THE SELECTION OF SURFACE FINISH FOR ENGINEERING COMPONENTS

BY

JOHN HENRY SALT: B.Sc. (Aston)., D.G.S (B'ham). C.Eng., M.I.Mech. E., M.I. Prod.E., F.I.E.I.

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CONTENTS

SUMMARY

One of the problems facing designers is specifying the surface textures required on surfaces in sliding contact. For a given application there is an optimum method of producing a suitable surface texture with respect to:-

(i) The cost of manufacture.

(ii) The Effect of the surface texture on the functioning of the components.

There is little published information available for guidance and most of this has been obtained by surveys of existing practise. Accordingly a research programme was carried out to investigate the effects on the rate of wear of:-

(i) The Surface textures produced by various manufacturing processes.

(ii) The orientation of the lay of the surface with respect to the direction of sliding.

As part of a general survey into methods of examining surface texture the use of a Scanning Electron Microscope (S.E.M.) was evaluated, since this instrument has a much greater depth of focus and higher magnification than optical instruments, and permits direct examination of the surface without the need for replica techniques.
Similarly techniques for the measurement of small amounts of wear have been investigated.

ILLUSTRATIONS

Illustrations (Continued)

Illustrations (Continued)

INTRODUCTION

1.1. Whenever components are machined or formed the surface resulting from the operation may have a marked effect on the functioning of the components. The most important field of activity is bearings and slideways but others, notably fatigue strength and noise are becoming increasingly important, as also is work on forming of sheet material. The main problems to be resolved in the correct specification of surface texture are in determining:

(i) Suitable parameters for defining surface texture.

(ii) The Effect of surface texture on the functioning of the component.

(iii) The effect of machining on the finished surfaces performance.

(iv) The cost of manufacture.

In determining the effect of surface texture on functioning it must be realised that it may have only a small effect on the performance as shown in Fig. 1.1. this diagram highlights the problem of repeating experimental work with such a large number of potential variables. Thus in a large number of research papers relating to friction and wear, little information is given on the surface texture of the specimens used and in some cases the manufacturing method viz. using emery paper to roughen the surfaces is not typical of present day production techniques and may not have the same effect on the surface and underlying metallurgical structure. Similarly the manufacturing technique used to produce a high quality surface may also lead to improvements

Introduction (Continued)

1.1. in other factors, notably geometric form i.e. roundness and straightness which may not be measured and whose effect is not considered.

Recent developments in the field of surface metrology have led to increased considerations of the "surface integrity" or the unimpaired or enhanced condition of a component after processing, since the actual values of fatigue strength, stress corrosion resistance and ultimate strength often depend as much on the surface condition of the part as they do on the base material (1) .

1.2. At this stage it is worth considering current theories of wear and the research that has been carried out. Rabinowitz (2) has classified wear into 4 distinct types viz.

a) Adhesive wear - attraction between surface atoms of two contacting materials, leading to the transfer of material from one surface to the other and eventually to the formation of loose fragments. This has been further subdivided by Hirst (3) into Mild Wear and Severe Wear.

b) Abrasive Wear - removal of materials by the filing action of a hard rough surface against a softer one, or by abrasive grains trapped between smooth surfaces.

c) Corrosive Wear - similar to ordinary corrosion except that the sliding dislodges products of corrosion.

d) Surface fatigue wear - fatigue cracks in or near the sliding surface, leading to formation of large wear fragments.

Sliding may give either one or a combination of these forms of wear.

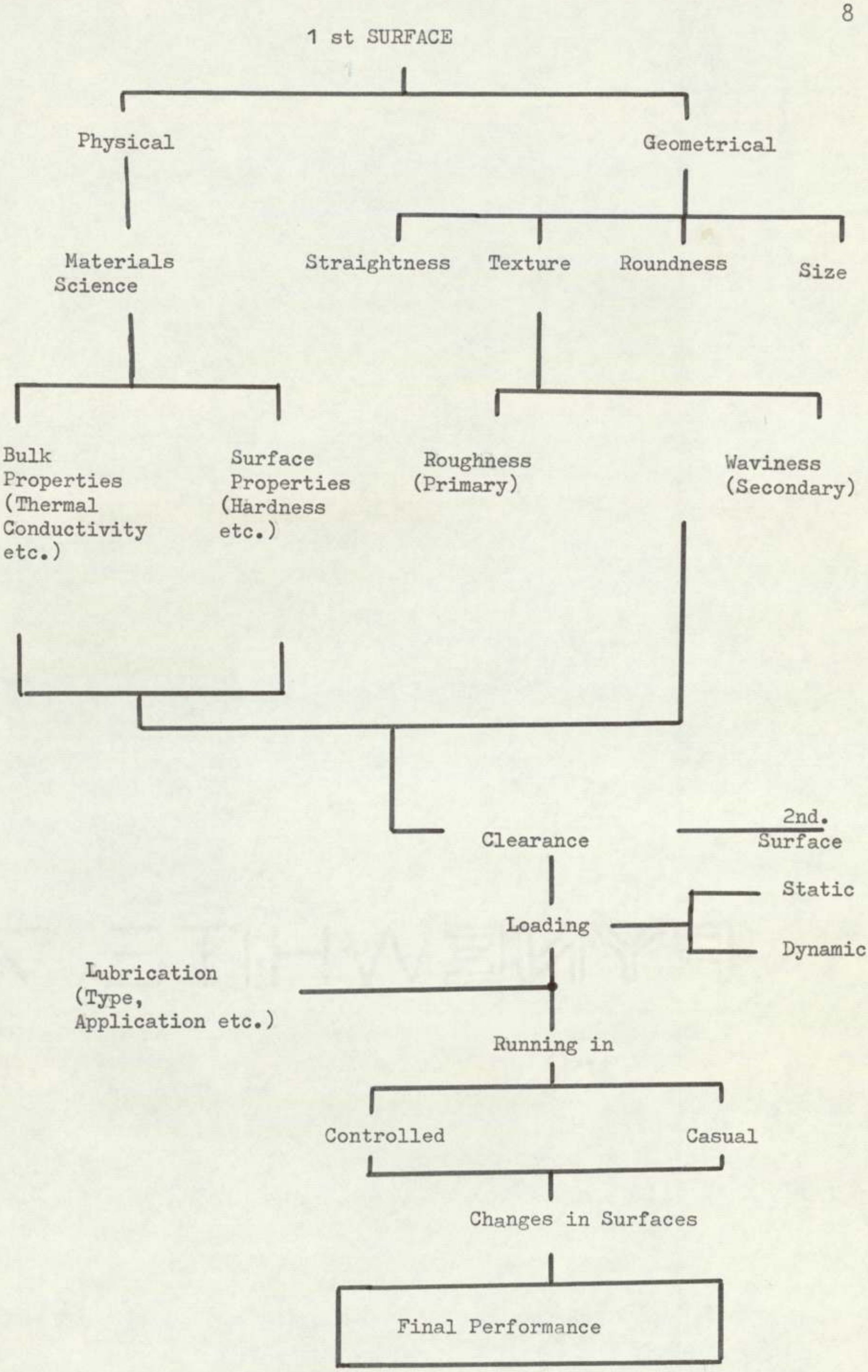


Fig. 1.1. Factors affecting Performance of Bearings & Slideways.

1.2. If we consider adhesive wear in more detail the main problem is to determine the action of two surfaces, each containing numbers of asperities, which may vary both in height, spacing and geometry, in contact with or without a lubricant film either artificial or a natural oxide, in relative motion. It is proposed to examine two main approaches to the problem

(i) Analytical i.e. Archard

(ii) Empirical i.e. I.B.M.

(i) Archard (4).

This first simple model assumed that the surface was covered with hemispherical asperities, when this is placed in contact with another surface the real area of contact A_r will be far less than the apparent area A and will increase as the load W increases due to plastic deformation.

$$W = p \times A_r \qquad (1)$$

W = Load perpendicular to the surface

A_r = Real area of contact

p = Flow strength or pentration hardness of the material.

Fig. 1.2. shows the basic model when the two surfaces move relatively the contact area will reduce to zero after sliding a distance "a", at the same time a new similar contact of diameter a will be fully established elsewhere on the surface. This must be so in order to support the applied load.

The wear fragments are assumed to be hemispherical, hence the volume of wear fragments is proportional to the cube of the contact diameter.

i.e. Worn Volume (ΔV) $\propto$ a^3; the effective sliding distance (L) will be proportional to a

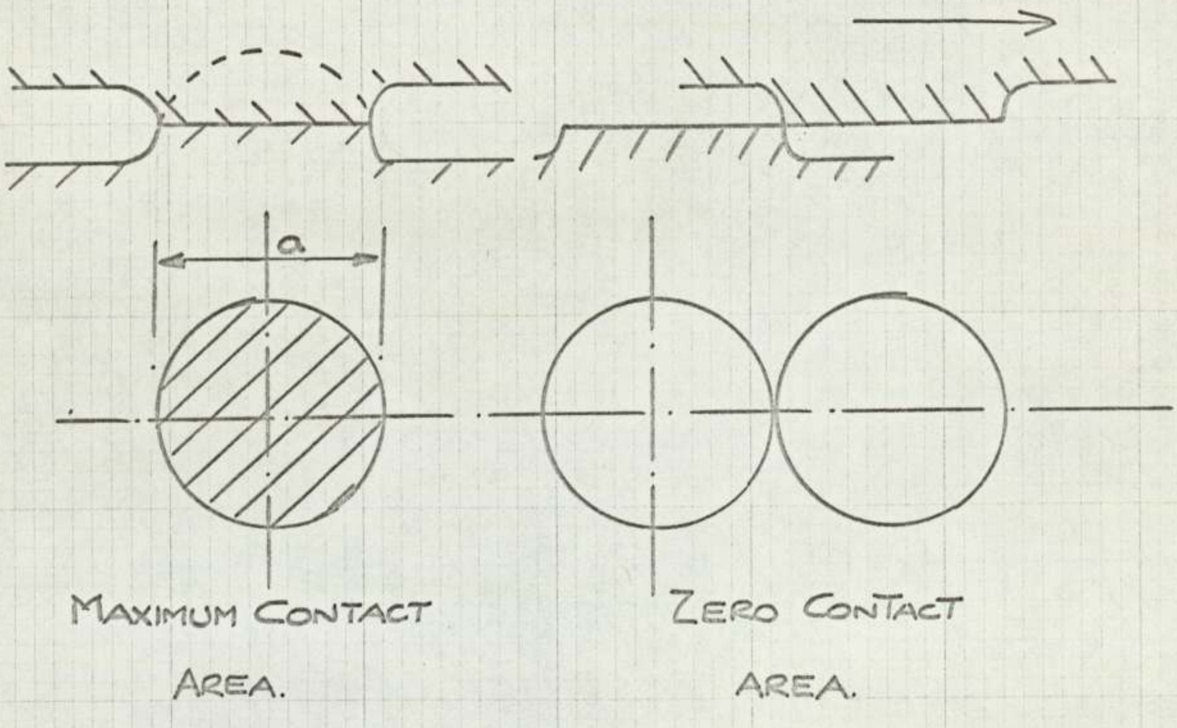


FIG. 1–2 ARCHARD'S MODEL FOR WEAR

$$L \propto a$$

$$\text{Wear/Unit distance} = \frac{V}{L} \propto \frac{a^3}{a} \propto a^2$$

$$\text{Total Wear Volume} = a^2.L \qquad (2)$$

but from basic model a^2 is related to A_r

$$a^2 \propto A_r \qquad (3)$$

Total Volume of Wear $\propto A_r.L$

Substituting for Ar from Equation 1.

Total Volume of Wear (V) $\propto \frac{WL}{p}$

$$V = \frac{K.W.L.}{p} \qquad (4)$$

K is the probability that a contact will produce a wear particle and is the proportion of contacts producing a wear particle.

By substituting in known experimental results the value of K can be calculated, this can vary over several orders of magnitude (5).

i.e. Mild Steel Pin on Mild Steel Ring $K = 7 \times 10^{-3}$ $\mu = 0.62$

Polythene Pin on Tool Steel Ring $K = 1.3 \times 10^{-7}$ $\mu = 0.65$

The coefficient of friction (μ) remains relatively constant. Archard suggests this is because all the contacts contribute towards friction whereas only a small proportion contribute to wear.

(ii) I.B.M. Endicott Development Laboratory.

This group was set up in 1952 to establish a system of "design data for wear" (6).

No prior assumption of the type of wear to be expected was made and wear was classified as follows:-

> "ZERO WEAR" is a change in the surface contour of such a magnitude that the surface finish in the wear track is not significantly different from the finish in the unworn portion. This limits the depth of the wear scar to approximately one-half the peak to valley value of the surface finish. "NON-ZERO" wear will result in a change of contour which is greater than the surface finish.

Considering the ZERO WEAR model in more detail, the engineering model is concerned with two bodies pressed together and subject to relative sliding movement. It states that wear can be controlled by limiting the maximum shear stress Tmax. occurring in the vicinity of the contact region.

It further states that wear can be held to a zero level for a particular number of passes N if T max is smaller or equal to a certain fraction (γ) of the yield point in shear of the material Ty.

$$T_{max} \leqslant \gamma . T_y \qquad (1)$$

For 2,000 passes the value of γ is designated γ_R

$$\text{where} \quad \gamma = \left\{ \frac{2 \times 10^3}{N} \right\}^{\frac{1}{9}} . \quad \gamma_R \qquad (2)$$

and the constant γ_R is found experimentally. Experience has shown that it can be restricted to two possible values for dry or boundary lubrication conditions, providing that restrictions are placed on the load and speed conditions to reduce heating effects.

Use of Design Procedure.

The essential point is to ensure that

$$T\,max \leqslant \left\{ \frac{2 \times 10^3}{N} \right\}^{\frac{1}{9}} . \gamma_R . Ty \qquad (3)$$

This involves evaluating

(i) Tmax. This is the maximum shear stress occurring in the vicinity of the contact and can be calculated from a knowledge of the geometry and forces involved.

(ii) N the number of passes for the entire lifetime, where a pass is defined as a distance of sliding, W equal to the dimension of the contact area taken in the direction of sliding.

N will be based on the number of cycles L required i.e. revolutions or strokes and the number of passes per cycle (n)

$$N = nL$$

(iii) Ty. This is usually tabulated for standard materials or may be obtained from micro-hardness readings.

(iv) γR. This is a function of the lubricant and combination of materials used. Values have been determined experimentally for a number of material combinations and are tabulated. If it is not known then the lowest value 0.2 is used.

By substituting these values in equation 3, it can be established if the inequality can be satisfied and hence the required lifetime obtained for a particular design, if not, material geometry must be changed and the procedure repeated until a suitable design is arrived at.

The workers at I.B.M. proposed that the wear v sliding distance curve would be built up as shown in Fig. 1.4 from a linear component which is due to steady state wear over a long sliding distance and a transient state attributed to the "breaking in" of the surface by removal of the surface irregularities associated with the original surface roughness (7).

This suggests that $W = B \ (1 - e^{-nL}) + KL$ (4)
and at long sliding distances

$$W \simeq B + KL$$

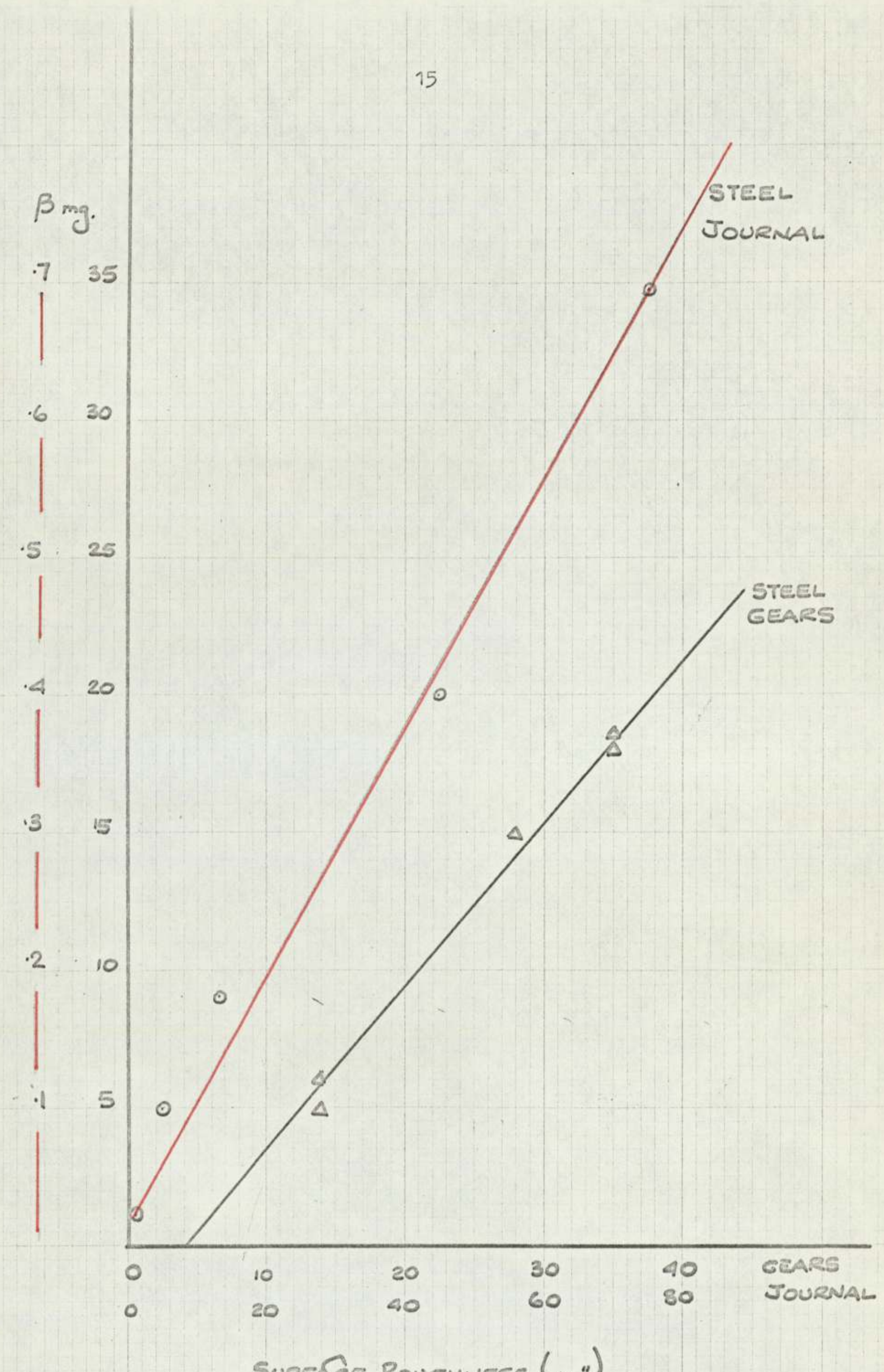
where B is the total contribution from the original surface texture. From equation (4) it is suggested that

(i) B should be proportional to "roughness"

(ii) It should be possible to evaluate B from a knowledge of surface geometry and profile.

Results from Lewis (8) were used to justify this equation Fig. 1.3.

A number of experiments have been carried out by various workers to determine the wear of sliding surfaces produced by different manufacturing methods (9) (10). No analytical work is reported and no details are given of the direction of lay. Fig. 1.5. shows the results of research work carried out by Opitz (11) which has been replotted on a base of h_{CLA}. The resulting graph is of the form $Y = 3.59 + 5.64 \ x^2$ using curvilinear regression, the use of a more sophisticated polynomial is not warranted in view of the small number of points and the lack of knowledge of the accuracy of the experimental results. Any confidence limits attributed to the graphs Fig. 1.3 and Fig. 1.5. would be low in view of these reasons. It must always be realised that each point on a wear v time or wear v surface roughness may represent the results of some hundreds of hours experimental time and hence the limited number of experimental points available and restricted use of statistical analysis, unlike experiments in such diciplines as metal cutting where the large number of results allow much greater precision in analysis.



GRAPHS OF "β" AGAINST INITIAL SURFACE ROUGHNESS

FIG. 1-3 (DATA FROM LEWIS (8))

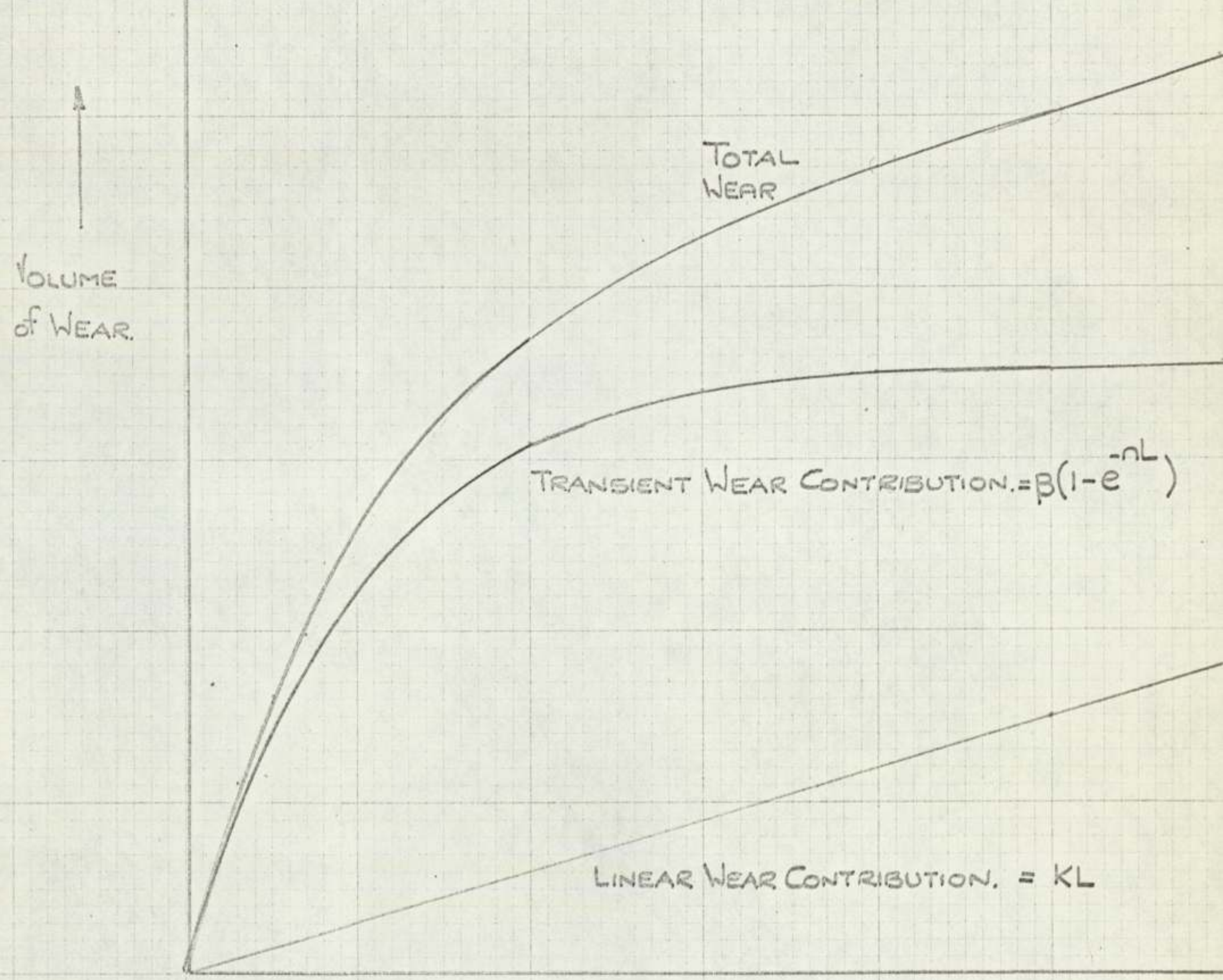


Fig. 1.4 Schematic Representation Of Total Wear As The Sum Of Two Components

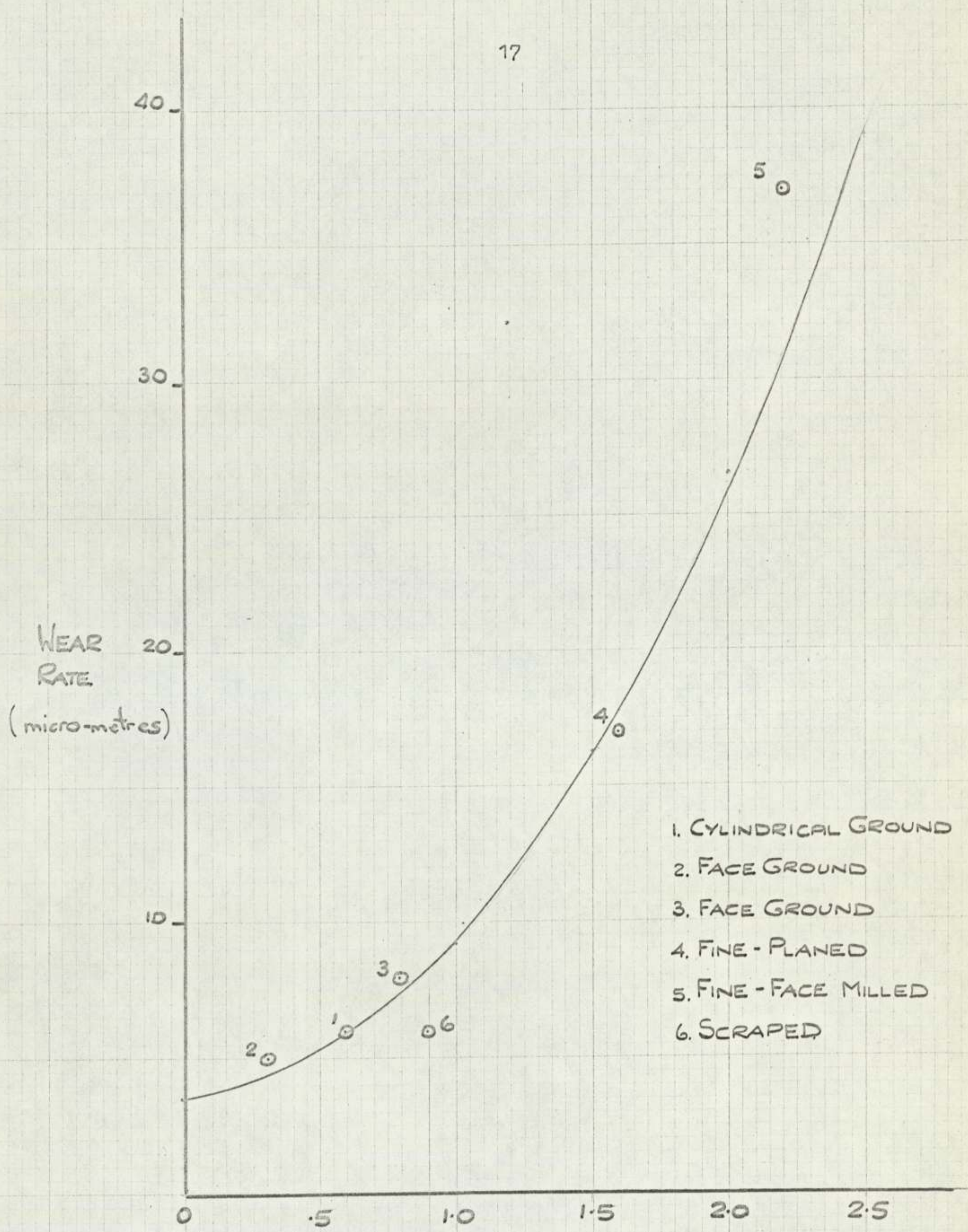


FIG. 1-5

WEAR RATE v Ra

DATA FROM OPITZ (11)

The graph predicts that wear will take place at zero surface finish. Unfortunately lack of data prevents Fig. 1.3 and Fig. 1.5 being combined.

In an experiment carried out at P.E.R.A. (12) on shearing of sheet metal, circular punches with similar surface finish where produced by

(a) Conventional circumferential grinding

(b) Longitudinal grinding using special set up and formed wheels.

The results of this work indicated that the rate of wear of punches was not influenced by the direction of grinding.

No other similar published work has been located, which is perhaps surprising since in a number of applications the direction of grinding or machining is perpendicular to the direction of sliding i.e. form ground gears, and in most testing machines of the disc type used to simulate wear conditions the direction of machining is parallel to the direction of sliding.

1.3. Assuming that the correct surface finish has been specified by the designer based on experimental work the problem becomes one of ensuring that the designers specification has been met. This may be considered using a systems approach Fig. 1.6.

The basic specification of surface texture has been the subject of discussion over a number of years, with the most commonly used ones shown in Fig. 1.7.

Of these the M system or Centre-Line Average system has found most international recognition and has been adopted as a standard in the following countries Gt. Britain, U.S.A, Holland, Spain and France.

The system has a number of defects viz:

(i) The C.L.A. value has no fixed relationship to the actual depth of the irregularities.

(ii) The graph and C.L.A. value are the result of a stylus traverse along a straight line and this may not give a true picture of the surface.

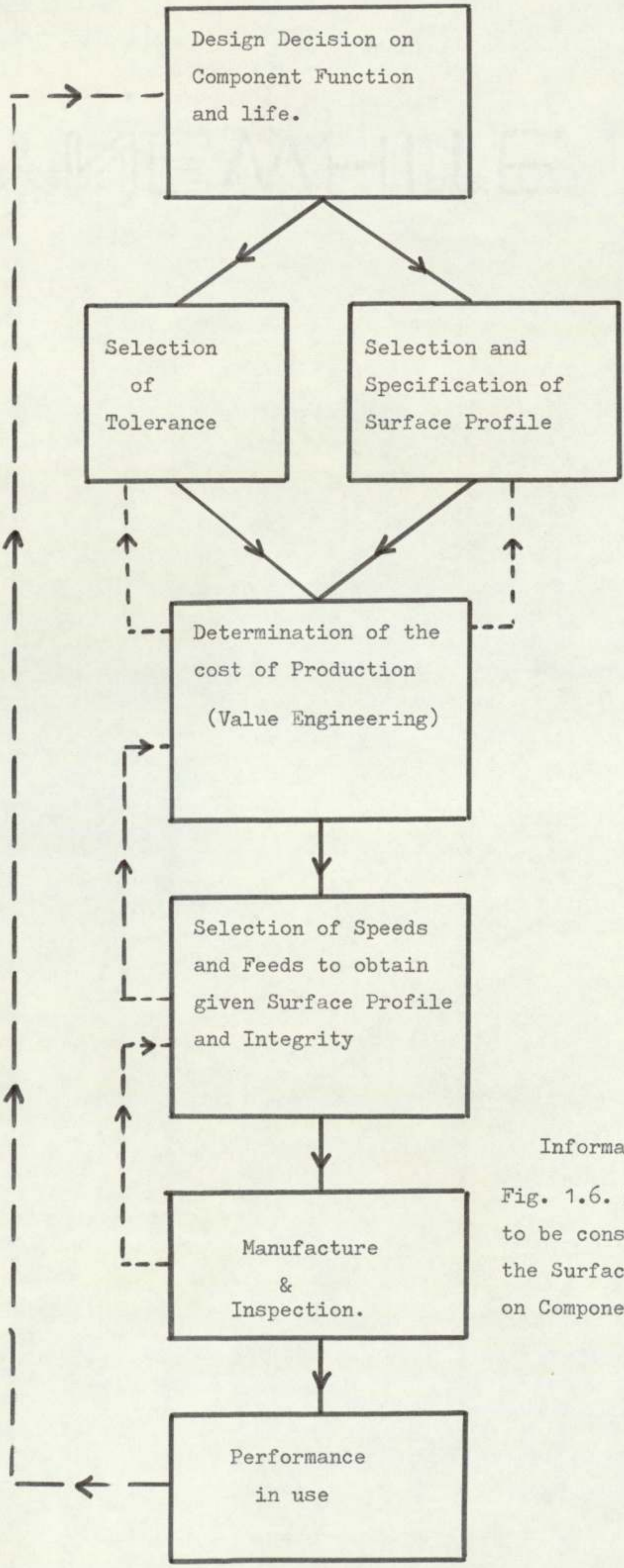
It is however, a system which can be instrumented easily and reliably and is suitable for controlling.

With all stylus instruments problems exist in providing a datum surface for the stylus, it must be recognised that there is always a danger of the phase relationship between datum and stylus giving a "false" C.L.A. value.

It is suggested by some workers that the "M" system could be extended by adding control over Peak to Valley height (13) and instruments are available which provide information on peaks and valleys. It is also possible to obtain Abbot-Firestone bearing area curves but Reason (14) has pointed out the main problems of using this curve as a means of specifying surface requirements.

a) The fraction determined from the profile is basically that of a length not an area of the surface.

b) The fraction is generally related only to a small sample of the surface, and ignores the gaps that may result from waviness and errors of form.



Information Feedback - - - -

Fig. 1.6. Engineering Factors to be considered when deciding the Surface Finish to be used on Components.

Standard	Formula	Used In
Maximal Depth	$R_{max} = (y_{max} - y_{min})$	Germany Austria Switzerland Italy Sweden Jugoslavia Poland Czechoslovakia Russia Belgium
Mean Depth	$R_m = \frac{1}{l}\int_0^l y\,dx$	Germany Austria
Depth of Smoothness	$R_p = G = R_{max} - R_m$ G stands for Glattungstiefe (German)	France Germany Switzerland
Arithmetical Average	$CLA = \frac{1}{l}\int_0^l \lvert y - R_m \rvert\,dx$	Gt. Britain USA Holland Spain France
Geometrical Average (Officially Abandoned by USA, but Still Used)	$RMS = \sqrt{\frac{1}{l}\int_0^l (y - R_m)^2\,dx}$	USA Russia Poland Czechoslovakia
Peak to Valley Average (Although Recommended by BS 1134, Very Rarely Used)	$PVA = \frac{(H_1 + H_3 + \cdots H_9) - (H_2 + H_4 + \cdots H_{10})}{5}$	Britain
Percentage Bearing Area	$B_A = \frac{L_1 + L_2 + L_3 + L_4}{l}\,100\%$	Germany Switzerland Austria
Swedish Standard	$H_{SMS} = (X - Y)$ Lines X and Y Positioned so that $\Sigma P = k_1 L$ $\Sigma V = k_2 L$ Swedish Standard Appoints $k_1 = 0{\cdot}05$ $k_2 = 0{\cdot}10$	Sweden

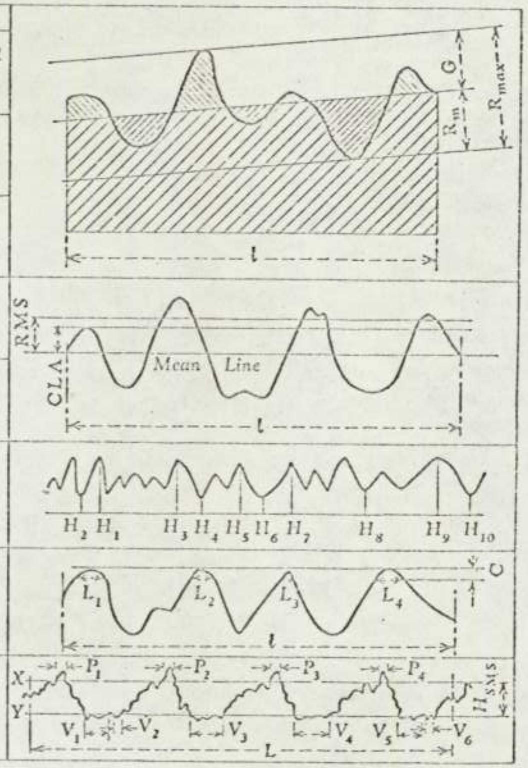


FIG 1-7

c) The measured fraction will be representative of the bearing area of the sample, only if the profile continues without change along the length of the lay. It might be logical to take, as the area fraction, the product of two length fractions measured along and across the lay, but for the measurement along the lay great care would have to be taken over the choice of cut-off and/or stylus shape. On ground surfaces for example, the crest spacing along the lay is many times the spacing across the lay, and a measurement along the lay taken with a stylus and cut-off suitable for measurement across the lay would have no practical meaning.

d) The fraction refers to the unloaded surface and assumes there is no elastic deformation.

e) In practice, two surfaces are required to form a slideway, and the topography of each has a part to play.

f) Wear is often accompanied by physical flow of the surfaces, and the geometrical concept of the crests being neatly truncated by a line drawn through them is probably unrealistic.

In the field of sheet metal forming it is found that the graph from a stylus instrument is useful in determining the drawing ability of sheet material and a recent paper (15) suggested that profiles on sheet materials could be classified under 6 heading viz:

(i) Open Smooth
(ii) Open irregular
(iii) Round Peak, Round Valley
(iv) Round Peak, Sharp Valley
(v) Sharp Peak, Round Valley
(vi) Sharp Peak, Sharp Valley

In view of the problems involved in relating surface texture to function a number of different approaches have been made by various workers. A technique of classifying surfaces using Ramdom Process Analysis has been developed by PEKLENIK (16). In this approach the surface profile generated in a manufacturing process is considered to vary between two basic profile shapes.

(i) A deterministic function without any random distortions
(ii) A wide band random noise

and surfaces are classified into groups based on analysis of their profiles using correlation functions.

At present no work has been published relating the surface classification with function.

Information for the analysis is obtained from a conventional stylus type instrument and associated data-logging equipment. It is felt that the information obtained from a stylus instrument may not be valid in some circumstances. Figs. 1.8, 1.9 show Stereoscan photographs of a ground surface which exhibits a series of crests as reported by several workers (17). This would appear to a stylus instrument as a solid metal ridge, but, in fact, would probably deform or break off very easily. Other workers have reported damage to the surface by the stylus during measurement (18) and whilst there is still controversy over this it raises the problem of the use of a sophisticated data-logging system if the basic measuring stylus may not be following the surface.

It must also be realised that since stylus loads are very small, that deformation due to stylus pressure must be far less than that actually encountered in service.

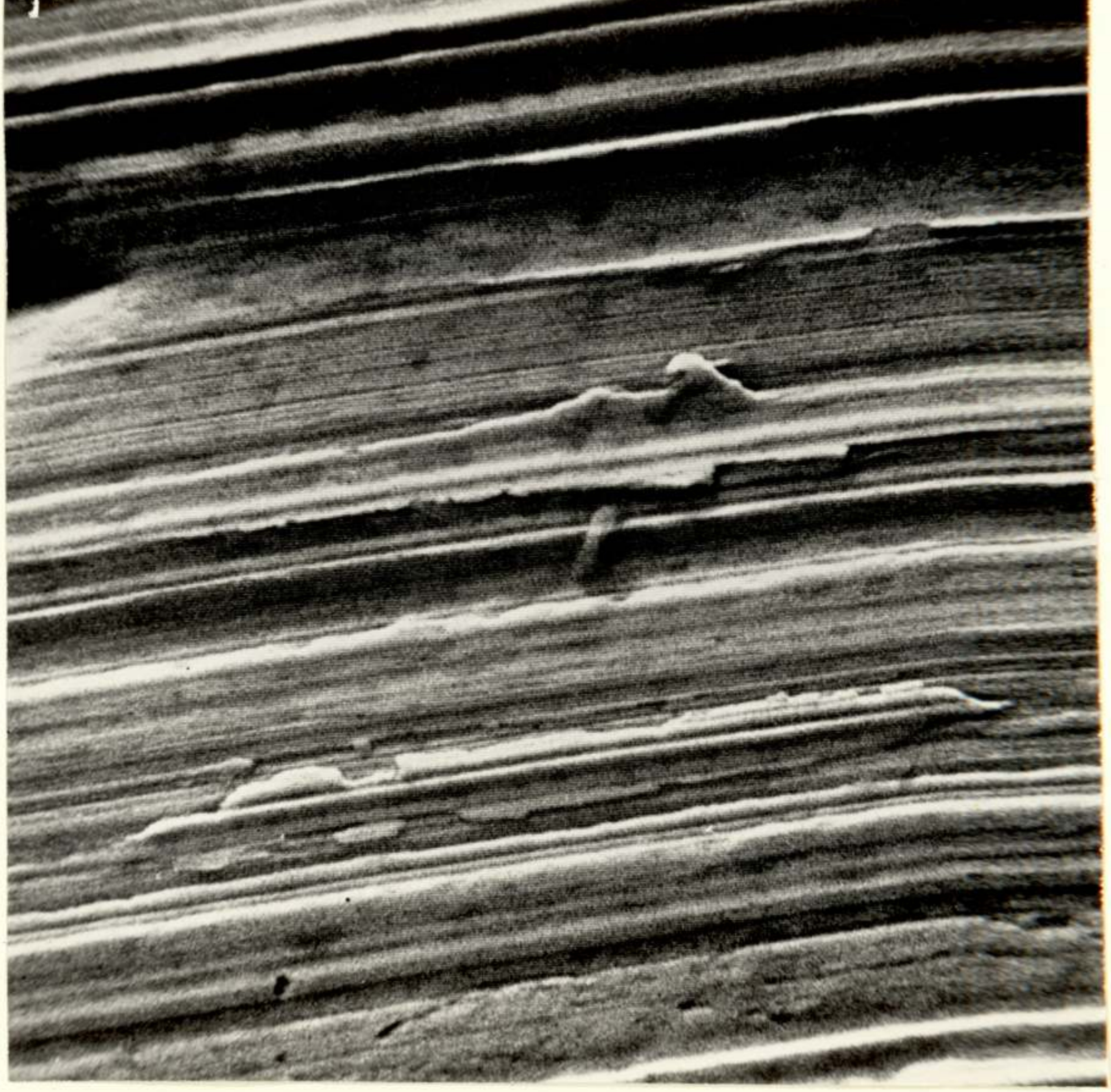


Fig. 1.8. Surface Ground Specimen showing "Wave Formation"

h_{CLA} = 0.31 micro-metres

x 4,500

Ref. No. 3.

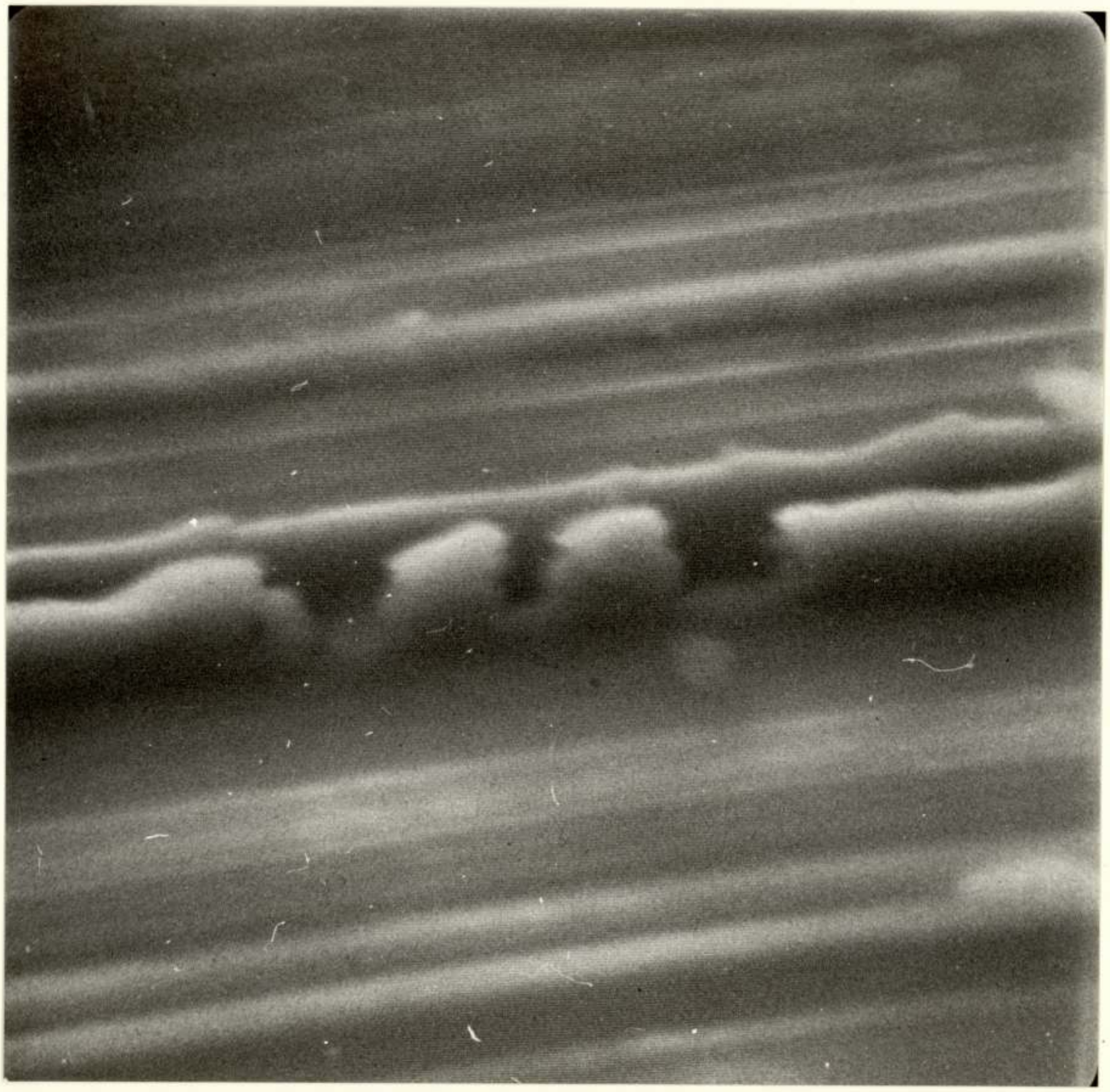


Fig.1.9. Vertical Ground Specimen
x 10.4 K.

Grinding Condition: Depth of Cut 0.01 mm
to spark out.
Coolant used.

Ref. No. 312.

1.4. A recent publication (19) in Czechoslovakia contains the results of a survey of surface finishes on engineering systems measured using the "M" system.

The measurements were carried out through the range of manufacturing organisations and the publication is intended as a guide to detail draughtsmen and designers. The information is coded using a Group Technology approach based on a functional classification Fig. 1.10a and b. This enables the designer to examine his mechanism and select the "family" to which it belongs and then to refer to a data sheet Fig. 1.11 which gives recommendations for individual components. Information is also given relating to production methods and costs.

Whilst no research has been carried out to determine if these are the optimum figures it remains a unique guide-analagous to B.S.1916 Part 2. "A guide to the selection of limits and fits".

The method of component classification would seem a suitable basis for a data retrieval system. A system of information retrieval has been developed by a commercial firm using punched cards as a basis Fig.1.12 and this also provides information for the designer, but does not consider functional aspects, its main purpose is to highlight manufacturing processes to give a stated surface finish.

A similar survey carried out in this country covering both surface finish and roundness would be very useful for both information and comparison purposes, particularly if the distribution curves for each application were made available. A start has been made by P.E.R.A. as part of a survey into turned parts and it is hoped to extend this into the field of grinding.

At this stage in the production of components decisions must be made as to the cost of producing the required finish. This must be linked with the designers decision on function, life and economic selling price. The use of Value Engineering has become more prominent in recent years and charts are available Fig. 1.13, 14, 15 (20) (21) showing the cost relationships for various machining operations. These can only be general guides since the actual decision and cost will depend upon the equipment available.

BASIC SCHEME FOR THE SELECTION OF COMPONENT SURFACE.

(TRANSLATED FROM THE CZECH).

					EXAMPLE
COMPONENT SURFACE	FUNCTIONAL SURFACES	MOUNTED ONE IN THE OTHER	0 MOVEABLE	01 ROTARY	PLAIN BEARING
				02 SLIDING	PISTON
			1 FIXED	11 DEMOUNTABLE	KEYWAY
				12 BEARING HOUSING	BALL BEARING HOUSING
				13 INTERFERENCE FIT	SHRUNK ON RIM
				14 SPLINES	SPLINED SHAFT
		MOUNTED ONE ON THE OTHER	2 MOVEABLE	21 SLIDING	MACHINE TOOL SLIDEWAY
				22 ROLLING	NEEDLE BEARINGS
			3 FIXED	31 DISSEMBLED	JOINT FACE
		WITH SPECIAL REQUIREMENTS	4 TRANSMISSIONS	41 SERRATED	GEARS
				42 SCREWED	WORM GEAR
				43 BELT & CHAINS	PULLEY
				44 FRICTION	CLUTCH FACE
				45 CAMS	I.C. ENGINE CAM
			5 ACTIVE SURFACE OF MEASURING TOOL	51 SLIDING	PLAIN RING GAUGE
				52 TOUCHING	MICROMETER ANVIL
				53 SITTING ON	PRECISION SQUARE
			6 TOOL	61 SAWING	MILLING CUTTER
				62 CUTTING	PRESS TOOL FOR BLANKING
				63 FORMING	" " " DRAWING
				64 CASTING.	INJECTION MOULDING TOOL
	FREE SURFACE		7 IMPORTANT	71 INFLUENCES PHYSICAL CHARACTERISTICS AND EVENTS	TURBINE BLADE PROFILE
				72 WITH SPECIAL REQUIREMENTS	MACHINE HANDLE.
			8 VISIBLE & PROTECTED ON THE SURFACE	81 VISIBLE & ON THE SURFACE	
				82 "BEFORE THE SURFACE PROJECTION OF THE COVER"	
			9 "MECHANICALLY"	91 FOR PRODUCTION REASONS	UNDERCUT ON SCREW-THREAD

J. SALT.

LIST OF TABLES

0 FUNCTIONAL SURFACES ASSEMBLED ONE INSIDE THE OTHER - MOVEABLE
- 01 With rotary movement
  - 011 Axle or pin in a bearing
  - 012 Surfaces with oscillatory movement
- 02 With sliding movement
  - 021 Cylindrical and other bodies sliding inside a body
  - 022 Packing for sliding surfaces
  - 023 Surfaces for guiding springs

1 FUNCTIONAL SURFACES ASSEMBLED ONE IN THE OTHER - FIXED
- 11 Rigid connections - demountable
  - 111 Cylindrical connection with accurate centering
  - 112 Conical surfaces with accurate centering
  - 113 Springs, wedges and elements of these
  - 114 Woodruff Keys
- 12 Immobile connection with intermediate support
  - 121 Easily dismantled connection transmitting force or torque
  - 122 Support for rolling bearings
- 13 Surfaces which cannot be dismantled
  - 131 Body or case pressed inside
  - 132 Rims of wheels
- 14 Splines

2 FUNCTIONAL SURFACES BEARING ONE ON ANOTHER - MOVEABLE
- 21 With sliding motion
  - 211 Sliding guides, flat or prismatic
  - 212 Thrust faces
- 22 Surfaces with rotary motion
  - 221 Needle Bearings
  - 222 Guide with rotary bodies
  - 223 Surfaces of wheels

3 FUNCTIONAL SURFACES BEARING ONE ON ANOTHER - IMMOBILE - FIXED
- 31 Fixed non-demountable connection
  - 311 Contact Surfaces plane and shaped
  - 312 Thrust Faces
  - 313 Sealing Surfaces

FIG. 1.10 b

LIST OF TABLES continued...

Fig. 1.10 b

2 — Funkční plochy dosedající jedna na druhou — pohyblivé — Tab. 18

21 — KLUZNÁ VEDENÍ PLOCHÁ A PRISMATICKÁ
Vybrané příklady z různých strojírenských oborů

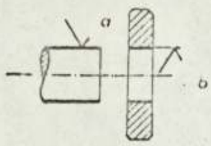
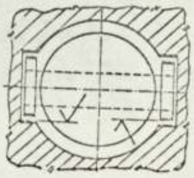
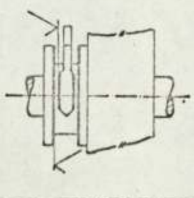
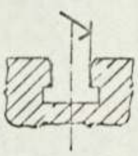
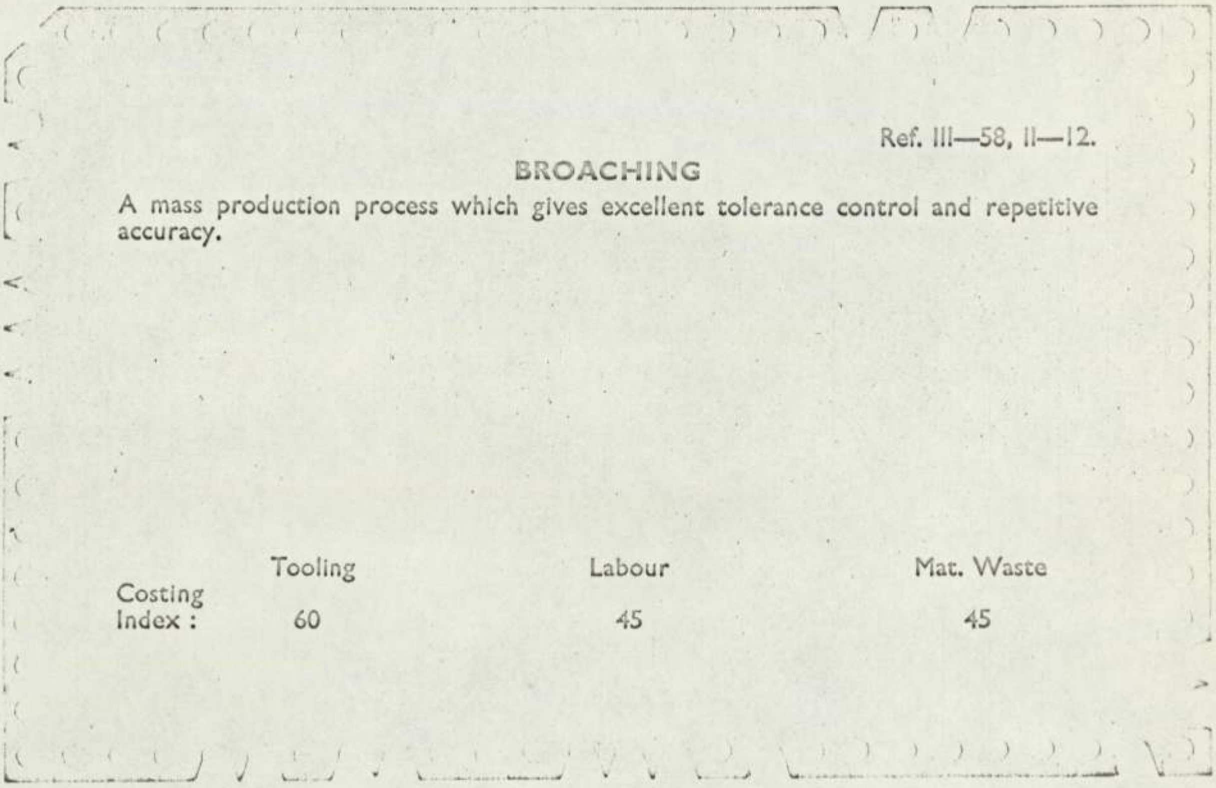
Příklady z výrobního oboru			Provedení	Drsnost povrchu R_a (μm)
211.31 	Nástroje	Vedení razníků	razník (a)	0,4
			vodicí otvor (b)	0,8
211.32 	Automobilní a letecký průmysl	Kluzná vedení kameny křížového kloubu, palec řadicí páky v kulisách apod.	přesné	0,4
			běžné	0,8
211.33 	Automobilní a letecký průmysl	Vedení pro zasouvací vidlici	přesné	0,8
			běžné	1,6
211.34 	Zemědělské stroje	Vodicí drážky a vodicí lišty	smykadla	0,4
			broušené	0,8
			frézované	1,6

FIG 1-11



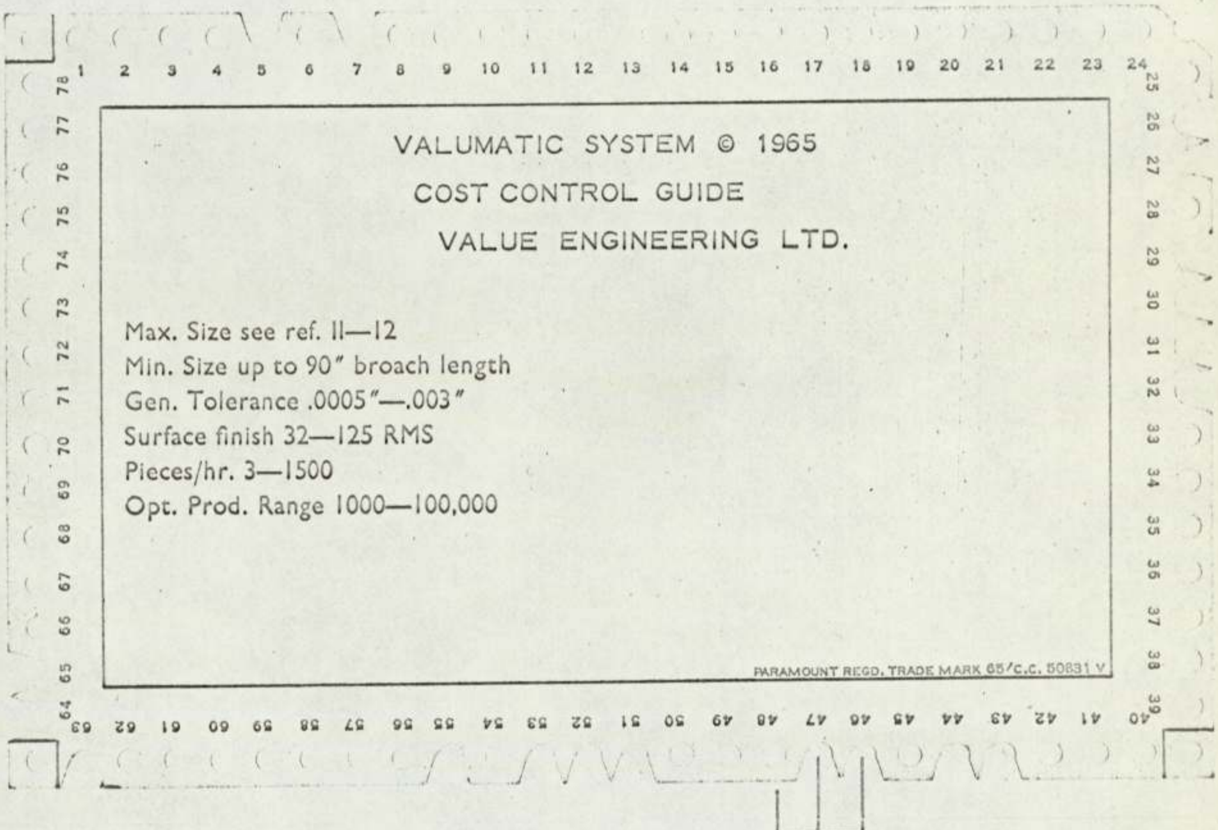
Ref. III—58, II—12.

BROACHING

A mass production process which gives excellent tolerance control and repetitive accuracy.

	Tooling	Labour	Mat. Waste
Costing Index :	60	45	45

a)Front



VALUMATIC SYSTEM © 1965

COST CONTROL GUIDE

VALUE ENGINEERING LTD.

Max. Size see ref. II—12
Min. Size up to 90" broach length
Gen. Tolerance .0005"—.003"
Surface finish 32—125 RMS
Pieces/hr. 3—1500
Opt. Prod. Range 1000—100,000

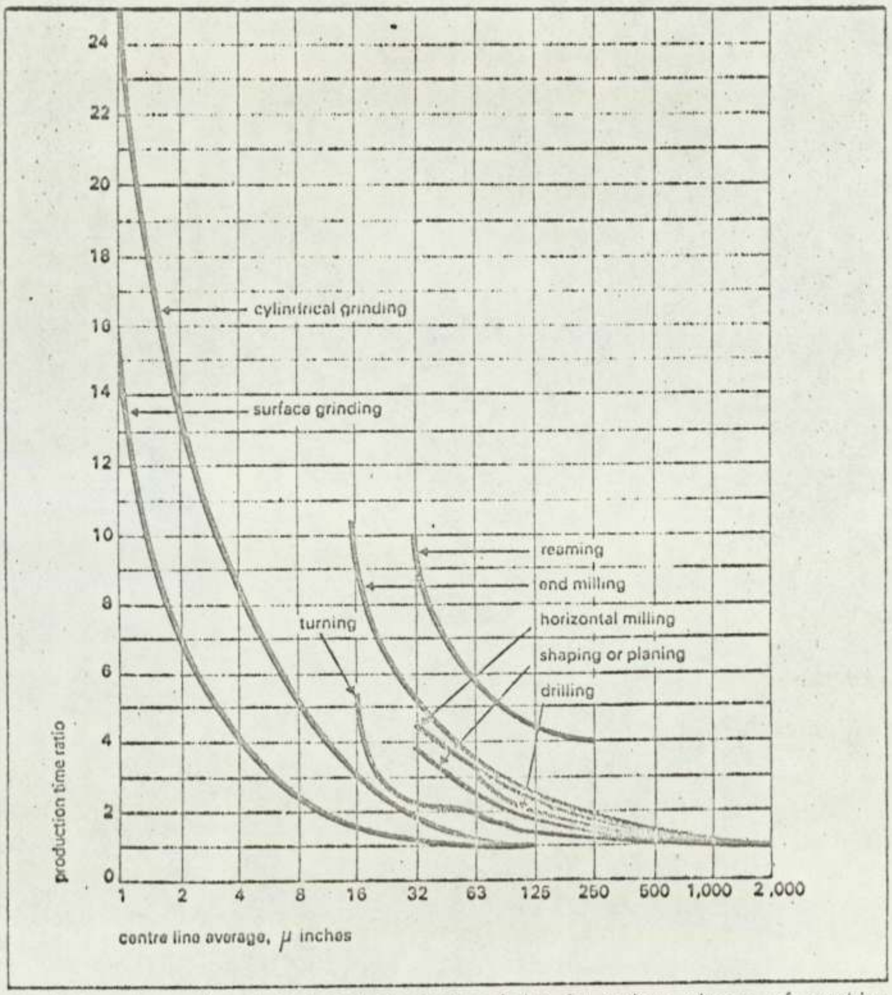
PARAMOUNT REGD. TRADE MARK 65/C.C. 50831 V

b)Back

h_{CLA} codes

46 <10
47 <100
48 <1,000

FIG 1-12



Machining time ratios plotted against surface finish for various classes of machine tools (compiled by M. P. Rubert)

FIG 1-13

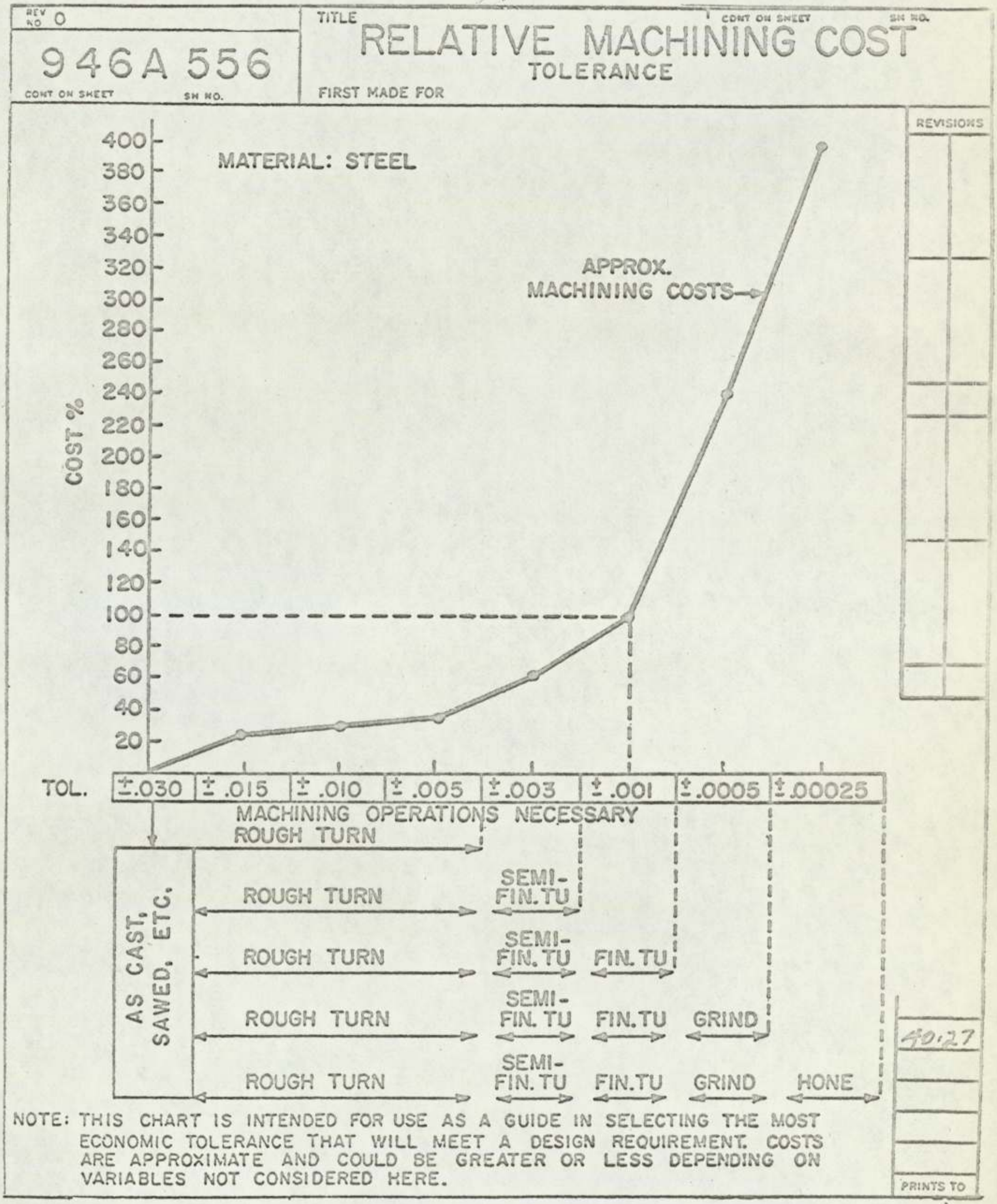

REV NO 0
946A 556
CONT ON SHEET
SH NO.
TITLE
RELATIVE MACHINING COST
TOLERANCE
FIRST MADE FOR
CONT ON SHEET
SH NO.
REVISIONS
MATERIAL: STEEL
COST %
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
APPROX.
MACHINING COSTS
TOL.
±.030
±.015
±.010
±.005
±.003
±.001
±.0005
±.00025
MACHINING OPERATIONS NECESSARY
ROUGH TURN
AS CAST, SAWED, ETC.
ROUGH TURN
SEMI-FIN. TU
ROUGH TURN
SEMI-FIN. TU
FIN. TU
ROUGH TURN
SEMI-FIN. TU
FIN. TU
GRIND
ROUGH TURN
SEMI-FIN. TU
FIN. TU
GRIND
HONE
NOTE: THIS CHART IS INTENDED FOR USE AS A GUIDE IN SELECTING THE MOST ECONOMIC TOLERANCE THAT WILL MEET A DESIGN REQUIREMENT. COSTS ARE APPROXIMATE AND COULD BE GREATER OR LESS DEPENDING ON VARIABLES NOT CONSIDERED HERE.
40.27
PRINTS TO

FIG 1-14

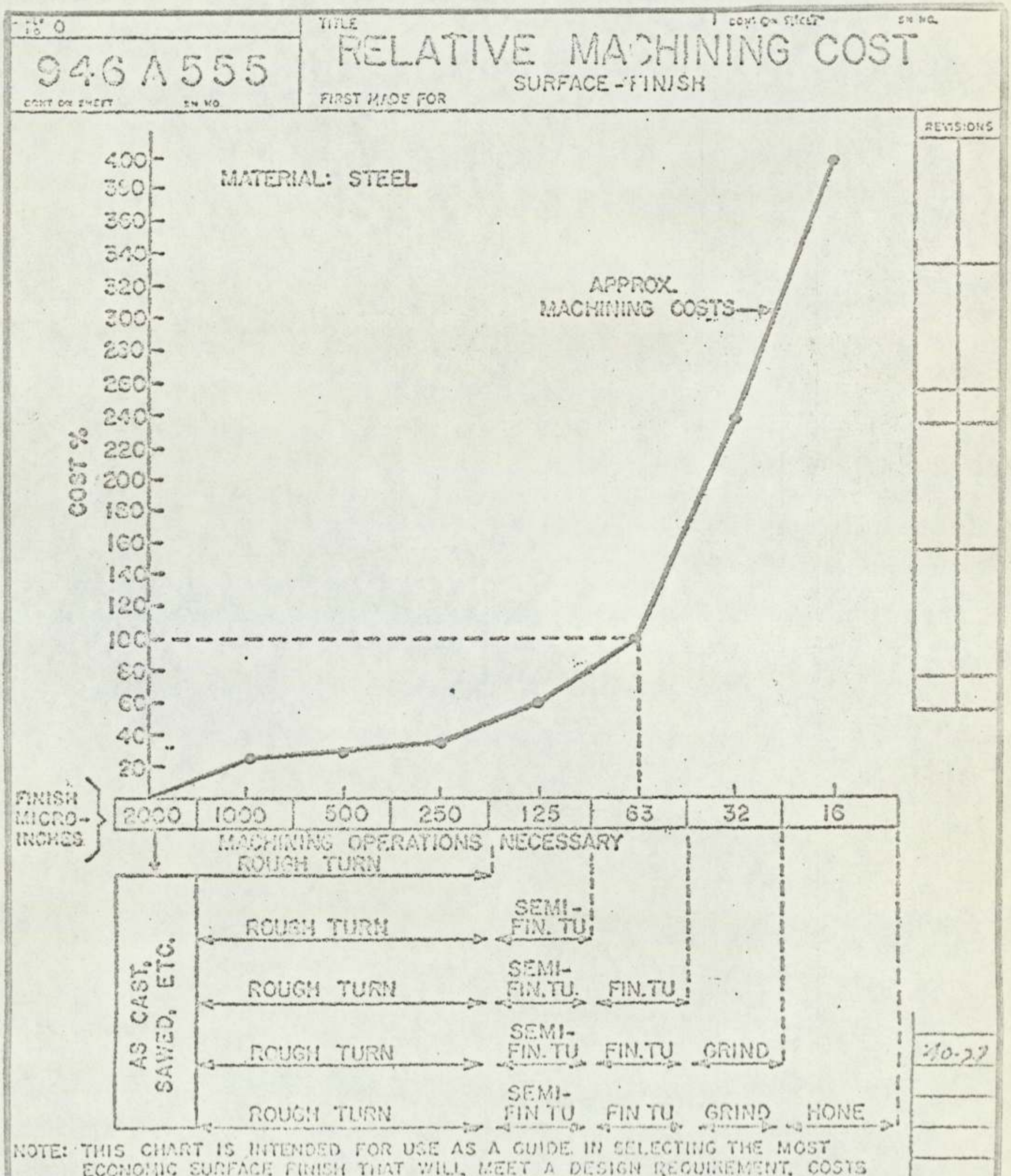

946 A 555
RELATIVE MACHINING COST
SURFACE-FINISH
FIRST MADE FOR
REVISIONS
MATERIAL: STEEL
APPROX. MACHINING COSTS
COST %
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
FINISH MICRO-INCHES
2000
1000
500
250
125
63
32
16
MACHINING OPERATIONS NECESSARY
ROUGH TURN
AS CAST, SAWED, ETC.
ROUGH TURN
SEMI-FIN. TU
ROUGH TURN
SEMI-FIN.TU.
FIN.TU
ROUGH TURN
SEMI-FIN. TU
FIN.TU
GRIND
ROUGH TURN
SEMI-FIN TU
FIN TU
GRIND
HONE
NOTE: THIS CHART IS INTENDED FOR USE AS A GUIDE IN SELECTING THE MOST ECONOMIC SURFACE FINISH THAT WILL MEET A DESIGN REQUIREMENT. COSTS SHOWN ARE APPROXIMATE AND COULD BE GREATER OR LESS DEPENDING ON VARIABLES NOT CONSIDERED HERE.
PRINTS TO

FIG I-15

1.5. Having decided the correct manufacturing technique the next problem will be to decide suitable feeds and speeds to obtain the given surface profile.

Research into the theoretical surface finish produced by machining operations has been carried out by a number of workers (22) (23) however, problems exist in reproducing these under workshop conditions, since the effects of vibration, materials are not considered.

The selection of speeds and feeds will define the "SURFACE INTEGRITY" which is the condition of the surface layer and substrate to a depth in the order of millimetres (1) (24). It would appear that for highly stressed parts it is no longer adequate to specify $16 \sqrt{\text{GRIND}}$ and leave the machining details to the operator, but to specify the speeds and feeds for each cut in order to produce the required sub surface e.g.

(i) Conventional grind to within 0.010 ins of final size

(ii) Remove 0.008 ins at 0.0005 ins per pass.

(iii) Remove the final 0.002 ins at 0.0002 ins per pass.
Use "soft" wheels running at approximately half normal grinding speed. 2,000 to 3,000 ft/min.
Fluid is also specified usually a sulphurchlorinated grinding oil.

Fig 1.16 shows the effect of an incorrect grinding technique, "abusive" plunge grinding on a distributer cam. This suggests that the use of NC machine tools would be essential for such parts, since the programme tape will ensure that the required machining sequence has been carried out and eliminates the "human" element.

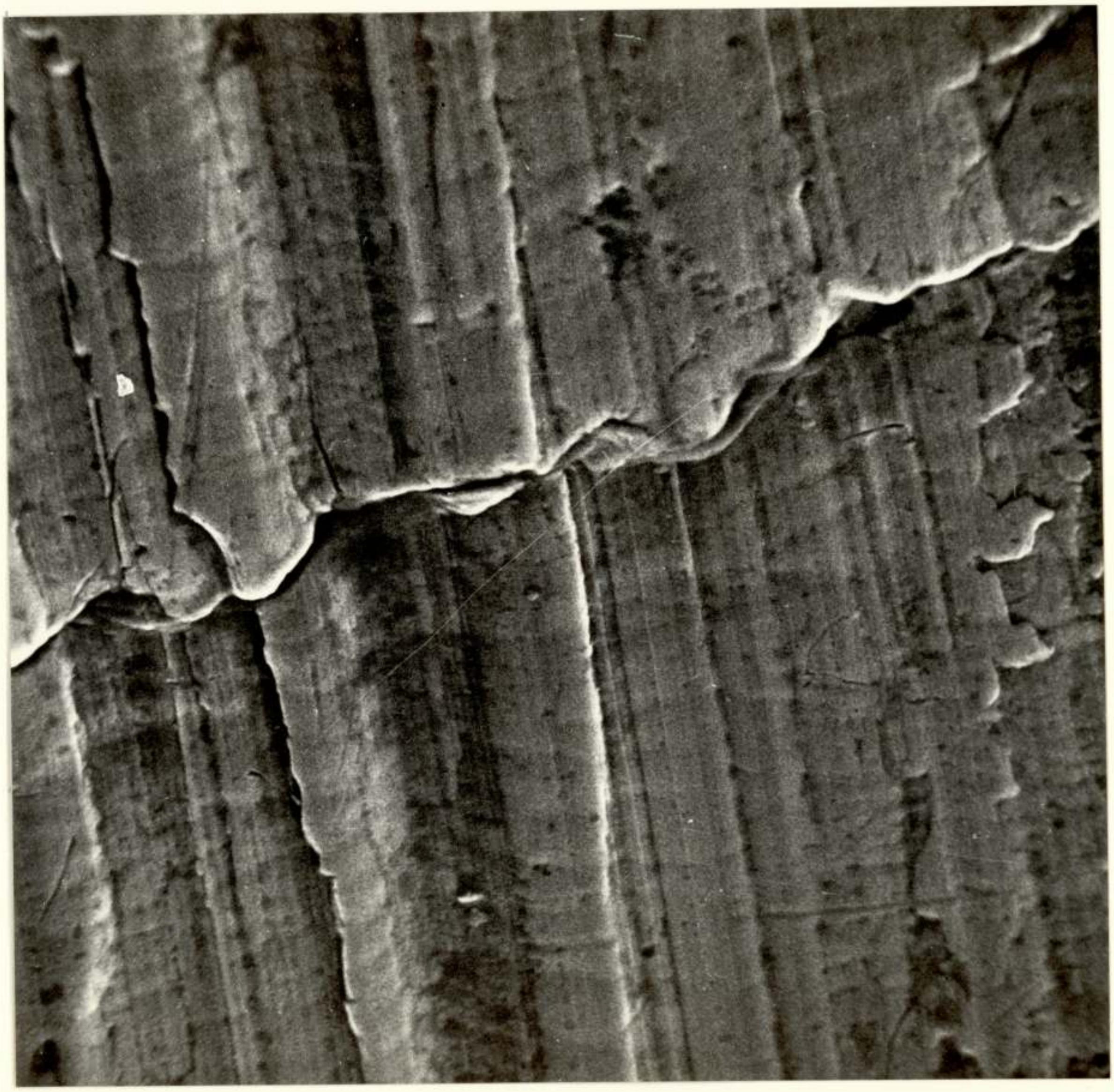


Fig. 1.16. Effect of Abusive Grinding on Distributor Cam Track.

Magnification 3,975

Ref. No. 306.

MEASUREMENT OF WEAR

2.1. In any investigation into wear the method of measuring wear is of prime importance. There are two main aspects worth considering:-

(i) Units of wear. These may be Weight loss or change in dimension.
Weight loss is much more convenient to use since only one measurement needs to be taken. However, in most engineering applications it is the change in dimensions that determines whether the life of the component has been reached e.g. leakage past pistons or effect on geometrical relationships as with limit gauges.

(ii) At what stage of the tests will wear measurements be taken
(a) After long periods under severe conditions when an appreciable amount of wear will have occurred but the surface present will have little if any relationship to that originally present.
(b) After a short period under very severe conditions i.e. accelerated tests when the conditions in (a) will have taken place. Problems will be present in relating information obtained from this type of test to a practical situation since the mode of failure may be different due to temperature effects.

(c) After short periods under normal loads when the amount of wear will be extremely small i.e. "Zero" or less than Peak to Valley depth.

Hence in this initial exploratory phase a study was made of the techniques currently available which would be of use when measuring dimension change.

These were (a) Comparative or Direct Measurement.

(b) Stylus instruments

(c) Optical Interference technique

(d) Indentation techniques

(e) Electron optics

(f) Holography

2.2. Comparative or Direct Measurement.

These techniques have been extensively used and range from the use of a single dial test indicator reading to 0.0001 in to sophisticated multi-gauge fixtures consisting of gauging heads each measuring to a mean error of $\pm$ 0.1 μ m (4 μ ins) with 95% confidence limits (25). The use of a number of gauging heads reduces the time for measurements and enables the changes to be mapped over an area, using electronic gauging heads enables the possibility of data-logging equipment to be explored, reducing human errors in measurement and enabling easier analysis of data or at work centralisation of indicating meters. Mapping of contours may also be carried out using a single stylus which can traverse in the X & Y axes of the surface to be measured using a large optical flat as the reference plane.

Such an instrument has been developed by PEKLENIK for the study of surface profiles (26). This has also been done using a conventional Talysurf 3 on suitable positioning jig (41).

Pneumatic techniques have been used (27) in order to reduce the measuring forces and consequent work piece or stylus deformation. Unfortunately the readings obtained are affected by changes in the surface profile which are inevitable in most wear tests (28). It is possible to apply corrections if the h_{cla} of the surface being measured is known(29) but the corrections are rarely applied, even in industrial air gauging applications.

2.3. Stylus Instruments.

In this technique a stylus is drawn across the surface under test and the resulting movements, with respect to a suitable datum, amplified electronically and recorded. The instruments used are usually of commercial design and designed primarily for the analysis of surface profiles. They have the limitation that the stylus has a relatively short traverse (.300 in approx) although by use of a traversing table the effective traverse can be extended to 6 ins (150 mm). This method has been used by several investigators to measure the wear groove obtained on a pin and disc machine using the unworn portion of the disc as a datum surface.

The development by Rank Taylor Holson of a straightness measuring instrument - the TALYLIN suggested its application to wear measurement of large specimens. This instrument can be used on a stand Fig.2.1. for measuring small specimens or directly on the work piece as shown in Fig.2.2. when measuring wear over large areas. It consists basically of a stylus which is traversed over the test surface for a maximum length of 4 ins. Vertical movement of this stylus gives the surface profile relative to an optical flat contained in the instrument which acts as the reference plane. Out put from the instrument is a voltage proportional to the vertical stylus movement, this is used to operate a chart recorder, analogue-digital converter and associated paper punch.

Reference grooves .25 ins. wide are machined in the surface to be tested at 4 ins pitch. The depth of the grooves must be greater than the total maximum amount of wear expected. On the work carried at present they have been .001 ins deep and produced by surface grinding using a fine grit wheel.

The straightness measuring instrument is then positioned relative to the test surface, and the optical flat aligned to the reference grooves. A chart recording as shown in Fig. 2.3. and a punched tape output are obtained by traversing the stylus between the two reference grooves, from these the mean height of the test surface above the reference groove is computed.
This procedure is then repeated after each test run and the change in mean height gives the average wear on the test surface.
By using a stylus traverse rate of 0.020 ins/sec and a sampling rate of 10 per sec. on the analogue-digital converter the vertical height of the test surface above the reference grooves at 0.002 in intervals over a length of 3.5 ins can be obtained in digital form.

This method has the following advantages:-

a) An extremely detailed picture of the wear on a test surface can be obtained quickly.

b) Data is recorded in a permanent form which can be processed later whilst the wear tests are continuing.

c) Small amounts of wear can be measured in the order of .00003". The punched tape output gives details of the surface which can be processed on a digital computor. At present the mean and standard deviation of the height of the test surface above the reference grooves are calculated. By using reference points positioned in a grid on the test surface it should be possible to obtain detailed information on how the plane of the test surface is wearing by computing the equations of the mean true plane and hence the deviations of the surface from it.

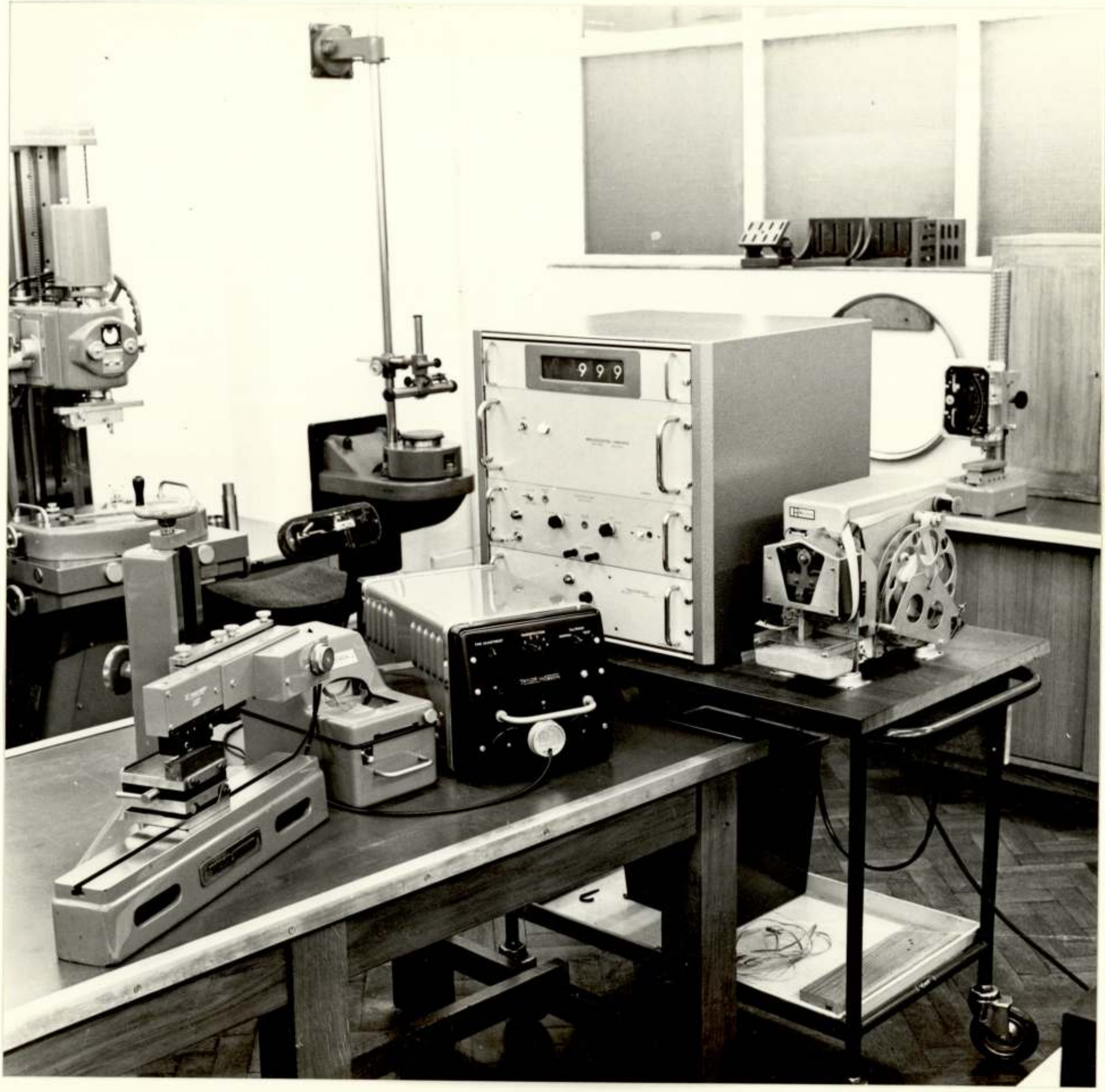


Fig. 2.1. Straightness Measuring Instrument and Associated Equipment arranged for the Measurement of Small Specimens.

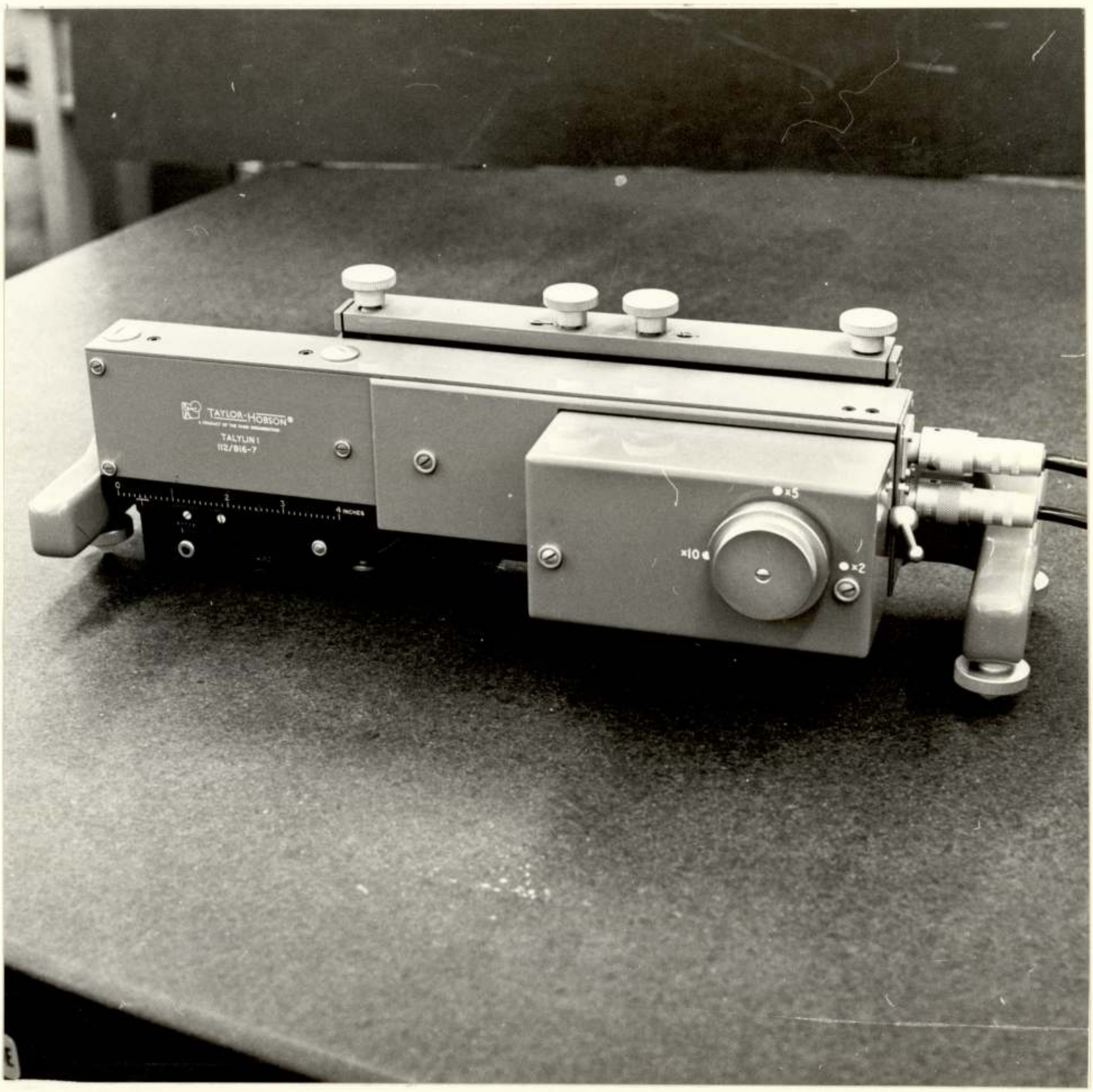


Fig. 2.2. Straightness Measuring Instrument Mounted in Frame for Measuring Wear on a Large Surface.

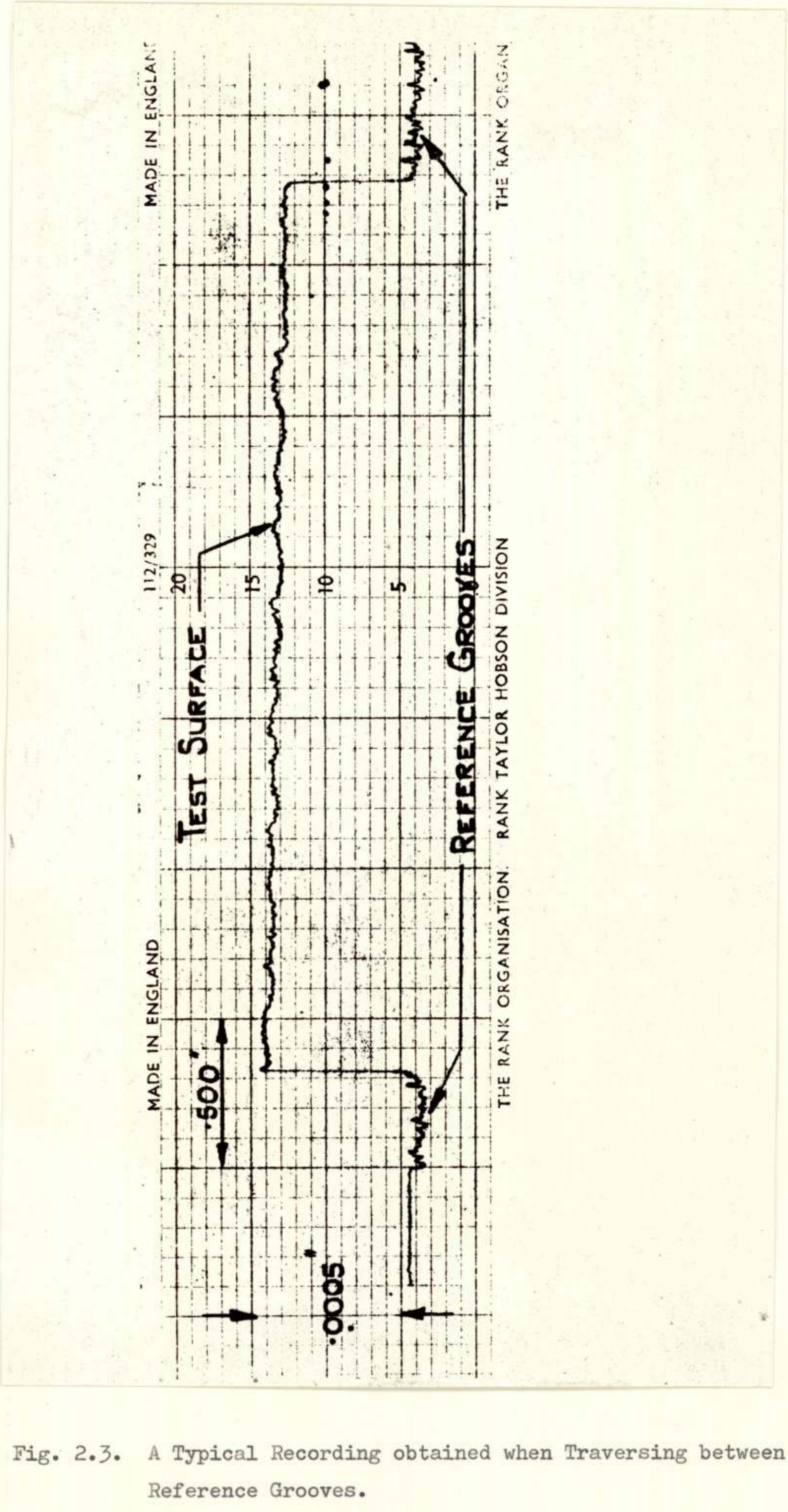


Fig. 2.3. A Typical Recording obtained when Traversing between Reference Grooves.

Magnifications: Vertical x 2,000

Horizontal x 2

2.4. Optical Interference Techniques.

The use of interference techniques for the study of surfaces has been well established. Its main application has been in the study of highly polished surfaces i.e. h_{CLA} of 1 to 2 u" e.g. Ball Bearings. The information obtained is qualitative rather than quanlitative although the depths of individual features can be measured to an accuracy of $\lambda/10$ - 2 u". The advantage over stylus methods is that area coverage is obtained and it is a non-contact method.

The problem of obtaining interference patterns for surfaces which are not optically reflecting, such as wear specimens, can be overcome by several techniques viz:-

(i) Cleaning and then coating the actual surfaces of the specimen with a thin layer of A1 or Gold using vacuum deposition techniques in order to obtain the necessary reflectivity.

This technique can only be used on specimens at the end of a wear test since the coating will contaminate the surface and it is only suitable for parts that can be viewed under an interference microscope.

(ii) Using a suitable plastic replica kit of which a number are commercially available and obtaining a replica using a casting technique. The replica may then be coated as before to obtain a suitable reflecting surface.

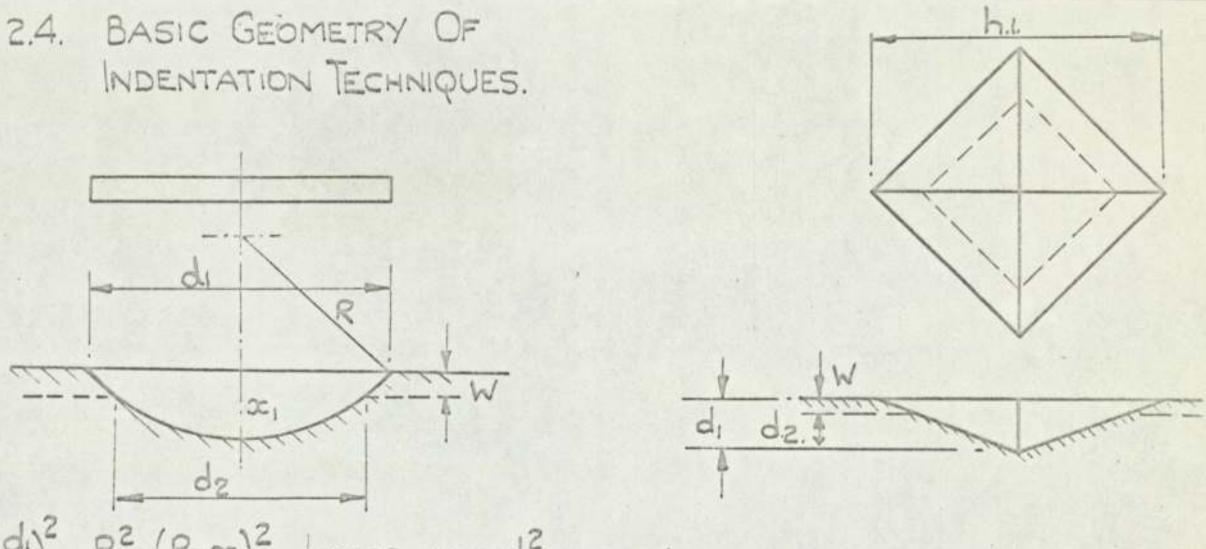
(iii) The use of a recently developed composite film "PRESS-O-FILM" (30). This consists of a MYLAR film coated with compressible, collapsible vinyl copolymer that has been metallised with gold or indium. This material is placed on the surface to be measured or inspected and pressure applied with a burnishing tool. This causes the metallised layer to collapse onto the surface taking its form, the film is then peeled off ready for examination using a conventional interferometer.

The methods (ii) and (iii) have the big advantage that they can be used to examine specimens where the surfaces cannot be reached for direct measurement or that cannot be moved to a micro-interferometer.

2.5. Indentation techniques.

The use of indentations suitably positioned on the test surface has been used for the measurement of wear (31). The indentation is of a known geometric shape i.e. Vickers diamond pyramid or a small circular arc cut with a small abrasive wheel i.e. a brass disc impregnated with diamond dust or a single point diamond cutter. From a knowledge of the geometry the wear can be measured viz.

FIG. 2.4. BASIC GEOMETRY OF INDENTATION TECHNIQUES.



$$\left(\frac{d_1}{2}\right)^2 = R^2 - (R - x)^2 \quad \text{hence} \quad x_1 = \frac{d_1^2}{8R}$$

$$\therefore \text{WEAR} = x_1 - x_2 = \frac{1}{8R}\left(d_1^2 - d_2^2\right).$$

$$W = (d_1 - d_2) = \frac{(h_1 - h_2)}{7}$$

The use of V.P.N. indentations has the following disadvantages:-

(i) A raised lip is formed around the indentation Fig.2.5. This will give a false impression of the wear.

(ii) Local work hardening will be caused, this may lead to the wear rate being measured to differ from that of the surfaces under test.

(iii) The shape of the impression may differ from that of the indenter due to elastic recovery.

(iv) In hard materials the physical size of the impression will be small and this will cause problems in locating and aligning the impression for measurement.

The use of the circular arc technique is claimed to overcome this and the reference (31) contains details of an instrument developed specifically for this purpose. However, in the light of grinding research carried out by various workers into single grit grinding (32) it is difficult to see how the problems of build up can be completely overcome.

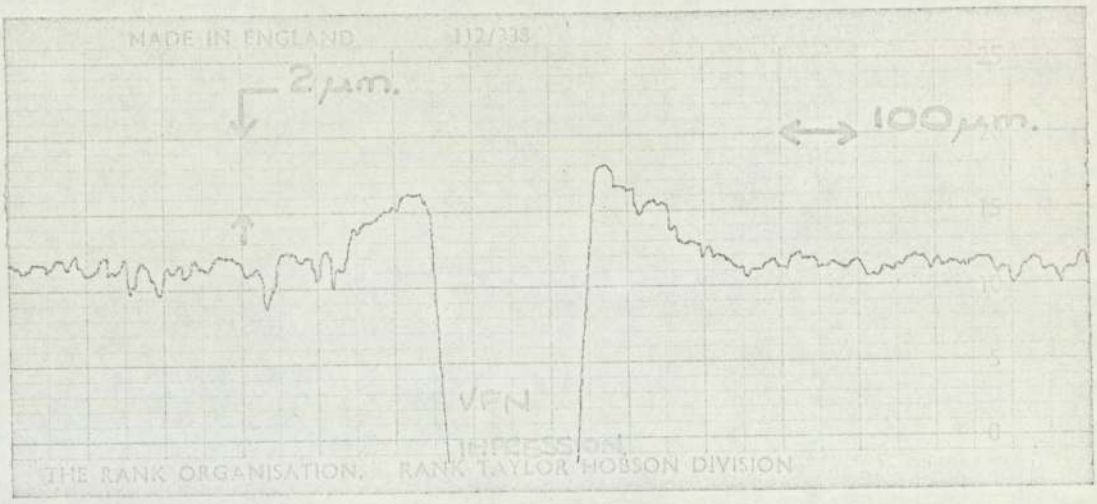


FIG.2.5. TALYSURF RECORD SHOWING RAISED LIP AROUND IMPRESSION.

MAGN. 5,000 VERTICALLY.
100 HORIZONTALLY.

2.6. Electron Optics.

The conventional electron microscope has been extensively used in the examination of worn surfaces (33) (34). This instrument uses a transmission mode, a transparent specimen being placed between electromagnetic lenses and requires special replica techniques for specimen preparation.
The development of the Scanning Electron Microscope (S.E.M.) has made available a versatile tool for engineers (35) (36).
The principle of the S.E.M. is illustrated in Fig. 2.6.
An electron gun produces an electron beam which is focussed by the electromagnetic lenses L1, L2, L3, to a diameter of 100 A^o.
This is scanned over the surface by two pairs of deflecting coils and at the same time the spots on the viewing and camera tubes are arranged to produce a similar but much larger raster in synchronism. This primary electron beam will be (i) Reflected (back-scattered) from the specimen, or (ii) Cause low energy secondary electrons to be emitted from the specimen, this is the more usual method when topographical detail is required.

The electrons from the specimen are gathered at the collector and the resulting current amplified and used to modulate the brightness of the spot on the viewing and camera screens.

The main advantages of using an S.E.M. are for the examination of surfaces i.e.

(i) Magnifications from x 20 to x 1000,000 instantly available, in practise, on surface finish specimens the range is from x 100 to x 8,000.

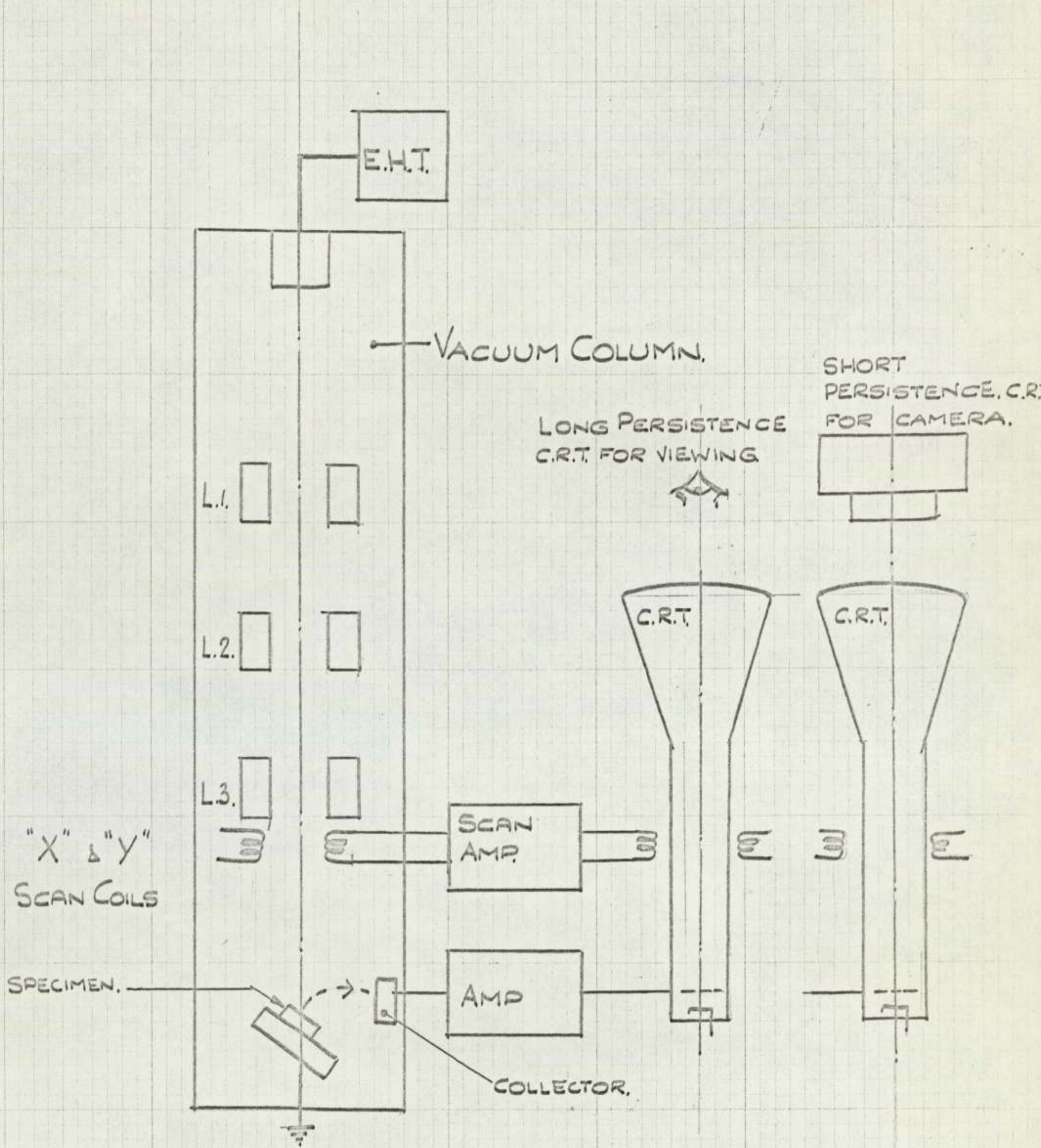


FIG. 2.6. LINE DIAGRAM OF SCANNING ELECTRON MICROSCOPE.

(ii) Large depth of focus, several hundred times greater than the optical microscope which has made possible a better understanding of surface topography (37).

(iii) The surface texture can be examined directly without the need for replica techniques, reducing the time and skill required for specimen preparation. However, if the specimen is non-conducting a suitable coating must be vacuum deposited upon it.

(iv) Like all optical instruments it gives area coverage.
Against these must be offset the capital outlay and the running cost which could vary between £3 and £20 per hour depending upon staff and overheads.
The basic instrument has a standard stage which limits specimen size (See Section 4.4. Page 65) but special stages are available which enable some experimental work to be carried out in the specimens chamber e.g. Tensile and compression tests up to 500 lbf.

2.7. Holography.

The use of holography as a means of measuring wear is promising since it should enable direct study of the topography of large areas to be carried out without the problem of obtaining an optically reflecting surface such as that required for interferometry or the need for an accurate datum plane. It is not certain at this stage whether the results will be affected by the variations in surface texture that occur during the wear period.

A wealth of literature has been produced on holography in the past 3 or 4 years (38). For the study of wear the basic arrangement shown in Fig. 2.7 was used, Fig. 2.8. shows the physical layout. This set up produces a simple hologram which can be reconstructed using either a HeNe Laser or a Mercury light source and a suitable filter.

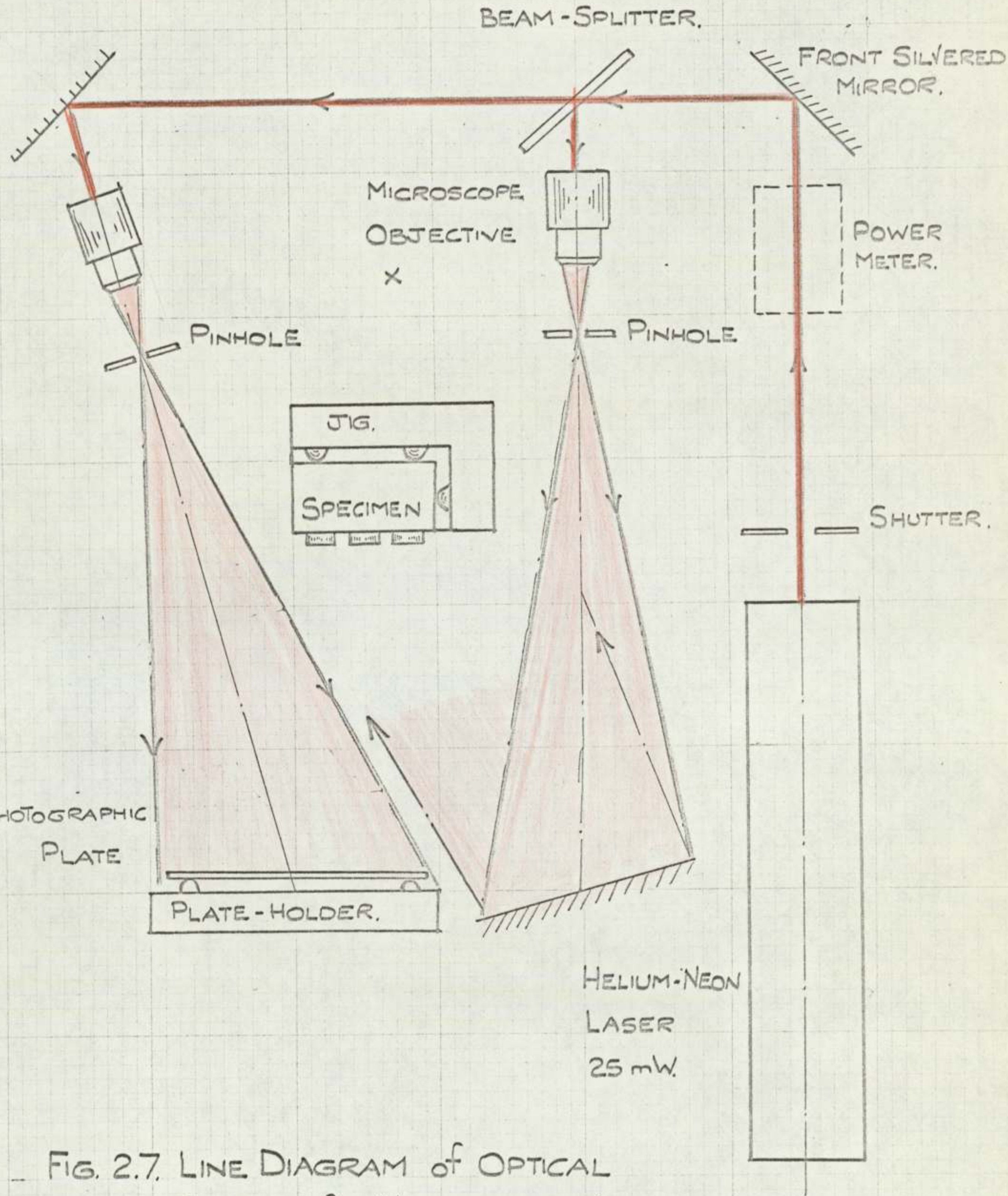


FIG. 2.7. LINE DIAGRAM of OPTICAL SYSTEM for HOLOGRAPHY.

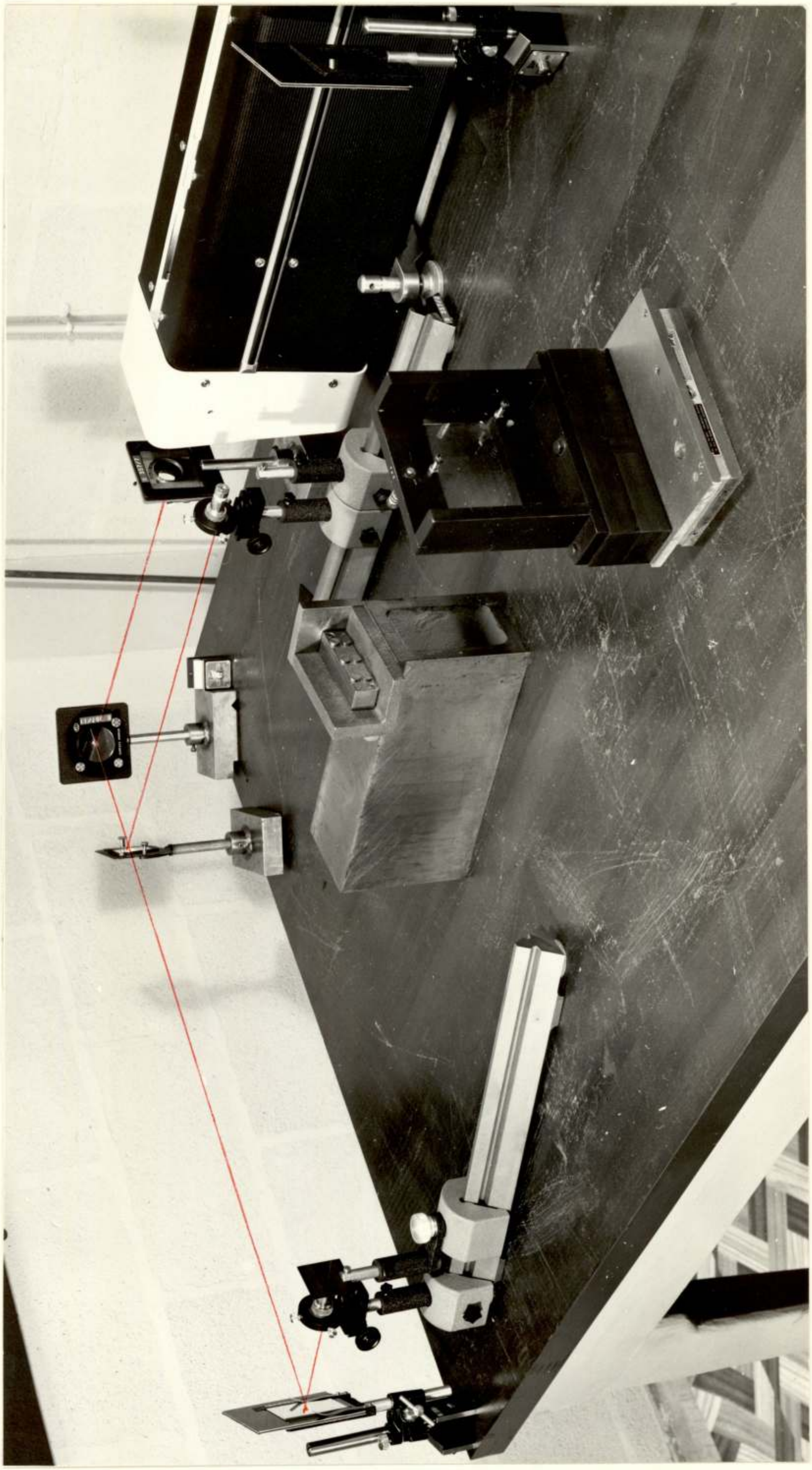
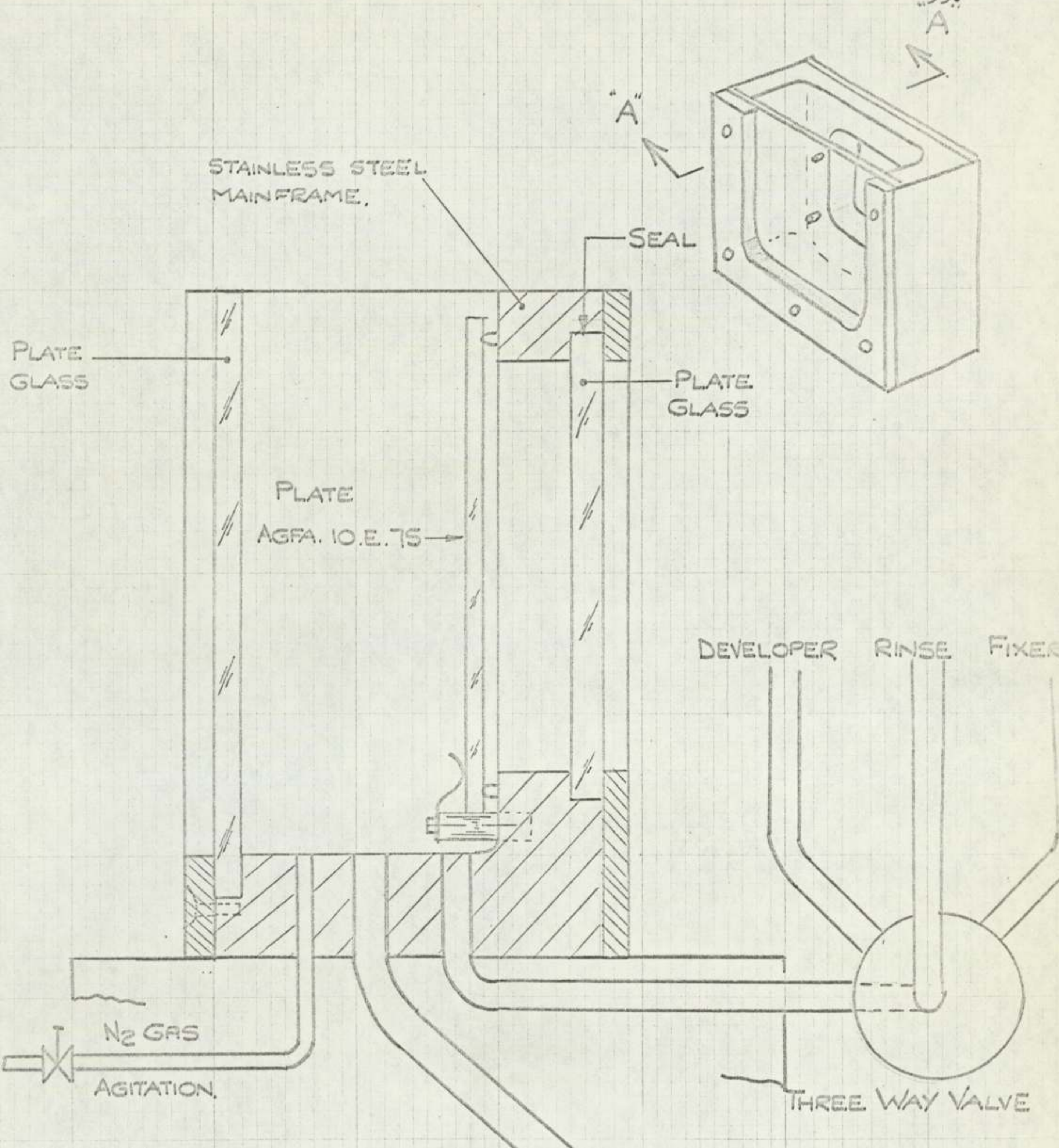


Fig. 2.8. Physical Arrangement of Equipment for Holography.



OPERATION.

1. LOAD PLATE
2. FILL WITH DISTILLED WATER
3. EXPOSE PLATE
4. DEVELOP
5. RINSE
6. FIX
7. RINSE

(Steps 4–7: AGITATE WITH N_2 GAS.)

8. REFILL WITH DISTILLED WATER.

FIG. 2.9. OUTLINE SCHEME FOR DEVELOPING HOLOGRAPHIC PLATES WITHOUT REMOVING FROM PLATE-HOLDER

In order to investigate the nature of the wear profile a live fringe technique is suggested.

(i) An exposure is made of the specimen before wear and the plate developed.

(ii) The specimen removed and the wear test carried out.

(iii) After completion of the wear period the specimen is replaced in its original position in the holography set-up and the developed hologram replaced in the plate holder.

The resulting image should show fringes occurring where-ever a change of contour of $\lambda/2$ has occurred and thus indicate in three dimensions the changes in topography that have taken place during the wear period, provided:-

(i) The optical components have not been moved.

(ii) The plate has been replaced exactly in the plate holder.

(iii) The wear specimen has been replaced exactly in the locating fixture.

All these operations must be carried out to an accuracy of approx. $\lambda/10$ or .02 micro-metres. These problems can be overcome by:

(i) Using a special plateholder whose design is based on kinematic principles. The one in current use is based on a NPL design.

(ii) Carrying out the plate developing in the plateholder. This is currently being investigated and Fig. 2.9 gives details of an outline scheme.

(iii) Design of a suitable mounting jig to hold the wear specimens.

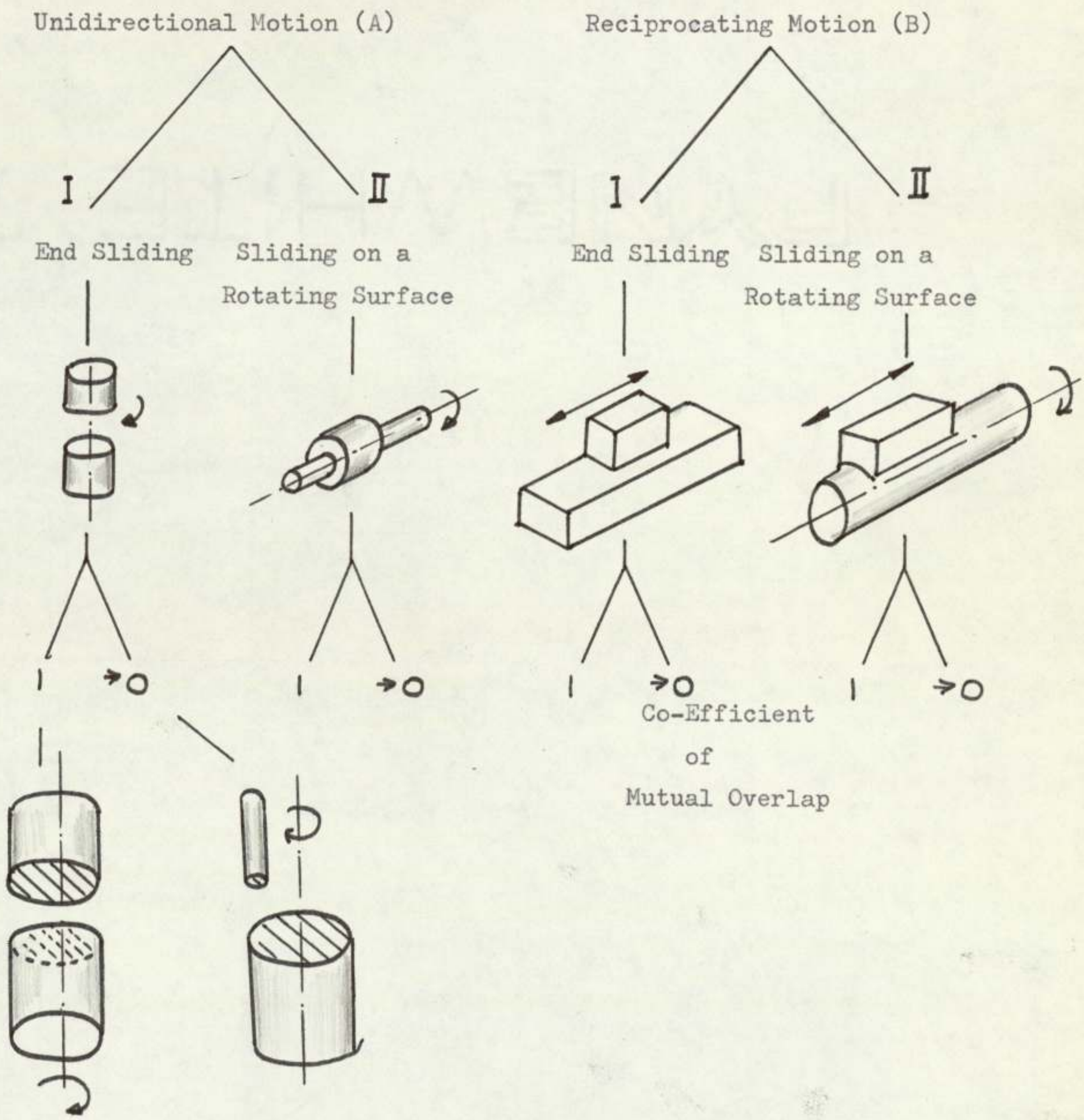
The use of live fringe "holography has already been used for measurement of strain, displacement and geometrical forms (39) and in particular the research work carried out on the measurement of cylinder bores offers some promise (40). It is possible that this technique could be used for the direct non-contact mapping of internal features.

Wear Test Rig Design.

3.1. In order to obtain experimental results which could be related to industrial practise and to verify the measuring methods under consideration a suitable wear test rig had to be used. A limited range of wear machines are available commercially at prices ranging from £1,300 to £6,500 per machine.

The necessary finance was not readily available to purchase a commercial unit and it was therefore decided to construct a test rig.

Wear test rigs have been classified as below (42) according to the relative movements of the test specimens.



3.1. Where the Coefficient of Mutual Overlap is defined as the ratio of the apparent areas of contact for the two surfaces.

This ratio will indicate whether the heat generated during sliding will be transferred into the atmosphere. It is possible that the variations in results obtained by different researchers may be attributed to the configuration of the particular wear test rig used.

It is felt that the best configuration would be flat on flat (B.I.) since if rotating members were used, problems would be encountered in the production of components with a consistent roundness and the results of the effect of roundness variation on wear do not appear to have been fully investigated, indeed the basic parameters for the measurement of roundness are still the subject of discussion. A further factor was the use of specimens of fairly large proportions.

3.2. The main variables in a wear test rig are usually:

(i) Speed
(ii) Load
(iii) Lubrication

In order to produce a machine at low cost the design was centered round an existing mechanical shaping machine. The machine provided a reciprocating motion of 14 ins (355 mm) stroke with the number of strokes per min varying between 11.5 to 120 insteps. This coupled with a variation of stroke would produce a suitable range of speeds. Unfortunately the quick return mechanism produced non-uniform velocity and variations in the velocity profile between forward and return strokes.

It was decided that a simple mechanical loading system would be utilised. The maximum force that could be exerted was limited to 450 lbf (2 kN) by the construction of the machine i.e. The upward force on the ram slideways.

3.3. Fig. 3.1. shows the design of the test rig. It was based on a 14" stroke Heavy Duty Shaping Machine manufactured by Ormerod Shapers Ltd.

The basic machine configuration dictated the design which differs from conventional designs in that the smaller specimen is the lower one.

The rig can accommodate two tests at the same time, since it consists of two identical units in parallel (Fig. 3.3.).

The top specimens which are mounted in a large block of mild steel which is fastened to the ram head by a fabricated structure. The specimens are clamped in position by set screws.

The bottom specimens are mounted in a holder which has provision for lubrication via felt wipers fed from a central sump by capillary action. The sump is replenished from an external supply via flexible tubing.

Loading is provided by a lever using dead weights. Since the alignment of the top and bottom specimens is provided by the shaping machine ram slideways it was felt necessary to provide kinematic location to ensure that the bottom specimen "floated" against the top specimen. This was carried out by applying the load through a ball bearing which was fastened to the loading lever (Fig 3.2). The specimen holder had a 120^{0} included angle dimple for location purposes. This arrangement allowed rotational movement in all three planes and coupled with a vertical movement obtained by rotation at the pivot accomodates any misalignment.

3.4. It must be pointed out that the experimental rig used was simple and lacked the sophisticated instrumentation required to obtain full results e.g.

Temperature
Dynamic Pressure
Friction Force

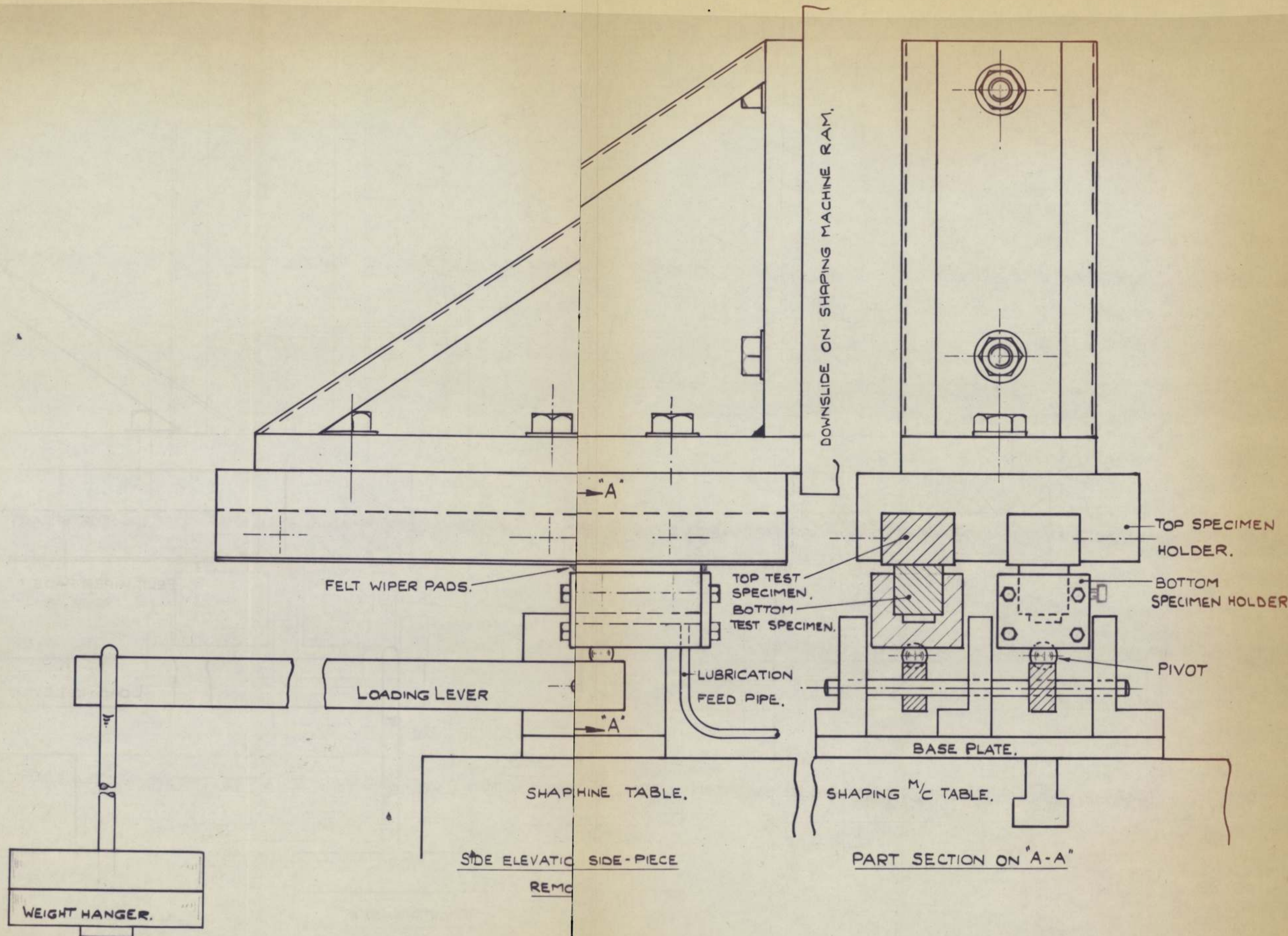


FIG. 3.1. GENERAL ARRANGEMENT OF TEST RIG.

SCALE: HALF SIZE.

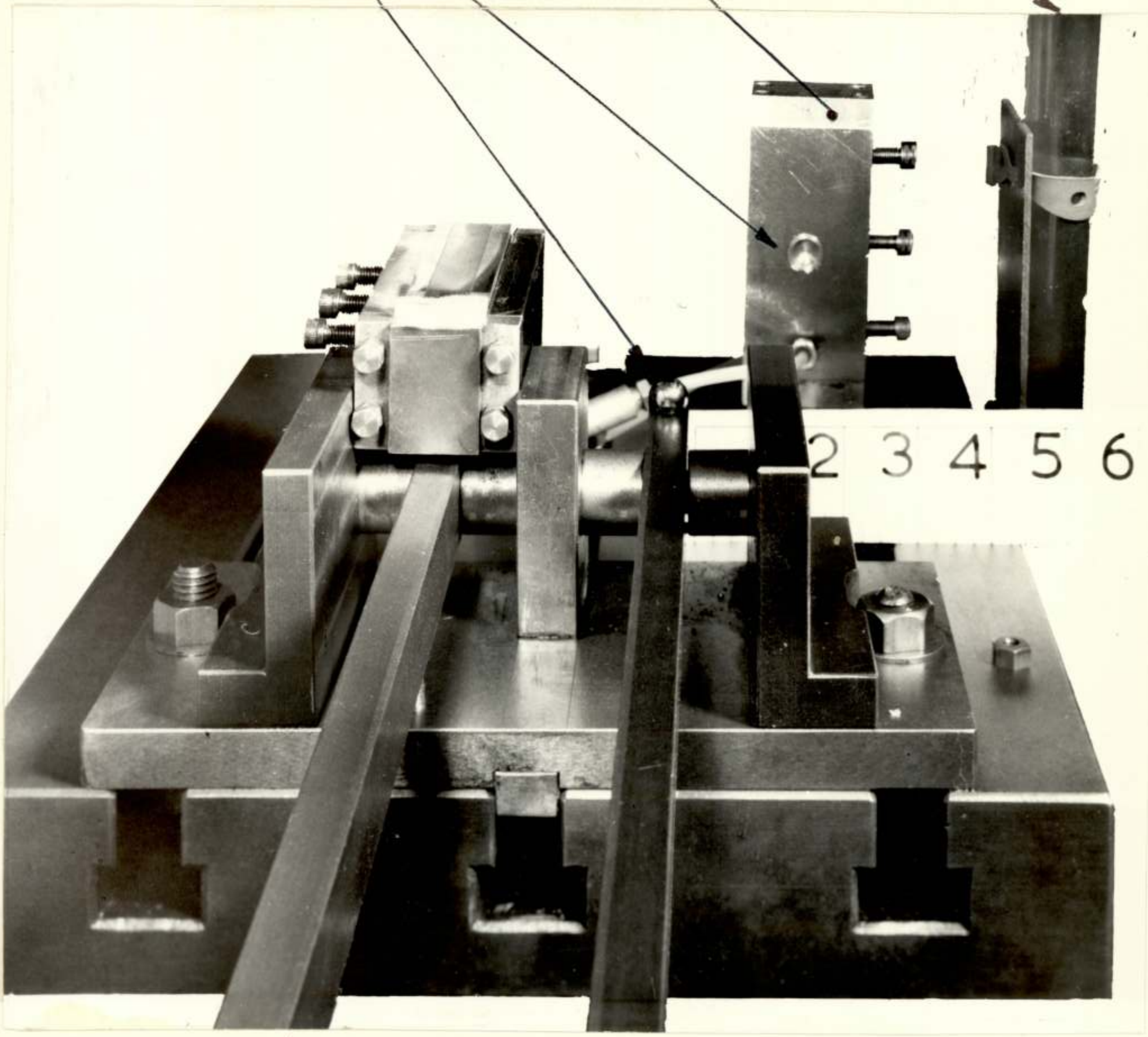


Fig. 3.2. View of Front of Test Rig Showing Underside of One Specimen Holder.

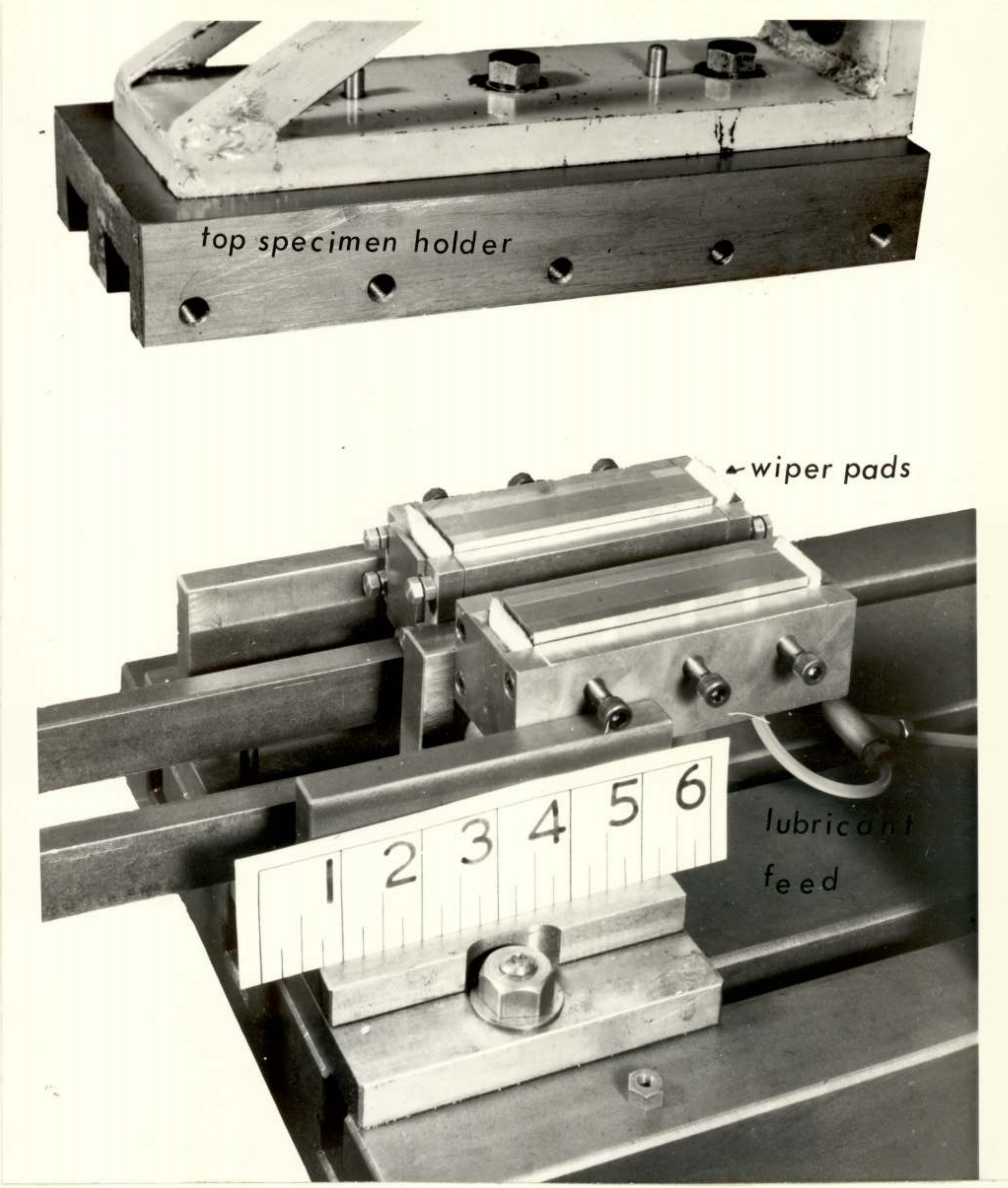


Fig. 3.3. VIEW OF SIDE OF TEST RIG

(TOP SPECIMENS REMOVED).

3.4 continued..

Indeed a major part of the cost of such a machine is the associated instrumentation. In the particular series of tests to be carried out the surface and rate of wear were under examination and hence sliding speed, pressure and lubrication were standardised.
To pursue the project further, consideration must be given to the design and construction of a batch of wear machines, since of necessity the tests will be of long duration in order to produce results of practical use, a number of tests will need to be carried out simultaneously. The use of accelerated tests may not give results which can be applied to industry since the heating effect may alter the mode of failure.
Fig. 3.4 indicates the form that such a scheme could take. The use of a common power pack would reduce cost/machine and the use of a scanning system will reduce the cost/channel.
It could well be that this would be a suitable project for a student studying for a higher degree in "Engineering Design"or "Instrumentation".

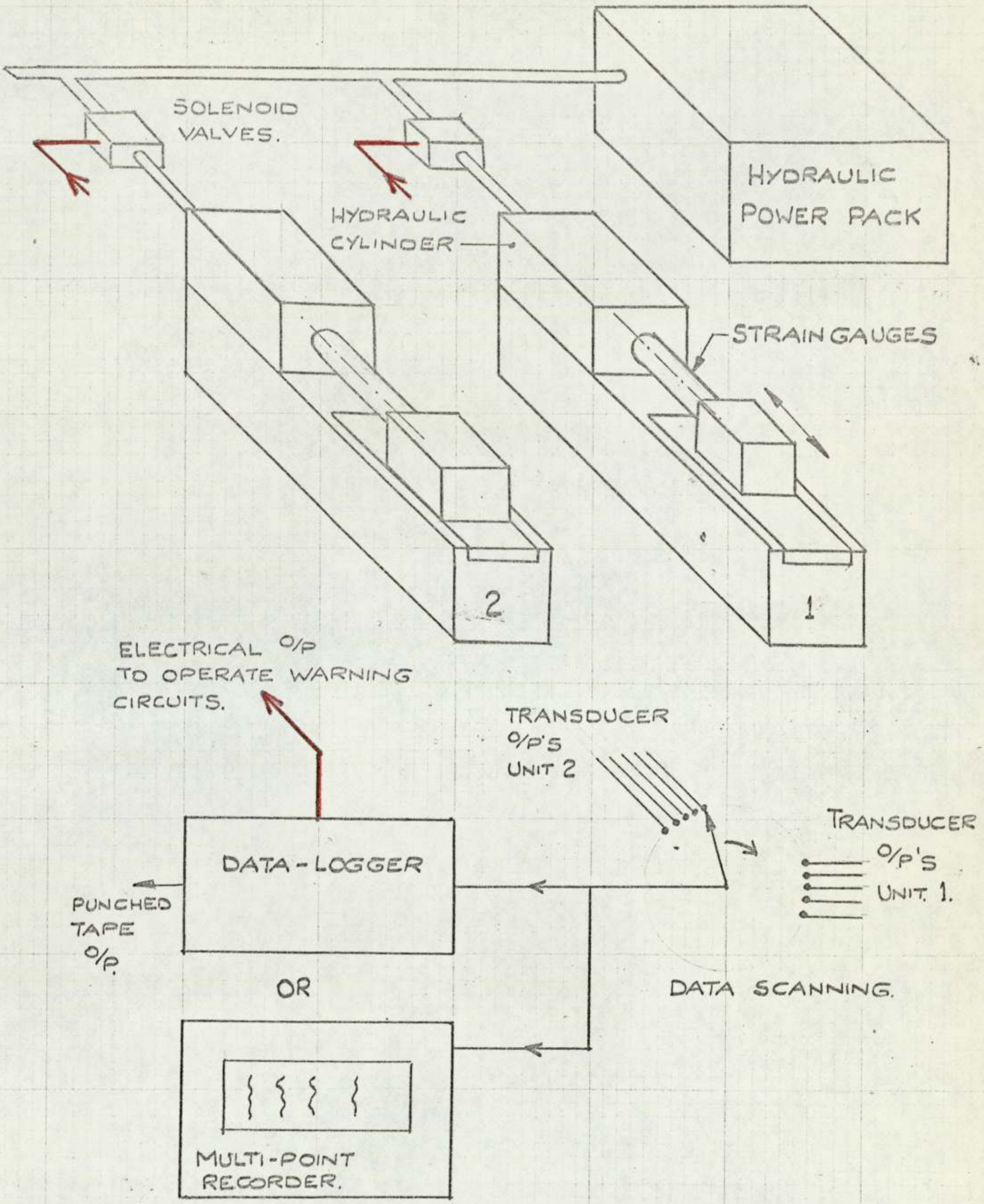


FIG. 3-4 SCHEMATIC DESIGN FOR WEAR TEST RIG FACILITY.

Wear Test Specimens.

4.1. The wear test specimens can be divided into three types:

(i) Top Specimen

(ii) Bottom Specimen

(iii) Scanning Electron Microscope Specimen

In each case the possible variables are:-

(a) Material

(b) Heat Treatment (if any)

(c) Manufacturing technique used

(d) Direction of machining

(e) Surface Finish

It must be realised that (a) will always to some extent be an uncontrollable variable, since variations in material composition and structure will vary even along the length of a bar of material.

Considering each type of specimen separately:

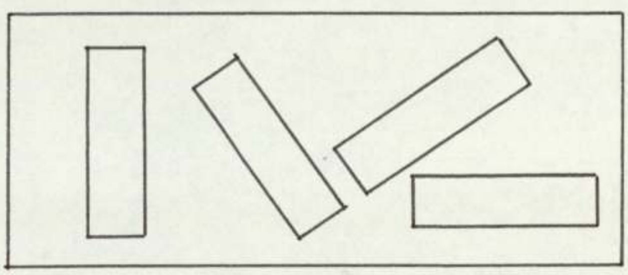
4.2. Top Specimen.

All specimens were manufactured from a length of cold drawn mild steel $1\frac{1}{2}$ ins x 1 in. in the "As Drawn" condition in order to reduce the effect of material variability.
The specimens were ground all over on a standard surface grinding machine and a series of VPN readings were taken to verify material homogeneity. The specimens were then positioned in pairs on the magnetic chuck and the final surface produced; in this case by grinding parallel to the longest side. The final surface finish obtained is determined by trial and error. No reliable method has yet been determined for predicting the surface finish produced for a given set of grinding conditions. After grinding and demagnetising a series of h_{CLA} readings were taken using a Talysurf 3 to verify that the surface finish was consistent.

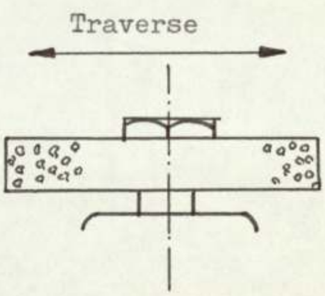
In all tests carried out the method of surface production was kept constant. Two sliding faces are available on each test surface and each face may be remachined several times before the specimen is useless.

4.3. Bottom Specimens.

The bottom specimens which measure 1 in x 1 in x 4 in. long were manufactured from a length of ground flat stock of oil-hardening carbon-chrome alloy steel. Four specimens were manufactured from the same length and heat treated together to reduce material variability. The procedure was once again to machine all over and then to grind the top surface to the finish required - once again using a trial and error approach. For these specimens the direction of lay with respect to the direction of sliding could be produced by setting the specimens at the required angle on the magnetic chuck viz:



Plan View of Chuck.



This will enable a similar surface finish to be produced on four different specimens with different lays.

Reference grooves were then ground at each end of each specimen to enable the wear measuring technique used in Chaper 2.3. to be used.

4.3. continued..

This required extreme care since the reference grooves required to be approximately 0.001 in. deep and be of good surface finish in order to utilise the maximum magnification of the Talylin. This was done by using a fine grit wheel, careful dressing and the use of engineers blue to determine the exact point in the downfeed of grinding wheel contact.
In the present set of experiments the use of the larger bottom specimens was discontinued owing to the availability in the Department of Metallurgy of a Scanning Electron Microscope with its attendant advantages (Chaper 2.6).

4.4. Scanning Electron Microscope Specimens.

One of the disadvantages of the S.E.M. is the relatively small size of the specimen that can be accommodated on the standard stage; 0.375 (9.53 mm) dia. x 0.25 (6.35 mm) long. Larger specimens can be accommodated if restrictions on specimen movement can be tolerated. Special work stages may be purchased, but cost is a problem as also is the time lost in removing the standard stage and replacing it with a Large Sample Manipulator Stage. The time factor is critical in view of the high utilisation of the S.E.M. Using the standard stage the specimen is usually held by an adhesive on to a standard aluminium stub for location in the workstage of the S.E.M. In order to produce a wear specimen which could be easily removed and replaced in the wear test rig, a small test specimen was designed which utilises a tapped hole to either hold the specimen in the wear test rig, or to hold an aluminium peg for mounting it in the workstage of the S.E.M. Fig. 4.1.

The "standard bottom Specimen" measures 4 in. x 1 in x 1 in and is clamped in the bottom specimen holder (Fig. 3.3.).
A special holder has been manufactured which accommodates 6 S.E.M. specimens Fig. 4.2. This is also used as a machining jig (Fig. 4.3a).

Accurate location of the specimens is obtained by initially lapping both specimen bases and holder. After machining, the locking pins are loosened and the direction of lay altered with respect to the direction of sliding Fig. 4.3b by partial rotation of the specimens. Index marks were made on each specimen and holder to allow accurate relocation after examination.

Two Vickers Pyramid indentations are made on the surface for identification purposes, when viewing on the S.E.M. and also when using a stylus type surface finish recorder to obtain graphs of the surface profile for comparison purposes. Specimens have been manufactured from Silver Steel in the normalised condition with finishes produced by:-

(i) Surface Grinding

(ii) Face milling using a single-point cutter

(iii) Machine Lapping

4.5. Initial trials were carried out to examine the uniformity of surfaces produced on specimens. Fig. 4.4. shows the general appearance of a faced surface produced by a single point tool, closer inspection Fig. 4.5a and 5b show the widely differing textures that may appear on the same surface.
It is probable that the torn area was due to the formation of a built-up edge on the cutting tool. These photographs together with Fig. 1.8 and 1.9. emphasise the care that must go into specimen manufacture and suggest why results obtained from different researchers may differ.
Indeed it emphasises the need for researchers to use modern production techniques for producing test surfaces rather than the "rubbed with coarse emery" approach.

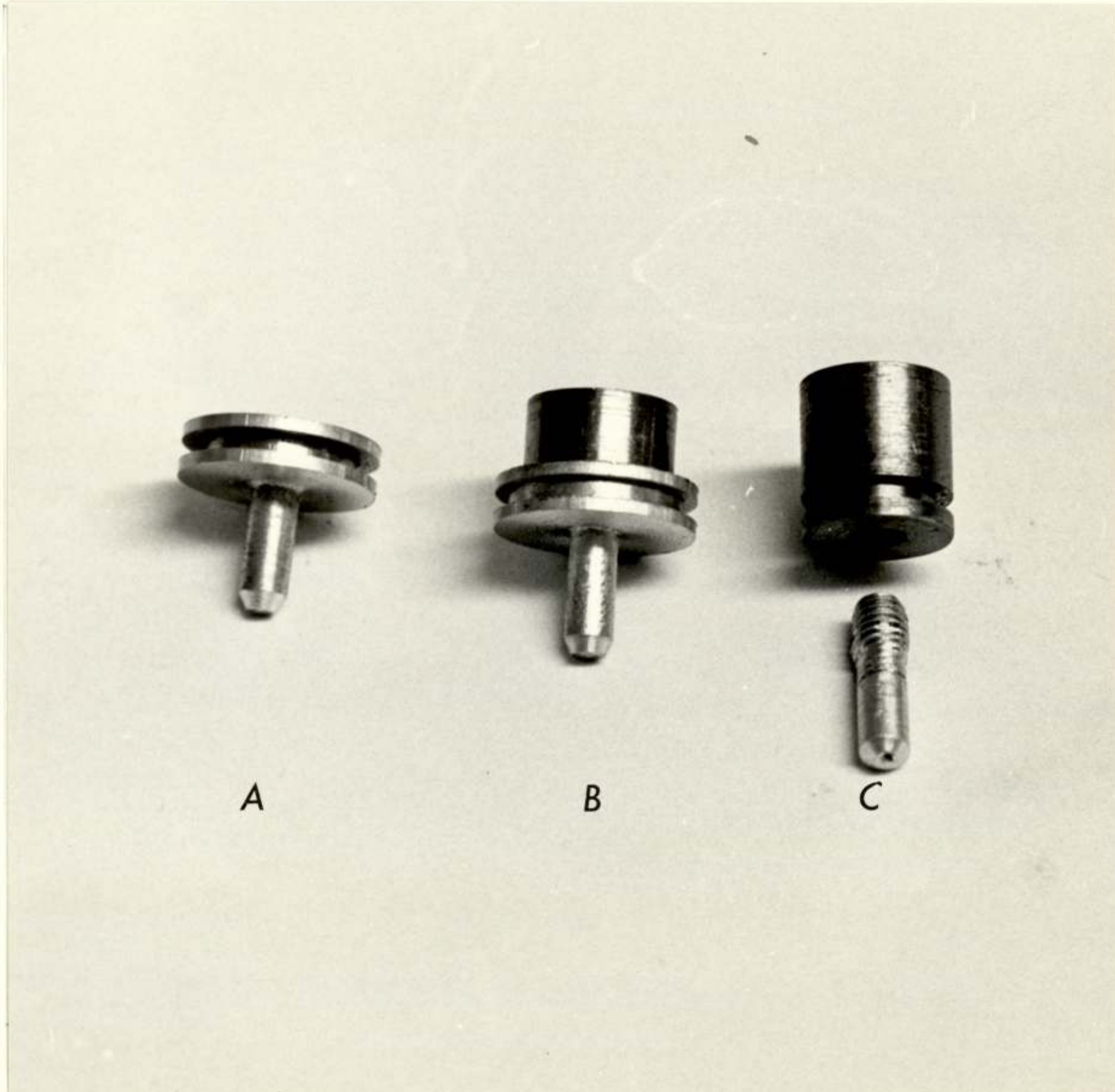


Fig. 4.1. Methods of Mounting Specimens in S.E.M. Workstage.

a) Standard Stub

b) Standard Stub with Specimen attached by "Evostick".

c) Modified Specimen with aluminium peg for location purposes.

Fig. 4.2. Bottom Test Specimen
One S.E.M. Type Specimen Removed.

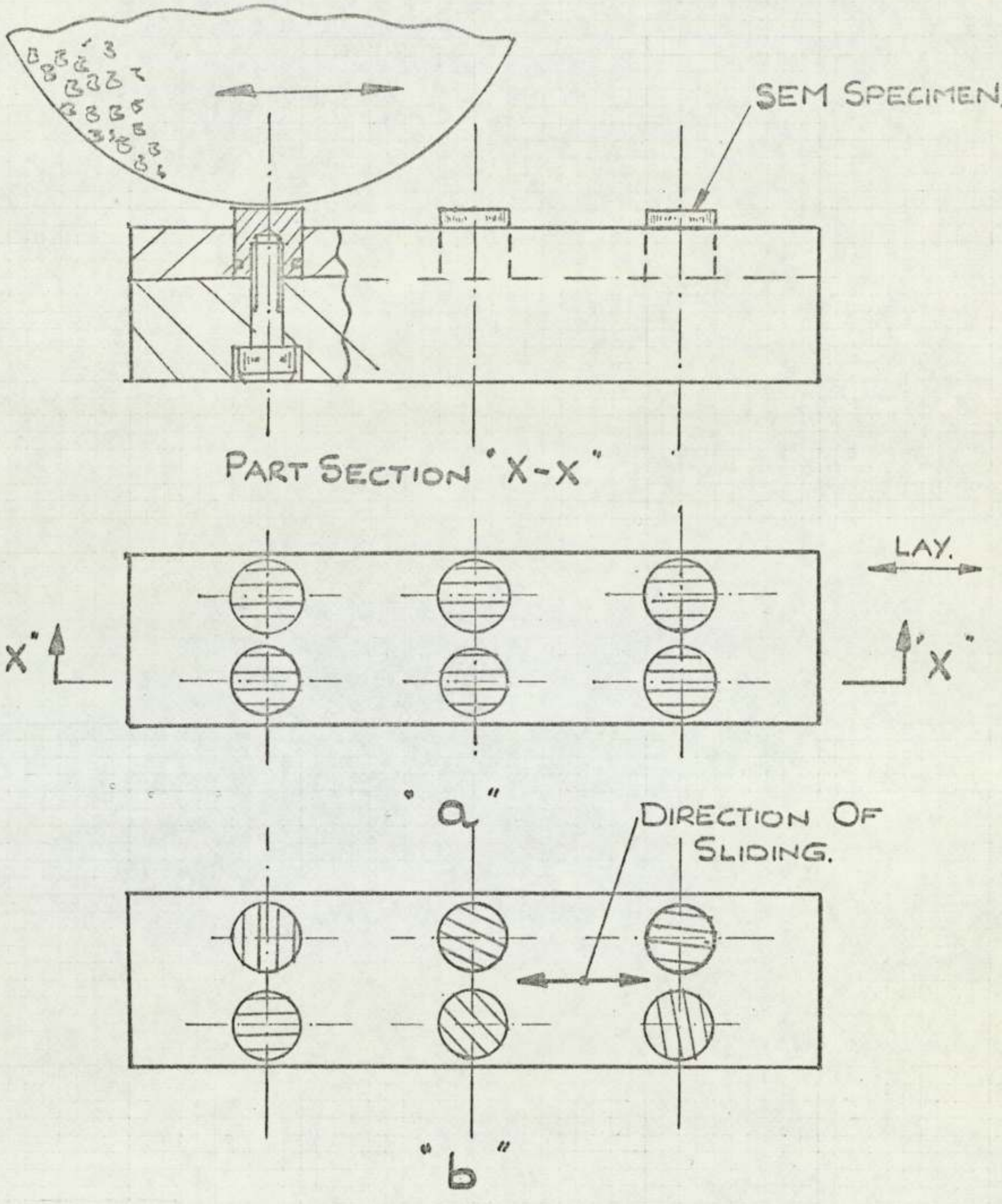


FIG. 4-3 DETAILS of SPECIMEN HOLDER SHOWING;

a) USE AS A MACHINING JIG.

b) PLAN OF SPECIMENS DURING WEAR TESTS.

SCALE: FULL SIZE.

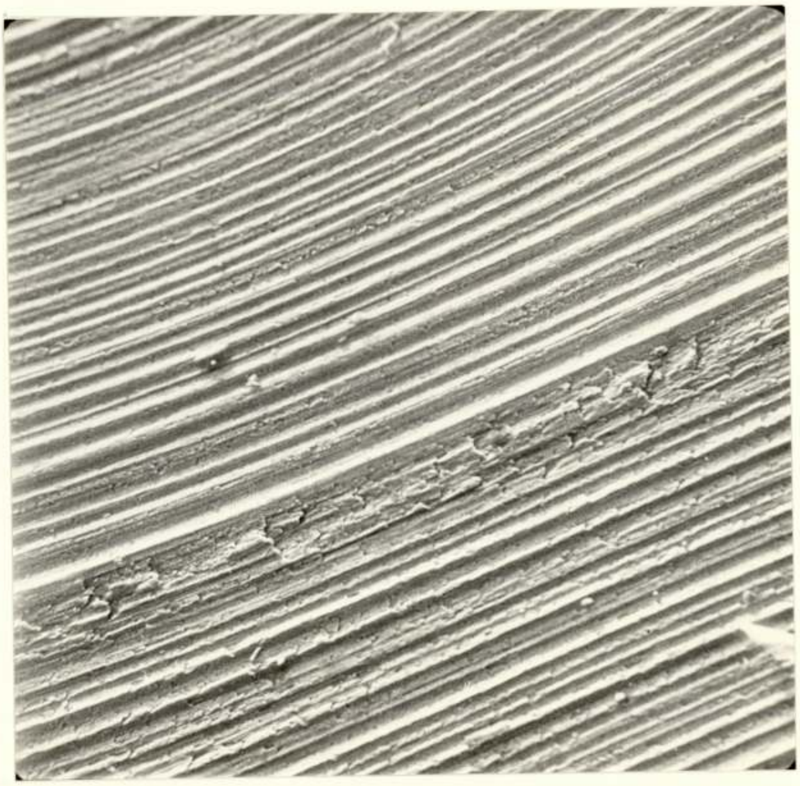
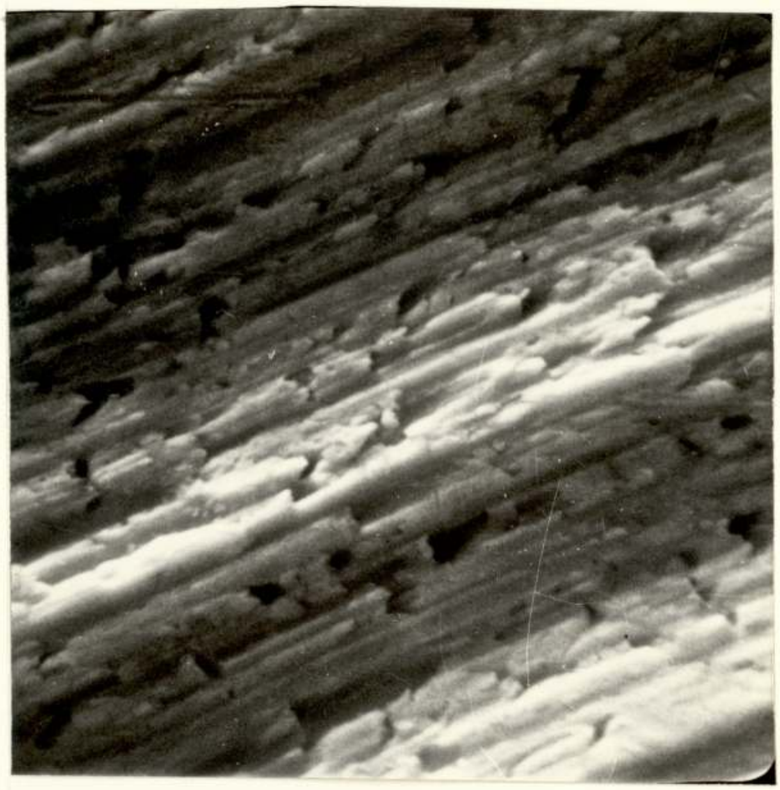
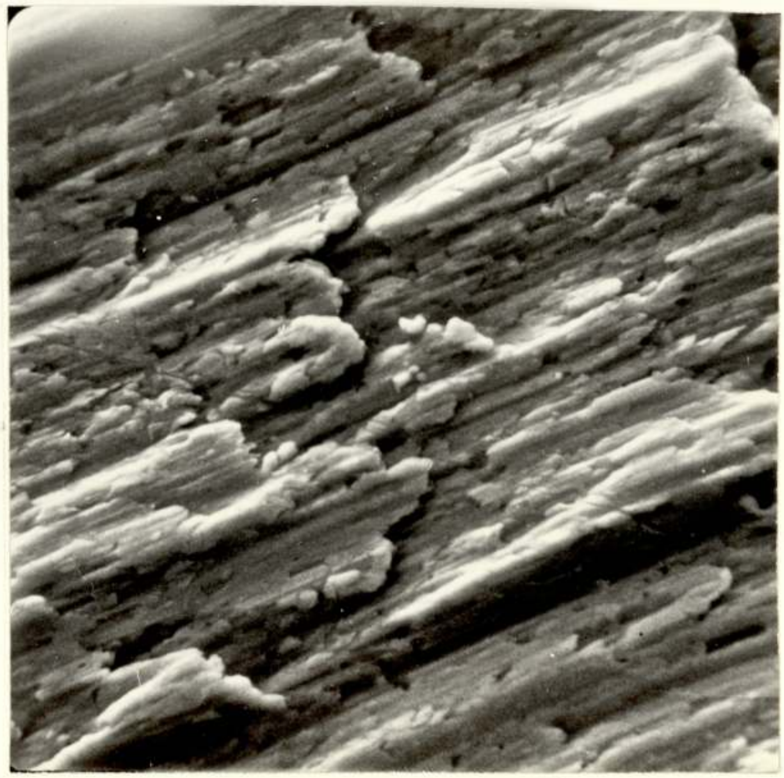


Fig. 4.4. S.E.M. Photograph of Faced Specimen
Magnification: 170
Feed = 0.00075 in.per rev.
Ref. No. 401.



a.



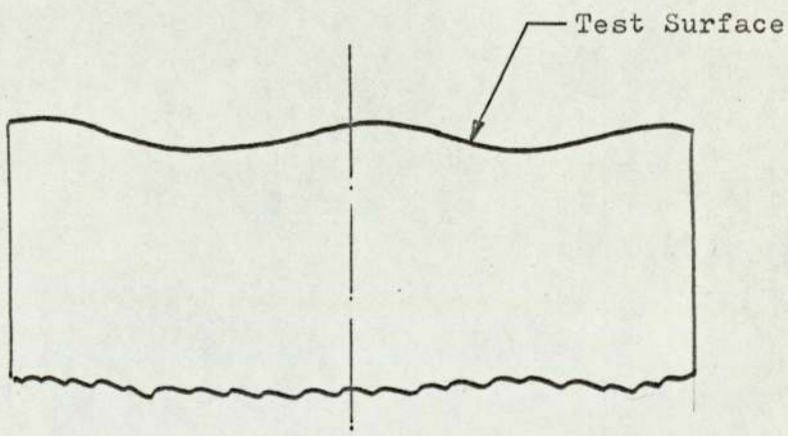
b.

FIG. 4.5. ENLARGED DETAILS OF FACED SPECIMEN
MAGN: 1,700
(a) "NORMAL" SURFACE (REF. NO: 404)
(b) TORN AREA (REF.NO: 406)

Section 5 Wear Test Procedure

5.1 In the particular series of experiments carried out the emphasis was placed on the smaller S.E.M. specimens and the procedures detailed relate to these specimens.

5.2 The specimens, each of which was identified by a reference number were machined as described in Section 4.4. The specimens were then removed and cleaned with acetone to remove traces of cutting fluid which would cause contamination in later wear trials and also cause contamination in the specimen chamber of the S.E.M. under vacuum conditions acetone was selected since it would not form a surface layer which would again affect later wear trials. After fitting the aluminium peg into place the specimen was located in the stage of the S.E.M. and the vacuum chamber pumped down. The specimen was then focussed at a low magnification and the orientation determined by the VPN marks. The surface was then examined and photographs taken of areas of interest. The magnification used varied from x28 to x14,000 but at the higher magnification resolution was low. It must be realised that even at 1,000 magnification the area covered is 0.004" x 0.004" and as each specimen may have a small amount of waviness present viz:-



the area selected for initial photographs may not be an area

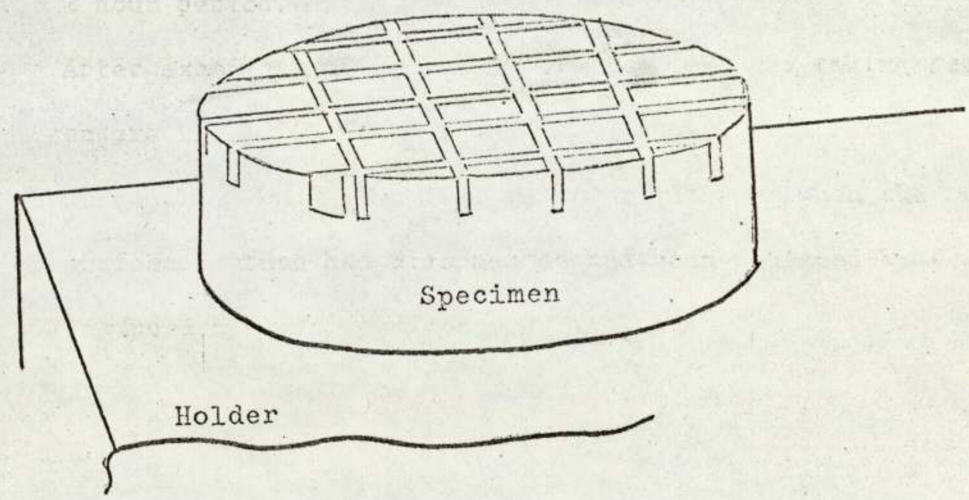
/cont.

of particular interest at a later examination.

This could be overcome in two possible ways:

(i) More extensive photographic coverage. This presents problems since the utilisation of the S.E.M. is extremely high in the order of 12 hours per day, and the average allocation of time for this project would be 1 to 2 hours per week. Also the economic aspect must be considered since S.E.M. time is expensive.

(ii) Improved recognition and positioning of specimens in the S.E.M. A possible solution here is the use of a grid pattern cut into each specimen using a thin blade in a spark erosion machine, viz:-



This would probably allow more detailed examination of a particular area but the grooves could possibly affect test results by increasing heat dissipation and acting as traps for abrasive particles.

After the S.E.M. photographs had been taken, recordings were taken of the surface profile using a Talysurf Model 3 fitted with a straight line datum.

The specimens were the orientated so that the lay was at the required inclination to the direction of sliding and a reference mark made on each specimen and holder to enable specimens to be relocated after removal. A check could be made on the exact angle of orientation from the photographic record, see Fig. 6- 2a and Fig. 6 - 5 a.

5.3 The wear test conditions selected for these trials were

(i) Lubrication-MOBIL D.T.E. Light Oil. fed to the sliding surface via felt wiper pads from a sump in the specimen holder.

(ii) Pressure and Sliding Speed. These are inter-connected since the life of a bearing is often related to the product of pressure and velocity (P.V.) value where $P = lbf/in^2$ and $V = ft/min$. Furthermore the maximum pressure available on the test rig was limited to total upward thrust of 450 lbf by the shaping machine construction. Using a total effective load of 8·0 lbf on the hanger:-

Average pressure on each specimen =

$$\frac{\text{Load x Mechanical Advantages}}{\text{No. of Specimens x Individual Specimen Area}}$$

$$= \frac{8 \times 10}{6 \times \frac{\pi}{4} \times .375^2}$$

$$= \underline{120 \text{ lbf/in}^2 \cdot (8.3 \text{ bar})}$$

The sliding velocity, will of course, vary owing to the design of the quick-return mechanism. The average sliding speed was taken as 2 x length of stroke x No. of strokes per minute. In this case the stroke selected was 8 ins., this allowing the maximum use of the top specimen. Using 38 strokes/min.

Average Sliding Speed = $\frac{2 \times 8 \times 38}{12}$ = 50 ft/min (0.254 m/s).

/cont.

These combined gave a P.V. value of 50 x 120 = 6000. This compares with a recommended value of approximately 1,000 as suggested in a paper by Neale (43). It was felt that this value would be high enough to give wear in a short period but not so high as to cause catastrophic failure. The wear test specimens were then positioned in the holder and the wear test carried out. The specimens were then removed and Talysurf traces produced, after the specimens were examined using the S.E.M. The procedure was generally as in 5.2. Visual examination of the specimen showed which areas had worn. These areas were located using a low magnification and then the higher magnifications used for examining areas of particular interest. It was found that 3 specimens could usually be examined in a 2 hour period.

After examination the specimens were replaced taking care to ensure the orientation remained constant and a further run was carried out. The test runs were stopped when the original surface texture had disappeared and been replaced by a surface produced by wear conditions.

RESULTS AND CONCLUSIONS

6.1. The experimental results may be classified into four main sections viz.

(i) General Specimens

(ii) Ground Specimens

(iii) Milled Specimens

(iv) Lapped Specimens

6.2. General Specimens: It was evident from the early results that the S.E.M. was a unique tool for the study of surface topography. The waves that were found on ground specimens due to the ploughing action of the grits appeared very clearly and were evident when horizontal or vertical grinding Fig. 1-8 and 1-9. It may be considered that the effect of these small fragments breaking off may have a significant effect on the wear of ground surfaces. The normal stylus instrument will not detect these waves and it is difficult to see how a surface profile parameter can take full account of this factor.

The examination of surfaces produced by a single point tool. Fig 4-4 and 4-5, showed very clearly the tearing effect and the variations in topography that may occur within a machined surface. In this case the profile along the lay will differ. and it shows the merit in moving away from the surface profile defined by a straight line to that of area consideration (41). The practical problem will however remain of the cost of assessing a surface profile. Some of the more recent techniques involve very sophisticated instrumentation techniques which could be well beyond the budget of most companies.

6.2. cont....

It is perhaps interesting to note that one of the cheapest forms of surface assessment; the tactile comparison specimen, does in fact offer area comparison. The effect of faulty production techniques is shown clearly in Fig. 1-16. In this case the cracks resulted from a plunge-grinding operation in which the stock removal rate was excessive. The production costs would be reduced at the expense of high warranty costs. The pattern of crack formation is roughly parallel and perpendicular to the direction of grinding. This particular component had not been in service.

6.3. Ground Specimens.

The examination of the specimens as "ground" revealed no unusual features, eveidence of the "wave" formation was present. Fig 6-1c shows the V.P.N. datum mark clearly, the texture is clearly visible in the indentation.
After 4 hours, the amount of wear on individual specimens varied. On Specimen 1 in which the direction of sliding was perpendicular to the direction of grinding, the original surface texture had completely disappeared, this is shown in Fig.6-2c. It is evident that considerable plastic flow had taken place, the sharp edge of the V.P.N. datum mark has been blurred and the corner filled in. Fig 6-2b.
Reference to the surface profiles Fig. 6-10 which are taken at right angles to the original direction of grinding show how the original surface has been smoothed down.
Fig. 6-10b and c are taken in the direction of sliding i.e. along the "valleys" produced by the wear process. Surface profiles taken perpendicular to the direction of sliding

6.3. cont...

Fig.6-11a and b show a remarkable resemblence to those from a ground surface Fig.6-10a. Examination of S.E.M. photographs reveal the same likeness, in this case on an area basis Fig. 6-3a shows a general view of the completely modified surface profile, the direction of the original grinding traverse can be seen in the V.P.N. indent.

The following table gives the changes that have taken place in the surface profile parameters:

Ground Specimen No.1.

	Micro-metres				
Description	h_{cla}	Peak	Valley	P to V	Fig No.
Before Wear ⊥ to lay	0.31	1.15	1.3	2.75	6-10a
After 4 hrs wear ⊥ to lay	0.13	0.5	0.5	1.0	6-10b
After 4 hrs wear Parallel to lay ⊥ to direction of sliding	0.27	2.0	1.8	3.7	6-11a
After 7 hours wear Parallel to lay ⊥ to direction of Sliding	0.26	1.5	2.1	3.6	6-11b

Note: The graphical records cannot be used to make exact comparisons with the meter readings, since the meter readings were obtained on tracks which were parallel and avoided the V.P.N. indents which would have produced incorrect readings.

Specimen 4 after 4 hours wear was only showing slight traces of wear, this was marked around the V.P.N. indentation, where the bulge produced by the indent was worn away first. Examination of the surface profiles confirm this, the points "A" are unchanged on Fig.6-12a and b. Deep scratches also showed up both on the profiles marked "B" and on the S.E.M. photographs, due probably to metal particles becoming trapped and causing ploughing or abrasive wear. The presence of such loose particles was evident in the V.P.N. indentations. This was also obvious in other specimens Fig 6-3b after 7 hours wear.

6.4. Milled Specimens.

The photographs of the milled specimens show a rough torn texture and the feed marks could be discerned on the lower magnification ones Fig. 6-4a. The rough texture was surprising in view of the care taken in machining the surface. A single point cutter having been used to prevent errors which may occur in a multi-tooth milling cutter with teeth of varying height.

After 2 hours testing, wear had taken place on the peaks of the profile. Fig 6-5a is a general view and reveals that large areas had been worn down to a smooth surface, in fact, a surface which had a similar appearance to that after grinding.

6.4. cont...

Unlike the ground specimens examined earlier there was little evidence of plastic flow Fig 6-5c shows the area around the V.P.N.datum mark and no sign of plastic flow is apparent, although it is evident that considerable wear had taken place. This photograph must be contrasted with Fig 6-2b which was obtained under identical sliding conditions. Only traces remain of the valleys, examination showed that these valleys exhibited only the original machines texture, without any sign of wear debris.

After 4 hours wear, the area of flat had further increased, there was still no evidence of plastic flow. The valleys of the original machining marks had remained unaltered Fig 6-6b. Closer examination of one of the worn areas revealed striations Fig.6-6c.

By 10 hours testing, the majority of the specimens surface had been modified and only traces of the original surface remained Fig. 6-7a. The resemblance of the striations to grinding was most marked. In Fig 6-7c signs of a "wave" type formation were present. An enlargement of the bottom of the groove still shows the original machined surface.

6.5. Lapped Specimens.

The details of the lapped specimens shows the random pattern resulting from the lapping process Fig. 6.8. Accordingly no attempt was made to alter the specimens angular position in the specimen holder. The surface appearance is of course that of a "soft" specimen and lapping is usually confined to specimens that have been hardened. Fig. 6.9a and b show the effect of wear, once again the worn area covers a large percentage of the original surface and a smoothing action has taken place, with consequent plastic flow. Examination of the worn area reveals the presence of striations which resemble grinding Fig. 6.3c is taken on a portion of the surface where the original surface has been completely modified.

6.6. The results obtained from this research could form the basis from which a long term research project can be mounted. This long term project should initially consist of the design and construction of suitable wear test rigs, see Fig.3.4. and then further experimental work carried out on a combination of sliding materials produced by various production processes. Measurement of wear can be carried out by the techniques already tested and found useful, viz.

i) Profile instruments to obtain values which typify industrial practice, using all the currently available parameters; h_{CLA}, Peak, Valley, Peak to Valley and Bearing Area and if possible storing the information of the surface profile on data-tapes.

(ii) The scanning Electron Microscope extended to the stereo- pair technique.

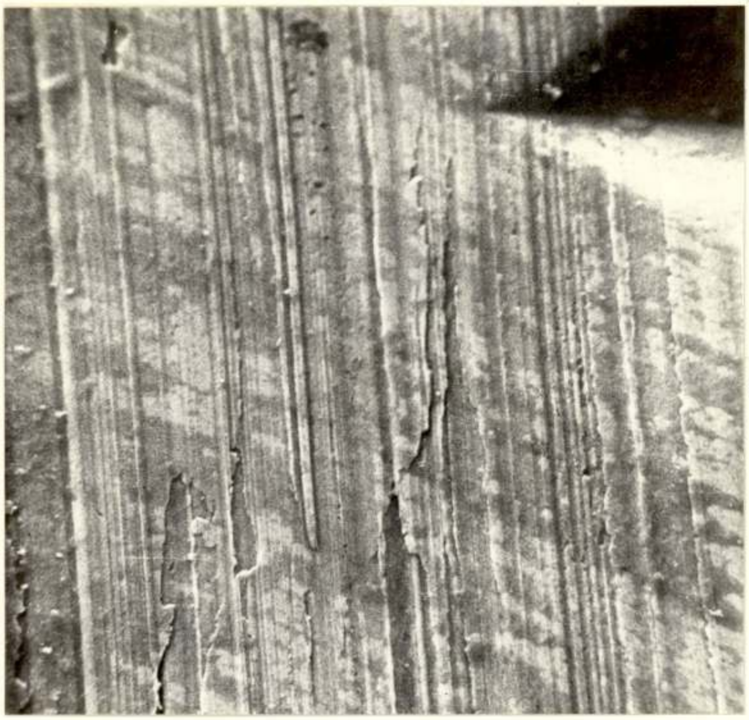
(iii) Further development work on holography as a means of mapping contour-lines on large areas. If this fails to provide accurate information due to variations in surface texture, then the existing topography mapping technique as outlined in (41) can be used.

The important feature will be the combination of existing techniques to study fully the changes that occur in a surface profile.

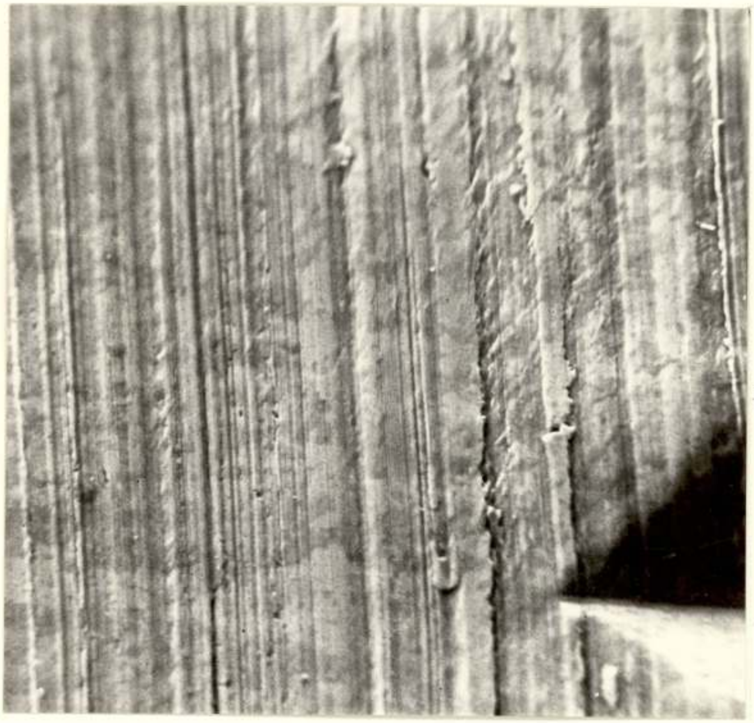
Of the particular results that require further investigation, is the apparent flow on a ground surface being greater than that of a surface produced by a single-point tool on similar work-piece materials. This raises the hypothesis that the wear rate may depend on "Surface integrity" and is a function of the production process rather than the surface parameters.

After the original surface had been under test the worn surface appeared analogous to that of grinding, irrespective of the initial method of surface production. This would suggest another line of research into a study of production techniques in order to determine which processes will modify to that of a ground surface as quickly as possible, but without releasing wear particles.

Due consideration must be given to the economic factors; the cost of production and the associated cost of failure if the component requires replacing before its design life has been reached.



a) 1,400
Ref No.5



b) 1,500
Ref. No.7.

c) 2,600
Ref. No.9.

Fig. 6.1.

GROUND SURFACE
BEFORE WEAR

a) 280
Ref. No.11.

b) 2,800
Ref. No.12.

c) 2,800
Ref. No.20.

Fig. 6.2.

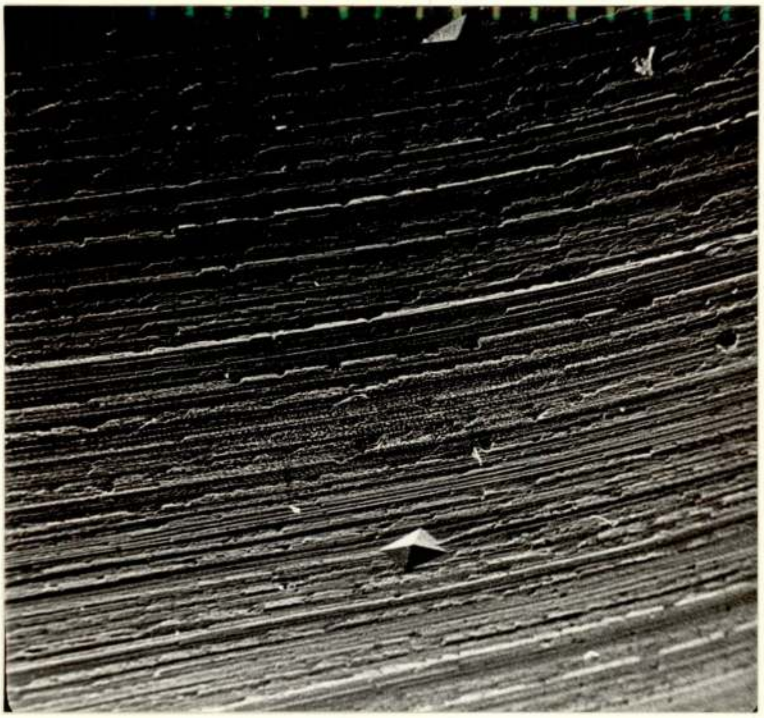
GROUND SURFACE
4 HOURS WEAR

a) x 280
Ref. No.24.

b) x 2,900
Ref. No.28.

c) x 285
Ref. No.30.

Fig. 6.3.
GROUND SURFACE
7 HOURS WEAR



a) x 27
Ref. No.106

b) x 310
Ref. No.103

c) x 6,500
Ref. No.110

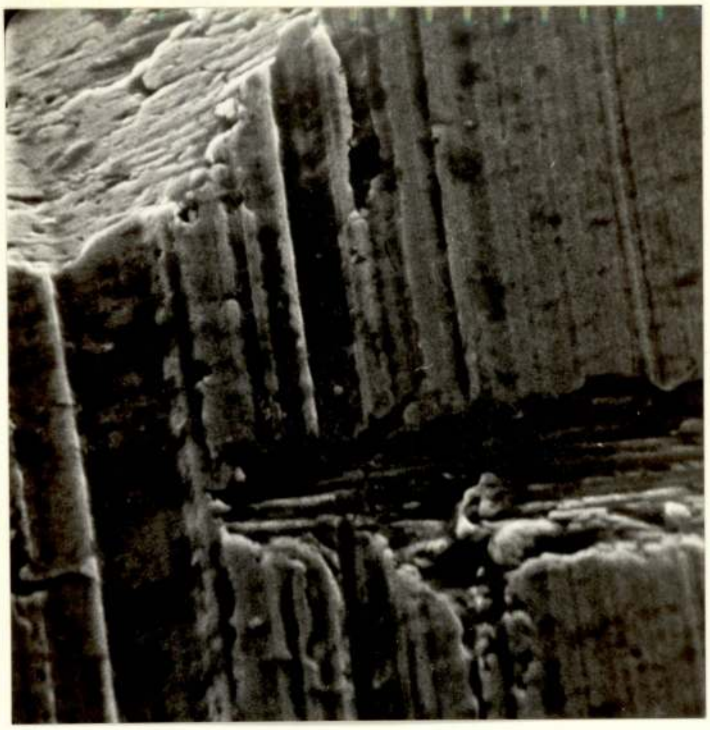
Fig. 6.4.
MILLED SURFACE
BEFORE WEAR

a) 75
Ref.No.116.

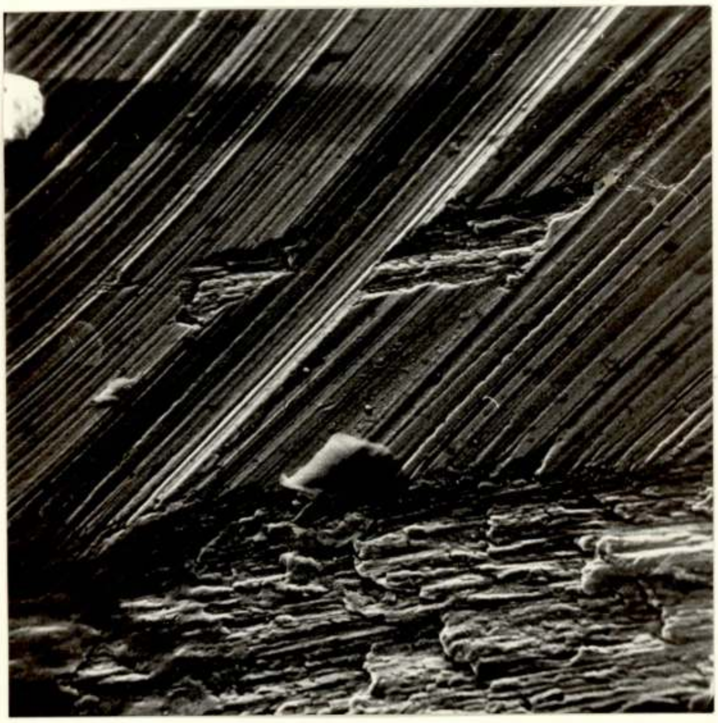
b) 2,900
Ref. No.119.

c) 265
Ref.No.126.

Fig. 6.5.
MILLED SURFACE
2 HOURS WEAR.



a) 2,650
Ref. No.129.

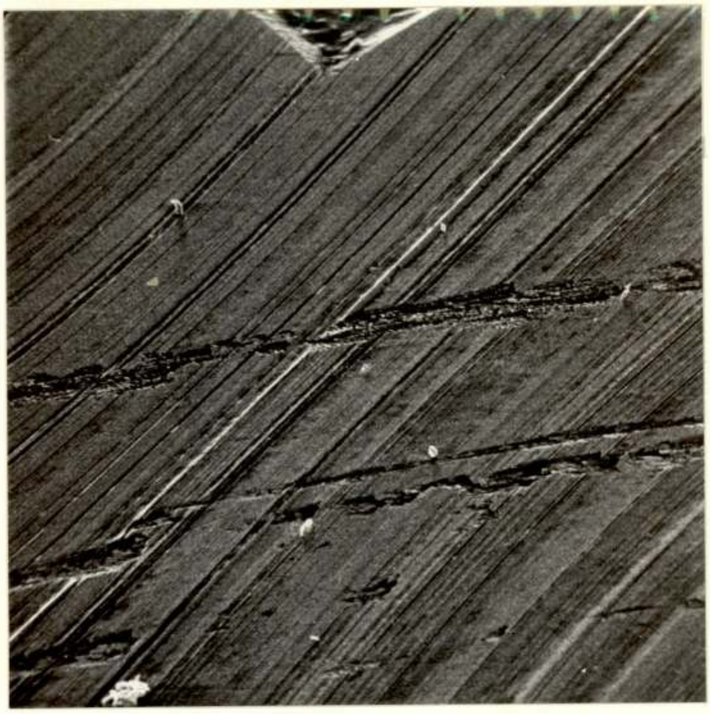


b) 700.
Ref. No.138

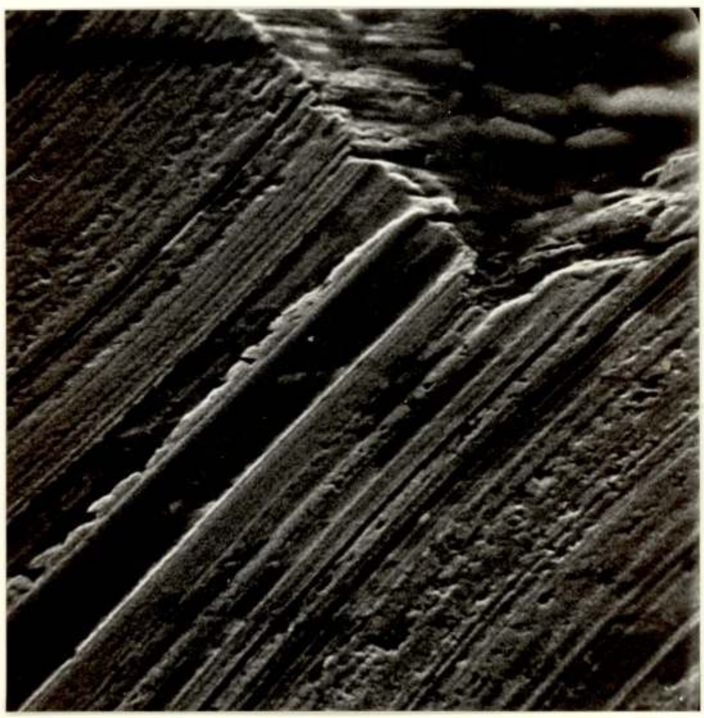
c) 7,000
Ref. No. 139

Fig. 6.6.

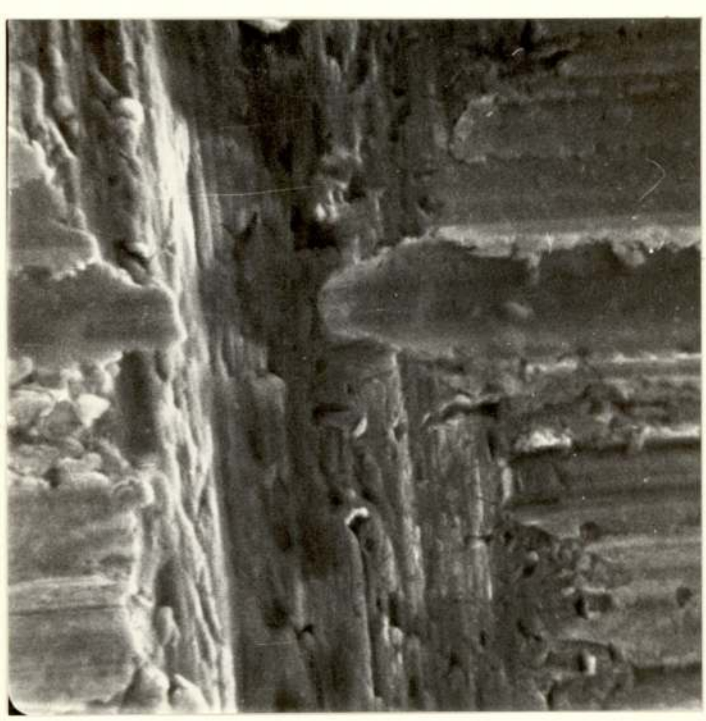
MILLED SURFACE
4 HOURS WEAR.



a) 120
Ref. No. 156



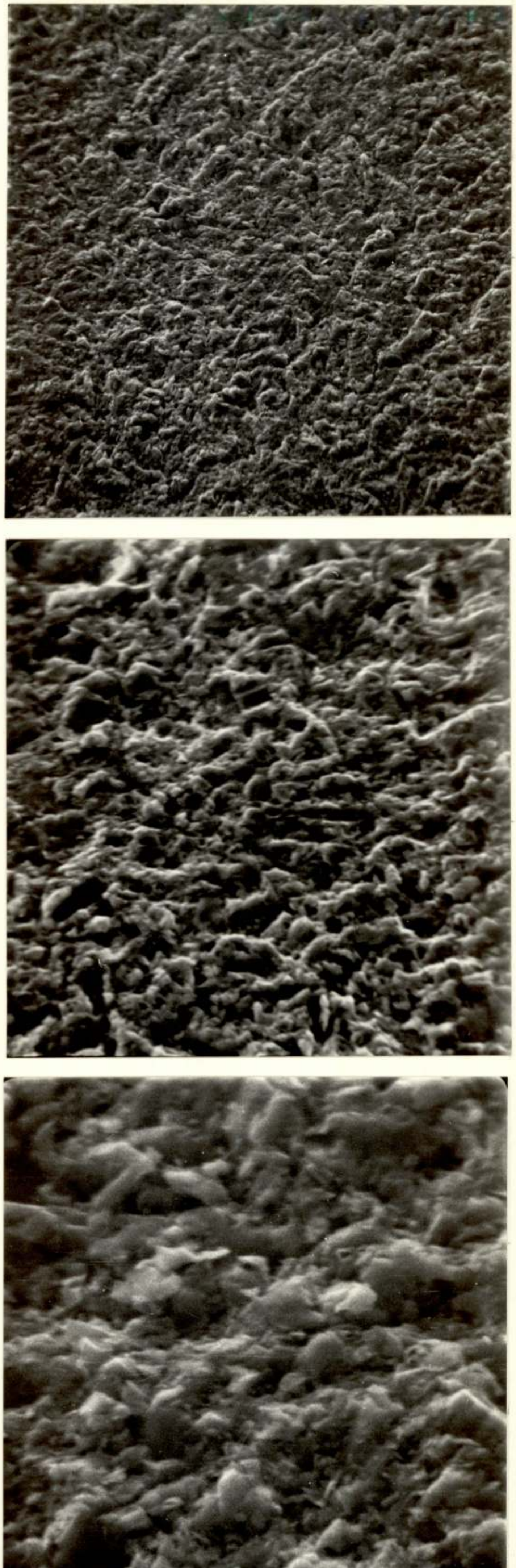
b) 1,200
Ref.No.158



c) 1,300
Ref.No. 144

Fig. 6.7.

MILLED SURFACE
10 HOURS WEAR



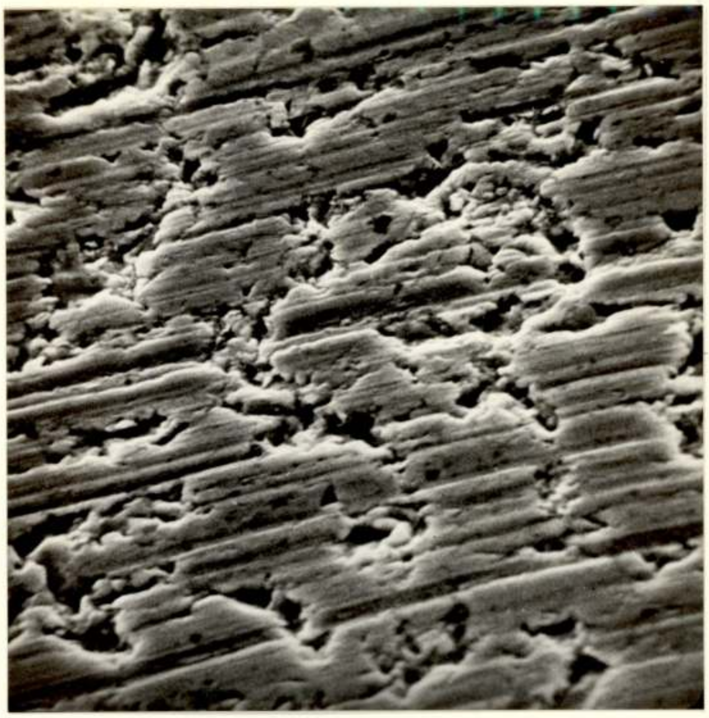
a) 1.35 K
Ref. No. 203

b) 2.6 K
Ref. No. 211

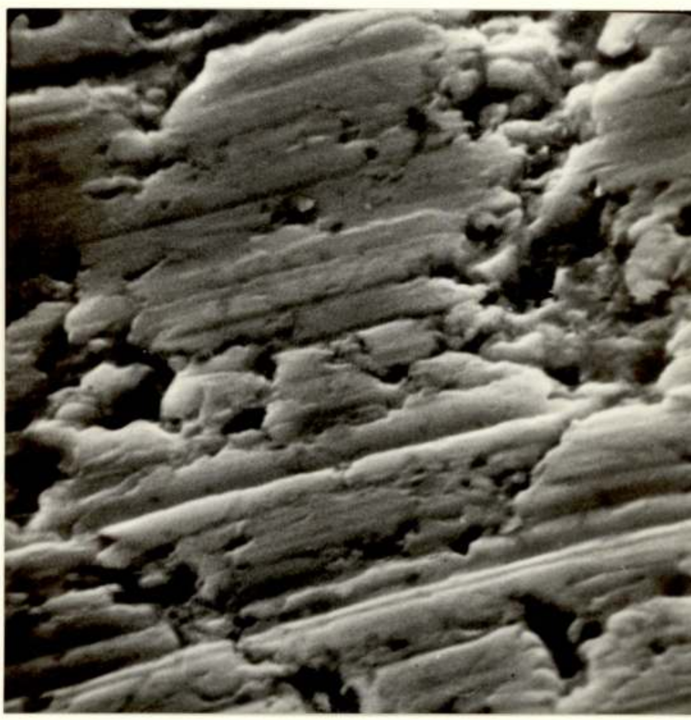
c) 6.8 K
Ref. No.202.

Fig. 6.8.

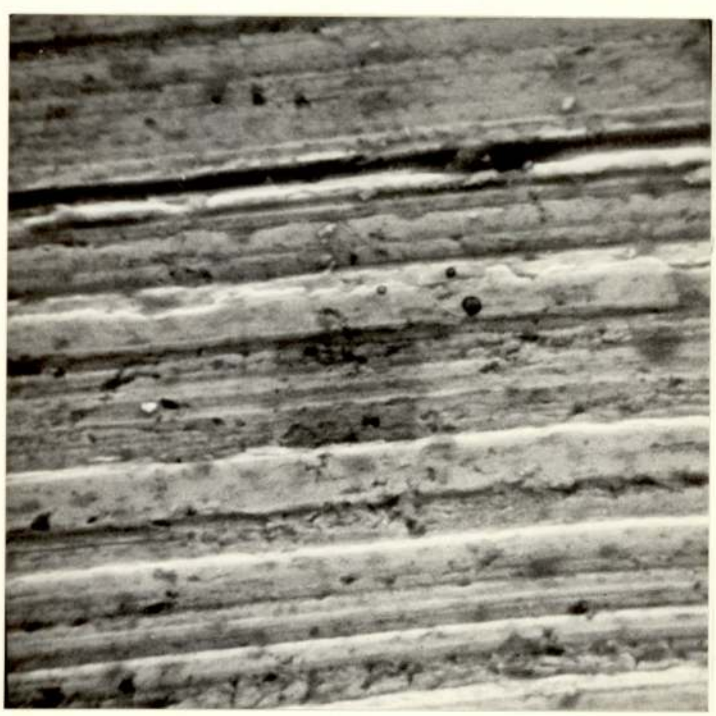
LAPPED SURFACE
BEFORE WEAR.



a) 2.9 K
Ref. No. 214

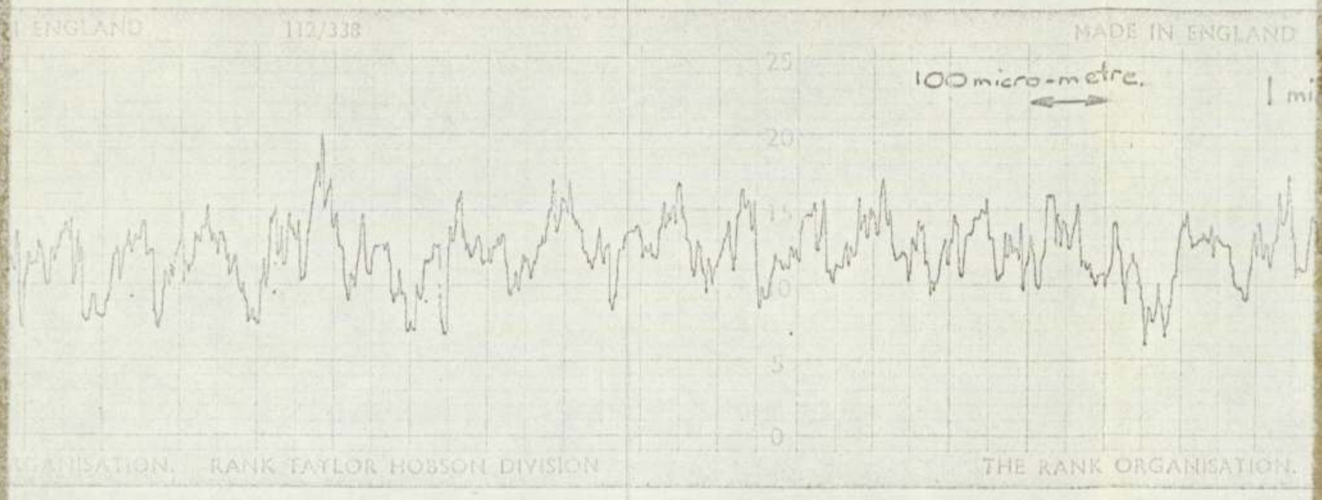


b) 7.9 K
Ref. No.215

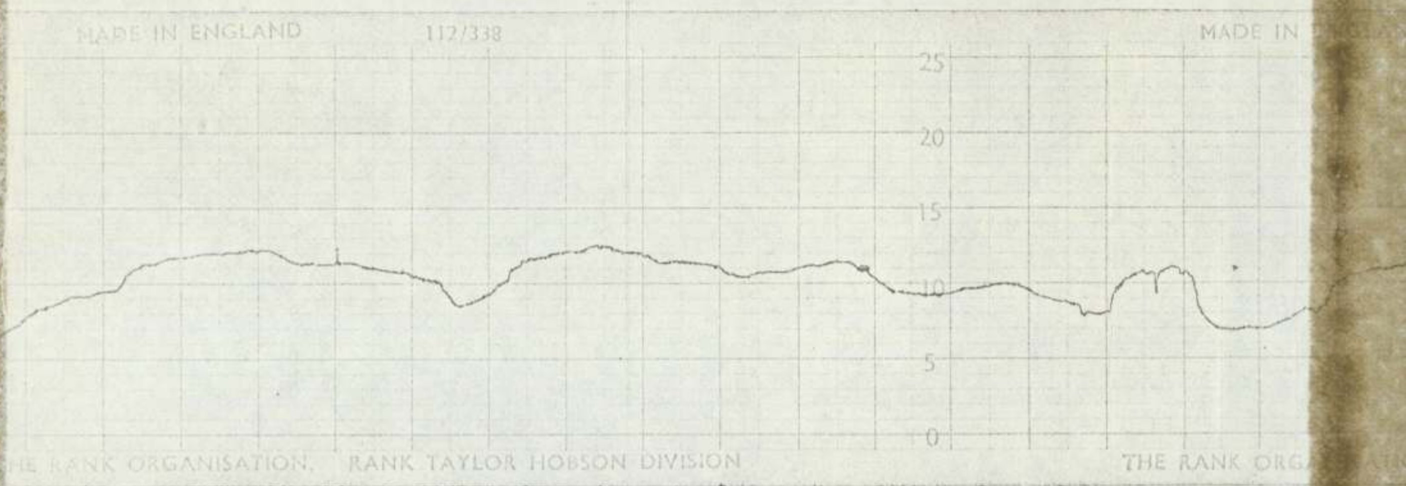


c) 2.3 K
Ref. No.220

Fig. 6.9
LAPPED SURFACE
2 HOURS WEAR



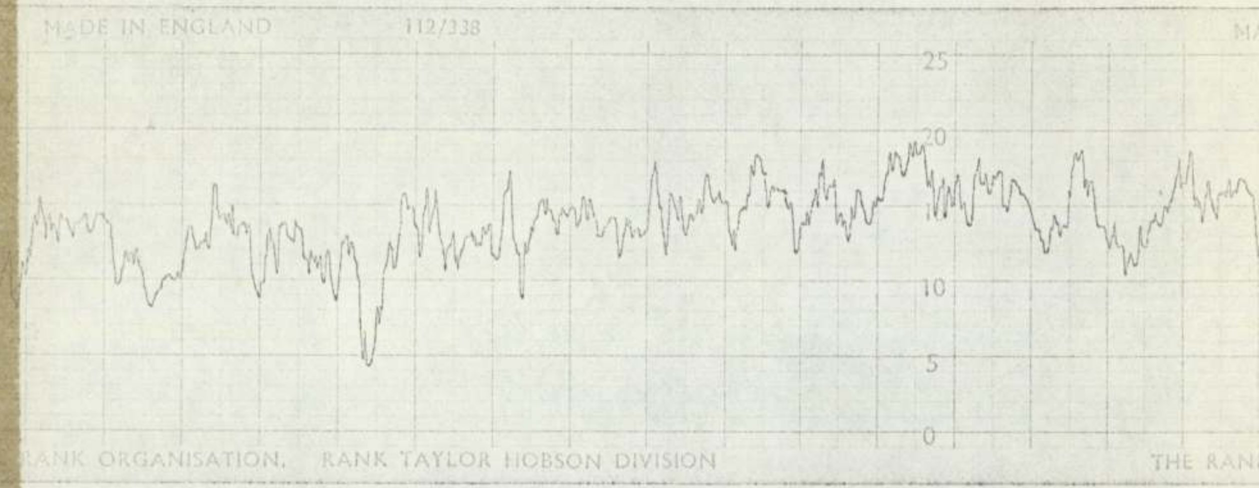
a) BEFORE WEAR.



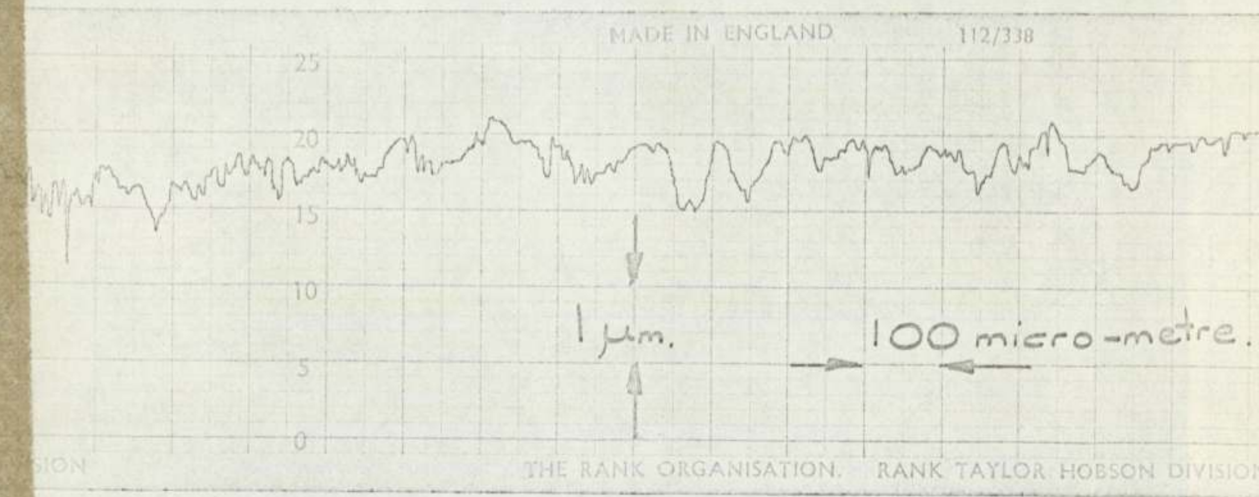
b) 4 HOURS WEAR

c) 7 HOURS WEAR.

a) BEFORE WEAR.



b) 4. HOURS WEAR.



c) 7. HOURS WEAR.

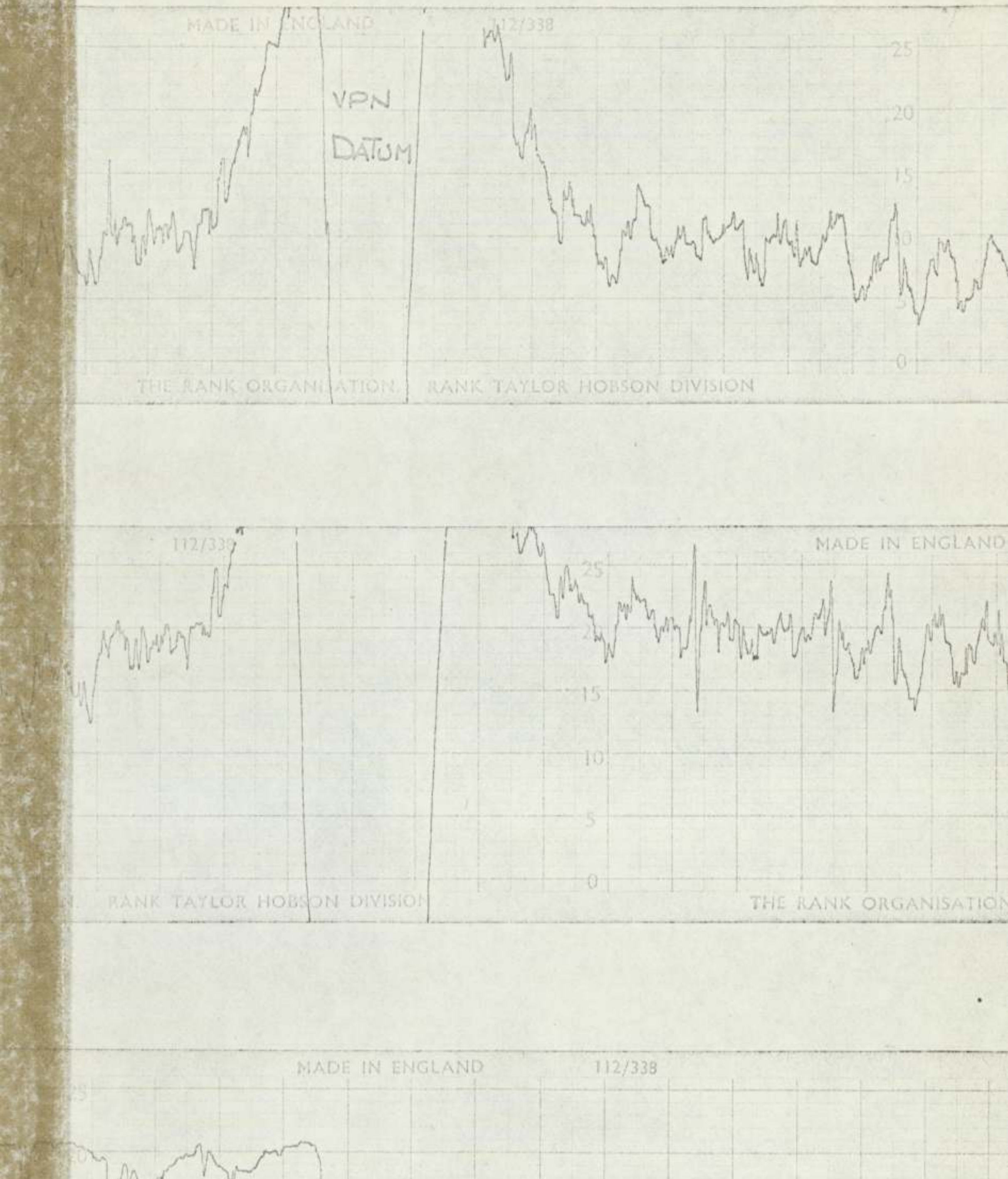
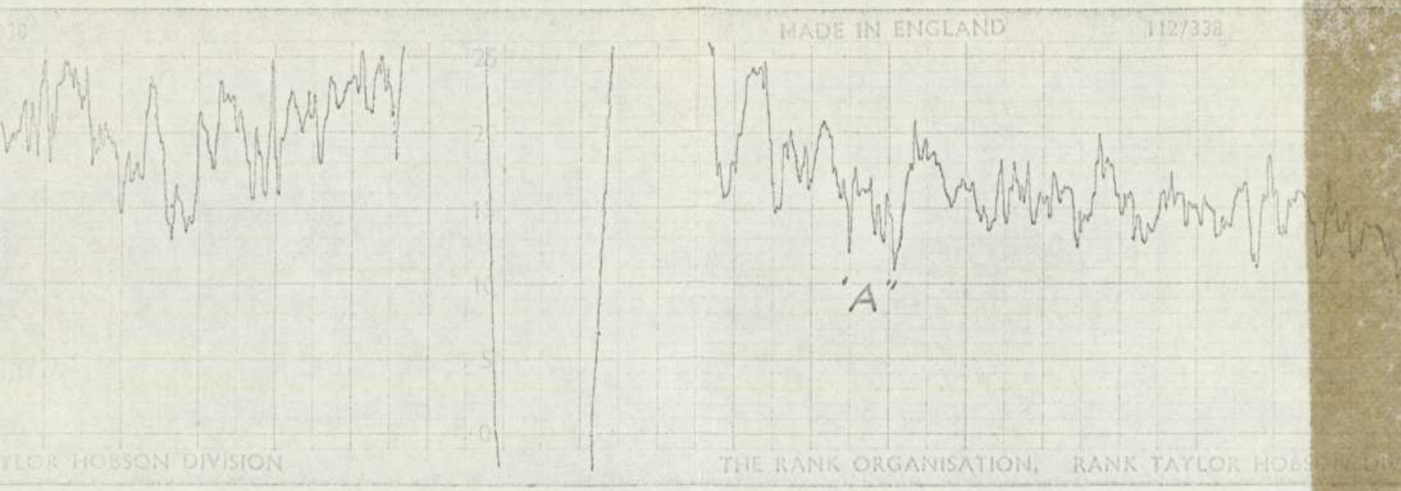
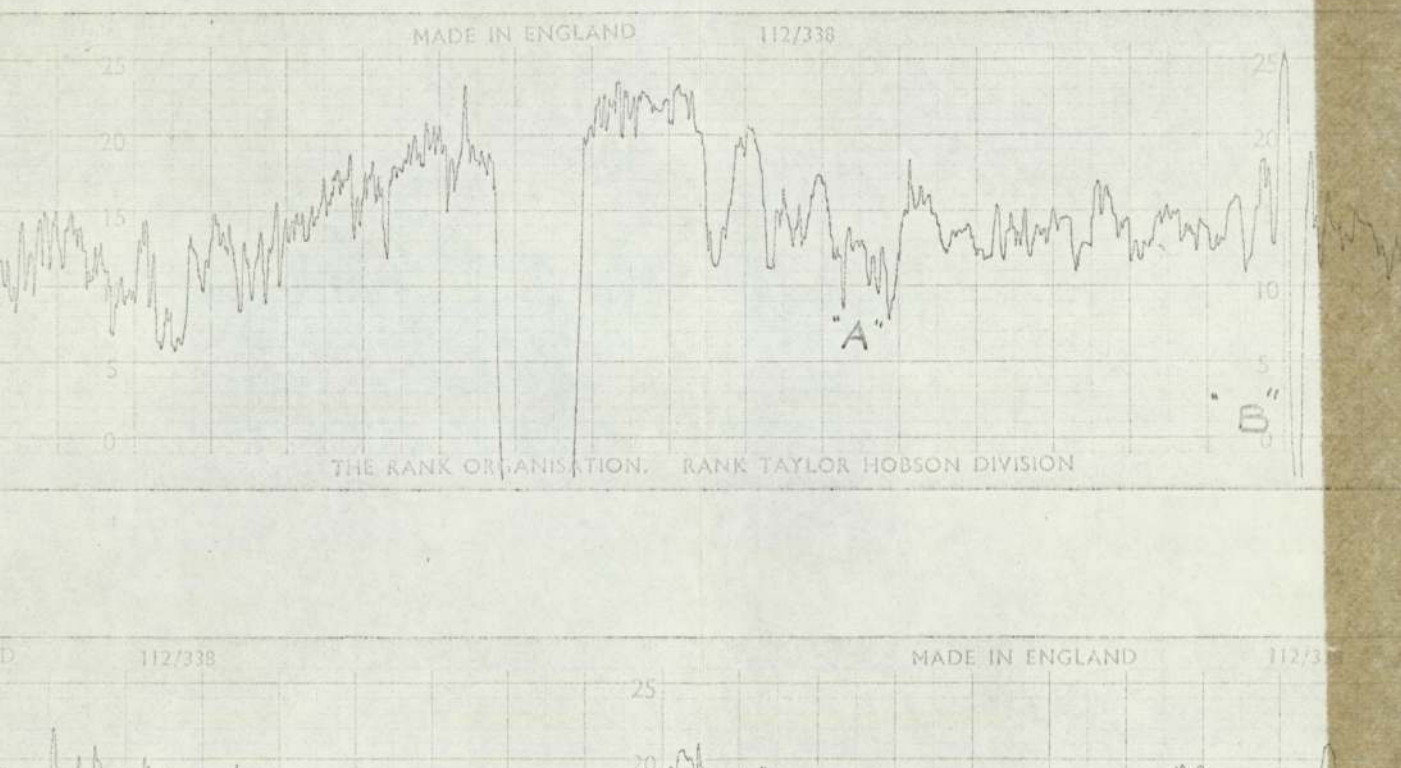


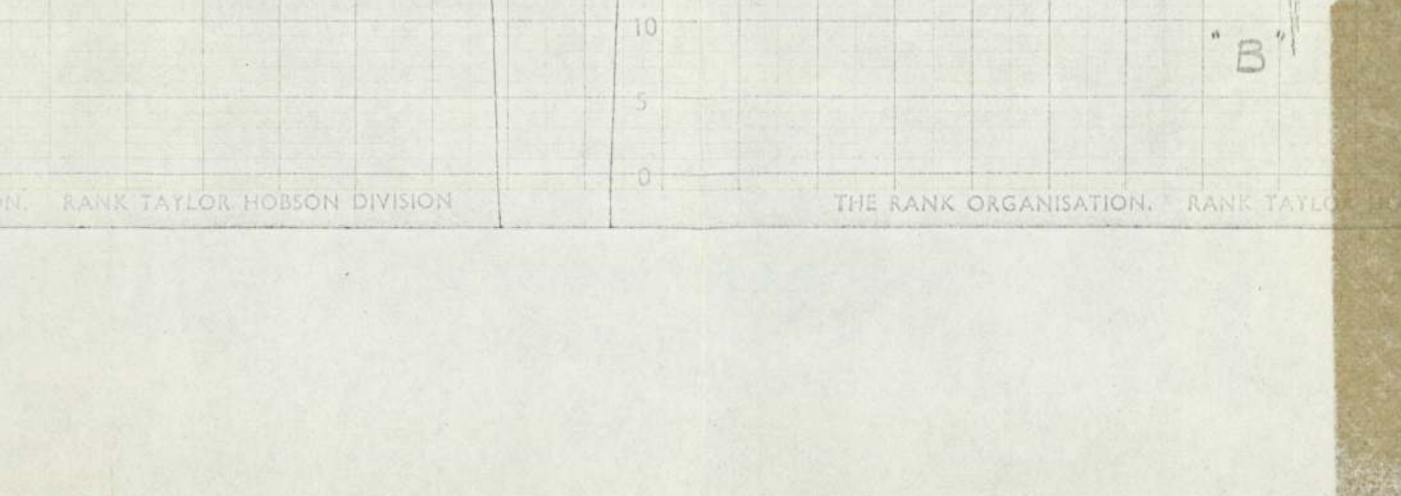
FIG. 6-12 TALYSURF PROFILES. SPECIMEN. 4.

SCALES: H ×100

V ×10,000


MADE IN ENGLAND
112/338
"A"
THE RANK ORGANISATION. RANK TAYLOR HOBSON DIVISION


MADE IN ENGLAND
112/338
25
20
15
10
5
0
"A"
"B"
THE RANK ORGANISATION. RANK TAYLOR HOBSON DIVISION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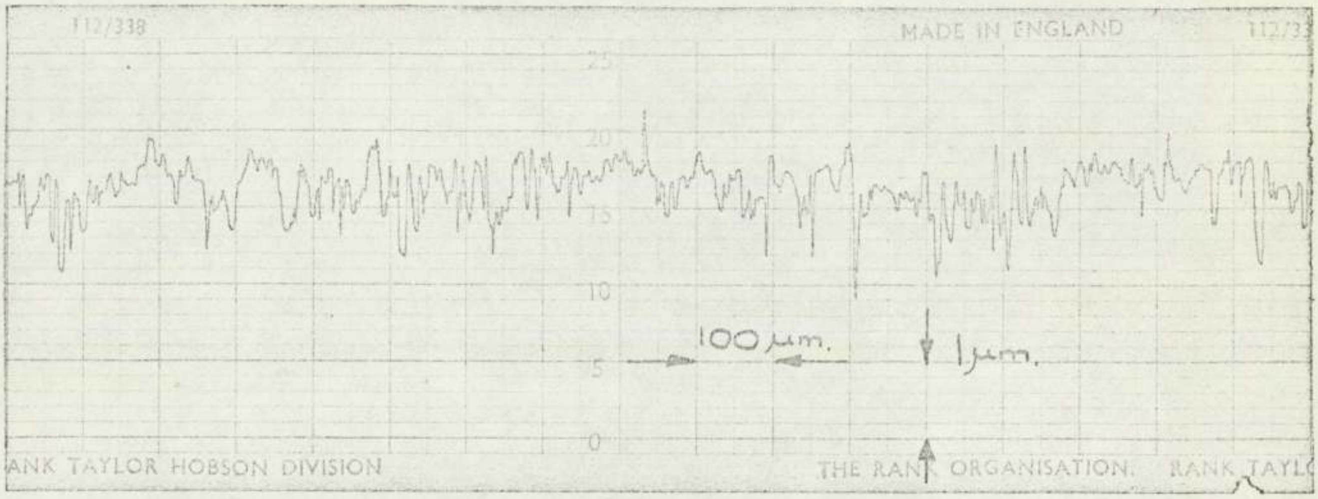
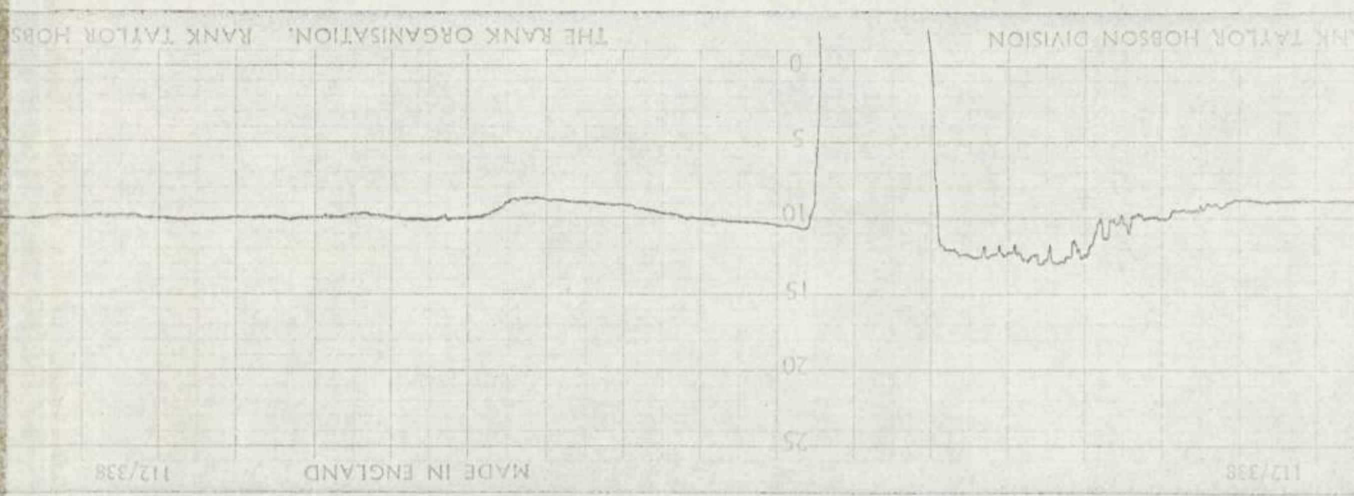
"B"
RANK TAYLOR HOBSON DIVISION
THE RANK ORGANISATION.



a) 4 HOURS WEAR

b) 7 HOURS WEAR

FIG. 6-11. TALYSURF PROFILES. SPECIMEN. 1.
PERPENDICULAR TO DIRECTION OF SLIDING.
MAG. H. ×100 ; V. ×10,000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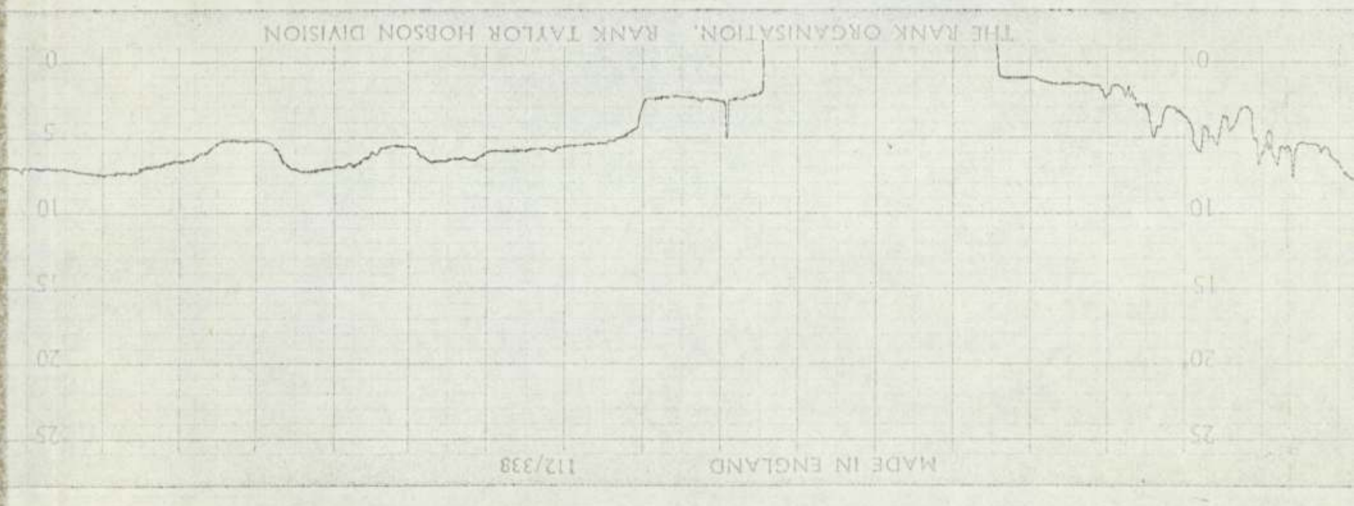
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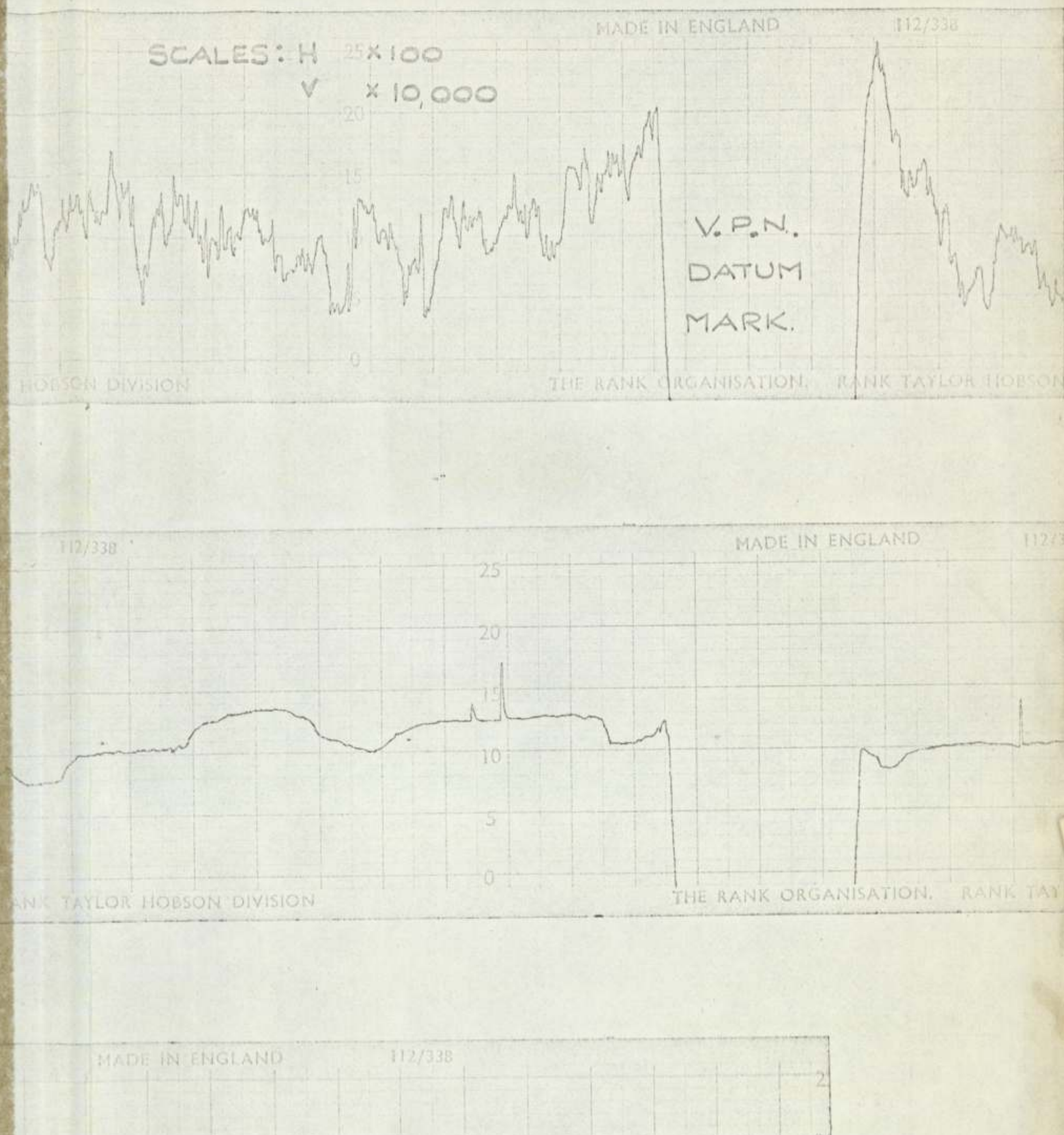

6-10. TALYSURF PROFILES. SPECIMEN. 1.

SCALES: H. ×100

V. ×10,000

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Appendix 1 - Catalogue of S.E.M. Photographs.

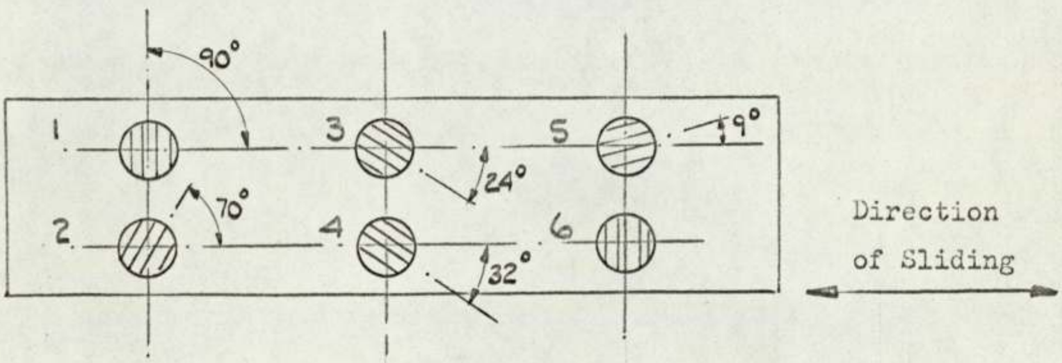
Test 1

Method of Manufacture: Surface Ground. h_{CLA} = 0.31 micro-metres

Specimen No.	Magn. *	Remarks		Ref. No.	Fig.No.
1	2,900		Before Wear	1	
	1,460		" "	2	
	3,000	Grinding Waves	" "	3	1.8
4	2,800		" "	4	
	1,400		" "	5	6.1a
	2,600	Grinding Waves	" "	6	
5	1500		" "	7	6.1b
	3,000		" "	8	
	2,600	Grinding Waves (Near VPN).	" "	9	6.1c

* Photograph 4" x 4"

Test 1 - Orientation.



After 4 hours Wear

Specimen No.	Magn.	Remarks	Ref. No.	Fig.No.
4	2,800		10	
	280	Worn at Edge of V.P.N.Indentation.	11	6.2a
	2,800	Flow at edge of V.P.N. "	12	6.2b
	280	Relative position of 12	13	
2	2,800	Corner of V.P.N.	14	
	280	Relative Position of 14.	15	
	2,800	Showing scratch	16	
	280	" "	17	
1	2,800	Near Edge (Interaction)	18	
	280		19	
	2,800	Near V.P.N. Showing wear	20	6.2c
	280	Relative Position of 20	21	
3	2,800	Interaction showing scratches	22	
	280	Relative Position of 22	23	

After 7 hours Wear

Specimen No.	Magn.	Remarks	Ref. No.	Fig.No.
1	280		24	6.3a
	2,900		25	
2	290	Near V.P.N.	26	
	7,500	Debris Near V.P.N.	27	
	2,900	Relative Position of 27	28	6.3b
5	800	Grinding Marks	29	
	285		30	6.3c
	2,830		31	
4	2,820	Flow near V.P.N.	32	
	7,200		33	

Test 2

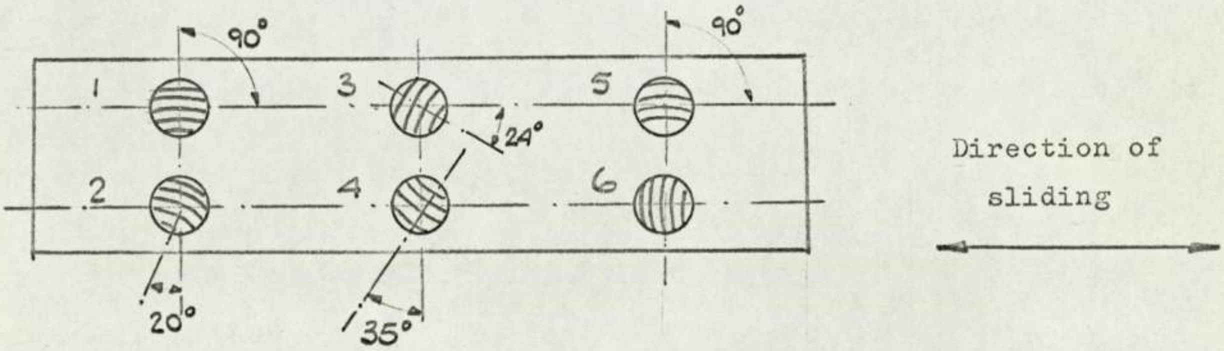
Method of Manufacture - Milling using Single Point Fly Cutter

Before Wear

Speed 480 Rev/min. Feed = 0.375 in/min.

Feed per rev. - 0.0008 in.

Specimen No.	Magn.	Remarks	Ref. No.	Fig.No.
1	28	O/all View of Indents	101	
	750		102	
	310		103	6.4 b.
	155		104	
	7,700		105	
2	27		106	6.4 a
	135		107	
	260		108	
	640		109	
	6,500		110	6.4 c
4	28		111	



Orientation

After 2 Hours Wear

Specimen No.	Magn	Remarks	Ref. No.	Fig.No.
1	26		112	
	65		113	
	260		114	
	1,300		115	
	75	Worn High Spots	116	6.5 a
	750		117	
	7,500		118	
	2,900		119	6.5 b
2	29		120	
	310		121	
	280		122	
4	70	Interaction	123	
	29	Between V.P.N.	124	
	130		125	
	265		126	6.5 c
	1,320		127	

After 4 Hours Wear

Specimen No.	Magn.	Remarks	Ref. No.	
1	260		128	
	2,650	Top V.P.N.	129	6.6 a
	13.2 K.		130	
	2,650		131	
	2,750		132	
	1,270		133	
	6.9 K		134	
	65		135	
	152		136	
4	68		137	
	700		138	6.6 b
	7,000		139	6.6 c

After 10 Hours Wear

Specimen No.	Magn.	Remarks	Ref. No.	Fig.No.
1	2.7 K	Interaction	143	
	1.3 K	"	144	6.7 c
	270	" "	145	
	14 K	Bottom of Machining	146	
	7 K	Groove	147	
	270	General View	148	
4	26		149	
	130	Poor Definition - Incorrect	150	
	130	raster on camera tube	151	
	255		152	
	1,250		153	
	6.5 K		154	
	26	Same view as 124	155	
	120		156	6.7 a
	240		157	
	1,200		158	6.7 b
	560		159	
	1,150		160	

Test 3

Method of Manufacture: Grinding and Machine Lapping h_{CLA} = 0.18 micro-metres

Before Wear

Specimen No.	Magn	Remarks	Ref. No.	Fig.No.
1	13.5 K	General View	201	
	6.8 K	" "	202	6.8 c
	1.35 K	" "	203	6.8 a
	680	" "	204	
4	12.8 K		205	
	2.5 K		206	
	2.7 K		207	
	6.8 K		208	
	13 K		209	
	7 K		210	
	2.6 K		211	6.8 b
			212	
			213	

After 2 Hours Wear

Specimen No.	Magn	Remarks	Ref. No.	Fig.No.
6	2.9 K	Same Area	214	6.9 a
	7.9 K	Same Area	215	6.9 b
	3.2 K	Same Area	216	
4	2.6 K		217	
	7.6 K	Unworn Portion (Poor Definition)	218	
	8.0 K		219	
	2.3 K	Similarity with appearance of ground surface.	220	6.9 c

General Specimens - Ground

Specimen.

(i) Distributor Cam Track. - Subject to Abusive Grinding.

Specimen No.	Magn.	Remarks	Ref.No.	Fig.No.
1	1.31 K	Pitted Portion	301	
	130	Surface Cracks Location 301.	302	
	6.6 K		303	
	1.31 K		304	
	660		305	
	2,650		306	1.1 b
	6.6 K	Enlargement of 306	307	
	2.65 K		308	
	1.32 K		309	
	1.32 K		310	
	670		311	

(ii) Circumferential Ground. Depth of cut 0.01 mm to spark-out, with coolant.

Specimen No.	Magn.	Remarks	Ref.No.	Fig.No.
1	7.5 K	Wave Formation	312	1.9
	1.5 K	" "	313	
	7.5 K	Repeat of 312	314	
	290		315	
2	3.1 K	Same area showing	316	
	7.7 K	Ploughing effect due to abrasive	317	
	1.55 K	Grit	318	
	2.7 K		319	
	1.35 K		320	

(iii) Ground Gear Tooth:

Specimen No.	Magn.	Remarks	Ref.No.	Fig.No.
			321	
	2.4 K		322	
	590		323	

General Specimens - Edge Cutting Tools

Face Turned - Single Point H.S.S. Tool.   Feed = 0.00075 in/rev.

Specimen No.	Magn.	Remarks	Ref.No.	Fig.No.
1	170		401	4.4
	340	Showing region of B.U.E.	402	
	840		403	
	1.7 K		404	4.5 a
	3.4 K		405	
	1.7 K	Showing Torn Area due to B.U.E.	406	4.5 b

End Milled

Specimen No.	Magn.	Remarks	Ref.No.	Fig.No.
1	28		407	
	150		408	
	700		409	
	1.4 K		410	
	2.8 K		411	
2	3.1 K		412	
	305		413	
	120		414	