SENSING OF DRILL WEAR AND PREDICTION OF DRILL LIFE

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ABSTRACT

Drill life is found to be a strong function of the work material hardness ($L \alpha H^{-16}$). This strong dependence may account for the large variation in the life of the drills, which is observed in industrial conditions.

Torque, thrust and power are observed to be functions of drill wear. In the drilling of cast iron using H.S.S. drills (13/32" dia.) at 690 RPM (73 FPM max.) the following relations were observed:

$$\text{Torque } (M) = .125\, H_B d^2 f + .289\, H_B d^2 r + .0487\, H_B d^2 w \quad (3)$$

$$\text{Thrust } (T) = .325\, H_B df + .1242\, H_B dw + .755\, H_B dr + .0022\, H_B d^2 \quad (7)$$

where H_B = Brinell hardness of work material

d = diameter of the drill

f = feed per revolution

w = average flank wear

r = radius at the cutting edge (.5 10^{-3} in.)

(All above in consistant units)

Flank wear of a drill increases rapidly at the end of its life. Torque, thrust and power reflect this change and seem to be potential variables for on line sensing of drill wear in multiple tool machining.

Thesis Supervisor: Nathan Cook
Title: Professor of Mechanical Engineering

CONTENTS

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I dedicate this work to my parents, who always care for my progress and welfare.

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6. INTRODUCTION

Manufacturing industries comprise a major element of the economy and their productivity strongly influences domestic living standards and competitive positions in international trade. Metal cutting is a large segment of the modern manufacturing industries. Recently the productivity of metal cutting operations have been increased greatly due to large volume production made possible by multiple tool machining. Multiple tool machining is a system in which a number of cutting tools operate simultaneously. Transfer line machining is a typical example of multiple tool machining.

To attain maximum efficiency of these lines, management and the machine tool operator alike should have accurate information available instantly. For example, the management should be informed of the exact life of a cutting tool, while the operator needs to know the exact condition of the tool that is operating. The information must be presented in a manner that is practical for the existing conditions. The situation is made to order for a computerized monitoring and reporting system programmed to anticipate potential down time. Down time is the non-productive idling of the machining system and it directly affects the efficiency of utilization of the system. The down time of a typical transfer line varies from 25 to 30% of the potential available time for operation(1) and the down time due to cutting tool failure is about one third that of the total down time(2). With proper means for sensing the tool condition, a computer based monitoring system should be able to reduce the down time due to tool failure significantly.

Drilling operations are a major component of multiple tool machining systems. Application of transfer line techniques to cylinder block and bearing cap production is very common and drilling holes is a major operation in these machining functions. For example it appears that materials represent about 50 percent of the costs of building a tractor, but 50 to 80 percent of the total chip making dollars are spent on making holes(3). Hence, it is proper to look at possible ways of sensing drill wear and to make an attempt to predict drill life, so that any monitoring and information processing system can be coupled to a tool wear sensing system to provide the necessary information for drill replacement at the right time and hence reduce tool breakage, non-programmed stoppage of the machine and avoid long tool change times.

The intent of this work is (a) to consider several variables and to determine their adaptability for drill wear sensing, (b) to be able to predict these variables as functions of tool wear and (c) to study the influence of work piece hardness on tool life. This information is presented in the following sections:

(9) Tool life vs. work piece hardness;

(10) Relationship between Torque, Thrust and Power and Flank wear of a drill;

(11) Torque, Thrust and Power as variables for drill wear sensing.

This work has been carried out under the "FIAT Project - Portable Monitor Development Program", administered by the Charles Stark Draper Laboratory, Massachusetts.

7. LITERATURE REVIEW

In order to optimize the production process, it is necessary to determine the optimal time to remove and regrind the individual tools. If a tool is removed and reground prematurely, excessive labor and machine idle time costs are incurred. On the other hand, if the cutting tool is allowed to become too dull, then unnecessary spoilage and greatly accelerated tool wear are incurred.

Presently there are several strategies employed for changing the cutting tool. One of the most common methods is to replace the tool after a predetermined number of parts. This method has led to considerable difficulties due to a wide spread in tool life observed in industrial conditions. It is not uncommon for a tool to wear out at such a high rate that premature breakage of the tool is encountered. The complexity of this case can be imagined when a programmed sequence of tool replacement (after every 1300 pieces) is adopted for a system in which 10 drills are operating simultaneously. From experimental data, gathered in an industrial transfer line, it was observed that the drills operating on a typical machining head failed after machining between 500 holes and 5000 holes with a median value of about 1800 holes(2).

One method of detecting tool wear is based on a detailed analysis of the vibration pattern produced by a cutting head, as it cuts the material. This vibration pattern changes form as the tools become dull and the problem therefore, is to determine and analyze these changes that predict tool wear. In this method, a machining system is calibrated for its vibration pattern with a new or sharp cutting tool, and thus a "tool signature" is obtained. The variations in the subsequent vibration pattern from the "tool signature" is determined by a continuous spectral analysis and gross changes are taken as manifestations of the wear of the tool.

Another method used for tool wear detection senses sonic vibrations or sound produced during the metal cutting operations(5,6). The vibration pattern or wave form is generally a very complex signal composed of many frequency components of varying amplitude. The changes that occur in the wave form, as the cutting head becomes dull, are usually subtle and consist of changes in both frequency and amplitude. Their complexity increases further when more than one tool is operating at a time. It is felt that the tools which are replaced at the times determined by these methods have a significant portion of their lives remaining and are probably removed too soon. Again, in multiple tool machining, these methods can indicate possible tool wear but can not identify the individual tool that is excessively worn.

Drill wear is a complex phenomenon and depends on many variables such as tool geometry, eccentricity, etc. in addition to the independent variables like hardness of the work piece, speed and feed rate of machining(7).

Any effort in tool wear sensing consists of monitoring one or more of the external manifestations of the progressive dulling of the tool. These can be broadly classified as:

(a) Manifestations on the tool: which consist of different wear measurements such as flank wear, crater wear, etc.

(b) Manifestations on the work piece: change in diameter, ovality of the hole, burr at the exit and entry side of the hole, etc.

(c) Manifestations at the tool - work interface: cutting forces and the associated torque or power, cutting temperatures, etc.

(d) Other manifestations like machine tool vibration, audible noise produced, etc. Usually the noise produced at the end of tool life is described as "screeching".

Attempts have been made to relate changes in the cutting forces during the beginning of cut and the end of cut or dwell(8). As early as 1956, it was pointed out in one work(9) that a dull drill exerts large thrust and requires large torque to drill a hole.

Tool life is the period of economical use of a tool and differs from Tool wear. However, the two are closely connected. It is the extent of wear on the tool that determines whether a tool has reached the limit of its economical life or not. As mentioned earlier, drill life varies greatly, but there has been very limited testing under "industrial" conditions. Drill life on repeated grinds is a function of thermal history of the drill during its previous tool life, the grinding practice used, and the point geometry and the accuracy of the geometry. Drill life is also affected by the nature of the operation--blind hole, through hole on cast surface, through hole on milled surface, intersecting holes, angle of entry, bushing location, coolant application, etc. Many, but not all studies of drill life in high volume production show a chi-square distribution, rather than the expected normal distribution(10). There is also a great variation in drill quality from one manufacturer to another. In tests conducted on drills from 14 different vendors, the drill life from best to worst was of the order of 2 to 1 in the number of holes drilled.

Machine condition, including the condition of spindle bearings and of the drill locating surface affect drill life. A method of grinding the tool tip called "radial point grinding" has increased the drill life phenomenally, on the order of 14 times(11). In addition to the above mentioned variations, the change in hardness of the work piece must be considered. Castings are very common for twist drill applications and a variation of 25 to 30 Brinell points is considered good in such cases. Tests conducted at an industrial plant(2) showed that work piece hardness explained half the variation in tool life, despite the presence of significant variations in many of the variables listed above. Another factor which has a significant impact on tool life is known as work piece softening(12). A work piece which softens at elevated temperatures was observed to give longer tool life than one which has higher hot hardness.

We have seen earlier that cutting forces on a dull tool are larger than those on a sharp tool. If the variations of these forces with the wear on the drill is to be quantitatively predicted, a knowledge of the cutting forces on a sharp tool must be obtained. Several attempts have been made to predict the cutting forces in drills. A simple, semi-empirical approach has been developed by Cook(13). Williams(14) has shown that the cutting action of a drill can be modeled by considering three different zones: (a) primary cutting action of the lips, (b) secondary cutting action of the chisel edge and (c) the extruding action of the chisel edge. It is found in practice that the drilling process is so complicated that a simple model can predict the forces and the torque as well as those models which appear to be more rigorous. We shall adopt the previous approach in our latter analysis.

8. EXPERIMENTAL PROCEDURE

All of the experiments were carried out using 13/32" diameter, 6-1/2"long (9" over all length) H.S.S. drills at a fixed speed of 690 rpm. (See figure 1). The drills used were identical to those used in the machining center of FIAT Co., Italy. A vertical milling machine was used as an experimental drilling machine. A standard slip bushing was held on a bushing holder and was mounted on the vertical slide of the milling machine frame. The bushing was used to guide the drill and was located 1/4" (approximately half the diameter) above the work surface (Figure 2). All of the holes drilled were 1" deep.

Material preparation:

The workpiece material was Meehanite cast iron, of grade A, of the composition shown in Table 1. The cast iron was obtained as round-stock, 8" in diameter, 12" long and was sectioned into discs of 1-1/2" thickness. The average hardness of this cast iron was found to be 175 BHN, but varies as shown in Figure 3.

To obtain different hardness values, the cast iron was heat treated. The heat treatment cycle, as shown in Figure 4, consists of a gradual heating of the cast iron disc to a hardening temperature T_h(1600°F) followed by retention at this temperature for two hours per inch of thickness. The disc is then quenched in an oil bath. The average hardness of the quenched specimen, after following this procedure, was about 45 Rc. The quenched specimen was then tempered in order to obtain the required hardness. This required a knowledge of the tempering temperature (T_t) for the required hardness. The T_t versus hardness curve was obtained after repeated trials and the result is shown in Figure 5.

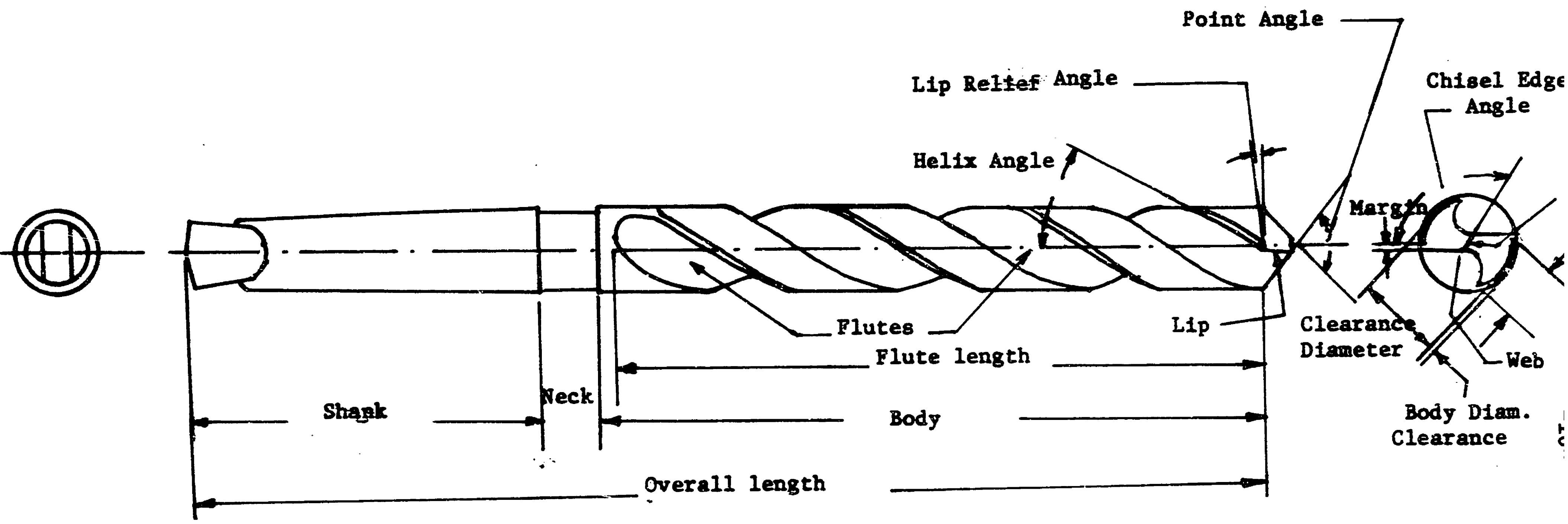
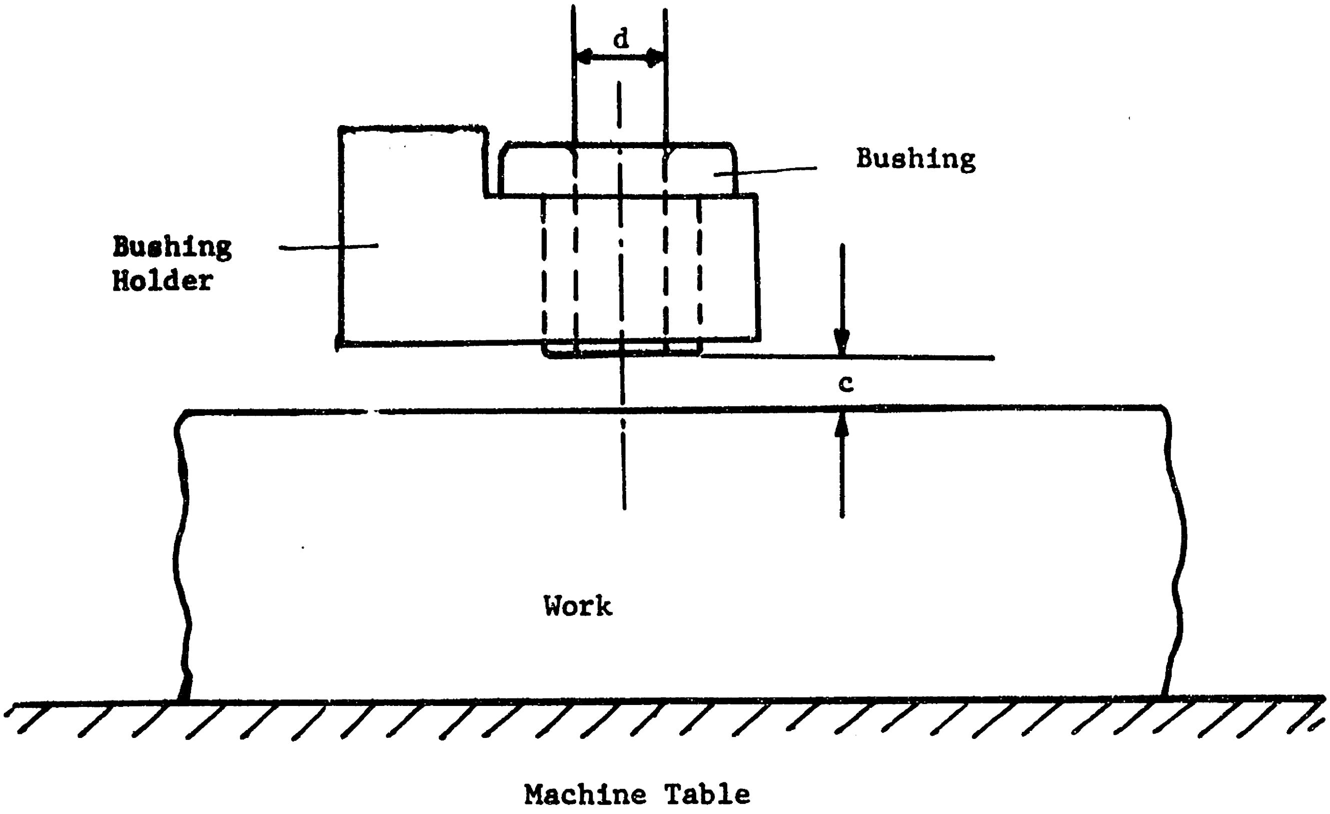


Figure 1. Twist Drill Nomenclature



c = clearance (approximately equal to d/2)

Figure 2. Schematic Diagram Showing the Position of the Drill Bushing.

TABLE I.

Composition of ASTM No. 25 (Heavy) Gray Cast Iron

Commercial Specification:	Grade A Meelanite C.I.
Carbon	3.00 - 3.30%
Silicon	1.90 - 2.20%
Phosphorous	.15 - .25%
Sulphur	.08 - .12%
Manganese	.50 - .80%
Carbon equivalent	3.82%

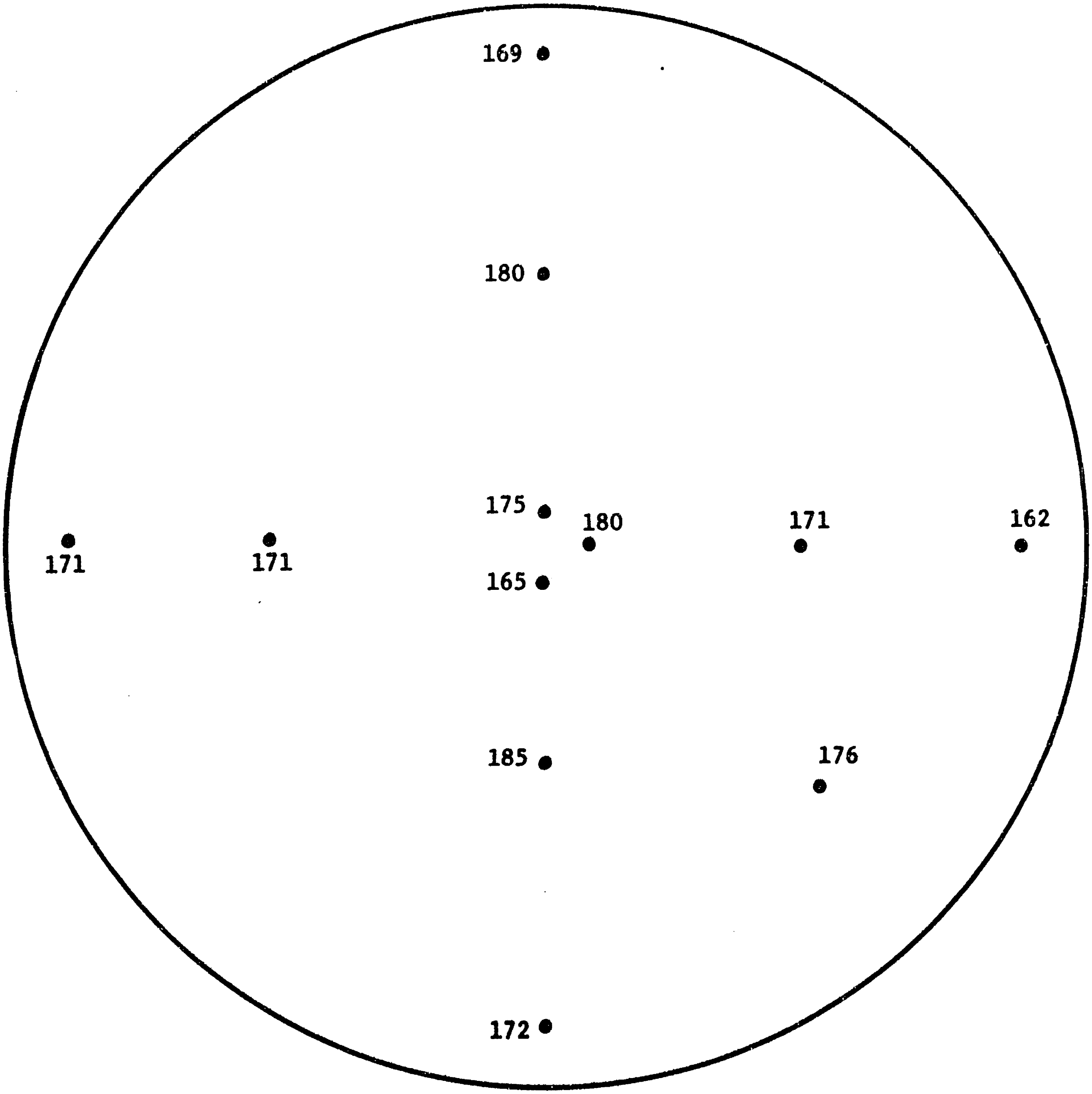
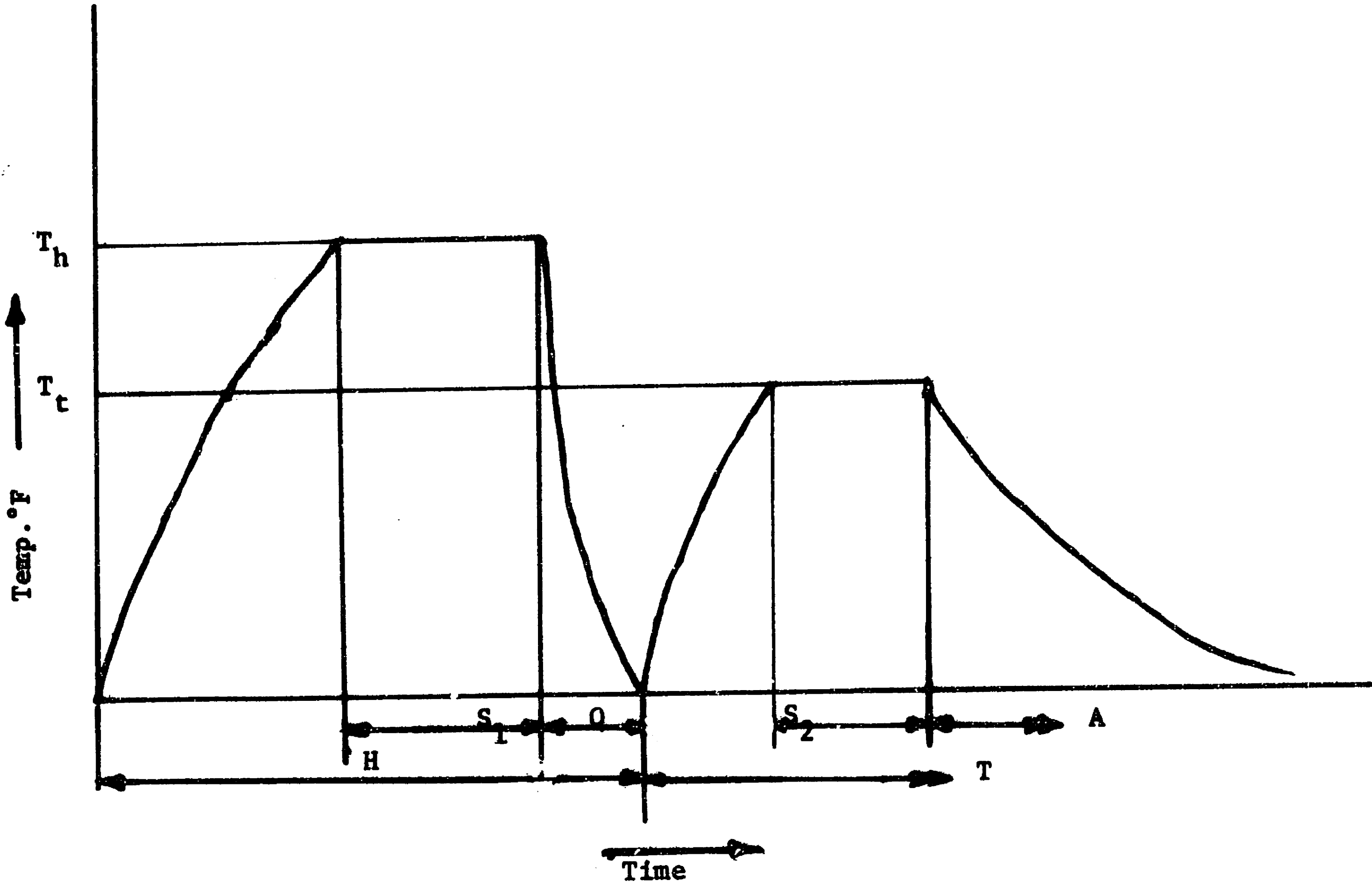


Figure 3. Typical Variation of the Hardness Across the Section of the Cast Iron Work Material



H = Hardneing

T = Tempering

S_1 = Soaking (2 hrs/inch thickness)

Q = Oil quench

S_2 = Soaking (1 hr/inch thickness)

A = Air cooling

T_h = Hardening temperature

T_t = Tempering temperature

Figure 4. Heat Treatment Cycle

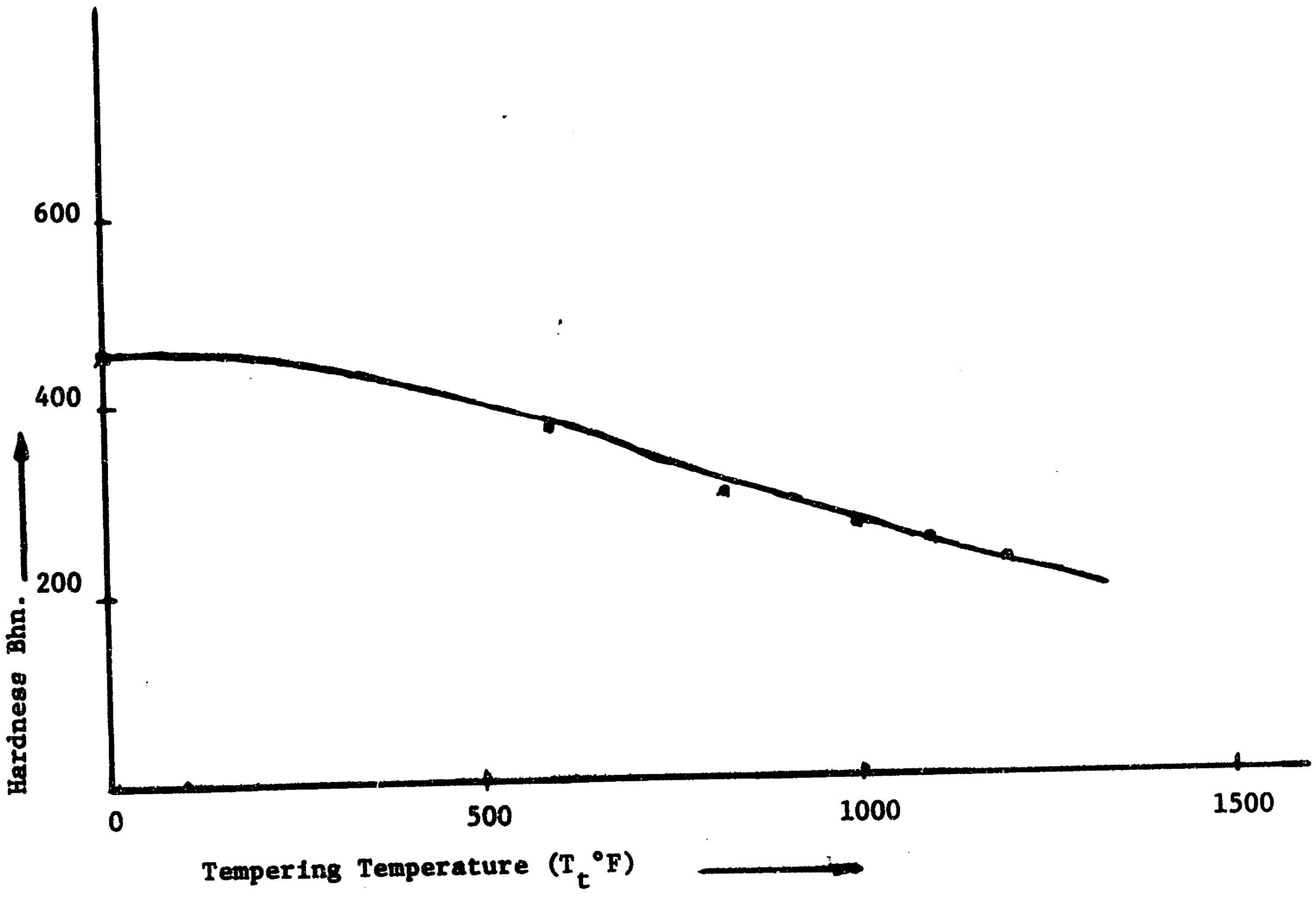


Figure 5. Tempering Temperature Vs. Hardness

Having obtained the above curve, work material of different hardness values was obtained by tempering the quenched specimens at the required temperature. The surfaces were machined down by 1/16" and a series of hardness measurements were made. The average hardness was chosen to represent the material. In general, the variation in hardness over the specimen was about 30 Bhn across and about 15 Bhn along the thickness.

Measurement methods:

To measure torque and thrust, a drilling dynamometer was used. The dynamometer employed temperature-compensated semi conductor strain gages. The principle of operation of this dynamometer is that the resistance of the strain gage elements vary in proportion to the strain which it is subjected to. By a suitable disposition of strain gages, torque and thrust can be measured independently(17). "Thrust" is the vertical compressive force experienced by an advancing drill. "Torque" is the moment required to twist the drill during the cutting operation. A view of the dynamometer in operation is shown in Figure 6. The dynamometer was calibrated using dead weights. The output of the dynamometer was recorded on a two channel Sanborn strip chart recorder.

The power input to the drive motor of the machine was measured using a 3-phase Wattmeter, hooked on to the line between the main switch and the input connection to the drive motor. The Wattmeter in position is shown in Figure 7.

The burr on the edge of the hole, at the entry side of the drill, was measured using a cylindrical pin, with a relieved square collar, in conjunction with a height gage. The measurement system is shown in Figure 8.

Figure 6. Drilling Dynamometer in Use

Figure 7. Wattmeter for Power Measurement

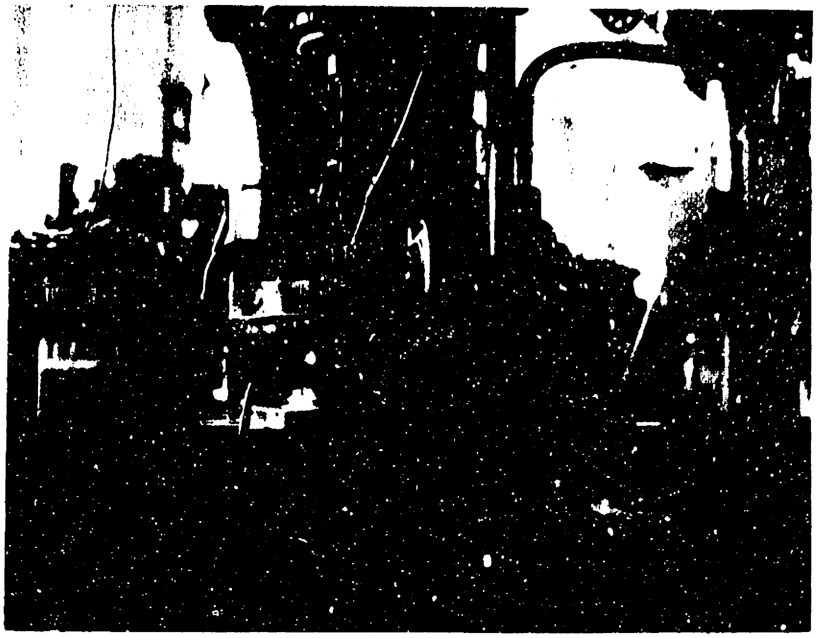


Figure 6. Drilling Dynamometer in Use

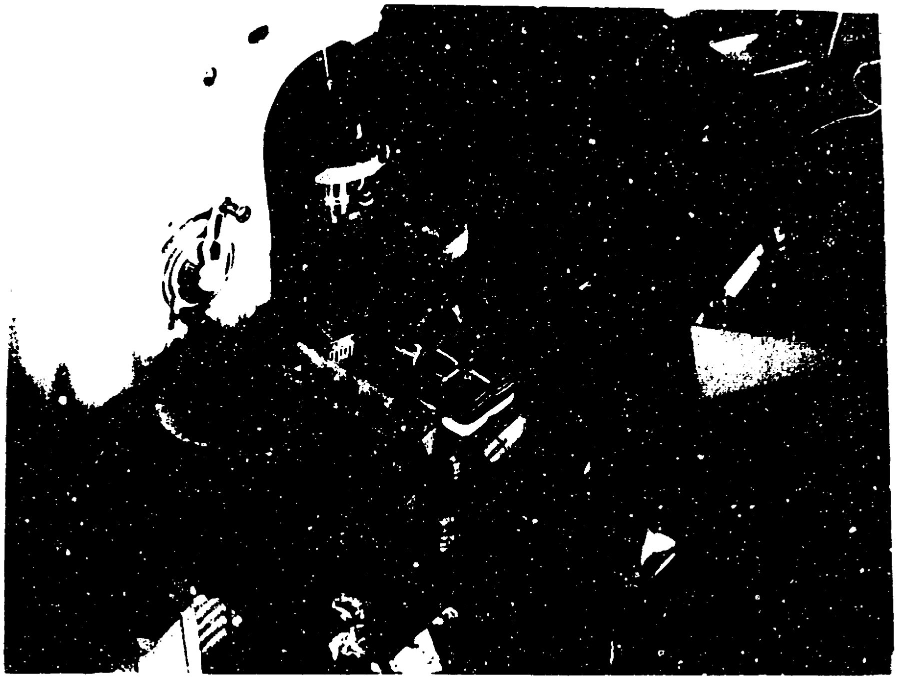
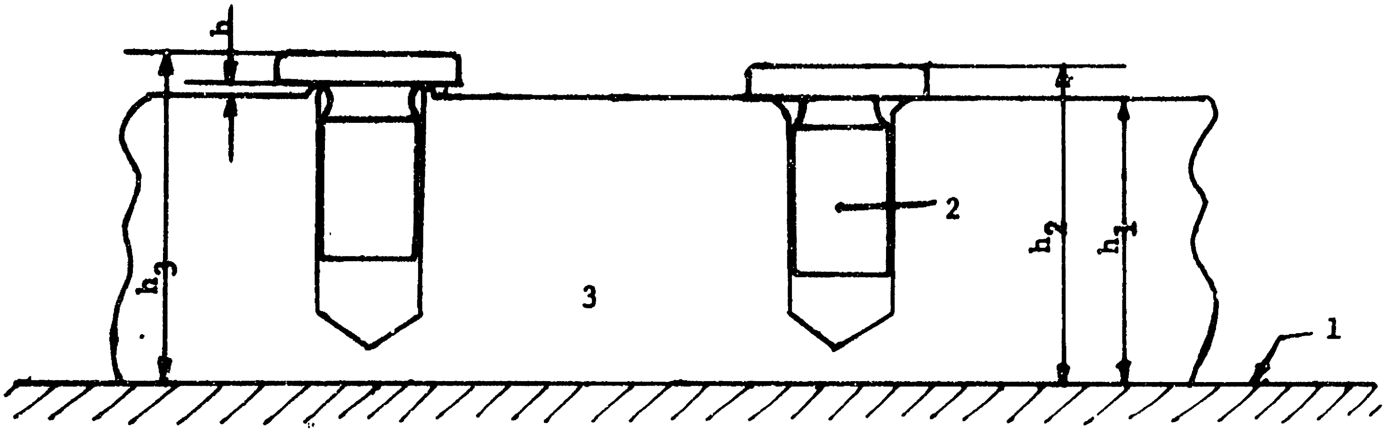


Figure 7. Wattmeter for Power Measurement



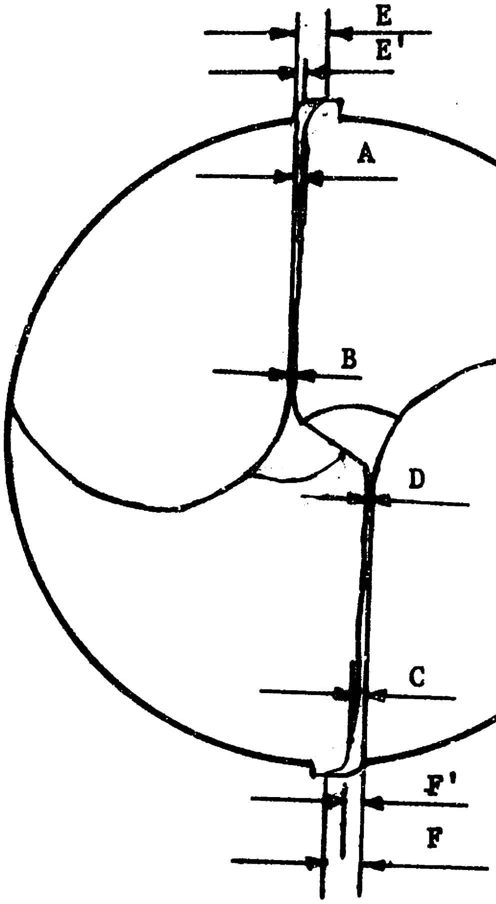
Burr height (h) = $(h_3 - h_2)$

1. Surface plate
2. Measuring Plug
3. Work piece

Figure 8. Burr Measurement

The wear on the flank or clearance side of the tool is known as flank wear. The drill was held vertically with a C-clamp and the different wear measurements were made on the flank, using an optical microscope at 5X magnification. The drill was always located in the same direction, using the lettering in the shank, so that the successive wear measurements refer to the same cutting edge. The different wear measurements are shown in Figure 9.

It appears that the tool tip becomes magnetized in the wear zone. To test this possibility the induced e.m.f. produced by oscillating a coil in the magnetic field of the drill was measured, using an oscilloscope. The measuring system is shown in Figure 10.



$$\text{Average Flank Wear} = \frac{A + B + C + D}{4}$$

$$\text{Average Corner Wear} = \frac{E + F}{2}$$

$$\text{Average Corner Loss} = \frac{E' + F'}{2}$$

Figure 9. Wear Measurements

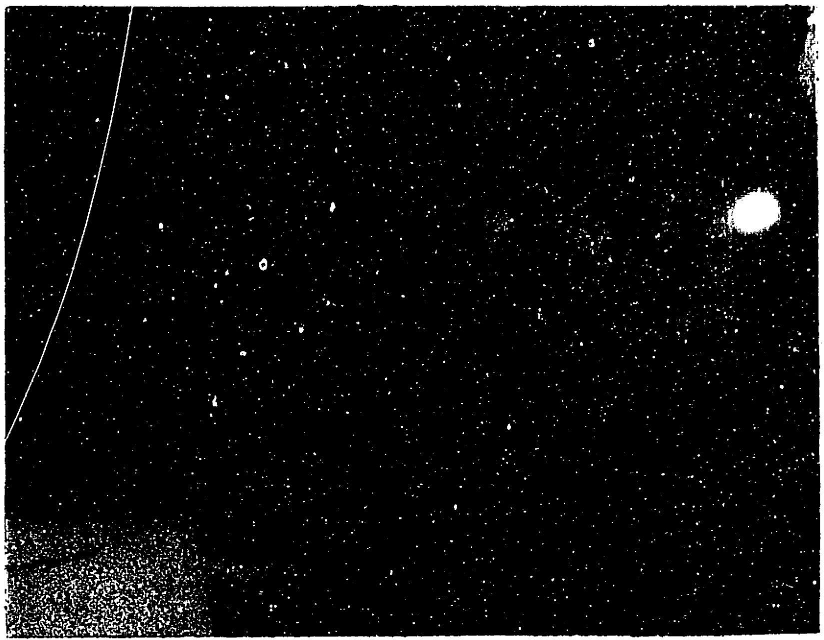


Figure 10. Induced e.m.f. Measurement

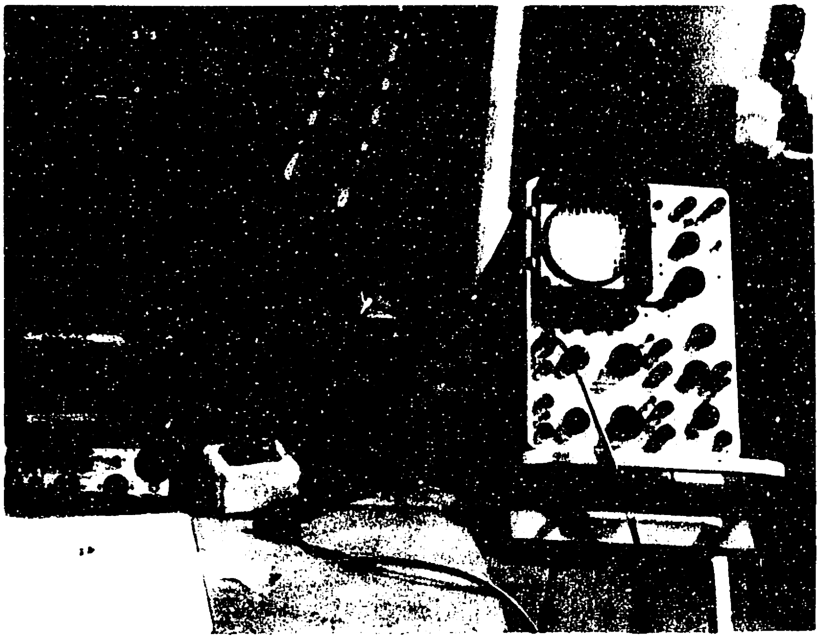


Figure 10. Induced e.m.f. Measurement

9. DRILL LIFE VS. HARDNESS OF WORK MATERIAL

To study the influence of workpiece hardness on drill life, the following set of experiments was carried out. Workpieces of different hardness values were produced. One drill was run at each hardness value until the tool failed. Failure of the tool was considered as the end of useful life of the drill. Failure of the drill was determined when the tool "labored" and would not produce a hole. Allowed to presist in this condition, the drill will be destroyed by irregular chipping along the cutting edges. The result of this experiment is shown in Figure 11. The result plotted on log-log paper shows a slope of approximately 1/16". In other words, a very strong relationship ($L \alpha H^{-16}$) between tool life and hardness is indicated. This relationship could explain the large variation in drill life under industrial conditions. Consider for example industrial castings varying in hardness from 180 to 220 Bhn being machined by a drill. The upper and lower limits of drill life can be placed at 10,000 and 400 holes. While this estimate is subject to experimental errors, the great influence of hardness can be realized. In other words, the effect on drill life of an occasional workpiece of high hardness is greater than the effect of a much larger number of holes drilled in a generally softer work material. In fact, tests made at the FIAT machining center in Italy show an exponent of hardness of about -12.

It may be noted that tool life has been shown to depend on the temperature (θ) at the interface, according to a relation such as $L \alpha \theta^{-12.6}$ [13]. It is also known that temperature rise varies essentially proportionally with hardness. Thus the observed variation of life with hardness ($L \alpha H^{-16}$) most likely reflects the variation of cutting temperature with hardness.

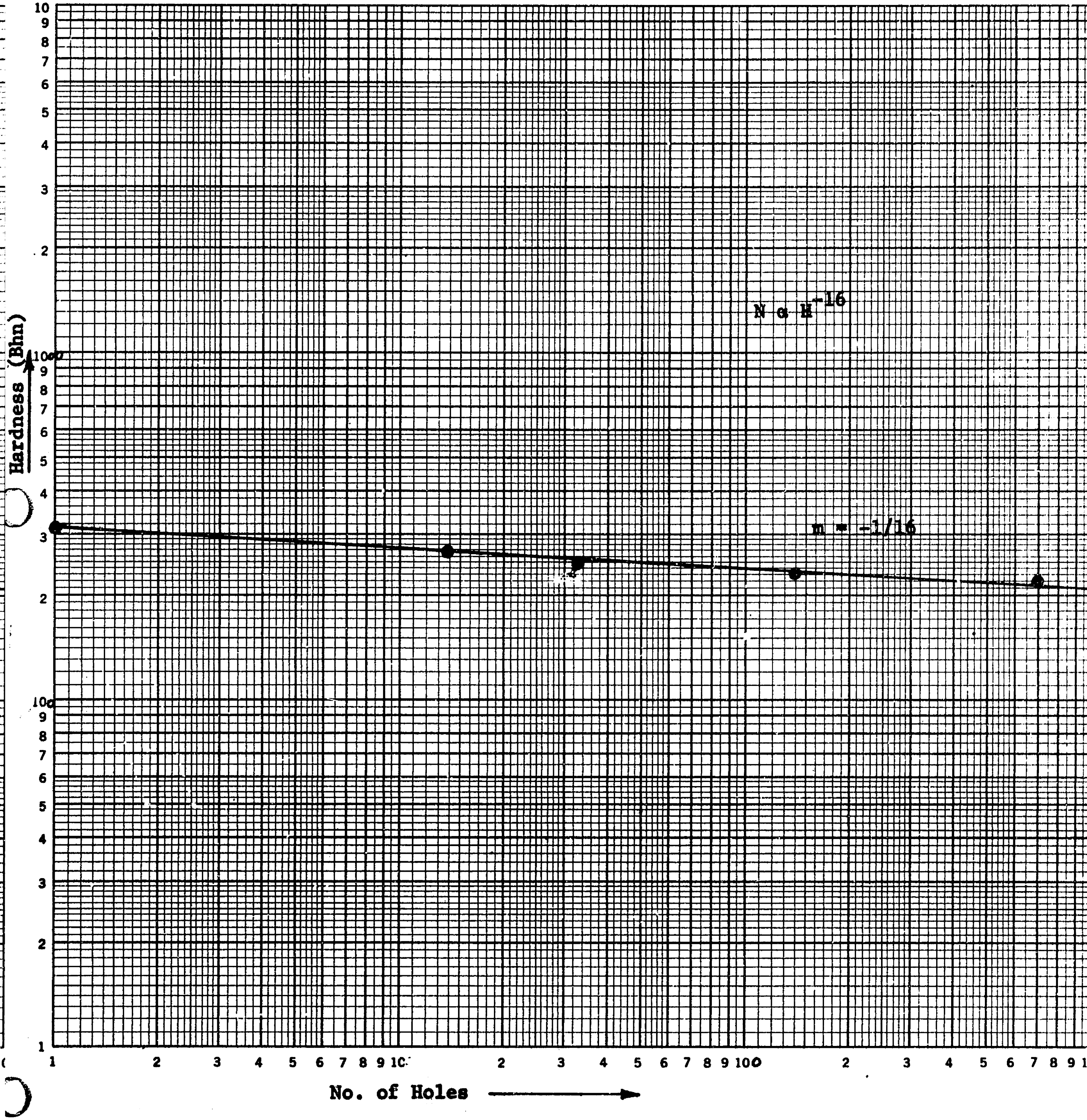


Figure 11. Tool Life Vs. Hardness

10. PREDICTION OF TORQUE, THRUST AND POWER AS A FUNCTION OF FLANK WEAR OF A DRILL

Since, in practice the geometry of cutting is often complex, most metal cutting research has dealt with the simplest type of cutting--called orthogonal cutting--in which the direction of relative work-tool motion is at right angles to the cutting edge of a wedge-shaped tool. Such a simple model of metal cutting is shown in Figure 12. The contact zone between tool and work may be divided into three main regions:

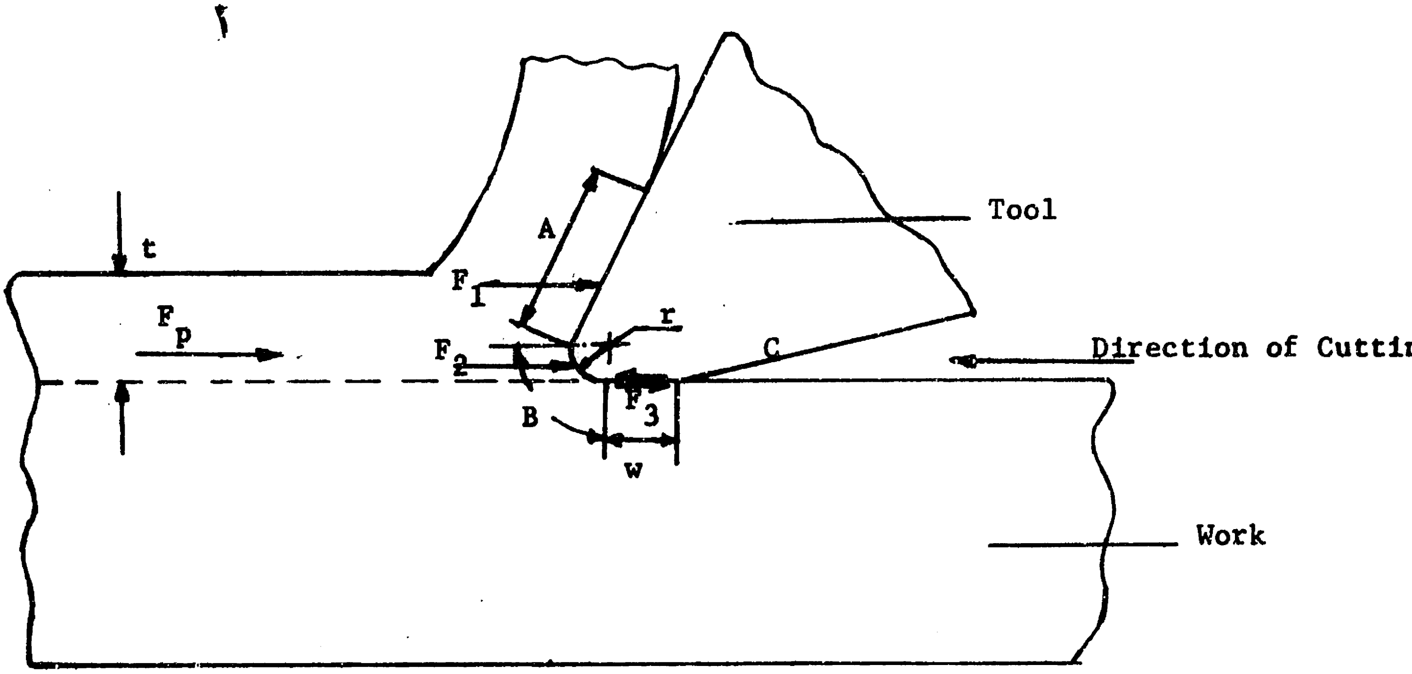
(a) The rake face of the tool which contacts the chip and transmits most of the force (F_1), necessary to perform the cutting action.

(b) The non-zero radius of the tool cutting edge (the transition surface between the rake and flank faces) which contacts the work material at the point where the chip and work separate. This edge radius causes an "indenting" force (F_2). The non-zero intercept observed for zero feed on a cutting force versus feed rate plots may be attributed to this effect.

(c) An area on the flank face having 0° clearance, known as the flank "wear band" which rubs against the work surface. The shear stress between the flank and the workpiece has been determined to be approximately equal to the work material yield shear stress (T_y).(18) The shear force caused by the flank wear is termed F_3.

From Figure 12, the component of the resultant force in the direction parallel to the direction of tool travel is then,

$$\begin{aligned} F_p &= F_1 + F_2 + F_3 \\ &= U_c \cdot b \cdot t + H_B \cdot r \cdot b + T_y \cdot W \cdot b \qquad (1) \end{aligned}$$



A = Rake face contact length

B = Edge roundness

C = Flank face

F_1 = Cutting component of force F_p

F_2 = Indentation or edge component of force F_p

F_3 = Shear component of force F_p

F_p = Total edge cutting force component parallel to cutting velocity

$= F_1 + F_2 + F_3$

t = Depth of cut

w = Wear land

b = Width of cut (perpendicular to page)
r = Edge radius

Figure 12. Single Point Cutting Tool

where,

U_c = energy per unit volume for cutting with $r = w = 0$

H_B (the Brinell hardness of the work material)$^{(13)}$

b = width of cut

= width of the cutting edge of the tool

r = radius at the edge of the tool (not "nose radius")

t = depth of cut (undeformed chip thickness)

w = flank wear

T_y = yield shear stress of the work material

$\frac{H_B}{6}$

(Note: all above are in consistant units).

For a drilling operation Figure 13 shows the power forces (F_p) acting on the cutting edges. The torque applied on the drill is

$$M = F_p \cdot \frac{d}{2} \tag{2}$$

where, d = diameter of the drill. For a drilling operation, the following substitutions can be made:

$$b = \frac{d}{2 \cos \alpha_p}$$

$$t = (f/2) \cdot \cos \alpha_p$$

where, f = feed per revolution

$$\alpha_p = 90 - \frac{\text{point angle}}{2} \quad \text{(see fig. 13)}$$

$$= 31°$$

w = average flank wear

Substituting eqn. (1) in eqn. (2) with the specified modifications, we get

$$M = H_B \frac{d}{2 \cos\alpha_p} \cdot \frac{f \cdot \cos\alpha_p}{2} + H_B \cdot r \cdot \frac{d}{2\cos\alpha_p} +$$

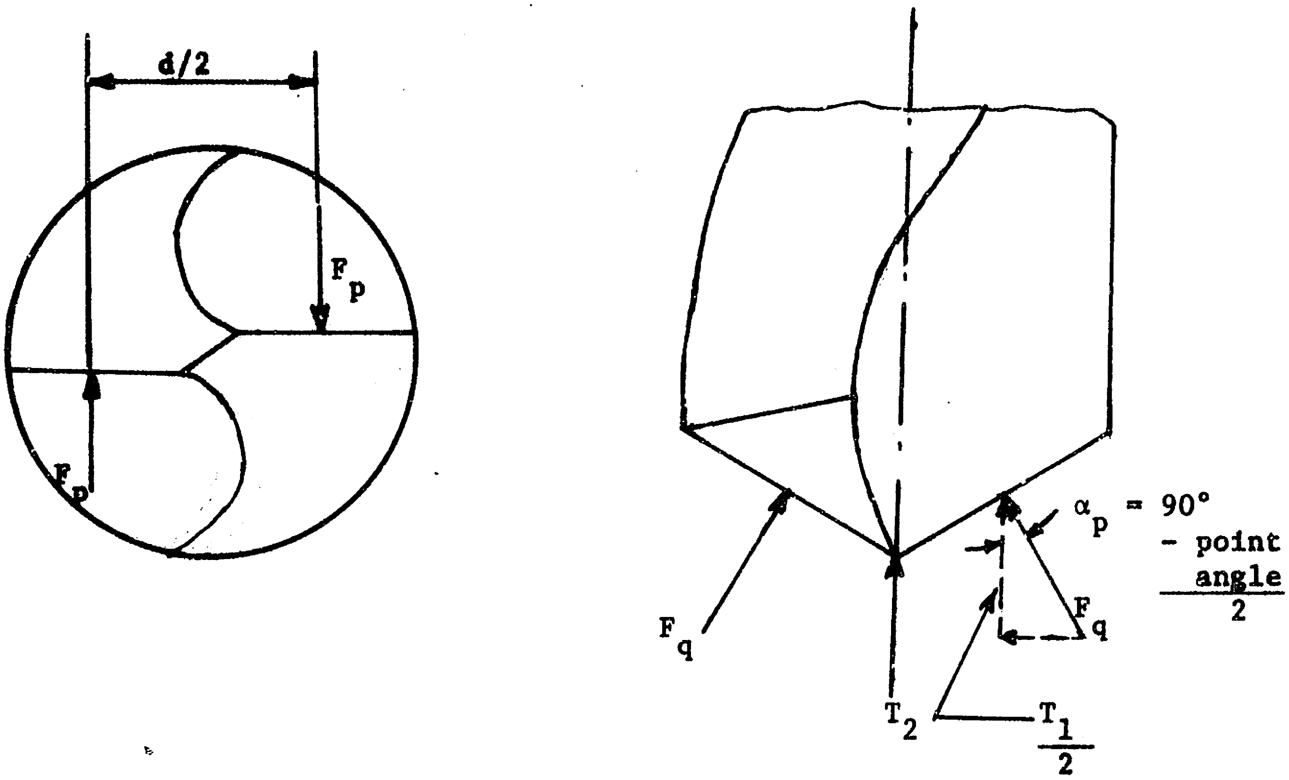


Figure 13. Cutting Forces Acting on a Drill

$$= \frac{H_B d^2 f}{8} + \frac{H_B d^2\ r}{4\ \cos\alpha_p} + \frac{H_B d^2 w}{24\ \cos\alpha_p}$$

$$= .125 H_B d^2 f + .289 H_B d^2 r + .0487 H_B d^2 w \qquad (3)$$

Hence if we measure the drilling torque using drills having different extents of flank wear, at different feed rates and using work material of different hardness values then a linear regression analysis can be made of the form,

$$M = P\,(H_B \cdot f) + Q(H_B \cdot w) + R(H_B) + S \qquad (4)$$

where P, Q, R are the regression coefficients and S is the error term approximately equal to zero if eqn. (3) is valid. Further it should also be true that,

$$\frac{P}{(d^2/8)} = 1$$

$$\frac{Q}{(d^2/24\cos\alpha_p)} = 1 \qquad (5)$$

$$\frac{R}{(d^2/4\ \cos\alpha_p)} = r$$

To test the validity of this model, a set of experiments were carried out. Drills obtained from an industrial plant were used for these testing purposes. The drills used were taken out of service after producing a specified number of holes. The drills used were taken from the same location on the machining head. The data obtained are shown in Table 2. A multiple linear regression was made using eqn. (4). The result is shown in Appendix (1). The regression equation obtained is:

$$M = .0169\,(H_B f) + .00885\,(H_B w) + .193 \times -10^4 (H_B) - 1.5$$

(d = diameter of the drill (13/22")).

Referring to equations (4) and (5) it can be seen that,

$$\frac{P}{d^2/8} = \frac{.0169}{.0206} = .820 \approx 1.0$$

$$\frac{Q}{(d^2/24\cos\alpha_p} = \frac{.00885}{.00793} = 1.115 \approx 1.0$$

$$\frac{R}{(d^2/4\cos\alpha_p} = \frac{.193 \times 10^{-4}}{.0475} = .407 \times 10^{-3} \approx .4 \times 10^{-3} \text{ inch}$$

S = the error term

= 1.5 (or) approximately 2.4% of the mean torque.

Hence, an equation of the form (3) can be used for determining the torque of a drill at different stages of its flank wear. It can be noted here that the edge radius is about half a thousandth of an inch, which is normally expected to exist between the intersection of any two surfaces.

The thrust force for a drill can be estimated from the following relations:

$$T = T_1 + T_2 \qquad (6)$$

$T_1 = 2 \cdot Fq \cdot \cos\alpha_p$ (See Fig. 13).

It is estimated that a probable value of $F_p / F_q = 0.5$ to 1.0 (13)

or $F_p \approx 0.75 \times F_q$

$$\alpha_p = 90° - \frac{\text{point angle}}{2}$$

For a standard point angle of 118°,

$\alpha_p = 31°$ and

$\cos\alpha = 0.864$

Therefore,

$$T_1 = 2 \times .864 \times .75 \times F_p$$

$$= 1.3F_p$$

To a first order of approximation, the extruding action of the chisel edge can be represented by a force $T_2 = .0022H_Bd^2$ (13). Then the thrust force

$$T = T_1 + T_2$$

$$= 1.3F_p + .0022d$$

$$= 1.3 \frac{H_B \cdot d \cdot f}{4} + \frac{H_B \cdot d \cdot w}{12 \cos\alpha_p} + \frac{H_B \cdot d \cdot r}{2 \cos\alpha_p} + .0022H_Bd^2$$

$$= .325 H_Bdf + .1242 H_Bdw + .755 H_Bdr + .0022 H_Bd^2 \qquad (7)$$

The measured force and the actual force are compared in Figure 14, using a value of $r = .0004$. It is seen that the estimated thrust is very close to the measured values.

Empirical Model

Based purely on empirical observations it is possible to estimate the torque, thrust and power in a drilling operation:

Consider an orthogonal cutting operation as shown in Figure 12. For simplicity let us assume that the edge radius (r) is zero. Then the edge cutting force

$$F_p = Ubt + T_w \cdot w \cdot b \qquad (8)$$

as shown in the previous section with

T_w = shear stress on the wear land.

Empirically it is observed that

$U = H_B$ (hardness of the work material).

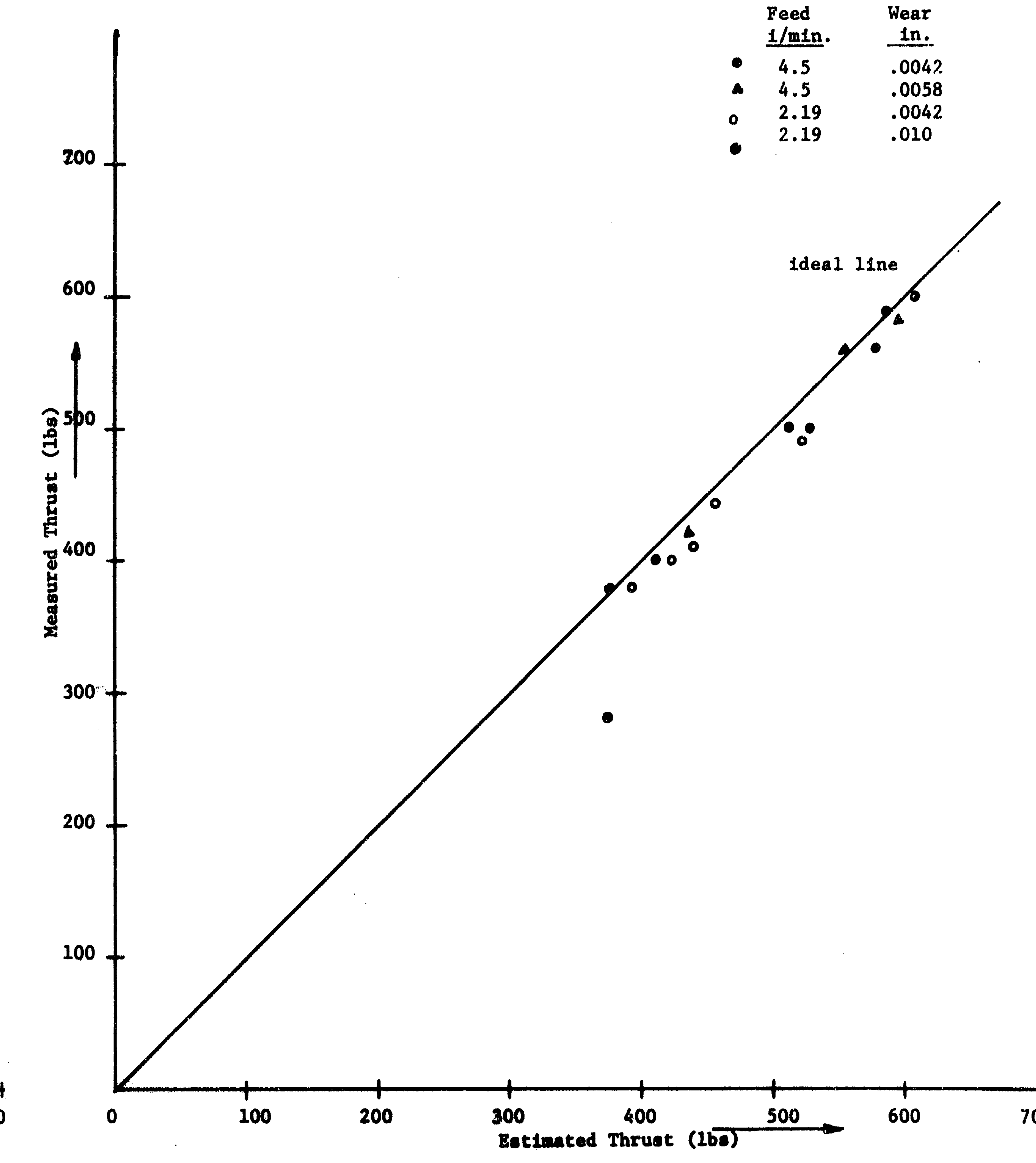
It is also known that (19)

$U = f(t^{-.2})$ and

TABLE 2.

Torque, Thrust and Power Measured by Varying Hardness, Flank Wear and Feed Rate

No.	Hardness (Brinell)	Feed (i.p.m.)	Wear (.001")	Thrust (lbs)	Torque (in lbs)	Power (watts)
1	230	4.5	4.2	500	50.0	720
2	248	4.5	4.2	560	52.5	680
3	257	4.5	4.2	590	57.5	760
4	267	4.5	4.2	600	65.0	800
5	180	4.5	4.2	400	60.0	600
6	230	4.5	5.8	560	65.0	720
7	248	4.5	5.8	580	62.5	760
8	180	4.5	5.8	420	50.0	640
9	230	2.19	4.2	380	37.5	-
10	248	2.19	4.2	400	37.5	440
11	257	2.19	4.2	410	41.0	460
12	267	2.19	4.2	445	41.0	480
13	305	2.19	4.2	490	-	-
14	180	2.19	10.0	280	50.0	400
15	248	2.19	10.0	500	52.5	800
16	230	2.19	10.0	380	50.0	1000
17	180	9.875	4.6	480	62.5	1520
18	230	9.875	4.6	540	69.0	1880
19	248	9.875	4.6	1310	110.0	2040
20	257	9.875	4.6	1960	150.0	2160



Material

Tool: H.S.S.
Work: Cast Iron
d = 13/32"
N = 690 R.P.M.

$$\frac{U}{T_w} = A(t/w)^{-.2} \quad (9)$$

Substituting (9) in (8) we get

$$F_p = Ubt + c \cdot U\ (t/w)^{.2}\ wb$$
$$= Ub \quad t + c \cdot t^{.2} w^{.8}$$

Proceeding as in the previous section we obtain

$$\text{Thrust force} \quad (T) = H_B d\ (Af + Bf^{.2} w^{.8} + cd) \quad (10)$$

$$\text{Torque} \quad (M) = H_B d^2\ (Af + Bf^{.2} w^{.8}) \quad (11)$$

$$\text{and} \quad \text{Power} \quad (P) = H_B d^2 n\ (Af + Bf^{.2} w^{.8}) \quad (12)$$

Using the data shown in Table 2, a multiple linear regression was performed, using equations (10), (11) and (12) and the results are shown in Appendix II. It is observed that the "Squared variation from the mean" explained in the case of thrust, torque and power are 68%, 75% and 94% respectively.

Hence, empirically it can be stated that thrust

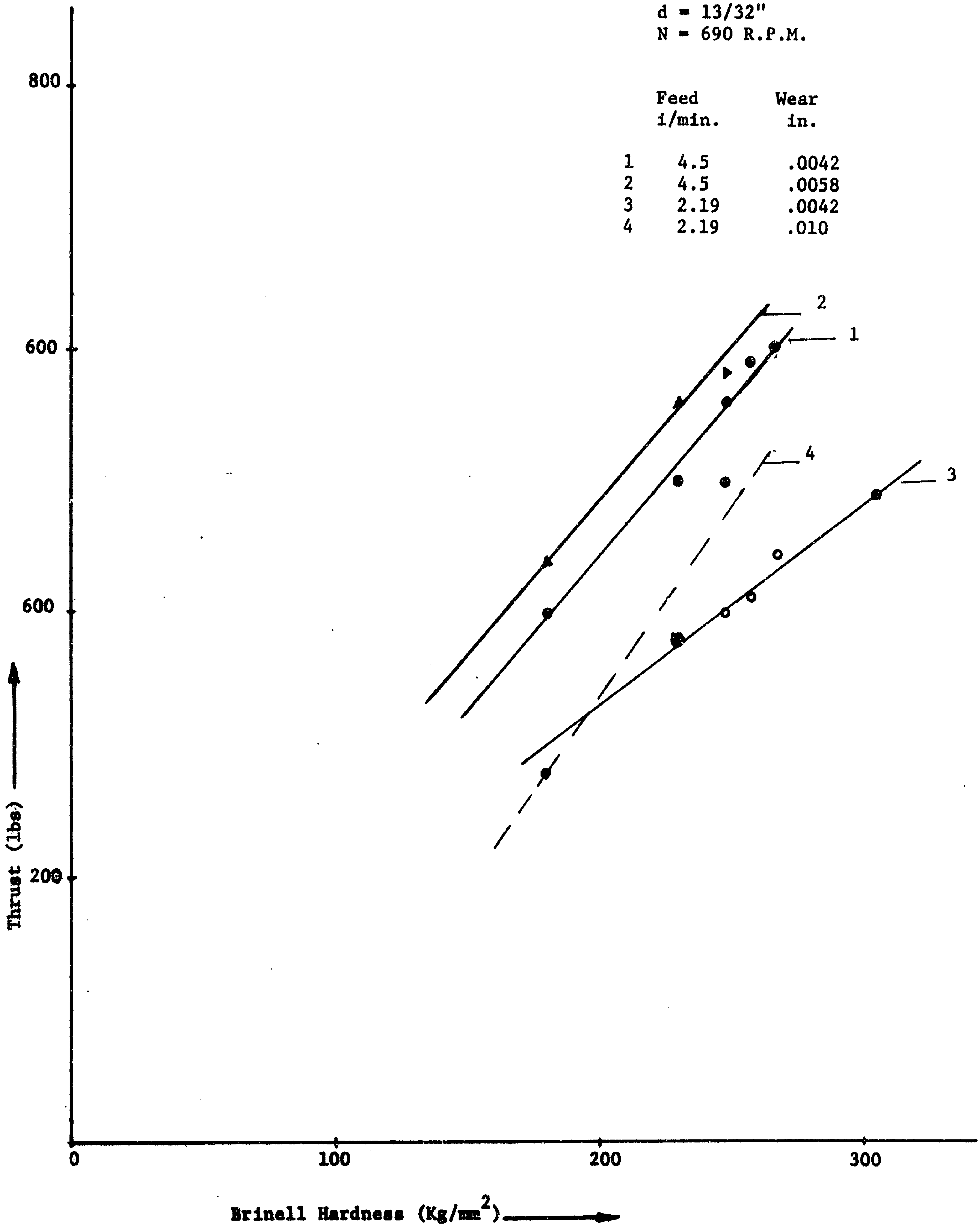
$$T = H_B d\ (.3f + .0022d + .17f^{.2} w^{.8}) \quad (13)$$

$$M = H_B d^2\ (f + f^{.2} w^{.8}) \quad (14)$$

The thrust force is plotted against hardness as shown in Figure 15. It is seen that thrust is directly proportional to the hardness. As a graphical validation of equation (13), the relation between $(T/H_B d)$ is plotted against $(.3f + .0022d + .17f^{.2} w^{.8})$ in Figure 16. It is seen that the data points lie fairly close to the ideal line.

Material
Tool: H.S.S.
Work: Cast Iron
d = 13/32"
N = 690 R.P.M.

	Feed i/min.	Wear in.
1	4.5	.0042
2	4.5	.0058
3	2.19	.0042
4	2.19	.010



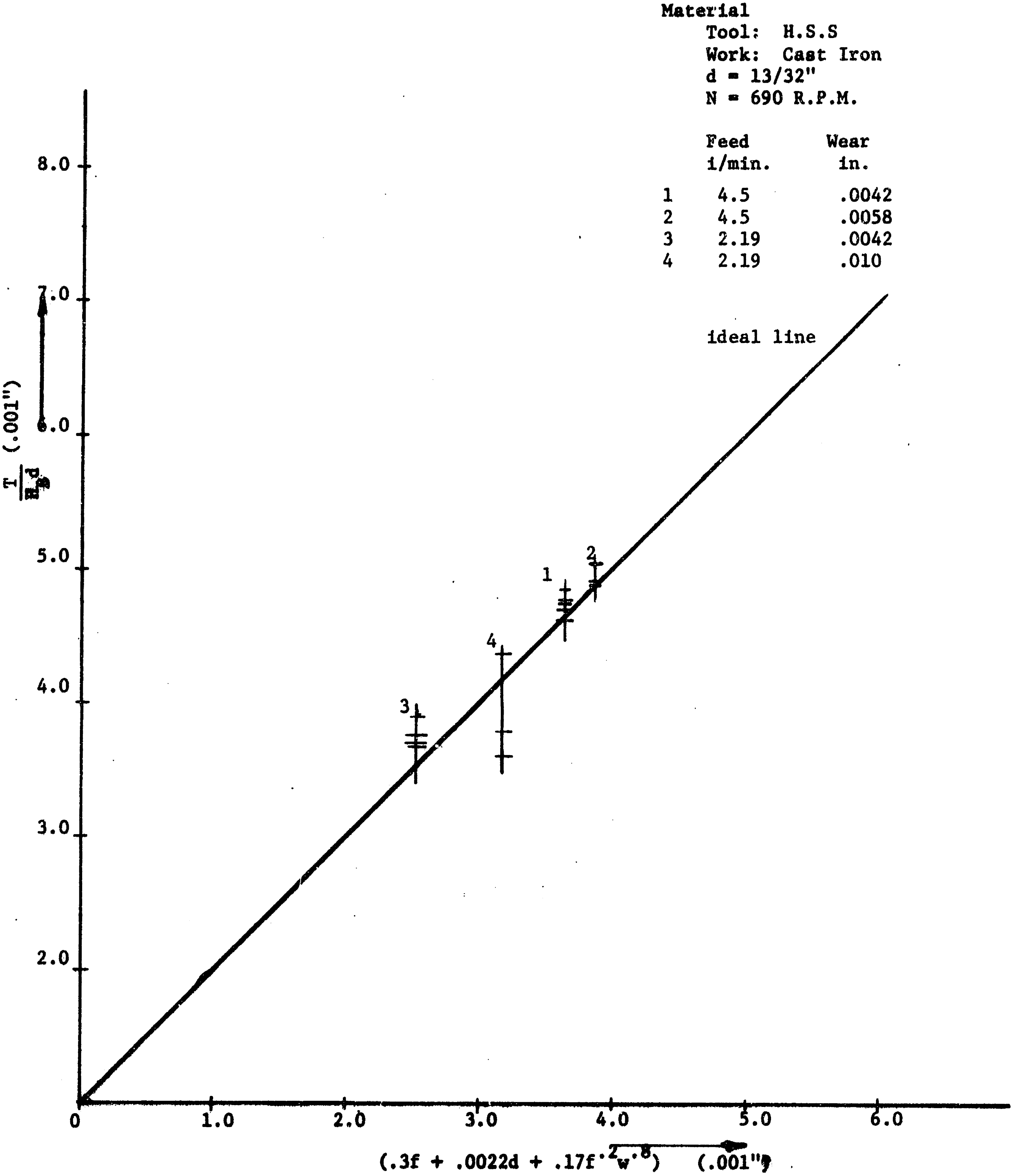


Figure 16. Validation of the Empirical Model

11. TORQUE, THRUST AND POWER AS VARIABLES FOR DRILL WEAR SENSING

In the previous chapter we have seen that torque, thrust and power depend on the flank wear of a drill (w). In general the wear observed on a drill is extensive on the flank face of the tool but negligibly small on the rake face (generally known as crater wear). Torque, thrust and power are basic process variables that depend solely on the cutting condition and the tool condition. Their variation in any situation, such as single or multiple tool operations, if all operating parameters are constant, depend solely on the condition of the individual tool in question. It is assumed here that individual drilling spindles are driven independently and that their speed of revolution remains constant. It is known(12) that the flank wear of a tool increases rapidly at the end of tool life. If it is true, that the torque, thrust and power vary with the flank wear then the changes in these variables should be significant and rapid at the end of the drill life. A careful and constant monitoring of these variables during the life of a drill should indicate their changes and, thus, a parallel indication or prediction of the flank wear.

To test the above hypothesis, a series of experiments was conducted. First, work material of specified hardness was obtained. The drill was then used to drill until it failed. Failure of the drill was marked by excessive laboring of the spindle. If the drill was allowed to persist beyond this point, it was observed that the result was a catastrophic failure of the drill with irregular chipping along the cutting edges. The drilling was stopped at intermittent times to drill instrumented test holes for measuring torque, thrust and power, and the drill was taken out of the spindle to measure the flank wear. Then the drilling was continued up to the next set of test holes. The results are shown in Tables 3 and 4, and also in Figures 17, 18, 19, and 20. To observe the exact nature of the variation in these variables at the end of tool life, a medium range test was made using workpieces of a hardness of 220 Bhn and the results are shown in Tables 5 and 6, and also in Figures 21, 22, 23, and 24. It is seen that the flank wear increases rapidly at the end of tool life and that torque, thrust and power reflect this situation. A sharp increase in the magnitude of these variables at the end of tool life is indeed a welcome feature for their acceptability as variables for drill wear sensing. Another test was undertaken to simulate large volume industrial production by running the drills at the specified feed and speed as in an industrial operation using an average hardness value of 180 Bhn for the work material. Since the experiments proved to be extremely lengthy and expensive in terms of materials, they were discontinued. However it was seen that all of the trends in the initial stages of this run were similar to those observed in all previous experiments and hence it is reasonable to assume that these short duration experiments truely reflect the situation in the long duration industrial runs. The results are shown in Tables 7 and 8 and Figure 25, 26, 27, and 28.

Additional experiments were conducted using the drills obtained from FIAT which were taken out of service after having produced different numbers of holes on a specific machining head. The results are shown in Table 9. These results show a significant variation in the thrust, torque and power for a worn drill as compared to a relatively sharp drill.

TABLE 3.

Data From Short Range Drill Life Tests

Hardness (BHN)	Hole No.	Torque (in lbs)	Thrust (lbs)	Power (watts)	Burr Height (.001")
267	2	51.0	520	700	2
	10	-	-	-	5
	12	75.0	1250	1050	11
230	2	37.5	440	600	2
	30	40.0	480	640	2
	80	42.5	500	720	4
	142	85.0	1040	1120	12
248	2	38.0	560	720	2
	16	42.5	650	800	3
	32	70.0	1240	1310	15

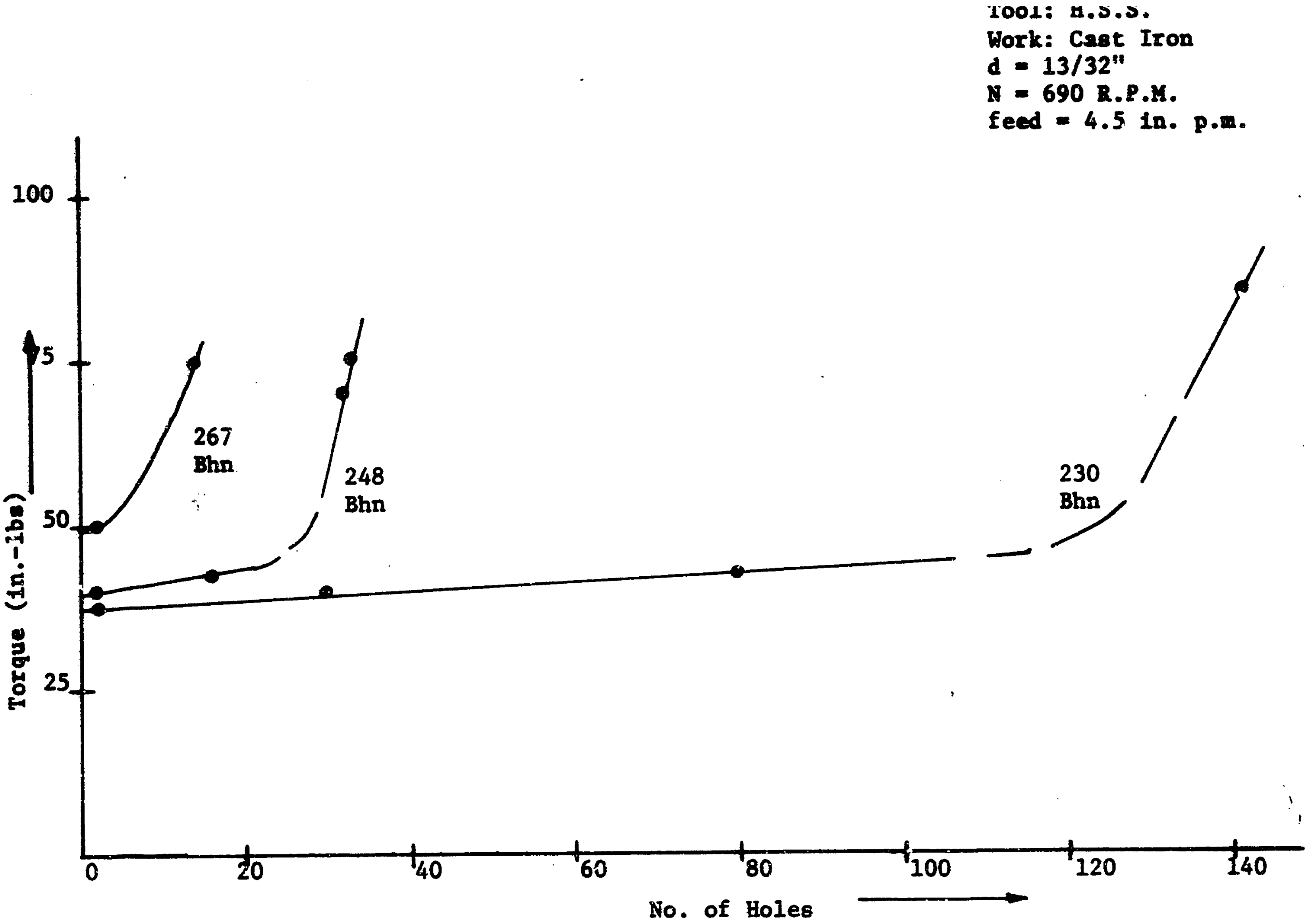


Figure 17. Torque Vs. No. of Holes (Short Range Tests)

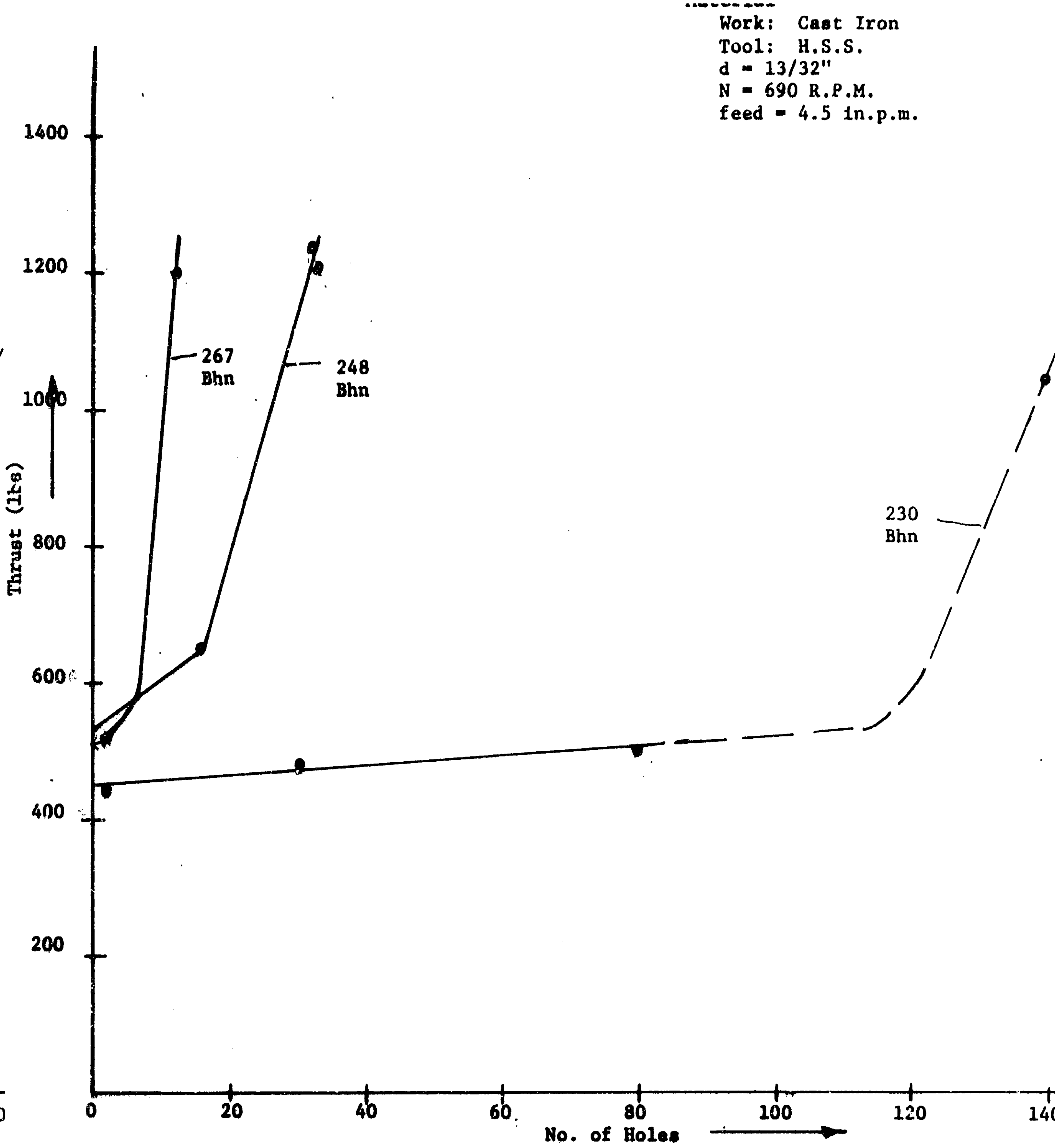
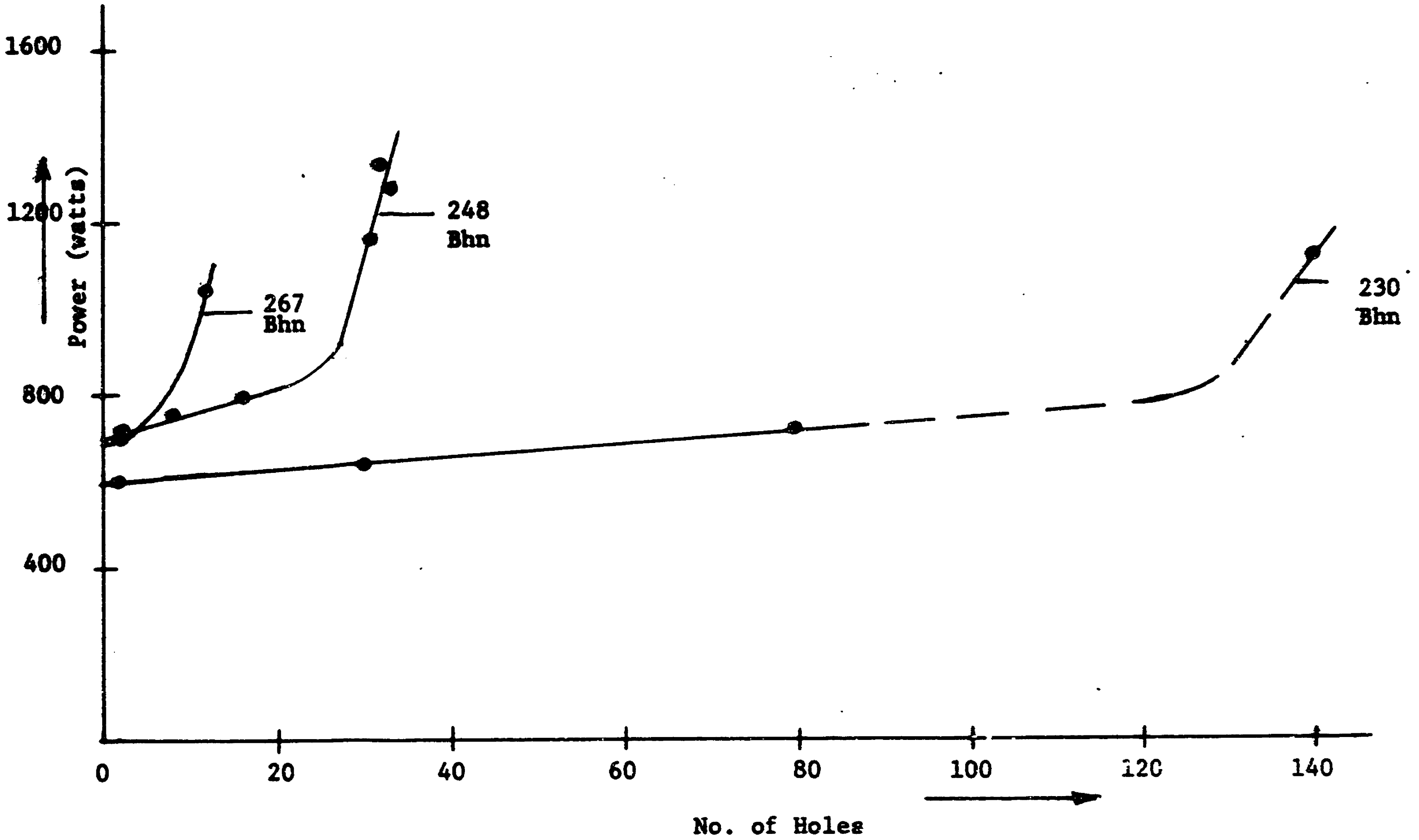


Figure 18. Thrust Vs. No. of Holes (Short Range Tests)



Material
Work: Cast Iron
Tool: H.S.S.
d = 13/32"
N = 690 R.P.M.
feed = 4.5 in. p.m.

Figure 19. Power Vs. No. of Holes (Short Range Tests)

TABLE 4.

Wear Measurements

(Short Range Drill Life Test)

(.001")

Hardness (BHN)	Hole No.	A	B	C	D	E'	E	F'	F
267	0	2.0	1.6	2.0	1.6	2.0	-	2.0	-
	2	3.4	1.6	3.2	1.6	4.6	8.4	5.0	9.6
	10	7.4	2.8	7.6	2.8	5.2	29.6	6.4	31.8
	12	15.0	3.6	14.6	2.6	9.6	24.6	8.2	32.4
230	0	1.6	1.2	1.8	2.0	-	5.2	-	8.8
	30	2.6	2.2	2.0	3.6	8.8	2.6	13.2	
	80	3.6	2.4	4.2	2.4	4.2	13.2	6.8	15.4
	140	5.0	-	5.2	-	-	-	-	-
248	0	-	-	-	-	-	-	-	-
	2	2.0	2.0	2.0	2.0	3.2	7.4	3.8	9.4
	15	3.4	2.2	3.4	2.0	4.2	13.6	5.8	17.8
	31	13.0	2.0	13.0	3.6	10.0	34.2	9.8	41.8

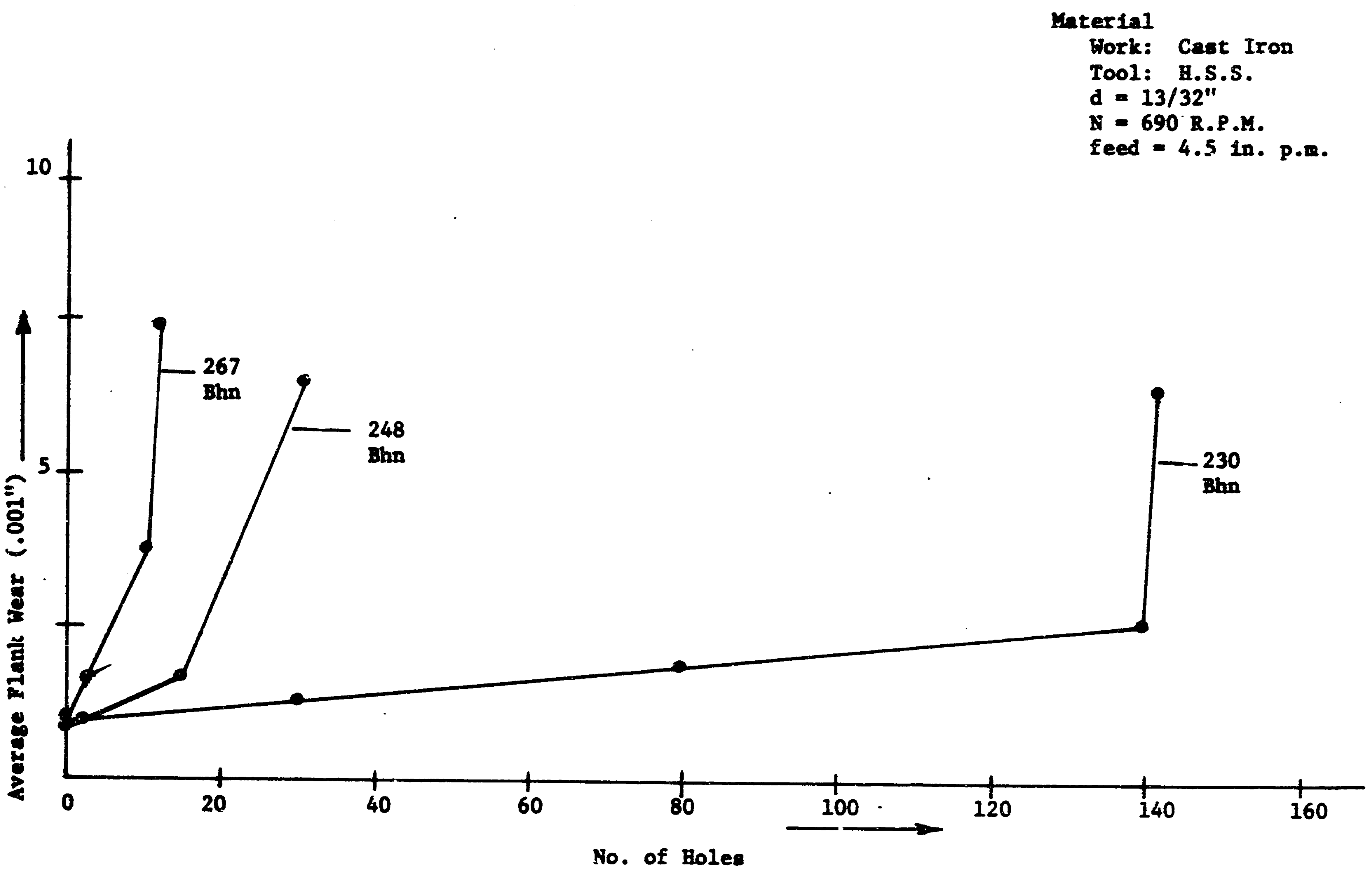


Figure 20. Average Flank Wear Vs. No. of Holes (Short Range Tests)

TABLE 5.

Medium Range Drill Life Test
(Hardness = 220 Bhn)

Hole No.	Torque (in lbs)	Thrust (lbs)	Power (Watts)	Burr Height (.001")
2	40.0	360	520	2
100	37.5	360	540	6
200	40.0	400	560	6
300	37.5	420	580	6
350	40.0	440	580	6
385	35.0	400	600	6.5
420	40.0	420	620	6.5
440	37.5	410	620	6.5
492	37.5	400	620	6.5
540	38.5	400	640	6.5
565	37.5	420	640	7
590	37.5	410	640	7
635	42.5	420	640	7
660	45.0	420	640	7.5
685	45.0	420	680	8
692	47.5	470	760	12
698	65.0	830	1000	17

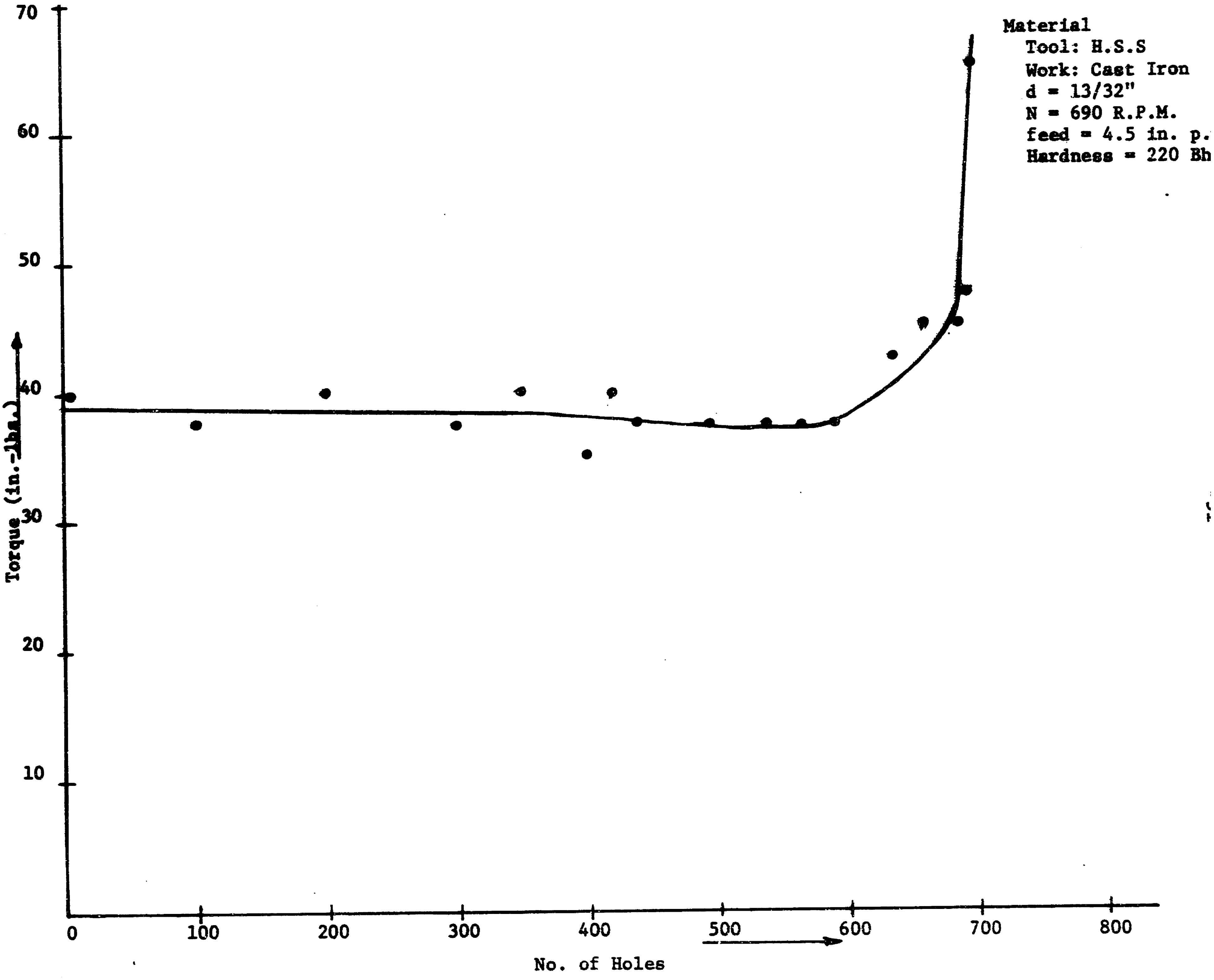
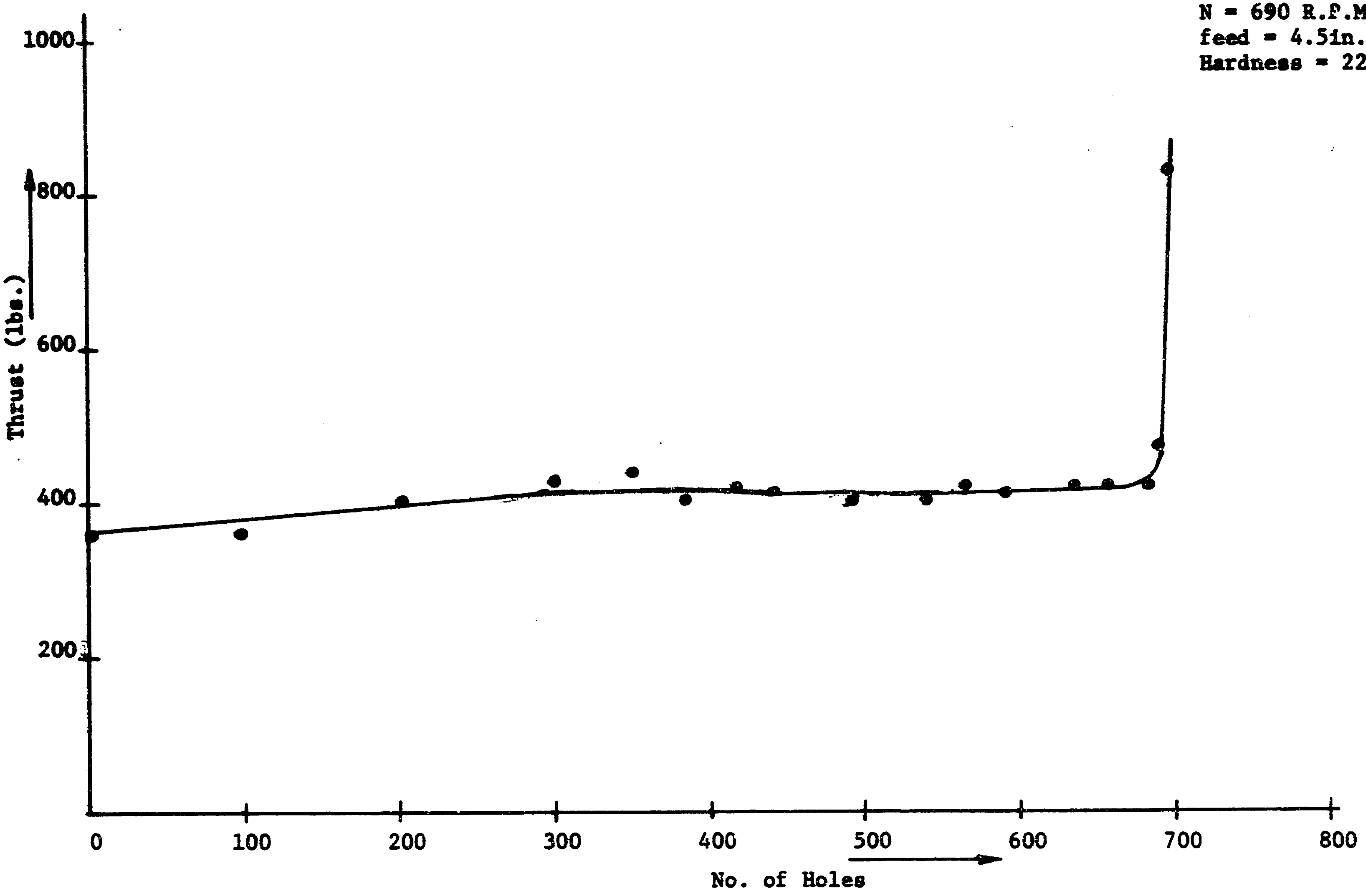


Figure 21. Torque Vs. No. of Holes (Medium Range Tests)



Material
Tool: H.S.S.
Work: Cast Iron
d = 13/32"
N = 690 R.P.M.
feed = 4.5in. p.m.
Hardness = 220 Bhn

Figure 22. Thrust Vs. No. of Holes (Medium Range Tests)

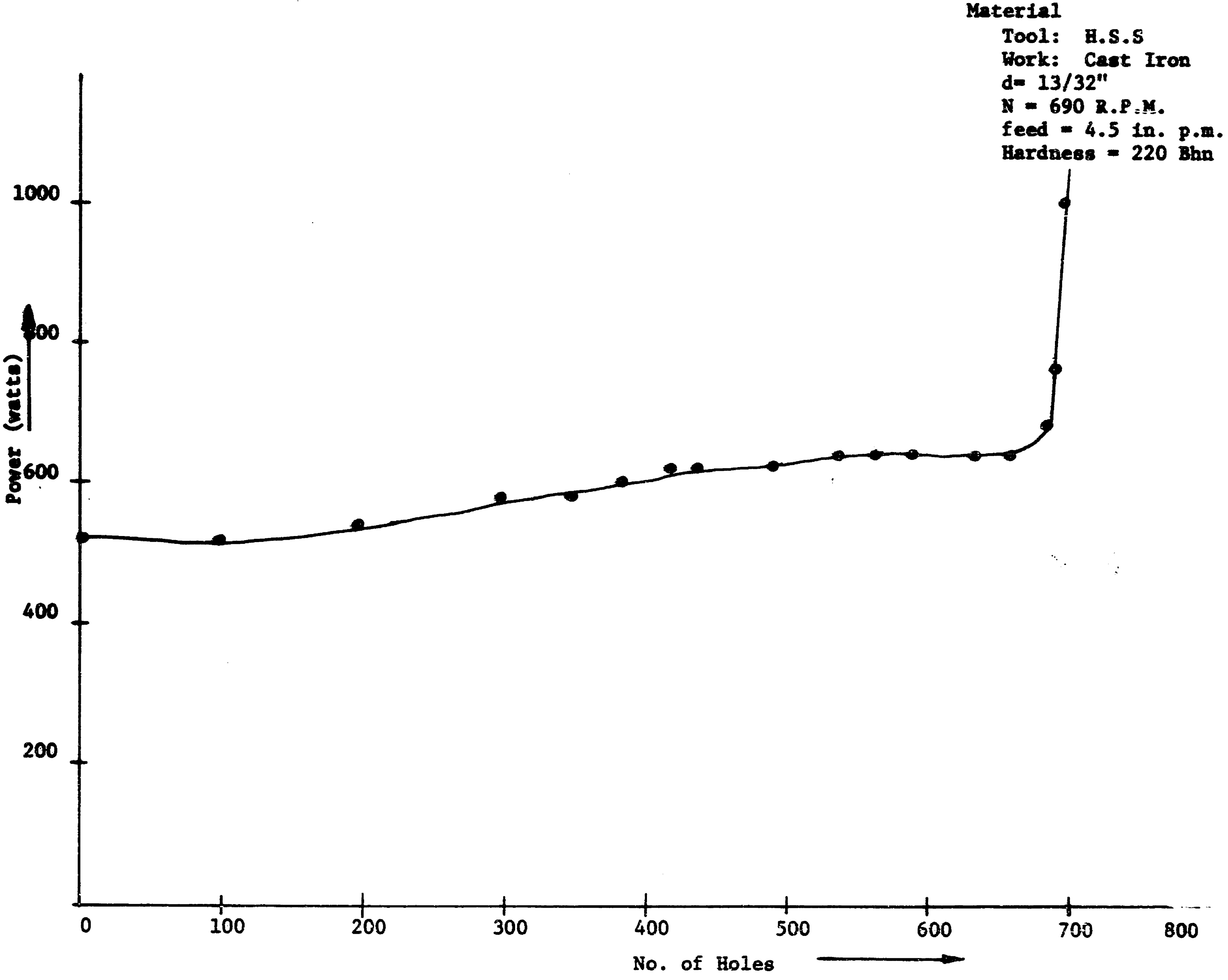

Material
Tool: H.S.S
Work: Cast Iron
d= 13/32"
N = 690 R.P.M.
feed = 4.5 in. p.m.
Hardness = 220 Bhn

Figure 23. Power Vs. No. of Holes (Medium Range Tests)

TABLE 6.

Wear Measurements

(Medium Range Drill Life Tests)

(.001")

Hole No.	A	B	C	D	E'	E	F'	F
2	1.8	1.2	1.4	0.8	2.0	5.4	2.8	7.0
100	3.0	1.2	2.0	1.0	4.6	8.6	3.6	5.8
200	4.4	2.0	3.2	1.6	1.4	10.4	3.0	12.0
300	4.0	1.6	2.4	2.0	3.2	13.6	4.6	11.6
350	3.8	2.0	3.4	1.2	2.0	10.0	5.0	9.6
385	3.4	2.8	3.4	1.6	1.8	13.6	4.0	13.2
420	4.4	2.4	3.8	2.0	2.6	12.6	4.2	16.0
440	3.4	2.4	3.6	1.4	1.8	12.6	4.2	13.8
492	4.8	2.0	4.0	2.4	3.4	12.2	5.4	16.8
540	4.4	1.8	3.0	1.8	1.8	17.2	5.2	13.8
565	3.4	2.0	3.8	2.0	2.0	14.0	5.0	13.6
590	4.4	1.8	4.0	1.6	2.2	13.2	4.4	14.8
635	5.2	2.8	4.0	2.6	1.8	15.2	6.6	14.8
660	4.6	2.4	4.8	2.0	2.4	16.2	10.4	17.6
685	6.0	2.2	5.0	2.8	2.2	20.0	7.8	24.4
692	6.8	3.4	8.0	2.2	4.8	40.4	11.6	40.8
698	14.2	2.8	14.0	2.8	7.6	41.0	17.4	45.6

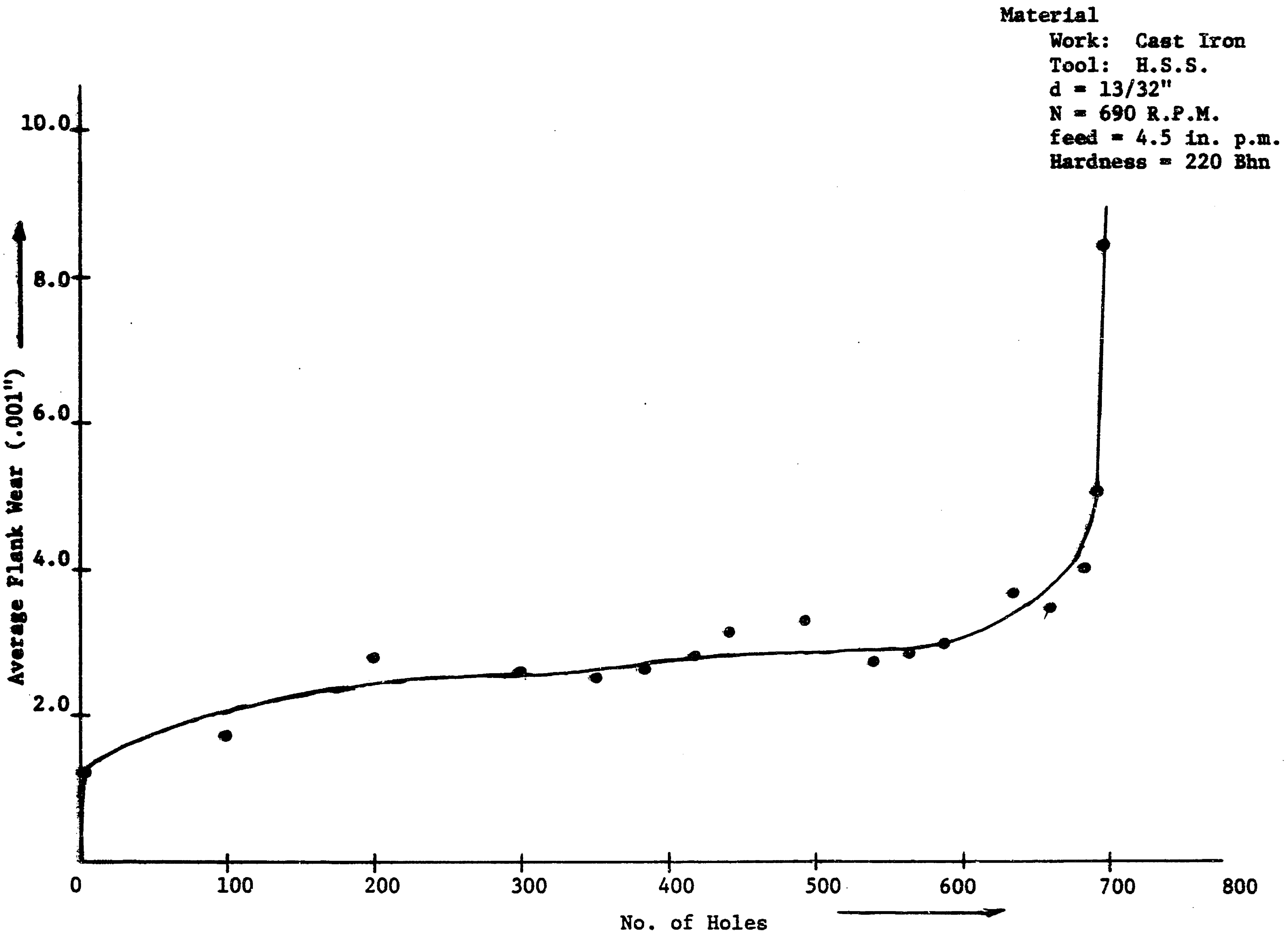


Figure 24. Average Flank Wear Vs. No. of Holes (Medium Range Tests)

TABLE 7.

Long Life Test

(Hardness: 180 Bhn)

Hole No.	Torque (in lbs)	Thrust (lbs)	Power (Watts)
100	62.5	330	580
150	55.0	320	540
200	57.5	320	560
250	67.5	300	580
300	38.0	400	580
350	56.0	380	580
400	54.0	320	580
450	53.5	340	580
500	62.5	300	580
550	62.5	360	620
600	61.2	350	620
650	60.0	400	620
700	62.5	430	600
750	57.5	430	640
800	40.0	427	540
850	56.2	410	600
900	53.0	435	600
950	57.5	357	580
1000	52.5	890	600
1050	30.0	462	600
1100	35.0	400	620
1150	46.2	410	720

TABLE 7.

(contd.)

Hole No.	Torque (in lbs)	Thrust (lbs)	Power (Watts)
1200	45.0	365	650
1250	40.0	435	640
1300	41.2	400	640
1350	50.0	417	640
1400	52.5	385	640
1450	54.0	460	640
1500	42.5	427	640
1550	49.5	400	640
1600	61.0	420	650
1650	57.0	430	600
1700	62.3	410	640
1750	52.8	450	640
1800	55.5	440	640
1850	62.3	430	620
1900	54.0	470	630
1950	65.0	432	680
2000	57.0	485	690
2050	63.7	442	690
2100	65.0	463	680
2150	69.0	510	680
2200	51.4	505	700
2250	48.7	495	700
2300	58.2	457	780

TABLE 7.

(contd.)

Hole No.	Torque (in lbs)	Thrust (lbs)	Power (Watts)
2350	52.5	475	740
2400	54.0	475	740
2450	47.0	495	740
2500	56.5	527	700
2550	55.2	537	720
2600	58.8	505	720
2650	50.0	567	700

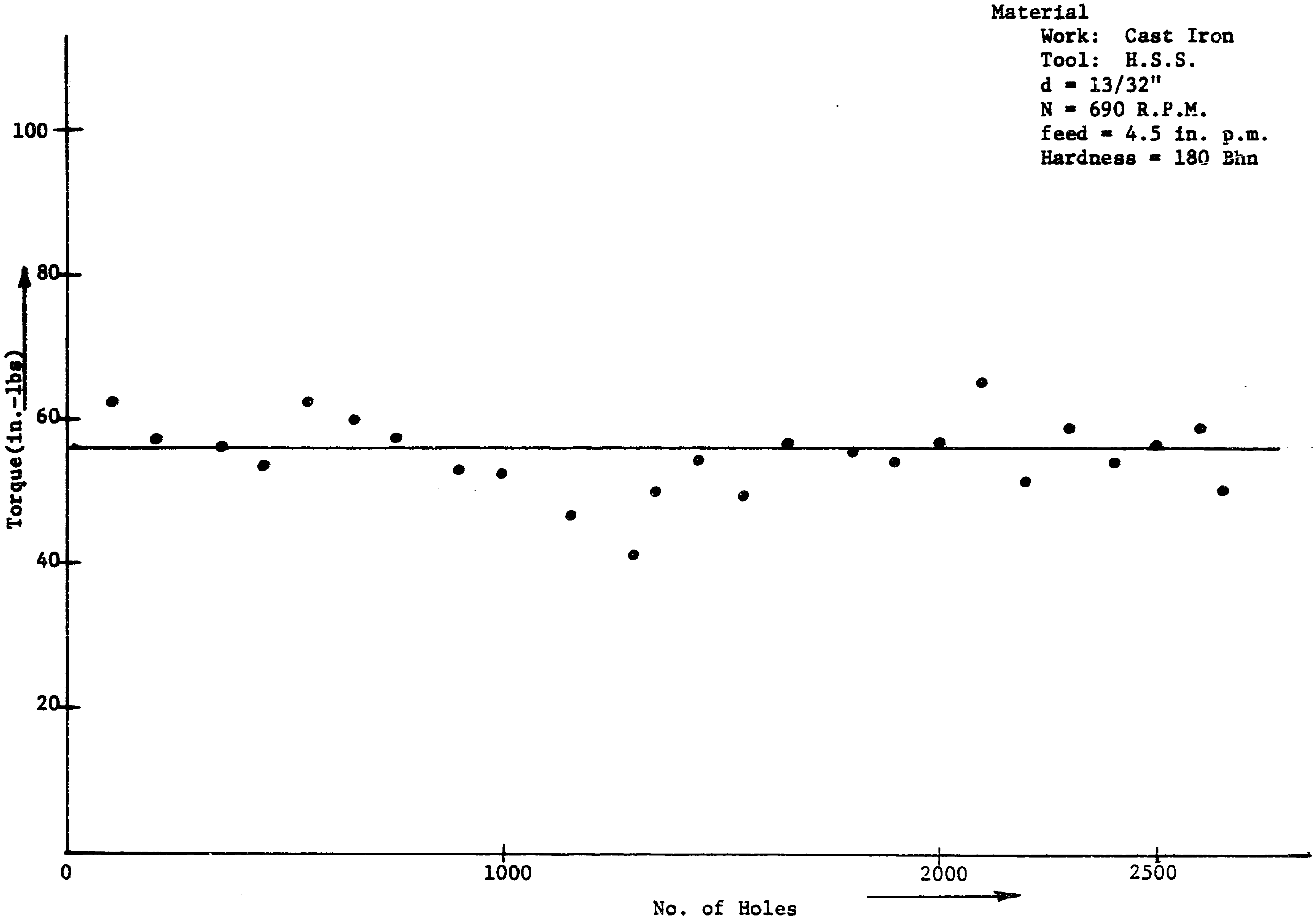


Figure 25. Torque Vs. No. of Holes (Long Range Tests)

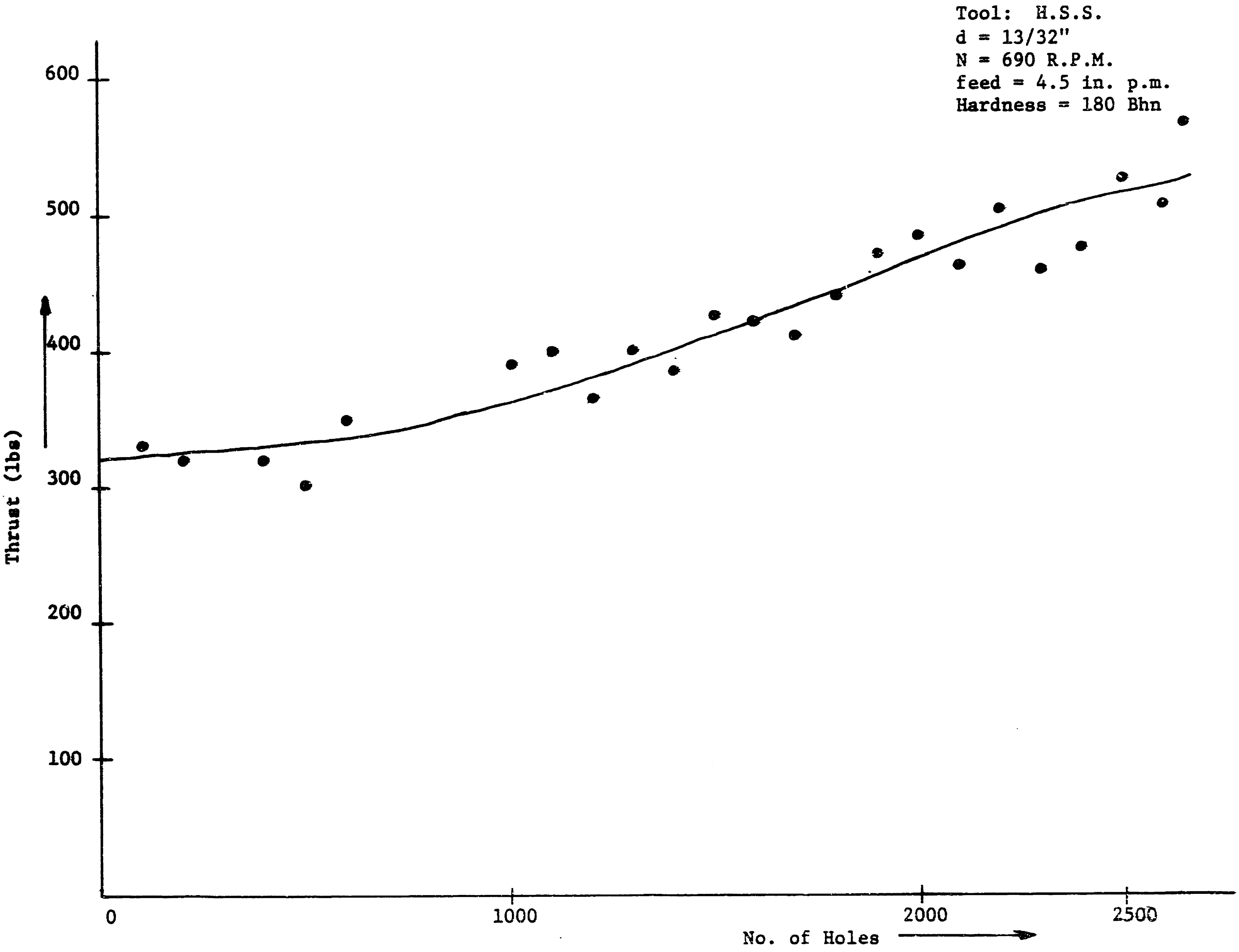
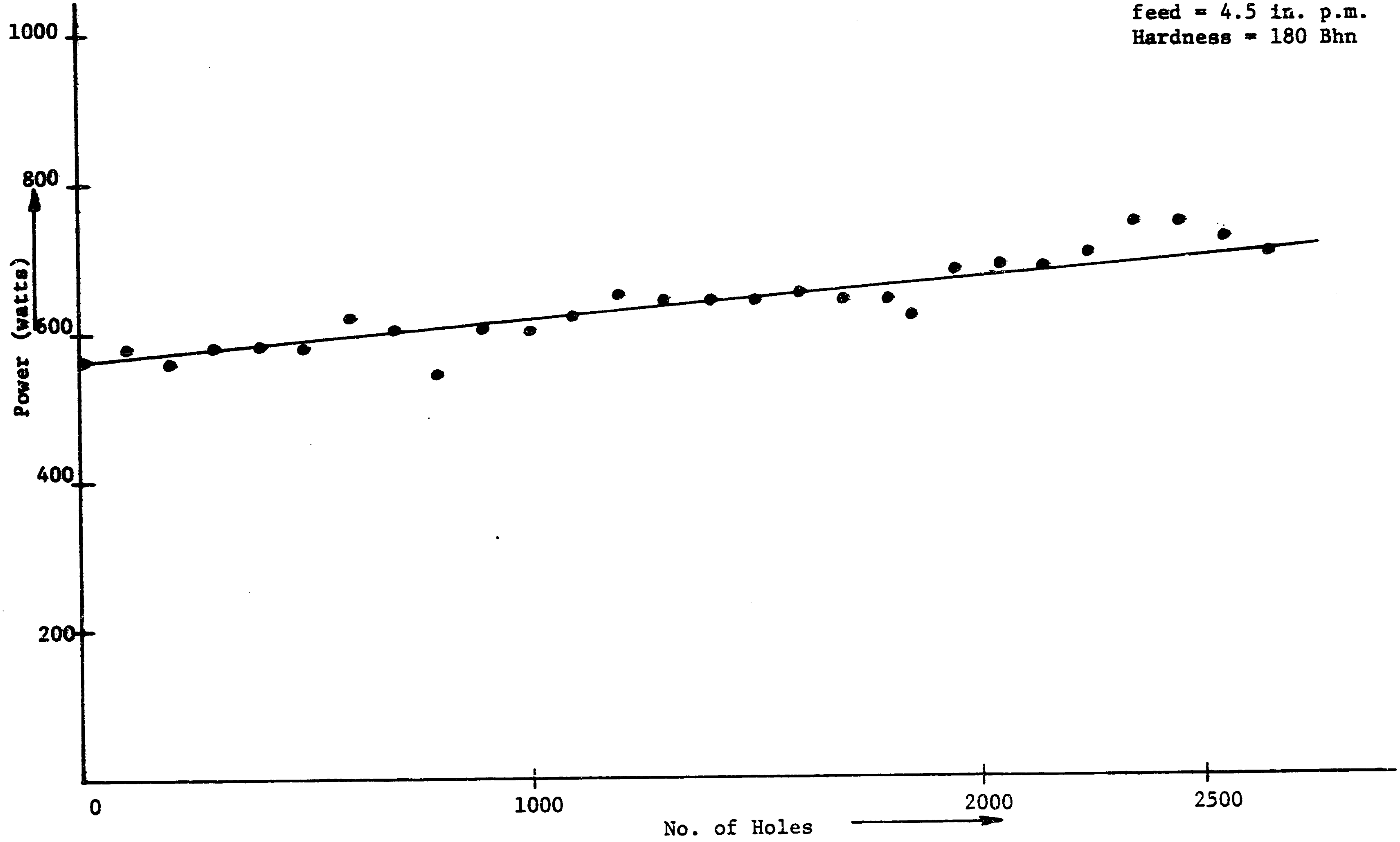


Figure 26. Thrust Vs. No. of Holes (Long Range Tests)



Material
Tool: H.S.S.
Work: Cast Iron
d = 13/32"
N = 690 R.P.M.
feed = 4.5 in. p.m.
Hardness = 180 Bhn

Figure 27. Power Vs. No. of Holes (Long Range Tests)

TABLE 8.

Wear Measurements

(Long Range Test)

(.001")

Hole No.	A	B	C	D	E'	E	F'	F
50	0.0	0.0	0.0	0.0	3.2	6.4	2.8	6.8
100	2.4	1.2	0.0	2.4	2.0	9.2	4.0	10.8
150	1.6	1.2	0.0	2.0	4.8	7.2	3.2	9.6
200	2.4	2.0	2.8	2.8	2.8	5.2	3.6	9.6
250	2.0	1.2	2.4	2.4	4.4	12.4	2.8	11.2
300	1.6	1.6	2.4	1.6	4.4	10.4	3.2	12.2
350	2.0	1.2	2.0	2.8	3.2	10.8	3.2	13.6
400	2.0	2.0	2.4	2.0	7.2	14.0	3.6	12.8
450	2.8	2.8	2.4	1.2	3.2	11.2	6.4	14.4
500	2.4	1.6	2.8	2.4	8.0	14.8	2.8	13.2
550	2.0	2.0	2.4	2.0	2.0	14.0	5.6	19.2
600	2.0	2.0	3.2	3.2	5.6	17.2	4.0	17.2
650	2.8	1.6	3.2	2.4	5.6	20.8	3.2	17.6
700	2.4	2.6	3.2	2.4	6.0	18.8	3.6	18.4
750	2.8	1.6	3.2	1.6	4.0	18.8	4.0	16.4
800	2.4	2.0	3.2	1.6	6.8	23.2	3.6	19.2
850	3.2	1.6	3.2	2.4	6.8	16.8	2.0	20.8
900	2.8	2.4	3.6	2.4	5.6	17.6	4.0	20.8
950	3.6	2.4	3.2	2.4	6.0	20.8	2.4	21.2
1000	3.2	2.0	3.2	2.4	8.4	26.0	3.6	23.2

TABLE 8.

Wear Measurements

(contd.)

(.001")

Hole No.	A	B	C	D	E'	E	F'	F
1050	3.2	2.4	4.0	2.4	6.0	18.0	5.2	21.6
1100	2.8	2.0	8.0	2.8	6.0	25.2	4.8	28.6
1150	3.2	2.4	7.2	2.0	3.6	23.6	4.8	31.2
1200	3.6	2.4	7.2	2.4	6.8	26.4	3.2	24.4
1250	2.8	2.4	3.6	2.8	8.4	26.8	3.6	26.4
1300	3.6	2.0	4.0	2.4	9.6	27.2	2.8	27.6
1350	2.8	2.4	3.6	2.8	6.0	26.0	2.8	27.2
1400	4.0	2.4	4.0	2.4	6.8	26.8	2.4	27.2
1450	4.0	2.4	4.0	2.4	7.6	26.4	1.6	28.0
1500	3.6	2.8	4.0	2.8	7.6	27.2	2.0	30.4
1550	4.4	2.8	4.4	2.8	12.0	29.6	2.0	29.2
1600	3.6	2.4	4.4	2.8	8.0	27.2	1.6	30.8
1650	3.2	2.4	4.4	2.8	6.8	22.4	2.0	32.4
1700	3.2	2.8	4.4	2.8	7.2	26.4	2.4	32.4
1750	4.0	2.8	4.8	2.8	8.4	28.0	2.4	33.6
1800	3.2	2.8	4.0	2.8	6.8	28.4	2.8	34.4
1850	3.6	2.8	4.4	3.2	6.0	28.0	2.8	34.4
1900	3.6	2.8	4.0	2.8	6.0	33.2	3.2	35.2
1950	4.4	2.8	4.4	2.8	8.4	27.6	2.4	40.8
2000	4.4	2.8	4.8	2.8	7.6	35.2	2.4	35.6

TABLE 8.

Wear Measurement

(contd.)

(.001")

Hole No.	A	B	C	D	E'	E	F'	F
2050	4.0	2.8	2.4	3.6	7.6	32.0	2.8	38.0
2100	5.2	2.8	4.4	3.2	8.4	36.8	2.4	39.6
2150	4.8	2.8	5.2	3.2	7.2	36.8	4.4	40.0
2200	4.0	2.8	4.8	3.2	7.6	38.0	3.2	40.4
2250	4.0	2.8	4.0	3.6	5.2	31.2	3.2	40.2
2300	4.4	3.6	5.2	3.2	7.2	31.6	3.6	42.4
2350	4.0	3.6	5.2	3.6	7.2	32.8	4.0	41.2
2400	4.0	3.2	5.2	3.6	7.6	38.4	3.2	42.8
2450	4.0	3.2	5.6	3.6	9.6	35.6	4.0	44.0
2500	4.4	3.6	6.0	3.6	8.8	37.2	4.0	43.6
2550	4.0	3.6	5.6	3.6	8.0	40.8	4.4	46.0
2600	3.6	3.6	5.2	3.2	8.0	44.8	3.6	46.4
2650	4.0	4.0	5.6	4.0	6.4	46.0	4.0	46.0

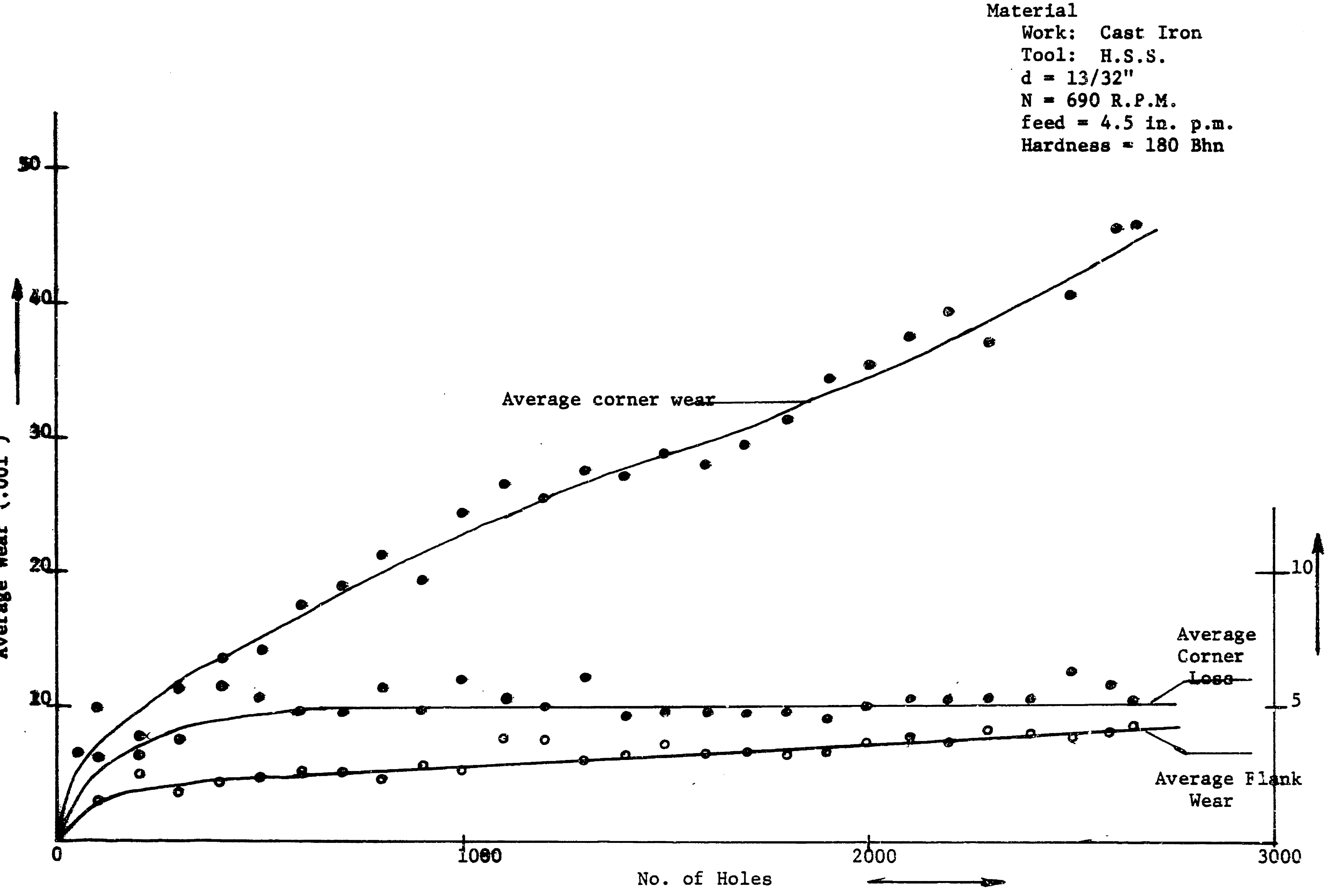


Figure 28. Average Wear Vs. No. of Holes (Long Range Tests)

TABLE 9.

Drill Wear Indicators Test

(FIAT drills)

Pieces Produced	Surface	Flank Wear (in.)	Burr Height (in.)	Torque (in-lbs.)	Thrust (lbs.)	Power (watts)	Temp. (mv)	Magnetization (mv)
0	-	-	-	37.5	320	520	4.2	3
300	2	.00625	.002	57.5	320	600	4.0	4
300	7	.005	.003	60.0	400	600	4.4	4
900	2	.005	.004	55.0	450	720	4.6	5
900	7	.00625	.002	50.0	420	640	3.8	3
1600	2	.0125	.008	62.5	500	800	4.6	6
1600	7	.010	.008	65.0	480	820	4.6	6

12. OTHER POSSIBLE VARIABLES FOR DRILL WEAR SENSING

So far we have seen that torque, thrust and power truly reflect the wear situation in a drill as represented by the flank wear. Vibration and noise are other manifestations of tool wear. There seem to be some other variables which have a potential for adaptation as tool wear sensors. We shall briefly consider two of these here.

The typical wear pattern of a drill is represented by a progressive wear at the corner of the drill. This corner wear is in fact a three dimensional one. The projection of this wear in a plane perpendicular to the axis of the drill is measured by E', E and F' and F, as shown in Figure 9. When a worn drill operates it performs a complex function involving these functions: drilling (cutting along the two cutting edges and extrusion over the chisel edge) and sliding against the work surface at the worn corners. These worn corners sliding with high contact pressure may effectively push the material beneath them sideways, forming a burr along the edge of the hole. The height of the burr then is a function of the plastic work done by the worn drill edges (the burr mentioned here is at the entry side of the hole produced and not the conventional burr observed at the exit side). The drilled holes were monitored for the burr height (measured as the difference between the work surface and the maximum height of the burr at the edge of the hole - Figure 6.). The results are shown in tables 3,5, and 9, and also in Figures 29, 30, 31. There is a significant change in the burr height observed at the end of the drill life. A metallographic section of a hole edge (in the entry side) in a piece produced in industrial drilling

Work: Cast Iron
Tool: H.S.S.
d = 13/32"
N = 690 R.P.M.
feed = 4.5 in. p.m.

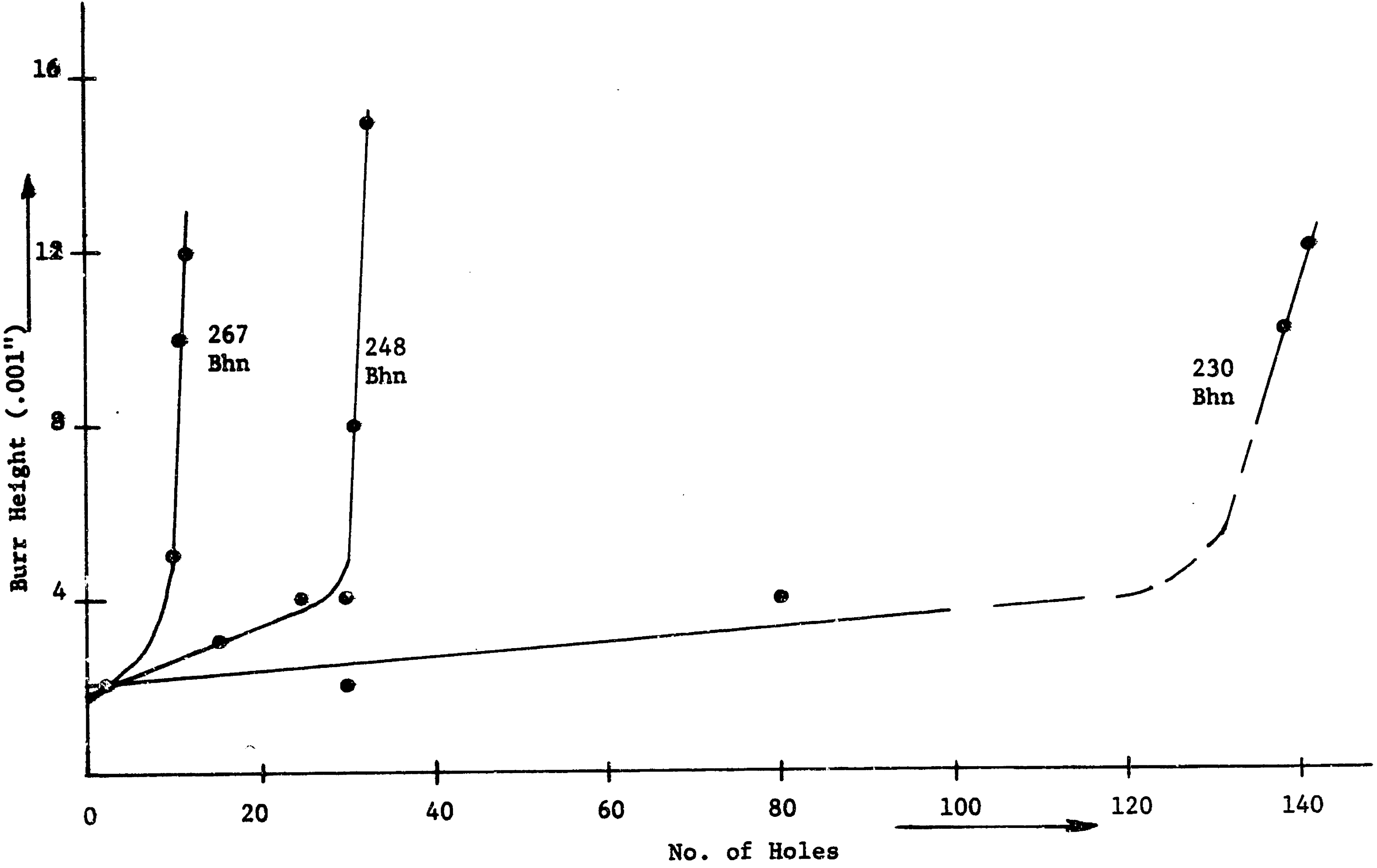


Figure 29. Burr Height Vs. No. of Holes (Short Range Tests)

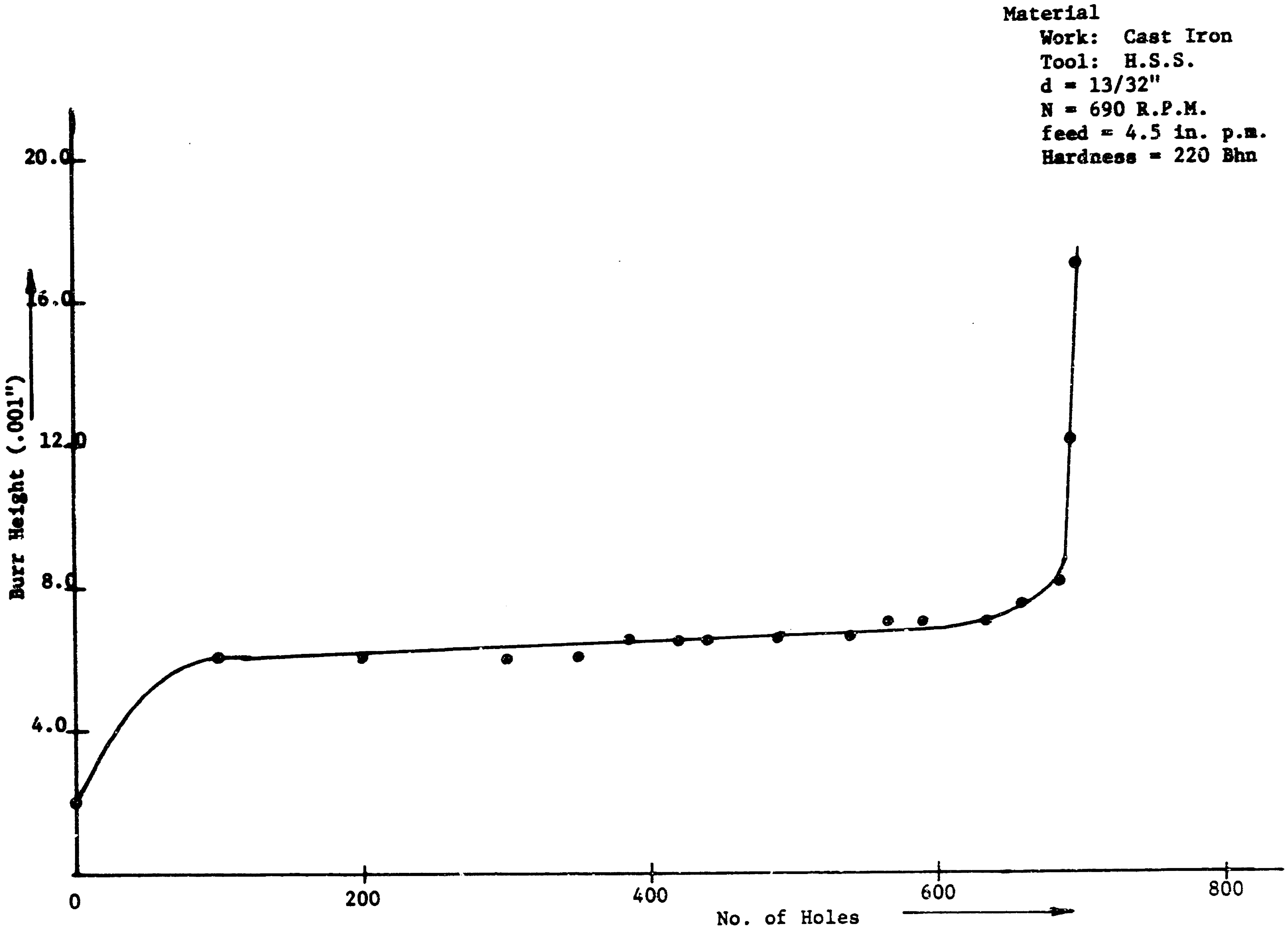
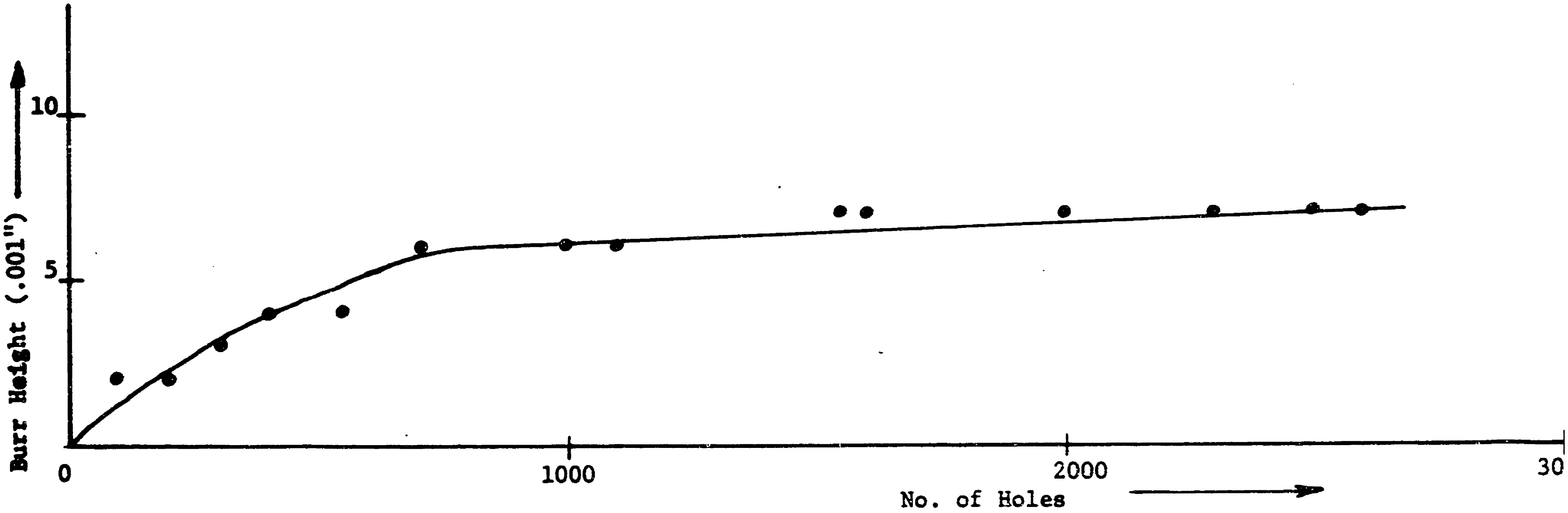


Figure 30. Burr Height Vs. No. of Holes (Medium Range Tests)



Material
Work: Cast Iron
Tool: H.S.S.
d = 13/32"
N = 690 R.P.M.
feed = 4.5 in. p.m.
Hardness = 180 Bhn

Figure 31. Burr Height Vs. No. of Holes (Long Range Tests)

is shown in Figure 32, showing the burr. It is interesting to note that the upper surface of the part rises gradually indicating an extended plastic deformation.

The use of burr height as a wear sensor has promising significance. In any production process, there would be a quality control system that checks the "go - no go" limit of the holes. A simple gauge of the same kind could be used to monitor the burr height and hence the tool producing that hole. However, this method is more of a cure than a prevention of catastrophic failure of tools in that a tool may have already exceeded its useful life when the test indicates failure.

High speed steels are usually non-magnetic in nature. However, drills obtained from an industrial plant, after having been worn to different extents, indicated that the tool tip, where the wear was severe, was magnetized, as revealed by the pick up of iron filings. To test further, the induced magnetism produced by the possible magnetic field at the tool tip was measured. A coil of about 500 turns of copper wire was oscillated vertically at a frequency of 300 cycles/sec. The results are shown in Table 9. A significant increase in the induced e.m.f. may be observed for the worn drill as compared to a new drill. Short duration tests did not reveal any significant magnetization, while some trends were observed in the long duration test (Table 10.).

Further studies are necessary for validation of the hypothesis that there exists an induced magnetism in the drill as a consequence of the wear process. If the effect exists, it offers exciting possibilities for simple and inexpensive ways for on-line monitoring of the drills.

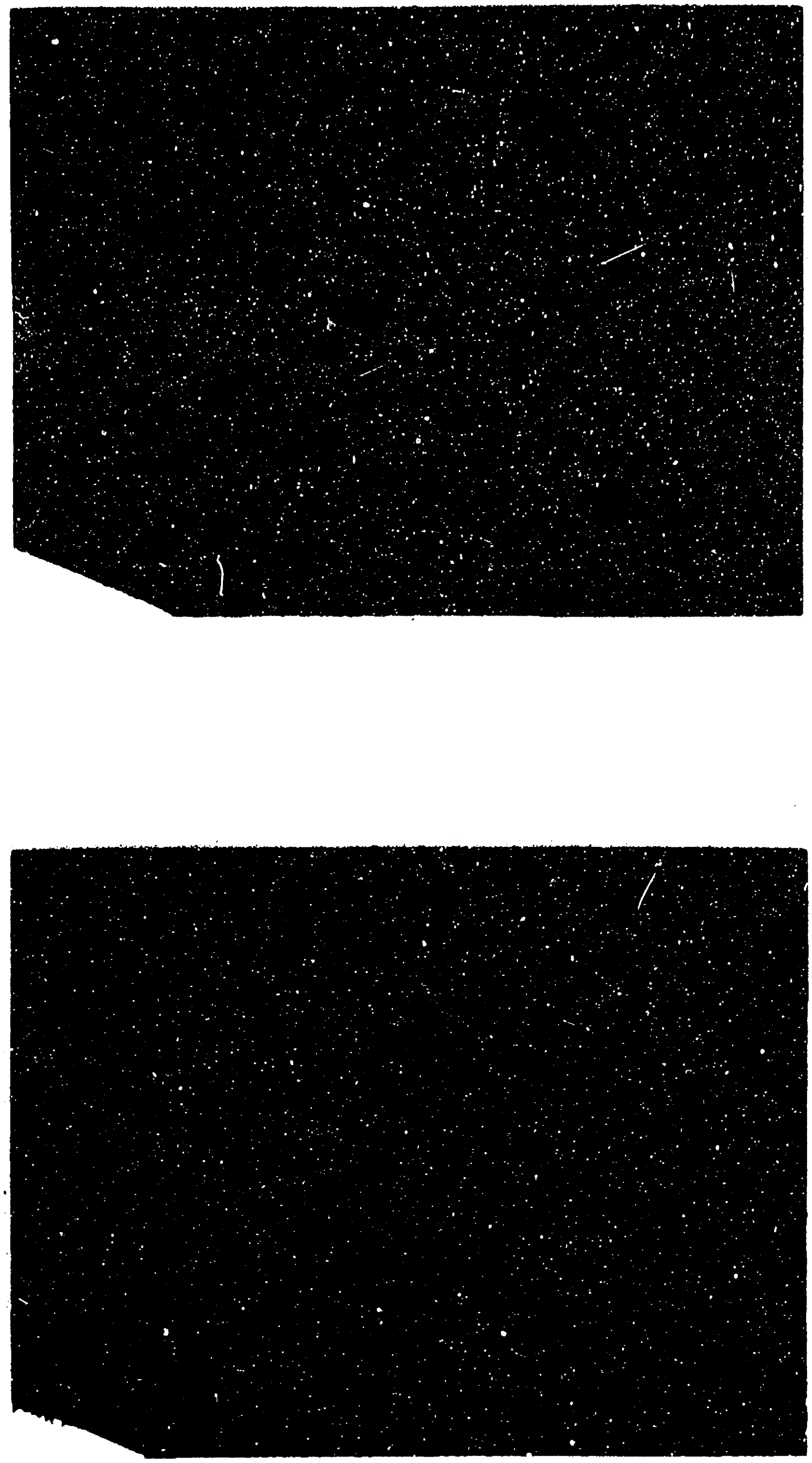


Figure 32. Section of the hole edge showing the burr (X 100).

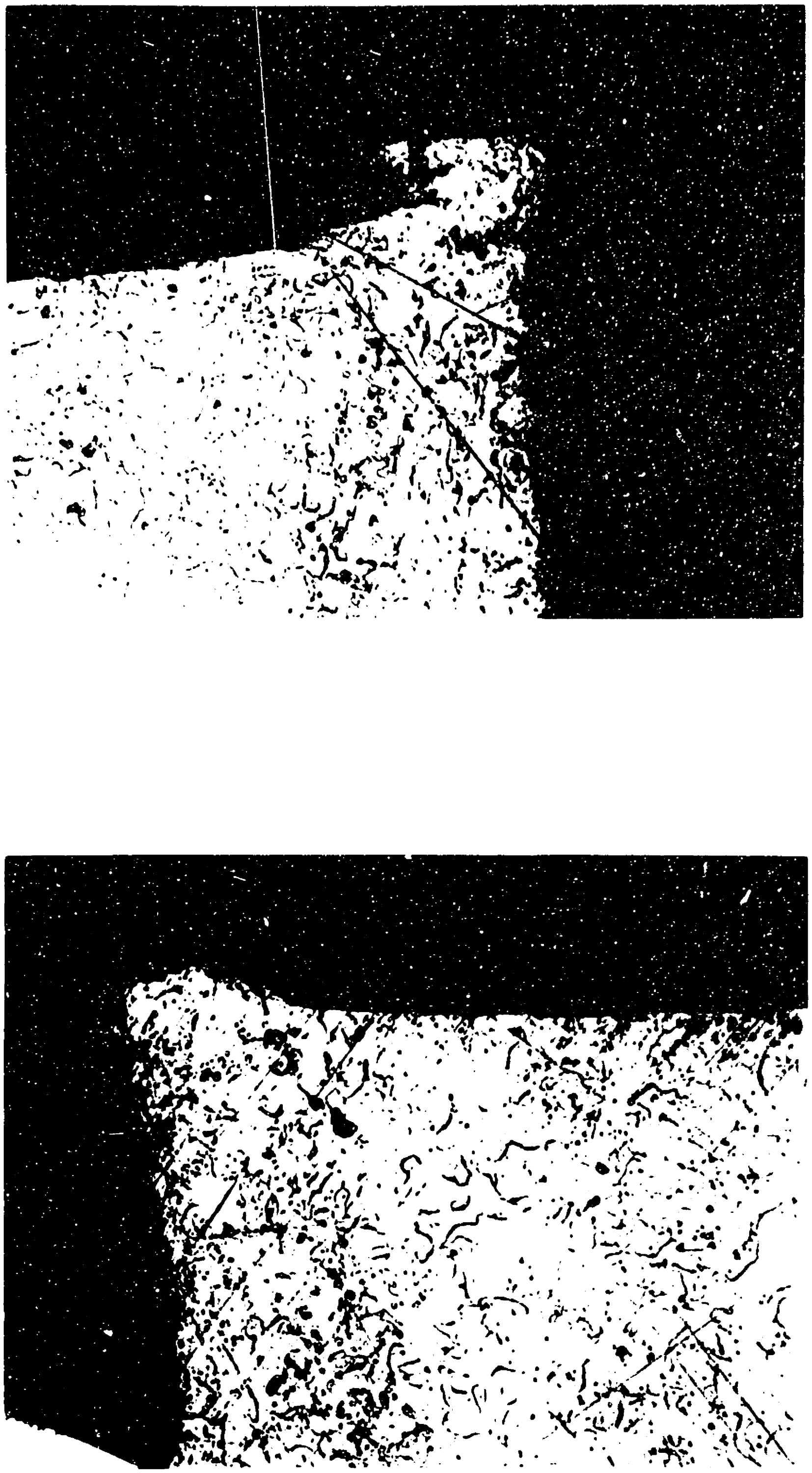


Figure 32. Section of the hole edge showing the burr (X 1[illegible]).

INTENTIONAL DUPLICATE EXPOSURE

TABLE 10.

Induced e.m.f. Measured in Long Range Test

Hole No.	Induced e.m.f. (mv)	Hole No.	Induced e.m.f (mv)
250	0.8	1550	2.2
500	0.9	1600	2.2
550	0.9	1650	2.2
600	1.2	1700	2.2
650	1.4	1750	2.2
700	0.8	1800	2.7
750	1.2	1850	2.5
800	1.2	1900	2.5
850	1.9	1950	3.2
900	1.0	2000	3.2
950	1.0	2050	5.2
1000	1.0	2100	4.2
1050	1.0	2150	3.1
1100	1.2	2200	3.2
1150	1.2	2250	3.2
1200	1.2	2300	3.2
1250	1.7	2350	3.2
1300	1.7	2400	3.2
1350	2.2	2450	3.2
1400	2.2	2500	3.2
1450	2.2	2550	3.2
1500	2.2	2600	3.2
		2650	4.2

There is a significant change in the size and shape of the chips produced by the drill as it becomes worn. It can be seen that the chips produced by the worn drill are in general smaller in size and that there is in general an increase in the ratio of fine to coarse particles observed in the total chip produced. This difference is seen in Figure 33.

Figure 33A. Chips produced by new drill.

Figure 33B. Chips produced by worn drill.

13. EFFECTS OF RESHARPENING AND THROUGH HOLE DRILLING ON FLANK WEAR

We have seen earlier that a large number of factors influence the drill wear. To look at the effect of some variables, a multiple stepwise regression analysis was made based on the data obtained from the drills used in the FIAT plant. Some of the results are detailed here. Flank wear, on the average, was 38 percent less in drills used in a station producing through holes. Resharpened tools show higher flank wear than new tools. However, these changes do not necessarily represent change in tool life under these conditions. Burr height increases with piece count and is significantly higher with new tools.

14. CONCLUSIONS

Drill life is a strong function of work material hardness ($L \alpha H^{-16}$). This strong dependence may account for the large variation in the life of drills which is encountered in industrial operations.

Torque, thrust and power are observed to be functions of drill wear. A model based on the cutting forces on the drill as a combination of a metal cutting force, an indentation force at the edge radius and a shear force at the wear land, seems to explain reasonably well the torque and thrust measured in drilling operations.

Torque, thrust and power increase rapidly near the end of drill life and appear to be potential variables for on-line sensing of drill wear. The change in these variables seem to be very rapid at the end of tool life. However, it is expected that in a continuously monitored system there is enough lead time between the beginning of this change and catastrophic failure, that remedial action can be effected. Burr height on the entry side of the hole produced also seems to be a good indicator of drill wear. The chips produced by a worn drill are significantly different from those produced by a sharp drill.

The wear pattern observed when drilling work material of higher hardness appears to be similar to that observed on drills used in normal industrial conditions. Hence, using a work material of higher hardness may be a better way of conducting accelerated tests under laboratory conditions than the conventional methods which use higher cutting speeds.

It is observed that the drills fail rapidly, within a few holes, at the end of the drill life. Also, dependence of drill life on hardness ($L \alpha H^{-16}$) leads to the conclusion that the drill wear may be a thermally activated process. It is possible that there is some thermal annealing which softens the tool edge and causes tool wear to accelerate rapidly just before failure.

The corner wear (E and F in Figure 7) always reaches the limit of the margin (Figure 1.) before tool failure. Generally a drill is said to be "worn" when the wear reaches the limit of the margin. It is observed that this is not always true. If the corner wear is considered as the representative wear measure, then the above definition is true for short duration runs. However, in the long duration runs, it was observed that the drill continues to operate well long after the corner wear reaches the limit of the margin. Wear land can not progress up to the margin, since the increased tool forces will break the tool.

The noise level and vibration of the machine tool increase rapidly at the end of tool life.

APPENDIX I.

LINEAR REGRESSION ANALYSIS FOR THEORETICAL/MODEL

```
FORTRAN IV G LEVEL  21                MAIN              DATF = 74029         16/03/24              PAGE 0001

 0001             DIMENSION A(400,8),S(400),IVAR(10),NDVAL(10),IVARCD(10)
 0002             N=20
 0003             REAL*8 NAMF (24)/
                X ' TORQUE ','(IN.LBS)'  ,
                X '    HARD','NESS    ',
                X '      FE','FD      ',
                X '      WE','AR      '/
 0004             READ(5,100) ((A(I,J),J=1,6),I=1,N)
 0005         100 FORMAT(6F7.2)
 0006             DO 1 I=1,N
 0007             S(I)=1
 0008             A(I,1)=A(I,1)*1470.
 0009             A(I,2)=A(I,2)/690.
 0010             A(I,3)=A(I,3)*.0002
 0011             A(I,6)=A(I,6)*.40
 0012             A(I,7)=A(I,1)*A(I,2)
 0013             A(I,8)=A(I,1)*A(I,3)
 0014           1 CONTINUE
 0015             S(9)=0
 0016             S(12)=0.
 0017             NCVAR=3
 0018             NDVAP=0
 0019             NCROSS=0
 0020             IVAR(1)=5
 0021             IVAR(2)=1
 0022             IVAP(3)=7
 0023             IVAP(4)=8
 0024             IVARCD(1)=3
 0025             DO 2 J=2,10
 0026           2 IVARCD(J)=1
 0027             CALL MLRG(N,8,A,S,NCVAR,NDVAR,NCROSS,IVAR,LCROSS,NDVAL,NAME,
                 XIVARCD)
 0028             STOP
 0029             END
```

```
VARIABLE     VARIABLE     CASE      MEAN      STANDARD
NUMBER         NAME                           DEVIATION
   1       TORQUE (IN.LBS)         0.626E 02 0.270E 02
   2           HARDNESS            0.342E 06 0.457E 05
   3             FEED              0.242E 04 0.145E 04
   4             WEAR              0.186E 04 0.689E 03

CORRELATION MATRIX

SYMETRIC MATRIX
   1.0000     0.1656     0.8331     -0.1064
   0.1656     1.0000     0.1223      0.0942
   0.8331     0.1223     1.0000     -0.3678
  -0.1064     0.0942    -0.3678      1.0000

STEP  1
VARIABLE  3 ENTERED
    R**2 INCREASED BY 0.69401 TO 0.69401
    F VALUE =36.29  WITH  1 INDEPENDENT VARIABLES
     0.859E 04  0.694E 00  0.859E 04  0.694E 00  0.124E 05  0.833E 00  0.363E 02  0.154E 02  0.252E 02  0.833E 00  0.154E 02
 VARIABLE REGRESSION  STD. DEV. OF   T-VALUE OF
          COEFFICIENT   REG. COEFF.  REG. COEFF.
    3      0.155E-01     0.256E-02     0.602E 01

STEP  2
VARIABLE  4 ENTERED
    R**2 INCREASED BY 0.04627 TO 0.74028
    F VALUE =21.38  WITH  2 INDEPENDENT VARIABLES
     0.573E 03  0.463E-01  0.916E 04  0.740E 00  0.124E 05  0.860E 00  0.214E 02  0.146E 02  0.445E 01  0.851E 00  0.151E 02
 VARIABLE REGRESSION  STD. DEV. OF   T-VALUE OF
          COEFFICIENT   REG. COEFF.  REG. COEFF.
    3      0.170E-01     0.262E-02     0.649E 01
    4      0.906E-02     0.554E-02     0.163E 01

STEP  3
VARIABLE  2 ENTERED
    R**2 INCREASED BY 0.00103 TO 0.74131
    F VALUE =13.37  WITH  3 INDEPENDENT VARIABLES
     0.128E 02  0.103E-02  0.917E 04  0.741E 00  0.124E 05  0.861E 0C  0.134E 02  0.151E 02 -0.150E 01  0.841E 00  0.161E 02
 VARIABLE REGRESSION  STD. DEV. OF   T-VALUE OF
          COEFFICIENT   REG. COEFF.  REG. COEFF.
    3      0.169E-01     0.275E-02     0.615E 01
    4      0.885E-02     0.579E-02     0.153E 01
    2      0.193E-04     0.818E-04     0.236E 00
```

Run A

APPENDIX II.

LINEAR REGRESSION ANALYSIS FOR EMPIRICAL MODEL.

```
FORTRAN IV G LEVEL  21                  MAIN              DATE = 74015          16/25/22            PAGE 0001

 0001             DIMENSION A(400,8),S(400),IVAR(10),NDVAL(10),IVARCD(10)
 0002             N=20
 0003             REAL*8 NAME (24)/
                 X '   POWER','        ',
                 X '     HARD','NESS    ',
                 X ' FEED CO','MPONENT ',
                 X ' WEAR CO','MPONENT '/
 0004             READ(5,100) ((A(I,J),J=1,6),I=1,N)
 0005         100 FORMAT(6F7.2)
 0006             DO 1 I=1,N
 0007             S(I)=1
 0008             A(I,1)=A(I,1)*1470.
 0009             A(I,2)=A(I,2)/690.
 0010             A(I,3)=A(I,3)*.0002
 0011             A(I,6)=A(I,6)*.40
 0012             A(I,7)=A(I,1)*A(I,2)
 0013             A(I,8)=A(I,1)*A(I,2)**.2*A(I,3)**.8
 0014           1 CONTINUE
 0015             S(9)=0
 0016             S(12)=0.
 0017             NCVAR=2
 0018             NDVAR=0
 0019             NCROSS=0
 0020             IVAR(1)=6
 0021             IVAR(2)=7
 0022             IVAR(3)=8
 0023             IVARCD(1)=3
 0024             DO 2 J=2,10
 0025           2 IVARCD(J)=1
 0026             CALL MLRG(N,8,A,S,NCVAR,NDVAR,NCROSS,IVAR,LCROSS,NDVAL,NAME,
                 XIVARCD)
 0027             STOP
 0028             END
```

Run

```
ARIABLE     VARIABLE    CASE      MEAN     STANDARD
NUMBER        NAME                         DEVIATION
   1         POWER                0.937E 00 0.563E 00
   2     feed component           0.242E 04 0.145E C4
   3     wear component T         0.187F 04 0.438E 03

ORRELATION MATRIX

YMETRIC MATRIX
   1.0000     0.9371     0.2896
   C.9371     1.0000     C.0536
   0.2896     0.0536     1.0000

TEP  1
ARIABLE  2 ENTERED
   R**2 INCREASED BY 0.87812 TO 0.87812
   F VALUE ******  WITH  1 INDEPENDENT VARIABLES
     0.472E-01  0.878E-00  0.472E-01  0.878E-00  0.538E-01  0.937E-00  0.115E-03  0.202E-00  -0.594E-01  0.937E-00  0.202E 00
VARIABLE REGRESSION  STC. DEV. CF    T-VALUE OF
         COEFFICIENT   REG. CCEFF.  REG. CCEFF.
   2      0.362E-03     C.338E-04     0.107E-02

TEP  2
ARIABLE  3 ENTERED
   R**2 INCREASED BY 0.05746 TO 0.93558
   F VALUE ******  WITH  2 INDEPENDENT VARIABLES
     0.309E 00  0.575E-C1  0.503E 01  0.936E 00  0.538E 01  0.967E 00  0.109E 03  0.152E 00 -0.506E 00  0.965E 00  0.157E 00
VARIABLE REGRESSION  STC. DEV. OF    T-VALUE CF
         COEFFICIENT   REG. CCEFF.  REG. COEFF.
   2      0.357E-03     C.254E-04     0.141E 02
   3      0.308E-03     0.843E-04     0.366E 01
```

```
RTRAN IV G LEVEL  21                MAIN            DATE = 74014         12/25/04             PAGE 0001

                  DIMENSION A(400,8),S(400),IVAR(10),NDVAL(10),IVARCD(10)
                  N=20
                  REAL*8 NAME (24)/
                 X ' TORQUE ','(IN.LBS)',
                 X '     HARD','NESS    ',
                 X ' FEED CO','MPONENT ',
                 X ' WEAR CO','MPCNENT '/
                  READ(5,100) ((A(I,J),J=1,6),I=1,N)
              100 FORMAT(6F7.2)
                  DO 1 I=1,N
                  S(I)=1
                  A(I,1)=A(I,1)*1470.
                  A(I,2)=A(I,2)/690.
                  A(I,3)=A(I,3)*.0002
                  A(I,6)=A(I,6)*.40
                  A(I,7)=A(I,1)*A(I,2)
                  A(I,8)=A(I,1)*A(I,2)**.2*A(I,3)**.8
                1 CONTINUE
                  S(12)=0.
                  NCVAR=2
                  NDVAR=0
                  NCROSS=0
                  IVAR(1)=5
                  IVAR(2)=7
                  IVAR(3)=8
                  IVARCD(1)=3
                  DO 2 J=2,10
                2 IVARCD(J)=1
                  CALL MLRG(N,8,A,S,NCVAR,NDVAR,NCROSS,IVAR,LCROSS,NDVAL,NAME,
                 XIVARCD)
                  STOP
                  END
```

```
IABLE     VARIABLE    CASE      MEAN     STANDARD
MBER        NAME                         DEVIATION
 1      TORQUE (IN.LBS)         0.612E 02 0.268E 02
 2      feed component          0.235E 04 0.145E 04
 3      wear component          0.184E 04 0.442E 03

RELATION MATRIX

ETRIC MATRIX
 1.0000     0.8407     0.3060
 0.8407     1.0000     0.1089
 0.3060     0.1089     1.0000

P  1
IABLE  2 ENTERED
 R**2 INCREASED BY 0.70679 TO 0.70679
 F VALUE =40.98  WITH  1 INDEPENDENT VARIABLES
   0.917E 04  0.707E 00  0.917E 04  0.707E 00  0.130E 05  0.841E 00  0.410E-02  0.150E-02  0.246E 02  0.841E 00  0.150E 02
RIABLE REGRESSION  STD. DEV. OF   T-VALUE OF
       COEFFICIENT   REG. COEFF.  REG. COEFF.
  2     0.156E-01     0.244E-02    0.640E 01

P  2
IABLE  3 ENTERED
 R**2 INCREASED BY 0.04656 TO 0.75335
 F VALUE =24.43  WITH  2 INDEPENDENT VARIABLES
   0.604E 03  0.466E-01  0.977E 04  0.753E 00  0.130E 05  0.868E 00  0.244E 02  0.141E 02  0.135E 01  0.860E 00  0.145E 02
RIABLE REGRESSION  STD. DEV. OF   T-VALUE OF
       COEFFICIENT   REG. COEFF.  REG. COEFF.
  2     0.152E-01     0.232E-02    0.654E 01
  3     0.132E-01     0.758E-02    0.174E 01
```

Ru

```
FORTRAN IV G LEVEL  21                  MAIN              DATE = 74010          10/57/44             PAGE 0001

 0001              DIMENSICN A(400,8),S(400),IVAR(10),NDVAL(10),IVARCD(10)
 0002              N=20
 0003              REAL*8 NAME (24)/
                  X ' THRUST ','(LBS.)  ',
                  X '    HARD','NESS    ',
                  X ' FEED CO','MPONENT ',
                  X ' WEAR CO','MPONENT '/
 0004              READ(5,100) ((A(I,J),J=1,6),I=1,N)
 0CC5          100 FORMAT(6F7.2)
 0006              DO 1 I=1,N
 0007              S(I)=1
 CCC8              A(I,1)=A(I,1)*1470.
 0009              A(I,2)=A(I,2)/690.
 0010              A(I,3)=A(I,3)*.0002
 0011              A(I,6)=A(I,6)*.40
 0012              A(I,7)=A(I,1)*A(I,2)
 0013              A(I,8)=A(I,1)*A(I,2)**.2*A(I,3)**.8
 0014            1 CONTINUE
 0015              NCVAR=3
 0016              NDVAR=0
 0017              NCROSS=0
 CC18              IVAR(1)=4
 0019              IVAR(2)=1
 0020              IVAR(3)=7
 0C21              IVAR(4)=8
 0022              IVARCD(1)=3
 0023              DO 2 J=2,10
 0024            2 IVARCD(J)=1
 0025              CALL MLRG(N,8,A,S,NCVAR,NDVAR,NCROSS,IVAR,LCROSS,NDVAL,NAME,
                  XIVARCD)
 0026              STOP
 0027              END
```

```
VARIABLE      VARIABLE    CASE      MEAN     STANDARD
 NUMBER         NAME                         DEVIATION
    1      THRUST (LBS.)            0.589E 03 0.382E 03
    2         HARDNESS              0.347E 06 0.494E 05
    3      FEED COMPONENT           0.230E 04 0.142E 04
    4      WEAR COMPONENT           0.184E 04 0.431E 03

CORRELATION MATRIX


SYMETRIC MATRIX
    1.0000    0.2701    0.7752    0.2574
    0.2701    1.0000    0.0366    0.1731
    0.7752    0.0366    1.0000    0.1124
    0.2574    0.1731    0.1124    1.0000

STEP  1
VARIABLE  3 ENTERED
    R**2 INCREASED BY 0.60101 TO 0.60101
    F VALUE =27.11  WITH  1 INDEPENDENT VARIABLES
      0.167E 07  0.601E 00  0.167E 07  0.601E 00  0.278E 07  0.775E 00  0.271E 02  0.248E 03  0.110E 03  0.775E 00  0.248E 03
 VARIABLE REGRESSION  STD. DEV. OF   T-VALUE OF
          COEFFICIENT   REG. COEFF.  REG. COEFF.
    3      0.208E 00     0.400E-01     0.521E 01

STEP  2
VARIABLE  2 ENTERED
    R**2 INCREASED BY 0.05851 TO 0.65951
    F VALUE =16.46  WITH  2 INDEPENDENT VARIABLES
      0.162E 06  0.585E-01  0.183E 07  0.660E 00  0.278E 07  0.812E 00  0.165E 02  0.236E 03 -0.535E 03  0.800E 00  0.242E 03
 VARIABLE REGRESSION  STD. DEV. OF   T-VALUE OF
          COEFFICIENT   REG. COEFF.  REG. COEFF.
    3      0.206E 00     0.380E-01     0.541E 01
    2      0.187E-02     0.110E-02     0.171E 01

STEP  3
VARIABLE  4 ENTERED
    R**2 INCREASED BY 0.01747 TO 0.67698
    F VALUE =11.18  WITH  3 INDEPENDENT VARIABLES
      0.485E 05  0.175E-01  0.188E 07  0.677E 00  0.278E 07  0.823E 00  0.112E 02  0.237E 03 -0.685E 03  0.799E 00  0.250E 03
 VARIABLE REGRESSION  STD. DEV. OF   T-VALUE OF
          COEFFICIENT   REG. COEFF.  REG. COEFF.
    3      0.202E 00     0.384E-01     0.526E 01
    2      0.170E-02     0.112E-02     0.152E 01
    4      0.120E 00     0.129E 00     0.930E 00
```

16. LIST OF REFERENCES

1. "Computer Boosts Transfer Line Efficiency", Bernard Feinberg, T & M Engg., October, 1969.

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