TNO-report
Div400.

The effect of DME on wear of fuel pump parts

Report

TNO Industrial Technology

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19

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1. Introduction

An important development in engine technology is to combine high fuel efficiency with higher engine power output. At same time it is increasingly important to reduce the CO_2 and NO_x emission of the engine. TNO Automotive strongly emphasises the potential of a new fuel for transport, power generation and household use: Dimethyl-ether (DME). An area of research is the effect of replacing diesel fuel by DME in specific applications, in this case a common rail diesel injection system.
It is been shown that the straightforward use of DME in a diesel injection system leads to a reduced lifetime of components. Especially the high-pressure pump is sensitive for failure due to the use of DME. The reason for this can be understood by assuming an inferior lubricating action of DME compared to diesel. TNO Automotive has asked the Tribology group of TNO Industrial Technology to perform an exploratory research on the effect of DME on component wear in general and on the wear of a high pressure pump in particular. Because of the expected poor lubricating action of the fuel, new material combinations have to be found, that compensate for the proor tribological performance of DME.

The aim of this research is to perform exploratory tribological experiments with improved contacting materials / surfaces using DME as medium.

Figure 1 shows the main components of the aforementioned high pressure pump. Two sliding contacts can be isolated form this figure: the cam - plunger tappet contact and the plunger shaft – bushing contact. The first contact is semi-continuous with respect to sliding speed and is subjected to relative high contact pressures. The second contact is reciprocal and subjected to relative low contact pressures due to the conformal contact. Cam, plunger and bushing materials are not known.

Working method

A widely recognised method to solve problems related to friction and wear is based on five steps:

1. Identification and analysis of the main tribological failure mechanisms;
2. Selection of materials and surface treatments suited for the application with expected improved performance;
3. Simulation of the contact situation at a laboratory scale with the present choice of contacting materials (reference measurements);
4. Performing tribo-tests with materials from step 2;
5. Comparing the results with the reference and advise a material combination for an industrial test to evaluate the results in the actual application.

These five steps are carried out in the project although the exploratory character of the research limits the depth of the analysis. This progress report is focussed on the first two steps of the scheme. The final report also includes the last three steps.

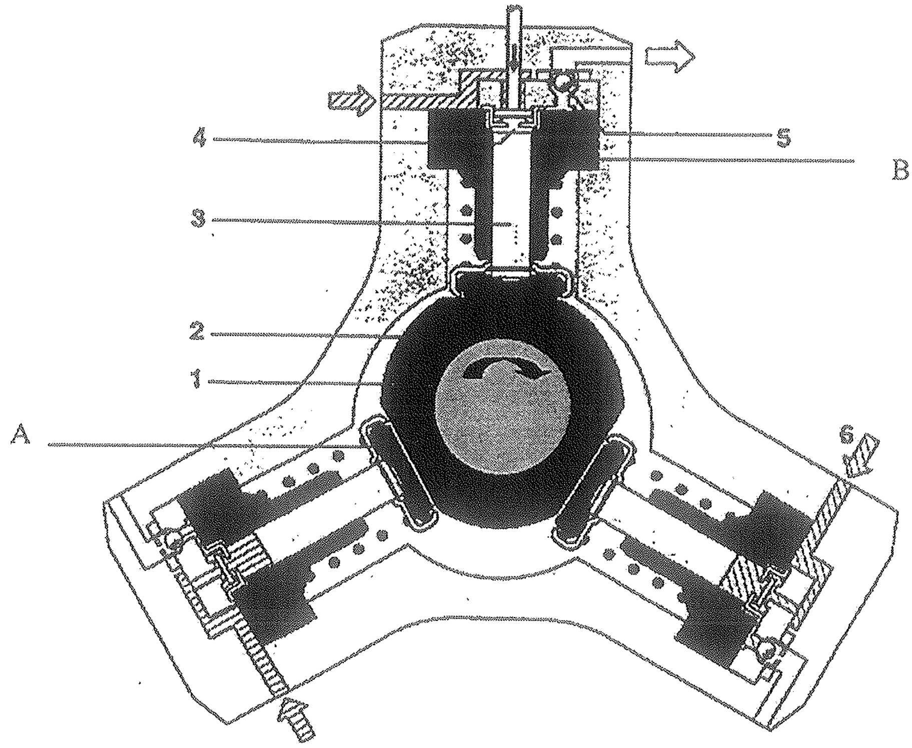


Figure 1 Cross section of the high-pressure pump. The selected tribological systems are:

- *Sliding contact between the cam (2) and the plunger tappet (A);*
- *Sliding contact between the plunger shaft (3) and the bushing (B).*

2. Analysis of pump parts delivered by TNO Automotive

2.1 *Roughness and profile measurements*

Roughness and profile measurements are taken at the surface of the cam and at the surface of the plunger tappet.

Clear signs of wear were spotted on the contact surfaces of the eccentric cam. Profile measurements are taken on all three contacting surfaces, cam 1 to 3. By comparing the profile of the unworn surface (trace A, D and G, see appendix) with a random trace in the wear scar it can be seen that the highest peaks of the roughness are worn off. Some minor scratches were found with a typical depth of 1-2 μm. Furthermore it can be seen that the initial surface of the cam is quite rough: $R_a = 0.20 \pm 0.05$ μm. It seems fair to assume that the surface is initially grinded.

Roughness measurements of the plunger tappet surface showed typical R_a – values of 0.03 ± 0.01 μm. These values are characteristic for polishing. The sliding action has smoothened the tappet surface even more. A typical profile measurement of the tappet surface is shown in the data-sheet 'pump plunger' of the appendix. Please notice the difference in scale between the plunger tappet profile and the cam profile. No signs of scratching or scuffing have been detected.

2.2 *Scanning electron and light microscopy*

The plunger tappet surface consists of a homogeneous steel, which is trough hardened. The Vickers hardness of the plunger tappet is 780 HV_{5kg} . Structure images (see Figure 2) reveal a fine martensite structure containing chromium carbides. Optical emission spectroscopy (OES) strongly suggests that the tappet is made of 100Cr6, a common ball bearing steel. The main components of 100Cr6 steel are summarised in table 1.

Table 1. Comparison of OES analysis with 100Cr6 characteristics.

	wt% C	wt% Si	wt% Mn	wt% Cr
100 Cr 6	0.95-1.10	0.15-0.35	0.25-0.45	1.35-1.65
OES plunger tappet	1.03	0.25	0.29	1.41
EDAX plunger shaft	-	0.5	0.4	1.6

The plunger shaft was to small to be analysed with the available OES technique. EDAX-analysis is therefore used to get a rough estimation of the main components of the steel used. Unfortunately the amount of carbon cannot be measured so a clear figure can not be given. Structure images looked similar to the ones from the plunger tappet (see Figure 3). A fine martensite structure with chromium carbides combined with a hardness of 790 HV_{5kg} indicates the use of a through hardened steel, probably 100Cr6 (see also Table 1).

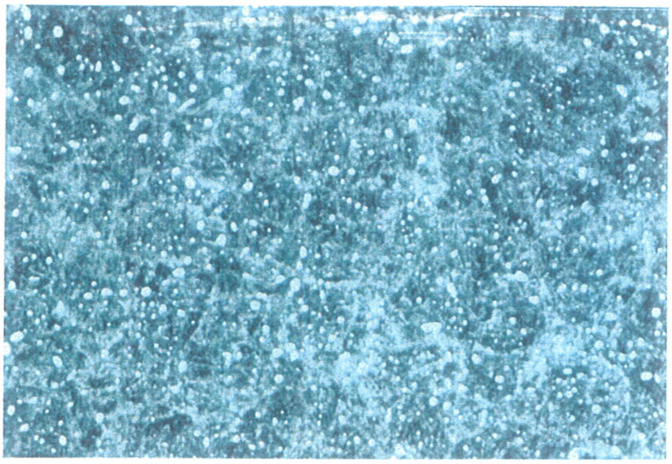


Figure 2 Structure of the plunger tappet. M = 1000 x [L2784]

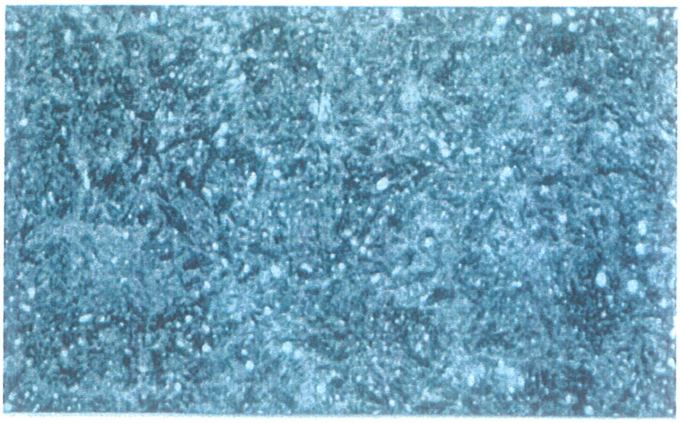


Figure 3 Structure of the plunger shaft. M = 1000 x [L2848]

No signs of coatings or other surface treatment techniques are found for both the plunger tappet and the plunger shaft.

OES analyses of the cam matrix material is given in Table 2, and compared with 21MnCr5, a steel type that is commonly used for cams, cam followers and gears. The same analysis made at the surface of the cam showed an increased percentage of nitrogen.

Table 2. Comparison of OES analyses cam matrix and surface with 21MnCr5

	wt% C	wt% Si	wt% Mn	wt% Cr	wt% N
21MnCr5	0.18-0.24	0.15-0.35	1.10-1.40	1.0-1.3	
OES cam matrix	0.21	0.19	1.20	1.02	0.007
OES cam surface	0.20	0.20	1.20	1.01	0.4
OES bushing	0.18	0.17	1.27	0.95	0.55

A representative cross section of the cam is shown in figure 4. The structure of the matrix changes when approaching the outer surface of the cam, indicating a heat treatment like nitriding of carburising. A thin hard layer of about 20 μm is present at the outer surface of the cam. The hardness of the cam increases from about 160 HV_{5kg} / 170 $HV_{0.5\ kg}$ to 500 $HV_{0.5\ kg}$ at the centre of the cam to 500 $HV_{0.5\ kg}$ just below the contacting surface, to 930 HV_{10g} at the outer 20 μm of the cam.

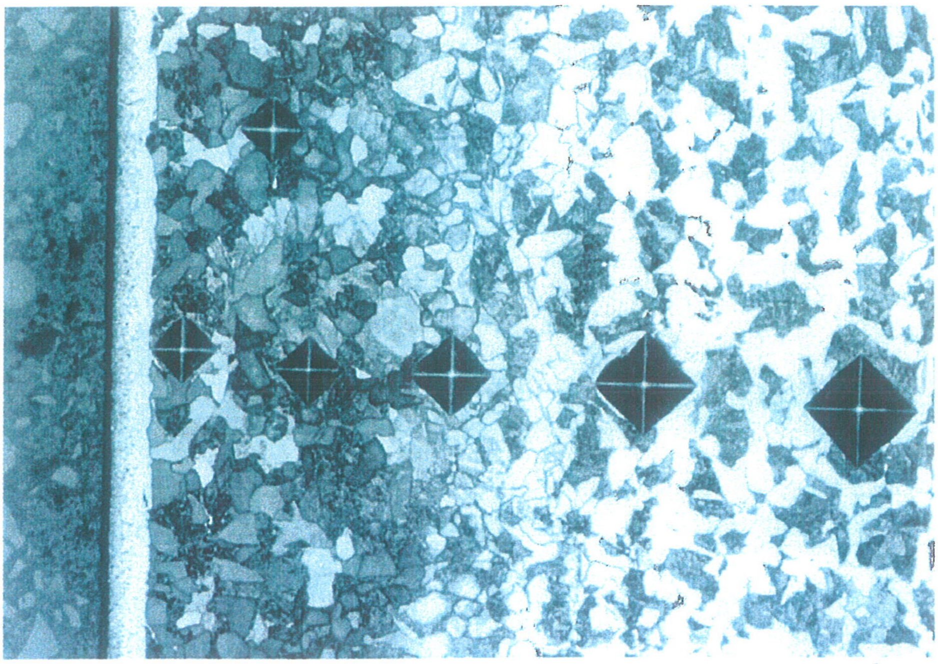


Figure 4 Cross section of the cam, showing hardness indention marks. M = 200 x [L 2796]

The structure of the cam doesn't change in the wear scar. This can be seen from Figure 5. Although part of the surface layer has been removed due to the sliding action it is still protected from direct contact with the softer layer just below the surface. The same conclusion can be drawn by comparing the EDAX analyses of the wear scar on the cam surface and a part of the same surface that has not been in contact with the plunger tappet (Figure 6). The spectra look similar and are quite common for steel surfaces used in sliding contacts. Iron, Chromium and Silicon are common for steel. The presence of Sulphur, Phosphorus and Barium indicate the use of a lubricant or the use of diesel fuel. Another possibility is that part of the grinding coolant fluid is still present at the cam surface. No relative changes in elements counted, can be seen when comparing the spectra of the worn and initial surface of the cam. The high amount of oxygen could be due to the heat treatment of the cam.

It is hard to be 100 % certain about the type of heat treatment that is applied on the cam. From WDX analyses it is concluded that the increased amount of nitrogen is accompanied by an increased amount of carbon. Nitrocarburising and carbonitriding are both possible heat treatments.

The bushing used to guide the plunger shaft is made from a heat treated steel comparable to that used for the cam (see Table 2). The hardness of the bushing increases from 430 HV_{5kg} (matrix) to about 700 HV_{5kg} just below the surface. It seems fair to assume a combination of nitriding and carburising. The diffusion zone is about 0.7 mm.

Conclusions:

The materials used in the selected systems are determined:

- the cam and bushing are made out off nitrocarburised or carbonitrided steel, probably 21MnCr5;
- the plunger shaft and tappet from through hardened steel, probably 100Cr6;

The combination of virtually no wear of the plunger tappet surface and minor wear of the cam surface indicates a relative mild wear process. No signs of severe scratching or scuffing are detected.

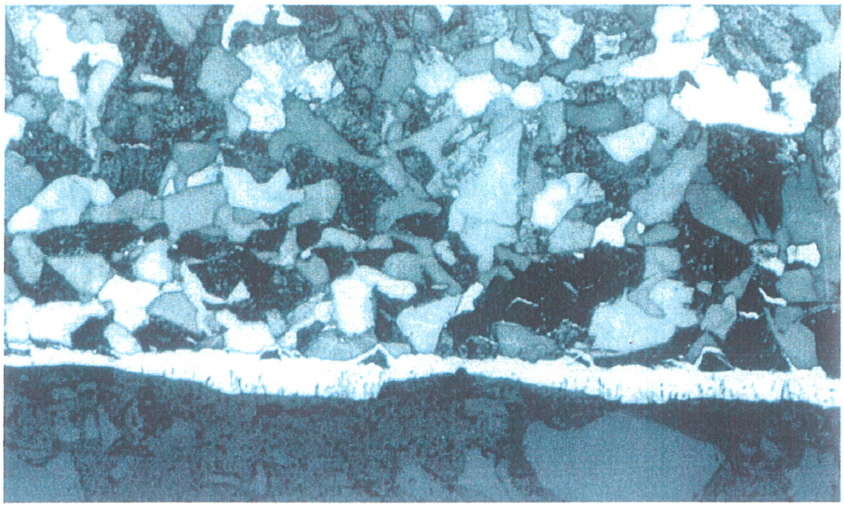


Figure 5 Cross section within the wear scar of the cam. M = 500 x [L2781]

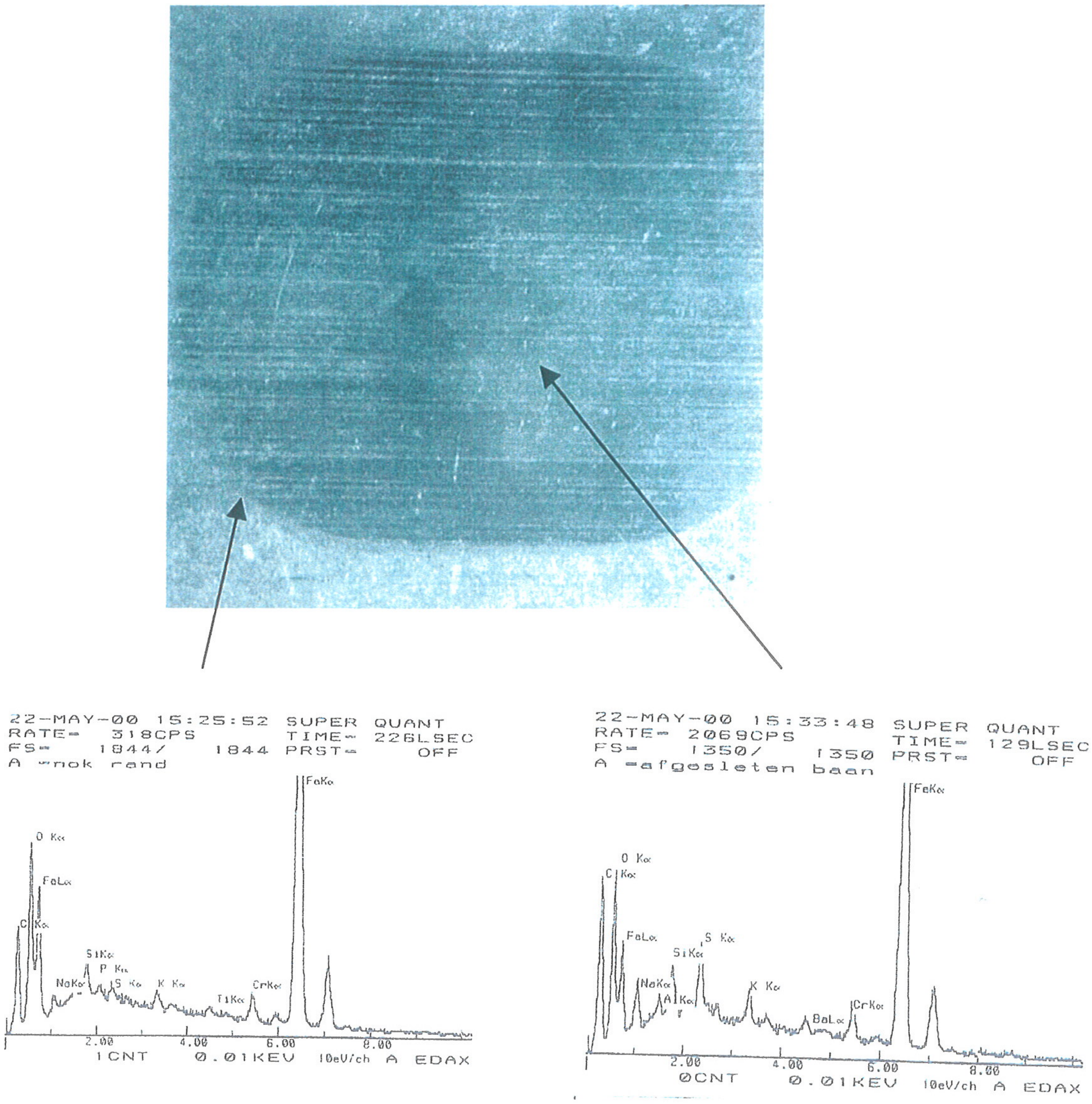


Figure 6 EDAX spectra for initial (left) and worn (right) cam surface. M = 3.1 x, [L 9841]

3. Proposed improvements concerning the choice of materials

Starting point for the choice of improved contacting surfaces is the restriction of using existing pump parts. The use of advanced contacting materials like ceramics or tungsten carbides is therefore excluded. Secondly, only minor changes of the contacting surfaces are allowed, especially with respect to dimensional changes and mechanical post treatment. The third important condition is the use of DME as medium. It is expected that DME has no or inferior lubrication properties compared to diesel and thus the risk of wear and consequent failure is high.

A widely used solution for this set of demands is the application of very thin hard or soft layers of about 2-5 µm. The selected surface layer must posses self-lubricating properties.

Figure 7 shows a representative cross section of surface treatment techniques, commonly used in industrial and automotive application. From this figure it can be seen that a large variety of process temperatures and layer thickness exists. The actual application window is determined by the maximum allowable dimensional changes of the pump parts and by the present heat treatment of the steel. The latter is quite important because of the fact that a hard matrix is needed to support the applied layer. Otherwise an egg-shall situation is created, with the risk of immediate failure due to cracking and spalling of the layer. A hard matrix will loose its hardness when it is heated above the tempering temperature that is used in the hardening process of the steel.

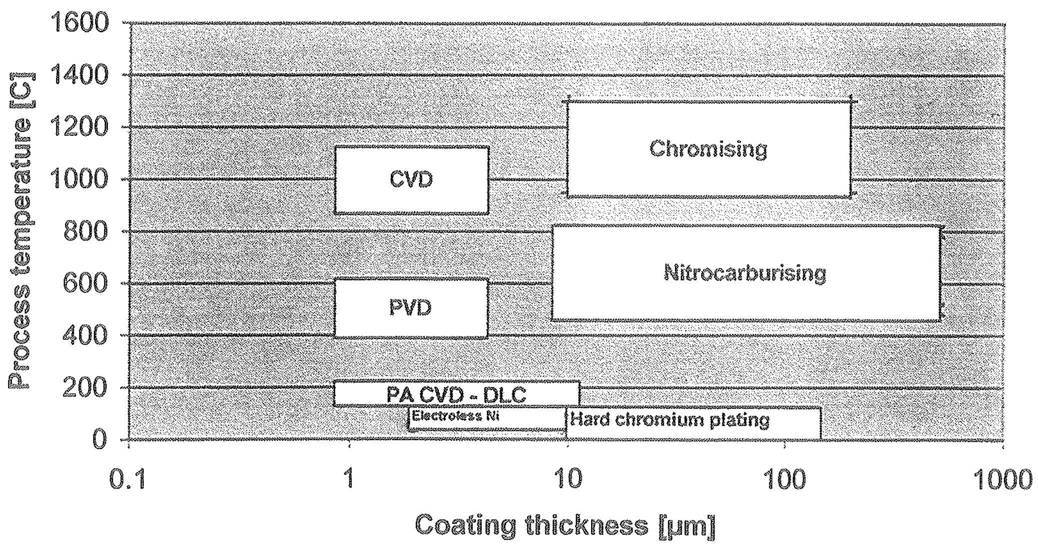


Figure 7 Representative cross section of available surface treatment techniques

From the set of available surface treatments it is expected that physical (PVD) or chemical vapor deposition (CVD) processes will have a large change of success in this application. These processes are flexible in the sense that a variety of compositions can be produced. Furthermore thin and very hard layers with uniform properties can be made. Grinding, polishing or other mechanical or chemical post treatment is not needed, contrary to for example hard chromium plating.

The materials used in the application are rather difficult to treat with PVD or CVD processes. Especially 100Cr6 is difficult to process because of the low tempering temperature of the steel: 180°C. Plasma assisted CVD processes (PA CVD) producing diamond-like-carbon (DLC) layers are a positive exception on the rule. The self-lubrication properties of this category of layers is proven in a number of papers and case studies.
Because of the low carbon content it is not possible to through harden the cam material 21MnCr5. Therefore the risk of a egg-shell situation exists. Surface treatment of 21MnCr5 is limited to the common and proven nitriding/carburising processes, which is also used in this case. An interesting point of research could be the application of the same category of diamond-like-carbon layers on top of the existing diffusion zone. The diffusion zone is then used as a hard backing for the thin DLC coating. Some preliminary results in a different application showed positive results although the adherence of the layer could be a critical aspect.

Soft-layers are not taken into account in this research because of the exploratory character of the project. Despite the fact that adherence of solid lubricants like MoS_2 is expected to be problematic, it could be possible to make some progress by applying experimental soft layers.

4. Conclusions

The main conclusions that can be drawn now are:

1. Two contact situations are isolated in the high pressure fuel pump: the plunger tappet – cam contact and the plunger shaft – bushing contact;
2. The materials, heat treatment and post treatment of the selected contact situations are estimated using SEM, OES, light microscopy and roughness measurements;
3. A mild wear process is found for the selected pump parts. No signs of severe scratching or scuffing are found.

Appendix Roughness and profile measurements

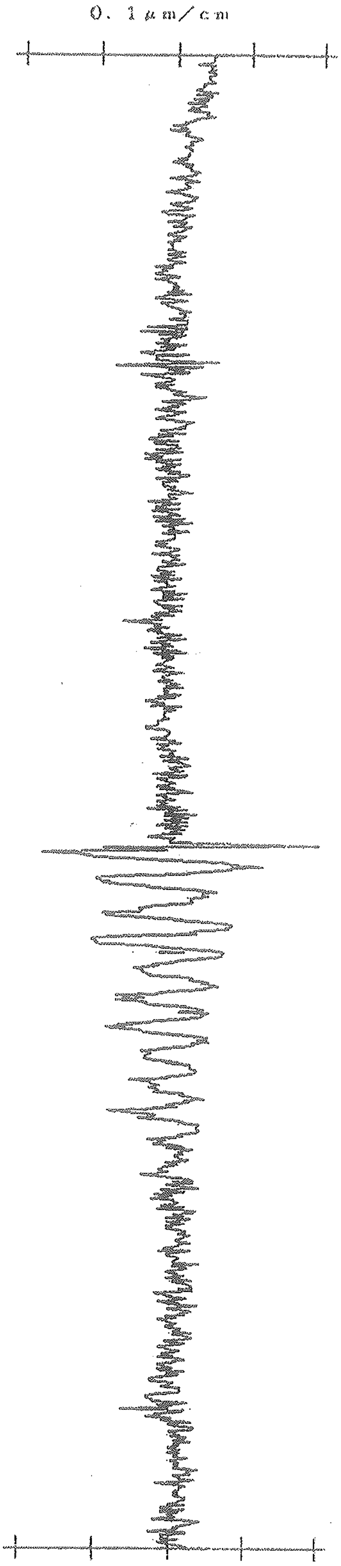
Appendix Roughness and profile measurements

May 2000	**DME pump**	Plunger tappet

Profiles and R_a measured with Mitutoyo Surftest 500

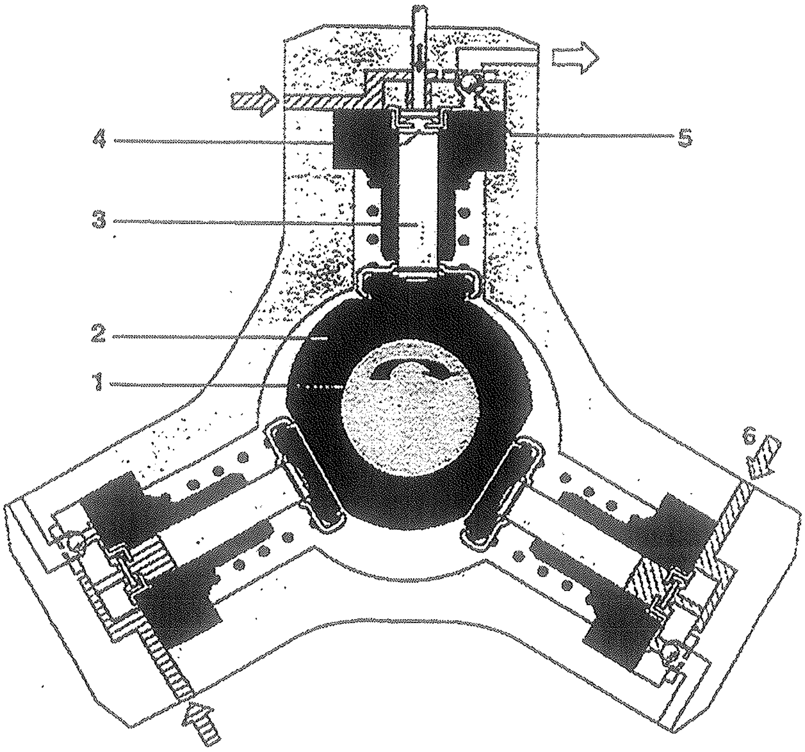
R_a pump plunger tappet: 0.03 ± 0.01 μm.
R_a cam : 0.20 ± 0.05 μm.

Roughness-curve tappet
L : 4mm
y-as : 0.1 μm/cm



Legenda:

1 : drive shaft
2 : cam
3 : plunjer shaft
4 : element room
5 : exhaust valve
6 : supply



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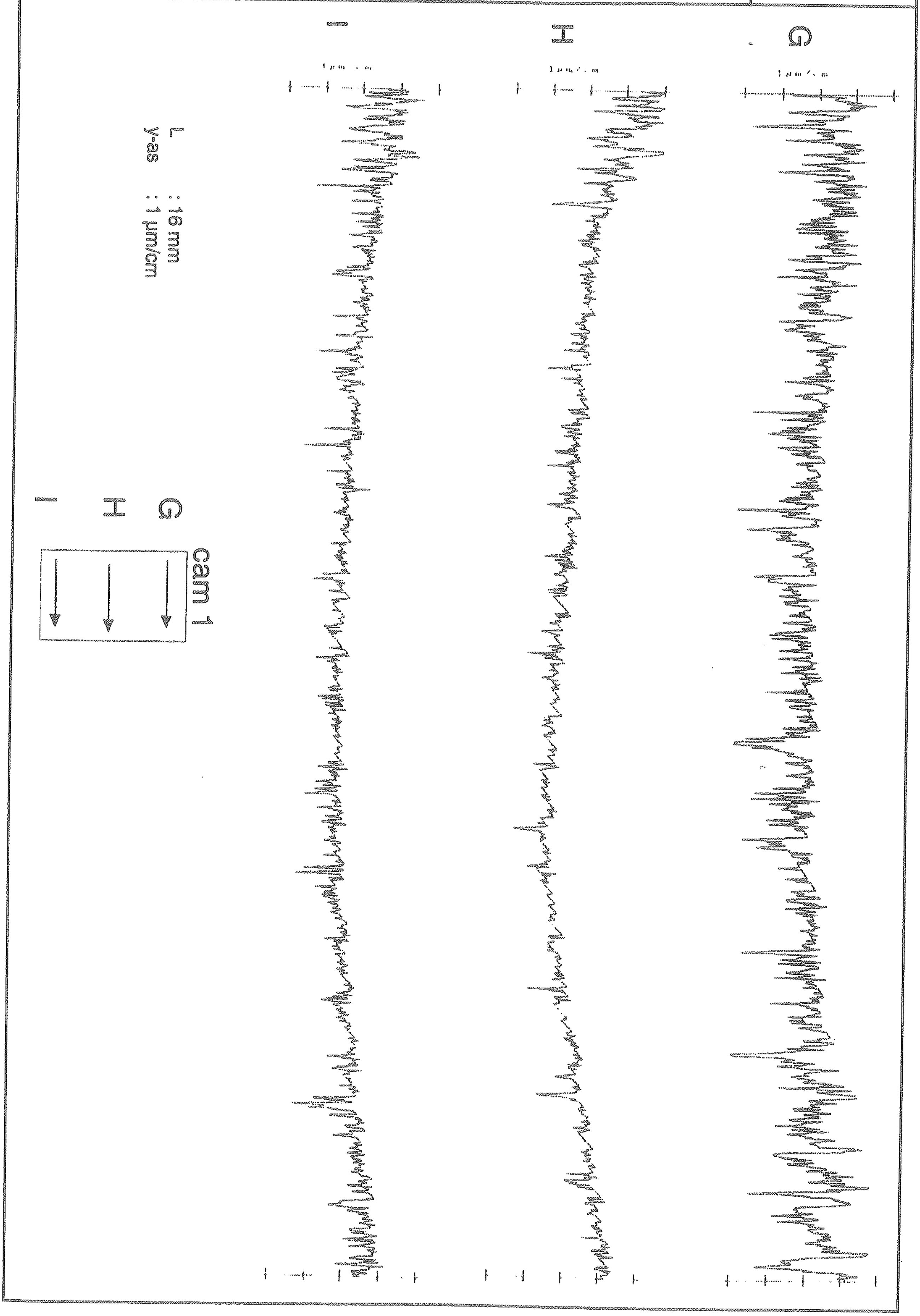
May 2000	Profile	cam 1



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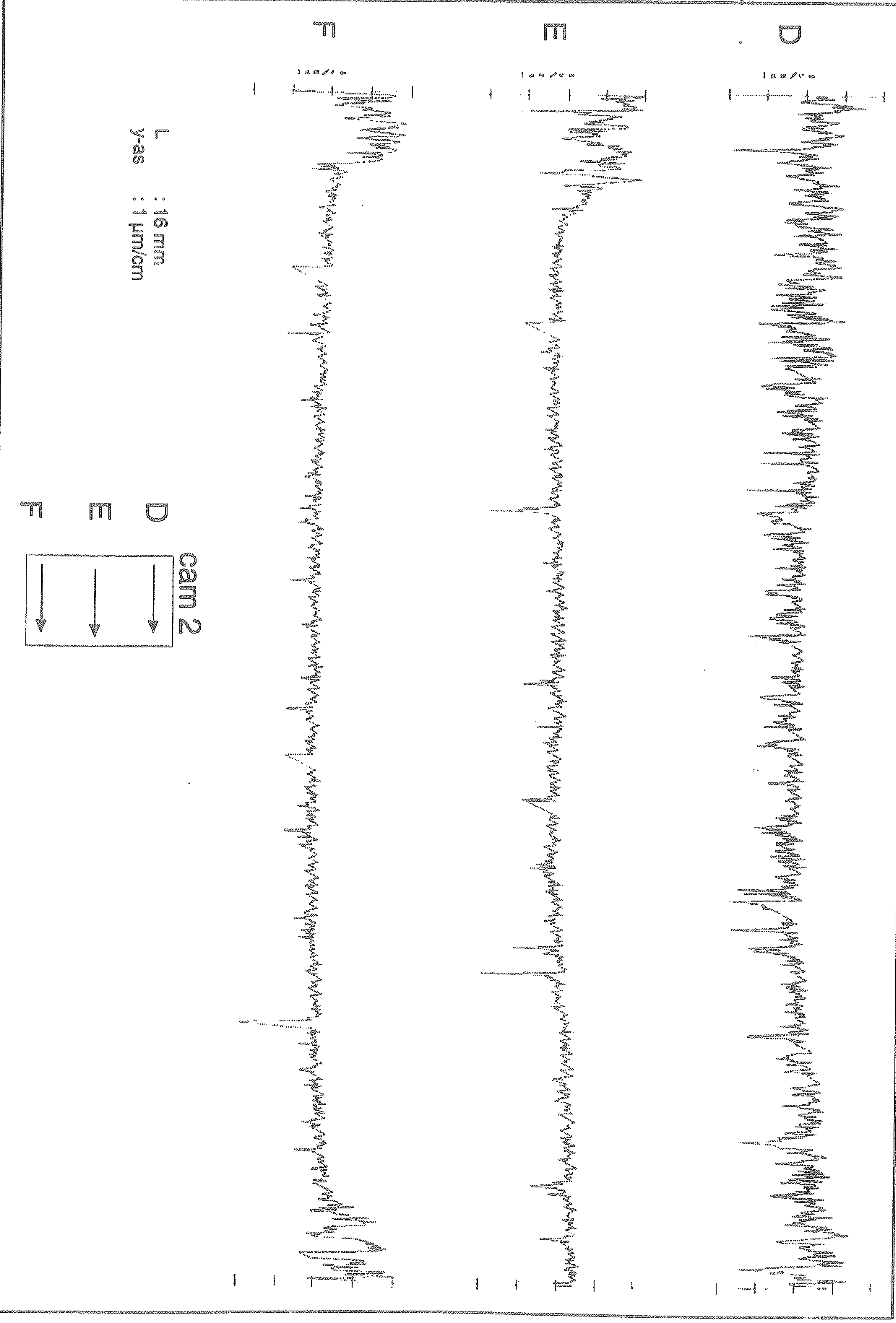
May 2000	Profile	cam 2



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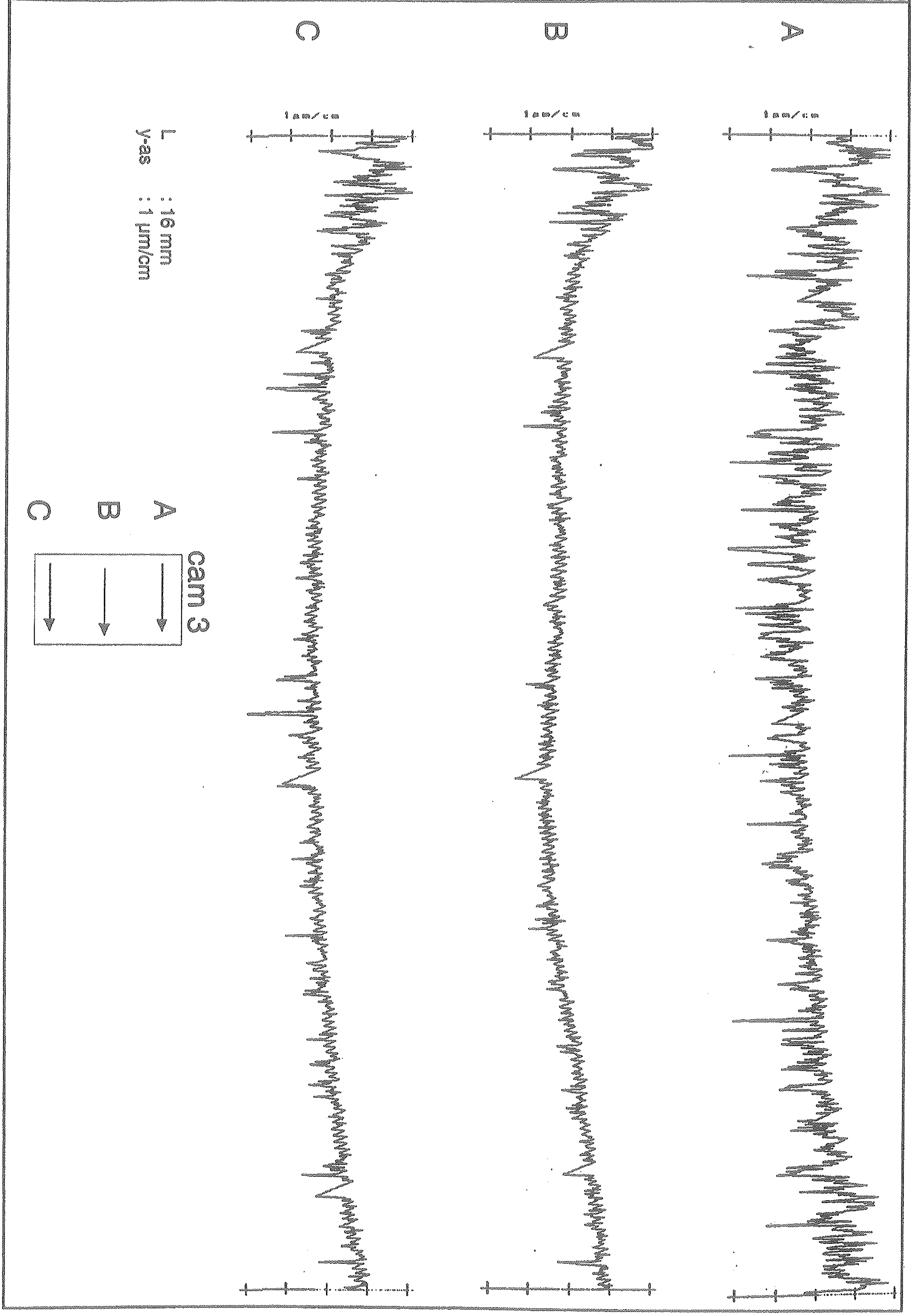
May 2000	Profile	cam 3



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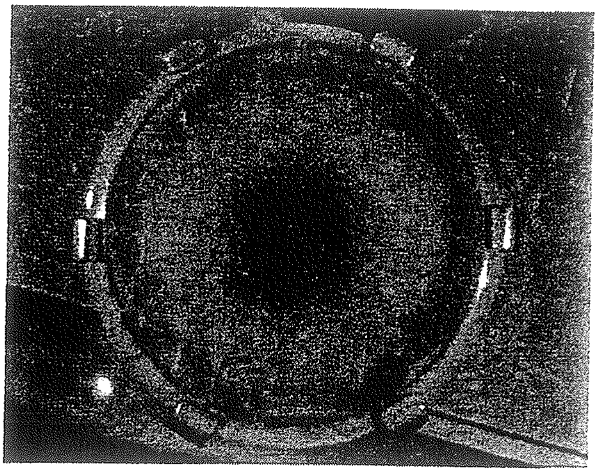
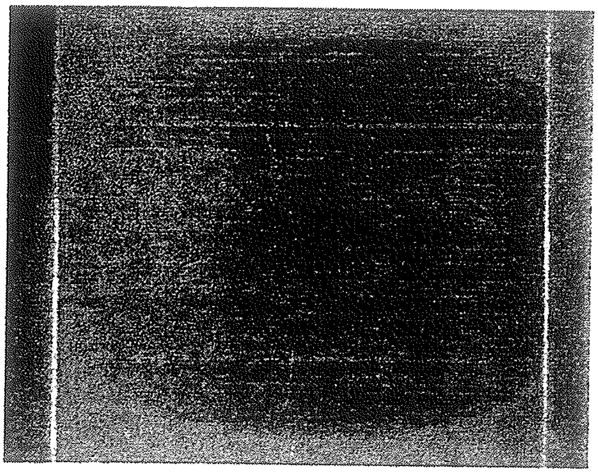
Pump plunjer

Eccentric camshaft 2

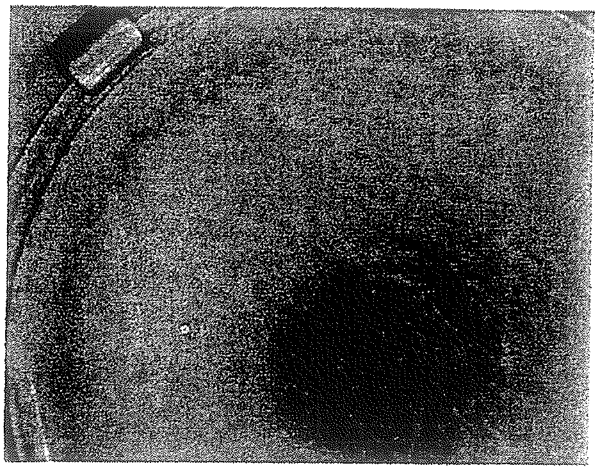
V = 4.2 x



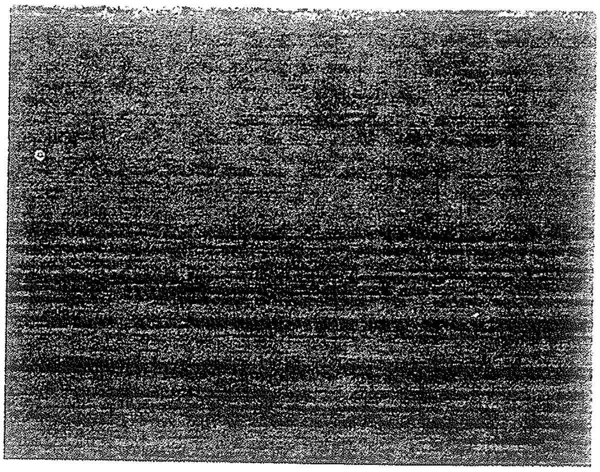
V = 4.2 x



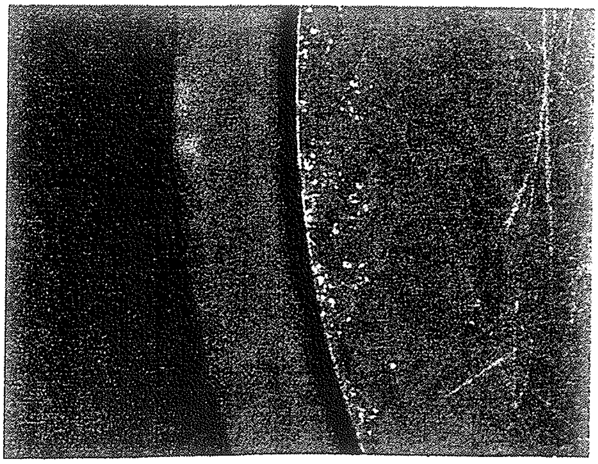
V = 8.4 x



V = 23 x



V = 23 x



V = 50 x