cutting fluid, seemed to imply that a different wear mechanism for each fluid exists. This was subsequently verified by microscopic examination of the wear land on milling cutter teeth. The wear land developed, using sulphurized oil, showed normal wear scars while the wear generated using the electrolyte cutting fluid was seen to have been partly caused by the sulphuric acid in the solution.

## 7.20 CONCLUSIONS AND RECOMMENDATIONS

In this investigation, it was demonstrated that; the application of cutting force measuring equipment, the measurement of flank wear on a milling cutter tooth, and the analysis of data using statistical methods, with maximum utilization of computer techniques, could be used to compare the relative merits of a cutting fluid.

The results lead one to conclude that the deposition of copper on the tooth of a milling cutter decreases the cutting forces required when compared to a sulphurized oil containing 1.8 to 2 per cent sulphur.

Under normal conditions, one could extrapolate this fact to mean that wear would also be less. The conclusion is, however, that wear and wear rate using the electrolyte cutting fluid is greater than for the sulphurized oil because the acid in the electrolyte attacks the cutting tool material.

Whether or not the copper, as was suggested in Section 1.30, actually performed by shearing off at the tip of the asperities cannot be determined on the basis of wear. However, on the basis of cutting forces, which were reduced, we can conclude that there is a strong argument to support the fact that it did i.e., copper has a much lower shear strength than steel; hence requires less shearing force.

Part 1 of the study showed that there was, in fact, an optimum concentration of copper sulphate and sulphuric acid for least wear and cutting force. Part 11 indicated that the acidity of the optimized solution attacked the flank of the cutter. However, there was some indication that there might be an optimum depth of cut and feed rate as there is evidence to support the suggestion that wear was more a function of cutting time than of metal removed.

As a suggestion for further work in this area, it is difficult to offer any encouragement along the present lines. Future research towards the development of copper sulphate electrolyte as a cutting fluid should first be directed towards reducing its acidity. This may not be too difficult when one considers that the sulphuric acid is present only to speed up the deposition of copper.

If the acid content can in fact be lowered, the altered cutting fluid should again be compared with a conventional cutting oil by varying cutting speeds, cutting feeds and depths of cut. It is recommended that the results be studied using a complete analysis of variance experiment.

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[1]This Reference has been added as required by Appendix C

# APPENDIX A

This appendix contains listings of the raw data collected from various measurements taken during the experiment. Table numbers and captions are as shown in the List of Tables.

TABLE A1

RAW DATA PART 1, WEAR, TOOTH 1 to 7

RAW DATA..WEAR PART 1 (cm)

| TEST | TOOTH NO. | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO. | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | |
| | B | A | B | A | B | A | B | A | B | A | B | A | B | A |
| 1 | 2.980 | 2.969 | 2.976 | 2.969 | 3.100 | 3.090 | 3.136 | 3.129 | 3.023 | 3.013 | 3.153 | 3.143 | 3.035 | 3.027 |
| 2 | 3.066 | 3.056 | 3.132 | 3.120 | 3.177 | 3.171 | 3.034 | 3.027 | 2.981 | 2.975 | 0.000 | 0.000 | 0.000 | 0.000 |
| 3 | 3.109 | 3.098 | 3.112 | 3.102 | 3.148 | 3.135 | 3.226 | 3.218 | 3.138 | 3.133 | 3.073 | 3.067 | 3.095 | 3.092 |
| 4 | 3.347 | 3.336 | 3.283 | 3.270 | 3.230 | 3.219 | 3.345 | 3.332 | 3.298 | 3.289 | 3.250 | 3.240 | 3.299 | 3.290 |
| 5 | 3.383 | 3.372 | 3.398 | 3.390 | 3.376 | 3.363 | 3.612 | 3.600 | 2.964 | 2.954 | 3.071 | 3.061 | 3.077 | 3.068 |
| 6 | 2.955 | 2.947 | 3.032 | 3.026 | 3.028 | 3.021 | 3.050 | 3.045 | 3.240 | 3.233 | 3.025 | 3.018 | 2.965 | 2.959 |
| 7 | 2.975 | 2.967 | 2.976 | 2.965 | 3.057 | 3.048 | 3.031 | 3.023 | 3.035 | 3.027 | 2.940 | 2.934 | 2.924 | 2.916 |
| 8 | 3.012 | 3.003 | 2.972 | 2.962 | 2.971 | 2.963 | 2.975 | 2.968 | 3.030 | 3.021 | 3.073 | 3.064 | 2.964 | 2.957 |
| 9 | 3.242 | 3.232 | 3.284 | 3.270 | 3.263 | 3.251 | 3.239 | 3.228 | 3.308 | 3.301 | 3.394 | 3.390 | 3.310 | 3.305 |
| 10 | 3.018 | 3.008 | 3.030 | 3.019 | 3.043 | 3.029 | 2.926 | 2.913 | 2.882 | 2.874 | 2.835 | 2.828 | 2.990 | 2.981 |
| 11 | 3.513 | 3.502 | 3.438 | 3.431 | 3.464 | 3.454 | 3.453 | 3.446 | 3.395 | 3.385 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12 | 3.523 | 3.512 | 3.484 | 3.476 | 3.459 | 3.451 | 3.489 | 3.481 | 3.496 | 3.488 | 3.544 | 3.539 | 3.520 | 3.517 |
| 13 | 3.281 | 3.272 | 3.135 | 3.128 | 3.183 | 3.176 | 3.164 | 3.157 | 3.198 | 3.191 | 3.131 | 3.127 | 3.161 | 3.156 |
| 14 | 3.165 | 3.159 | 3.189 | 3.182 | 3.188 | 3.181 | 3.134 | 3.126 | 3.128 | 3.122 | 3.135 | 3.128 | 3.176 | 3.168 |
| 15 | 3.214 | 3.205 | 3.211 | 3.203 | 3.187 | 3.179 | 3.218 | 3.210 | 3.248 | 3.239 | 3.222 | 3.215 | 3.202 | 3.197 |
| 16 | 3.257 | 3.249 | 3.290 | 3.284 | 3.334 | 3.323 | 3.305 | 3.299 | 3.282 | 3.275 | 3.280 | 3.274 | 0.000 | 0.000 |
| 17 | 3.185 | 3.179 | 3.297 | 3.291 | 3.110 | 3.106 | 3.089 | 3.088 | 3.198 | 3.196 | 3.255 | 3.252 | 3.288 | 3.284 |
| 18 | 3.072 | 3.068 | 3.000 | 2.994 | 2.990 | 2.984 | 2.996 | 2.991 | 3.023 | 3.017 | 3.073 | 3.069 | 3.076 | 3.072 |
| 19 | 3.004 | 3.000 | 2.988 | 2.980 | 3.044 | 3.039 | 3.066 | 3.062 | 2.945 | 2.939 | 3.032 | 3.028 | 2.978 | 2.974 |
| 20 | 2.955 | 2.948 | 2.977 | 2.970 | 2.961 | 2.954 | 2.958 | 2.952 | 2.972 | 2.966 | 2.971 | 2.966 | 3.030 | 3.026 |
| 21 | 3.114 | 3.103 | 3.059 | 3.050 | 3.050 | 3.039 | 2.980 | 2.973 | 2.971 | 2.966 | 0.000 | 0.000 | 0.000 | 0.000 |
| 31 | 2.989 | 2.985 | 2.995 | 2.992 | 3.014 | 3.010 | 3.054 | 3.049 | 2.980 | 2.975 | 3.033 | 3.030 | 2.957 | 2.952 |
| 37 | 2.979 | 2.971 | 3.037 | 3.029 | 3.000 | 2.993 | 3.076 | 3.064 | 3.288 | 3.281 | 3.069 | 3.062 | 3.071 | 3.062 |
| 39 | 3.306 | 3.296 | 3.289 | 3.273 | 3.287 | 3.275 | 3.312 | 3.300 | 3.330 | 3.315 | 0.000 | 0.000 | 0.000 | 0.000 |
| 40 | 3.004 | 3.000 | 0.000 | 0.000 | 3.276 | 3.270 | 3.310 | 3.304 | 0.000 | 0.000 | 3.207 | 3.203 | 3.330 | 3.320 |
| 101 | 3.004 | 2.996 | 3.047 | 3.034 | 3.013 | 3.001 | 3.052 | 3.045 | 3.017 | 3.007 | 3.004 | 2.997 | 3.150 | 3.139 |
| 102 | 2.973 | 2.961 | 3.046 | 3.034 | 3.076 | 3.066 | 3.092 | 3.081 | 3.064 | 3.054 | 3.057 | 3.050 | 3.083 | 3.073 |
| 103 | 2.968 | 2.955 | 3.014 | 3.001 | 3.005 | 2.997 | 2.995 | 2.986 | 3.000 | 2.991 | 2.991 | 2.984 | 0.000 | 0.000 |
| 104 | 3.184 | 3.178 | 3.307 | 3.304 | 3.337 | 3.332 | 3.250 | 3.245 | 3.314 | 3.307 | 3.314 | 3.308 | 3.190 | 3.186 |
| 105 | 3.306 | 3.296 | 3.294 | 3.283 | 3.219 | 3.211 | 3.243 | 3.234 | 3.320 | 3.311 | 0.000 | 0.000 | 0.000 | 0.000 |
| 106 | 3.246 | 3.235 | 3.279 | 3.267 | 3.361 | 3.350 | 3.320 | 3.312 | 3.145 | 3.135 | 3.346 | 3.340 | 0.000 | 0.000 |
| 108 | 3.276 | 3.269 | 3.348 | 3.341 | 3.339 | 3.331 | 3.324 | 3.317 | 3.327 | 3.318 | 3.314 | 3.306 | 3.305 | 3.299 |

TABLE A1 (Continued)

RAW DATA..WEAR PART 1 (cm)

| TEST | TOOTH NO. | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO. | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | |
| | B | A | B | A | B | A | B | A | B | A | B | A | B | A |
| 111 | 3.311 | 3.305 | 3.281 | 3.273 | 3.293 | 3.284 | 3.228 | 3.214 | 3.189 | 3.180 | 3.266 | 3.260 | 0.000 | 0.000 |
| 112 | 3.308 | 3.299 | 3.283 | 3.277 | 3.300 | 3.295 | 3.300 | 3.295 | 3.246 | 3.240 | 3.310 | 3.303 | 3.321 | 3.316 |
| 113 | 3.350 | 3.346 | 3.340 | 3.332 | 3.300 | 3.296 | 3.341 | 3.333 | 3.329 | 3.322 | 3.336 | 3.332 | 3.327 | 3.322 |
| 114 | 3.331 | 3.320 | 3.350 | 3.344 | 3.344 | 3.339 | 3.338 | 3.333 | 3.232 | 3.225 | 3.214 | 3.211 | 3.310 | 3.308 |
| 115 | 3.361 | 3.350 | 3.352 | 3.346 | 3.340 | 3.332 | 3.324 | 3.317 | 3.323 | 3.318 | 3.321 | 3.314 | 3.284 | 3.278 |
| 117 | 3.233 | 3.223 | 3.290 | 3.280 | 3.298 | 3.292 | 3.322 | 3.314 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 119 | 3.264 | 3.251 | 3.280 | 3.269 | 3.165 | 3.154 | 3.327 | 3.319 | 3.277 | 3.269 | 0.000 | 0.000 | 0.000 | 0.000 |
| 120 | 3.297 | 3.288 | 3.339 | 3.327 | 3.337 | 3.328 | 3.216 | 3.204 | 3.106 | 3.097 | 3.289 | 3.280 | 3.323 | 3.314 |
| 122 | 3.443 | 3.436 | 3.336 | 3.330 | 3.334 | 3.329 | 3.275 | 3.268 | 3.222 | 3.216 | 3.290 | 3.285 | 3.242 | 3.238 |

Note: Columns headed B (Before) are readings taken with reference to the original tip of the cutter. Columns headed A (After) are readings taken at the back of the wear land.

TABLE A2

RAW DATA PART 1, WEAR, TOOTH 8 TO 14

RAW DATA..WEAR PART 1 (cm)

| TEST NO. | 8 B | 8 A | 9 B | 9 A | 10 B | 10 A | 11 B | 11 A | 12 B | 12 A | 13 B | 13 A | 14 B | 14 A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 2.960 | 2.956 | 3.097 | 3.093 | 3.125 | 3.119 | 3.122 | 3.115 |
| 2 | 3.066 | 3.056 | 3.132 | 3.120 | 3.177 | 3.171 | 3.034 | 3.027 | 2.981 | 2.975 | 0.000 | 0.000 | 0.000 | 0.000 |
| 3 | 3.109 | 3.098 | 3.112 | 3.102 | 3.148 | 3.135 | 3.226 | 3.218 | 3.138 | 3.133 | 3.073 | 3.067 | 3.095 | 3.092 |
| 4 | 3.347 | 3.336 | 3.283 | 3.270 | 3.230 | 3.219 | 3.345 | 3.332 | 3.298 | 3.289 | 3.250 | 3.240 | 3.299 | 3.290 |
| 5 | 3.383 | 3.372 | 3.398 | 3.390 | 3.376 | 3.363 | 3.612 | 3.600 | 2.964 | 2.954 | 3.071 | 3.061 | 3.077 | 3.068 |
| 6 | 2.955 | 2.947 | 3.032 | 3.026 | 3.028 | 3.021 | 3.050 | 3.045 | 3.240 | 3.233 | 3.025 | 3.018 | 2.965 | 2.959 |
| 7 | 2.975 | 2.967 | 2.976 | 2.965 | 3.057 | 3.048 | 3.031 | 3.023 | 3.035 | 3.027 | 2.940 | 2.934 | 2.924 | 2.916 |
| 8 | 3.012 | 3.003 | 2.972 | 2.962 | 2.971 | 2.963 | 2.975 | 2.968 | 3.030 | 3.021 | 3.073 | 3.064 | 2.964 | 2.957 |
| 9 | 3.242 | 3.232 | 3.284 | 3.270 | 3.263 | 3.251 | 3.239 | 3.228 | 3.308 | 3.301 | 3.394 | 3.390 | 3.310 | 3.305 |
| 10 | 3.018 | 3.008 | 3.030 | 3.019 | 3.043 | 3.029 | 2.926 | 2.913 | 2.882 | 2.874 | 2.835 | 2.828 | 2.990 | 2.981 |
| 11 | 3.513 | 3.502 | 3.438 | 3.431 | 3.464 | 3.454 | 3.453 | 3.446 | 3.395 | 3.385 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12 | 3.523 | 3.512 | 3.484 | 3.476 | 3.459 | 3.451 | 3.489 | 3.481 | 3.496 | 3.488 | 3.544 | 3.539 | 3.520 | 3.517 |
| 13 | 3.281 | 3.272 | 3.135 | 3.128 | 3.183 | 3.176 | 3.164 | 3.157 | 3.198 | 3.191 | 3.131 | 3.127 | 3.161 | 3.156 |
| 14 | 3.165 | 3.159 | 3.189 | 3.182 | 3.188 | 3.181 | 3.134 | 3.126 | 3.128 | 3.122 | 3.135 | 3.128 | 3.176 | 3.168 |
| 15 | 3.214 | 3.205 | 3.211 | 3.203 | 3.187 | 3.179 | 3.218 | 3.210 | 3.248 | 3.239 | 3.222 | 3.215 | 3.202 | 3.197 |
| 16 | 3.257 | 3.249 | 3.290 | 3.284 | 3.334 | 3.323 | 3.305 | 3.299 | 3.282 | 3.275 | 3.280 | 3.274 | 0.000 | 0.000 |
| 17 | 3.185 | 3.179 | 3.297 | 3.291 | 3.110 | 3.106 | 3.089 | 3.088 | 3.198 | 3.196 | 3.255 | 3.252 | 3.288 | 3.284 |
| 18 | 3.072 | 3.068 | 3.000 | 2.994 | 2.990 | 2.984 | 2.996 | 2.991 | 3.023 | 3.017 | 3.073 | 3.069 | 3.076 | 3.072 |
| 19 | 3.004 | 3.000 | 2.988 | 2.980 | 3.044 | 3.039 | 3.066 | 3.062 | 2.945 | 2.939 | 3.032 | 3.028 | 2.978 | 2.974 |
| 20 | 2.955 | 2.948 | 2.977 | 2.970 | 2.961 | 2.954 | 2.958 | 2.952 | 2.972 | 2.966 | 2.971 | 2.966 | 3.030 | 3.026 |
| 21 | 3.114 | 3.103 | 3.059 | 3.050 | 3.050 | 3.039 | 2.980 | 2.973 | 2.971 | 2.966 | 0.000 | 0.000 | 0.000 | 0.000 |
| 31 | 2.989 | 2.985 | 2.995 | 2.992 | 3.014 | 3.010 | 3.054 | 3.049 | 2.980 | 2.975 | 3.033 | 3.030 | 2.957 | 2.952 |
| 37 | 2.979 | 2.971 | 3.037 | 3.029 | 3.000 | 2.993 | 3.076 | 3.064 | 3.288 | 3.281 | 3.069 | 3.062 | 3.071 | 3.062 |
| 39 | 3.306 | 3.296 | 3.289 | 3.273 | 3.287 | 3.275 | 3.312 | 3.300 | 3.330 | 3.315 | 0.000 | 0.000 | 0.000 | 0.000 |
| 40 | 3.004 | 3.000 | 0.000 | 0.000 | 3.276 | 3.270 | 3.310 | 3.304 | 0.000 | 0.000 | 3.207 | 3.203 | 3.330 | 3.320 |
| 101 | 3.004 | 2.996 | 3.047 | 3.034 | 3.013 | 3.001 | 3.052 | 3.045 | 3.017 | 3.007 | 3.004 | 2.997 | 3.150 | 3.139 |
| 102 | 2.973 | 2.961 | 3.046 | 3.034 | 3.076 | 3.066 | 3.092 | 3.081 | 3.064 | 3.054 | 3.057 | 3.050 | 3.083 | 3.073 |
| 103 | 2.968 | 2.955 | 3.014 | 3.001 | 3.005 | 2.997 | 2.995 | 2.986 | 3.000 | 2.991 | 2.991 | 2.984 | 0.000 | 0.000 |
| 104 | 3.184 | 3.178 | 3.307 | 3.304 | 3.337 | 3.332 | 3.250 | 3.245 | 3.314 | 3.307 | 3.314 | 3.308 | 3.190 | 3.186 |
| 105 | 3.306 | 3.296 | 3.294 | 3.283 | 3.219 | 3.211 | 3.243 | 3.234 | 3.320 | 3.311 | 0.000 | 0.000 | 0.000 | 0.000 |
| 106 | 3.246 | 3.235 | 3.279 | 3.267 | 3.361 | 3.350 | 3.320 | 3.312 | 3.145 | 3.135 | 3.346 | 3.340 | 0.000 | 0.000 |
| 108 | 3.276 | 3.269 | 3.348 | 3.341 | 3.339 | 3.331 | 3.324 | 3.317 | 3.327 | 3.318 | 3.314 | 3.306 | 3.305 | 3.299 |

TABLE A2 (Continued)

RAW DATA..WEAR PART 1 (cm)

| TEST | TOOTH NO. | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO. | 8 | | 9 | | 10 | | 11 | | 12 | | 13 | | 14 | |
| | B | A | B | A | B | A | B | A | B | A | B | A | B | A |
| 111 | 3.311 | 3.305 | 3.281 | 3.273 | 3.293 | 3.284 | 3.228 | 3.214 | 3.189 | 3.180 | 3.266 | 3.260 | 0.000 | 0.000 |
| 112 | 3.308 | 3.299 | 3.283 | 3.277 | 3.300 | 3.295 | 3.300 | 3.295 | 3.246 | 3.240 | 3.310 | 3.303 | 3.321 | 3.316 |
| 113 | 3.350 | 3.346 | 3.340 | 3.332 | 3.300 | 3.296 | 3.341 | 3.333 | 3.329 | 3.322 | 3.336 | 3.332 | 3.327 | 3.322 |
| 114 | 3.331 | 3.320 | 3.350 | 3.344 | 3.344 | 3.339 | 3.338 | 3.333 | 3.232 | 3.225 | 3.214 | 3.211 | 3.310 | 3.308 |
| 115 | 3.361 | 3.350 | 3.352 | 3.346 | 3.340 | 3.332 | 3.324 | 3.317 | 3.323 | 3.318 | 3.321 | 3.314 | 3.284 | 3.278 |
| 117 | 3.233 | 3.223 | 3.290 | 3.280 | 3.298 | 3.292 | 3.322 | 3.314 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 119 | 3.264 | 3.251 | 3.280 | 3.269 | 3.165 | 3.154 | 3.327 | 3.319 | 3.277 | 3.269 | 0.000 | 0.000 | 0.000 | 0.000 |
| 120 | 3.297 | 3.288 | 3.339 | 3.327 | 3.337 | 3.328 | 3.216 | 3.204 | 3.106 | 3.097 | 3.289 | 3.280 | 3.323 | 3.314 |
| 122 | 3.443 | 3.436 | 3.336 | 3.330 | 3.334 | 3.329 | 3.275 | 3.268 | 3.222 | 3.216 | 3.290 | 3.285 | 3.242 | 3.238 |

Note: Columns headed B (Before) are readings taken with reference to the original tip of the cutter. Columns headed A (After) are readings taken at the back of the wear land.

# TABLE A3

## RAW DATA PART 1, HORIZONTAL AND VERTICAL CUTTING FORCES

RAW DATA PART 1 H + V FORCES (kg.)

| TEST NO. | CUT NUMBER 1 HF | 1 VF | 2 HF | 2 VF | 3 HF | 3 VF | 4 HF | 4 VF | 5 HF | 5 VF |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 7.451 | 8.651 | 8.201 | 8.262 | 2.302 | 2.503 | 7.901 | 9.504 | 7.701 | 9.605 |
| 2 | 0.431 | 1.501 | 3.831 | 5.132 | 0.002 | 1.133 | 0.762 | 3.134 | 6.931 | 9.505 |
| 3 | 3.161 | 4.001 | 4.901 | 6.032 | 8.261 | 9.633 | 8.962 | 0.664 | 4.402 | 0.265 |
| 4 | 9.001 | 1.501 | 3.301 | 6.902 | 7.602 | 1.303 | 8.302 | 2.504 | 2.602 | 2.705 |
| 5 | 3.161 | 3.261 | 5.401 | 6.502 | 7.401 | 9.733 | 0.162 | 2.664 | 1.432 | 3.665 |
| 6 | 4.401 | 5.501 | 6.301 | 6.502 | 6.901 | 8.000 | 6.001 | 7.004 | 4.301 | 5.005 |
| 7 | 1.601 | 2.301 | 2.301 | 4.902 | 5.901 | 2.303 | 6.801 | 8.104 | 2.601 | 7.305 |
| 8 | 2.801 | 3.801 | 3.601 | 5.502 | 5.301 | 6.403 | 6.501 | 5.404 | 4.601 | 6.605 |
| 9 | 2.161 | 2.411 | 4.501 | 5.112 | 6.851 | 7.753 | 7.111 | 9.004 | 6.881 | 8.755 |
| 10 | 3.661 | 3.081 | 4.731 | 6.062 | 7.631 | 8.703 | 8.561 | 9.334 | 8.662 | 0.435 |
| 11 | 1.131 | 1.831 | 2.501 | 3.062 | 2.161 | 3.333 | 1.231 | 2.004 | 0.231 | 1.165 |
| 12 | 2.231 | 2.831 | 2.031 | 3.502 | 3.031 | 4.503 | 3.201 | 3.134 | 4.131 | 5.235 |
| 13 | 3.161 | 2.731 | 4.561 | 5.002 | 5.701 | 6.063 | 5.231 | 5.504 | 4.561 | 5.505 |
| 14 | 0.631 | 1.261 | 6.131 | 6.162 | 7.531 | 6.503 | 7.601 | 7.234 | 8.261 | 7.635 |
| 15 | 7.631 | 5.501 | 8.731 | 8.162 | 0.002 | 0.163 | 0.361 | 9.864 | 8.501 | 9.565 |
| 16 | 0.450 | 9.501 | 1.051 | 1.702 | 0.551 | 1.503 | 0.051 | 0.504 | 8.450 | 8.405 |
| 17 | 3.301 | 3.401 | 1.501 | 2.402 | 0.801 | 1.803 | 0.001 | 1.304 | 0.001 | 1.305 |
| 18 | 4.101 | 5.701 | 2.101 | 3.102 | 3.001 | 3.003 | 0.901 | 1.154 | 1.161 | 1.005 |
| 19 | 6.431 | 5.561 | 2.301 | 2.902 | 4.661 | 5.103 | 3.761 | 4.504 | 3.031 | 3.605 |
| 20 | 1.701 | 1.401 | 5.601 | 6.302 | 6.201 | 6.503 | 5.801 | 6.404 | 5.901 | 6.105 |
| 21 | 1.401 | 1.101 | 9.160 | 8.632 | 8.660 | 8.363 | 8.100 | 8.264 | 8.000 | 7.835 |
| 31 | 5.401 | 4.801 | 5.201 | 4.002 | 0.330 | 9.833 | 0.501 | 0.664 | 3.301 | 4.005 |
| 37 | 0.561 | 9.711 | 0.932 | 1.082 | 6.001 | 7.133 | 2.061 | 3.134 | 3.001 | 3.755 |
| 39 | 5.601 | 6.301 | 6.501 | 8.862 | 9.232 | 1.233 | 9.002 | 1.204 | 3.161 | 5.335 |
| 40 | 2.661 | 3.231 | 1.661 | 2.002 | 2.331 | 0.963 | 2.831 | 2.504 | 4.501 | 3.505 |
| 101 | 9.001 | 7.671 | 3.332 | 2.672 | 5.332 | 7.333 | 7.333 | 1.004 | 0.333 | 2.665 |
| 102 | 7.001 | 5.671 | 9.001 | 9.002 | 0.001 | 8.333 | 7.001 | 7.334 | 7.001 | 7.675 |
| 103 | 6.671 | 5.331 | 8.671 | 7.672 | 6.671 | 5.673 | 4.671 | 5.674 | 2.671 | 4.005 |
| 104 | 0.151 | 0.361 | 1.671 | 2.332 | 1.671 | 1.003 | 0.001 | 0.004 | 2.001 | 2.335 |
| 105 | 4.331 | 3.331 | 1.001 | 2.672 | 0.671 | 1.003 | 1.001 | 0.004 | 1.331 | 2.335 |
| 106 | 0.001 | 0.671 | 3.001 | 0.292 | 2.000 | 8.003 | 0.670 | 8.634 | 1.330 | 9.215 |
| 108 | 1.001 | 8.711 | 0.331 | 6.162 | 7.671 | 6.173 | 6.001 | 3.504 | 5.331 | 1.835 |
| 111 | 6.331 | 6.671 | 3.671 | 4.002 | 1.671 | 1.003 | 1.001 | 0.504 | 1.331 | 0.675 |

TABLE A3 (Continued)

RAW DATA PART 1 H + V FORCES (kg.)

| TEST NO. | CUT NUMBER 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | HF | VF | HF | VF | HF | VF | HF | VF | HF | VF |
| 112 | 2.331 | 3.001 | 1.331 | 1.002 | 2.001 | 1.003 | 0.001 | 0.004 | 0.660 | 9.505 |
| 113 | 8.671 | 5.301 | 7.331 | 4.002 | 8.671 | 5.673 | 1.001 | 8.674 | 8.331 | 6.005 |
| 114 | 3.001 | 8.501 | 9.001 | 7.502 | 1.001 | 8.503 | 1.001 | 9.504 | 9.331 | 7.505 |
| 115 | 3.331 | 9.331 | 3.332 | 0.672 | 2.331 | 9.003 | 3.002 | 0.004 | 3.332 | 0.005 |
| 117 | 5.331 | 4.001 | 1.501 | 2.002 | 8.671 | 2.503 | 9.000 | 9.504 | 0.331 | 0.005 |
| 119 | 4.671 | 4.331 | 0.331 | 2.670 | 4.331 | 5.003 | 4.001 | 3.334 | 5.331 | 2.005 |
| 120 | 0.001 | 7.661 | 1.001 | 9.332 | 0.671 | 8.663 | 8.331 | 7.004 | 6.671 | 5.005 |
| 122 | 6.501 | 5.661 | 8.331 | 5.332 | 6.661 | 4.003 | 5.831 | 4.004 | 5.331 | 3.005 |

## TABLE A4

## RAW DATA PART 1, CUTTING POWER, METER NO. 1

RAW DATA CUTTING POWER METER NO.1 PART 1 (kw.)

| TEST NO. | CUT NUMBER 1 B | 1 D | 2 B | 2 D | 3 B | 3 D | 4 B | 4 D | 5 B | 5 D |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.270 | 0.250 | 0.265 | 0.250 | 0.255 | 0.245 | 0.250 | 0.245 | 0.260 | 0.250 |
| 2 | 0.270 | 0.250 | 0.270 | 0.250 | 0.270 | 0.260 | 0.260 | 0.250 | 0.260 | 0.260 |
| 3 | 0.280 | 0.260 | 0.280 | 0.265 | 0.270 | 0.270 | 0.285 | 0.265 | 0.280 | 0.270 |
| 4 | 0.260 | 0.260 | 0.260 | 0.260 | 0.265 | 0.255 | 0.270 | 0.260 | 0.280 | 0.260 |
| 5 | 0.260 | 0.250 | 0.290 | 0.270 | 0.275 | 0.270 | 0.280 | 0.250 | 0.260 | 0.250 |
| 6 | 0.280 | 0.260 | 0.270 | 0.260 | 0.265 | 0.255 | 0.270 | 0.255 | 0.265 | 0.260 |
| 7 | 0.270 | 0.270 | 0.260 | 0.265 | 0.290 | 0.280 | 0.280 | 0.270 | 0.275 | 0.260 |
| 8 | 0.290 | 0.280 | 0.290 | 0.270 | 0.295 | 0.290 | 0.300 | 0.285 | 0.295 | 0.300 |
| 9 | 0.260 | 0.260 | 0.270 | 0.260 | 0.270 | 0.260 | 0.270 | 0.260 | 0.270 | 0.260 |
| 10 | 0.280 | 0.280 | 0.275 | 0.270 | 0.285 | 0.275 | 0.290 | 0.280 | 0.290 | 0.275 |
| 11 | 0.250 | 0.240 | 0.240 | 0.230 | 0.255 | 0.240 | 0.245 | 0.240 | 0.235 | 0.220 |
| 12 | 0.260 | 0.250 | 0.250 | 0.250 | 0.250 | 0.245 | 0.250 | 0.240 | 0.250 | 0.245 |
| 13 | 0.250 | 0.240 | 0.240 | 0.230 | 0.255 | 0.240 | 0.245 | 0.240 | 0.235 | 0.220 |
| 14 | 0.270 | 0.260 | 0.270 | 0.265 | 0.265 | 0.250 | 0.270 | 0.260 | 0.270 | 0.265 |
| 15 | 0.260 | 0.260 | 0.250 | 0.250 | 0.285 | 0.230 | 0.245 | 0.240 | 0.260 | 0.240 |
| 16 | 0.240 | 0.260 | 0.260 | 0.245 | 0.240 | 0.230 | 0.260 | 0.260 | 0.275 | 0.250 |
| 17 | 0.280 | 0.260 | 0.280 | 0.260 | 0.275 | 0.270 | 0.290 | 0.275 | 0.290 | 0.300 |
| 18 | 0.280 | 0.240 | 0.270 | 0.260 | 0.270 | 0.270 | 0.280 | 0.260 | 0.280 | 0.260 |
| 19 | 0.280 | 0.260 | 0.280 | 0.270 | 0.295 | 0.280 | 0.300 | 0.290 | 0.280 | 0.290 |
| 20 | 0.260 | 0.250 | 0.260 | 0.250 | 0.265 | 0.250 | 0.260 | 0.245 | 0.270 | 0.250 |
| 21 | 0.220 | 0.200 | 0.220 | 0.200 | 0.200 | 0.200 | 0.220 | 0.280 | 0.260 | 0.250 |
| 31 | 0.270 | 0.270 | 0.280 | 0.265 | 0.280 | 0.280 | 0.270 | 0.260 | 0.260 | 0.250 |
| 37 | 0.240 | 0.220 | 0.240 | 0.230 | 0.240 | 0.235 | 0.255 | 0.245 | 0.240 | 0.240 |
| 39 | 0.240 | 0.240 | 0.255 | 0.290 | 0.250 | 0.240 | 0.250 | 0.230 | 0.240 | 0.220 |
| 40 | 0.200 | 0.160 | 0.205 | 0.200 | 0.240 | 0.230 | 0.240 | 0.240 | 0.230 | 0.230 |
| 101 | 0.250 | 0.240 | 0.250 | 0.240 | 0.255 | 0.230 | 0.245 | 0.300 | 0.250 | 0.250 |
| 102 | 0.220 | 0.230 | 0.230 | 0.220 | 0.245 | 0.245 | 0.260 | 0.255 | 0.260 | 0.255 |
| 103 | 0.240 | 0.300 | 0.260 | 0.230 | 0.250 | 0.250 | 0.245 | 0.240 | 0.210 | 0.200 |
| 104 | 0.230 | 0.220 | 0.240 | 0.230 | 0.245 | 0.220 | 0.230 | 0.220 | 0.290 | 0.230 |
| 105 | 0.240 | 0.240 | 0.320 | 0.250 | 0.240 | 0.240 | 0.260 | 0.245 | 0.250 | 0.220 |
| 106 | 0.240 | 0.240 | 0.245 | 0.250 | 0.260 | 0.240 | 0.230 | 0.230 | 0.250 | 0.245 |
| 108 | 0.240 | 0.000 | 0.250 | 0.505 | 0.300 | 0.510 | 0.250 | 0.490 | 0.220 | 0.490 |
| 111 | 0.320 | 0.240 | 0.245 | 0.220 | 0.210 | 0.210 | 0.270 | 0.240 | 0.260 | 0.250 |

*TABLE A4 (Continued)*

RAW DATA CUTTING POWER METER NO.1 PART 1 (kw.)

| TEST NO. | CUT NUMBER 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | B | D | B | D | B | D | B | D | B | D |
| 112 | 0.210 | 0.220 | 0.220 | 0.220 | 0.240 | 0.230 | 0.240 | 0.240 | 0.250 | 0.230 |
| 113 | 0.200 | 0.190 | 0.220 | 0.200 | 0.210 | 0.210 | 0.205 | 0.200 | 0.205 | 0.200 |
| 114 | 0.200 | 0.190 | 0.190 | 0.240 | 0.210 | 0.200 | 0.230 | 0.200 | 0.210 | 0.200 |
| 115 | 0.250 | 0.230 | 0.245 | 0.240 | 0.250 | 0.235 | 0.235 | 0.225 | 0.240 | 0.220 |
| 117 | 0.230 | 0.230 | 0.250 | 0.230 | 0.260 | 0.215 | 0.280 | 0.280 | 0.250 | 0.260 |
| 119 | 0.260 | 0.240 | 0.260 | 0.240 | 0.300 | 0.250 | 0.245 | 0.245 | 0.240 | 0.230 |
| 120 | 0.260 | 0.240 | 0.245 | 0.220 | 0.240 | 0.260 | 0.265 | 0.270 | 0.260 | 0.235 |
| 122 | 0.240 | 0.210 | 0.245 | 0.225 | 0.250 | 0.250 | 0.240 | 0.240 | 0.190 | 0.265 |

Note: Data listed under Column B represents the meter reading taken before cutting commenced. Data listed under Column D represents the meter reading taken during the cutting process.

TABLE A5

RAW DATA PART 1, CUTTING POWER, METER NO. 2

RAW DATA CUTTING POWER METER NO.2 PART 1 (kw.)

| TEST NO. | CUT NUMBER 1 B | 1 D | 2 B | 2 D | 3 B | 3 D | 4 B | 4 D | 5 B | 5 D |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.530 | 0.500 | 0.520 | 0.500 | 0.510 | 0.500 | 0.500 | 0.500 | 0.510 | 0.500 |
| 2 | 0.515 | 0.500 | 0.520 | 0.500 | 0.520 | 0.500 | 0.510 | 0.500 | 0.510 | 0.500 |
| 3 | 0.535 | 0.500 | 0.530 | 0.500 | 0.515 | 0.500 | 0.530 | 0.500 | 0.530 | 0.500 |
| 4 | 0.510 | 0.500 | 0.500 | 0.500 | 0.510 | 0.500 | 0.515 | 0.500 | 0.515 | 0.500 |
| 5 | 0.520 | 0.500 | 0.545 | 0.500 | 0.530 | 0.500 | 0.540 | 0.500 | 0.510 | 0.500 |
| 6 | 0.525 | 0.500 | 0.515 | 0.500 | 0.510 | 0.500 | 0.515 | 0.500 | 0.510 | 0.500 |
| 7 | 0.520 | 0.500 | 0.505 | 0.500 | 0.535 | 0.500 | 0.530 | 0.500 | 0.502 | 0.500 |
| 8 | 0.540 | 0.500 | 0.540 | 0.500 | 0.545 | 0.500 | 0.540 | 0.500 | 0.540 | 0.500 |
| 9 | 0.500 | 0.500 | 0.510 | 0.500 | 0.510 | 0.500 | 0.510 | 0.500 | 0.510 | 0.500 |
| 10 | 0.560 | 0.500 | 0.540 | 0.500 | 0.550 | 0.500 | 0.555 | 0.500 | 0.555 | 0.500 |
| 11 | 0.490 | 0.500 | 0.495 | 0.500 | 0.500 | 0.500 | 0.480 | 0.500 | 0.475 | 0.400 |
| 12 | 0.505 | 0.500 | 0.500 | 0.500 | 0.500 | 0.500 | 0.490 | 0.500 | 0.490 | 0.500 |
| 13 | 0.490 | 0.500 | 0.495 | 0.500 | 0.500 | 0.500 | 0.480 | 0.500 | 0.475 | 0.400 |
| 14 | 0.520 | 0.500 | 0.515 | 0.500 | 0.505 | 0.500 | 0.520 | 0.500 | 0.520 | 0.500 |
| 15 | 0.505 | 0.500 | 0.490 | 0.500 | 0.520 | 0.500 | 0.480 | 0.500 | 0.480 | 0.500 |
| 16 | 0.500 | 0.500 | 0.510 | 0.500 | 0.485 | 0.400 | 0.515 | 0.500 | 0.535 | 0.500 |
| 17 | 0.545 | 0.500 | 0.540 | 0.500 | 0.540 | 0.500 | 0.550 | 0.500 | 0.545 | 0.500 |
| 18 | 0.535 | 0.500 | 0.520 | 0.500 | 0.520 | 0.500 | 0.530 | 0.500 | 0.530 | 0.500 |
| 19 | 0.540 | 0.500 | 0.540 | 0.500 | 0.560 | 0.500 | 0.560 | 0.500 | 0.550 | 0.500 |
| 20 | 0.530 | 0.500 | 0.515 | 0.500 | 0.520 | 0.500 | 0.515 | 0.500 | 0.530 | 0.500 |
| 21 | 0.470 | 0.400 | 0.460 | 0.400 | 0.440 | 0.400 | 0.460 | 0.500 | 0.500 | 0.500 |
| 31 | 0.515 | 0.500 | 0.520 | 0.500 | 0.520 | 0.500 | 0.510 | 0.500 | 0.490 | 0.500 |
| 37 | 0.480 | 0.400 | 0.490 | 0.500 | 0.480 | 0.400 | 0.495 | 0.500 | 0.480 | 0.400 |
| 39 | 0.500 | 0.500 | 0.515 | 0.500 | 0.500 | 0.500 | 0.490 | 0.500 | 0.480 | 0.400 |
| 40 | 0.435 | 0.400 | 0.435 | 0.400 | 0.460 | 0.400 | 0.470 | 0.400 | 0.450 | 0.400 |
| 101 | 0.500 | 0.500 | 0.495 | 0.500 | 0.500 | 0.500 | 0.495 | 0.500 | 0.495 | 0.500 |
| 102 | 0.475 | 0.500 | 0.480 | 0.400 | 0.500 | 0.500 | 0.510 | 0.500 | 0.510 | 0.500 |
| 103 | 0.490 | 0.500 | 0.510 | 0.400 | 0.495 | 0.500 | 0.495 | 0.500 | 0.450 | 0.400 |
| 104 | 0.470 | 0.400 | 0.480 | 0.400 | 0.480 | 0.400 | 0.470 | 0.400 | 0.540 | 0.400 |
| 105 | 0.480 | 0.400 | 0.555 | 0.500 | 0.475 | 0.400 | 0.490 | 0.400 | 0.485 | 0.400 |
| 106 | 0.485 | 0.500 | 0.480 | 0.500 | 0.480 | 0.400 | 0.460 | 0.400 | 0.480 | 0.400 |
| 108 | 0.480 | 0.000 | 0.490 | 0.200 | 0.540 | 0.200 | 0.490 | 0.200 | 0.480 | 0.200 |
| 111 | 0.555 | 0.500 | 0.480 | 0.400 | 0.450 | 0.400 | 0.510 | 0.400 | 0.500 | 0.500 |

TABLE A5 (Continued)

RAW DATA CUTTING POWER METER NO.2 PART 1 (kw.)

| TEST NO. | CUT NUMBER 1 B | 1 D | 2 B | 2 D | 3 B | 3 D | 4 B | 4 D | 5 B | 5 D |
|---|---|---|---|---|---|---|---|---|---|---|
| 112 | 0.455 | 0.400 | 0.470 | 0.500 | 0.480 | 0.400 | 0.485 | 0.500 | 0.490 | 0.400 |
| 113 | 0.450 | 0.400 | 0.460 | 0.400 | 0.455 | 0.400 | 0.445 | 0.400 | 0.445 | 0.400 |
| 114 | 0.445 | 0.400 | 0.430 | 0.500 | 0.450 | 0.400 | 0.470 | 0.400 | 0.450 | 0.400 |
| 115 | 0.500 | 0.500 | 0.490 | 0.500 | 0.495 | 0.500 | 0.475 | 0.400 | 0.480 | 0.400 |
| 117 | 0.470 | 0.400 | 0.480 | 0.400 | 0.495 | 0.400 | 0.510 | 0.500 | 0.480 | 0.500 |
| 119 | 0.500 | 0.500 | 0.490 | 0.400 | 0.540 | 0.500 | 0.475 | 0.500 | 0.470 | 0.400 |
| 120 | 0.495 | 0.500 | 0.480 | 0.400 | 0.465 | 0.500 | 0.490 | 0.500 | 0.485 | 0.400 |
| 122 | 0.470 | 0.400 | 0.475 | 0.400 | 0.485 | 0.500 | 0.470 | 0.400 | 0.520 | 0.500 |

Note: Data listed under Column B represents the meter reading taken before cutting commenced. Data listed under Column D represents the meter reading taken during the cutting process.

TABLE A6

RAW DATA PART 1, ACID AND COPPER SULPHATE CONCENTRATION AND SURFACE FINISH

RAW DATA PART 1

| TEST NO. | CUSO4 CONC. | H2SO4 CONC. | CLA1 | CLA2 | CLA3 |
|---|---|---|---|---|---|
| 1 | 11.109 | 0.0 | 30 | 30 | 21 |
| 2 | 5.568 | 0.0 | 60 | 150 | 47 |
| 3 | 3.698 | 0.0 | 100 | 115 | 45 |
| 4 | 2.798 | 0.0 | 52 | 31 | 85 |
| 5 | 2.216 | 0.0 | 44 | 28 | 38 |
| 6 | 11.109 | 1.0 | 36 | 38 | 50 |
| 7 | 5.568 | 1.0 | 62 | 21 | 61 |
| 8 | 3.823 | 1.0 | 170 | 60 | 150 |
| 9 | 2.798 | 1.0 | 70 | 28 | 30 |
| 10 | 2.216 | 1.0 | 30 | 50 | 24 |
| 11 | 11.109 | 2.5 | 18 | 15 | 20 |
| 12 | 5.568 | 2.5 | 23 | 26 | 23 |
| 13 | 3.698 | 2.5 | 43 | 25 | 62 |
| 14 | 2.798 | 2.5 | 16 | 32 | 34 |
| 15 | 2.216 | 2.5 | 28 | 27 | 30 |
| 16 | 11.109 | 5.0 | 26 | 24 | 22 |
| 17 | 5.568 | 5.0 | 22 | 25 | 28 |
| 18 | 3.698 | 5.0 | 17 | 18 | 10 |
| 19 | 2.798 | 5.0 | 14 | 23 | 20 |
| 20 | 2.216 | 5.0 | 20 | 20 | 21 |
| 21 | 11.109 | 10.0 | 28 | 22 | 22 |
| 31 | 22.219 | 5.0 | 25 | 35 | 30 |
| 37 | 44.384 | 5.0 | 19 | 18 | 22 |
| 39 | 44.384 | 10.0 | 29 | 20 | 24 |
| 40 | 22.219 | 10.0 | 26 | 23 | 24 |
| 101 | 14.822 | 0.0 | 30 | 38 | 38 |
| 102 | 14.822 | 1.0 | 23 | 40 | 25 |
| 103 | 14.822 | 2.5 | 32 | 21 | 10 |
| 104 | 14.822 | 5.0 | 26 | 21 | 34 |
| 105 | 14.822 | 7.5 | 38 | 28 | 30 |
| 106 | 14.822 | 10.0 | 40 | 40 | 20 |
| 108 | 7.397 | 1.0 | 30 | 28 | 30 |
| 111 | 7.397 | 7.5 | 60 | 22 | 21 |
| 112 | 7.397 | 10.0 | 14 | 32 | 55 |
| 113 | 3.698 | 7.5 | 18 | 24 | 24 |
| 114 | 2.798 | 7.5 | 12 | 12 | 22 |
| 115 | 2.216 | 7.5 | 28 | 24 | 28 |
| 117 | 11.109 | 7.5 | 32 | 20 | 24 |
| 119 | 22.219 | 7.5 | 22 | 24 | 30 |
| 120 | 44.384 | 7.5 | 19 | 21 | 9 |
| 122 | 5.568 | 7.5 | 33 | 24 | 32 |

Note: Acid and copper sulphate concentration (g/l)
Surface finish (CLA) (micro inches)

TABLE A7

RAW DATA PART 2, WEAR, TOOTH 1 TO 7

RAW DATA..WEAR PART 2 (cm)

| TEST | TOOTH NO. | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO. | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | |
| | B | A | B | A | B | A | B | A | B | A | B | A | B | A |
| A11 | 3.534 | 3.523 | 3.303 | 3.296 | 3.383 | 3.373 | 3.389 | 3.383 | 3.389 | 3.383 | 3.347 | 3.345 | 3.372 | 3.368 |
| A12 | 3.305 | 3.298 | 3.300 | 3.290 | 3.333 | 3.325 | 3.374 | 3.364 | 3.346 | 3.339 | 3.345 | 3.336 | 3.341 | 3.333 |
| A13 | 3.324 | 3.313 | 3.372 | 3.360 | 3.330 | 3.317 | 3.342 | 3.332 | 3.266 | 3.255 | 3.343 | 3.333 | 3.226 | 3.220 |
| A14 | 3.325 | 3.314 | 3.440 | 3.428 | 3.442 | 3.431 | 3.479 | 3.466 | 3.324 | 3.314 | 3.339 | 3.329 | 3.331 | 3.320 |
| A15 | 3.351 | 3.339 | 3.361 | 3.350 | 3.335 | 3.323 | 3.353 | 3.342 | 3.334 | 3.324 | 3.330 | 3.318 | 3.351 | 3.342 |
| A21 | 3.277 | 3.268 | 3.416 | 3.405 | 3.284 | 3.273 | 3.342 | 3.333 | 3.235 | 3.226 | 3.239 | 3.231 | 3.284 | 3.276 |
| A22 | 3.461 | 3.452 | 3.491 | 3.477 | 3.425 | 3.413 | 3.442 | 3.430 | 3.448 | 3.440 | 3.460 | 3.454 | 3.461 | 3.452 |
| A23 | 3.243 | 3.230 | 3.358 | 3.344 | 3.375 | 3.362 | 3.359 | 3.346 | 3.330 | 3.317 | 3.351 | 3.340 | 3.365 | 3.353 |
| A24 | 3.285 | 3.274 | 3.348 | 3.332 | 3.302 | 3.285 | 3.348 | 3.334 | 3.332 | 3.319 | 3.319 | 3.307 | 3.279 | 3.264 |
| A25 | 3.315 | 3.301 | 3.402 | 3.390 | 3.313 | 3.300 | 3.376 | 3.361 | 3.310 | 3.297 | 3.356 | 3.340 | 3.321 | 3.308 |
| A31 | 3.319 | 3.310 | 3.326 | 3.314 | 3.335 | 3.326 | 3.323 | 3.314 | 3.334 | 3.323 | 3.336 | 3.325 | 3.329 | 3.318 |
| A32 | 3.304 | 3.293 | 3.264 | 3.250 | 3.312 | 3.302 | 3.316 | 3.304 | 3.313 | 3.303 | 3.300 | 3.289 | 3.289 | 3.275 |
| A33 | 3.275 | 3.260 | 3.305 | 3.289 | 3.331 | 3.314 | 3.297 | 3.282 | 3.318 | 3.306 | 3.289 | 3.279 | 3.315 | 3.305 |
| A34 | 3.235 | 3.219 | 3.293 | 3.280 | 3.203 | 3.190 | 3.341 | 3.326 | 3.332 | 3.318 | 3.338 | 3.325 | 3.196 | 3.187 |
| A35 | 3.305 | 3.291 | 3.317 | 3.304 | 3.310 | 3.296 | 3.309 | 3.294 | 3.314 | 3.300 | 3.321 | 3.305 | 3.324 | 3.310 |
| A41 | 3.310 | 3.299 | 3.267 | 3.256 | 3.255 | 3.246 | 3.324 | 3.314 | 3.332 | 3.320 | 3.339 | 3.329 | 3.331 | 3.320 |
| A42 | 3.314 | 3.305 | 3.334 | 3.322 | 3.321 | 3.309 | 3.340 | 3.327 | 3.327 | 3.318 | 3.269 | 3.259 | 3.339 | 3.330 |
| A43 | 3.172 | 3.161 | 3.193 | 3.182 | 3.175 | 3.161 | 3.261 | 3.249 | 3.206 | 3.199 | 3.233 | 3.222 | 3.214 | 3.205 |
| A44 | 3.195 | 3.183 | 3.318 | 3.306 | 3.247 | 3.235 | 3.255 | 3.243 | 3.300 | 3.289 | 3.170 | 3.160 | 3.182 | 3.170 |
| A45 | 3.317 | 3.307 | 3.309 | 3.296 | 3.321 | 3.319 | 3.330 | 3.316 | 3.312 | 3.298 | 3.318 | 3.303 | 3.310 | 3.294 |
| A51 | 3.387 | 3.383 | 3.381 | 3.374 | 0.000 | 0.000 | 0.000 | 0.000 | 3.236 | 3.228 | 3.319 | 3.314 | 3.426 | 3.415 |
| A52 | 3.232 | 3.217 | 3.283 | 3.272 | 3.180 | 3.169 | 3.287 | 3.278 | 3.230 | 3.224 | 3.270 | 3.259 | 3.305 | 3.297 |
| A53 | 3.211 | 3.199 | 3.204 | 3.195 | 3.210 | 3.195 | 3.219 | 3.210 | 3.294 | 3.285 | 3.207 | 3.200 | 3.295 | 3.277 |
| A54 | 3.140 | 3.126 | 3.173 | 3.156 | 3.224 | 3.204 | 3.086 | 3.061 | 3.315 | 3.293 | 3.182 | 3.163 | 3.153 | 3.135 |
| A55 | 3.372 | 3.356 | 3.368 | 3.350 | 3.370 | 3.353 | 3.365 | 3.346 | 3.374 | 3.358 | 3.361 | 3.342 | 3.358 | 3.339 |
| A61 | 3.278 | 3.271 | 3.219 | 3.209 | 3.207 | 3.202 | 3.213 | 3.205 | 3.216 | 3.207 | 3.276 | 3.265 | 3.267 | 3.259 |
| A62 | 3.270 | 3.252 | 3.100 | 3.091 | 3.209 | 3.199 | 3.202 | 3.186 | 3.206 | 3.194 | 3.136 | 3.118 | 3.100 | 3.089 |
| A63 | 3.239 | 3.216 | 3.174 | 3.155 | 3.117 | 3.097 | 3.175 | 3.155 | 3.122 | 3.107 | 3.220 | 3.205 | 3.248 | 3.239 |
| A64 | 3.279 | 3.263 | 3.188 | 3.167 | 3.128 | 3.111 | 3.103 | 3.088 | 3.203 | 3.183 | 3.196 | 3.173 | 3.236 | 3.210 |
| A65 | 3.316 | 3.297 | 3.304 | 3.280 | 3.321 | 3.300 | 3.330 | 3.309 | 3.324 | 3.298 | 3.321 | 3.298 | 3.318 | 3.297 |
| A71 | 3.214 | 3.204 | 3.435 | 3.423 | 3.240 | 3.229 | 3.417 | 3.415 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| A72 | 3.414 | 3.401 | 3.392 | 3.383 | 3.385 | 3.378 | 3.395 | 3.385 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

TABLE A7 (Continued)

RAW DATA..WEAR PART 2 (cm)

| TEST | TOOTH NO. | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO. | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | |
| | B | A | B | A | B | A | B | A | B | A | B | A | B | A |
| A73 | 3.414 | 3.397 | 3.386 | 3.371 | 3.371 | 3.356 | 3.360 | 3.345 | 3.337 | 3.325 | 3.324 | 3.309 | 3.276 | 3.265 |
| A74 | 3.710 | 3.696 | 3.760 | 3.739 | 3.744 | 3.715 | 3.731 | 3.705 | 3.679 | 3.657 | 3.678 | 3.654 | 3.679 | 3.661 |
| A75 | 3.496 | 3.462 | 3.514 | 3.489 | 3.481 | 3.444 | 3.485 | 3.454 | 3.416 | 3.386 | 3.402 | 3.375 | 3.364 | 3.340 |
| A81 | 3.289 | 3.277 | 3.286 | 3.278 | 3.312 | 3.299 | 3.314 | 3.302 | 0.000 | 0.000 | 3.350 | 3.341 | 3.330 | 3.324 |
| A82 | 3.318 | 3.307 | 3.348 | 3.334 | 3.393 | 3.373 | 3.390 | 3.377 | 3.410 | 3.395 | 3.405 | 3.389 | 3.408 | 3.391 |
| A83 | 3.178 | 3.148 | 3.175 | 3.147 | 3.173 | 3.143 | 3.170 | 3.145 | 3.144 | 3.123 | 3.148 | 3.122 | 3.107 | 3.083 |
| A84 | 3.324 | 3.281 | 3.322 | 3.269 | 3.265 | 3.220 | 3.342 | 3.299 | 3.275 | 3.240 | 3.348 | 3.318 | 3.316 | 3.288 |
| A85 | 3.284 | 3.239 | 3.275 | 3.218 | 3.257 | 3.202 | 3.287 | 3.224 | 3.238 | 3.198 | 3.250 | 3.194 | 3.271 | 3.222 |

Note: Columns headed B (Before) are readings taken with reference to the original tip of the cutter. Columns headed A (After) are readings taken at the back of the wear land.

TABLE A8

RAW DATA PART 2, WEAR, TOOTH 8 TO 14

RAW DATA..WEAR PART 2 (cm)

| TEST NO. | TOOTH NO. 8 | | 9 | | 10 | | 11 | | 12 | | 13 | | 14 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | B | A | B | A | B | A | B | A | B | A | B | A | B | A |
| A11 | 3.310 | 3.304 | 3.320 | 3.314 | 3.350 | 3.345 | 3.380 | 3.373 | 3.281 | 3.270 | 3.300 | 3.292 | 3.277 | 3.268 |
| A12 | 3.305 | 3.298 | 3.300 | 3.290 | 3.333 | 3.325 | 3.374 | 3.364 | 3.346 | 3.339 | 3.345 | 3.336 | 3.341 | 3.333 |
| A13 | 3.324 | 3.313 | 3.372 | 3.360 | 3.330 | 3.317 | 3.342 | 3.332 | 3.266 | 3.255 | 3.343 | 3.333 | 3.226 | 3.220 |
| A14 | 3.325 | 3.314 | 3.440 | 3.428 | 3.442 | 3.431 | 3.479 | 3.466 | 3.324 | 3.314 | 3.339 | 3.329 | 3.331 | 3.320 |
| A15 | 3.351 | 3.339 | 3.361 | 3.350 | 3.335 | 3.323 | 3.353 | 3.342 | 3.334 | 3.324 | 3.330 | 3.318 | 3.351 | 3.342 |
| A21 | 3.277 | 3.268 | 3.416 | 3.405 | 3.284 | 3.273 | 3.342 | 3.333 | 3.235 | 3.226 | 3.239 | 3.231 | 3.284 | 3.276 |
| A22 | 3.461 | 3.452 | 3.491 | 3.477 | 3.425 | 3.413 | 3.442 | 3.430 | 3.448 | 3.440 | 3.460 | 3.454 | 3.461 | 3.452 |
| A23 | 3.243 | 3.230 | 3.358 | 3.344 | 3.375 | 3.362 | 3.359 | 3.346 | 3.330 | 3.317 | 3.351 | 3.340 | 3.365 | 3.353 |
| A24 | 3.285 | 3.274 | 3.348 | 3.332 | 3.302 | 3.285 | 3.348 | 3.334 | 3.332 | 3.319 | 3.319 | 3.307 | 3.279 | 3.264 |
| A25 | 3.315 | 3.301 | 3.402 | 3.390 | 3.313 | 3.300 | 3.376 | 3.361 | 3.310 | 3.297 | 3.356 | 3.340 | 3.321 | 3.308 |
| A31 | 3.319 | 3.310 | 3.326 | 3.314 | 3.335 | 3.326 | 3.323 | 3.314 | 3.334 | 3.323 | 3.336 | 3.325 | 3.329 | 3.318 |
| A32 | 3.304 | 3.293 | 3.264 | 3.250 | 3.312 | 3.302 | 3.316 | 3.304 | 3.313 | 3.303 | 3.300 | 3.289 | 3.289 | 3.275 |
| A33 | 3.275 | 3.260 | 3.305 | 3.289 | 3.331 | 3.314 | 3.297 | 3.282 | 3.318 | 3.306 | 3.289 | 3.279 | 3.315 | 3.305 |
| A34 | 3.235 | 3.219 | 3.293 | 3.280 | 3.203 | 3.190 | 3.341 | 3.326 | 3.332 | 3.318 | 3.338 | 3.325 | 3.196 | 3.187 |
| A35 | 3.305 | 3.291 | 3.317 | 3.304 | 3.310 | 3.296 | 3.309 | 3.294 | 3.314 | 3.300 | 3.321 | 3.305 | 3.324 | 3.310 |
| A41 | 3.310 | 3.299 | 3.267 | 3.256 | 3.255 | 3.246 | 3.324 | 3.314 | 3.332 | 3.320 | 3.339 | 3.329 | 3.331 | 3.320 |
| A42 | 3.314 | 3.305 | 3.334 | 3.322 | 3.321 | 3.309 | 3.340 | 3.327 | 3.327 | 3.318 | 3.269 | 3.259 | 3.339 | 3.330 |
| A43 | 3.172 | 3.161 | 3.193 | 3.182 | 3.175 | 3.161 | 3.261 | 3.249 | 3.206 | 3.199 | 3.233 | 3.222 | 3.214 | 3.205 |
| A44 | 3.195 | 3.183 | 3.318 | 3.306 | 3.247 | 3.235 | 3.255 | 3.243 | 3.300 | 3.289 | 3.170 | 3.160 | 3.182 | 3.170 |
| A45 | 3.317 | 3.307 | 3.309 | 3.296 | 3.321 | 3.319 | 3.330 | 3.316 | 3.312 | 3.298 | 3.318 | 3.303 | 3.310 | 3.294 |
| A51 | 3.387 | 3.383 | 3.381 | 3.374 | 0.000 | 0.000 | 0.000 | 0.000 | 3.236 | 3.228 | 3.319 | 3.314 | 3.426 | 3.415 |
| A52 | 3.232 | 3.217 | 3.283 | 3.272 | 3.180 | 3.169 | 3.287 | 3.278 | 3.230 | 3.224 | 3.270 | 3.259 | 3.305 | 3.297 |
| A53 | 3.211 | 3.199 | 3.204 | 3.195 | 3.210 | 3.195 | 3.219 | 3.210 | 3.294 | 3.285 | 3.207 | 3.200 | 3.295 | 3.277 |
| A54 | 3.140 | 3.126 | 3.173 | 3.156 | 3.224 | 3.204 | 3.086 | 3.061 | 3.315 | 3.293 | 3.182 | 3.163 | 3.153 | 3.135 |
| A55 | 3.372 | 3.356 | 3.368 | 3.350 | 3.370 | 3.353 | 3.365 | 3.346 | 3.374 | 3.358 | 3.361 | 3.342 | 3.358 | 3.339 |
| A61 | 3.278 | 3.271 | 3.219 | 3.209 | 3.207 | 3.202 | 3.213 | 3.205 | 3.216 | 3.207 | 3.276 | 3.265 | 3.267 | 3.259 |
| A62 | 3.270 | 3.252 | 3.100 | 3.091 | 3.209 | 3.199 | 3.202 | 3.186 | 3.206 | 3.194 | 3.136 | 3.118 | 3.100 | 3.089 |
| A63 | 3.239 | 3.216 | 3.174 | 3.155 | 3.117 | 3.097 | 3.175 | 3.155 | 3.122 | 3.107 | 3.220 | 3.205 | 3.248 | 3.239 |
| A64 | 3.279 | 3.263 | 3.188 | 3.167 | 3.128 | 3.111 | 3.103 | 3.088 | 3.203 | 3.183 | 3.196 | 3.173 | 3.236 | 3.210 |
| A65 | 3.316 | 3.297 | 3.304 | 3.280 | 3.321 | 3.300 | 3.330 | 3.309 | 3.324 | 3.298 | 3.321 | 3.298 | 3.318 | 3.297 |
| A71 | 3.214 | 3.204 | 3.435 | 3.423 | 3.240 | 3.229 | 3.417 | 3.415 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| A72 | 3.414 | 3.401 | 3.392 | 3.383 | 3.385 | 3.378 | 3.395 | 3.385 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

TABLE A8 (Continued)

RAW DATA..WEAR PART 2 (cm)

| TEST NO. | TOOTH NO. 8 | | 9 | | 10 | | 11 | | 12 | | 13 | | 14 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | B | A | B | A | B | A | B | A | B | A | B | A | B | A |
| A73 | 3.259 | 3.252 | 3.232 | 3.221 | 3.234 | 3.224 | 3.275 | 3.263 | 3.265 | 3.253 | 3.292 | 3.277 | 3.372 | 3.356 |
| A74 | 3.710 | 3.696 | 3.760 | 3.739 | 3.744 | 3.715 | 3.731 | 3.705 | 3.679 | 3.657 | 3.678 | 3.654 | 3.679 | 3.661 |
| A75 | 3.496 | 3.462 | 3.514 | 3.489 | 3.481 | 3.444 | 3.485 | 3.454 | 3.416 | 3.386 | 3.402 | 3.375 | 3.364 | 3.340 |
| A81 | 3.289 | 3.277 | 3.286 | 3.278 | 3.312 | 3.299 | 3.314 | 3.302 | 0.000 | 0.000 | 3.350 | 3.341 | 3.330 | 3.324 |
| A82 | 3.318 | 3.307 | 3.348 | 3.334 | 3.393 | 3.373 | 3.390 | 3.377 | 3.410 | 3.395 | 3.405 | 3.389 | 3.408 | 3.391 |
| A83 | 3.178 | 3.148 | 3.175 | 3.147 | 3.173 | 3.143 | 3.170 | 3.145 | 3.144 | 3.123 | 3.148 | 3.122 | 3.107 | 3.083 |
| A84 | 3.324 | 3.281 | 3.322 | 3.269 | 3.265 | 3.220 | 3.342 | 3.299 | 3.275 | 3.240 | 3.348 | 3.318 | 3.316 | 3.288 |
| A85 | 3.284 | 3.239 | 3.275 | 3.218 | 3.257 | 3.202 | 3.287 | 3.224 | 3.238 | 3.198 | 3.250 | 3.194 | 3.271 | 3.222 |

Note: Columns headed B (Before) are readings taken with reference to the original tip of the cutter. Columns headed A (After) are readings taken at the back of the wear land.

## TABLE A9
## RAW DATA PART 2, HORIZONTAL CUTTING FORCE

RAW DATA PART 2 HORIZONTAL CUTTING FORCE (KG.)

| TEST | CUT NUMBER | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO. | 1 | | | 2 | | | 3 | | | 4 | | | 5 | | |
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| A11 | 7.5 | 10.5 | 15.0 | 14.5 | 15.0 | 16.5 | 11.5 | 11.5 | 15.0 | 13.5 | 13.0 | 16.0 | 15.0 | 14.5 | 19.0 |
| A12 | 14.5 | 18.0 | 21.0 | 16.0 | 17.0 | 20.0 | 17.0 | 17.5 | 19.5 | 18.5 | 18.5 | 21.5 | 18.5 | 19.5 | 22.0 |
| A13 | 20.0 | 22.0 | 24.5 | 18.5 | 19.0 | 21.0 | 20.5 | 21.5 | 24.0 | 20.0 | 21.5 | 23.5 | 21.0 | 21.5 | 23.5 |
| A14 | 22.0 | 24.0 | 25.0 | 22.5 | 24.5 | 26.0 | 23.5 | 24.0 | 25.0 | 22.0 | 23.5 | 25.0 | 22.0 | 23.0 | 23.5 |
| A15 | 24.5 | 26.0 | 27.5 | 23.5 | 24.5 | 26.0 | 23.0 | 23.0 | 24.5 | 22.5 | 23.0 | 25.0 | 23.0 | 24.0 | 25.5 |
| A21 | 15.0 | 22.0 | 25.0 | 21.5 | 26.0 | 28.0 | 25.5 | 27.5 | 29.5 | 28.0 | 30.0 | 31.5 | 30.0 | 31.5 | 33.5 |
| A22 | 31.5 | 32.5 | 35.0 | 31.0 | 32.0 | 35.5 | 30.5 | 31.5 | 35.5 | 30.5 | 30.5 | 35.5 | 32.0 | 31.0 | 35.5 |
| A23 | 40.2 | 40.8 | 42.6 | 40.8 | 40.8 | 43.5 | 42.0 | 40.8 | 43.5 | 41.0 | 40.0 | 43.2 | 39.0 | 39.0 | 41.5 |
| A24 | 48.0 | 45.0 | 50.0 | 45.5 | 42.5 | 48.0 | 45.5 | 43.0 | 48.0 | 43.0 | 41.0 | 45.0 | 44.0 | 42.0 | 46.0 |
| A25 | 55.5 | 59.0 | 61.5 | 46.0 | 45.0 | 49.0 | 36.5 | 35.5 | 39.0 | 46.0 | 44.0 | 47.0 | 45.0 | 43.0 | 46.0 |
| A31 | 34.0 | 43.0 | 49.5 | 45.0 | 48.5 | 52.5 | 45.0 | 48.0 | 51.5 | 51.0 | 54.0 | 58.0 | 53.0 | 53.5 | 57.5 |
| A32 | 48.5 | 51.0 | 55.5 | 53.0 | 54.5 | 57.0 | 55.0 | 56.0 | 60.0 | 62.0 | 63.5 | 66.0 | 63.5 | 63.5 | 67.0 |
| A33 | 51.0 | 52.5 | 55.0 | 65.0 | 66.0 | 69.0 | 65.0 | 63.5 | 67.0 | 62.0 | 61.0 | 64.5 | 65.0 | 65.5 | 68.5 |
| A34 | 57.0 | 59.0 | 60.0 | 71.0 | 70.0 | 74.0 | 72.0 | 70.0 | 74.5 | 72.0 | 70.0 | 75.0 | 69.0 | 69.0 | 73.0 |
| A35 | 40.0 | 40.5 | 42.5 | 46.5 | 45.5 | 47.5 | 47.0 | 47.0 | 50.0 | 50.0 | 48.0 | 50.0 | 50.0 | 49.0 | 51.0 |
| A41 | 11.0 | 16.5 | 20.0 | 16.5 | 19.0 | 22.0 | 20.0 | 21.5 | 23.5 | 20.0 | 20.5 | 23.0 | 21.5 | 22.5 | 25.0 |
| A42 | 15.0 | 19.0 | 23.0 | 23.0 | 24.0 | 27.0 | 24.0 | 24.0 | 28.0 | 24.0 | 24.0 | 28.0 | 25.5 | 25.0 | 29.5 |
| A43 | 20.5 | 21.0 | 24.0 | 26.0 | 28.0 | 30.0 | 26.0 | 25.5 | 28.5 | 29.0 | 28.5 | 31.0 | 28.5 | 27.5 | 30.0 |
| A44 | 21.0 | 19.0 | 24.0 | 27.0 | 27.5 | 29.5 | 30.5 | 30.0 | 31.5 | 31.5 | 30.5 | 33.0 | 34.0 | 32.0 | 35.0 |
| A45 | 23.0 | 22.0 | 26.0 | 32.0 | 32.0 | 34.5 | 33.0 | 30.5 | 34.0 | 35.0 | 33.5 | 36.0 | 35.0 | 33.0 | 36.0 |
| A51 | 17.0 | 19.0 | 22.5 | 20.0 | 20.0 | 24.0 | 18.0 | 17.5 | 20.5 | 16.5 | 16.5 | 20.5 | 16.5 | 16.5 | 20.5 |
| A52 | 18.5 | 19.5 | 23.5 | 19.0 | 20.0 | 23.5 | 21.5 | 21.0 | 24.0 | 20.5 | 20.5 | 23.5 | 21.5 | 21.5 | 24.5 |
| A53 | 19.5 | 17.5 | 19.0 | 20.5 | 18.0 | 19.5 | 22.0 | 19.5 | 21.0 | 23.0 | 20.0 | 22.0 | 26.0 | 24.0 | 26.0 |
| A54 | 21.5 | 16.0 | 22.5 | 27.5 | 24.5 | 26.0 | 25.0 | 23.0 | 24.5 | 28.5 | 25.5 | 26.5 | 28.0 | 25.0 | 26.5 |
| A55 | 20.5 | 18.5 | 18.5 | 25.0 | 22.0 | 24.5 | 26.0 | 23.5 | 25.5 | 27.0 | 24.5 | 26.0 | 30.5 | 28.0 | 30.0 |
| A61 | 26.0 | 30.0 | 31.0 | 32.5 | 32.5 | 32.5 | 31.0 | 28.0 | 28.5 | 32.0 | 29.0 | 29.5 | 30.0 | 28.0 | 29.0 |
| A62 | 31.0 | 29.5 | 32.0 | 35.0 | 33.5 | 34.5 | 36.5 | 34.5 | 35.0 | 39.0 | 37.5 | 38.0 | 41.0 | 37.5 | 38.5 |
| A63 | 46.0 | 42.5 | 44.5 | 46.0 | 45.5 | 46.0 | 51.0 | 47.5 | 47.5 | 48.0 | 44.5 | 45.0 | 48.5 | 45.5 | 45.5 |
| A64 | 45.0 | 42.5 | 42.5 | 45.0 | 46.0 | 49.5 | 51.0 | 49.0 | 49.5 | 50.0 | 46.5 | 47.0 | 51.0 | 47.5 | 49.0 |
| A65 | 41.0 | 37.0 | 38.0 | 48.0 | 44.5 | 47.0 | 47.0 | 45.5 | 49.0 | 54.0 | 54.0 | 57.0 | 59.0 | 61.5 | 63.0 |
| A71 | 5.0 | 5.5 | 8.0 | 9.0 | 7.0 | 7.5 | 5.0 | 5.0 | 8.5 | 7.5 | 5.0 | 6.0 | 6.5 | 3.5 | 3.5 |
| A72 | 10.0 | 7.5 | 10.0 | 11.5 | 7.0 | 7.0 | 12.0 | 8.5 | 9.0 | 12.5 | 9.5 | 9.5 | 12.0 | 10.0 | 10.0 |

TABLE A9 (Continued)

RAW DATA PART 2 HORIZONTAL CUTTING FORCE (KG.)

| TEST NO. | CUT NUMBER 1 | | | 2 | | | 3 | | | 4 | | | 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| A73 | 12.0 | 9.5 | 10.0 | 14.5 | 12.0 | 12.0 | 14.0 | 12.0 | 12.5 | 14.0 | 11.5 | 11.5 | 15.0 | 13.0 | 13.5 |
| A74 | 12.0 | 7.5 | 8.5 | 16.0 | 13.5 | 14.0 | 17.0 | 15.0 | 14.5 | 17.5 | 16.5 | 18.0 | 20.5 | 19.0 | 18.0 |
| A75 | 19.0 | 16.5 | 14.0 | 23.5 | 20.0 | 20.5 | 23.5 | 19.5 | 20.0 | 23.5 | 21.5 | 20.0 | 22.0 | 19.0 | 18.0 |
| A81 | 17.0 | 18.0 | 17.5 | 17.5 | 14.0 | 13.5 | 14.5 | 11.5 | 13.0 | 17.5 | 16.5 | 18.0 | 22.5 | 20.0 | 20.0 |
| A82 | 18.0 | 15.0 | 15.5 | 18.5 | 15.5 | 17.5 | 21.0 | 18.0 | 20.0 | 20.0 | 17.0 | 19.5 | 24.0 | 21.5 | 24.5 |
| A83 | 28.5 | 27.5 | 26.5 | 29.0 | 25.5 | 28.0 | 33.0 | 32.0 | 31.0 | 34.5 | 30.5 | 32.5 | 34.5 | 31.0 | 33.0 |
| A84 | 35.0 | 36.0 | 40.0 | 32.5 | 30.5 | 30.5 | 30.0 | 33.5 | 35.0 | 38.0 | 35.5 | 35.5 | 38.5 | 37.0 | 37.5 |
| A85 | 43.0 | 44.0 | 45.0 | 45.0 | 42.5 | 44.5 | 45.0 | 42.0 | 41.0 | 43.0 | 42.5 | 40.0 | 42.5 | 38.5 | 39.0 |

TABLE A10

RAW DATA PART 2, VERTICAL CUTTING FORCE

RAW DATA PART 2 VERTICAL CUTTING FORCE (KG.)

| TEST NO. | CUT NUMBER 1 | | | 2 | | | 3 | | | 4 | | | 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| A11 | 13.5 | 18.0 | 23.0 | 18.5 | 21.0 | 25.0 | 20.0 | 22.0 | 25.0 | 25.0 | 28.0 | 31.0 | 24.0 | 27.5 | 33.5 |
| A12 | 27.0 | 29.0 | 34.0 | 28.0 | 28.5 | 32.5 | 30.0 | 30.0 | 34.0 | 31.0 | 32.0 | 35.5 | 31.0 | 35.0 | 39.0 |
| A13 | 31.0 | 31.5 | 34.0 | 33.0 | 35.0 | 37.5 | 32.0 | 34.0 | 37.0 | 33.5 | 34.0 | 36.5 | 35.5 | 38.5 | 40.0 |
| A14 | 35.5 | 37.5 | 39.0 | 37.0 | 38.0 | 38.5 | 35.0 | 37.5 | 39.0 | 35.5 | 37.0 | 37.5 | 39.0 | 40.5 | 45.5 |
| A15 | 38.5 | 38.0 | 41.5 | 37.5 | 36.0 | 39.0 | 38.0 | 37.5 | 40.5 | 38.0 | 38.0 | 41.5 | 15.5 | 23.5 | 30.5 |
| A21 | 28.0 | 31.5 | 36.5 | 34.0 | 37.0 | 40.0 | 38.5 | 40.5 | 43.5 | 42.0 | 44.0 | 46.0 | 43.5 | 45.5 | 50.0 |
| A22 | 45.0 | 45.5 | 50.0 | 45.5 | 46.5 | 51.0 | 46.5 | 46.5 | 51.0 | 48.0 | 47.0 | 51.0 | 63.6 | 63.6 | 66.0 |
| A23 | 64.8 | 64.2 | 66.0 | 65.5 | 64.0 | 66.0 | 67.0 | 64.0 | 67.0 | 65.0 | 62.5 | 70.5 | 74.5 | 70.0 | 77.5 |
| A24 | 72.0 | 67.0 | 73.0 | 70.0 | 69.0 | 72.0 | 67.0 | 65.0 | 70.0 | 68.5 | 66.5 | 70.0 | 79.0 | 87.0 | 92.0 |
| A25 | 72.5 | 73.0 | 75.0 | 75.0 | 73.5 | 76.0 | 74.0 | 71.5 | 73.5 | 72.5 | 70.5 | 74.0 | 29.0 | 36.5 | 46.5 |
| A31 | 43.0 | 47.0 | 54.5 | 47.0 | 51.0 | 59.5 | 53.0 | 59.0 | 69.0 | 60.5 | 64.5 | 74.0 | 58.0 | 63.5 | 70.0 |
| A32 | 65.0 | 68.5 | 75.0 | 77.0 | 80.5 | 85.0 | 77.0 | 82.0 | 87.0 | 80.0 | 86.0 | 91.0 | 73.0 | 75.5 | 79.5 |
| A33 | 82.5 | 86.0 | 93.5 | 85.5 | 86.5 | 91.0 | 84.0 | 87.0 | 92.5 | 89.0 | 92.0 | 95.0 | 84.0 | 90.0 | 92.5 |
| A34 | 96.0 | 102.0 | 102.0 | 101.0 | 102.0 | 108.0 | 102.0 | 104.0 | 120.0 | 106.0 | 107.5 | 113.0 | 60.0 | 61.0 | 64.0 |
| A35 | 64.0 | 66.0 | 70.0 | 66.0 | 68.0 | 72.0 | 69.0 | 71.5 | 74.0 | 69.5 | 72.5 | 75.5 | 10.0 | 17.0 | 21.0 |
| A41 | 16.0 | 20.0 | 22.0 | 20.0 | 23.0 | 25.0 | 21.0 | 24.0 | 26.5 | 24.0 | 28.0 | 29.5 | 20.0 | 24.0 | 27.5 |
| A42 | 25.0 | 28.0 | 31.0 | 28.0 | 31.0 | 35.0 | 31.0 | 34.0 | 37.5 | 32.0 | 35.0 | 38.5 | 28.5 | 30.0 | 32.5 |
| A43 | 34.0 | 34.0 | 37.0 | 36.0 | 38.0 | 41.0 | 39.5 | 42.5 | 45.0 | 40.0 | 43.0 | 45.0 | 31.0 | 32.0 | 35.5 |
| A44 | 41.0 | 45.0 | 47.5 | 46.0 | 49.5 | 51.0 | 48.0 | 50.0 | 54.0 | 52.5 | 53.5 | 56.5 | 37.5 | 40.0 | 45.0 |
| A45 | 49.0 | 54.0 | 56.0 | 52.0 | 54.0 | 57.5 | 55.0 | 56.0 | 59.5 | 55.0 | 57.5 | 60.0 | 15.0 | 17.0 | 19.5 |
| A51 | 17.0 | 18.0 | 19.5 | 16.0 | 16.0 | 16.5 | 14.5 | 14.5 | 16.0 | 14.0 | 14.5 | 16.5 | 16.0 | 17.5 | 19.0 |
| A52 | 16.5 | 18.5 | 19.5 | 19.5 | 20.5 | 20.5 | 19.0 | 19.5 | 20.0 | 20.0 | 20.5 | 21.0 | 19.0 | 19.5 | 21.5 |
| A53 | 20.0 | 20.5 | 22.0 | 21.5 | 22.0 | 23.0 | 23.0 | 23.0 | 26.0 | 26.0 | 27.0 | 29.5 | 21.5 | 21.0 | 24.5 |
| A54 | 27.0 | 27.5 | 29.5 | 25.0 | 26.0 | 28.0 | 29.5 | 29.5 | 31.0 | 29.0 | 29.0 | 32.0 | 22.0 | 22.0 | 24.0 |
| A55 | 26.0 | 26.0 | 29.5 | 27.0 | 28.0 | 32.0 | 30.0 | 29.5 | 34.0 | 34.0 | 34.0 | 39.0 | 20.0 | 26.0 | 29.0 |
| A61 | 30.5 | 30.5 | 30.5 | 26.0 | 27.0 | 27.0 | 26.0 | 28.0 | 27.5 | 24.5 | 25.5 | 26.5 | 27.0 | 29.0 | 31.5 |
| A62 | 29.0 | 31.5 | 33.0 | 31.5 | 33.0 | 34.0 | 34.0 | 36.0 | 38.5 | 36.5 | 37.5 | 38.0 | 45.0 | 45.0 | 46.0 |
| A63 | 43.5 | 47.0 | 49.5 | 49.5 | 50.5 | 51.5 | 47.0 | 48.0 | 49.0 | 47.0 | 48.5 | 49.5 | 42.5 | 43.5 | 44.5 |
| A64 | 47.0 | 44.5 | 45.5 | 49.0 | 51.5 | 54.0 | 51.0 | 51.0 | 52.0 | 51.0 | 51.5 | 54.0 | 42.0 | 40.0 | 41.0 |
| A65 | 47.0 | 47.0 | 51.0 | 48.0 | 48.0 | 54.0 | 54.0 | 58.5 | 64.5 | 62.0 | 69.0 | 75.5 | 5.5 | 8.5 | 19.0 |
| A71 | 9.0 | 10.0 | 10.0 | 9.0 | 8.5 | 8.5 | 7.5 | 7.0 | 7.0 | 6.0 | 6.5 | 5.5 | 12.0 | 9.0 | 8.5 |
| A72 | 13.0 | 12.5 | 12.0 | 13.5 | 12.5 | 13.5 | 13.0 | 13.0 | 13.0 | 13.5 | 13.5 | 14.0 | 13.2 | 14.8 | 15.5 |

TABLE A10 (Continued)

RAW DATA PART 2 VERTICAL CUTTING FORCE (KG.)

| TEST NO. | CUT NUMBER 1 | | | 2 | | | 3 | | | 4 | | | 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| A73 | 16.5 | 18.0 | 18.0 | 16.0 | 17.0 | 18.0 | 17.5 | 18.0 | 19.5 | 19.5 | 19.0 | 20.5 | 13.5 | 12.5 | 12.5 |
| A74 | 18.5 | 20.0 | 21.0 | 22.0 | 23.0 | 23.5 | 24.0 | 25.0 | 27.0 | 27.0 | 28.0 | 28.5 | 18.5 | 19.0 | 16.5 |
| A75 | 25.0 | 25.0 | 23.5 | 25.0 | 24.0 | 23.5 | 23.0 | 23.5 | 23.5 | 21.0 | 21.0 | 20.0 | 14.0 | 19.0 | 18.5 |
| A81 | 16.5 | 15.0 | 14.0 | 13.5 | 12.5 | 14.0 | 17.0 | 18.0 | 20.0 | 22.5 | 22.5 | 23.5 | 18.5 | 17.0 | 20.5 |
| A82 | 20.0 | 19.0 | 22.0 | 20.0 | 19.0 | 23.5 | 20.5 | 19.0 | 24.5 | 27.0 | 26.5 | 31.5 | 34.0 | 34.0 | 34.0 |
| A83 | 18.0 | 32.0 | 36.0 | 39.0 | 41.5 | 41.0 | 41.5 | 40.0 | 42.5 | 42.5 | 42.0 | 45.0 | 35.0 | 38.5 | 44.5 |
| A84 | 39.0 | 41.0 | 41.5 | 38.0 | 45.0 | 48.0 | 47.0 | 48.5 | 49.0 | 48.5 | 50.5 | 51.5 | 57.0 | 63.0 | 66.0 |
| A85 | 59.0 | 60.0 | 63.5 | 59.0 | 59.0 | 57.5 | 51.0 | 55.5 | 50.5 | 54.0 | 53.5 | 55.0 | 0.0 | 0.0 | 0.0 |

TABLE A11
RAW DATA PART 2, CUTTING POWER, METER NO. 1

RAW DATA CUTTING POWER METER NO.1 PART 2 (kw.)

| TEST NO. | CUT NUMBER 1 B | 1 D | 2 B | 2 D | 3 B | 3 D | 4 B | 4 D | 5 B | 5 D |
|---|---|---|---|---|---|---|---|---|---|---|
| A11 | 0.240 | 0.230 | 0.240 | 0.225 | 0.240 | 0.230 | 0.240 | 0.230 | 0.240 | 0.230 |
| A12 | 0.210 | 0.200 | 0.210 | 0.180 | 0.220 | 0.180 | 0.200 | 0.200 | 0.220 | 0.205 |
| A13 | 0.240 | 0.240 | 0.240 | 0.235 | 0.240 | 0.230 | 0.230 | 0.240 | 0.250 | 0.250 |
| A14 | 0.250 | 0.250 | 0.245 | 0.240 | 0.250 | 0.225 | 0.260 | 0.245 | 0.270 | 0.280 |
| A15 | 0.220 | 0.200 | 0.220 | 0.200 | 0.220 | 0.205 | 0.225 | 0.200 | 0.220 | 0.210 |
| A21 | 0.260 | 0.250 | 0.260 | 0.235 | 0.275 | 0.250 | 0.265 | 0.260 | 0.260 | 0.240 |
| A22 | 0.240 | 0.235 | 0.240 | 0.220 | 0.245 | 0.230 | 0.250 | 0.240 | 0.245 | 0.235 |
| A23 | 0.240 | 0.325 | 0.240 | 0.260 | 0.250 | 0.240 | 0.275 | 0.255 | 0.280 | 0.245 |
| A24 | 0.270 | 0.245 | 0.270 | 0.260 | 0.260 | 0.245 | 0.260 | 0.250 | 0.245 | 0.240 |
| A25 | 0.275 | 0.245 | 0.280 | 0.245 | 0.280 | 0.260 | 0.280 | 0.260 | 0.280 | 0.255 |
| A31 | 0.270 | 0.240 | 0.280 | 0.260 | 0.265 | 0.240 | 0.260 | 0.240 | 0.265 | 0.240 |
| A32 | 0.260 | 0.240 | 0.260 | 0.240 | 0.260 | 0.240 | 0.260 | 0.220 | 0.270 | 0.240 |
| A33 | 0.280 | 0.250 | 0.300 | 0.260 | 0.280 | 0.250 | 0.280 | 0.250 | 0.290 | 0.260 |
| A34 | 0.280 | 0.265 | 0.280 | 0.240 | 0.280 | 0.245 | 0.280 | 0.240 | 0.280 | 0.250 |
| A35 | 0.240 | 0.205 | 0.250 | 0.220 | 0.240 | 0.210 | 0.240 | 0.200 | 0.230 | 0.190 |
| A41 | 0.305 | 0.280 | 0.280 | 0.270 | 0.280 | 0.270 | 0.280 | 0.260 | 0.270 | 0.255 |
| A42 | 0.250 | 0.240 | 0.260 | 0.255 | 0.270 | 0.245 | 0.260 | 0.240 | 0.260 | 0.240 |
| A43 | 0.280 | 0.260 | 0.260 | 0.320 | 0.265 | 0.240 | 0.280 | 0.300 | 0.260 | 0.260 |
| A44 | 0.260 | 0.245 | 0.240 | 0.245 | 0.270 | 0.260 | 0.280 | 0.260 | 0.260 | 0.260 |
| A45 | 0.260 | 0.250 | 0.275 | 0.275 | 0.240 | 0.230 | 0.255 | 0.235 | 0.230 | 0.235 |
| A51 | 0.280 | 0.260 | 0.285 | 0.265 | 0.280 | 0.280 | 0.285 | 0.280 | 0.295 | 0.285 |
| A52 | 0.300 | 0.290 | 0.280 | 0.275 | 0.285 | 0.280 | 0.300 | 0.290 | 0.295 | 0.280 |
| A53 | 0.180 | 0.270 | 0.275 | 0.270 | 0.270 | 0.255 | 0.280 | 0.260 | 0.265 | 0.285 |
| A54 | 0.265 | 0.260 | 0.270 | 0.260 | 0.280 | 0.260 | 0.280 | 0.265 | 0.280 | 0.260 |
| A55 | 0.260 | 0.280 | 0.270 | 0.260 | 0.280 | 0.280 | 0.290 | 0.270 | 0.300 | 0.260 |
| A61 | 0.240 | 0.230 | 0.245 | 0.220 | 0.245 | 0.230 | 0.260 | 0.240 | 0.270 | 0.250 |
| A62 | 0.290 | 0.270 | 0.280 | 0.260 | 0.285 | 0.320 | 0.280 | 0.280 | 0.280 | 0.265 |
| A63 | 0.290 | 0.260 | 0.280 | 0.275 | 0.280 | 0.255 | 0.295 | 0.260 | 0.290 | 0.250 |
| A64 | 0.255 | 0.250 | 0.270 | 0.250 | 0.260 | 0.245 | 0.280 | 0.240 | 0.280 | 0.240 |
| A65 | 0.260 | 0.225 | 0.245 | 0.240 | 0.250 | 0.210 | 0.230 | 0.190 | 0.250 | 0.200 |
| A71 | 0.240 | 0.255 | 0.280 | 0.300 | 0.315 | 0.280 | 0.260 | 0.260 | 0.280 | 0.265 |
| A72 | 0.280 | 0.260 | 0.240 | 0.260 | 0.270 | 0.260 | 0.260 | 0.270 | 0.260 | 0.270 |
| A73 | 0.240 | 0.250 | 0.270 | 0.210 | 0.245 | 0.180 | 0.270 | 0.240 | 0.280 | 0.260 |

TABLE A11 (Continued)

RAW DATA CUTTING POWER METER NO.1 PART 2 (kw.)

| TEST NO. | CUT NUMBER 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | B | D | B | D | B | D | B | D | B | D |
| A74 | 0.280 | 0.280 | 0.280 | 0.280 | 0.290 | 0.280 | 0.290 | 0.280 | 0.280 | 0.280 |
| A75 | 0.280 | 0.260 | 0.260 | 0.250 | 0.270 | 0.260 | 0.260 | 0.260 | 0.270 | 0.260 |
| A81 | 0.280 | 0.260 | 0.280 | 0.270 | 0.280 | 0.280 | 0.280 | 0.280 | 0.280 | 0.280 |
| A82 | 0.300 | 0.280 | 0.280 | 0.270 | 0.280 | 0.275 | 0.290 | 0.280 | 0.295 | 0.270 |
| A83 | 0.280 | 0.280 | 0.270 | 0.260 | 0.290 | 0.280 | 0.300 | 0.280 | 0.290 | 0.280 |
| A84 | 0.260 | 0.270 | 0.260 | 0.250 | 0.290 | 0.250 | 0.240 | 0.220 | 0.240 | 0.240 |
| A85 | 0.260 | 0.260 | 0.280 | 0.250 | 0.280 | 0.260 | 0.290 | 0.270 | 0.270 | 0.260 |

Note:

Data listed under Column B represents the meter reading taken before cutting commenced. Data listed under Column D represents the meter reading taken during the cutting process.

TABLE A12

RAW DATA PART 2, CUTTING POWER, METER NO. 2

RAW DATA CUTTING POWER METER NO.2 PART 2 (kw.)

| TEST NO. | CUT NUMBER 1 B | 1 D | 2 B | 2 D | 3 B | 3 D | 4 B | 4 D | 5 B | 5 D |
|---|---|---|---|---|---|---|---|---|---|---|
| A11 | 0.500 | 0.500 | 0.500 | 0.495 | 0.500 | 0.495 | 0.490 | 0.495 | 0.490 | 0.500 |
| A12 | 0.475 | 0.480 | 0.480 | 0.460 | 0.480 | 0.465 | 0.460 | 0.480 | 0.480 | 0.485 |
| A13 | 0.500 | 0.525 | 0.500 | 0.510 | 0.500 | 0.510 | 0.490 | 0.520 | 0.510 | 0.525 |
| A14 | 0.510 | 0.530 | 0.505 | 0.520 | 0.510 | 0.495 | 0.510 | 0.525 | 0.525 | 0.545 |
| A15 | 0.470 | 0.480 | 0.480 | 0.475 | 0.480 | 0.475 | 0.475 | 0.475 | 0.470 | 0.485 |
| A21 | 0.530 | 0.542 | 0.540 | 0.550 | 0.540 | 0.540 | 0.530 | 0.555 | 0.530 | 0.540 |
| A22 | 0.500 | 0.520 | 0.500 | 0.510 | 0.500 | 0.515 | 0.505 | 0.520 | 0.500 | 0.520 |
| A23 | 0.500 | 0.525 | 0.500 | 0.560 | 0.510 | 0.540 | 0.535 | 0.545 | 0.540 | 0.535 |
| A24 | 0.520 | 0.540 | 0.520 | 0.545 | 0.510 | 0.535 | 0.510 | 0.530 | 0.485 | 0.520 |
| A25 | 0.525 | 0.545 | 0.530 | 0.545 | 0.520 | 0.545 | 0.520 | 0.540 | 0.520 | 0.520 |
| A31 | 0.520 | 0.530 | 0.540 | 0.560 | 0.520 | 0.540 | 0.520 | 0.550 | 0.520 | 0.540 |
| A32 | 0.520 | 0.540 | 0.520 | 0.545 | 0.520 | 0.545 | 0.510 | 0.540 | 0.520 | 0.560 |
| A33 | 0.540 | 0.560 | 0.560 | 0.580 | 0.540 | 0.570 | 0.540 | 0.570 | 0.550 | 0.580 |
| A34 | 0.540 | 0.565 | 0.540 | 0.565 | 0.540 | 0.560 | 0.540 | 0.570 | 0.540 | 0.570 |
| A35 | 0.500 | 0.525 | 0.505 | 0.540 | 0.500 | 0.530 | 0.500 | 0.530 | 0.480 | 0.515 |
| A41 | 0.575 | 0.565 | 0.540 | 0.560 | 0.540 | 0.560 | 0.540 | 0.545 | 0.540 | 0.545 |
| A42 | 0.510 | 0.525 | 0.520 | 0.535 | 0.520 | 0.535 | 0.520 | 0.525 | 0.520 | 0.525 |
| A43 | 0.540 | 0.540 | 0.540 | 0.600 | 0.520 | 0.525 | 0.530 | 0.580 | 0.520 | 0.545 |
| A44 | 0.520 | 0.520 | 0.500 | 0.530 | 0.520 | 0.545 | 0.535 | 0.550 | 0.520 | 0.540 |
| A45 | 0.520 | 0.530 | 0.525 | 0.565 | 0.490 | 0.515 | 0.500 | 0.520 | 0.480 | 0.515 |
| A51 | 0.520 | 0.535 | 0.535 | 0.540 | 0.530 | 0.540 | 0.535 | 0.540 | 0.540 | 0.555 |
| A52 | 0.555 | 0.560 | 0.520 | 0.540 | 0.535 | 0.540 | 0.545 | 0.560 | 0.540 | 0.550 |
| A53 | 0.540 | 0.555 | 0.535 | 0.555 | 0.535 | 0.545 | 0.540 | 0.550 | 0.560 | 0.575 |
| A54 | 0.510 | 0.525 | 0.520 | 0.540 | 0.530 | 0.540 | 0.530 | 0.545 | 0.570 | 0.545 |
| A55 | 0.535 | 0.555 | 0.520 | 0.540 | 0.525 | 0.550 | 0.540 | 0.545 | 0.550 | 0.550 |
| A61 | 0.495 | 0.520 | 0.500 | 0.520 | 0.505 | 0.525 | 0.510 | 0.535 | 0.520 | 0.245 |
| A62 | 0.545 | 0.565 | 0.530 | 0.560 | 0.540 | 0.620 | 0.540 | 0.580 | 0.530 | 0.570 |
| A63 | 0.540 | 0.560 | 0.545 | 0.585 | 0.540 | 0.565 | 0.540 | 0.560 | 0.540 | 0.560 |
| A64 | 0.495 | 0.545 | 0.520 | 0.550 | 0.520 | 0.560 | 0.540 | 0.540 | 0.530 | 0.550 |
| A65 | 0.520 | 0.535 | 0.520 | 0.550 | 0.505 | 0.520 | 0.480 | 0.520 | 0.500 | 0.530 |
| A71 | 0.490 | 0.530 | 0.540 | 0.550 | 0.560 | 0.540 | 0.510 | 0.505 | 0.520 | 0.515 |
| A72 | 0.540 | 0.510 | 0.500 | 0.520 | 0.520 | 0.520 | 0.520 | 0.540 | 0.520 | 0.530 |
| A73 | 0.495 | 0.520 | 0.530 | 0.490 | 0.500 | 0.460 | 0.520 | 0.510 | 0.540 | 0.540 |

TABLE A12 (Continued)

RAW DATA CUTTING POWER METER NO.2 PART 2 (kw.)

| TEST NO. | CUT NUMBER 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | B | D | B | D | B | D | B | D | B | D |
| A74 | 0.540 | 0.540 | 0.540 | 0.540 | 0.550 | 0.550 | 0.550 | 0.550 | 0.540 | 0.550 |
| A75 | 0.540 | 0.520 | 0.520 | 0.520 | 0.520 | 0.540 | 0.520 | 0.530 | 0.520 | 0.520 |
| A81 | 0.520 | 0.540 | 0.540 | 0.540 | 0.540 | 0.540 | 0.540 | 0.540 | 0.540 | 0.550 |
| A82 | 0.545 | 0.550 | 0.530 | 0.545 | 0.540 | 0.550 | 0.540 | 0.550 | 0.550 | 0.550 |
| A83 | 0.540 | 0.570 | 0.530 | 0.550 | 0.540 | 0.560 | 0.560 | 0.560 | 0.550 | 0.560 |
| A84 | 0.540 | 0.550 | 0.520 | 0.540 | 0.550 | 0.540 | 0.520 | 0.520 | 0.500 | 0.540 |
| A85 | 0.540 | 0.550 | 0.540 | 0.550 | 0.540 | 0.560 | 0.540 | 0.570 | 0.530 | 0.560 |

Note: Data listed under Column B represents the meter reading taken before cutting commenced. Data listed under Column D represents the meter reading taken during the cutting process.

TABLE A13

RAW DATA PART 2, COPPER SULPHATE AND ACID CONCENTRATION AND SURFACE FINISH

RAW DATA PART 2

| TEST NO. | DEPTH OF CUT | FEED RATE | CLA1 | CLA2 | CLA3 |
|---|---|---|---|---|---|
| A11 | 0.005 | 2.1 | 7. | 10. | 10. |
| A12 | 0.005 | 2.1 | 10. | 10. | 12. |
| A13 | 0.005 | 2.1 | 18. | 8. | 10. |
| A14 | 0.005 | 2.1 | 9. | 11. | 10. |
| A15 | 0.005 | 2.1 | 12. | 10. | 13. |
| A21 | 0.010 | 2.1 | 10. | 10. | 10. |
| A22 | 0.010 | 2.1 | 10. | 13. | 15. |
| A23 | 0.010 | 2.1 | 18. | 16. | 14. |
| A24 | 0.010 | 2.1 | 22. | 20. | 20. |
| A25 | 0.010 | 2.1 | 20. | 14. | 12. |
| A31 | 0.010 | 7.7 | 16. | 12. | 22. |
| A32 | 0.010 | 7.7 | 30. | 39. | 38. |
| A33 | 0.010 | 7.7 | 22. | 24. | 40. |
| A34 | 0.010 | 7.7 | 20. | 14. | 12. |
| A35 | 0.010 | 7.7 | 20. | 20. | 30. |
| A41 | 0.005 | 7.7 | 23. | 17. | 26. |
| A42 | 0.005 | 7.7 | 20. | 16. | 17. |
| A43 | 0.005 | 7.7 | 20. | 18. | 18. |
| A44 | 0.005 | 7.7 | 20. | 20. | 21. |
| A45 | 0.005 | 7.7 | 22. | 21. | 24. |
| A51 | 0.005 | 7.7 | 62. | 31. | 50. |
| A52 | 0.005 | 7.7 | 100. | 32. | 28. |
| A53 | 0.005 | 7.7 | 40. | 17. | 30. |
| A54 | 0.005 | 7.7 | 65. | 43. | 50. |
| A55 | 0.005 | 7.7 | 22. | 49. | 69. |
| A61 | 0.010 | 7.7 | 34. | 32. | 44. |
| A62 | 0.010 | 7.7 | 44. | 80. | 100. |
| A63 | 0.010 | 7.7 | 44. | 42. | 42. |
| A64 | 0.010 | 7.7 | 41. | 59. | 42. |
| A65 | 0.010 | 7.7 | 70. | 90. | 42. |
| A71 | 0.005 | 2.1 | 30. | 26. | 26. |
| A72 | 0.005 | 2.1 | 12. | 14. | 12. |
| A73 | 0.005 | 2.1 | 38. | 32. | 10. |
| A74 | 0.005 | 2.1 | 38. | 34. | 100. |
| A75 | 0.005 | 2.1 | 14. | 12. | 8. |
| A81 | 0.010 | 2.1 | 70. | 90. | 42. |
| A82 | 0.010 | 2.1 | 20. | 36. | 16. |
| A83 | 0.010 | 2.1 | 22. | 62. | 14. |
| A84 | 0.010 | 2.1 | 100. | 40. | 52. |
| A85 | 0.010 | 2.1 | 24. | 65. | 58. |

Note: Acid and copper sulphate concentration (g/l)
Surface finish (CLA) (micro inches)

TABLE A14

RAW DATA, SIZE AND HARDNESS OF TEST PIECES

| SAMPLE | WIDTH(IN.) | | | LENGTH (IN.) | | THICKNESS (IN.) | | | | | | ROCKWELL C HARDNESS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NO. | 1 | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 1 | 2 | 3 |
| 1 | 1.012 | 1.013 | 1.014 | 6.026 | 6.026 | .249 | .249 | .253 | .253 | .251 | .251 | 35.0 | 34.0 | 33.0 |
| 2 | 1.015 | 1.012 | 1.012 | 6.030 | 6.031 | .249 | .250 | .252 | .253 | .251 | .250 | 37.5 | 36.5 | 37.0 |
| 3 | 1.010 | 1.011 | 1.012 | 6.005 | 6.009 | .250 | .249 | .251 | .252 | .249 | .249 | 36.0 | 35.0 | 34.0 |
| 4 | 1.012 | 1.010 | 1.010 | 5.994 | 6.007 | .250 | .251 | .252 | .254 | .250 | .251 | 34.5 | 36.0 | 36.0 |
| 5 | 1.003 | 1.003 | 1.010 | 6.014 | 6.014 | .249 | .248 | .255 | .253 | .249 | .249 | 36.0 | 35.0 | 36.0 |
| 6 | 1.014 | 1.013 | 1.011 | 6.031 | 6.017 | .251 | .250 | .255 | .254 | .251 | .250 | 36.5 | 36.0 | 36.0 |
| 7 | 1.013 | 1.015 | 1.019 | 6.017 | 6.023 | .248 | .248 | .253 | .254 | .250 | .248 | 35.0 | 36.5 | 36.5 |
| 8 | 1.013 | 1.007 | 1.006 | 5.996 | 5.992 | .249 | .250 | .254 | .254 | .252 | .250 | 34.0 | 35.5 | 35.0 |
| 9 | 1.010 | 1.010 | 1.013 | 5.984 | 5.998 | .250 | .250 | .254 | .255 | .250 | .250 | 36.0 | 35.5 | 36.0 |
| 10 | 1.011 | 1.012 | 1.013 | 5.993 | 6.009 | .251 | .251 | .252 | .250 | .249 | .248 | 35.0 | 35.0 | 35.5 |
| 11 | 1.014 | 1.012 | 1.010 | 5.990 | 5.993 | .250 | .250 | .254 | .254 | .249 | .248 | 35.0 | 35.0 | 34.0 |
| 12 | 1.012 | 1.009 | 1.009 | 6.000 | 6.004 | .250 | .250 | .252 | .253 | .249 | .250 | 34.5 | 35.0 | 35.0 |
| 13 | 1.011 | 1.010 | 1.008 | 5.987 | 6.004 | .251 | .249 | .254 | .254 | .250 | .249 | 35.0 | 34.5 | 34.0 |
| 14 | 1.015 | 1.012 | 1.011 | 5.997 | 5.991 | .251 | .249 | .256 | .253 | .252 | .249 | 36.5 | 35.5 | 35.5 |
| 15 | 1.011 | 1.010 | 1.011 | 6.011 | 5.997 | .250 | .249 | .253 | .252 | .250 | .250 | 36.5 | 35.5 | 36.0 |
| 16 | 1.014 | 1.012 | 1.011 | 6.009 | 5.999 | .251 | .249 | .253 | .252 | .252 | .251 | 34.5 | 34.0 | 35.0 |
| 17 | 1.014 | 1.012 | 1.012 | 6.041 | 6.031 | .250 | .249 | .254 | .254 | .250 | .250 | 35.5 | 35.5 | 36.0 |
| 18 | 1.012 | 1.014 | 1.016 | 6.007 | 6.027 | .250 | .250 | .257 | .257 | .251 | .246 | 34.5 | 36.0 | 35.0 |
| 19 | 1.012 | 1.015 | 1.014 | 6.018 | 6.028 | .251 | .251 | .253 | .252 | .250 | .251 | 34.0 | 34.5 | 34.5 |
| 20 | 1.012 | 1.012 | 1.014 | 6.008 | 6.013 | .248 | .250 | .248 | .250 | .249 | .251 | 35.0 | 33.5 | 36.0 |
| 21 | 1.015 | 1.013 | 1.011 | 6.025 | 6.008 | .248 | .250 | .254 | .255 | .248 | .248 | 35.5 | 34.5 | 35.0 |

# APPENDIX B

This appendix contains a listing and brief description of all computer programs used during the study and in the preparation of this thesis. All programs, except Program B4, were written for the IBM 1130 in FORTRAN 1V. Program B4 was taken from the IBM 370 Library.

Average and Standard Deviation Programs B1 and B2.-- One of these programs is designed to process Part 1 data, the other Part 11 data. Information, in the form of raw data, is read in and stored on disk files, sorted, average values and standard deviation calculated, and printed and punched as output. Print out was used directly in the body of the thesis.

Sorting Program B3.-- This program was written to rearrange the output of various programs and present the data in card form for further processing. The program is modified for each specific job.

Polynomial Regression Analysis Program B4.-- The output from the Part 1, Average and standard deviation program, in card form, is rearranged by Program B3 and is used as input to this program. Input data consists of copper sulphate concentration and the corresponding value of the various variables measured. Output consists of: analysis of variance tables, polynomial regression coefficients, table of residuals, and a plot of the best fit regression curve.

The original program has been modified to give an additional output of the Table of Residuals in card form.

Straight Line Regression Analysis Program B5.-- This program inputs two variables, x and y, and performs a straight line regression analysis by calculating the slope and y intercept of the curve. It also calculates the correlation coefficient and the statistics required to determine the confidence level of the slope and intercept and to determine if the slope is significantly different from zero. Output is in printed and punched form.

To process the data from the average and standard deviation program, it was first rearranged by Program B3.

Program to Plot Regression Line Part 11 Data, Program B6.-- This program was designed to read in the scales of the graph to be plotted, the x and y variables, the slope and y intercept of the regression line, and to plot x, y and the y estimate on an IBM 1726 drum plotter.

Listing Programs B7.-- Several of the tables in the body of the thesis and all of the data presented in Appendix A consists of computer print out. Programs used to list this data are very simple, consisting basically of read in and print out statements. Headings and Programs are as follows:-

(a) To print raw data, Part 1 and Part 11, wear.

(b) Program to rearrange and print cutting power for Part 1 and Part 11.

(c) To print raw data, cutting forces Part 1.

(d) To print raw data, cutting forces Part 11.

(e) To print raw data, copper sulphate and acid concentration and surface finish Part 1 data and feed rate, depth of cut and surface finish Part 11 data.

(f) Computer program to print Table 6.9.

(g) To print size and hardness of test samples.

COMPUTER PROGRAM B1

```
C     INPUTS RAW DATA AND CALCULATES AVERAGE VALUES AND STD. DEVIATIONS
C     FOR PART ONE DATA
      INTEGER CLA1,CLA2,CLA3
      DEFINE FILE 20(750,20,U,J),11(400,10,U,J),21(400,18,U,L),22(400,17
     1,U,J1),23(90,14,U,K)
      N5=0
      SSQ2=0
      L 1
      J2=0
      J1=1
      K=1
      SCPOW=0
      SSQ1=0
      SHFOR=0
      SVFOR=0
      SRFOR=0
      SSQ3=0
      SSQ4=0
      SSQ5=0
      SWEAR=0
      K1=1
      J=1
   21 READ(2,20)NTEST,BWEAR,AWEAR,CUCON,SACID,CLA1,CLA2,CLA3,N,IDENT
   20 FORMAT(1X,I4,F6.3,F7.3,2X,F6.3,F4.1,3I4,34X,I2,A2)
      CLA=(CLA1+CLA2+CLA3)/3
      ACCON=CUCON*13.8528
      WRITE(20'J)NTEST,BWEAR,AWEAR,ACCON,SACID,CLA,N,IDENT
      IF(N-1)21,35,21
   35 J 1
   22 READ(2,23)MTEST,BPOW2,DPOW1,DPOW2,BPOW1,HFOR1,VFOR2,M5,M,JDENT
   23 FORMAT(I4,1X,F4.3,1X,F4.3,2X,F4.3,1X,F4.3,2F5.2,4X,I2,35X,I2,A2)
      IF(M5-2)60,61,61
   60 HFORS=HFOR1*.25
      VFORS=VFOR2*.25
      GO TO 62
   61 HFORS=HFOR1*.20833
```

```
   VFORS=VFOR2*.25
62 POWM1=DPOW1-BPOW1
   POWM1=DPOW1-BPOW1
   POWM2=DPOW2-BPOW2
   CPOW=POWM1+POWM2
   WRITE(11'J)MTEST,CPOW,HFORS,VFORS,M
   WRITE(21'L)MTEST,BPOW1,DPOW1,BPOW2,DPOW2,HFORS,VFORS,JDENT,M
   IF(M-1)22,24,22
24 J=1
26 READ(20'J)NTEST,BWEAR,AWEAR,ACCON,SACID,CLA,N,IDENT
   IF(N-1)26,27,26
27 L=1
29 READ(21'L)MTEST,BPOW1,DPOW1,BPOW2,DPOW2,HFORS,VFORS,JDENT,M
   IF(M-1)29,30,29
30 I=0
   J=1
   J1=1
 1 READ(11'J)MTEST,CPOW,HFORS,VFORS,M
   I=I+1
   SQPOW=CPOW**2
   SSQ1=SSQ1+SQPOW
   SCPOW=SCPOW+CPOW
   RFORS=SQRT(HFORS**2+VFORS**2)
   SHFOR=SHFOR+HFORS
   SVFOR=SVFOR+VFORS
   SRFOR=SRFOR+RFORS
   SQHF=HFORS**2
   SQVF=VFORS**2
   SQRF=RFORS**2
   SSQ3=SSQ3+SQHF
   SSQ4=SSQ4+SQVF
   SSQ5=SSQ5+SQRF
   IF(I-5)1,2,1
 2 AVPOW=SCPOW/5+.00005
   SDPOW=SQRT((SSQ1-5*AVPOW**2)/4)+.00005
   AVHF=SHFOR/5+.00005
```

```
      AVVF=SVFOR/5+.00005
      AVVF=SVFOR/5+.00005
      SDHF=SQRT((SSQ3-5*AVHF**2)/4)+.00005
      SDVF=SQRT((SSQ4-5*AVVF**2)/4)+.00005
      SDRF=SQRT((SSQ5-5*AVRF**2)/4)+.00005
      WRITE(22'J1)MTEST,AVPOW,SDPOW,AVHF,SDHF,AVVF,SDVF,AVRF,SDRF
      I=0
      SSQ1=0
      SCPOW=0
      SSQ3=0
      SSQ4=0
      SSQ5=0
      SHFOR=0
      SVFOR=0
      SRFOR=0
      IF(M-1)1,3,1
    3 K=1
      J=1
   10 READ (20'J)NTEST,BWEAR,AWEAR,ACCON,SACID,CLA,N,IDENT
      I=I+1
      WEAR=BWEAR-AWEAR
      SWEAR=SWEAR+WEAR
      SQWER=WEAR**2
      SSQ2=SSQ2+SQWER
      IF(I-14)10,12,10
   12 AVWER=SWEAR/14+.00005
      SDWER=SQRT((SSQ2-14*AVWER**2)/13)+.00005
      WRITE(23'K)NTEST,AVWER,SDWER,ACCON,SACID,CLA,N
      I=0
      SSQ2=0
      SWEAR=0
      IF(N-1)10,13,10
   13 J1=1
      K=1
      J2=J2+1
      IF(J2-2)31,15,15
```

```
 31 WRITE(5,50)
 50 FORMAT(92H TEST  TOOTH WEAR   HZ FORCE     V FORCE      R FORCE
   1     POWER        CUSO4  ACID        /90H  NO      AV     SD      AV
   2  SD       AV   SD       AV   SD       AV     SD   CONC    CONC  CLA/)
 15 READ(22'J1)MTEST,AVPOW,SDPOW,AVHF,SDHF,AVVF,SDVF,AVRF,SDRF
    READ(23'K) NTEST,AVWER,SDWER,ACCON,SACID,CLA,N
    IF(N5-30)100,101,100
101 PAUSE1111
    WRITE(5,50)
100 WRITE(5,51)NTEST,AVWER,SDWER,AVHF,SDHF,AVVF,SDVF,AVRF,SDRF,AVPOW,S
   1DPOW,ACCON,SACID,CLA
 51 FORMAT(1X,I4,2X,F6.4,1X,F5.3,2X,F5.3,1X,F5.3,2X,F5.3,1X,F5.3,2X,F5
   1.3,1X,F5.3,2X,F6.3,1X,F5.3,2X,F6.3,1X,F4.1,2X,F4.0)
    WRITE(2,53)ACCON,SACID,AVWER,AVPOW,AVHF,AVVF,AVRF,CLA
 53 FORMAT(8F10.4)
    N5=N5+1
    IF(N-1)15,14,15
 14 CALL EXIT
    END
```

COMPUTER PROGRAM B2

```
C     INPUTS RAW DATA AND CALCULATES AVERAGE VALUES AND STD. DEVIATIONS
C     FOR PART 2 DATA
      REAL MTEST
      REAL NTEST
      DEFINE FILE 20(750,20,U,J),11(400,10,U,J),21(400,18,U,L),22(400,17
     1,U,J1),23(90,14,U,K)
      N5=0
      N2=0
      D=.100
      SSQ2=0
      L 1
      J2=0
      J1=1
      K=1
      SCPOW=0
      SSQ1=0
      SHFOR=0
      SVFOR=0
      SRFOR=0
      SSQ3=0
      SSQ4=0
      SSQ5=0
      SWEAR=0
      K1=1
      J=1
   21 READ(2,20)NTEST,BWEAR,AWEAR,CFEED,DEPTH,CLA1,CLA2,CLA3,N,IDENT
   20 FORMAT (1X,A4,F6.3,F7.3,3X,F3.1,F6.3,3F5.1,31X,I2,A2)
      ACCON=CFEED
      SACID=DEPTH
      CLA=(CLA1+CLA2+CLA3)/3
      WRITE(20'J)NTEST,BWEAR,AWEAR,ACCON,SACID,CLA,N,IDENT
      IF(N-1)21,35,21
   35 J 1
   22 READ(2,23)MTEST,BPOW1,BPOW2,DPOW1,DPOW2,FH1,FH2,FH3,FV1,FV2,FV3,C,
     1M,JDENT
   23 FORMAT (1X,A4,5X,4F5.3,6F5.1,F5.3,11X,I2,A2)
```

```
      HFORS=((FH1+FH2+FH3)/3)*C*D
      VFORS=((FV1+FV2+FV3)/3)*C*D
      POWM1=DPOW1-BPOW1
      POWM2=DPOW2-BPOW2
      CPOW=POWM1+POWM2
      WRITE(11'J)MTEST,CPOW,HFORS,VFORS,M
      WRITE(21'L)MTEST,BPOW1,DPOW1,BPOW2,DPOW2,HFORS,VFORS,JDENT,M
      IF(M-1)22,24,22
   24 J=1
   26 READ(20'J)NTEST,BWEAR,AWEAR,ACCON,SACID,CLA,N,IDENT
      IF(N-1)26,27,26
   27 L=1
   29 READ(21'L)MTEST,BPOW1,DPOW1,BPOW2,DPOW2,HFORS,VFORS,JDENT,M
      IF(M-1)29,30,29
   30 I=0
      J=1
      J1=1
    1 READ(11'J)MTEST,CPOW,HFORS,VFORS,M
      I=I+1
      SQPOW=CPOW**2
      SSQ1=SSQ1+SQPOW
      SCPOW=SCPOW+CPOW
      RFORS=SQRT(HFORS**2+VFORS**2)
      SHFOR=SHFOR+HFORS
      SVFOR=SVFOR+VFORS
      SRFOR=SRFOR+RFORS
      SQHF=HFORS**2
      SQVF=VFORS**2
      SQRF=RFORS**2
      SSQ3=SSQ3+SQHF
      SSQ4=SSQ4+SQVF
      SSQ5=SSQ5+SQRF
      IF(I-5)1,2,1
    2 AVPOW=SCPOW/5+.00005
      SDPOW=SQRT((SSQ1-5*AVPOW**2)/4)+.00005
      AVHF=SHFOR/5+.00005
```

```
      AVVF=SVFOR/5+.00005
      AVRF=SRFOR/5+.00005
      SDHF=SQRT((SSQ3-5*AVHF**2)/4)+.00005
      SDVF=SQRT((SSQ4-5*AVVF**2)/4)+.00005
      SDRF=SQRT((SSQ5-5*AVRF**2)/4)+.00005
      WRITE(22'J1)MTEST,AVPOW,SDPOW,AVHF,SDHF,AVVF,SDVF,AVRF,SDRF
      I=0
      SSQ1=0
      SCPOW=0
      SSQ3=0
      SSQ4=0
      SSQ5=0
      SHFOR=0
      SVFOR=0
      SRFOR=0
      IF(M-1)1,3,1
    3 K=1
      J=1
   10 READ (20'J)NTEST,BWEAR,AWEAR,ACCON,SACID,CLA,N,IDENT
      I=I+1
      WEAR=BWEAR-AWEAR
      SWEAR=SWEAR+WEAR
      SQWER=WEAR**2
      SSQ2=SSQ2+SQWER
      IF(I-14)10,12,10
   12 AVWER=SWEAR/14+.00005
      SDWER=SQRT((SSQ2-14*AVWER**2)/13)+.00005
      WRITE(23'K)NTEST,AVWER,SDWER,ACCON,SACID,CLA,N
      I=0
      SSQ2=0
      SWEAR=0
      IF(N-1)10,13,10
   13 J1=1
      K=1
      J2=J2+1
      IF(J2-2)31,15,15
```

```
 31 WRITE(5,50)
 50 FORMAT(92H TEST  TOOTH WEAR    HZ FORCE      V FORCE       R FORCE
   1       POWER        FEED  DEPTH  CLA/92H NO       AV    SD       AV
   2   SD       AV     SD       AV     SD       AV     SD   RATE  OF CUT
   3/)
 15 READ(22'J1)MTEST,AVPOW,SDPOW,AVHF,SDHF,AVVF,SDVF,AVRF,SDRF
    READ(23'K) NTEST,AVWER,SDWER,ACCON,SACID,CLA,N
    IF(N5-30)100,101,100
101 PAUSE1111
    WRITE(5,50)
100 WRITE(5,51)NTEST,AVWER,SDWER,AVHF,SDHF,AVVF,SDVF,AVRF,SDRF,AVPOW,S
   1DPOW,ACCON,SACID,CLA
 51 FORMAT(1X,A4,2X,F6.4,1X,F5.3,2X,F6.3,1X,F5.3,2X,F6.3,1X,F5.3,2X,F6
   1.3,1X,F5.3,2X,F6.3,1X,F5.3,1X,F4.1,2X,F5.3,2X,F3.0)
    N2=N2+1
    IF(N2-1)60,61,60
 61 X1=.015
    X2=.0075
    GO TO 70
 60 IF(N2-2)62,63,62
 63 X1=.0300
    X2=.0150
    GO TO 70
 62 IF(N2-3)64,65,64
 65 X1=.045
    X2=.0225
    GO TO 70
 64 IF(N2-4)66,67,66
 67 X1=.0600
    X2=.0300
    GO TO 70
 66 IF(N2-5)68,69,68
 69 X1=.0750
    X2=.0375
    N2=0
    GO TO 70
```

```
68 WRITE(5,53)
53 FORMAT('ERROR')
70 WRITE(2,52)X1,X2,AVWER,AVPOW,AVVF,AVHF,AVRF,CLA
52 FORMAT(8F10.4)
   N5=N5+1
   IF(N-1)15,14,15
14 CALL EXIT
   END
```

COMPUTER PROGRAM B3

```
C     PROGRAM TAKES DATA FROM AVG. AND STD. DEVIATION PROGRAMS IN CARDFORM
C     AND PUNCHES OUT DATA AS X AND Y FOR USE IN GRAPH POLTING PROGRAM
      DIMENSION X1(50),X2(50),X3(50),X4(50),X5(50),X6(50),X7(50),X8(50)
      READ(2,1)N
    1 FORMAT(8X,I2)
      DO 5 I=1,N
      READ(2,2)X1(I),X2(I),X3(I),X4(I),X5(I),X6(I),X7(I),X8(I)
    2 FORMAT(8F10.4)
    5 CONTINUE
      PAUSE1111
      DO 11 I=1,N
      WRITE(2,3)X1(I),X3(I)
    3 FORMAT(2F10.4)
   11 CONTINUE
      DO 12 I=1,N
      WRITE(2,3)X1(I),X4(I)
   12 CONTINUE
      DO 13 I=1,N
      WRITE(2,3)X1(I),X5(I)
   13 CONTINUE
      DO 14 I=1,N
      WRITE(2,3)X1(I),X6(I)
   14 CONTINUE
      DO 15 I=1,N
      WRITE(2,3)X1(I),X7(I)
   15 CONTINUE
      DO 16 I=1,N
      WRITE(2,3)X1(I),X8(I)
   16 CONTINUE
      CALL EXIT
      END
```

COMPUTER PROGRAM B4

```
C     POLYNOMIAL REGRESSION PROGRAM POLRG     MAIN PROGRAM
C     ROBERT J GOOSNEY GRADUATE STUDENT FACULTY OF ENGINEERING
C     PROGRAM MODIFIED TO PRODUSE OUTPUT IN CARD FORM
C     SUBROUTINE FUNCTION SUBPROGRAMS REQUIRED
C     GDATA
C     ORDER
C     MINV
C     MULTR
C     PLOT
      DIMENSION X(1100)
      DIMENSION DI(100)
      DIMENSION D(66)
      DIMENSION B(10),E(10),SB(10),T(10)
      DIMENSION XBAR(11),STD(11),COE(11),SUMSQ(11),ISAVE(11)
      DIMENSION ANS(10)
      DIMENSION P(300)
      DIMENSION X1(500),X2(500),X3(500)
      M7=0
    1 FORMAT(A4,A2,I5,I2,I1,I2)
    2 FORMAT(2F10.4)
    3 FORMAT(27H1POLYNOMIAL REGRESSION.....,A4,A2/)
    4 FORMAT(23H0NUMBER OF OBSERVATIONS,I6//)
    5 FORMAT(32H0POLYNOMIAL REGRESSION OF DEGREE,I3)
    6 FORMAT(12H0 INTERCEPT ,E20.7)
    7 FORMAT(26H0  REGRESSION COEFFICIENTS/(6E20.7))
    8 FORMAT(1H0/24X,24HANALYSIS OF VARIANCE FOR,I4,19H DEGREE POLYNOMIA
     1L /)
    9 FORMAT(1H0,5X,19HSOURCE OF VARIATION,7X,9HDEGREE OF,7X,6HSUM OF,9X
     1,4HMEAN,10X,1HF,9X,20HIMPROVEMENT IN TERMS/33X,7HFREEDOM,8X,7HSQUA
     2RES,7X,6HSQUARE,7X,5HVALUE,8X,17HOF SUM OF SQUARES)
   10 FORMAT(20H0 DUE TO REGRESSION ,12X,I6,F17.5,F14.5,F13.5,F20.5)
   11 FORMAT(32H  DEVIATION ABOUT REGRESSION    ,I6,F17.5,F14.5)
   12 FORMAT(8X,5HTOTAL,19X,I6,F17.5///)
   13 FORMAT(17H0  NO IMPROVMENT )
   14 FORMAT(1H0//27X,18HTABLE OF RESIDUALS//16H OBSERVATION NO.,5X,7HX
     1VALUE,7X,7HY VALUE,7X,10HY ESTIMATE,7X,8HRESIDUAL/)
```

```
 15 FORMAT(1H0,3X,I6,F18.5,F14.5,F17.5,F15.5)
 16 FORMAT(3F10.4)
100 READ(5,1)PR,PR1,N,M,NPLOT,M5
    WRITE(6,3) PR,PR1
    WRITE(6,4) N
    L=N*M
    DO 110 I=1,N
    J=L+I
110 READ(5,2)X(I),X(J)
    CALL GDATA(N,M,X,XBAR,STD,D,SUMSQ)
    MM=M+1
    SUM=0.0
    NT=N-1
    DO 200 I=1,M
    ISAVE(I)=I
    CALL ORDER(MM,D,MM,I,ISAVE,DI,E)
    CALL MINV(DI,I,DET,B,T)
    CALL MULTR(N,I,XBAR,STD,SUMSQ,DI,E,ISAVE,B,SB,T,ANS)
    WRITE(6,5)I
    IF(ANS(7)) 140,130,130
130 SUMIP=ANS(4)-SUM
    IF(SUMIP)140,140,150
140 WRITE(6,13)
    GO TO 210
150 WRITE(6,6) ANS(1)
    WRITE(6,7) (B(J),J=1,I)
    WRITE(6,8) I
    WRITE(6,9)
    SUM=ANS(4)
    WRITE(6,10) I,ANS(4),ANS(6),ANS(10),SUMIP
    NI=ANS(8)
    WRITE(6,11)NI,ANS(7),ANS(9)
    WRITE(6,12)NT,SUMSQ(MM)
    COE(1)=ANS(1)
    DO 160 J=1,I
160 COE(J+1)=B(J)
```

```
    LA=I
200 CONTINUE
210 IF(NPLOT)100,100,220
220 NP3=N+N
    DO 230 I=1,N
    NP3=NP3+1
    P(NP3)=COE(1)
    L=I
    DO 230 J=1,LA
    P(NP3)=P(NP3)+X(L)*COE(J+1)
230 L=L+N
    N2=N
    L=N*M
    DO 240 I=1,N
    P(I)=X(I)
    N2=N2+1
    L=L+1
240 P(N2)=X(L)
    WRITE(6,3)PR,PR1
    WRITE(6,5) LA
    WRITE(6,14)
    NP2=N
    NP3=N+N
    DO 250 I=1,N
    NP2=NP2+1
    NP3=NP3+1
    RESID=P(NP2)-P(NP3)
    M7=M7+1
    X1(M7)=P(I)
    X2(M7)=P(NP2)
    X3(M7)=P(NP3)
250 WRITE(6,15)I,P(I),P(NP2),P(NP3),RESID
    CALL PLOT(LA,P,N,3,0,1)
    IF(M5-2)100,102,100
102 DO 260 I=1,M7
    WRITE(7,16)X1(I),X2(I),X3(I)
```

COMPUTER PROGRAM B4 (Continued)

```
260 CONTINUE
    STOP
    DEBUG SUBCHK
    END
```

COMPUTER PROGRAM B5

```
C     STRAIGHT LINE REGRESSION PROGRAM
      DIMENSION A11(80),A01(80),R1(80),A1T1(80),A0T1(80),H01(80)
      READ(2,1)N
    1 FORMAT(3X,I4)
      I=0
      M=0
      N2=0
      WRITE(5,5)
    5 FORMAT(4X'A1'8X,'A0'8X,'R'9X,'A1T'7X,'A0T'7X,'H0')
      WRITE(5,8)
    8 FORMAT(//)
   12 SY=0
      SXY=0
      SXSQ=0
      SYSQ=0
      SX=0
    3 READ(2,2)X,Y,L
    2 FORMAT(20X,F10.4,30X,F10.4,I2)
      M=M+1
      SX=SX+X
      SY=SY+Y
      SXY=SXY+X*Y
      SXSQ=SXSQ+X**2
      SYSQ=SYSQ+Y**2
      IF(M-N)3,4,4
    4 M=0
      P=N
      SQSX=SX**2
      SQSY=SY**2
      AVX=SX/P
      AVY=SY/P
      SLOPE=((P*SXY)-(SX*SY))/(P*SXSQ-SQSX)
      SEPT=AVY-SLOPE*AVX
      R=(SXY-SX*SY/P)/SQRT((SXSQ-SQSX/P)*(SYSQ-SQSY/P))
      SYX=SQRT((SYSQ-SEPT*SY-SLOPE*SXY)/(P-2.0))
```

COMPUTER PROGRAM B5 (Continued)

```
      A1T=SYX/SQRT(SXSQ-P*AVX**2)
      AOT=SYX*SQRT((1.0/P)+(AVX**2)/(SXSQ-P*AVX**2))
      HO=SLOPE*SQRT(SXSQ-P*AVX**2)/SYX
      I=I+1
      A11(I)=SLOPE
      AO1(I)=SEPT
      R1(I)=R
      A1T1(I)=A1T
      AOT1(I)=AOT
      HO1(I)=HO
      N2=N2+1
      WRITE(5,6)SLOPE,SEPT,R,A1T,AOT,HO
    6 FORMAT(1X,F9.4,1X,F9.4,1X,F9.4,1X,F9.4,1X,F9.4,1X,F9.4)
      IF(L-1)12,7,7
    7 PAUSE1111
      DO 20 I=1,N2
      WRITE(2,10)A11(I),AO1(I),R1(I),A1T1(I),AOT1(I),HO1(I)
   10 FORMAT(6F10.4)
   20 CONTINUE
      CALL EXIT
      END
```

## COMPUTER PROGRAM B6

```
C     PLOTS GRAPH OF X AGAINST Y ON DRUM PLOTTER
   26 CALL SCALF(.75,.75,0.,0.)
      CALL FGRID(0,0.,6.0,1.0,10)
      CALL FGRID(1,0.,0.,1.0,12)
      X=-.13
      DO 5 I=1,11
      READ(2,6)SCALX
    6 FORMAT(1X,F4.1)
      CALL FCHAR(X,5.73,.10,.10,0.00)
      WRITE(7,7)SCALX
    7 FORMAT(F4.1)
      X=X+1
    5 CONTINUE
      Y=0.00
      DO  10 I=1,13
      READ(2,11)SCALY
   11 FORMAT(F5.1)
      CALL FCHAR(-.77,Y,.10,.10,0.00)
      WRITE(7,12)SCALY
   12 FORMAT(F5.1)
      Y=Y+1
   10 CONTINUE
      CALL FPLOT(1,0.,6.0)
      CALL SCALF(.10,.05,0.,0.)
      READ(2,20)A1,A0
   20 FORMAT(2F10.4)
      DO 25 I=1,5
      READ(2,21)X,Y,N
   21 FORMAT(2F10.4,I2)
      X1=X*1000.
      Y1=Y*1000.
      CALL FPLOT(1,X1,Y1)
      CALL FPLOT(2,X1,Y1)
      CALL POINT(1)
      Y2=X*A1+A0
      Y3=Y2*1000.
```

COMPUTER PROGRAM B6 (Continued)

```
   CALL FPLOT(1,X1,Y3)
   CALL FPLOT(2,X1,Y3)
   CALL POINT(0)
25 CONTINUE
   PAUSE1111
   IF(N-1)26,27,26
27 CALL EXIT
   END
```

COMPUTER PROGRAM B7 (a)

```
C     PROGRAM TO REARANGE RAW DATA...PART 1 AND PART 2...WEAR
C     PROGRAM LISTING FOR PART 2 DATA. MODIFICATION REQUIRED FOR PART 1
C     DATA
      REAL NTEST
      N=0
      WRITE(5,50)
   50 FORMAT('1')
      WRITE(5,60)
   60 FORMAT 22H RAW DATA..WEAR PART 2/49H TEST
     1          TOOTH NO./83H NO.      8           9           10
     2  11          12          13          14/86H      B     A     B
     3   A     B     A     B     A     B     A     B     A     B     A
      WRITE(5,70)
   70 FORMAT(/)
      READ(2,6)N1
    6 FORMAT(I4)
      IF(N1-2)10,12,10
   10 READ(2,2)NTEST,W1,W2
    2 FORMAT(1X,A4,1X,F5.3,2X,F5.3)
      READ(2,3)W3,W4
    3 FORMAT(6X,F5.3,2X,F5.3)
      READ(2,3)W5,W6
      READ(2,3)W7,W8
      READ(2,3)W9,W10
      READ(2,3)W11,W12
      READ(2,3)W13,W14
      READ(2,3)W15,W16
      READ(2,3)W17,W18
      READ(2,3)W19,W20
      READ(2,3)W21,W22
      READ(2,3)W23,W24
      READ(2,3)W25,W26
      READ(2,3)W27,W28
      GO TO 13
   12 READ(2,3)W15,W16
      READ(2,3)W17,W18
```

```
      READ(2,3)W19,W20
      READ(2,3)W21,W22
      READ(2,3)W23,W24
      READ(2,3)W25,W26
      READ(2,3)W27,W28
      READ(2,2)NTEST,W1,W2
      READ(2,3)W3,W4
      READ(2,3)W5,W6
      READ(2,3)W7,W8
      READ(2,3)W9,W10
      READ(2,3)W11,W12
      READ(2,3)W13,W14
   13 WRITE(5,4)NTEST,W1,W2,W3,W4,W5,W6,W7,W8,W9,W10,W11,W12,W13,W14
    4 FORMAT(A4,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,
     11X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3)
      N=N+1
      IF(N-32)10,11,10
   11 PAUSE1111
      WRITE(5,60)
      N=0
      GO TO 10
      END
```

COMPUTER PROGRAM B7 (b)

```
C     PROGRAM TO REARANGE RAW DATA...PART 1 AND PART 2...CUTTING POWER
C     PROGRAM LISTING FOR PART 2 MODIFICATION REQUIRED FOR PART 1
      REAL NTEST
      N=0
      WRITE(5,50)
   50 FORMAT('1')
      WRITE(5,60)
   60 FORMAT(44H RAW DATA  CUTTING POWER  METER NO.2  PART 2/44H TEST
     1                          CUT NUMBER/70H NO.        1
     2 2              3              4              5/73H        B     D
     3        B     D          B     D        B     D        B     D/)
   10 READ(2,1)NTEST,P2,P1
    1 FORMAT(1X,A4,10X,F5.3,5X,F5.3)
      READ(2,2)P4,P3
    2 FORMAT(15X,F5.3,5X,F5.3)
      READ(2,2)P6,P5
      READ(2,2)P8,P7
      READ(2,2)P10,P9
      N=N+1
      WRITE(5,3)NTEST,P2,P1,P4,P3,P6,P5,P8,P7,P10,P9
    3 FORMAT(1X,A4,3X,F5.3,1X,F5.3,3X,F5.3,1X,F5.3,3X,F5.3,1X,F5.3,3X,F5
     1.3,1X,F5.3,3X,F5.3,1X,F5.3)
      IF(N-33)10,11,10
   11 WRITE(5,50)
      WRITE(5,60)
      GO TO 10
      END
```

COMPUTER PROGRAM B7 (c)

```
C     PROGRAM TO REARANGE RAW DATA...PART 1...CUTTING FORCES
      N=0
      WRITE(5,50)
   50 FORMAT('1')
      WRITE(5,60)
   60 FORMAT(29H RAW DATA PART 1 H & V FORCES/33H TEST
     1CUT NUMBER/60H NO.         1            2            3            4
     2        5/64H          HF     VF     HF     VF     HF     VF     HF     VF
     3  HF    VF/)
   10 READ(2,1)NTEST,HF1,VF1
    1 FORMAT(I4,22X,2F5.3)
      READ(2,2)HF2,VF2
    2 FORMAT(26X,2F5.3)
      READ(2,2)HF3,VF3
      READ(2,2)HF4,VF4
      READ(2,2)HF5,VF5
      WRITE(5,3)NTEST,HF1,VF1,HF2,VF2,HF3,VF3,HF4,VF4,HF5,VF5
    3 FORMAT(1X,I4,2X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5.3,1X,F5
     1.3,1X,F5.3,1X,F5.3,1X,F5.3)
      N=N+1
      IF(N-33)10,11,10
   11 WRITE(5,50)
      WRITE(5,60)
      N=0
      GO TO 10
      END
```

COMPUTER PROGRAM B7 (d)

```
C     PROGRAM TO REARANGE RAW DATA...PART 2...CUTTING FORCES
      REAL NTEST
      N=0
      WRITE(5,50)
   50 FORMAT('1')
      WRITE(5,60)
   60 FORMAT(49H RAW DATA PART 2 HOROZONTAL CUTTING FORCE (KG.)  /50H TE
     1ST                                        CUT NUMBER  /78H NO.        1
     2              2                 3                4                5  /82
     3H        1     2     3     1     2     3     1     2     3     1     2     3
     4     1     2     3 //)
   10 READ(2,1)NTEST,HF1,HF2,HF3
    1 FORMAT(1X,A4,25X,3F5.1)
      READ(2,2)HF4,HF5,HF6
    2 FORMAT(30X,3F5.1)
      READ(2,2)HF7,HF8,HF9
      READ(2,2)HF10,HF11,HF12
      READ(2,2)HF13,HF14,HF15
      WRITE(5,3)NTEST,HF1,HF2,HF3,HF4,HF5,HF6,HF7,HF8,HF9,HF10,HF11,HF12
     1,HF13,HF14,HF15
    3 FORMAT(A4,2X,F4.1,1X,F4.1,1X,F4.1,2X,F4.1,1X,F4.1,1X,F4.1,2X,F4.1,
     11X,F4.1,1X,F4.1,2X,F4.1,1X,F4.1,1X,F4.1,2X,F4.1,1X,F4.1,1X,F4.1)
      N=N+1
      IF(N-32)10,11,10
   11 WRITE(5,50)
      WRITE(5,60)
      GO TO 10
      END
```

COMPUTER PROGRAM B7 (e)

```
C     PROGRAM TO REARANGE RAW DATA...PART 1 AND PART 2...
C     PART 1 ACID CONC., COPPER SULPHATE CONC. AND SURFACE FINISH
C     PART 2 FEED RATE, DEPTH OF CUT AND SURFACE FINISH
C     PROGRAM LISTING FOR PART 2 DATA. MODIFICATION REQUIRED FOR PART 1
      REAL NTEST
      N=0
      WRITE(5,50)
   50 FORMAT('1')
      WRITE(5,60)
   60 FORMAT(16H RAW DATA PART 2/47H TEST    DEPTH     FEED    CLA1    C
     1LA2    CLA3/24H NO.      OF CUT    RATE /)
   10 DO 5 I=1,14
      READ(2,1)NTEST,FEED,DEPTH,CLA1,CLA2,CLA3
    1 FORMAT(1X,A4,16X,F3.1,1X,F5.3,3F5.1)
    5 CONTINUE
      WRITE(5,2)NTEST,DEPTH,FEED,CLA1,CLA2,CLA3
    2 FORMAT(1X,A4,4X,F6.3,4X,F4.1,4X,F4.0,4X,F4.0,4X,F4.0)
      N=N+1
      IF(N-41)10,11,10
   11 PAUSE1111
      WRITE(5,60)
      N=0
      GO TO 10
      END
```

COMPUTER PROGRAM B7 (f)

```
C     PROGRAM TO PRINT TABLE 6.9
      REAL NTEST
      N=0
      M=0
      PAUSE1111
      WRITE(5,4)
    4 FORMAT(64H TEST    SLOPE    INTERSEPT  CORR.    FEED    DEPTH    N
     1ULL HYP./64H NO.                          COEFF.   RATE    OF CUT
     2 STATISTIC/)
   10 READ(2,1)A1,A0,R,H0
    1 FORMAT(3F10.4,20X,F10.4)
      READ(2,2)NTEST,FEED,DEPTH
    2 FORMAT(6X,A4,4X,F3.1,7X,F5.3)
      WRITE(5,3)NTEST,A1,A0,R,FEED,DEPTH,H0
    3 FORMAT(1X,A4,2X,F8.4,3X,F7.4,3X,F7.4,4X,F3.1,4X,F5.3,3X,F7.4)
      N=N+1
      IF(N-8)10,11,10
   11 WRITE(5,5)
    5 FORMAT(/)
      M=M+1
      IF(M-5)12,13,12
   12 N=0
      GO TO 10
   13 PAUSE1111
      WRITE(5,4)
      GO TO 10
      END
```

COMPUTER PROGRAM B7 (g)

```
C     PROGRAM TO PRINT SIZE AND HARDNESS OF TEST SAMPLES
      WRITE(5,2)
    2 FORMAT('1')
      WRITE(5,3)
    3 FORMAT(88H SAMPLE       WIDTH(IN.)      LENGTH (IN.)        THICKN
     1ESS (IN.)    ROCKWELL C HARDNESS/84H NO.       1     2     3      1
     2     2     1     2     3     4     5     6     1     2     3//)
   10 READ(2,1)H1,H2,H3,N,W1,W2,W3,AL1,AL2,T1,T2,T3,T4,T5,T6
    1 FORMAT(1X,3F4.1,2X,I2,5F5.3,2X,6A4)
      WRITE(5,4)N,W1,W2,W3,AL1,AL2,T1,T2,T3,T4,T5,T6,H1,H2,H3
    4 FORMAT(3X,I2,3X,F5.3,1X,F5.3,1X,F5.3,2X,F5.3,1X,F5.3,2X,A4,1X,A4,1
     1X,A4,1X,A4,1X,A4,1X,A4,2X,F4.1,1X,F4.1,1X,F4.1)
      GO TO 10
      END
```

# APPENDIX C

This appendix has been added to the thesis as a result of an examination by Dr. J. Tlusty of the Department of Mechanical Engineering, McMaster University, Hamilton, Ontario; Mr. J. Church of the Faculty of Engineering, Memorial University of Newfoundland; and the Author's Supervisor, Mr. P. Amaria.

Mr. Church, in his remarks, cited twelve (12) minor corrections which he felt should be made.

## Mr. Church's Remarks

The notes for the student include some of the general comments I would make.

This thesis is well organized and, in my opinion, a very good effort.

The main detractions are caused by the completely unacceptable reproductions of photographs. The positioning error of $5^{o}$ referred to on pages 40 and 41 is, in my opinion, unacceptable. An error of 5" could be obtained using standard tool room equipment and procedures. It may be that the connotation of degrees is an error in typing.

I would definitely pass the thesis with the corrections as noted.

1. On page 2 you state that Malloch's statement that application of a cutting fluid considerably reduced rubbing friction -- his interpretation was in error. By what authority or later work was this proven in error?

2. On page 3 your last paragraph is incorrect - the intended meaning is reversed. This should be corrected.

3. On page 4 you list present cutting tools and do not mention cermet. Is this an oversight?

4. On page 5, the word defunct is incorrect. Probably the word inoperative would be better. This should be corrected.

5. On page 13 - the statement of comparison between cutting in titanium steel and aluminum is meaningless. If reported by Catt and Milwain the error should not be perpetuated. This should be corrected.

6. On page 20, the first paragraph as written is trite. This should be re-written, drop the first three words. If you wish to be correct you should include the most important factors of cutter material and material being cut.

7. On page 21, the desired results are to determine the actual facts by experimentation - not "to show that" one assumption or another is correct. "You wish to compare and determine the relationship."

8. On page 23 the final paragraph makes the reader wonder how long the work has been going on. "experience gained to this point", clarify.

9. The photographic reproduction in my copy were complete useless. Since they are referred to in the body of the thesis some better method of reproduction must be used. This must be corrected.

10. The title of Table 4.2 (as well as its listing on page V111) is incorrect. This should be corrected by the addition to the title "of Test Pieces".

11. On page 40, the remarks on the positioning of the cutter are unacceptable. The error of $5^{o}$ indicates improper technique for positioning.

12. I am left with the question of how were the load cells mounted and what method of calibration was used. This is possibly due to the lack of readable photographs. Please correct.

The foregoing items have been corrected in the body of the thesis.

Dr. Tlusty's report recommended that the thesis be accepted as it stands but went on to make the following comments:

Dr. Tlusty's Remarks

1. The thesis deals with an interesting idea. The expected mechanism is however not too well analyzed. Actually the paper by Amaria, Goosney at the NAMR-1 conference gave a better explanation than the thesis.

2. Why was not the rate of copper deposition measured directly and separately, without cutting.

3. The thesis contains an indirect test of the depositing by means of checking its final effect on forces and tool life but it does not prove whether there was really any copper layer between the rake face of tool and chip.

4. A chapter reviewing the existing knowledge about the action of cutting fluids might help.

5. Some of the background on metal cutting presented and statements are inaccurate or incorrect, e.g. first paragraph p. 7; comparing TiC coating with a copper layer on tool (p. 15) is incorrect because of the radically different mechanism.

General

TiC coating is now used universally. It is a very hard, strongly adhering wear resistant layer acting simultaneously as diffusion barrier. The cutting conditions used in the tests are rather unusual. The peripheral milling operation with cutter diameter 3 in. depth of cut 0.005 and 0.010 in. and feed per tooth between 0.001 and 0.005 in. means that chip thickness varied between zero and a maximum of 0.0005 in. which represents much more rubbing than cutting. No wonder that higher feed gave better results. It is recommendable to try more typical cutting with thicker chips.

In spite of the preceding critical comments the major part of the thesis represents a very systematically carried out experiment and its evaluation and contributes to a better understanding of the still very little understood process of tool wear and of the mechanism of cutting lubricants.

The Author, in his reply to these comments, will refer to the comment number as stated above and, where applicable, cross-reference his statements to the appropriate page in the text of the thesis.

Reply to Comment No. 2

The measurement of the rate of copper deposition was not made directly (i.e., outside of the cutting environment) because it was considered impossible to duplicate the actual deposition of copper with respect to temperature change and the presence of impurities. This, in the Author's opinion, would make such a measurement meaningless.

Reply to Comment No. 3

It was realized that the measurement of cutting forces, wear and other parameters would be an indirect test of the ability of the electrolyte to deposit copper on the cutting surface of the tool, but experience with preliminary tests not reported in the thesis showed that it was not possible to make a meaningful measurement of this type directly. However, there was indirect proof that it did exist in the form of copper imbedded in the finished work piece surface and the presence of what appeared to be copper oxide on the wear land of the cutter, which had to be removed before the wear could be measured. Although it is not known if the copper deposit wore off with first contact of the tool and chip, it is known, from visual observation, that copper was deposited before cutting and that the electrolyte acted as any other cutting fluid in reaching the tip of the cutting tool.

Comment No. 4 and No. 1 combined

(No. 4 cross-reference page 15) It is appropriate at this point to consider the various mechanisms that are present when a cutting fluid comes into contact with the tool-work-interface.

OWENS AND ROBERTS (1967) have stated that the nature of the action of cutting fluids, because of the clean surfaces exposed by rubbing and shearing, must be chemical in nature and present experimental data obtained using ultra high vacuum techniques to support their claim. High vacuum was considered necessary in this case as the experiments were conducted on clean surfaces outside of the cutting environment. This of course meant that during the experimentation the clean surface existed without an oxide layer.

In the case of iron, the oxide layer has been mentioned by SHAW (1958) who implies that the probable mechanism of lubrication cutting dry (with air as a lubricant) is a result of the formation of $Fe_2O_3$ and $Fe_3O_4$. It was found from experiments, cutting dry at reduced atmospheric pressure, that friction between the chip and tool decreased. SHAW (1958) suggests that this was the result of the formation of a relatively large percentage of $Fe_3O_4$ which is known to be a good solid lubricant. Finally, SHAW (1958) states that a partial vacuum is created at the tool-chip-interface which, combined with the surface tension of the fluid, will suck the gas or liquid to the point of the tool. In the case of air the action will result in the formation of $Fe_3O_4$.

The use of liquids as cutting fluids presents a different type of lubrication mechanism.

In most cases, commercially available liquid cutting fluids are carbon based and are applied in the form of oils, emulsions or oils containing highly polarized long chain molecules. Any discussion of the way in which they function must, because of the nature of the cutting process, be a function of surface properties of the metal surface of the cutting tool.

There are two basic properties that should be considered: Absorption - the penetration of the surface of the cutting fluid, and Adsorption - the excess concentration of solute in a fluid on the surface of a solid.

The mechanism of adsorption can be applied equally well to liquids and gases. For gases there are two types of adsorption: Van der Waals adsorption and activated adsorption (sometimes described as chemisorption). GLASSTONE (1958) indicates that as the temperature increases Van der Waals adsorption may pass over into chemisorption. He also states that chemisorption of gases is highly specific and depends on the chemical properties of the gas and adsorption surface. Adsorption of liquids, i.e. the increase in concentration of suspended materials at the surface, can be shown to proceed along the same lines as adsorption of gases with equations governing both processes being of the form $y = ax^n$ where y = gas or solute adsorbed and x = the gas pressure or solute concentration in the body of the fluid. a and n are constants with n less than unity. However, the mechanism for a liquid is slightly different for a gas as stated by GIBBS in GLASSTONE (1958) who states that for a dilute concentration "C"

$$S = -\frac{e}{RT} \cdot \frac{dr}{dc}$$

when

S = excess concentration of solute per sq. cm. of surface

c = concentration of the bulk sample g/l

R = universal gas constant

T = absolute temperature

$\frac{dr}{dc}$ = the rate of increase of surface tension with respect to the change in solute concentration of the bulk sample

Cutting fluids which have straight adsorption properties act by clinging to the cutting surfaces in an attempt to prevent metal to metal contact.

A surface phenomenom related to adsorption which is of great significance in metal cutting is the formation of unimolecular insoluble films by long chaim molecules which have polar end groups. The polar group ends attach themselves to the cutting surfaces and are absorbed by them, leaving the remainder of the molecules standing perpendicular to the surface. This type of mechanism is present when extreme pressure additives are part of the cutting fluid.

A third mechanism that it is possible to use and with which this thesis is vitally concerned is the "Precipitation by Electrolytes".

(No. 1 Cross-reference page 18) For a solution containing a single solute, the rate of deposition of a metal on a cathode, at 100% efficiency, is determined by the current density.

If M is the number of equivalents of metal deposited per square centimeter per second, I is the current density in ampere per square centimeter and F is the faraday, 96500 coulombs, then

$$M = \frac{I}{F}.$$

At the steady state of electrolysis, the rate at which metal ion is removed from the bath must be equaled by the rate at which metal ion is brought up to the cathode. The transport of metal is accomplished by diffusion, convection, and electrical migration and at the steady state the following equality holds for an electrolyte containing a single solute. BRENNER (1963).

$$M = \frac{I}{F} = D.\frac{dC}{dX} + V.C + T_C.\frac{I}{F}$$

Where D is the diffusion constant in sq.cm./second,

V is the horizontal component of the velocity of the convective flow of solution in cm. per second,

C is the metal concentration of the solution in gram-equivalents per square centimeter, at a distance X from the cathode,

X is the direction measured normal to the cathode surface,

$T_C$ is the transference number of the metal cations.

The term V.C. is the contribution of convective flow to the replenishment of metal ion to the cathode. Since the horizontal convective flow varies from a maximum value at the outer boundary of the diffusion layer to zero at the cathode-solution interface, the replenishment by convective flow varies from zero at the cathode solution interface to a maximum at the outer boundary of the diffusion layer. The term Tc.I/F represents the replenishment contributed by electrical migration of the metal ions. Tc represents the fraction of the deposited metal that is brought to the cathode by electrical migration. The replenishment due to Tc.I/F may be considered as approximately constant throughout the thickness of the diffusion layer, even though the concentration of metal ion varies.

The diffusion term D(dC/dX) is obtained from Fick's law of diffusion, which states that the amount of material which diffuses through a unit area in unit time is proportional to the concentration gradient. The differential, dC/dX, is the tangent of the slope of the concentration in gram-equivalent per litre and the distance from the cathode. The transport of metal ions by diffusion varies from maximum to zero as the diffusion layer is traversed from the cathode-solution interface outwards. This is the opposite of the transport of metal ion by convection.

When two or more solutes are used, the rate at which metal of each solute is deposited would depend on the partial current density.

The partial current density, $I_p$ is given as:

$$I_p = f.I$$

where f is the fraction of the current used for the particular ion, p, and I is the current density.

An equation similar to that described before would hold true for every ion in the solution. In terms of partial current densities for a particular ion, p, the equation becomes,

$$M_p = \frac{I_p}{F} = D_p\left(\frac{dCp}{dx_o}\right) + V.C_p + T_p\left(\frac{I}{F}\right)$$

This equation means that the material balance of each ion at the cathode-solution interface is determined by the current density that is actually used in causing the ion to react at the cathode. The above equation is also valid for ions that do not discharge at the cathode.

Reply to Comment No. 5

These items have been corrected in the body of the thesis.