THE COLLEGE OF AERONAUTICS
CRANFIELD

MACHINABILITY DYNAMOMETERS USED
AT THE COLLEGE OF AERONAUTICS

by

J. CHERRY
THE COLLEGE OF AERONAUTICS
CRANFIELD

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by


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INTRODUCTION

Much more interest in machinability investigations has been shown in recent years, both by colleges and by Industrial Research departments, due partly to the difficulty encountered in machining some of the new gas turbine materials and partly to the availability of simple and economical dynamometers as are described in this Note.

These dynamometers were designed to provide simple robust instruments capable of being easily applied to a wide range of machines without modification. Direct mechanical movement is the basis of their construction and this has been justified by the trouble free service given over a period of five years. Almost onehundred of each of these instruments are being used, and so many requests have been received for a more comprehensive account of their range of uses that the preparation of this Note seemed justified.

It is encouraging to see the vigour displayed by industry and the Colleges in this field since so much remains to be done to establish practical machinability, data for British materials. By collaboration between investigators it should be possible to arrange a programme of research to cover a wide range of materials with the minimum duplication.

The illustrations of the instruments are shown by the courtesy of Coventry Grinders Ltd., Coventry.

2. LATHE DYNAMOMETER

2. 1. Construction

The instrument resolves the resultant load on the tool into three components in the principal planes as shown in Fig. 1. This is achieved by designing the Toolholder Body, shown in Fig. 2, to permit rocking in the vertical and horizontal directions and to allow sliding in the backwards direction. In the diagrammatic section, Fig. 3, the Toolholder Body is shown in position. A vertical load 'V' causes the toolholder to rock on the cylindrical surfaces 'AA', the movement being resisted by diaphragm (6) whose deflection is measured by the dial indicator shown. Similarly a horizontal load 'H' causes the toolholder to rock on surfaces 'BB', resistance being applied by diaphragm (7). Surfaces 'AA' and 'BB' are ground and lapped to be a close sliding fit in housing (8), hence a back load 'Z' causes the toolholder to slide backward against diagram (10). Thus the values of all three components can be determined. Housing (8) is made into two parts to permit adjustment to the closest degree. The lower part which carries the load is made integral with the shank for maximum support.
2.2 Calibration and Toolsetting

Calibration tests are conducted on the apparatus shown in Fig. 4 in which actual cutting tests are simulated as closely as possible.

In calibrating, an adaptor replaces the tool and the vertical and horizontal loads are applied at a position one inch from the end of the clamping shank. This face is used as a datum for setting the tool which should also be one inch to the centre of the cut, hence the toolpoint should be one inch plus half the depth of cut from the datum face as shown in Fig. 5. A typical calibration chart is shown in Fig. 6.

2.3 General Information

A photograph of the dynamometer is shown in Fig. 7.

Overall Dimensions

Length = 6\(\frac{1}{4}\)" , width = 4", depth = 3\(\frac{3}{4}\)" (including dial indicators)

Loading Range

The standard range of diaphragms will permit the following loads to be applied:

Vertical \[1000 \text{ lbs. (1 div.} = 10 \text{ lbs. approx.)}
Horizontal \[500 \text{ lbs. (1 div.} = 5 \text{ lbs. approx.)}
Back \[300 \text{ lbs. (1 div.} = 3 \text{ lbs. approx.)}

\[
\text{using } \frac{1}{10,000} \text{ indicators}
\]

Should it be required to increase or decrease the sensitivity it is a simple procedure to change the diaphragms, however re-calibration would be necessary.

Fitting to Lathe

The standard shank is 1" x 1" x 4\(\frac{9}{16}\)" , hence the dynamometer will fit any machine suitable for a tool of 1" square section.

Tools

The toolholder body is ground for 3\(\frac{3}{4}\)" round tools but square tools up to \(\frac{1}{2}\)" may be used by employing an adaptor as shown in Fig. 5.

Dial Indicators

\[\frac{1}{10,000}\]

Three dial indicators are used.
2. 4 Uses of Lathe Dynamometer

Some of the purposes for which the dynamometer may be used are outlined below:

2. 4. 1. Determination of power available for cutting, also machine efficiency
2. 4. 2. Determination of optimum tool geometry
2. 4. 3. Determination of machinability data for materials
2. 4. 4. Comparison of lubricants and coolants
2. 4. 5. Analysis of cutting force relationships
2. 4. 6. Workshop machinability comparator
2. 4. 7. Special Applications

2. 4. 1. Determination of power available for cutting, also machine efficiency

When estimating machining times it is necessary to know the maximum power available at the cutting tool, otherwise a task may be set beyond the capacity of the machine. The dynamometer may be used to measure power available directly.

Under normal cutting conditions it is only necessary to measure the vertical load, at maximum motor load, as the other loads are not significant.

The calculation is:

\[ \text{HP at Tool} = \frac{\text{Vert. load} \times \text{speed feet/min (at the mean depth of cut)}}{33,000} \]

Machine efficiency \[= \frac{\text{HP at Tool}}{\text{Electrical HP consumed (Watts)}} \]

This data may be usefully recorded for estimating purposes.

2. 4. 2. Determination of optimum tool geometry

By judicious use of the dynamometer an approximation to the optimum tool shape for maximum metal removal can speedily be obtained. The sequence in the determination of angles is as follows:

2. 2. 1. Best True Rake Angle
2. 2. 2. Best Clearance Angle
2. 2. 3. Best Plan Approach Angle.
A description of the test for best true rake will serve as a guide for the other angles.

2.4.2.1. Best True Rake Angle

For this test a series of knife tools with different side rakes is used, as shown in Fig. 9. With this type of tool the true rake and side rake are coincidental hence it is a simple matter to vary the true rake. Tests are conducted under standard conditions in which the vertical and horizontal loads are measured for varying true rakes. These tests are repeated for different rates of feed. Typical results are shown in Figs. 9a and 9b.

Inspection of the results for .020 feed/revolution reveal a minimum load at 20° true rake with an increase beyond this angle. Such a result indicates that edge breakdown has occurred on the 25° tool during the period of the test therefore it would be prudent to select an angle less than 20°. Since tool life is affected by the friction caused by the cutting load and the volume of tool material dissipating heat a compromise has to be made between maximum true rake and maximum volume of tool material. The choice will be governed to a degree by the tool material and the process for which the data is required. Milling with tungsten carbide tools would prejudice the choice to a less acute angle than when turning with high speed tools. The curves shown in Fig. 9 were for turning with high speed tools and under these conditions a choice of 15° true rake would appear satisfactory. Examination of the effect of this choice on the other feed rates supports the likelihood of its suitability.

In order to check this assumption life tests were conducted in which the tools were run to destruction. The results of these tests which were conducted over the extreme rates of feed are shown in Fig. 10. It is therefore apparent that with practice and a knowledge of the operating conditions close approximation to optimum angles can quickly be obtained by using the dynamometer technique.

2.4.2.2. Best clearance angle

Using the true rake as previously determined, the clearance angles are varied and cutting loads measured as previously.

2.4.2.3. Best plan approach angle

Adopting the angles previously determined a similar procedure is conducted for the plan approach angle.

* For further information on the definition of true rake angle see 'Fundamentals of cutting tool geometry' by C. V. Stabler.
Other angles may be determined in a similar manner.

When time and material supply permits, full scale life tests should be subsequently performed, for conclusive results.

2. 4. 3. Determination of machinability data for materials

Once the optimum tool shape has been derived for a given material further experiment can proceed to determine various machinability data such as:

2. 4. 3. 1. Machinability index for power
2. 4. 3. 2. Specific cutting capacity
2. 4. 3. 3. Effect on power of variation in depth of cut and rate of feed.

2. 4. 3. 1. Machinability index for power

This machinability index gives a measure of the ease with which a material cuts and is defined as the vertical pressure on the tool required to shear a standard chip section of 0.1" depth x 0.010" thickness, thus

\[ M, I (P) = \text{vertical pressure for } .1'' \times .010'' \text{ chip section.} \]

This is easily obtained by setting the dynamometer to cut a standard chip section 0.1" x 0.010" and measuring the vertical load.

2. 4. 3. 2. Specific cutting capacity

An alternative method of expressing the ease by which a material machines is by stating the volume removable per horse power consumed, this is termed the Specific Cutting Capacity, thus

\[ S, C, C. = \frac{\text{Volume removable per HP/minute}}{396} \]

\[ \text{Machinability index} \]

This information is also of value for estimating purposes.

2. 4. 3. 3. Effect on power of variation in depth of cut and rate of feed

In most practical situations it is not convenient to use the standard chip section, therefore it is necessary to know the effect on power consumption when a departure is made from standard conditions.

The relationship between vertical pressure on the tool, depth of cut and rate of feed can be expressed in the form
V. P. = \( M \cdot L \times 1000 \times d^x f^y \)

V. P. = vertical pressure
Where \( d \) = depth of cut (ins.)
and \( f \) = rate of feed (ins.)

The value of \( y \) is found by keeping \( d \) constant and varying \( f \).
The value of \( x \) is found by keeping \( f \) constant and varying \( d \).

S. C. C. can then be adjusted to suit the operating conditions.

2.4.4. Comparison of lubricants and coolants

When conducting experiments of the above nature it is generally necessary to replace the standard diaphragms by the more sensitive type.

The effect of different lubricants and coolants on the machinability index can be measured directly by the dynamometer. Unless the fluids under comparison have appreciable differences in their chemical combination with the tool material, a comparison of the cutting loads gives guidance to their relative proficiency.

2.4.5. Analysis of cutting force relationship

Much of the credit for the advances made into the theory of metal cutting must go to M. E. Merchant, Cincinnati Milling Machine Co., Ohio. His paper on 'Mechanics of the Metal Cutting Process' presents an elegant method of analysing the cutting force system. Merchant considers the chip as being in equilibrium under equal and opposite resultant forces \( R \) and \( R^1 \) as shown in Fig. 11a. Fig. 11b represents these forces in a condensed form.

Measurement of forces \( F_c \) and \( F_t \) are made by the dynamometer from which the resultant force \( R \), the friction force \( F \) and the coefficient of friction \( \gamma \) can be derived.

Readers interested in this analysis are recommended to study Merchant's paper.

2.4.6. Workshop Machinability Comparator

It is often found in practice that material which meets the normal specification with regard to Brinell hardness and tensile strength behaves very differently when being machined. Loss of production often results from the lower rates of cutting necessary when material
has poor machining characteristics. In conjunction with other factors the determination of the machinability index by the dynamometer provides an indication of the machining characteristics of the material.

Much argument between operators and rate-fixers could be avoided if a standard of machinability was set and material tested for machinability before being issued to the workshop.

2. 4. 7. Special Applications

In addition to the normal turning operations the lathe dynamometer has been used for planing tests. Work of this type has been conducted by Sheffield University for planing rock (see Fig. 16) with satisfactory results.

3. DRILL DYNAMOMETER

3.1. Construction

The drill dynamometer measures thrust and torque during the drilling operation. This is achieved by direct mechanical means as illustrated diagrammatically in Fig. 12.

Test specimens are clamped to table (2), the thrust load being translated through spindle (1) which rests on a ball bearing and whose movement is resisted by diaphragm (4). Deflection of this diaphragm is measured by dial indicator (6) through bell crank (5).

Torque is also translated by means of spindle (1). In this case ball bearing (10) which is fitted to the spindle is resisted from turning by cantilever (9) whose deflection is measured by a dial indicator as shown.

3.2. Calibration and toolsetting

The instrument is calibrated in the manner illustrated in Fig. 13.

Before clamping the test specimen to the table it is important to ensure alignment of machine spindle and dynamometer spindle. A centre hole is provided in the dynamometer spindle for this purpose.

3.3. General information

Range:- The standard instrument has the following range -

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<table>
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<tbody>
<tr>
<td>Thrust</td>
<td>500 lbs.</td>
</tr>
<tr>
<td>Torque</td>
<td>100 inch lbs.</td>
</tr>
</tbody>
</table>
Overall dimensions:-

\[
\text{Dia.} = 5\frac{3}{4}'' \\
\text{Height} = 5''
\]

Dial indicators:-

\[
\frac{1}{10,000} \text{ dial indicators are used}
\]

Extension piece:-

An extension piece is necessary for fitment to the thrust indicator. (This is supplied with the instrument).

3.4. Uses of the drill dynamometer

Although the variables in the drilling process are not so easily manipulated or controlled as in the turning process none the less with adequate care most of the functions of the lathe dynamometer can be achieved with the drilling instrument, as the following list illustrates:-

3.4.1. Determination of power available for cutting also machine efficiency
3.4.2. Determination of optimum tool geometry
3.4.3. Determination of machinability data for materials
3.4.4. Comparison of lubricants and coolants
3.4.5. Analysis of cutting force relationships
3.4.6. Workshop machinability comparator
3.4.7. Special applications

3.4.1. Determination of power available for cutting also machine efficiency

Horsepower available for drilling is found in a similar manner as for turning. In this case the torque (inch lbs.) at maximum electrical load is noted also the drill speed and converted to HP. as follows:-

\[
\text{HP. available at drill} = \frac{\text{Torque (ins. lbs.)}}{198,000} \times \text{RPM}
\]

Machine efficiency is determined from the relationship

\[
\% \text{ machine efficiency} = \frac{\text{mech. HP. available at max. load}}{\text{electrical HP. consumed}} \times 100
\]
3. 4. 2. Determination of optimum tool geometry

The principal angles of a drill are - helix angle, clearance angle and point angle as shown in Fig. 14.

3. 4. 2. 1. Helix angle

The helix angle corresponds to the side rake in turning, however it is only possible to alter the helix angle when conducting tests by changing the drill hence care has to be taken to ensure that other features such as web thickness, point angle and clearance angle are identical. It is advisable that a set of drills is selected and retained for this test.

The selection of this angle is determined similarly as for the true rake angle in turning.

3. 4. 2. 2. Clearance angle

In determining this angle it is preferable to retain the same drill throughout and re-grind the different clearance angles. By this procedure there is greater opportunity of maintaining consistency of the other features.

3. 4. 2. 3. Drill point angle

Similarly with this investigation one drill only should be used and reground with different point angles.

It is stressed once more that when time and material permit full scale life tests should be made.

3. 4. 3. Determination of machinability data for materials

The drill dynamometer can be used to determine similar data as the lathe instrument such as:-

3. 4. 3. 1. Machinability index for power
3. 4. 3. 2. Specific cutting capacity
3. 4. 3. 3. Effect on power of variation of drill diameter and rate of feed.

3. 4. 3. 1. Machinability index (power)

To conform to the standard chip section as for turning, i.e. 0.10" depth of cut x 0.010 width, a simple procedure is used to obtain the desired depth of cut. In this, a No. 33 drill (.1130 dia.) is reduced to .1125 dia. and is used to drill a pilot hole in the specimen.
11.

Subsequently a 5/16" (0.3125") dia. hole is drilled thus making 0.10" depth of cut.

Using the above procedure in conjunction with a feed rate of 0.010" per rev. the torque is measured in inch pounds.

The machinability index (power) is then calculated as follows:-

\[ M, I \text{ (power)} = \frac{\text{Torque (in lbs.)}}{0.212} = \text{pressure on cutting edge} \]

3.4.3.2. Specific cutting capacity

As for turning

\[ S, C, C. = \frac{396}{\text{machinability index}} \]

3.4.3.3. Effect on power of variation of drill diameter and rate of feed

When the standard chip section is varied the effect on power may be determined by applying the exponential indices for diameter and feed per rev. as found in the following relationship.

\[ \text{Pressure on cutting edge} = M, I \times d^a \times f^b \times 1000 \]

'a' is determined by keeping 'f' constant and varying 'd'; similarly 'b' is determined by keeping 'd' constant and varying 'f'.

3.4.4. Comparison of lubricants and coolants

It is more difficult to control this experiment in the drilling operation since the swarf may prevent effective functioning of the test fluids. One method which assists the application of the lubricants and coolants is to employ test specimens of a smaller diameter than the drill being used; the workpiece is then completely drilled away thus eliminating clogging of the swarf.

3.4.5. Comparison of cutting force relationships

An approximation to orthogonal cutting can be achieved if the drill is ground with a flat (180°) cutting point. To avoid the effect of web thickness it is necessary to drill a pilot hole as in section 3.4.3.1. Also, to prevent the flat drill from wandering it should be guided in a drill bush as shown in Fig. 15.
12.

The translation of torque and thrust readings into Merchant's nomenclature of cutting force \( F_c \) and thrust force \( F_t \) is as follows:

\[
F_c = \frac{\text{dynamometer thrust load}}{2}
\]

\[
F_t = \frac{\text{torque (inch lbs.)}}{\text{mean dia. of cut}}
\]

**Example**

Assuming a pilot hole of \( 0.1125 \) diameter has been drilled, followed by a drill of \( 0.3125 \) diameter then the
mean dia. of cut = \( 0.3125 - (\frac{0.3125 - 0.1125}{2}) \)

\[
= 0.2125
\]

The values for friction \( F \) and the coefficient of friction \( \tau \) are derived as formerly.

3.4.6. Workshop machinability comparator

In combination with other factors and as hardness, strength etc. the machinability index as described in Section 3.4.3.1. gives guidance to the machining characteristics of a material and an inspection of this feature prior to the commencement of machining often prevents bad material being issued to the works.

3.4.7. Special applications

**Tapping**

The drill dynamometer may be used for the measurement of torque during tapping operations. Since torque is an important factor on tap breakage this measurement assists in the evaluation of tap design and lubrication.
APPENDIX I

Users of Lathe Dynamometers

Acton Technical College  Acton  London
Cumberland Technical College  Workington  Cumberland
Grantham Technical College  Grantham  Lincoln
Chance Technical College  Smethwick  Birmingham
Hatfield Technical College  Hatfield  Herts.
Nottingham & District Technical College  Nottingham
The University of Leeds  Leeds
Ipswich School of Technology  Ipswich
Leeds College of Technology  Leeds
Rotheram College of Technology  Rotherham
Murex Limited  Rainham  Essex
Jarrow Technical Institute  Jarrow  Durham
Durham University, Kings College  Newcastle-upon-Tyne
Rhondda Technical Institute  Tonypandy  Rhondda, Glam.
Medway Technical College  Gillingham  Kent
Merthyr Tydfil Technical College  Merthyr Tydfil  Glam.
Aylesbury Technical School  Aylesbury  Bucks.
Wolverton Technical College  Wolverton  Glasgow
Glasgow Stow College  Wrexham
Denbighshire Technical College  Middlesex
Twickenham Technical College  Twickenham  Croydon
Croydon Polytechnic  Leicester
Leicester College of Technology and Commerce  Glasgow
Mechanical Engineering Research Laboratory  Gloucester.
Stroud Technical College  Stroud  Bucks.
College of Aeronautics  Cranfield  Rugby
British Thomson-Houston Co, Ltd.  Coventry
Armstrong Siddeley Motors Ltd.  Reading
Reading Technical College  Reading
Maidstone Technical Institute  Maidstone  Kent
Burnley Municipal College  Burnley  Lancs.
Isle of Wight Technical College  Isle of Wight
Swansea Technical College  Swansea
Basingstoke Technical Institute  Basingstoke  Hants.
Wimbledon Technical College  Wimbledon  London
Bristol College of Technology  Bristol
Accrington College of Further Education,  Accrington, Lancs.
Keighley Technical College  Keighley  Yorks.
Fletcher Miller Ltd.  Hyde  Manchester
Melbourne University  Victoria  Australia
Coventry Grinders Ltd.  Coventry  Warwick.
Gorvic Products Ltd.  Coventry  Warwick.
Derby Technical College  Derby.
<table>
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<td>Manchester Oil Refinery Ltd.</td>
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APPENDIX I (Contd.)

Kidderminster College of Further Education
Short Brothers & Harland Ltd.
Southampton Technical College
Sheffield College of Technology
Glamorgan Technical College  Treforest

Kidderminster
Belfast
Southampton
Sheffield 1.
Glam.
# APPENDIX II

## Users of Drill Dynamometers

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<th>College</th>
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<tr>
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<td>Cranfield</td>
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<td>British Thomson-Houston Co. Ltd.</td>
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<td>Warwick.</td>
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<td>Glam.</td>
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<td>Hants.</td>
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<td>Ches.</td>
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<td>Manchester</td>
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<td>Cumberland</td>
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<td>Australia</td>
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<td>Melbourne University</td>
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<td>Warwick.</td>
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<td>Warwick.</td>
</tr>
<tr>
<td>Gorvic Products Ltd.</td>
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</table>
APPENDIX II (Contd.)

Derby Technical College  
Impregnated Diamond Products Ltd.  
North Staffordshire Technical College, Stoke-on-Trent, Staffs.  
Royal Aircraft Establishment  
Dartford Technical College  
Woolwich Polytechnic  
Portsmouth Municipal College  
Dewsbury & Batley Technical & Art School, Batley  
Erith Technical College  
Chesterfield Technical College  
North East Essex Technical College, Colchester  
North Herts Technical College, Letchworth  
Guildford County Technical College, Guildford  
Birkenhead Technical College, Birkenhead  
Kingston Technical College, Kingston-upon-Thames, Surrey  
Stafford County Technical College, Stafford  
Wigan & District Mining & Technical College, Wigan, Lancs.  
Birmingham College of Technology  
Glamorgan Technical College  
Openshaw Technical College  
Cambridge University  
Warrington Technical College  
Barrow Central College of Further Education, Barrow-in-Furness, Lancs.  
Wolverhampton & Staffordshire Technical College, Wolverhampton  
Newton Heath Technical College  
Slough College of Further Education, Slough  
Newport Technical College  
High Wycombe College of Further Education, High Wycombe, Bucks.  
Southall Technical College  
Rolls Royce Ltd.  
North Oxfordshire Technical College, Banbury  
Constantine Technical College  
Brighton Technical College  
North West Wilts College of Further Education, Chippenham, Wilts.  
Kidderminster College of Further Education  
St. Helens Technical College  
Darlington Technical College  
Enfield Technical College  
Manchester Oil Refinery Ltd.  
Luton College of Further Education  
Sheffield College of Technology  

Derby  
Gloucester  
Hants.  
Dartford  
Woolwich  
Hants.  
Yorks.  
Kent  
Kent  
Essex  
Herts  
Surrey  
Cheshire  
Stafford  
Birmingham, 1.  
Lancs.  
Manchester  
Lancs.  
Mons.  
Middlesex  
Derby  
Oxon.  
Middlesborough  
Brighton  
Kidderminster  
Lancs.  
Darlington  
Middlesex  
Manchester, 17.  
Luton  
Sheffield, 1.
FIG. 1.

DIAGRAM OF LOADS
ACTING ON TOOL

FIG. 2.

TOOL HOLDER BODY

FIG. 3.

CONSTRUCTION OF DYNAMOMETER
FIG. 4.
CALIBRATION UNIT

FIG. 5.
DIAGRAM OF LATHE TOOL DYNAMOMETER.
FIG. 6. LATHE DYNAMOMETER

CALIBRATION CHART
FIG. 7. LATHE DYNAMOMETER

FIG. 8. 10° SIDE RAKE TOOL
FIG. 9a. VERTICAL TOOL LOADS FOR VARIOUS TRUE RAKE ANGLES

FIG. 9b. HORIZONTAL TOOL LOADS FOR VARIOUS TRUE RAKE ANGLES

FIG. 10. TOOL LIFE FOR VARIOUS TRUE RAKE ANGLES
**FIG. 11a.**

FORCE SYSTEM HOLDS CHIP IN STABLE MECHANICAL EQUILIBRIUM.

**FIG. 11b**

CONDENSED FORCE DIAGRAM SHOWING RELATIONSHIPS BETWEEN COMPONENTS
FIG. 12.
DIAGRAM OF DRILL DYNAMOMETER

SECTION XX

FIG. 13.
CALIBRATION UNIT

CALIBRATION FOR THRUST
PULLEY
WEIGHT

CALIBRATION FOR TORQUE.
CUTTING ANGLES FOR DRILLS TERMINOLOGY

FIG. 14.

DRILLING WITH GUIDE BUSH.

FIG. 15.
FIG. 16.
LATHE DYNAMOMETER USED FOR
TESTS ON PLANING ROCK