

THE DEVELOPMENT

OF A

STANDARD DRILLING TEST FOR MACHINABILITY

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## TABLE OF CONTENTS

	Page No.
I. INTRODUCTION.....	1
II. REVIEW OF LITERATURE.....	5
a. Review of Statistical Literature.....	5
b. Review of Machinability Literature.....	10
III. INVESTIGATION.....	15
a. Object of Investigation.....	15
b. Preliminary Experimentation.....	15
c. Apparatus Used.....	23
IV. DATA AND DISCUSSION OF RESULTS.....	36
V. CONCLUSIONS.....	52
VI. SUMMARY.....	53
VII. RECOMMENDATIONS.....	55
VIII. ACKNOWLEDGEMENTS.....	56
IX. GLOSSARY OF SYMBOLS.....	57
X. BIBLIOGRAPHY.....	58

LIST OF TABLE, FIGURES, AND CURVE SHEETS

<u>Tables</u>		Page No.
TABLE	I. Preliminary Test Plan and Data for Steel.....	16
TABLE	II. Analysis of Variance of Preliminary Steel Data.....	16
TABLE	III. Second Preliminary Test Plan and Data for Steel....	18
TABLE	IV. Preliminary Plan of Analysis Including Orthogonal.. Polynomials	18
TABLE	V. Analysis of Variance of Second Preliminary Steel... Data	19
TABLE	VI. Second Preliminary Plan of Analysis for Steel..... Including Orthogonal Polynomials	21
TABLE	VII. Test Plan and Data for Steel.....	36
TABLE	VIII. Plan of Analysis Including Orthogonal Polynomials..	36
TABLE	IX. Analysis of Variance of Steel Data.....	37
TABLE	X. Test Plan and Data for Cast Iron.....	42
TABLE	XI. Analysis of Variance of Cast Iron Data.....	42
TABLE	XII. Test Plan and Data for Aluminum.....	46
TABLE	XIII. Analysis of Variance of Aluminum Data.....	46
TABLE	XIV. Tabulation of <u>F</u> Values.....	50
TABLE	XV. Tabulation of Calculated Indices with their..... Confidence Limits	51

Figures

Figure 1.	Carriage Mounted in Position to Operate.....	24
Figure 2.	Underside View of Carriage.....	25
Figure 3.	Sample Indicator Cards for Steel and Cast Iron.....	27

	<u>Figures</u>	Page No.
Figure 4.	Sample Indicator Card for Cast Iron and..... Aluminum. Indicator Card for Cast Iron Showing Unsatisfactory 67 RPM Drilling	28
Figure 5.	Oliver 510 Drill Pointer.....	35

	<u>Curve Sheets</u>	
Curve Sheet 1.	Time vs. Weight-Steel.....	43
Curve Sheet 2.	Time vs. Weight-Cast Iron.....	45
Curve Sheet 3.	Time vs. Weight-Aluminum.....	47
Curve Sheet 4.	Curves Showing Relative Spread of Confidence... Limits for Test Materials	49

## INTRODUCTION

Professor Stanley A. Wykes, Associate Professor of Industrial Engineering at Texas Agriculture and Mechanical College, recommended at the conclusion of his thesis, which culminated in the design and testing of a machinability testing machine in the Virginia Polytechnic Institute Shops, that "Tests should be made on drilling."<sup>1</sup> The purpose of this investigation will be to carry on Professor Wykes' experimentation and if possible, to develop a standard drilling test for machinability making use of Professor Wykes' testing machine and concepts of machinability.

Although concepts and means of expressing the property, machinability, are myriad, Professor Wykes based his work on the field of removing a set volume of material per unit time while varying machine conditions. His machine resulted from an attempt to develop a standard test using standard equipment that could be reproduced in any shop. If this concept were to be universally accepted, machinability would have the same meaning to everyone and old lathes could be converted to test machines throughout industry.

The present obscurity of the term, or property, machinability can be directly blamed on the failure of investigators to standardize both the concept and testing apparatus. Some of the more common methods of

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<sup>1</sup>Stanley A. Wykes, The Development of a Testing Machine for Machinability Tests, Industrial Engineering Department, Virginia Polytechnic Institute (June, 1946)

measuring machinability are listed by O. W. Boston as follows:<sup>2</sup>

1. The measurement of the force on a tool to cut a metal under standardized conditions.
2. The measurement of the power or energy required to remove a given chip under standardized conditions.
3. The ability of a standardized tool to cut various metals, in terms of tool life or cutting speed.
4. A measurement of the finish left on the cut surface.
5. The penetration of a standardized drill when cutting at constant speed and under a given load.
6. The torque developed by a drill while drilling various metals under standardized conditions.
7. A cutting speed for a certain tool life under standardized conditions expressed in terms of physical properties of the material being cut.
8. The hardness numbers of the materials as indicated by a hardness testing machine.
9. The measurement of heat generated and the hardness induced by the cutting process.

Almost all of these methods as developed by previous investigators involved some special equipment which either could not be exactly duplicated or would require a large amount of time and/or money to duplicate. The V. P. I. Machinability Testing Machine is, on the contrary, made from a standard machine using an essentially simple timing device. Standard cutting tools, speeds, and materials were investigated by Professor Wykes; standard drills, speeds, and materials will form the basis of this study.

A striking similarity between all treatises is found in the complete lack of any definite conclusions being reached with regards to analysis of

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<sup>2</sup>O. W. Boston, "Machinability of Metals," Transactions of the American Society for Steel Treating, vol. 13, pp. 49-86, 94, 1928.

the machinability data. The literature abounds with such phrases as "appears to be related," "is assumed to be," "is reason for believing," and "seem to be." The majority of machinability papers describe equipment and tests, tabulate data, and show curves, smooth or otherwise, of the data. Few definite predictions of future performances are made. If difficulties were encountered with replication, they are on a whole not discussed. In fact, replication is hardly ever considered. Certainly a field containing the inherent variability found in machinability data would require two or more replications to yield any valid conclusions at all.

Before this investigation was planned as finally run, one of the investigators started work by following the usual procedure of running tests under one set of conditions and then running the next test under a different set. However, just out of curiosity he attempted to reproduce his previous work for one set of conditions. As far as he could tell, there was no direct correlation between the two sets of data, even though the same speed, material, applied force, and drill were utilized. This result immediately led to a quest for some mathematical technique that could be used to analyze data.

This quest ended in the ultimate use of statistics, or specifically, the analysis of variance technique. Statistical techniques were especially designed to isolate and classify tendencies not otherwise discernible in masses of data. The analysis of variance is a statistical tool for the isolation of particular components for assessment by comparison with error variance. This technique is particularly adaptable since it can be used to study data taken under several different conditions and show

the tendencies predominant throughout all tests.

The analysis of variance can be used to show the relative effect of changing weights and speeds and replication. It can also be used to resolve the variation caused by weights into linear, quadratic, cubic, and residual effects. A measure of the inherent variability of the test and test specimens is found in the experimental error term. Significant differences between weight effects at different speeds can be shown, if they exist. In other words, almost all of the conclusions alluded to by other investigators but not directly claimed could have been definitely shown to exist or not exist on a probability basis, if the work had been planned and analyzed by the use of statistical methods.

The authors believe that the strength of this paper will lie as much in its use and exposition of statistical techniques in the analysis of engineering data as in its approach to the machinability problem.

## LITERATURE REVIEW

### Review of Statistical Literature

Although applications of statistical designs and techniques in many phases of industrial work, especially quality control and sampling procedure, have become widespread, many of the most effective tools of the statistician have been overlooked, except in isolated instances. Analysis of variance and covariance, invaluable to biologists and agronomists who have to deal with problems containing a great deal of inherent variability, has scarcely been applied in work dealing with the characteristics of metals which in many cases also have wide variability.

The strength of a variance analysis, originally devised by Ronald Aylmer Fisher, University of London, lies in its ability to differentiate between random and systematic variation and under certain conditions to estimate these variations. This result is exactly what engineers have been attempting to achieve for years through the media of tests and guesses. In some cases engineers have been correct, in others completely wrong, though frequently unproved for many years. Analysis of variance offers a mathematically sound approach which has a myriad of possible applications. This investigation will attempt to exploit one.

Probability, which might be considered the basic theory of statistics, had its inception in the seventeenth century when Blaise Pascal was approached by a gentleman gambler, le Chevalier de Mere, who requested information concerning the division of stakes between two players who

separate without finishing their game.<sup>3</sup> Pascal discussed the problem via an exchange of letters with his friend, Pierre de Fermat, until finally they had raised this elementary difficulty to the importance of a fundamental mathematical concept.

Also highly interested in the early probability theories were Jacques Bernoulli and Abraham De Moivre, the latter being one of the first to apply the binomial theorem. De Moivre was also the first to discover and characterize by equation the normal curve which has since become one of the basic statistical concepts, particularly with regards to industrial quality control and sampling procedures. In fact, many of the recent treatises on probability and sampling approach the matter by a method quite similar to De Moivre's use of the binomial expansion during the early eighteenth century.

Another early use of the statistical approach occurred in the original population sampling techniques, an interesting example being Halley's selection of mortality statistics (1693) in Breslau to form the basis of his life table. From samples of this one city he reached general conclusions on the "mortality of mankind."<sup>4</sup> Between 1765 and 1778, Messance, Moheau, and Lavoisier estimated the human and animal population of France with more precise methods. At the beginning of the nineteenth century Sir Frederick Morton Eden made population estimates

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<sup>3</sup>Helen M. Walker, Studies in the History of Statistical Methods (Baltimore: Williams and Wilkins Company, 1929), pp. 4-5.

<sup>4</sup>Frederick F. Stephan, "History of the Uses of Modern Sampling Procedures," Joint Arrangements Committee for the International Statistical Conferences, (Washington, August 30, 1947), p. 2

of Great Britain based on samples. These estimates were confirmed by the 1801 census.

However, the theory of probability was not applied to sampling until the twentieth century. The biggest advances were made during the 1930's when a large number of government administrations were actively engaged in polls of all sorts which required accurate sampling methods. Stephan lists the most widespread applications today as follows: agricultural crop and livestock estimates, economic statistics, social surveys and health surveys, and public opinion polls. He also notes the increasingly extensive use of statistical sampling procedures in quality control and inspection methods.<sup>5</sup>

The analogy between the statistical function obtained by taking the sum of the  $n^{\text{th}}$  powers of the deviations in any given distribution, and the mechanical concept of a moment, had been noticed by other writers (La Place, Kramp, Gauss, Encke, Czuber, Quetelet, and De Forest) before Pearson, but none of them had perceived in that function the powerful tool which he has developed.<sup>6</sup> Today use of moment generating functions is imperative in the study of pure mathematical statistics and its applications. The theory of these functions is thoroughly treated by Professor Paul G. Hoel of the University of California at Los Angeles in his Introduction to Mathematical Statistics.<sup>7</sup>

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<sup>5</sup>Stephan, op. cit., pp. 3-7

<sup>6</sup>Walker, op. cit., pp. 71-74

<sup>7</sup>Paul G. Hoel, Introduction to Mathematical Statistics (New York John Wiley and Sons, Inc., 1947)

Although the discovery of regression, from which the concept of correlation developed, was made by Galton in 1877 while working on heredity traits, this treatment is common to the engineer. It is used to solve that frequently arising problem of determining "whether an apparent relation between two variables is significant, and having shown it to be significant, to determine the best form of representation."<sup>8</sup> The establishment of a regression line will be attempted in this experiment together with an analysis of variance of the relationship represented by that line. The statistical approach, rather than the straight mathematical approach utilized by the majority of engineers will be followed.

Galton's coworker and follower, Professor Karl Pearson, solved the distribution in 1900 which according to Fisher, "is in reality equivalent to the distribution of the variance as estimated from normal samples, of which the solution was not given until 1908, and then quite tentatively, and without complete mathematical proof, by 'Student'."<sup>9</sup> "Student's" t-test is one of the most common methods of eliminating the error in large-sample methods when testing the difference between two means in the same manner as for one mean.

Fisher originated the analysis of variance in the early 1920's as a means of separating the variance ascribable to one group of causes, from the variance ascribable to other groups. The analysis of variance results

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<sup>8</sup>Kenneth A. Brownlee, Industrial Experimentation (Brooklyn, N.Y.: Chemical Publishing Co., Inc., 1947) p. 56

<sup>9</sup>Ronald A. Fisher, Statistical Methods for Research Workers (London: Oliver and Boyd, 1928) p. 16

as first devised were tested by a Z distribution involving the use of logarithms. However, since that time a modification has been made by Professor George W. Snedecor of Iowa State College which tests the results for statistical significance by the use of an F test not requiring logarithms. This test was named in honor of Fisher.

Use of the analysis of variance as a technique in determining the differences among several means in industrial experimentation is covered by Professor H.A. Freeman of the Massachusetts Institute of Technology in his Industrial Statistics.<sup>10</sup> Churchill Eisenhart of the National Bureau of Standards in Techniques of Statistical Analysis also points out the procedures and assumptions involved in separating systematic from random causes of variance by means of analysis of variance.<sup>11</sup>

The technique consists of breaking down experimental data by sources of variation into factors known as sums of squares. These sums of squares are then divided by the number of degrees of freedom assignable to each source of variation thus giving another factor known as the mean square. The mean square of each supposedly systematic source of variation is compared with the mean square due to random variation through the medium of the afore-mentioned F test to determine what, if any, statistical significance the systematic source of variation has.

A recent application of analysis of variance at the Virginia Poly-

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<sup>10</sup>H.A. Freeman, Industrial Statistics (New York: John Wiley and Sons, Inc., 1942) pp. 52-95.

<sup>11</sup>Statistical Research Group, Columbia University, Techniques of Statistical Analysis (New York: McGraw-Hill Book Company, 1947) pp. 297-318

technic Institute may be found in Paul Whaley's thesis, The Application of Statistical Quality Control to the Centrifugal Casting of Iron Pipe.<sup>12</sup>

Mr. Whaley separated variation between machines from four sources of variation as the most significant cause of a lack of control in the manufacture of Super-de-Lauvaud pipe. Although this particular application is not the type that will be utilized in the machinability project, it does show one of the many uses of the analysis of variance technique.

A large number of papers on the machinability of metals were consulted in an effort to find some statistical approaches to machinability; however, none were available. Thus the authors believe that their statistical analysis of machinability data will be completely original.

#### Review of Machinability Literature

A general review of machinability studies was included by Professor Stanley A. Wykes in his treatise on the development of a standard testing machine for machinability.<sup>13</sup> No attempt will be made in this review to cover the machinability field as a whole; instead, only papers containing information on machinability investigations dealing with the drilling operation will be considered. Almost all of these investigations were conducted in effort to find some relationship in terms of torque or thrust. However, machinability as defined by Professor Wykes consists of a relation between the time required to remove a specified volume of material and the force applied to the carriage carrying the test specimen.

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<sup>12</sup>Paul A. Whaley, The Application of Statistical Quality Control to the Centrifugal Casting of Iron Pipe, Industrial Engineering Department, Virginia Polytechnic Institute (Blacksburg, 1947)

<sup>13</sup>S.A. Wykes, op. cit., pp. 10-23

Consequently, most of the literature reviewed had no bearing on the tests of this project as finally run.

B. W. Benedict and A. W. Hershey of the University of Illinois investigated the relationship between the drill torque and Brinell hardness numbers of several different types of steel. While they reported that there was no apparent relationship existing between hardness and the torque developed, the tests indicated a comparative index of the machinability of the seven grades of steel used. Standard twist drills, a drill press, and a torque and thrust dynamometer were used in conducting the experimental work. Endurance tests utilizing helix angles from fifteen to forty-five degrees were completed on the different steels and also cast iron. Final results pointed to decreasing power requirements for increasing helix angles.<sup>14</sup>

A drill press equipped with meters for measuring instantaneous loads in pressure against depth of penetration and torque against depth of penetration was designed and built by W. L. Watt at the Michigan Experiment Station. Pressure and torque readings were recorded simultaneously on indicator cards by the testing equipment. Standard twist drills were used in all tests except those studying binding effects. No machinability index was obtained by the investigation.<sup>15</sup>

Another study using a thrust and torque dynamometer together with a manufacturing-type drill press was made by O. W. Boston, chairman of

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<sup>14</sup>Bruce W. Benedict and Albert W. Hershey, "An Investigation of Twist Drills," University of Illinois Bulletin, No. 159 (November, 1926)

<sup>15</sup>W. L. Watt, "A Test for the Machinability of Metals," Michigan Engineering Experiment Station Bulletin, vol. 21, no. 1 (July, 1945)

the Department of Metal Processing at the University of Michigan. The drilling tests were only one part of the investigation of the machining properties of cold drawn steels. A stop-watch recorded the time required for the drill to penetrate one quarter of an inch into the metal being drilled. From preliminary work the investigator concluded that dulling of the cutting edge was insufficient to alter results; consequently all tests, thirteen in number, were run with only one drill grinding. No attempt was made to correlate the time required for drilling with the force applied to the drill into a machinability index.<sup>16</sup>

The drill press and dynamometer were also used by O.W. Boston working in conjunction with C. J. Oxford in tests to determine the power required to drill cast iron and steel. Drills ranging in diameter from 1/2 to 1-1/2 inches of the standard twist-drill type were used while taking independent readings of torque and thrust. A coolant was used in all tests which were listed under special and commercial types. The commercial tests had a peripheral speed of 60 feet per minute. The feed for each drill size was held as close as possible to the usual commercial feeds.

Special tests were run in an effort to determine the influence of speed, feed, and drill diameter on torque and thrust. The results gave no correlation. An attempt was also made to correlate the hardness values of the materials as determined by the Brinell, Rockwell, Scleroscope,

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<sup>16</sup>O. W. Boston, "Machining Properties of Some Cold Drawn Steels," Transactions of the American Society of Mechanical Engineers, vol. 53, no. 10, pp. 41-55 (May - August, 1931).

and Herbert Pendulum tests with the drilling torque; but analysis showed no satisfactory relationship between these properties.<sup>17</sup>

Still another investigation was completed using a drill press together with the torque and thrust dynamometer, this series of tests being distinguished from the other by the use of a distilled water - filled calorimeter to measure the heat dissipated by the drilling operation. Nine Dowmetal alloys were drilled to find the correlation between energy dissipated into the water by the cutting and the energy and torque supplied during the tests. The calorimetric method gave results comparable to those of a well calibrated dynamometer.<sup>18</sup>

Using the same drill press and dynamometer, Boston and Oxford studied the performance of drills at a peripheral speed of 60 feet per minute under the influence of eleven different cutting fluids. A saving of power was found in the drilling of aluminum alloy, cast iron, and steel with the fluids. No appreciable difference in drill power consumption as compared with the power consumption of dry drilling was discerned when cutting fluids were used with free cutting brass. This decrease in required power for some materials due to the utilization of cutting fluids indicated that cutting fluids had some effect on the

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<sup>17</sup>O. W. Boston and C. J. Oxford, "Power Required to Drill Cast Iron and Steel," Transactions of the American Society of Mechanical Engineers, vol. 52, no. 3, pp. 5-26 (January, 1930)

<sup>18</sup>A. O. Schmidt, W. W. Gilbert, and O. W. Boston, "A Thermal - Balance Method and Mechanical Investigation for Evaluating Machinability," Transactions of the American Society of Mechanical Engineers, vol. 67, no. 4, pp. 225-232 (May, 1945)

machinability of metals.<sup>19</sup>

Professor Wykes, in his thesis detailing the results of the first experimentation with the V. P. I. Machinability Testing Machine that he developed, plotted curves showing the relationship of cutting time to weight applied to the lead screw and curves showing the relationship between cutting time and surface speed. From visual observation of the time vs. weight curves he wrote, "This investigator believes that, once a sufficient number of tests have been made, ... difference in the slope of the lines on the upper ranges of the forces applied may become an important factor in the establishment of a machinability rating for materials of all kinds."

He further surmised, "...the slope of the lines for any given material may turn out to be constant, and different from that of another material having a different machinability index."<sup>20</sup> These observations formed the basis upon which the quest for a standard machinability test by drilling was organized and run.

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<sup>19</sup>O. W. Boston and C. J. Oxford, "Performance of Cutting Fluids in Drilling Various Metals," Transactions of the American Society of Mechanical Engineers, vol. 55, no. 12, (September, 1933)

<sup>20</sup>Wykes, op. cit., p. 52

## INVESTIGATION

### Object of Investigation

The object of this investigation was to set up a standard test for the machinability of metals by drilling.

### Preliminary Experimentation

Before designing the tests that would be utilized in reaching final conclusions, preliminary drillings were performed to determine statistically the characteristics of the machine, various techniques, and one test material, steel. The results of these first drillings and analyses of variance formed the basis upon which all subsequent tests were designed and run.

To determine the relative effect of speed, weight applied to the carriage, and replication, a simple two factor, two replication experiment was performed employing the speeds 169.6 rpm and 67 rpm, and the weights 7 and 9 pounds. These last two weights were applied in addition to the weight of the weight holder.

The plan of the first test (Table I) together with calculations and results in the form of an analysis of variance table (Table II) are shown below. Time in minutes required for a 37/64" drill entering a 1/8" lead hole to pass through one inch of steel was recorded from indicator cards in the table shown.

### Definition of Symbols

$N_1$ -169.6 rpm.	$W_0$ -7 lb.	SS-Sum of Squares	df-Degrees of Freedom
$N_2$ -67 rpm.	$W_1$ -9 lb.	MS-Mean Square	y-individual times

TABLE I

	$W_0N_1$	$W_0N_2$	$W_1N_1$	$W_1N_2$	
Replication #1	7.0	8.0	3.6	8.2	26.8
Replication #2	4.2	11.0	3.0	9.2	27.4
	11.2	19.0	6.6	17.4	54.2

TABLE II

Source of Variation	df	SS	MS
Replication	1	0.05	0.05
Weight (W)	1	4.85	4.85
Speed (N)	1	43.52	43.52
Interaction (NW)	1	1.19	1.19
Experimental Error	3	8.98	2.99
Total	7	58.59	

### Calculations

$$SS \text{ Total} = S_y^2 - G^2/8$$

$$S_y^2 = (7)^2 + (4.2)^2 \dots + (9.2)^2 = 425.74$$

$$G^2/8 = (54.2)^2/8 = 367.15$$

$$SS_T = 58.59$$

$$SS \text{ Replications} = (R_1 - R_2)^2/8 = (26.8 - 27.4)^2/8 = 0.051$$

$$SS \text{ Weight} = (W_0 - W_1)^2/8 = (30.2 - 24.0)^2/8 = 4.85$$

$$SS \text{ Speed} = (N_1 - N_2)^2/8 = (17.8 - 36.4)^2/8 = 43.52$$

$$SS \text{ Interaction} = (N_1W_0 + N_2W_1 - N_1W_1 - N_2W_0)^2/8$$

$$= (28.6 - 25.6)^2/8 = 1.19$$

$$\begin{aligned} \text{SS Experimental Error} &= \text{SS Total} - (\text{SS } \underline{R} / \text{SS } \underline{W} / \text{SS } \underline{N} / \text{SS } \underline{NW}) \\ &= 58.59 - 49.61 = 8.98 \end{aligned}$$

From observation, without applying the F-test, any replication or interaction effect could be discounted due to the relatively small values of their mean squares. The replication mean square value indicated that the characteristics of the machine and the test methods were of such a nature that repetition of the tests did not significantly alter test data. The small interaction effect similarly showed the absence of any interaction caused by the use of one particular speed with a particular weight. Of course, these results were based on only a few indicator cards and could not be taken as final.

An F value of  $43.52/2.99 = 14.6$  for speed effect is highly significant at the frequently used 5% probability level, thus indicating that the change in speed accounted for a large proportion of the variability of the test.

The F value of  $4.85/2.99 = 1.62$  for weights is not significant even at the 20% level. If the investigation were to be designed specifically to show the variation of cutting feed with change in applied weight, larger increments covering a different weight range would probably have been required. The effect of speed, over the ranges considered, definitely was the most important source of variation.

This first experimental work indicated the need for still further investigation of weight effect. Consequently, a test of the form shown in Table III was performed and analyzed following the previous procedure with the exception of the addition of tests with 11 and 13 pound weights.

Equal increments of weight were added in order that orthogonal polynomials might be used to determine linear, quadratic, cubic and residual effects without deriving equations of those effects. The orthogonal polynomials used are listed in Table IV.

The symbols apply as before with additions as follows:  $W_3 = 11$  lb. and  $W_5 = 13$  lb.

TABLE III

	$W_0N_1$	$W_1N_1$	$W_3N_1$	$W_5N_1$	$W_0N_2$	$W_1N_2$	$W_3N_2$	$W_5N_2$	
Replication #1	7.8	4.8	4.6	4.5	13.7	10.5	10.0	7.8	63.7
Replication #2	9.5	5.4	4.7	5.0	14.3	8.8	10.6	8.0	66.3
	17.3	10.2	9.3	9.5	28.0	19.3	20.6	15.8	130.0

TABLE IV

Plan of Analysis Including Orthogonal Polynomials <sup>21</sup>								
	$W_0N_1$	$W_1N_1$	$W_3N_1$	$W_5N_1$	$W_0N_2$	$W_1N_2$	$W_3N_2$	$W_5N_2$
Speed	-1	-1	-1	-1	/1	/1	/1	/1
Weights								
Linear	-3	-1	/1	/3	-3	-1	/1	/3
Quadratic	/1	-1	-1	/1	/1	-1	-1	/1
Cubic	-1	/3	-3	/1	-1	/3	-3	/1
Interaction								
SL	/3	/1	-1	-3	-3	-1	/1	/3
SQ	-1	/1	/1	-1	/1	-1	-1	/1
SC	/1	-3	/3	-1	-1	/3	-3	/1

<sup>21</sup>P. L. Anderson and E. E. Houseman, "Tables of Orthogonal Polynomials Values Extended to  $N = 104$ " Iowa State Research Bulletin no. 297 (April, 1942)

TABLE V  
Analysis of Variance

Source of Variation	df	SS	MS
Replication	1	0.42	0.42
Treatments			
Speed	1	87.42	87.42
Weights			
Linear	1	44.40	44.40
Quadratic	1	7.84	7.84
Cubic	1	5.61	5.61
Interactions			
SL	1	1.51	1.51
SQ	1	0.95	0.95
SC	1	1.51	1.51
Experimental Error	7	2.95	0.44
Total	15	152.61	

Calculations

$$SS \text{ Total} = S_y^2 - G^2/16$$

$$S_y^2 = (7.8)^2 + (9.5)^2 + (4.8)^2 \dots + (8)^2 = 1208.86$$

$$G^2/16 = (130)^2/16 = 149.03$$

$$SS_T = 152.61$$

$$SS \text{ Replications} = (R_1 - R_2)^2/16 = (63.7 - 66.3)^2/16 = 0.423$$

$$SS \text{ Speed} = (N_1 - N_2)^2/16 = (46.3 - 83.7)^2/16 = 87.42$$

$$SS_{L, Q, C} = (\sum cy)^2 / (c_1^2 + c_2^2 \dots + c_n^2) n_r$$

Where  $c$  = the orthogonal polynomial coefficients,

and  $n_r$  = number of replications.

$$\text{SS Linear} = (-51.9 - 10.2 + 9.3 + 28.5 - 84.0 - 19.3 \\ + 20.6 + 47.4)^2 / (40)(2) = 44.40$$

$$\text{SS Quadratic} = (17.3 - 10.3 - 9.3 + 9.5 + 28 - 20.6 - 19.3 \\ + 15.3)^2 / (8)(2) = 7.84$$

$$\text{SS Cubic} = (-17.3 + 30.6 - 27.9 + 9.5 - 28 + 57.9 - 61.8 \\ + 15.8)^2 / 80 = 5.61$$

Calculation of interaction effects follows the same form that was utilized in calculating linear, quadratic, and cubic effects.

#### Interaction

$$\text{SS } \underline{SL} = (51.9 + 10.2 - 9.3 - 28.5 - 84.0 - 19.3 + 20.6 \\ + 47.4)^2 / (40)(2) = 1.51$$

$$\text{SS } \underline{SQ} = (-17.3 + 10.2 + 9.3 - 9.5 + 28.0 - 19.3 - 20.6 \\ + 15.8)^2 / (8)(2) = 0.95$$

$$\text{SS } \underline{SC} = (17.3 - 30.6 + 27.9 - 9.5 - 28.0 + 57.9 - 61.8 \\ + 15.8)^2 / 80 = 1.51$$

$$\text{SS Experimental Error} = \text{SS Total} - \sum \text{SS} = 152.61 - 149.66 = 2.95$$

The analysis of variance of this experiment still indicated the predominant speed effect. Replication effect was again a negligible quantity thus lending more credance to the conclusion of the previous experiment concerning the effect of replication. The larger number of weights introduced a much more significant weight factor which could be broken into component parts, the predominant tendency of which was linear as indicated by the high value of linear mean square when compared

with the other mean squares.

The interaction mean squares, showing differences between linear, quadratic, and cubic tendencies at the two different speeds, were negligible thus indicating that no significant difference existed between the curves of these characteristics.

Visual observation of the data brought to mind the possibility that the majority of variability might be accounted for by the difference between the effect of the seven pound weight when compared with the other weights. This was immediately tested by the orthogonal polynomials (Table VI) and calculations shown below.

TABLE VI

	$W_0N_1$	$W_1N_1$	$W_3N_1$	$W_5N_1$	$W_0N_2$	$W_1N_2$	$W_3N_2$	$W_5N_2$
Comparison of $W_0$ with $W_1 - W_3 - W_5$	-3	$\neq 1$	$\neq 1$	$\neq 1$	-3	$\neq 1$	$\neq 1$	$\neq 1$
Linear		$\neq 1$	$\neq 0$	-1		$\neq 1$	0	-1
Quadratic		$\neq 1$	-2	$\neq 1$		$\neq 1$	-2	$\neq 1$

$$SS_{Comp.} = (-3 \times 17.3 \neq 10.2 \neq 9.3 \neq 9.5 - 3 \times 28 \neq 19.3 \neq 20.6 \neq 15.8)^2 / (24)(2) = 54.61$$

$$SS_{Linear} = (29.5 - 25.3)^2 / (4)(2) = 2.20$$

$$SS_{Cubic} = (54.8 - 59.8)^2 / (12)(2) = 1.04$$

The results definitely substantiated conclusions based on the visual observation (Dr. Harshbarger's). The high mean square, from the sum of squares, resulting from a comparison of the seven pound effect with the combined nine, eleven, and thirteen pound effects indicates the large

difference between the seven pound factor and other factors. The small mean squares attributable to linear and quadratic characteristics among the nine, eleven, and thirteen pound weights show that there is no significant difference between the last three weight effects.

This fact focused attention on the possibility of developing a machinability index covering a range of weights, in this case from nine to thirteen pounds. Subsequent tests were run in attempt to find this index for the materials being tested.

Preliminary tests were also tried with a  $57/64$ " drill in search of a relationship between surface speed and machinability as defined by the removal of a specified volume of material per unit time. However, the time required to remove one quarter of a cubic inch of metal with the  $57/64$ " drill was less than half the time required to remove the same volume of material with the  $37/64$ " drill at the same surface speed. Due to a lack of correlation between the tests, experimentation with the larger drill was discontinued.

## Apparatus Used

### V. P. I. Machinability Testing Machine

The basic structure of the V.P.I. Machinability Testing Machine is a 14" Prentice lathe, four feet between centers. This lathe was modified by Mr. Stanley A. Wykes, then Associate Professor of Industrial Engineering at the Virginia Polytechnic Institute, for his thesis The Development of a Testing Machine for Machinability Tests.<sup>22</sup>

The lathe was stripped of its original carriage and feed screw. Four parallel surfaces in a horizontal plane and two parallel surfaces in a vertical plane at right angles to the horizontal surfaces were machined on the lathe bed. The six surfaces were used as ways for a carriage to carry the test samples.

The weight of the carriage rested upon four rollers mounted on roller bearings. There are also four more rollers mounted on the front and rear aprons of the carriage, and four rollers mounted against the two vertical ways. The carriage mounted in position to operate is shown in Figure 1. Figure 2 shows the underside view of the carriage showing the arrangement of the 12 rollers.

A 1-1/8" Acme double-thread screw having a pitch of 1/4" and a lead of 1/2" was mounted on the side of the lathe for the purpose of moving the carriage. The screw was mounted in thrust bearings at either end with a two-inch diameter pulley attached at the headstock end. Around this pulley was wrapped a line in such a manner that a weight attached

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<sup>22</sup>Wykes, op. cit.

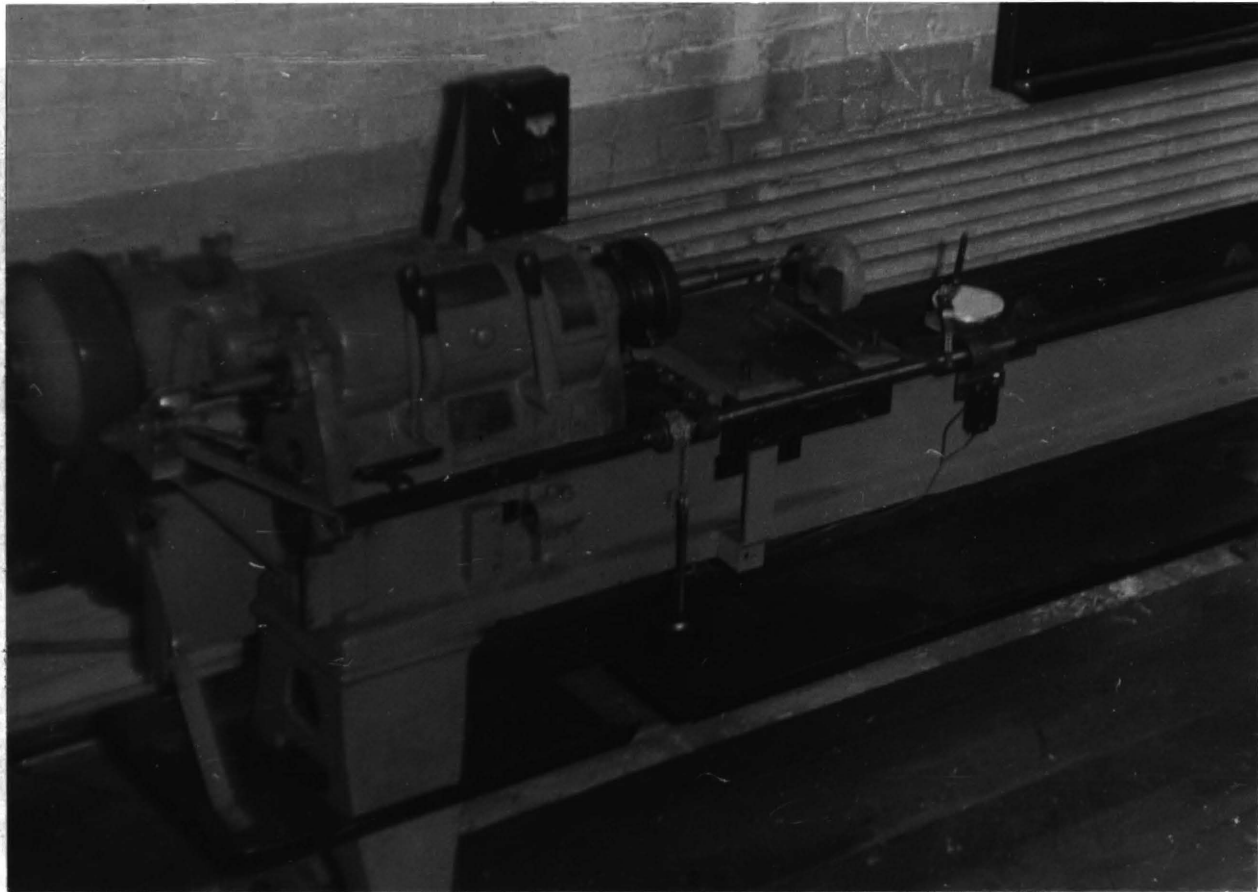


Figure 1. Carriage Mounted in Position to Operate

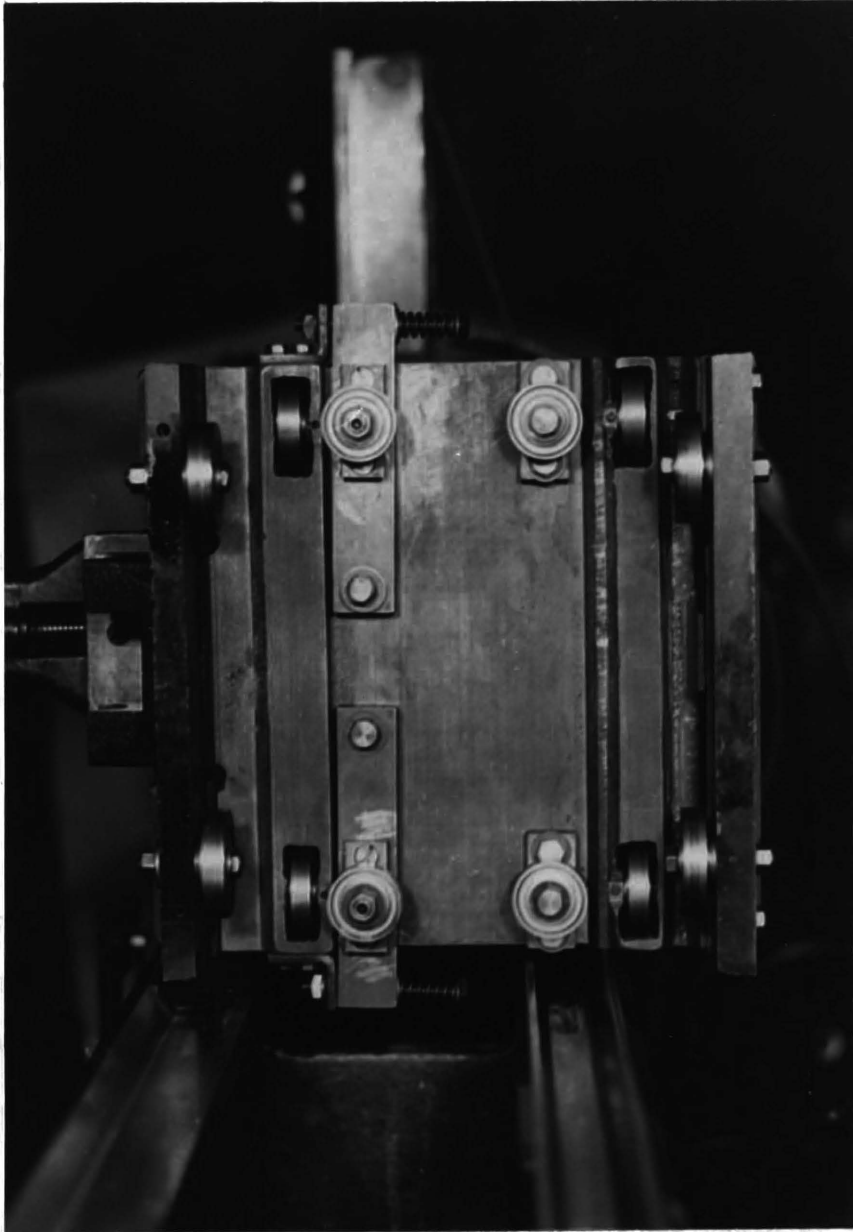


Figure 2. Underside View of Carriage

to the line caused the lead screw to revolve thus moving the carriage forward with the test specimen. The drill was inserted in the headstock. By changing the weights on the line, the force pulling the test specimens against the drill was varied from nine to thirteen pounds in one pound increments (these weights being in addition to the weight holder which weighed 1.356 pounds).

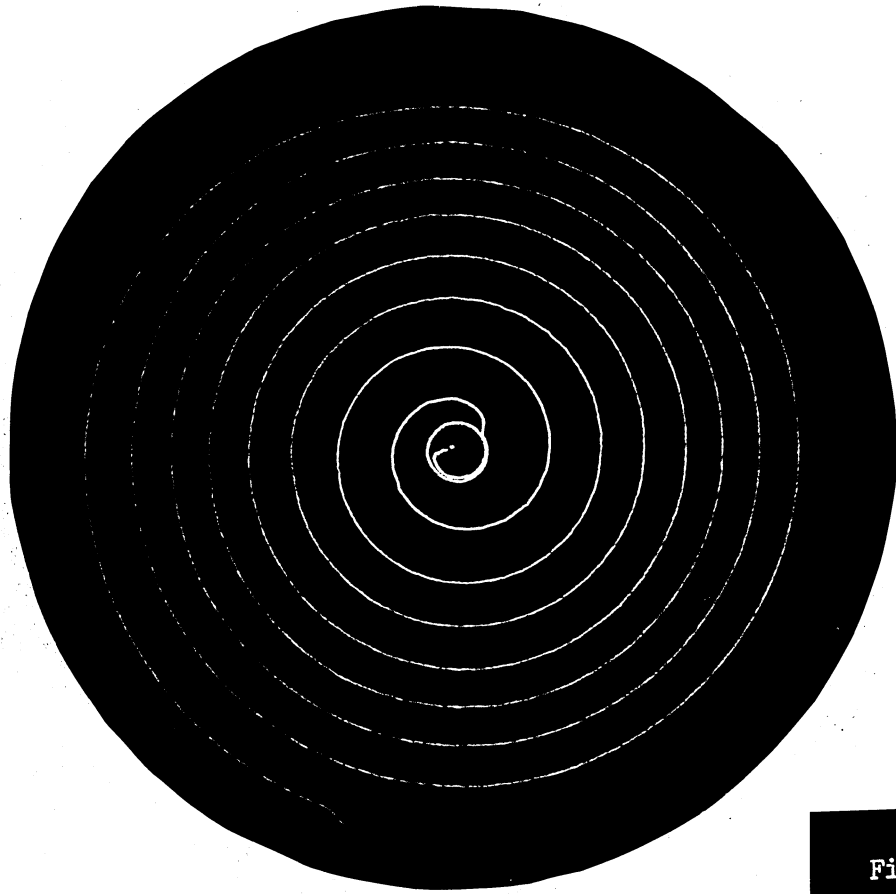
The variations of time and penetration of the drill were recorded by a recording pen attached to the carriage which marked a circular indicator card. Figures 3 and 4 shows several sample indicator cards. These cards were attached to a turntable mounted on a one rpm synchronous motor. Variation in time was measured by the number of revolutions; depth of penetration was measured radially. Thus an accurate picture of all phases of the drilling operation was available. Bad spots in the test specimens, inconsistent cutting rates, and other discrepancies showed up on the cards where they could be studied and eliminated, if necessary.

#### Test Drills

High-speed taper shank twist drills were used in this investigation due to their prevalent use in industry. Further tests with the same type drills could be run on materials other than those used in this project and the results could be correlated with the results of this study. Following standard testing procedure, all drills were sharpened on an Oliver 510 drill pointer so that their cutting edges could be reproduced for subsequent drillings.<sup>23</sup> Before running any tests, each newly ground

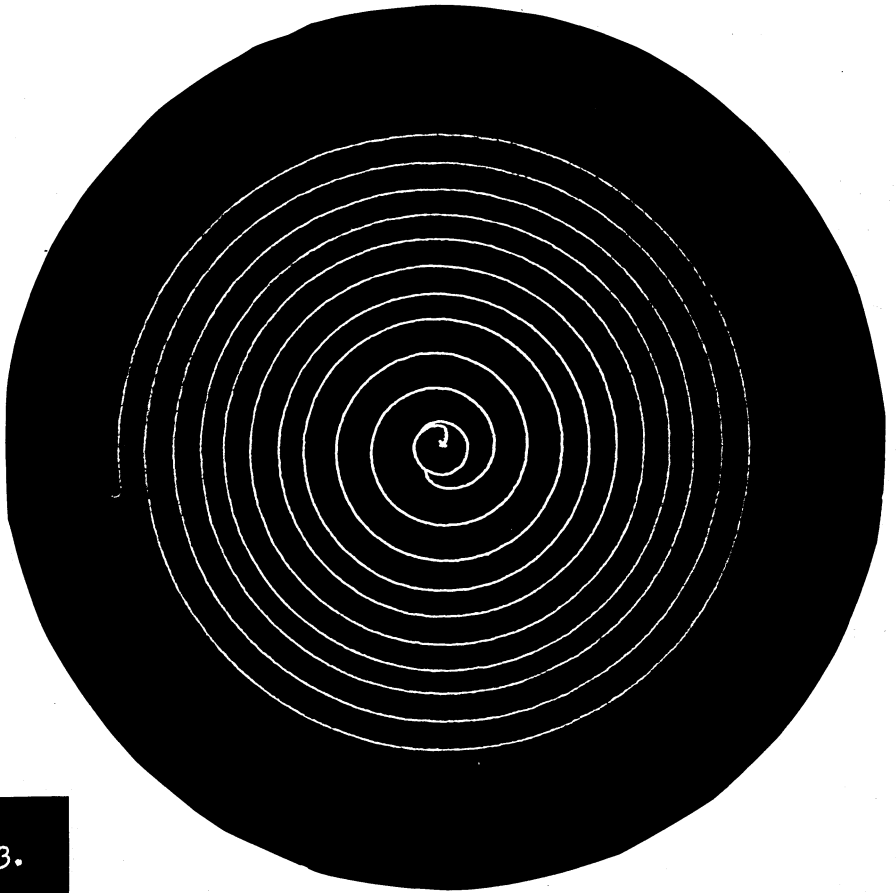
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<sup>23</sup>Boston, op. cit.

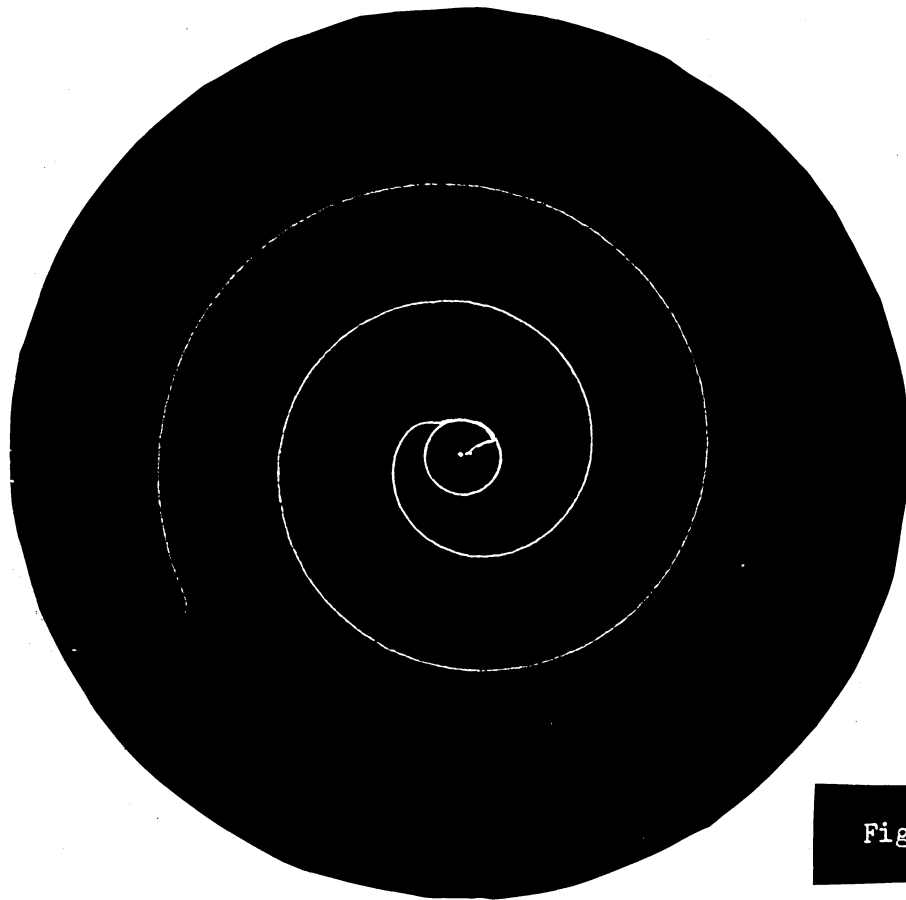


Sample Cast Iron Indicator Card

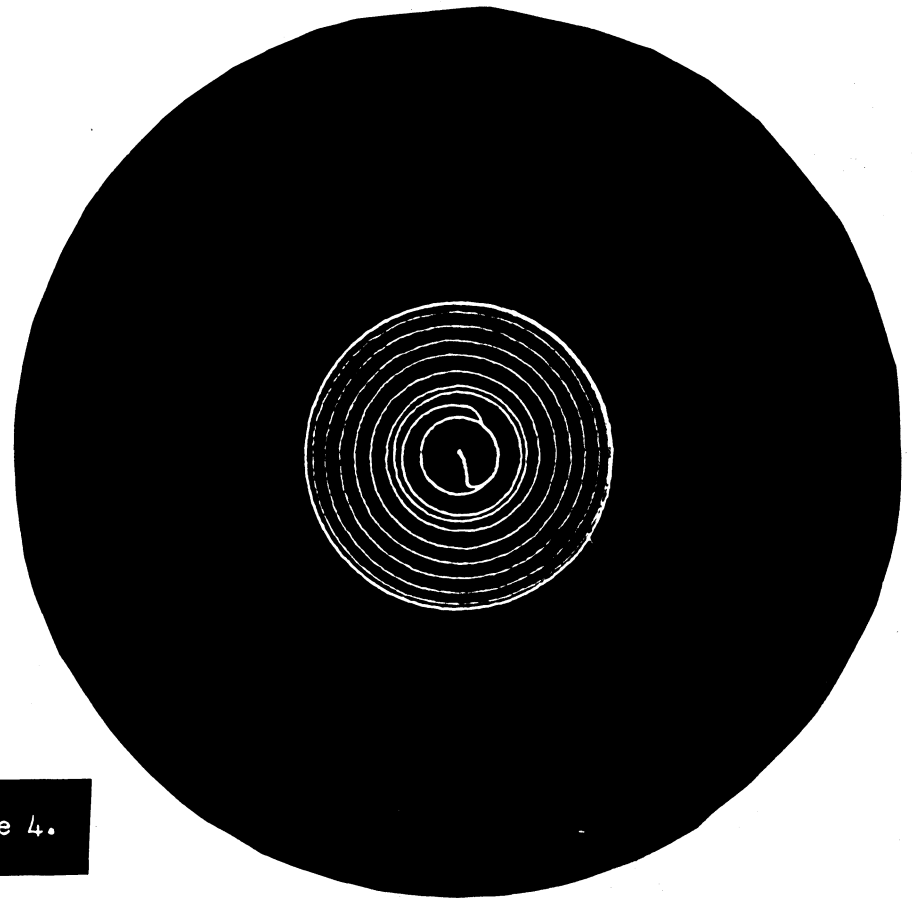
Figure 3.



Sample Steel Indicator Card



Sample Aluminum Indicator Card



Sample Cast Iron Indicator Card

Figure 4.

Indicator Card for Cast Iron Showing Unsatisfactory  
67 RPM Drilling

drill was used to drill one hole to remove any feather edge that might be left by the grinding operation. The drill and test specimens were cooled by water to normal room temperature between tests. Due to the proved effect of cutting fluid on machinability, no cutting fluid was used in the tests.<sup>24</sup> This omission further eased the standardization problem. Although O. W. Boston reported no significant dulling effect when thirteen holes were drilled between grindings, the drill used in this study was repointed after every five drillings.<sup>25</sup> A point angle of 118 degrees was used for all tests.

#### Speeds

The V. P. I. Machinability Testing Machine developed by Professor Wykes had fixed spindle speeds ranging from 23.4 to 315 revolutions per minute. Variations from the fixed spindle speeds could not be obtained. Since original plans included the use of two drills, one of 37/64" diameter and the other of 57/64" diameter, only three speed combinations could be used to give the same peripheral speed for each drill. Two of these speeds were 169.6 rpm and 67 rpm for the 37/64" drill. Preliminary tests showed the inadvisability of running tests with the 57/64" drills; but since some work had been done at the aforementioned speeds, an attempt was made to use 169.6 rpm and 67 rpm as base speeds for the establishment of a machinability index.

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<sup>24</sup>Boston and Oxford, op. cit.

<sup>25</sup>Boston, op. cit.

The two drill sizes were selected since convenient lead drills of 1/8" and 11/16" sizes could be used to produce the removal of 0.25 cubic inch of material for each inch of carriage displacement.

#### Volume of Material Removed

The volume of material removed by each drilling operation was 0.25 cubic inch. Removal of the specified volume was accomplished by first drilling the material with a lead drill of such a size that the remaining volume to be removed by the test drill was 0.25 cubic inch for one inch of carriage level. A 1/8" drill was used for the lead hole for the 37/64" test drill, while a 11/16" drill was used in preparation for the 57/64" test drill. Depth of penetration of the drill and the time elapsed for drilling were measured on the indicator card rotated by the one rpm synchronous motor.

#### Materials

A representative group of metals including cast iron, bronze, aluminum, and steel was chosen to be tested for a possible index. Financial considerations involved in obtaining commercially used test materials limited the number of different materials that were studied. This group was still further reduced when drilling of the bronze with the test drill was found impossible on account of the 45 degree helix angle of the drill. The drill failed to penetrate the bronze. It merely dug into the surface of the test specimens and jammed there. Drilling of bronze requires a zero degree helix angle; but since this investigation was attempting to establish a standard test using one type of standard

drill, bronze was dropped from the materials to be tested.

The cast iron and aluminum were cast in a commercial foundry, the cast iron being delivered in the form of cylindrical castings five inches in diameter and fourteen inches in length, all castings coming from the same melt. The aluminum was obtained in the form of cast discs five inches in diameter and 1-1/2" in thickness. One cold rolled S.A.E. 1020 steel bar 3-15/16" in diameter and five feet in length was the source of steel test specimens.

The steel and cast iron test bars were cut into discs of 1-1/2" thickness. The aluminum cast discs were machined 1/8" on a side in preparation for the drilling tests. All of the test specimens were drilled in the center in order that a bolt could be inserted to attach the specimen to the machine carriage. Outer surfaces of the discs were not machined.

#### Applied Force

The force applied to the lathe carriage was varied by adding weights to or removing weights from the weight holder attached to the end of the lead screw chain. As already stated, preliminary tests showed the advisability of applying weights from nine to thirteen pounds plus the weight holder which weighed 1.36 pounds. These weights were increased in equal increments of one pound each in order that statistical techniques which required less time for calculation might be used to analyze the data.

## Method of Making Tests

Preliminary tests to determine the best sequence of testing were made using steel specimens since an adequate supply of steel was available in the machine shop. Many of the first tests were complete failures owing to the drill freezing in the test specimen before completion of the test. This trouble was caused by excessive heating of the drill and specimens when the specimen and drill were utilized several times in succession without allowing either to cool. The problem was solved by immersing the drill and test specimen in a container of water at room temperature after each drilling.

Difficulties were also encountered when the drill was allowed to completely pierce the material being drilled. The drill tended to dig into the metal and cause the specimen to turn about the bolt and small plate holding the specimen to the machine carriage. A larger holding plate making possible more secure binding of test materials to the carriage eliminated test specimen rotation during the tests.

Preliminary plans included the drilling of lead holes with the test machine by the use of a 1/8" drill mounted in a small drill chuck. However the slow spindle speeds available were found completely inadequate for small drill work. Not only was the time of drilling entirely too long, but any bad spot in the test specimen or local overheating resulted in broken lead drills. Consequently lead holes were drilled on a drill press.

Statistical analysis of preliminary tests indicated that there were no significant differences between the different test specimens cut from the bar of steel. Consequently, no particular specimen sequence was

followed in making the steel tests. Each replication of the cast iron tests was made on a test specimen coming from a different cylinder. Statistical analysis showed no significant difference between cylinders. Since a large number of aluminum test specimens were prepared before experimentation was started, a different specimen was drilled for each test. Again statistical analysis showed no differences between specimens.

The same procedure was followed in making tests with each material.

This procedure is detailed as follows:

1. The drill was sharpened to a 118 degree point angle on an Oliver 510 drill pointer (Figure 5) after every five drilling operations.
2. After each sharpening, the drill was used to drill one hole in a piece of scrap material to remove any feather edge before test specimens were drilled.
3. Lead and center holes were drilled in the test specimens on a drill press. The specimens were first scribed on the testing machine so that the lead holes would be centered correctly when tests were made.
4. A small drill chuck holding a 1/8" drill was used to center the lead holes of the test specimens as the specimens were attached to the lathe carriage. The drill chuck was inserted in the tapered sleeve that customarily held the test drills and the test specimens were so adjusted that the 1/8" drill entered the lead hole. This procedure insured perfect centering for the tests.
5. Once the specimens had been mounted, an indicator card was centered on the turn-table by using the recording pen to find the center of rotation. One recorded revolution of the table with the carriage stationary accurately located the center point which was essential for accurate radial linear measurements.
6. The lathe was started at the test speed.
7. Test weights were added to the weight holder.
8. The weights were removed and the machine stopped before the drill had completely penetrated the test specimen in order that any

8. tendency for the test drill to become jammed in the test specimen would be obviated.
9. Both the drill and test specimen were immersed in water at the end of each test.

Since the data was to be analyzed statistically, no test values were arbitrarily discarded because they looked either larger or smaller than the average of several runs under the same conditions. Only those values which were incorrect as a result of faulty equipment set-up, such as improperly pointed drill or accidentally varied conditions, were not included in the calculations for final machinability estimates. The inclusion of all test data and a subsequent accurate estimate of population variance is still another advantage of the statistical approach.

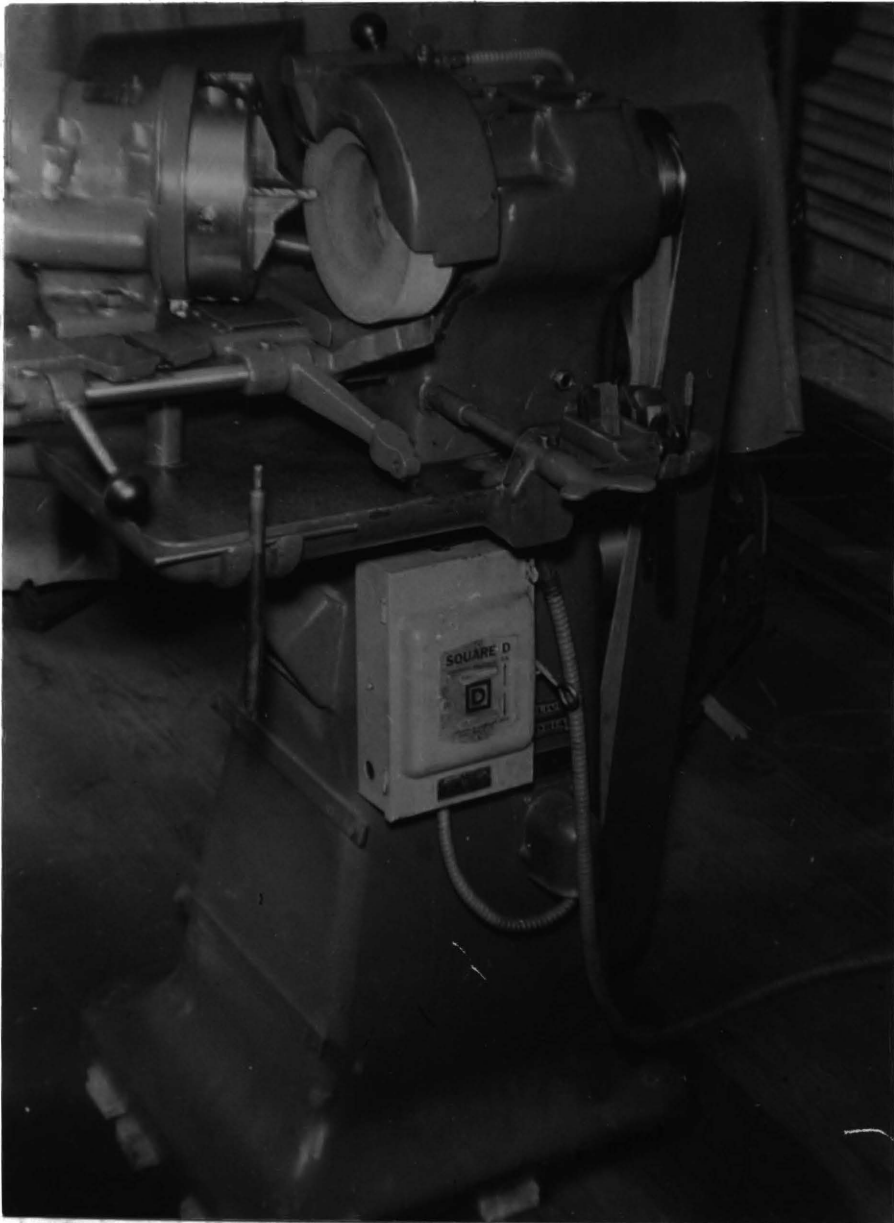


Figure 5. Oliver 510 Drill Pointer

DATA AND DISCUSSION OF RESULTS

Following the procedure recommended by statistical analysis of preliminary tests, two replications of two speeds and five different weights at equal (1 pound) increments were performed. The test plan which includes individual time values in minutes for the conditions listed is found in Table VII. The plan of analysis including orthogonal polynomials is shown in Table VIII.

TABLE VII

Steel - Time in Minutes

	N <sub>1</sub> W <sub>1</sub>	N <sub>1</sub> W <sub>2</sub>	N <sub>1</sub> W <sub>3</sub>	N <sub>1</sub> W <sub>4</sub>	N <sub>1</sub> W <sub>5</sub>	N <sub>2</sub> W <sub>1</sub>	N <sub>2</sub> W <sub>2</sub>	N <sub>2</sub> W <sub>3</sub>	N <sub>2</sub> W <sub>4</sub>	N <sub>2</sub> W <sub>5</sub>	
Replication #1	4.3	4.7	3.9	3.8	3.0	10.0	9.0	8.9	8.2	7.2	63.0
Replication #2	4.0	4.0	3.3	3.1	2.8	11.0	10.0	8.8	8.5	7.7	63.2
	8.3	8.7	7.2	6.9	5.8	21.0	19.0	17.7	16.7	14.9	126.2

TABLE VIII

Plan of Analysis Including Orthogonal Polynomials

	N <sub>1</sub> W <sub>1</sub>	N <sub>1</sub> W <sub>2</sub>	N <sub>1</sub> W <sub>3</sub>	N <sub>1</sub> W <sub>4</sub>	N <sub>1</sub> W <sub>5</sub>	N <sub>2</sub> W <sub>1</sub>	N <sub>2</sub> W <sub>2</sub>	N <sub>2</sub> W <sub>3</sub>	N <sub>2</sub> W <sub>4</sub>	N <sub>2</sub> W <sub>5</sub>	
Speed	∓1	∓1	∓1	∓1	∓1	-1	-1	-1	-1	-1	
Weight											
Linear	-2	-1	0	∓1	∓2	-2	-1	0	∓1	∓2	
Quadratic	∓2	-1	-2	-1	∓2	∓2	-1	-2	-1	∓2	
Cubic	-1	∓2	0	-2	∓1	-1	∓2	0	-2	∓1	
Exp. Error	∓1	-4	∓6	-4	∓1	∓1	-4	∓6	-4	∓1	

TABLE VIII, cont'd

	N <sub>1</sub> W <sub>1</sub>	N <sub>1</sub> W <sub>2</sub>	N <sub>1</sub> W <sub>3</sub>	N <sub>1</sub> W <sub>4</sub>	N <sub>1</sub> W <sub>5</sub>	N <sub>2</sub> W <sub>1</sub>	N <sub>2</sub> W <sub>2</sub>	N <sub>2</sub> W <sub>3</sub>	N <sub>2</sub> W <sub>4</sub>	N <sub>2</sub> W <sub>5</sub>
Interaction										
SL	-2	-1	0	/1	/2	/2	/1	0	-1	-2
SQ	/2	-1	-2	-1	/2	-2	/1	/2	/1	-2
SC	-1	/2	0	-2	/1	/1	-2	0	/2	-1
SResidual	/1	-4	/6	-4	/1	-1	/4	-6	/4	-1

The data was studied by the method of analysis of variance. The calculations are shown below and the results are tabulated in the analysis of variance Table IX.

TABLE IX

## Analysis of Variance

Steel			
Source of Variation	df	SS	MS
Replication	1	0.00	0.00
Speed	1	137.29	137.29
Weights			
Linear	1	11.34	11.34
Quadratic	1	0.02	0.02
Cubic	1	0.01	0.01
Residual	1	0.12	0.12
Interaction SL	1	1.48	1.48
Experimental Error	12	2.26	0.19
Total	19	152.52	

Sample Calculations for Steel

$$SS_{\text{Total}} = \sum y^2 - \frac{G^2}{20} = (4.3)^2 + (4.0)^2 + \dots + (7.7)^2 - \left(\frac{126.2}{20}\right)^2$$

$$= 152.52$$

$$SS_{\text{Replication}} = \left(\frac{R_1 - R_2}{20}\right)^2 = \left(\frac{63.0 - 63.2}{20}\right)^2 = 0.002$$

$$SS_{\text{Speed}} = \left(\frac{N_1 - N_2}{20}\right)^2 = \left(\frac{36.9 - 89.3}{20}\right)^2 = 137.288$$

Weights

$$SS_{\text{Linear}} = \frac{(\sum cy)^2}{(c_1^2 + c_2^2 + \dots + c_{10}^2)n_r}$$

$$= \frac{(-16.6 - 8.7 + 6.9 + 11.6 - 42 - 19 + 16.7 - 29.8)^2}{(4 + 1 + 1 + 4)(2)(2)}$$

$$= 11.34$$

$$SS_{\text{Quadratic}} = \frac{(16.6 - 8.7 - 14.4 - 6.9 + 11.6 + 42.0 - 19.0)(4 + 1 + 4 + 1 + 4) - 35.4 - 16.7 + 29.8)^2}{(2)(2)}$$

$$= 0.022$$

$$SS_{\text{Cubic}} = \frac{(-8.3 + 17.4 - 13.8 + 5.8 - 21.0 + 38.0 - 33.4)(1 + 4 + 4 + 1) + 14.9)^2}{(2)(2)}$$

$$= 0.004$$

$$SS_{\text{Residual}} = \frac{(8.3 - 34.8 + 43.2 - 27.6 + 5.8 + 21.0 - 76.0)(1 + 16 + 36 + 16 + 1) + 106.2 - 66.8 + 14.9)^2}{(2)(2)}$$

$$= 0.120$$

Interaction

$$SS_{\text{Speed-Linear}} = \frac{(-16.6 - 8.7 - 6.9 + 11.6 + 42.0 + 19.0 - 16.7)}{(4 + 1 + 1 + 4)} \\ \frac{-29.8^2}{(2)(2)} \\ = 1.48$$

$$SS_{\text{Experimental Error}} = SS_{\text{Total}} - \sum SS$$

F - value for linear interaction

$$F = \frac{1.48}{0.19} = 7.8$$

Although conventional analysis of variance procedure would include breaking the interaction source of variation into four sources, each using up one degree of freedom, the analysis was calculated with only the linear interaction term being considered. The decision was based on previous steel tests which indicated that the cubic, quadratic, and residual interaction effects were not significant. Checks on the data being analyzed yielded the same result. The advantage of eliminating three interaction terms with their degrees of freedom lies in a better estimate of experimental error resulting from the additional degrees of freedom for the error term.

The replication term was nonsignificant as it had been in all preliminary testing. The low replication mean square showed that the properties of both the testing machine and tested material were so constant

that the difference between replications, or repeated tests, was insignificant.

Once again change in speed accounted for the greatest portion of the variability of the tests. The large speed mean square as compared to the other mean squares of the other sources of variation showed this relationship. The linear weight effect was also statistically significant thus indicating that variation due to increasing weight can be represented by a straight line, or a linear regression relationship as the statisticians define it. The small quadratic, cubic, and residual mean squares further showed that no statistically significant variation can be expressed by or attributed to these relations. These low mean squares further emphasize the importance of a straight line in expressing the variation due to weight effect.

From visual observation, the linear interaction term seemed quite low; but an  $F$ -test as calculated below showed this term to be significant at the 5% probability level. The significance of this term indicated that the straight line relationships already predicted for the two different speeds would have different slopes. All of the predicted relationships proved correct when equations for the two lines were calculated and plotted as shown by Curve Sheet #1. Calculation of the equations follows.

$$169.6 \text{ rpm} \quad a = \frac{\sum Y}{n} = \bar{Y} = 3.69$$

$$\bar{X} = \frac{\sum X}{n} = \frac{110}{10} = 11$$

$$b = \frac{\sum (Y-\bar{Y})(X-\bar{X})}{\sum (X-\bar{X})^2} = \frac{(0.46)(-2) + (0.66)(-1) + (-0.24)}{(2)^2 + (1)^2 + (-1)^2}$$

$$\frac{(1) + (-0.79)(2)}{+ (-2)^2}$$

$$= -0.34$$

$$Y = a + b (X-\bar{X}) = 3.69 - 0.34 (X-11)$$

$$= \underline{\underline{7.43 - 0.34X}}$$

67 rpm  $a = \frac{\sum Y}{n} = \bar{Y} = \frac{89.3}{10} = 8.93$

$$\bar{X} = \frac{\sum X}{n} = \frac{110}{10} = 11$$

$$b = \frac{\sum (Y-\bar{Y})(X-\bar{X})}{\sum (X-\bar{X})^2} = \frac{(1.57)(-2) + (0.57)(-1) + (-0.58)}{(2)^2 + (1)^2 + (-1)^2}$$

$$\frac{(1) + (-1.48)(2)}{+ (-2)^2}$$

$$= -0.725$$

$$Y = a + b (X-\bar{X}) = 8.93 - 0.725 (X-11)$$

$$= \underline{\underline{16.91 - 0.73X}}$$

The cast iron tests were first performed by following the same plan as that utilized in steel experimentation. However, analysis of the data for two replications showed a much higher variance for the cast iron than that which had been calculated for steel. Consequently, two more replications were made in order that a more accurate estimate might be made of the error term which is also a measure of the variance of the machine and materials. The times for all four replications under the

ten different sets of conditions are listed in Table X. The same plan and orthogonal polynomials (Table VIII) were applied in this variance analysis as were applied to the steel analysis. Calculations followed the form already illustrated. The results of this analysis are tabulated in Table XI.

TABLE X

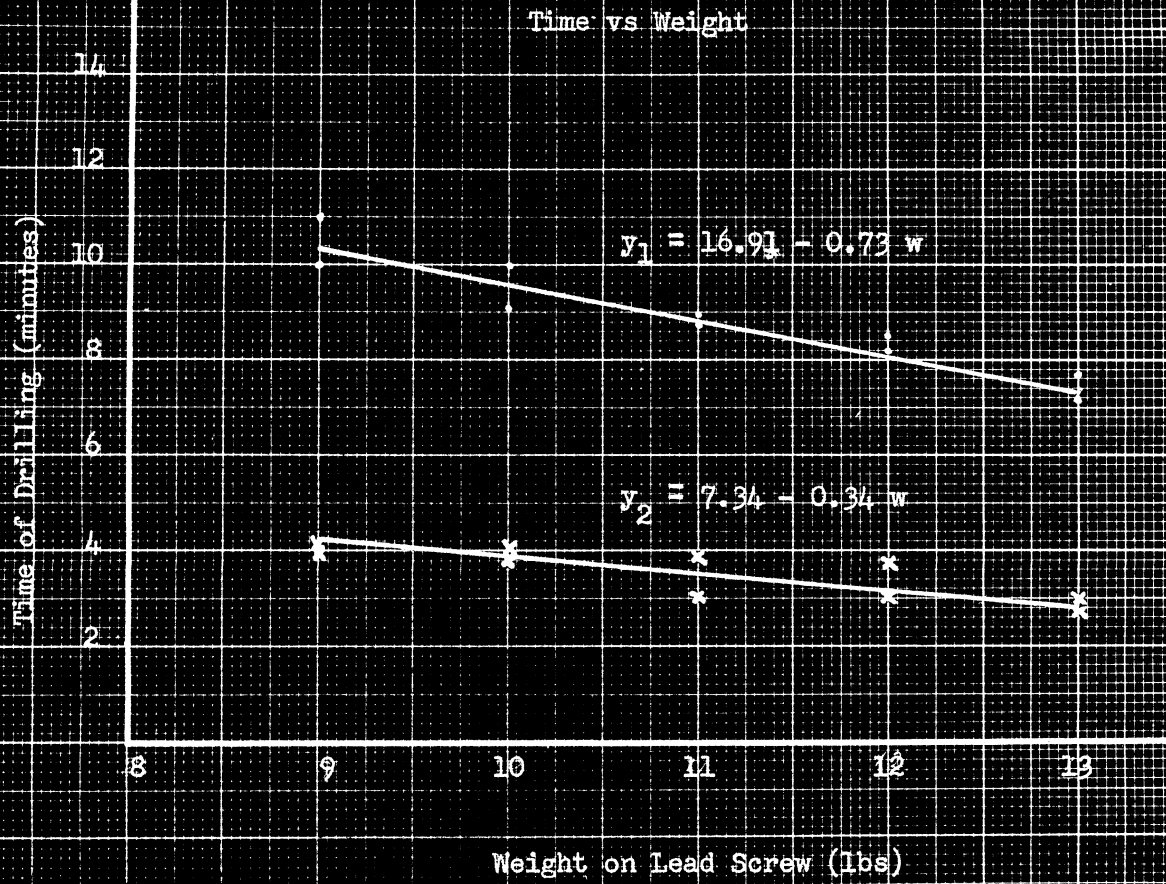
Cast Iron											
	$N_1W_1$	$N_1W_2$	$N_1W_3$	$N_1W_4$	$N_1W_5$	$N_3W_1$	$N_3W_2$	$N_3W_3$	$N_3W_4$	$N_3W_5$	
Replication #1	6.4	6.2	5.0	2.8	2.6	13.0	8.0	10.2	3.5	3.3	61.0
Replication #2	4.1	4.3	3.2	2.8	2.8	9.2	8.4	6.6	7.2	7.0	55.6
Replication #3	6.5	6.0	5.5	4.7	4.3	8.5	6.7	8.0	5.2	5.2	60.6
Replication #4	6.0	5.3	6.2	4.6	4.7	12.8	8.8	8.2	6.8	6.6	70.0
	23.0	21.8	19.9	14.9	14.4	43.5	31.9	33.0	22.7	22.1	247.2

TABLE XI

Analysis of Variance

Cast Iron			
Source of Variation	df	SS	MS
Replication	3	10.8	3.6
Speeds	1	87.6	87.6
Weights	4	78.6	19.7
Linear	1	72.4	72.4
Residual	3	6.2	2.1
Interaction	4	14.1	3.5
Linear	1	9.7	9.7
Residual	3	4.4	1.5

Curve Sheet 1



Material - S.A.E. 1020 Steel

Speed - 1 - 67 rpm

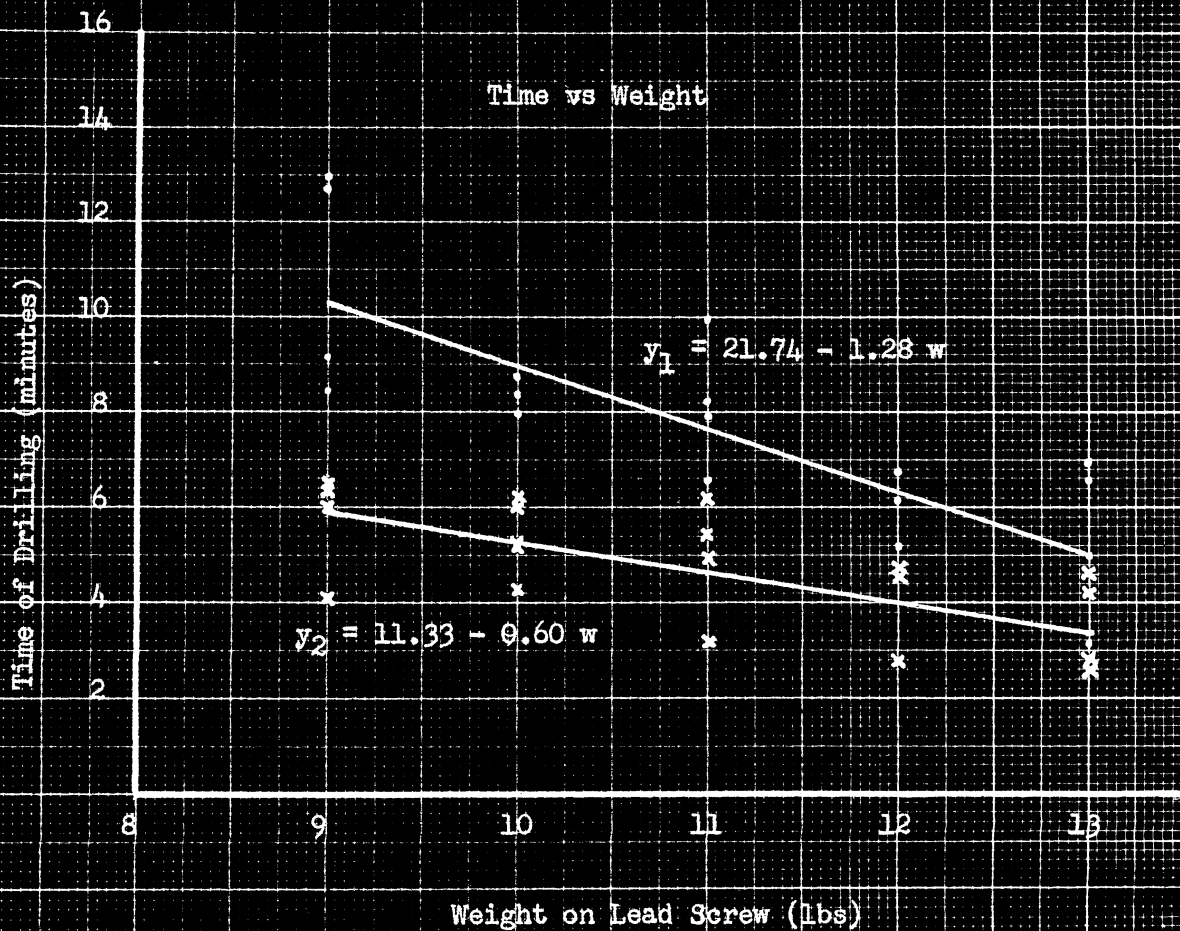
2 - 169.6 rpm

TABLE XI, cont'd

Source of Variation	df	SS	MS
Experimental Error	27	49.6	1.8
Total	39	240.7	

Once again the replication effect was not statistically significant and the speed effect was the strongest source of variation. The weight effect was also significant with the linear term showing the only significant relationship. The residuals of the weight factor were not significant. Of the interaction terms, only the linear mean square was statistically significant at the 5% level. The results of this variance analysis were the same in tendency as those of the steel tests, namely two straight lines with different slopes. These linear regression lines are shown together with their equations by Curve Sheet #2. Calculation of the equations follows the same form as that shown in the calculation of linear regression lines for steel.

Since tests of aluminum at 169.6 rpm proved impractical with the test equipment, only one speed, 67 rpm, was tested. The results of four replications are listed in Table XII. The aluminum variance analysis also made use of the orthogonal polynomials given in Table VIII. The analysis calculations paralleled steel computations except for the fact that no speed or interaction terms existed since only one speed was investigated.



Material - Cast Iron  
Speed - 1 - 110 rpm  
          2 - 169.6 rpm

TABLE XII

Aluminum						
	$N_2W_1$	$N_2W_2$	$N_2W_3$	$N_2W_4$	$N_2W_5$	
Replication #1	2.2	2.0	1.8	1.7	1.5	9.2
#2	1.9	1.7	1.7	1.6	1.3	8.2
#3	2.2	2.2	1.8	1.6	1.7	9.5
#4	2.6	1.7	1.6	1.2	1.3	8.4
	8.9	7.6	6.9	6.1	5.8	35.3

TABLE XIII

## Analysis of Variance

Aluminum			
Source of Variation	df	SS	MS
Replication	3	0.24	0.08
Weights			
Linear	1	1.48	1.48
Quadratic	1	0.06	0.06
Cubic	1	0.00	0.00
Residual	1	0.00	0.00
Experimental Error	12	0.49	0.04
Total	19	2.27	

Replication effect was again negligible. The linear portion of the weight mean square was the only significant source of variation. Consequently, a straight line was also predicted for aluminum. This line, computed by the same method as that shown for steel, is plotted

Curve Sheet 3

Time vs. Weight

Time of Drilling (minutes)

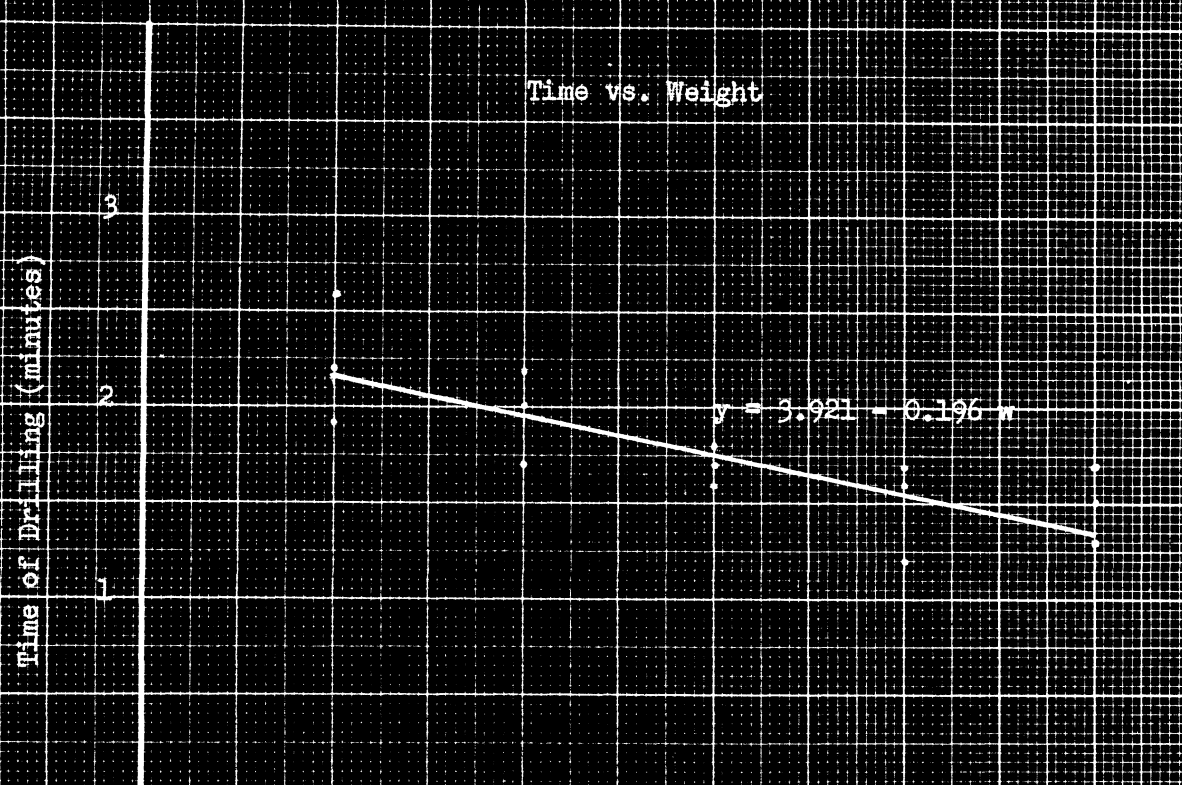
3  
2  
1

8 9 10 11 12 13

Weight on Lead Screw (lbs)

$$y = 3.921 - 0.196 w$$

Material - Aluminum  
Speed - 67 rpm



from its equation on Curve Sheet #3. Experimental points are shown on all three sheets to give an idea of the data spread.

The statistical estimate of variance for each set of tests is found in the experimental error term of each analysis of variance table. Inasmuch as the indices to be recommended by this investigation will be based on four replications, or tests under one set of conditions, the confidence limits, also a measure of the variability of the materials, were calculated for test points based on the average of four separate tests. The calculations are shown below. Results are compared on Curve Sheet #4.

Calculation of Confidence Limits...

$$\sigma^2 = \text{experimental error}$$

$$\sigma = \text{standard deviation}$$

Index value experimentally determined should fall within

$$\text{the } Y_c \pm \frac{t \sigma}{\sqrt{n}} \text{ range}$$

The value  $t$  was taken at the 1% probability level and depends upon the number of degrees of freedom assignable to the error term.

	$\sigma^2$	$\sigma$	$t$	$\pm \frac{t \sigma}{\sqrt{n}}$
Steel	0.19	0.44	3.05	0.67
Cast Iron	1.80	1.34	2.77	1.86
Aluminum	0.04	0.20	3.05	0.31

As can be observed from the comparative confidence limits of Curve Sheet #4, cast iron has by far the greatest variability. This would

Curve Sheet 4

Curves Showing Relative Spread of Confidence  
Limits of Test Materials

Material - S.A.E. 1020 Steel  
Speed - 169.6 rpm

Time of Drilling (minutes)

Time vs. Weight

8  
6  
4  
2

8

9

10

11

12

13

Weight on Lead Screw (pounds)

Material - Cast Iron  
Speed - 169.6 rpm

Time of Drilling (minutes)

Time vs. Weight

8  
6  
4  
2

8

9

10

11

12

13

Weight on Lead Screw (pounds)

Material - Aluminum  
Speed - 67 rpm

Time of Drilling (minutes)

Time vs. Weight

8  
6  
4  
2

8

9

10

11

12

13

Weight on Lead Screw (pounds)

naturally be expected from the physical nature of the metal which frequently includes widespread structural discontinuities. Steel, a much more homogenous substance having the added benefits of hot and cold working, exhibits noticeably smaller confidence limits. Aluminum, an almost pure metal, shows the smallest amount of variability.

F-tests, showing that the experimental error terms of all three materials were significantly different at the 5% probability level, were made. They are shown below.

Sample Calculation for Cast Iron and Aluminum

$$F = \frac{\sigma_{CI}^2}{\sigma_{Al}^2} = \frac{1.80}{0.04} = 45.0$$

TABLE XIV

Comparison of	df	F
CI and Al	27 and 12	45.0
CI and Steel	27 and 12	9.47
Al and Steel	12 and 12	4.75

All of the F values calculated were statistically significant at the 5% level. For this particular problem a two-tailed F distribution at the 2½% probability level was used.

The tests definitely prove that the variability of each of the test metals is different from each of the other metals.

TABLE XV

<u>Tabulation of Calculated Indices with their Confidence Limits</u>					
Materials	RPM	Weight	Time	<u>Confidence Limits</u>	
				Upper	Lower
Cast Iron	169.6	9	5.93	7.79	4.07
		10	5.33	7.19	3.47
		11	4.73	6.59	2.87
		12	4.13	5.99	2.27
		13	3.53	5.39	1.67
	110.0	9	10.22	12.08	8.36
		10	8.94	10.80	7.08
		11	7.66	9.52	5.80
		12	6.38	8.24	4.52
		13	5.10	6.96	3.24
Aluminum	67.0	9	2.16	2.47	1.85
		10	1.96	2.27	1.65
		11	1.77	2.07	1.46
		12	1.57	1.88	1.26
		13	1.37	1.68	1.07
Steel	67.0	9	10.34	11.01	9.67
		10	9.61	10.28	8.94
		11	8.88	9.55	8.21
		12	8.15	8.82	7.48
		13	7.42	8.09	6.75
	169.6	9	4.28	4.95	3.61
		10	3.94	4.61	3.27
		11	3.60	4.27	2.93
		12	3.26	3.93	2.59
		13	2.92	3.59	2.25

## CONCLUSIONS

The V.P.I. Machinability Testing Machine may very definitely be used to measure the quality machinability as defined by the time in minutes required to remove one quarter of a cubic inch of material for one inch of carriage travel. This statement is made with reference to a  $37/64$ " drill following a  $1/8$ " lead hole.

For the materials and conditions tested, a straight line relationship which can be defined by equation is existant. The inherent variability of each material can be shown by establishment of confidence limits for each linear regression line.

Machinability indices based on the above-mentioned equations plus and minus the calculated confidence limits may be set up.

## SUMMARY

The purpose of this thesis might be subdivided under two headings - modification of the testing machine so that it would be suitable for drilling tests and development of a standard drilling test for machinability which would employ the modified machine.

The first mission was accomplished by the substitution of a specimen-holder in the form of an angle iron for the tool holder already attached to the carriage. One other modification consisted of replacing the timing circuit of the machine with a 1 rpm indicator card mount which, together with a recording pen, gave a pictorial record of the progress of the drill through test specimens.

The second purpose of the investigation was fulfilled when the straight line portion of the machinability curve was found, proved, and defined by equation. Also of equal interest with regards to this machinability concept was the establishment of confidence limits showing the relative variability of the materials tested.

Perhaps the statement should be made that the exact values of these confidence limits depend on the number of test specimens being included in the index determination. The investigators based their calculations on a sub-group containing four specimens. This sub-group size was believed sufficiently high to detect any test equipment defect, such as a feather edge on the drill or an incorrectly set speed, without requiring an excessive number of drilling operations.

Although the index values calculated and listed in Table #13 are

correct for the materials tested, they are not recommended for general use since they are based on test specimens all coming from one source. A larger number of tests on specimens from a large number of foundries and steel mills would be necessary for a true estimate of the machinability of the test materials.

## RECOMMENDATIONS

1. A larger number of tests on materials from different foundries and steel mills should be run in order that an accurate estimate might be made of the linear regression lines and also of the confidence limits.
2. Tests should be run using speed and time at constant weights as a basis of an index.
3. A higher speed motor with a larger number of possible speeds should be substituted for the motor now powering the machine. A small d-c compound motor with a rheostat in the shunt field circuit and a tachometer attached to the drive would not only give higher speeds, but would also allow equal increments of increased speed. Equal increments are essential to the use of orthogonal polynomials if experimentation is to be carried on using speed as the main observed source of variation.
4. The effect of cutting fluids on the machinability of metals should be studied.
5. Indexes with their confidence limits should be established not only for the materials already tested, but also for other materials.

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## GLOSSARY OF SYMBOLS

- $\sigma^2$  = variance  $Y_c$  = calculated index
- $\sigma$  = standard deviation
- $N_1$  = 169.6 rpm
- $N_2$  = 67 rpm
- $N_3$  = 110 rpm
- $W_0$  = 7 pounds
- $W_1$  = 9 pounds
- $W_2$  = 10 pounds
- $W_3$  = 11 pounds
- $W_4$  = 12 pounds
- $W_5$  = 13 pounds
- SS = sum of squares
- MS = mean square
- df = degrees of freedom
- $y$  = individual test time in minutes for the removal of one quarter of a cubic inch of material with one inch of carriage travel.
- $c$  = orthogonal polynomials coefficients
- $n_r$  = number of replications
- $R_1$  = replication #1
- $R_2$  = replication #2
- $R_3$  = replication #3
- $R_4$  = replication #4
- $\Sigma SS$  = sum of all sum of square terms except the total and experimental error
- $t$  = "Student"  $t$
- $G$  = sum of all individual times for one complete set of tests

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