Surface Finish Treatise in Relation to Cylinder Liners

by Eric Willis

Quality Manager

GKN Sheepbridge Stokes Limited

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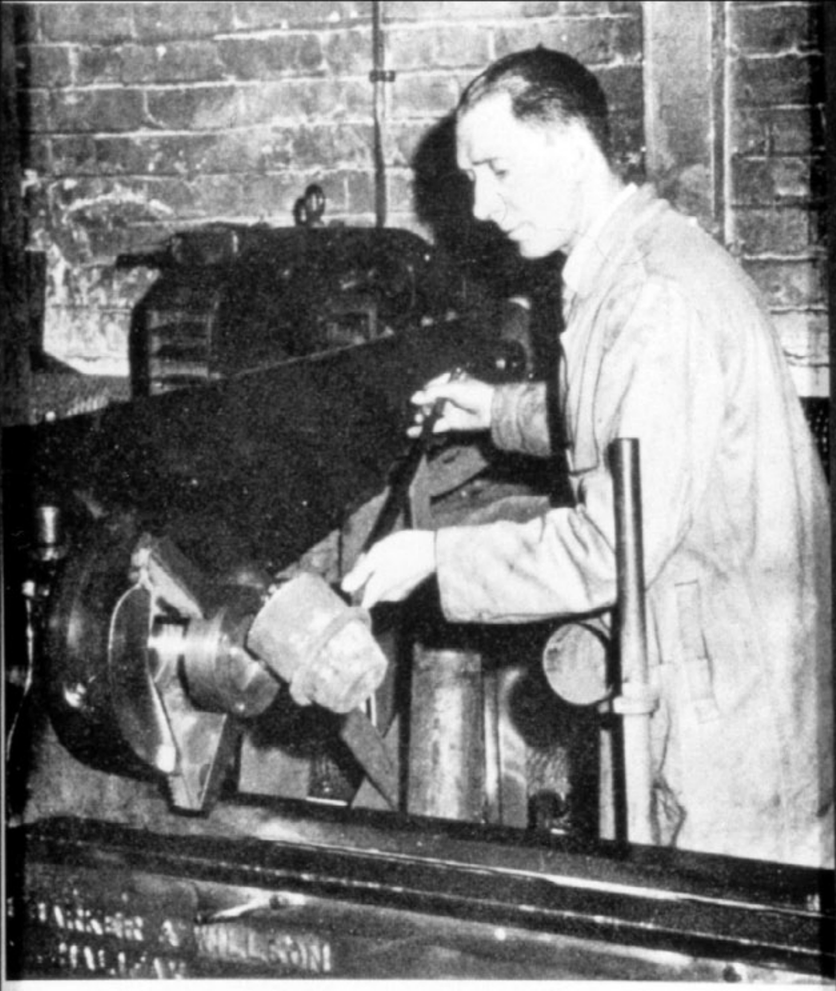
INTRODUCTION

The Centrifugally spun casting was developed by F. W. Stokes at his Foundry in Mansfield, Nottinghamshire, as near as the records can show the year was approximately 1917. He first developed the spinning technique using a centre lathe for the purpose (FIG 1), the object was to give a closer grained cast iron and ensure greater wearability as opposed to static cast iron bearing an open grain structure. He amalgamated with Sheepbridge in the early 1920's and became known as Sheepbridge Stokes Limited.

Manufacturing growth was swift, but the design of cylinder liners used in combustion engines remained the same throughout the years up to the war period of 1939. Very little change, if any, had taken place. Even up to the present time the determination of surface finish quality of cylinder bores has been a matter of individual concern of various Engine Builders and this paper is intended to portray the various elements involved in the process of producing a suitable surface texture and the consequences of such surfaces for the benefit or detrimental effect in an engine, this process and its functions are practical for both petrol and diesel engines. The ultimate object is to produce a surface finish giving a suitable oil reservoir which will minimise the necessity of a running in period, and withstand further rapid wear under load.

It was thought in those pioneer years that a surface of very high smoothness, free from scratches, was the ideal surface for a piston and rings to perform its necessary function. Seizures were commonplace,



First experiments in centrifugal casting.

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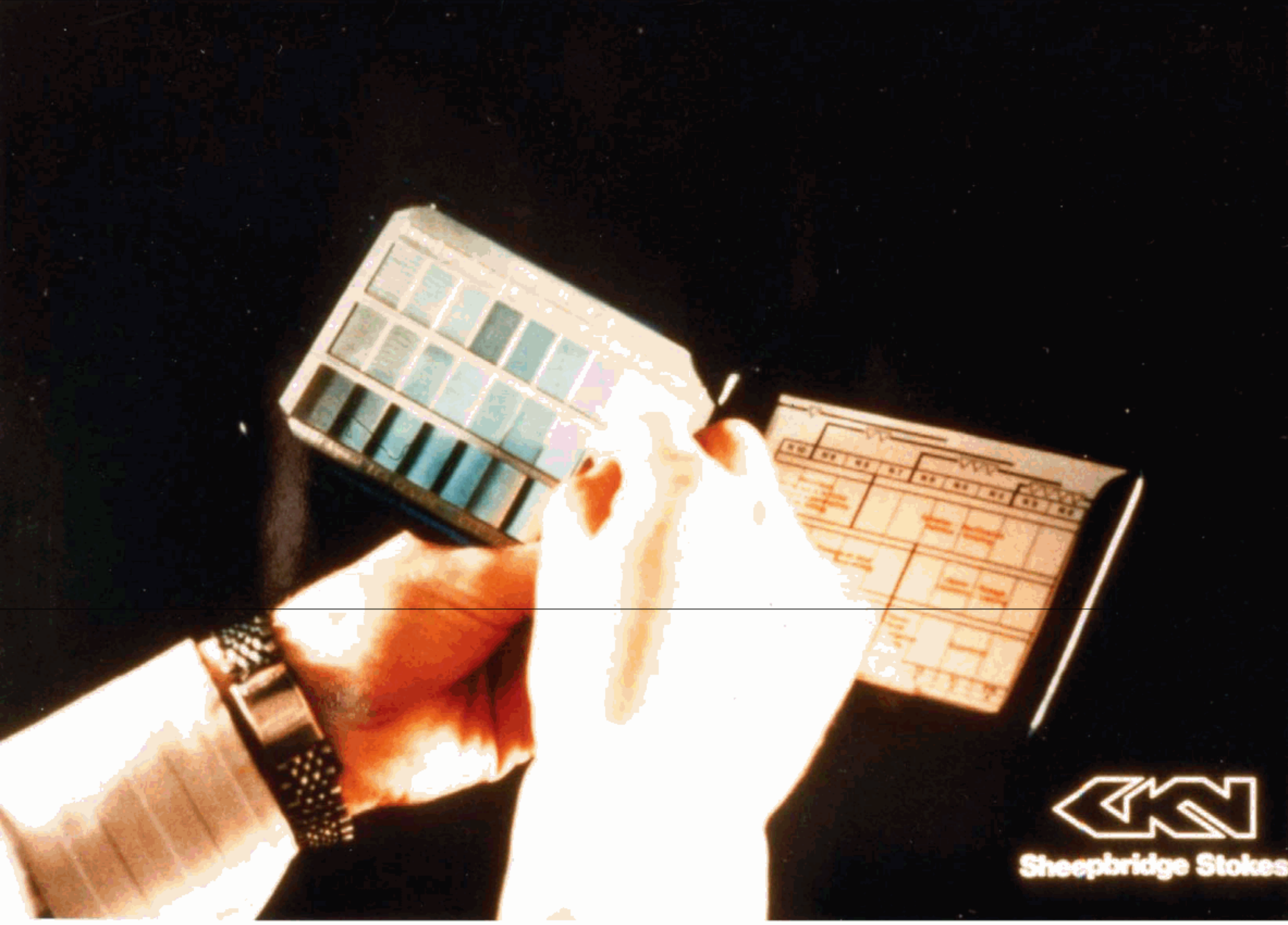
more emphasis was placed on material analysis to enable the graphite structure to promote the required lubrication and obviate metal to metal contact between the machined surfaces than to assist the aid of machine tools for this purpose.

Two eminent engineers B. J. Abbott & F. A. Firestone introduced a paper in 1933 Specifying Surface Quality by definition the 'Abbot' or 'bearing area curve', but the information given was somewhat ignored, probably due to the fact that measuring techniques, necessary to evaluate such surfaces, had not progressed scientifically to meet this requirement. Helix angles of oil retention grooves were non-existant.

This method continued until the introduction of the Talysurf 1 by Taylor, Taylor, Hobson, in 1942 to measure the Centre Line Average (C.L.A.) values. Considering this was a major step in the development of surface texture, no further improvements appear to have been made until the early 1960's and in some cases to the present date. Thumb nail comparisons from visual aids such as Rugger tests was the nearest one could expect in the early evaluation periods (FIG 2). It is now realised a C.L.A. factor in its own right is insufficient data to describe a suitable cylinder bore surface finish.

FOREWORD

So far as we are aware no-one has given a concise historical survey of the surface textures of cylinder bores used in combustion engines, although of course, references to it are to be found in most text books and papers written by various institutes and engine builders. In this paper I will develop a practical appraisal of surface finishes from the non specifics of the early 1940's to the present day higher technology demands, never losing sight of the engineering required.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My real investigations in the surface finish of cylinder liner bores came about when studying engines with scuffed cylinder bores. Surfaces from these cylinders were examined using a polarized light source and found to contain non-metallic inclusions (FIGS 3 & 4). To further investigate these non-metallic inclusions, samples were viewed by an Electron Scanner Microscope which, in turn, revealed differing sources which could be attributed to scuffing.

It was then decided to examine surfaces produced by different honing tools, namely Ceramic and Diamond in conjunction with Rubber and Cork.

Talysurf traces were taken from the base honing of a Ceramic tool. Thus revealing peakiness which could score pistons and rings during a running in period (FIG 5). The use of Rubber and Cork tools removed these peaks and created a plateau surface leaving sufficient valleys to give a suitable oil retention (FIG 6). From a graphical trace it appeared to be an ideal surface to enable a piston and rings to pass over, but under examination by the Electron Scanner Microscope folded metal was revealed (FIG 7).

Next using Diamond tools, torn and folded metal was very much apparent (FIG 8). Using Rubber or Cork tools to remove the peaks revealed a folding over of these peaks similar to ceramic tools. These would naturally break off during the initial running-in of an engine, do great damage to the piston and rings and also to the bearings where the same oil came in contact.

We were satisfied that Ceramic tools gave the best results when pertaining to torn and folded metals, but at the same time, after using Rubber or Cork tools to remove the peaks, the Electron Scanner Microscope had revealed that as with Diamond tools there was evidence of folding over.

Viewed under polarised light x 400

Finish Honed Bore

Showing heavy distribution of Non Metallic inclusions impregnated into the bore surface by the use of Diamond Honing Stones.

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Viewed under polarised light x 800

Finish Honed Bore

Showing very light distribution of Non Metallic inclusions impregnated into the bore surface by the use of Silicon-Carbide Honing Stones.

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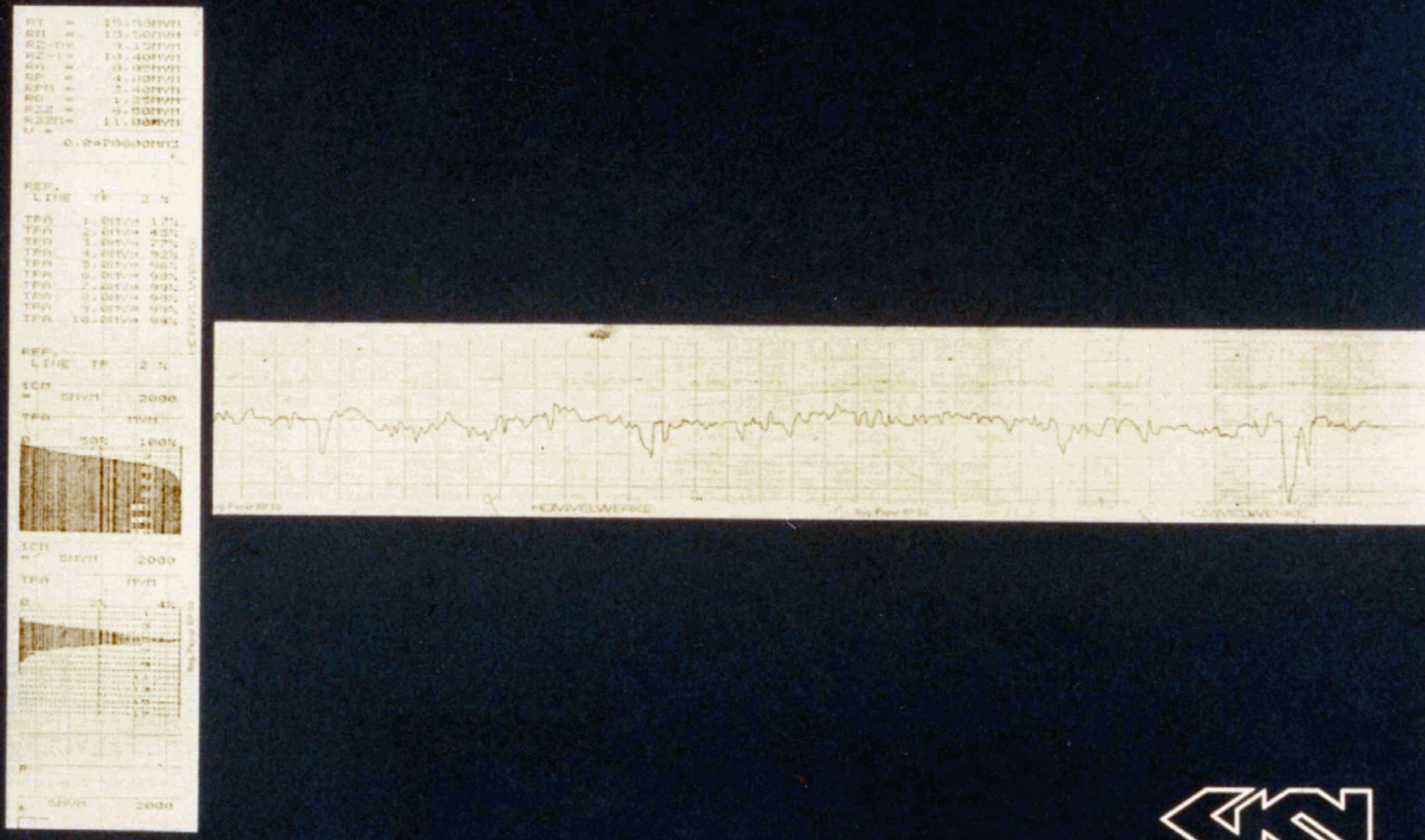

```
RT   =   15.50MYM
RM   =   15.50MYM
RZ-D=     9.15MYM
RZ-I=    10.40MYM
RA   =    0.85MYM
RP   =    4.00MYM
RPM  =    3.40MYM
RQ   =    1.25MYM
R3Z  =    6.50MYM
R3ZM=    11.00MYM
V =
     0.0470000MM3

REF.
 LINE   TP    2 %

TPA    1.0MYM= 17%
TPA    2.0MYM= 45%
TPA    3.0MYM= 77%
TPA    4.0MYM= 92%
TPA    5.0MYM= 96%
TPA    6.0MYM= 98%
TPA    7.0MYM= 99%
TPA    8.0MYM= 99%
TPA    9.0MYM= 99%
TPA   10.0MYM= 99%

REF.
 LINE   TP    2 %

1CM
=    5MYM     2000

TPA         MYM

0     50%    100%

1CM
=    5MYM     2000

TPA         MYM

0      3%      4%

     5MYM     2000
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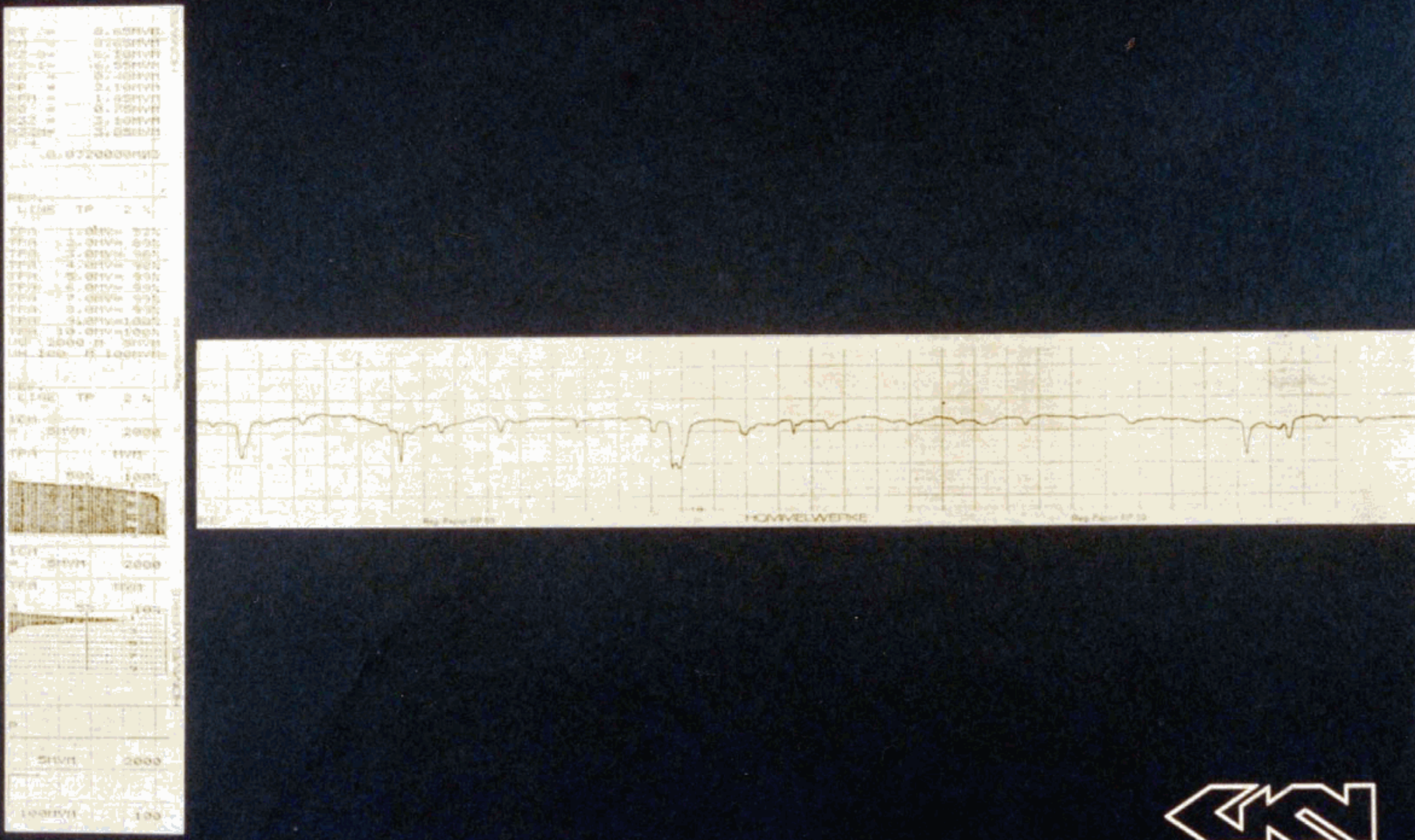

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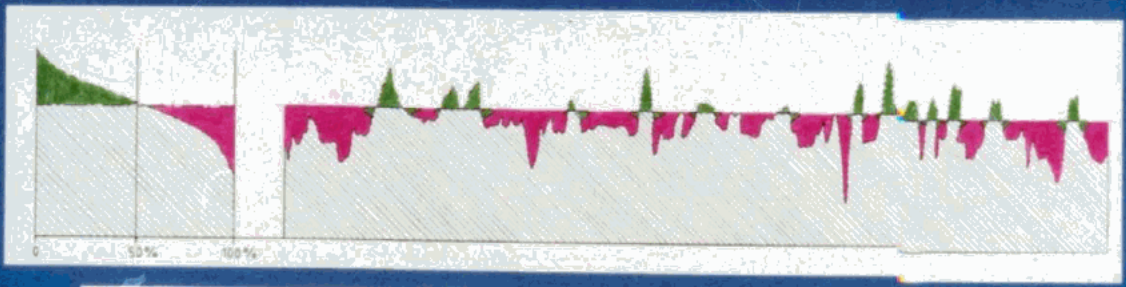

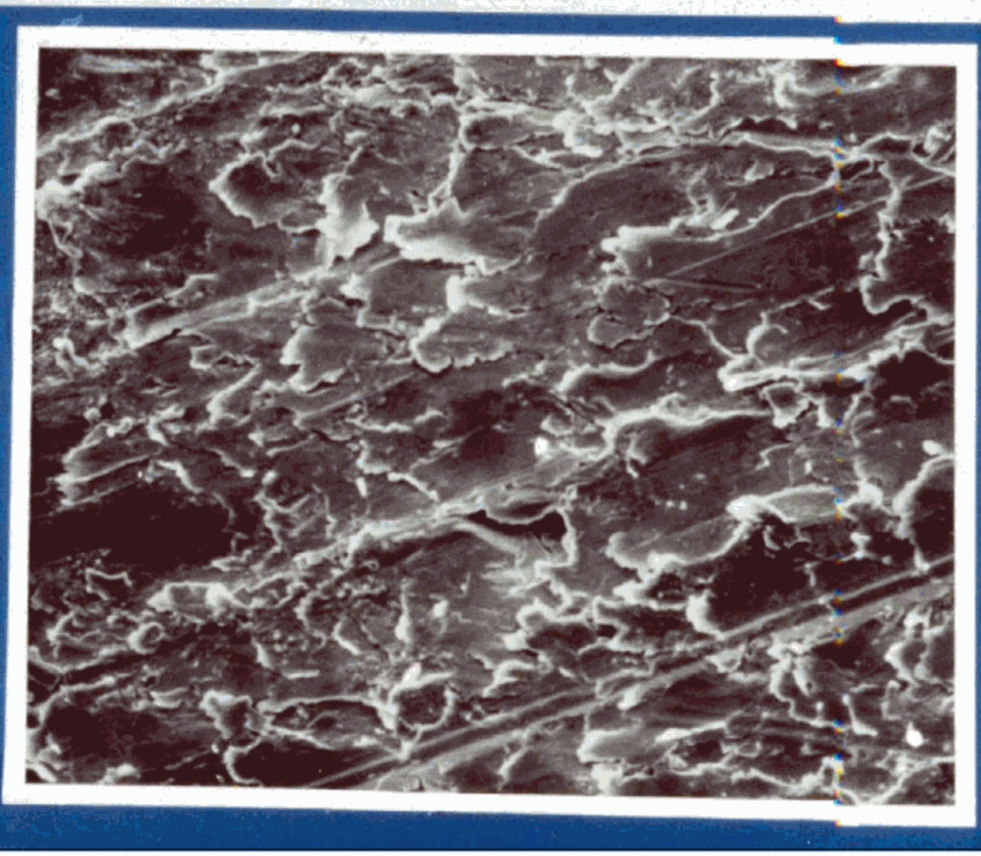

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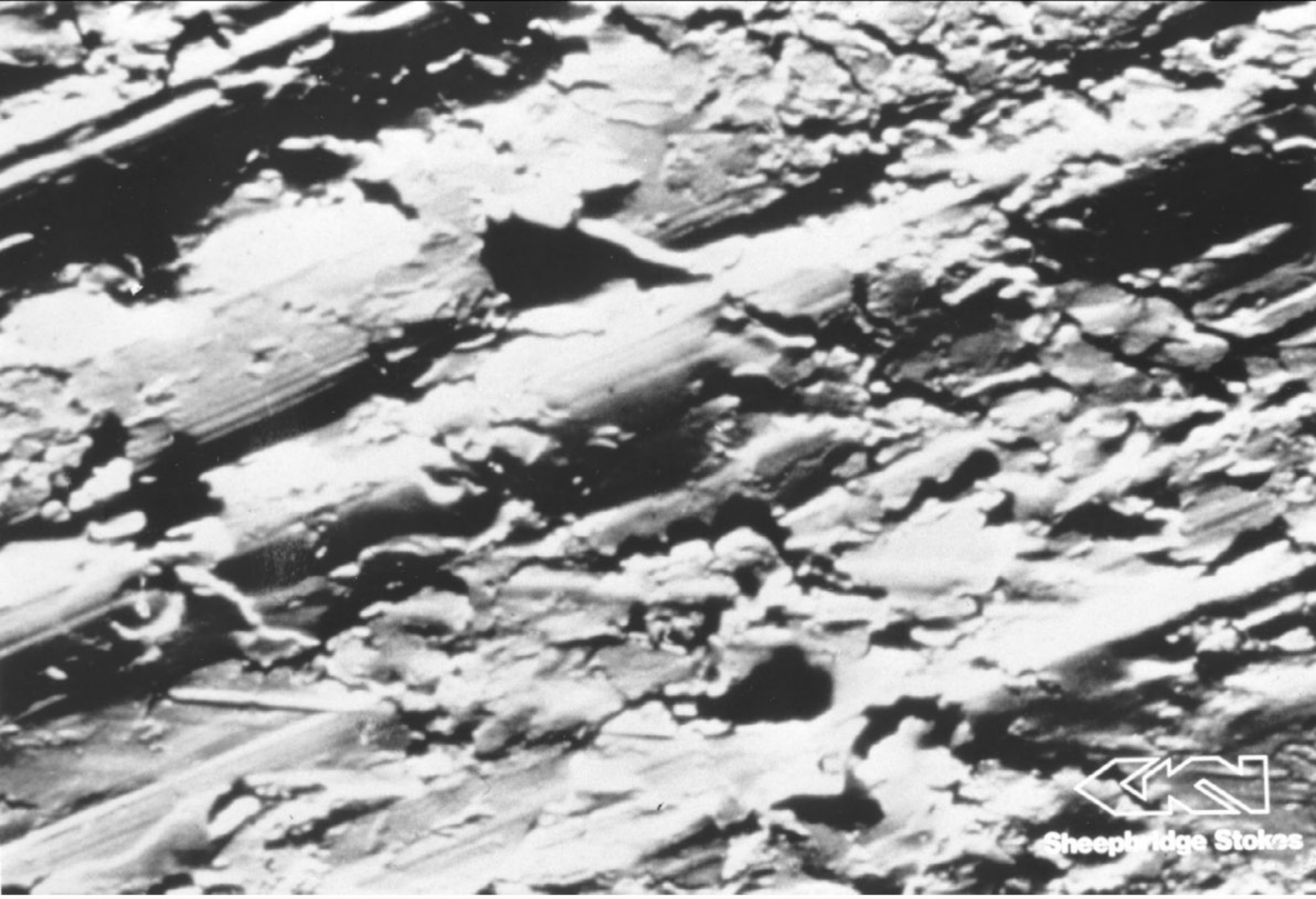
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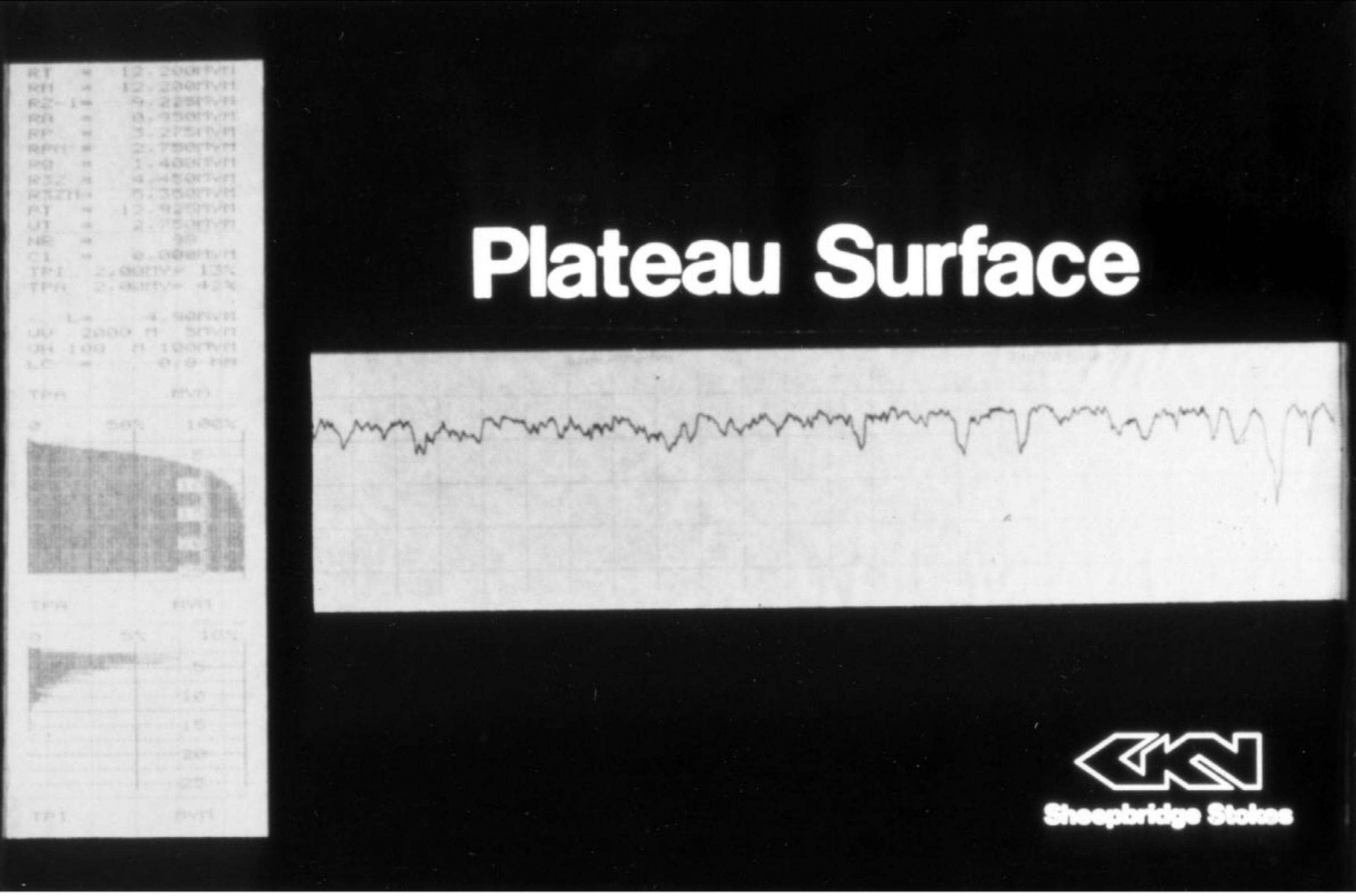
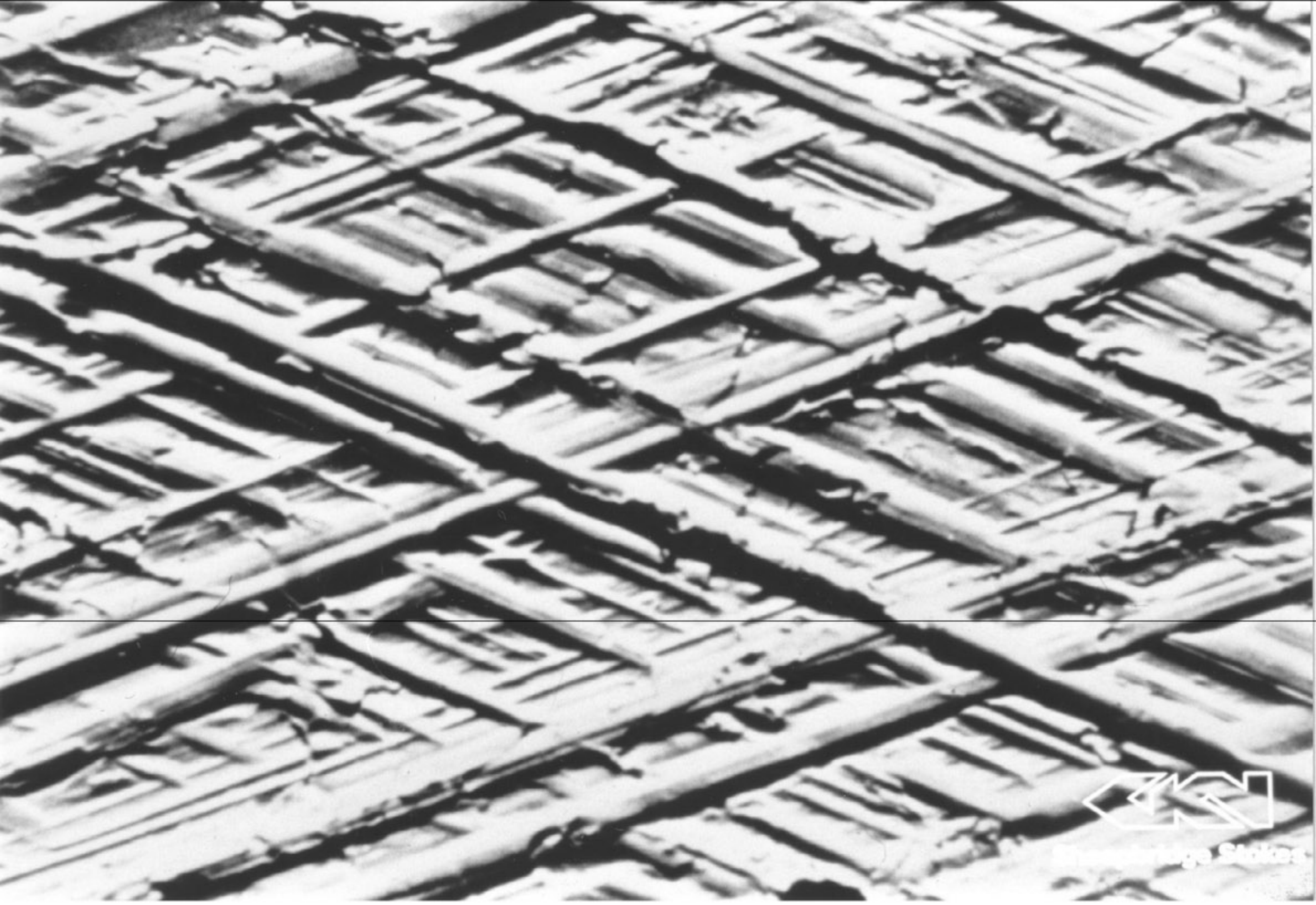
From these exercises it was essential to find a method of removing the peaks and eliminate folding over. The next move was the use of a finer grit abrasive tool for this purpose. The results were very encouraging both from the talysurf trace and the Electron Scanner Microscope.

The topography using this method gave a cutting effect finish to the plateau and minimised folding over (FIGS 9 &10), this being distinct from a smooth plateau by using Rubber or Cork tools. This finer cutting action on the plateau surface enabled rings to bed with the cylinder walls in the running-in period, instead of promoting a glazing effect which is apparent from the very smooth plateau produced by Rubber or Cork tools. Engine performance with liners produced in this manner has so far proved exceptionally successful, for running in and oil consumption.

Having achieved the correct plateau surface my thoughts centred around the many variables in our production, not necessarily on the plateau surface, although this was affected slightly, the main variable was in the base honing. I examined the operations prior to honing, i.e. Fine boring or Rough honing and checked the amount of stock left for the final honing tools to remove. This varied considerably and viewing from a talysurf trace the variation in stock removal gave a variation in the finished piece after honing (FIG 11). The ideal condition would be to remove the machining marks of the pre-honing operation to the bottom of their valleys and at this time create the surface finish required. It is appreciated this is rather difficult because the pre-honing operators require a working tolerance, excessive stock to be removed created a glazing up of the honing tools and affected the finish required. By selection of sizes and finishes prior to honing I was able to create conditions that gave repeatability at the honing operation, this is most important.





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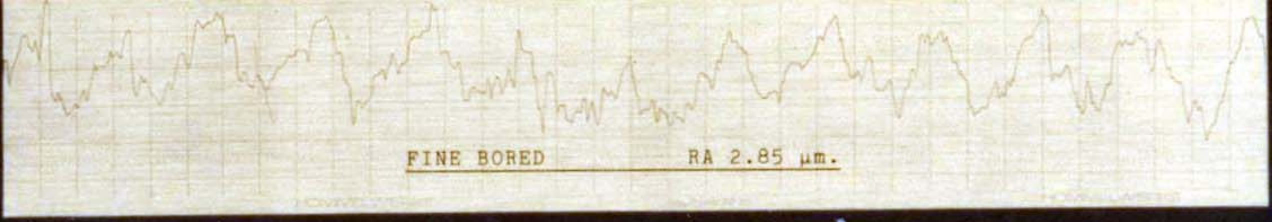
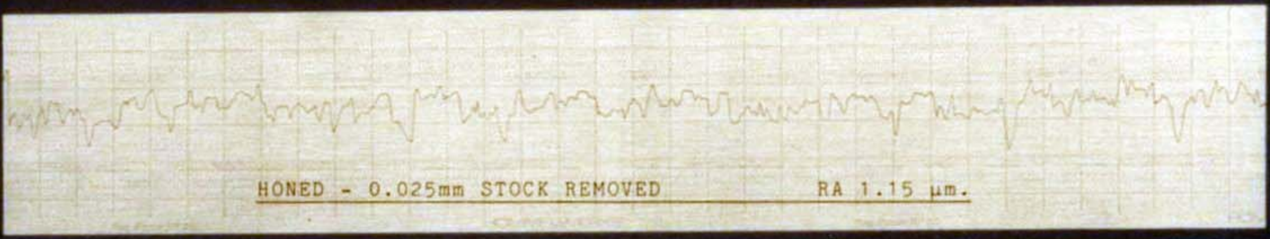
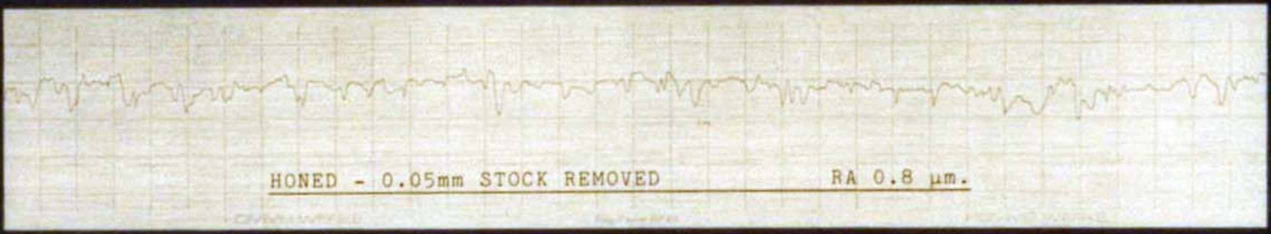


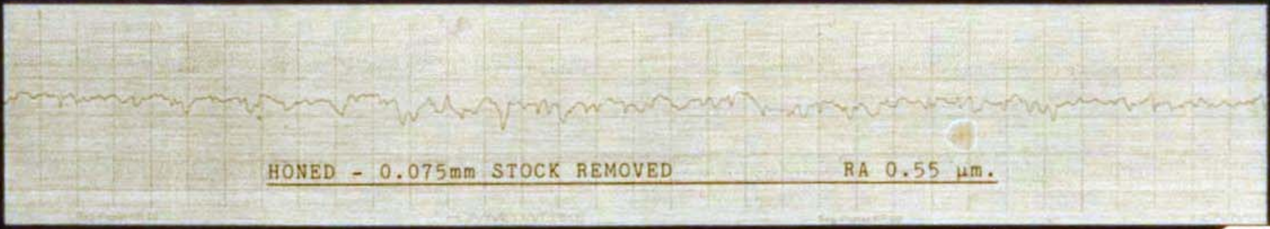
FINE BORED RA 2.85 µm.



HONED - 0.025mm STOCK REMOVED RA 1.15 µm.



HONED - 0.05mm STOCK REMOVED RA 0.8 µm.



HONED - 0.075mm STOCK REMOVED RA 0.55 µm.

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The hardness of honing tools play a significant part naturally, in the manufacture of the surface to be produced. We were committed to the tool manufacturers regarding the quality of tools supplied, having no means whatsoever of checking the quality until I came into contact with the manufacturers of Grindo-Sonic in June 1979, this equipment will measure the hardness of a honing tool. The first set of honing tools measured were from a complete box from one manufacturer and found to cover three grades of hardness, in this case 120 points of the Grindo-Sonic readings (40 points represented one grade hardness (FIG 12). Selecting these tools from one end of the hardness range to the other and grouping them into 10 points of the Grindo-Sonic reading, from the softer end of the range only 15 components were honed and from the harder end of the range 900, but in each case it was found the honing tools wore down equally with each other. Previously uneven wear was taking place within one set of tools. This was a major breakthrough in the use of honing tools.

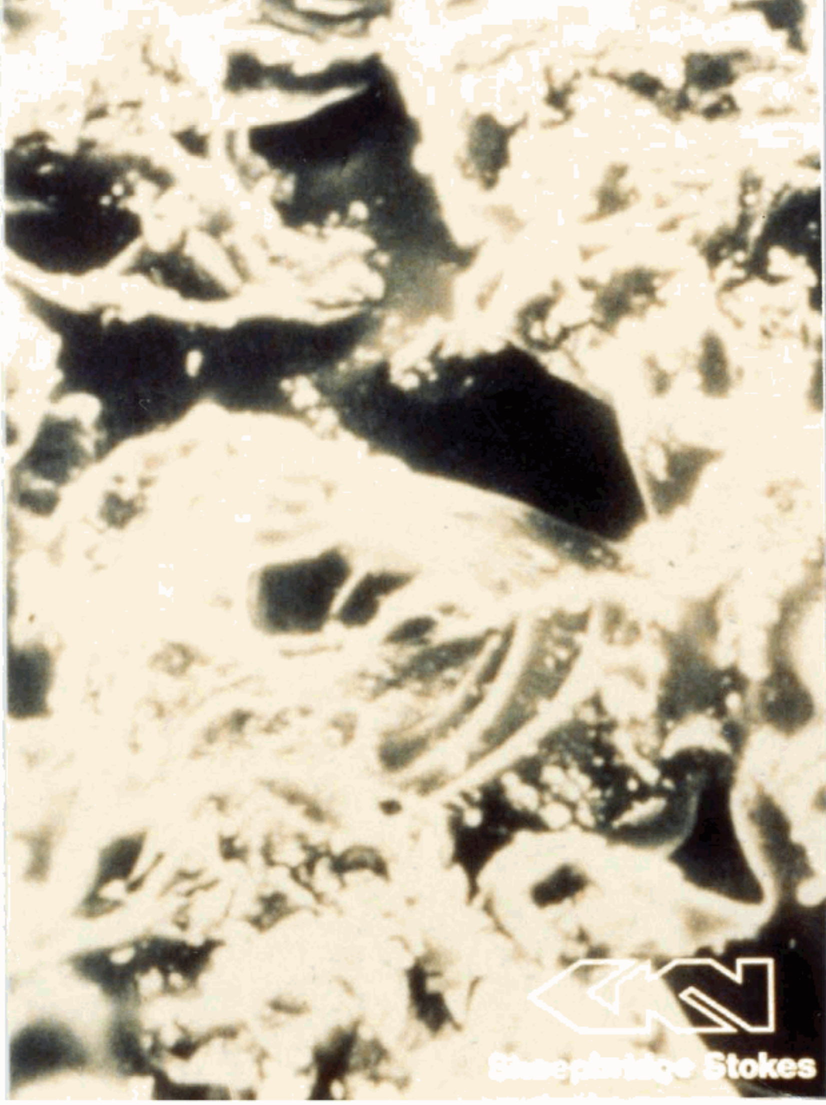
Now every honing tool that comes into our factory is graded and grouped into 10 point Grindo-Sonic readings, the honing operators are enthusiastic with the assistance that has been given to them. We as manufacturers are also delighted, this helps to keep better control over surface finishes giving better results and longer life from the honing tools.

We can now claim two major breakthroughs :-

1) Plateau Honing producing a minimum of folded metal,

2) Base Honing giving repeatability,

During the course of this study it had been observed that the talysurf trace showed evidence of a spurious valley not evident to the naked eye (FIG 13). This valley or scratch mark, having no pattern,



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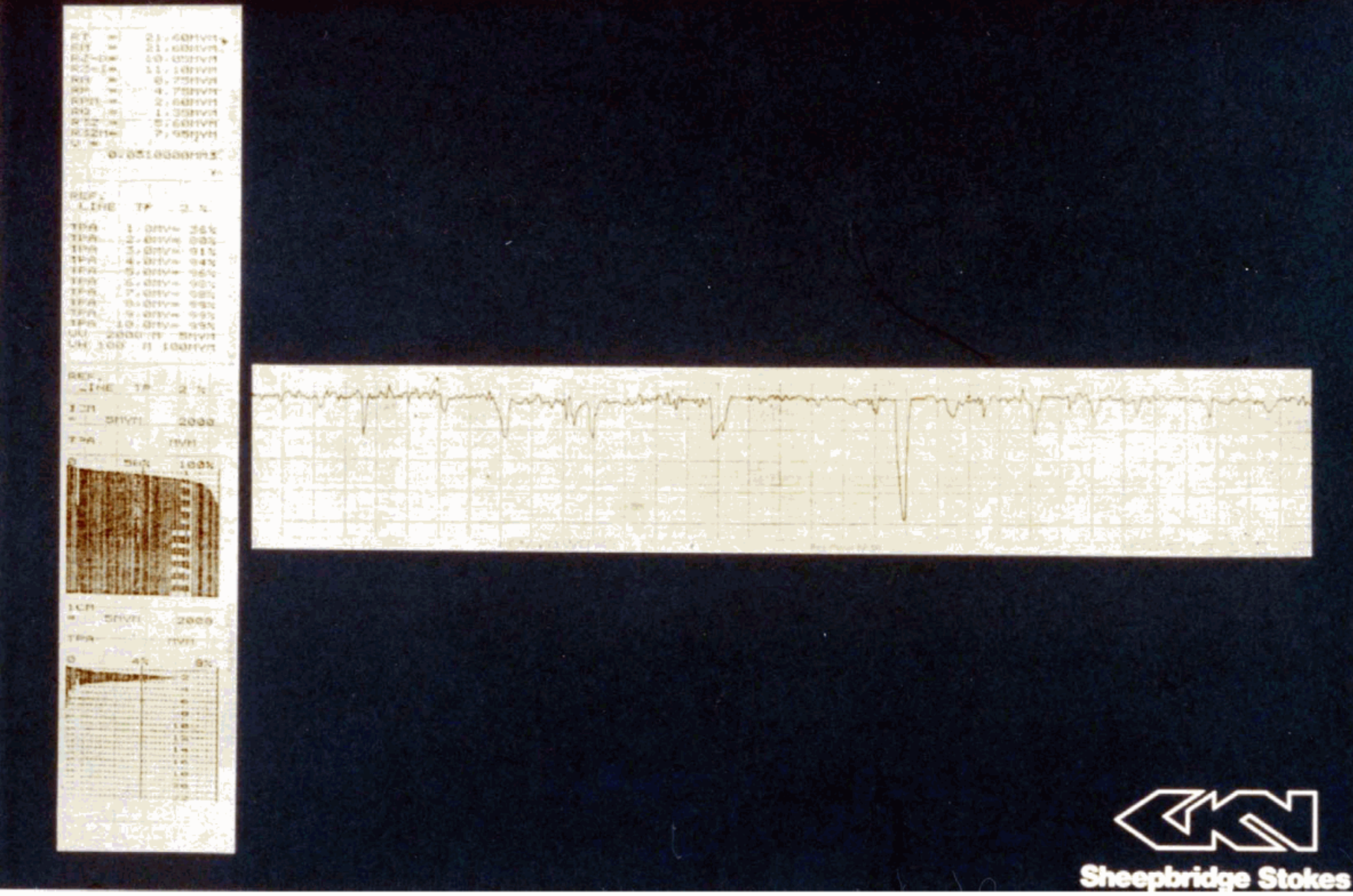

```
RT  =    21.40MVM
RM  =    21.60MVM
RZ-D=    10.05MVM
RZ-I=    11.10MVM
RA  =     0.75MVM
RP  =     4.75MVM
RPM =     2.60MVM
RQ  =     1.35MVM
R3Z =     5.60MVM
R3ZM=     7.95MVM
V  =
    0.051000MM3

REF.
 LINE  TP   2 %

TPA   1.0MV= 36%
TPA   2.0MV= 88%
TPA   3.0MV= 91%
TPA   4.0MV= 94%
TPA   5.0MV= 96%
TPA   6.0MV= 98%
TPA   7.0MV= 98%
TPA   8.0MV= 99%
TPA   9.0MV= 99%
TPA  10.0MV= 99%
VV  2000 M  5MVM
VH 100   M 100MVM

REF.
 LINE  TP   2 %
1CM
=     5MVM      2000
TPA          MVM
0      50%     100%

1CM
=     5MVM      2000
TPA          MVM
0       4%       8%
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could not be from the honing tool. The next step was to cut-out a section of liner with the mark and view under the Electron Scanner Microscope at a higher magnification. It revealed an openness of material, (FIG 14) and one large hole (FIG 15). The stylus point on the comparator was able to drop into this hole and identify it as a spurious scratch.

Even if you moved the piece very slightly the stylus would find it difficult to locate the scratch again. However,curious with the findings we searched deeper, increased the magnification on the Electron Scanner Microscope to 3,000 times and was amazed with what it revealed, crushed and crazed material (FIG 16), frightening to a degree, but realised this must have been happening throughout the years in the manufacture of cast iron cylinder liners. Believing it was the honing tools that was creating this crushed material condition, we made numerous changes with pressure, coolants, feeds and speeds, but to no avail. On each occasion when viewing on the Electron Scanner Microscope at 3,000 times magnification the same results appeared, crushed metal. The fine boring operation gave the same effect and in the first cutting operation which is applied to a casting this crushed metal is initiated (FIG 17), machining further material of approximately 0.25 mm by fine boring and subsequent honing crushed metal is still apparent. May be it is something we cannot remove, and is of no detrimental consequence to an engine.

Further, Engine Manufacturers consider that the Graphite Flakes outcropping to the machined bore surface have been either closed or rolled over due to the machining process. Counts of these closed and rolled over Graphite Flakes have been made along the machine surface and at varying depths below that surface throughout the micro section, these counts have proved that away from the machined surface similar amounts of closed


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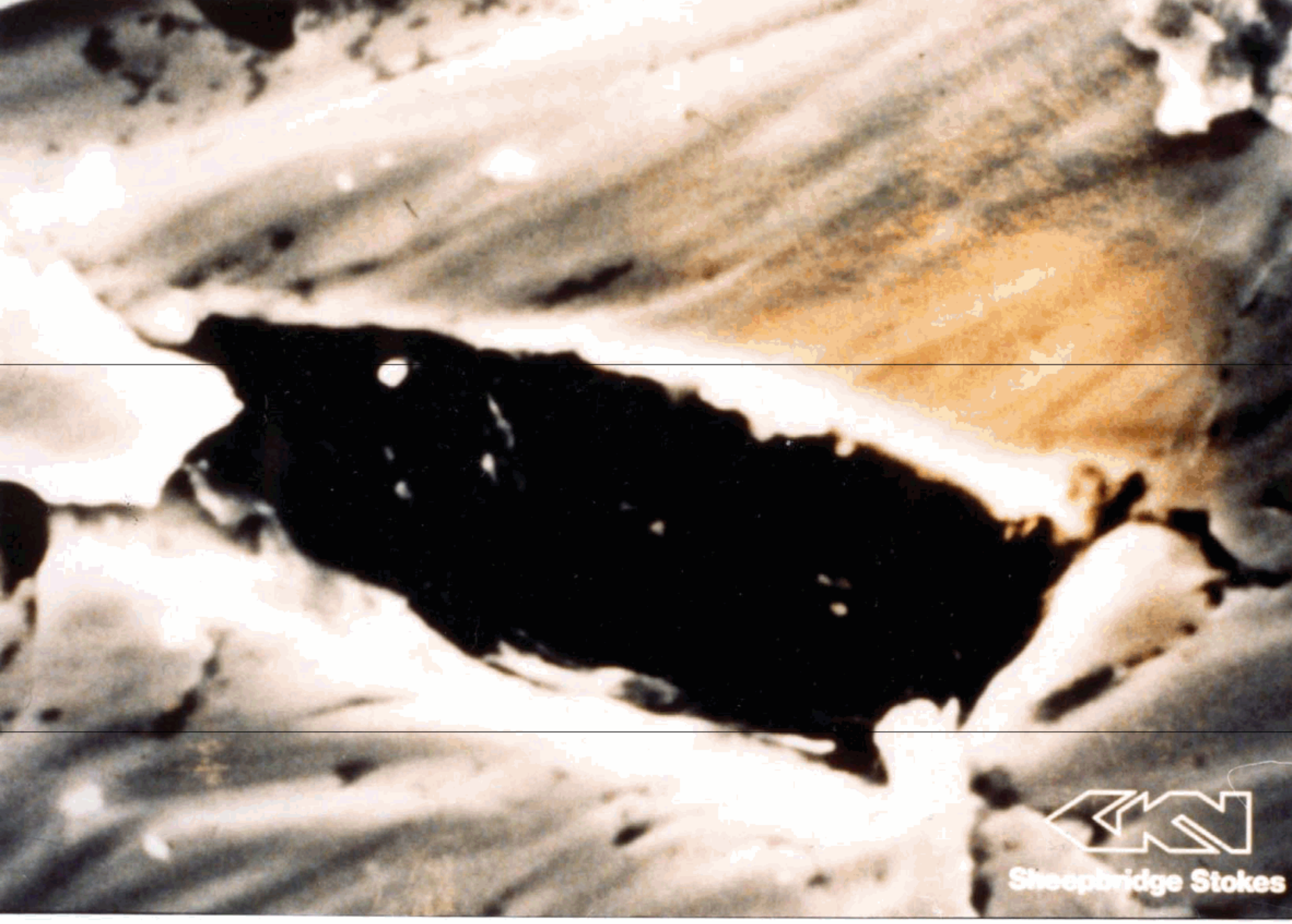
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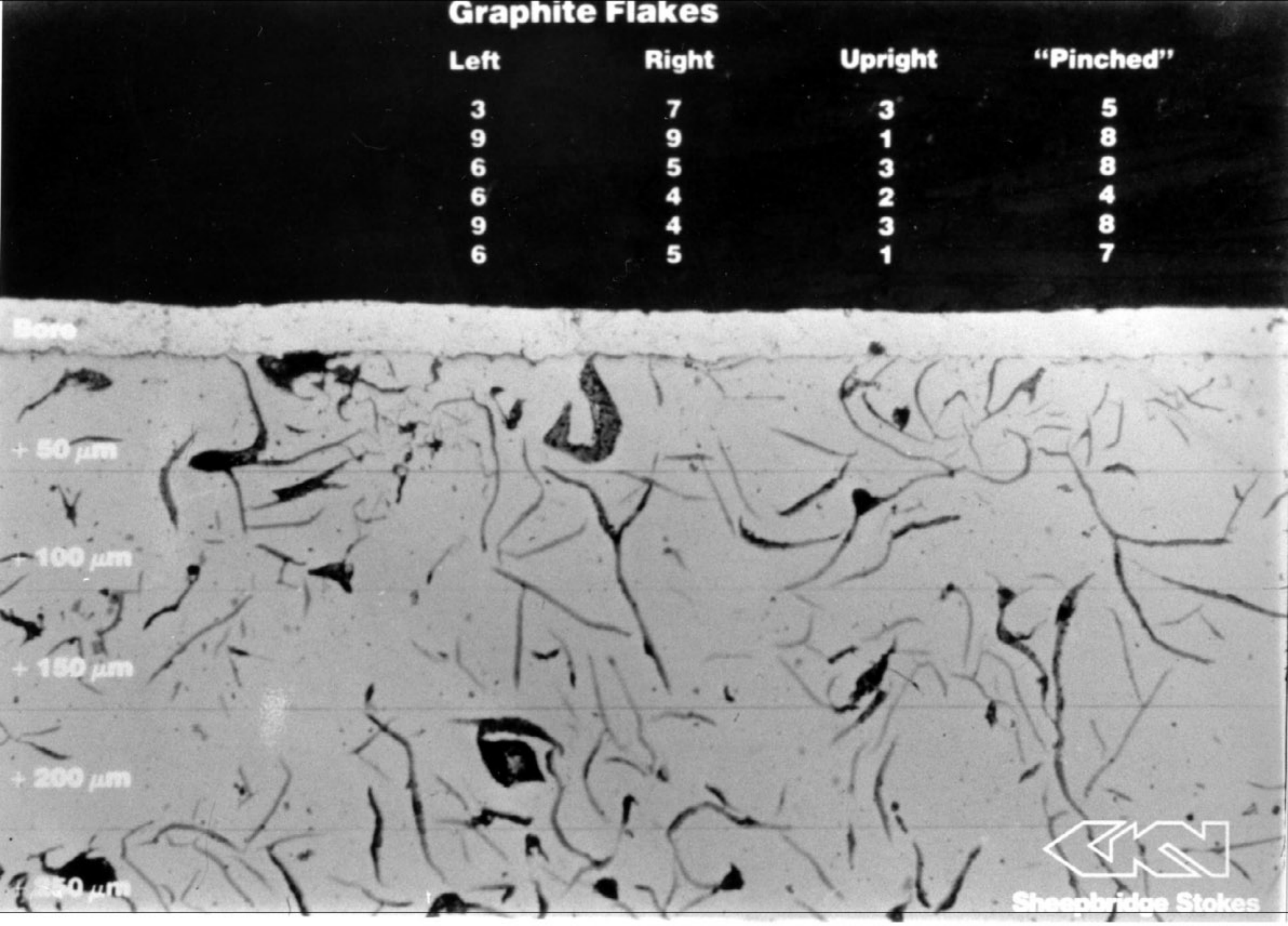
and rolled flakes are visible, therefore, it must be discounted that the machining process is the prime factor in creating this condition (FIG 18).

If we can recap on the works of Abbott & Firestone when we said that no measuring instruments were available at that time to measure the parameters they had introduced. We had, through the years in the cylinder liner business, thought the cylinder bore had to be a very smooth finish, the slightest scratch would be reject. Now it is a series of scratches throughout the bore with different parameter measurements to establish control of these scratches.

Searching through the archives from the commencement of cylinder liner manufacture we could not find any drawings which related to a specification in bore surface finish. Industry recommenced after the war years in 1945, during that year I found four drawings from different customers, the first one stated smooth surface, similar to what we had been producing during all the years of manufacture, three others indicated a C.L.A. Value (Centre Line Average) this was new to us, we had no instrumentation to measure it. However, we found a scratch like instrument which one could move manually on the surface backwards and forwards. The display needle did the same reaction, backwards and forwards, and it was left to the individual to assess what C.L.A Value they had interpreted.

The next step was when Rank Taylor Hobson - Measuring Instrument Manufacturers improved their development further and related to Rt Values (Roughness Total). Seeing complications arising from these types of parameters I decided to investigate more deeply into the measurements of C.L.A. Values and realised that a number of



Graphite Flakes

Left	Right	Upright	"Pinched"
3	7	3	5
9	9	1	8
6	5	3	8
6	4	2	4
9	4	3	8
6	5	1	7

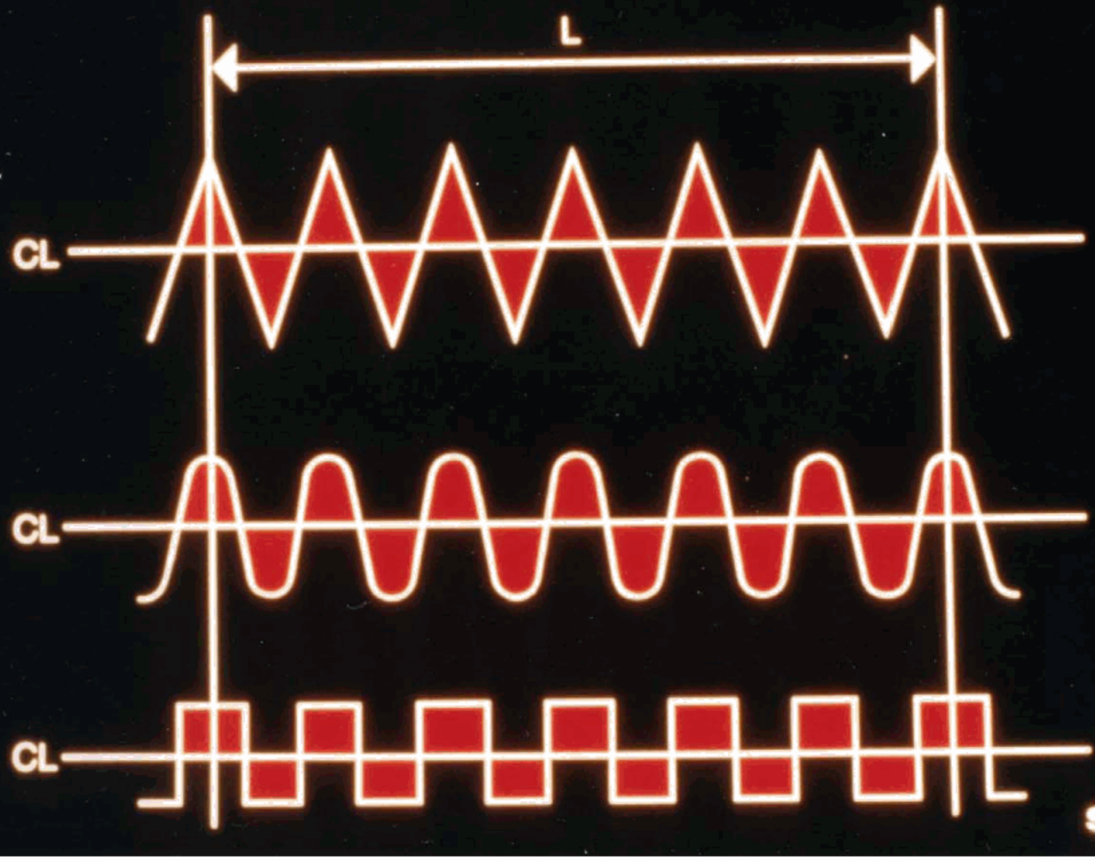
different forms could be evaluated and all give the same C.L.A. Value, some looked rather ridiculous, but nevertheless without supporting evidence from another parameter a C.L.A. Value in its own right is useless (FIG 19). I then looked at the Rt Value, this again in its own right is a useless factor. Numerous ways of looking at the Rt Value can give the same result, or at least the same direct readout (FIG 20). I decided to look at the Rz, this can be known in two types :-

a) The Rz I.S.O which is a ten point height parameter (FIG 21), it is measured over a single sampling length and an average of several peak values. Numerically, it is the average height difference between the five highest peaks and the five lowest valleys within the sampling lengths. It is not the measurement that we recommend to be used, again variations can take place which can be rather misleading.

b) The Rz D.I.N. method is an average roughness depth (FIG 22) in five sequential measuring lengths, we consider this the best average method of measuring a surface finish. The Rz D.I.N. factor is good, better in our view than Rz I.S.O and gives excellent guidance should you require control throughout the works on instant readout instruments, when the production methods have been evaluated.

I would suggest the oil reservoir is the parameter that should be used in the future to establish the running surface of a cylinder liner bore. Irrespective of whatever parameter is mentioned, and there are many, they are found confusing and create problems to the Manufacturing Unit. I have already explained some of the problems, which are shown in the C.L.A and the Rt parameters and have said the Rz D.I.N. parameter is the best to evaluate a surface, but even this has its limitations and can also be confusing (FIG 23).

Possible Variation of CLA Factor



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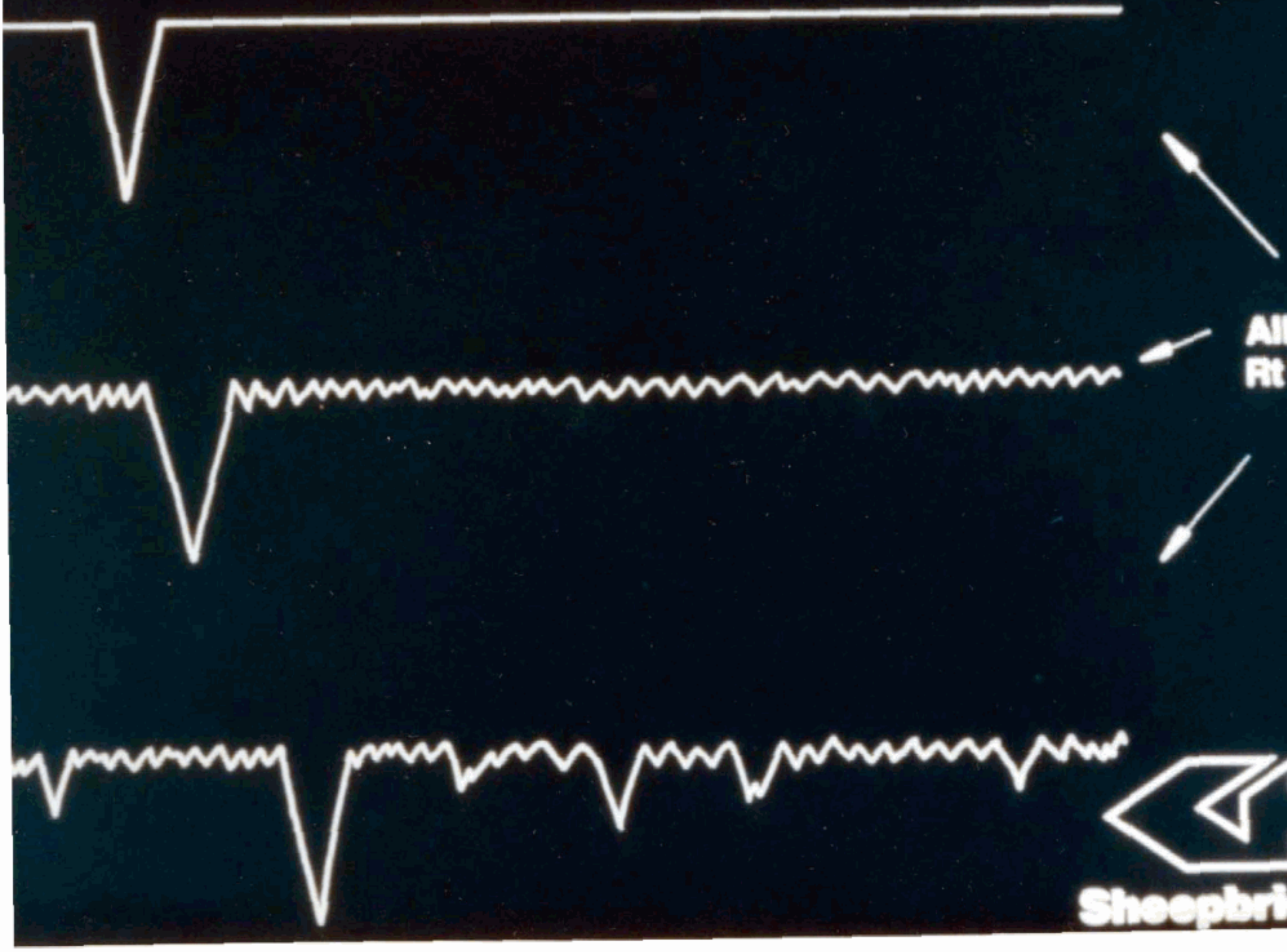
Variations of a Rt Factor



All the same
Rt Value

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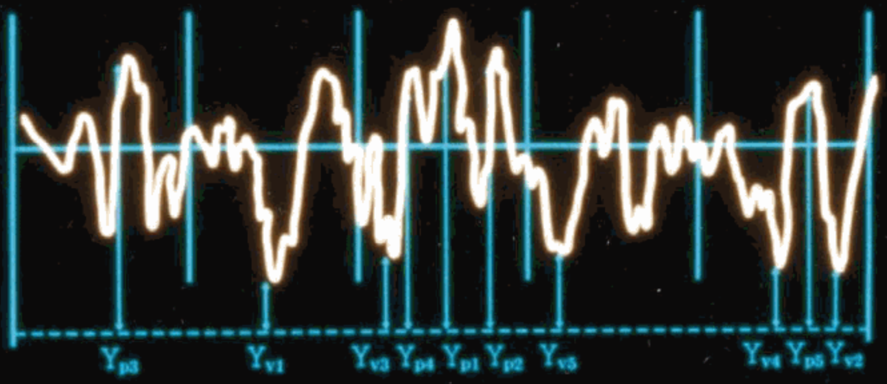
R_Z (ISO)



R_Z Also known as the ISO 10 point height parameter, is measured on the unfiltered profile only and is numerically the average height difference between the five highest peaks and the five lowest valleys within the traverse length.

$$R_Z\ (\mathrm{ISO}) = \frac{(Y_{p1}+Y_{p2}+Y_{p3}+Y_{p4}+Y_{p5})-(Y_{v1}+Y_{v2}+Y_{v3}+Y_{v4}+Y_{v5})}{5}$$

$$= \frac{1}{5}\left(\sum_{i=1}^{i=5} Y_{pi} - \sum_{i=1}^{i=5} Y_{vi}\right)$$

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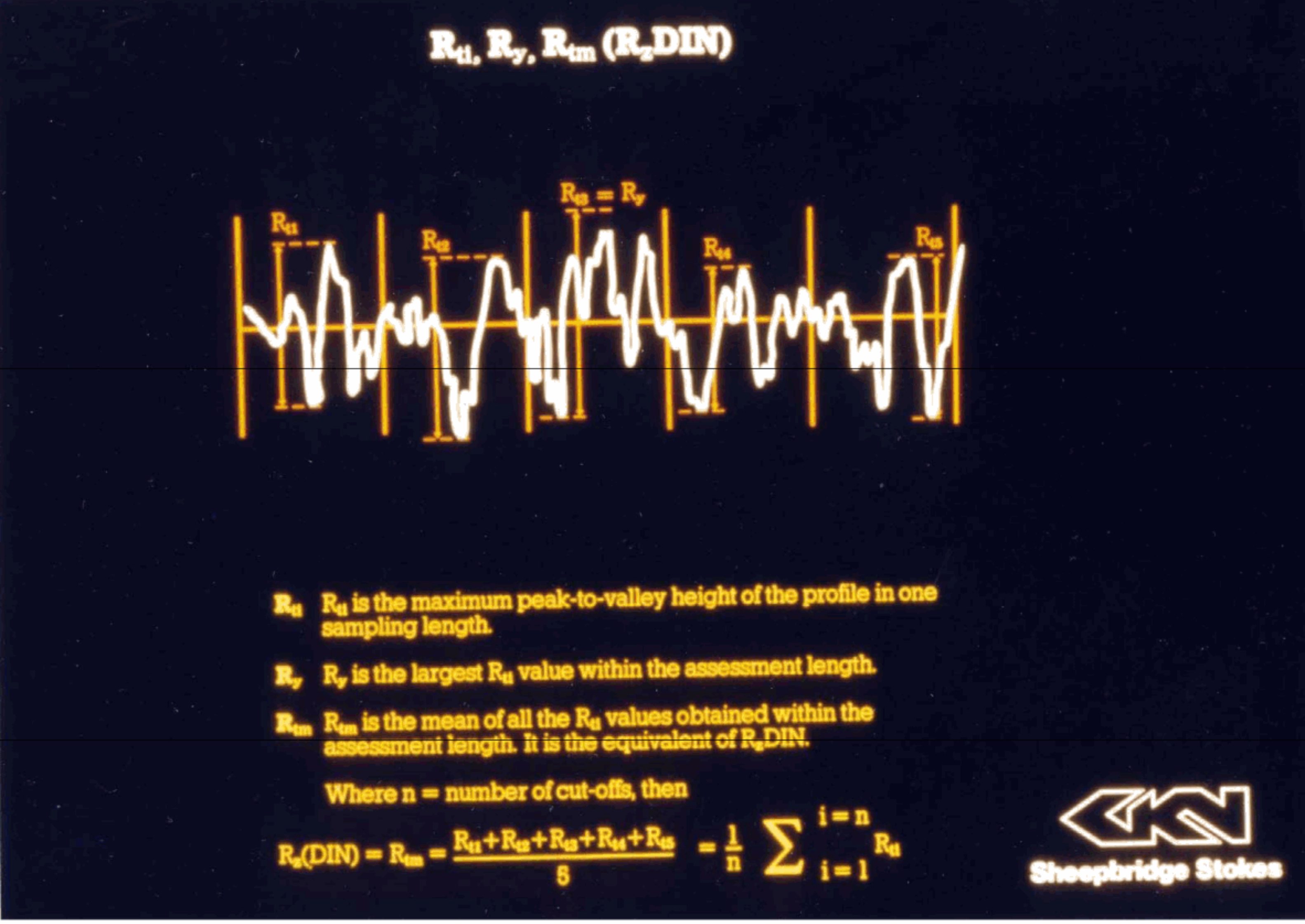

R_{t1}, R_y, R_{tm} (R_zDIN)

R_{ti} R_{ti} is the maximum peak-to-valley height of the profile in one sampling length.

R_y R_y is the largest R_{ti} value within the assessment length.

R_{tm} R_{tm} is the mean of all the R_{ti} values obtained within the assessment length. It is the equivalent of R_zDIN.

Where n = number of cut-offs, then

$$R_z(DIN) = R_{tm} = \frac{R_{t1}+R_{t2}+R_{t3}+R_{t4}+R_{t5}}{5} = \frac{1}{n} \sum_{i=1}^{i=n} R_{ti}$$

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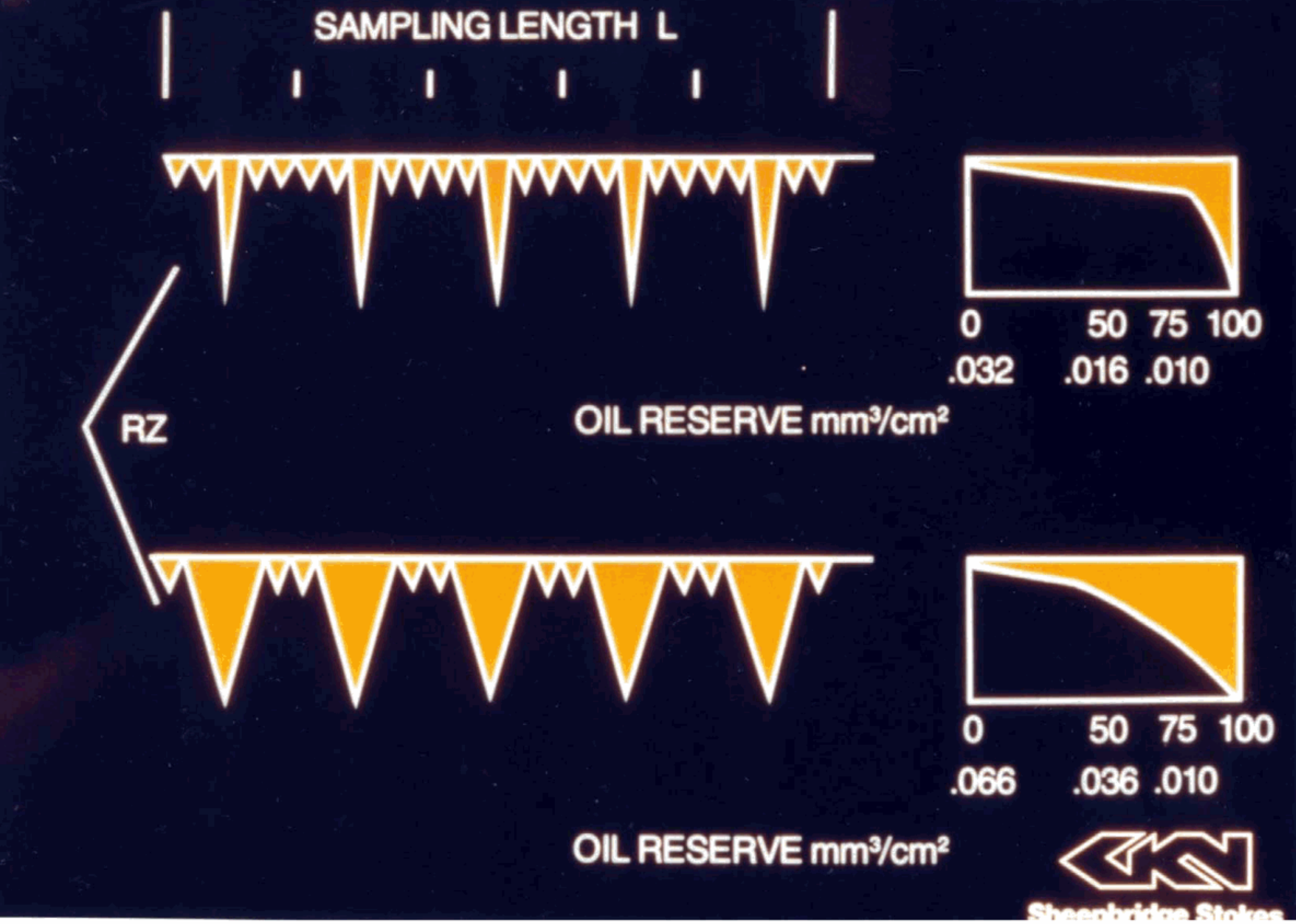
SAMPLING LENGTH L
RZ
0
50
75
100
.032
.016
.010
OIL RESERVE mm³/cm²
0
50
75
100
.066
.036
.010
OIL RESERVE mm³/cm²
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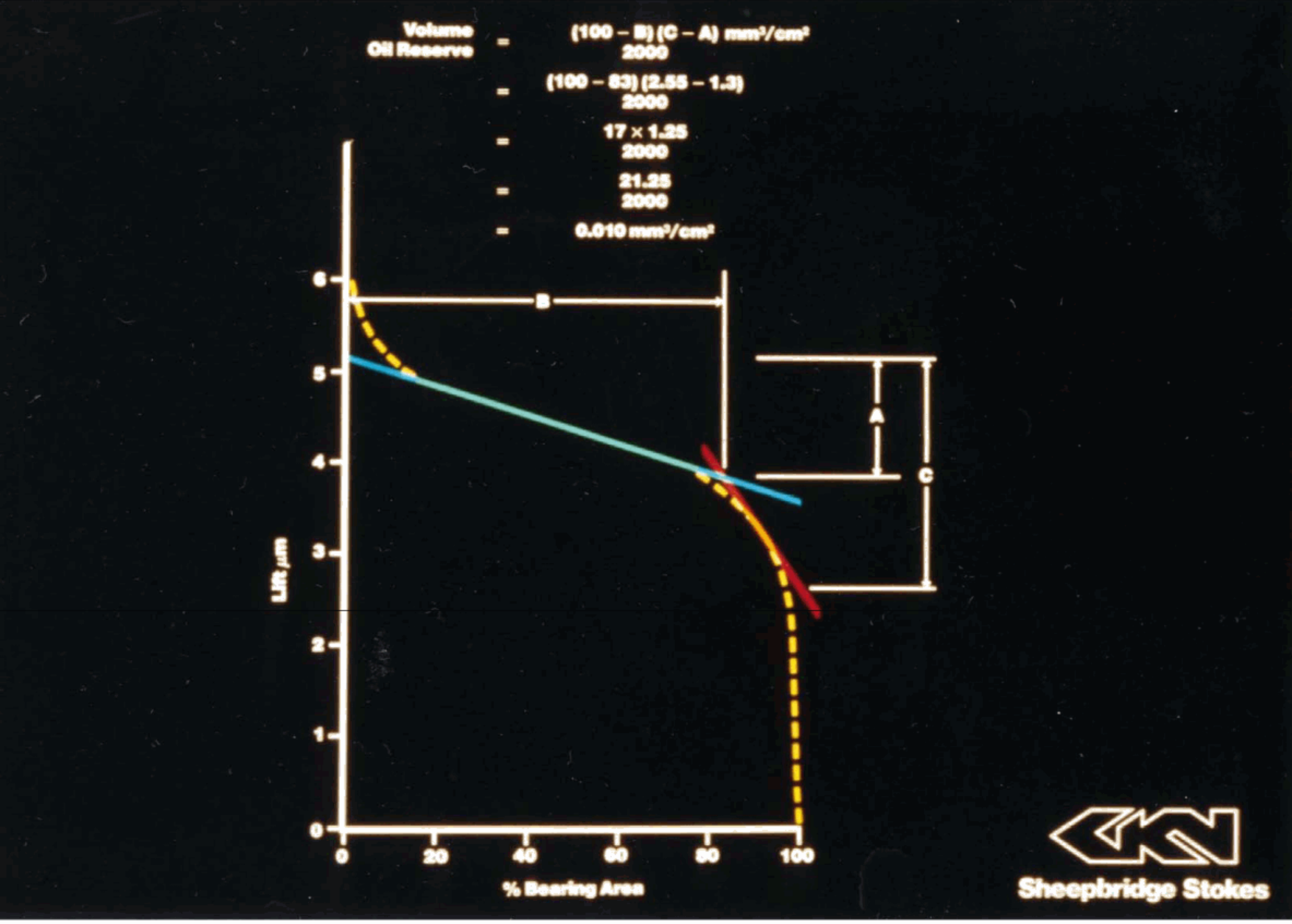
The one parameter remaining after all the others have been changed due to running in and wear is the oil reservoir, which in my opinion is the most important.

When the engine commences its function with the piston moving along the bore surface, each parameter immediately and progressively changes as wear takes place. This change occurs very rapidly in the initial running in of an engine, until the bearing area surface is around 60%. At 60%, unless something abnormal has taken place, no further major wear should take place for some considerable time. What we must know is the amount of oil contained in the remaining valleys from 60% to 100% bearing area (an Abbot & Firestone parameter referred to earlier in my talk) this value never changes throughout the life of the running-in period. After 60%, naturally it will gradually lessen. Irrespective of the parameters engineering have adopted to use, the ultimate is to evaluate the amount of oil lubricating the rings and pistons. That is the most important value, coupled with it of course, the Rz D.I.N. Value and the plateau topography. These are the three parameters necessary to control the surface finish of a cylinder bore used in combustion engines.

The initial development stages of determining the oil reservoir was rather laborious, all the slice levels were plotted, a triangle evaluated to roughly calculate the oil reservoir. It was not a complete volume, some of the oil reservoir was missing from each side of the triangle (FIG 24). Having taken a new measuring instrument, the Hommel T20, Hommelwerke were asked if they could manufacture a micro-chip to fit in this instrument to enable the oil reservoir to be calculated at any % bearing area we wish to call,(FIG 25) After many calculations and discussions with Hommel, the chip materialised, was tested and correctly evaluates



$$\text{Volume Oil Reserve} = \frac{(100 - B)\,(C - A)}{2000}\ \text{mm}^3/\text{cm}^2$$

$$= \frac{(100 - 83)\,(2.55 - 1.3)}{2000}$$

$$= \frac{17 \times 1.25}{2000}$$

$$= \frac{21.25}{2000}$$

$$= 0.010\ \text{mm}^3/\text{cm}^2$$

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Volume of Oil Reservoir Relative to Percentage Bearing Area

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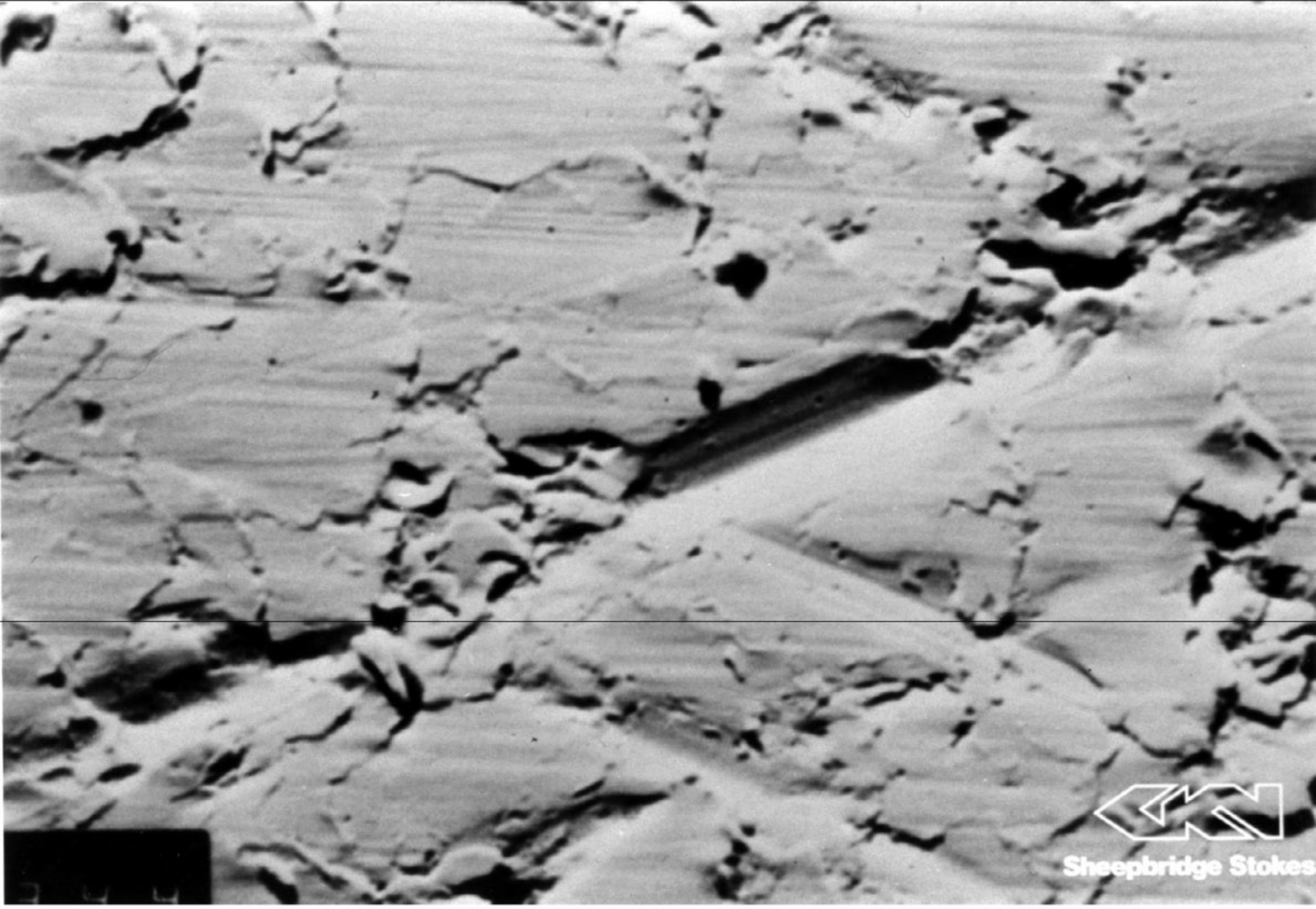
fully the volume of oil available in mm^3/cm^2 at any percentage bearing area requested. The traverse length is 10 mm, we need to establish a 3D dimension of 10 mm to complete the equation cm^2. This can be requested from the instrument, but what one must remember is that to calculate a measurement of 10 mm in depth is to assume the honing pattern is the same configuration throughout this depth, similar to how one would view a screwed thread. This is not exactly factual because the honing pattern can vary in form throughout this 10 mm, however slightly. On experimental work the cylinder bore circumference is divided into 10 sections, approximately equal, 10 traces 10 mm in length x 1 mm in depth are recorded to get a broader outline on that particular surface. This to our knowledge is the only instrument in existance that can give this information of bore surface finishes, and we are confident that these will be the parameters that will be used in the not too distant future World-Wide.

Earlier in this paper I made reference to the use of Diamond Stones and the detrimental effect they had in an engine, we have recently made some interesting discoveries in three particular engines - One Petrol and Two Diesel, the petrol engine used in one of the most famous saloon cars in the world, is produced by Diamond Tools for the Base Hone and Rubber or Cork tools to produce the plateau (FIG 26). One of the Diesel engines is produced in the same manner, this engine had a testing failure rate of 40%. It is now 5% (FIG 27). Further tests are taking place using Diamond Tools for the Base Hone and Silicon Carbide Tools to produce the plateau. The third engine, a diesel, had been final honed using a Silicon Carbide slurry. The manufacturers of this particular method claim the silicon carbide impregnation into the bore surface enables the engine to run with little or no oil consumption. Viewing this piece on the Electron Scanner Microscope there was great difficulty in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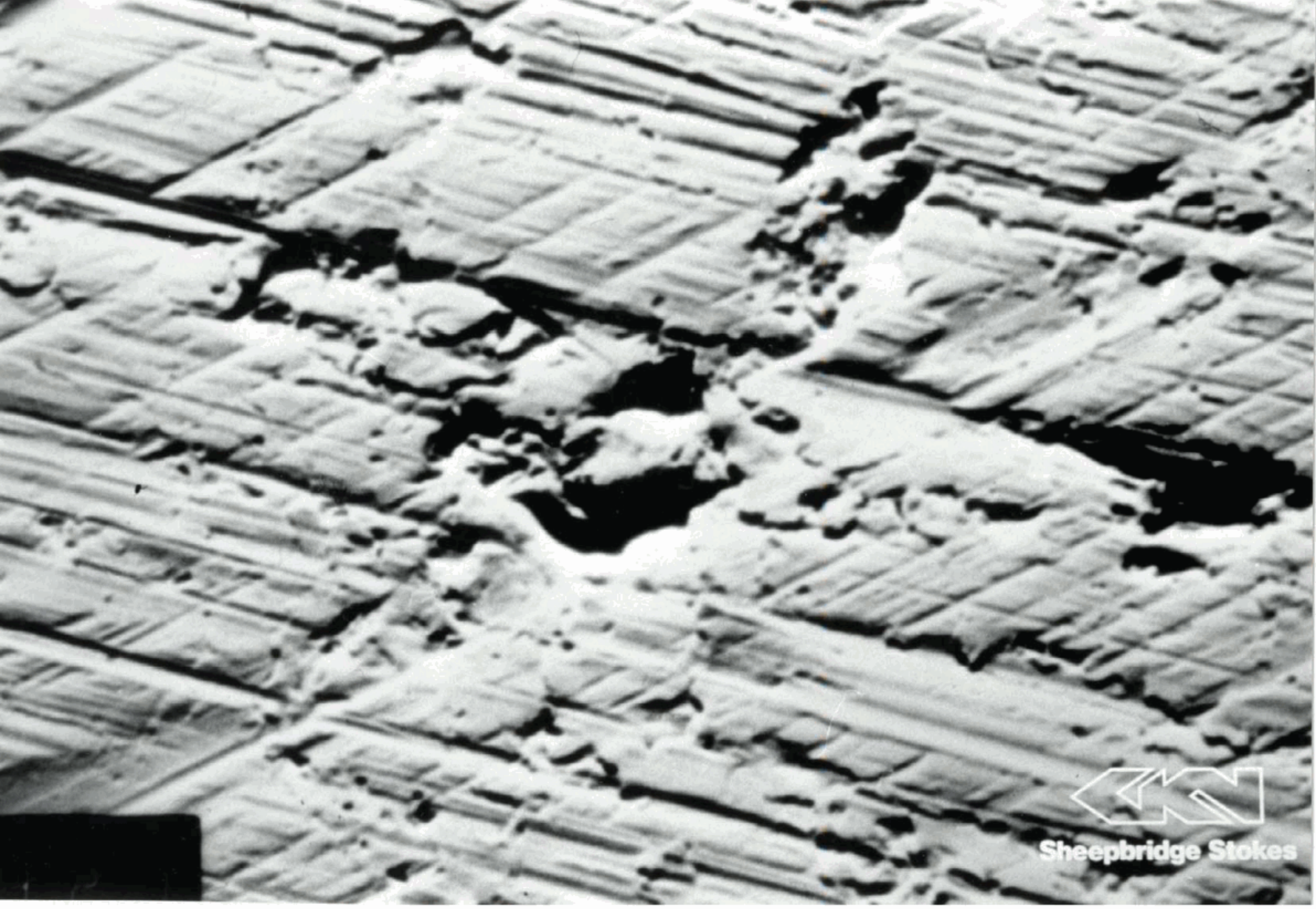
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locating even small particles of Silicon Carbide (FIG 28). What did surprise us was the porous like appearance of this surface displaying very rough and folded metal (FIG 29). Nevertheless the oil consumption and performance in this particular engine is very encouraging.

Could it be 25 years ago when we first used Diamond Tools that had we Plateau Honed at that time would we have found a difference in the performance in an engine. If this method, using Diamond Tools for the Base Hone and Silicon Carbide Tools for the plateau is successful the manufacturing units will find a big difference in ensuring repeatability, recent tests have proved this is a good working surface.

Further Engine Testing is currently being undertaken and we are confident of success.

To assist us to evaluate more accurately the cylinder bore surface, we are now able to look at the surface in a third dimension, using the Hommel T20S measuring instrument. A maximum of 15 traces can be taken at whatever spacings one would care to choose:10 different parameters are evaluated during each trace and their values stored in the instrument's memory. When the last trace has been taken, all the values are analysed by the instrument and a print out is given, displaying the average parameter readings and their ranges (FIG 30).

Having the advantage of this broad spectrum, we can, by careful location marking, follow the wear behaviour throughout the cylinder bore life, giving further knowledge to the Engine Designer in his quest for better performance (FIG 31).


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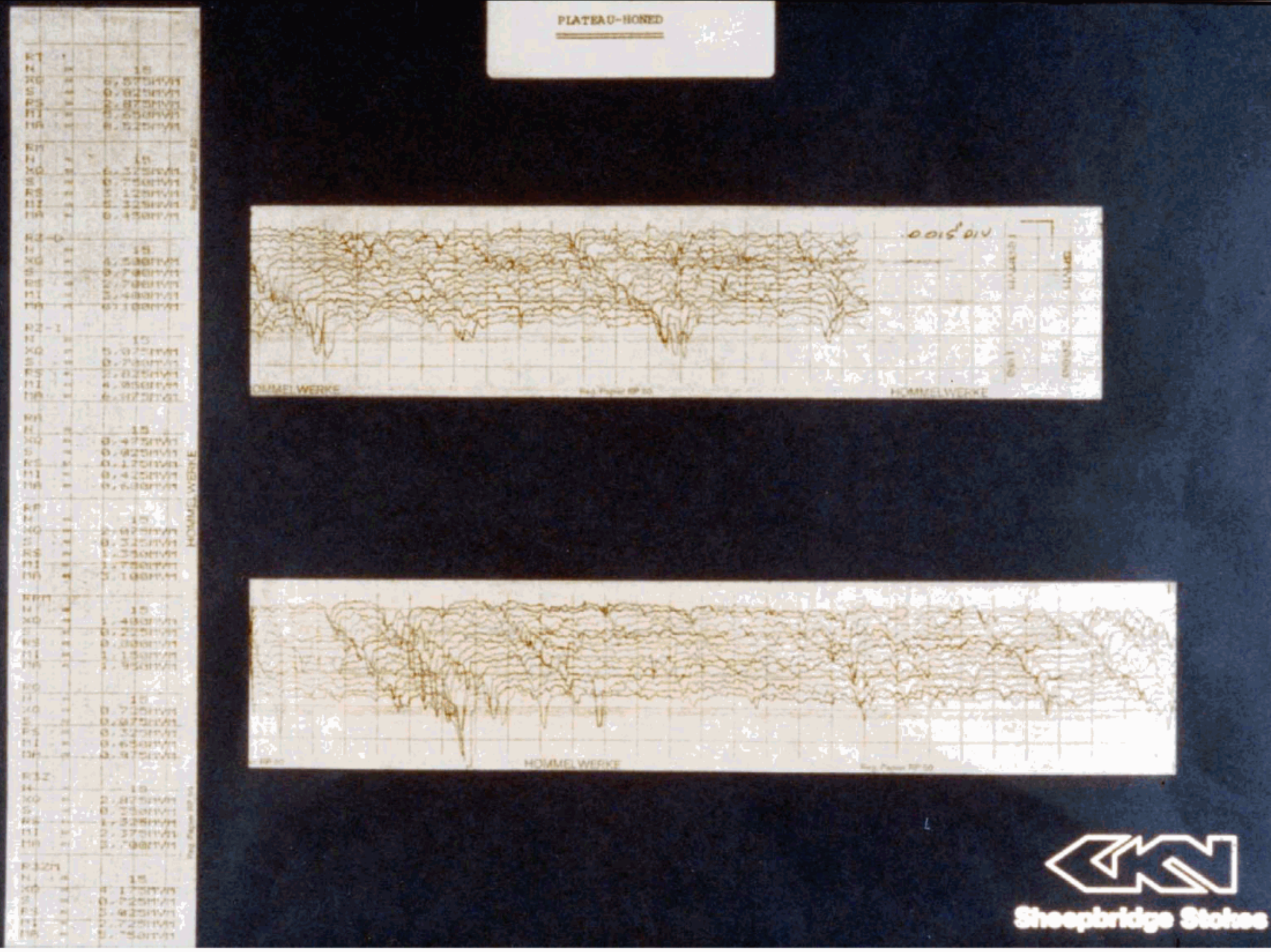

PLATEAU-HONED

```
R1
N  =    15
XQ =    6.575MYM
S  =    0.825MYM
RS =    2.875MYM
MI =    3.650MYM
MA =    8.525MYM

RM
N  =    15
XQ =    6.325MYM
S  =    0.750MYM
RS =    3.125MYM
MI =    5.325MYM
MA =    8.450MYM

RZ-D
N  =    15
XQ =    6.500MYM
S  =    0.700MYM
RS =    2.700MYM
MI =    5.400MYM
MA =    8.100MYM

RZ-I
N  =    15
XQ =    5.975MYM
S  =    0.750MYM
RS =    2.825MYM
MI =    4.850MYM
MA =    6.875MYM

RA
N  =    15
XQ =    0.475MYM
S  =    0.025MYM
RS =    0.175MYM
MI =    0.425MYM
MA =    0.630MYM

RP
N  =    15
XQ =    2.875MYM
S  =    0.325MYM
RS =    1.350MYM
MI =    1.750MYM
MA =    3.100MYM

RPM
N  =    15
XQ =    1.400MYM
S  =    0.225MYM
RS =    0.800MYM
MI =    1.150MYM
MA =    1.950MYM

RQ
N  =    15
XQ =    0.725MYM
S  =    0.075MYM
RS =    0.325MYM
MI =    0.650MYM
MA =    0.975MYM

R3Z
N  =    15
XQ =    2.875MYM
S  =    0.250MYM
RS =    1.325MYM
MI =    2.375MYM
MA =    3.700MYM

R3ZM
N  =    15
XQ =    4.175MYM
S  =    0.725MYM
RS =    3.025MYM
MI =    2.725MYM
MA =    5.750MYM
```

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