INTRODUCTION

Wear of machine elements is inevitable and anticipated consequence of surface contact between machine parts such as shafts, bearing, gears and bushings which occurs even in properly lubricated systems. Wear particles generated from machine elements carry an important information about machine health. For example, wear debris from gearboxes or the oil sump of IC engines can be used to establish the wear condition of machine components (ref.1, 2, 3). It is evident that in sliding wear of steel surfaces, for instant, different types of wear particles are generated which depend on the specific regime of lubrication conditions (ref. 4, 5, 6). There is much evidence that specific wear debris types are generated from different wear mechanisms (ref. 7, 8, 9, 10). Three basic approaches to wear debris examination have been used and these are direct detection methods, debris collection methods, and sample-laboratory analysis methods (ref.11). For wear debris examination, there are equipments undergoing evaluation and development for detecting the presence of metal wear particles and indicating this to maintenance personnel without removal or disassembly of machine parts. Clearly, the number of wear debris examination techniques is enormous. A select group of them which are used to monitor oil-lubricated system will be discussed.

TYPICAL MECHANICAL-RELATED WEAR PROCESSES

Wear is a process of material loss from a component surface by a particular wear process which generally requires contact between the components. As the specific wear process which predominates between any two contacting surfaces is generally thought to dictate the morphology and size of particle removed, it is necessary to understand the various wear processes which may occur in the system in order to aid in the assessment of component condition. The typical wear process generally thought to occur are : (a) Rubbing wear (b) Cutting wear (c) Rolling fatigue wear (d) Combined rolling and sliding wear and (e) Severe sliding wear. Each of these wear processes will be discussed briefly.

1. Rubbing wear

Rubbing wear is the most common kind of wear and occurs when one metal slides over another metal surface, normally under light load. The repeated rubbing produces a unique layer in which the long-range crystalline order of the atoms of the metal is disrupted. The layer, known as the shear mixed layer, is not tightly bonded to the underlying surface, and with successing passes of the metal surfaces, sections of the layer spall off. In addition smaller peeling of the layer make flake off and become rubbing wear particles. Rubbing wear particles are platelets, typically ranging in size from 15 μm down to 0.5 μm in major dimension (ref. 12).

2. Cutting wear

Cutting wear occurs when two surfaces that are in relative motion and under loads normal to their general planes may make asperities contact and at these points the asperities must elastically/plastically deform until the actual area of contact is sufficient to bear the load. As the contacting areas slide across on another material may be removed by a process of surface penetration which generates particles much as a lathe tool creates machining swarf ; except on a relatively microscopic scale. Particles produces this way are normally coarse and large, averaging 2.5 μm wide 25-100 μm long.

3. Rolling fatigue wear (Rolling contact bearing)

Rolling contact fatigue results from the high stresses imposed by repeatedly loading and unloading, for example near the tip of a heavily loaded gear teeth. Cracks develop on the surface and perpendicularly to it. Eventually the surface and underlying cracks link up and typical wear particles spall out, leaving minute pits on the surface (ref.3). Three distinct particle types have been associated with rolling contact fatigue. Namely, fatigue spall particles, spherical particles and laminar particles.

4. Combined rolling and sliding wear (Gear system)

Gear teeth theoretically contact each other along lines or points (ref. 13). The relative motion at the contacting are varies from predominantly rolling (at or near the pitch line) to predominantly sliding (at the addendum, tip, or dedendeem, root). If contact between teeth is made at either of the sliding areas scuffing wear particles are produced. These particles are generally flat, irregular shaped and often contain striations on their surfaces. Since there is a large variation in both sliding and rolling velocities at the wear contacts, there are corresponding variations in the characteristics of particles generated (ref. 12). For instant, fatigue wear particles from a gear pitch line have much in common with rolling bearing fatigue particles. They generally have a smooth surface and frequently irregularly shaped.

5. Severe sliding wear

Severe sliding wear occurs when the wear surface stresses become excessive due to load and/or speed. The unique layer, known as shear mixed layer, then becomes unstable and large particles break away causing an increase in the wear rate. Severe sliding wear particles range in size from 20 μm up. Some of these particles have surface striations as a result of sliding. Table 1 shows the typical wear particles corresponding to a specific wear process.

In dealing with wear debris examination, there are basically 4 major wear particle parameters as follows (ref. 14) :

(a) Size distribution: it may indicate how close a particular element is to failure. Indication are that a machine functioning "normally" generated particles with an average size of 5 μm. As an element approaches failure, average wear particle size becomes larger.

(b) Shape, or particle morphology, can give clues to the type of failure. Jagged "clip like" particles, for example, seem to indicate sliding wear while rolling contact fatigue generates spherical particles.

(c) Composition of the particles may tell what component it came from, for example, indications of Bronze, Copper, or a special type of steel may be traced to specific bearings.

(d) The wear particle concentration or the wear rate can be monitored along side with shape, composition, and size distribution to predict the impending failure mode.

WEAR DEBRIS ANALYSIS TECHNIQUES

In comparing the different techniques, it is important first to recognise the limits on the size range of particles which can be detected. Second, that some techniques are better suited to qualitative analysis while others provide direct quantitative information about the extent (quantity) and type (size distribution) of wear. Tabel 2 provides a summary of the situation as a basis for initial selection.

ROTARY PARTICLE DEPOSITOR

The Rotary Particle Depositor(RPD) was developed as a response to the operating difficulties encountered when using the Ferrograph. The mode of operation of the RPD is the deposition of a fixed volume of sample containing wear debris at the centre of a plain rotating substrate fixed over a magnetic system. Deposition in this manner ensures an excellent of the wear particles and also enable the use of various solvent solutions for the disposal and removal of the carrier fluid. The process produces a clean debris-carrying substrate which most suitable for microscopic or image analysis examination. Figure 1 shows the outlook of the RPD machine.

PARTICLE QUANTIFIER

The Particle Quantifier (PQ) is a magnetometer instrument which gives a digital reading according to the amount of debris present.

This is a rapid method taking only a few seconds and is most suitable for wear trend plotting. Using this technique, a value for the debris present in, for example, a gear box oil sample, can be obtained within a few minutes. It may be used to quantify the deposited debris on a substrate or wear debris in used lubricant. The outlook of the PQ machine is shown in Figure 2.

DIRECT READING FERROGRAPH (DR)

The direct reading ferrograph provides a means for quantifying the amount and approximate size distribution of wear particles which are magnetically trapped on the inside wall of a transparent glass tube by a high-gradient magnetic fields. It can detect particle in the size range of 1-100 μm and give reading proportional to the optical density of the captured particles.

SPECTROMETRIC OIL ANALYSIS (SOA)

SOA is a preventive maintenance tool used to determine the type and amount of metal fragments in lubricating oil from engines and in fluids of hydraulic equipments. It can be used to measure the concentration, in parts per million (ppm), of about 30-40 elements which include metals and non-metals. There are principally 2 types of SOA. Namely, Atomic Emission Spectroscopy and Atomic Absorbtion Spectroscopy.

IMAGE ANALYSIS SYSTEM

The image analyser attempts to do what the eye does when an image is presented to it. The human eye is designed with infinite care and is vastly superior in detection minute features of interest but the image analyser has the ability to provide precise dimensional measurements, and record the evidence. Most image analyser system come in three parts (ref. 15):

(a) A means of optically examing the debris (e.g. microscope).

(b) A device to convert the image to electronic form, e.g. a TV camera, electronmicroscope and a frame grabber.

(c) Image processing hardware which converts the image for re-display, and performs high -speed analysis.

This particular technique which is currently being used in this research project will be discussed in detail later.

PARTICLE CHARACTERISATION

As far as the Swansea work is concerned, there are six attributes which can be used to characterise wear particles; typically, outline profile, edge detail, surface texture, size, thickness ratio and colour. For the purpose of extracting particle characteristics, an image analysis system is employed. A schematic layout of the system is shown in Figure 3. The optical microscope used is an Olympus bi-chromatic unit with facility for viewing is transmission and/or incident light. Images are transmitted from the field of view in the optical microscope via a Panasonic vidicon camera to the monitor. The image analyser framestore unit is linked directly to a Mertec AT IBM compatible computer which contains appropriate software facility for inputting commands, retrieving and displaying data, and for performing calculation routines to determine size and shape characteristics. Edge detail is obtained from measuring the change in angle that occurs from incrementing three adjacent points systematically around the periphery. An angle is formed from two lines draw through the points such that they intercept one another. Thus, convex and concave undulations are represented by positive and negative angles, respectively. Based on the curvature pattern derived for the whole of the particle periphery, statistical analysis is performed to establish mean($\bar{x}$), standard deviation (R_q), coefficient of variation (C_v), skewness (R_{sk}) and kurtosis (R_{ku}) data. Two additional parameters : aspect ratio (Length/Breadth) and roundness factor ($(\text{Perimeter})^2/4\pi$ (Area)), are also utilised.

EXPERIMENTAL WORK

1. IAE Gear Tests

Tests using an IAE Gear Lubricant Testing Machine MkIII were undertaken according to Institute of Petroleum IP166/77 Condition C-6000 rev/min and an oil jet temperature of 110°c. Samples for wear debris analysis were taken from a position in the scavenge line immediately after the test chamber. The lubricant under test was OX165 and the Mean Failure Load was established at 355 N. The history of the test is briefly as follows:- Visible damage to the root and tips of opposing teeth was observed at 180 N load. The damage area increased rapidly after 270 N and final failure occured at 360 N.

2. Four-ball Tests

The Stanhope-Seta four-ball machine was used throughout to generate typical wear debris. The relevant features of the machine are three AISI 52100, 12.7 mm. in diameter, ball bearings, arranged in the form of an equilateral tetrahedron and held stationary while a fourth (top ball) is free to rotate at 1500 rev/min. under a specific load. At least three repeat runs were made for each test condition (both scuffing and pitting tests).

2.1 Scuffing test

A series of one minute runs were carried out at a top ball rotational speed of 1500 rev/min. The lubricant used was SAE10 base oil with no anti-wear or extreme pressure additives. For each run, the bath contained 8cc. of test oil and from which samples containing wear debris were taken for analysis. Particle concentrations were determined using the Particle Quantifier, PQ90-see ref. 16 for further details of measuring method. The load range was 13 to 112 kg, based on IP 239/82. Figure 4 shows the variation in average wear scar diameter with load, and Figure 5 depicts the corresponding variation in PQ index. The micrographs of typical wear debris both before and after transition period are shown in Figure 11 and the worn surface appearances of lower balls are shown in Figure 12.

2.2 Pitting test

Tests were carried out using the rolling contact facility to obtain debris representative of the situations before, and after, pitting. The first test, at 600 kg and 1500 rev/min., was run until fatigue failure of the top ball occurred after 154 minutes. The second test was conducted under the same operating conditions of load and speed as the first test but was stopped after 30 minutes of running and before failure has occurred. Debris was separated from the oil using the filter technique and examined under the optical microscope before selecting a number of individual particles for shape analysis. The results are presented in Figures 6 and 7. Typical image of debris from both before and fater pitting wear stagea are illustrated in Figure 13.

DISCUSSION

1. IAE Gear Tests

Wear debris analysis was carried out using Spectrographic Oil Analysis (SOA), Direct Reading Ferrography (DR) and Particle Quantifier (PQ) techniques. Figures 8, 9 and 10 show the results of quantitative analysis. Running-in wear occurs up to 135 N and the initial damage at 180 N is clearly indicated by the DR and PQ measurements. The increase in scuffed tooth area visibly observed from 315 N to 360 N is hence adequately detected by the wear monitoring devices.

2. Four-ball tests

The purpose of the tests was to establish whether it was possible to distinguish between different types of wear behaviour by analysing wear debris taken from the same machine and using the same lubricant type throughout. In the scuffing tests it is evident that initial seizure occurs after 45 kg and that the filter method provides the clearest indication of the increase in wear debris concentration after seizure. In the pitting tests, where the wear particle maps were applied, it is immediately evident that the combination of coefficient of variation vs roundness factor, and also R_{ku} vs aspect ratio, appear to show a distinctive region between the period of "before and after" pitting failure mode.

CONCLUSION

1. The results of analysis of particles captured from different wear situations have shown that distinctions are evident between wear modes in several instances.

2. Different particle formation mechanisms produce particles of different shapes. They can be differentiated from each other on the basis of their shape characteristics.

3. The wear particle analysis can be used in conjunction with other means of condition monitoring methods, i.e. oil analysis, vibration analysis, performance measurement analysis, to monitor the wear stage of machine elements. It is also a practical method for predicting machine failures caused by wear in oil lubricated machines.

In summary, the quantitative monitoring of wear debris generated from machine elements is feasible. The multiparameters for wear particle shape, quantitative size/shape distribution and concentration level of the wear particles is significant in identification the state of the machine and any likely failures. The morphology of particles present is a function of the type of part wearing and its wear mode. In a sense, the wear particle maps give information on the type of wear which already occured in a specific wearing part. Frequently sampling and observation of the particles in used oils is crucial in determining what action is required to maintain the machine at its best performance.

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TABLE 1 TYPICAL WEAR PARTICLES

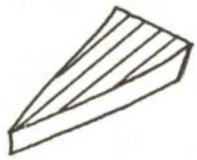
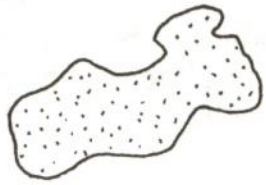
RUBBING WEAR	CUTTING WEAR	SEVERE WEAR
		
SPHERICAL	LAMINAR	OTHER TYPES
		

TABLE 2 COMPARISON OF WEAR MONITORING METHODS

METHOD	SIZE RANGE (MICRON)	QUANTITY	SIZE-DISTRIBUTION	MORPHOLOGY	COMPOSITION
SOA	LESS THAN 10	/			/
DR	1 TO 100	/			
PQ	1 TO 2000	/			
RPD	1 TO 2000	/	/	/	
IMAGE ANALYSIS	1 TO 2000		/	/	

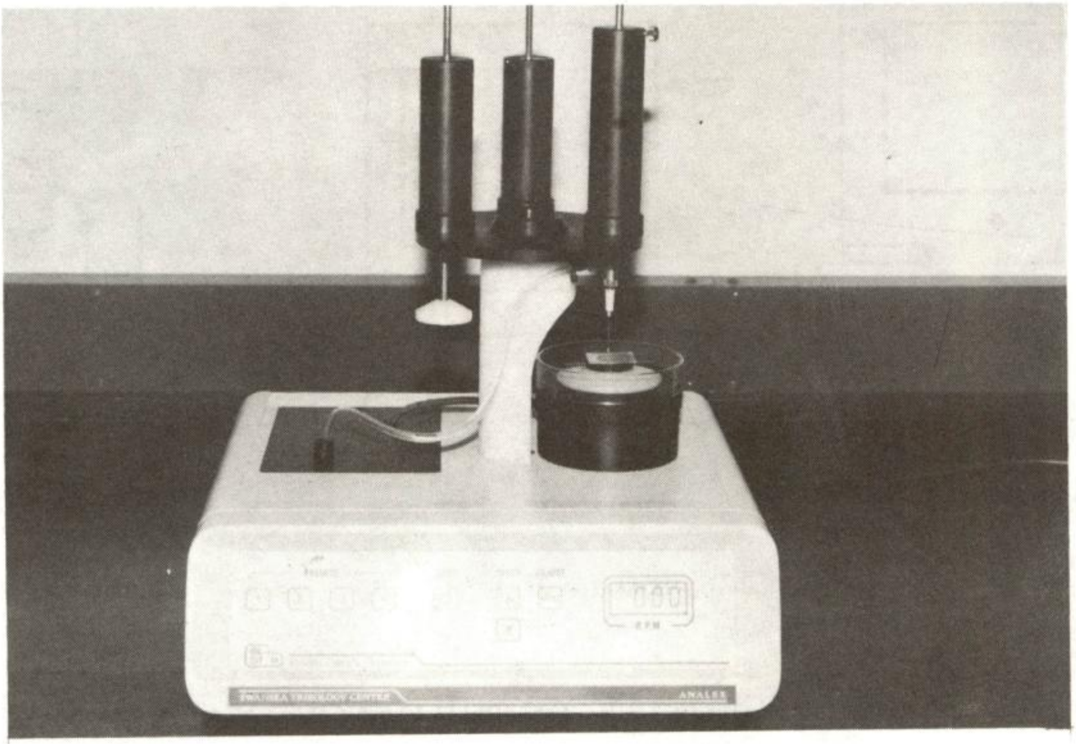
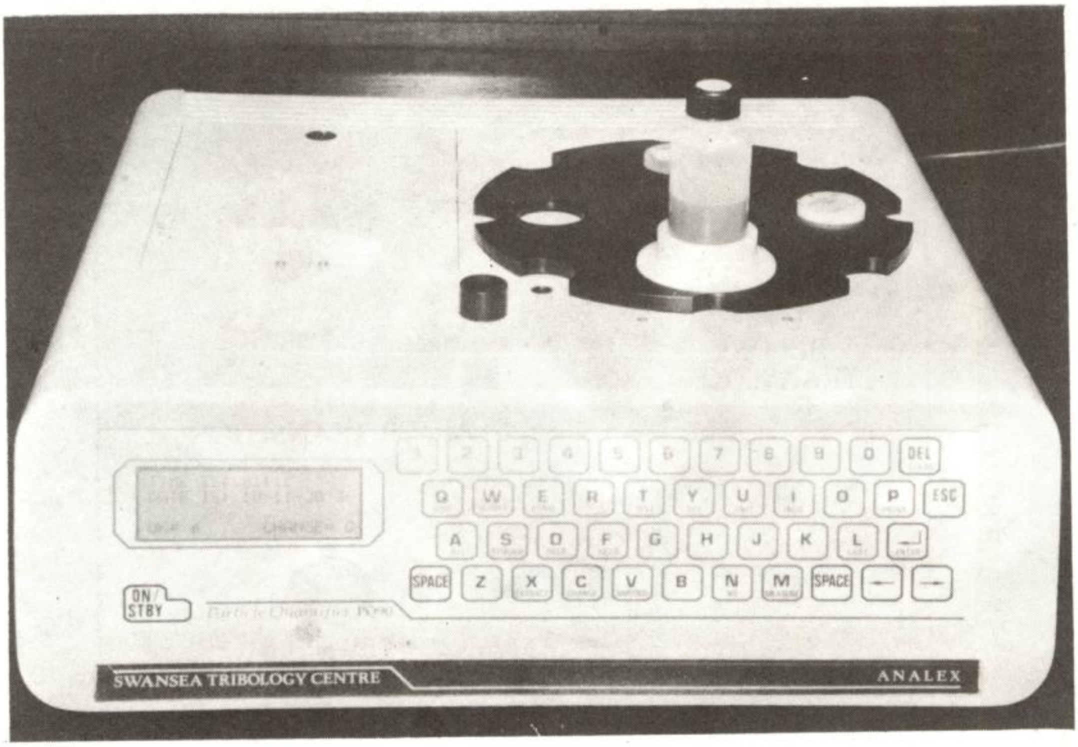


Figure 1 The Rotary Particle Depositor



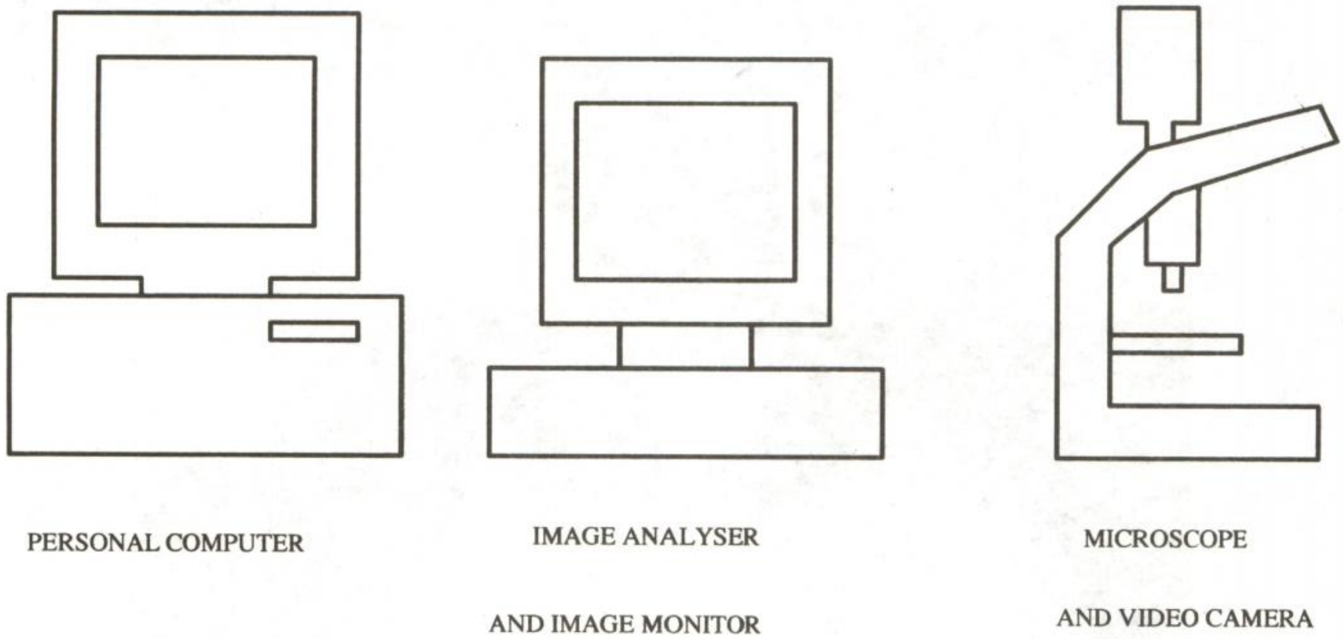


FIGURE 3 SCHEMATIC DIAGRAM OF THE IMAGE ANALYSIS SYSTEM

FIGURE 4 WEAR SCAR DIAMETER VS LOAD

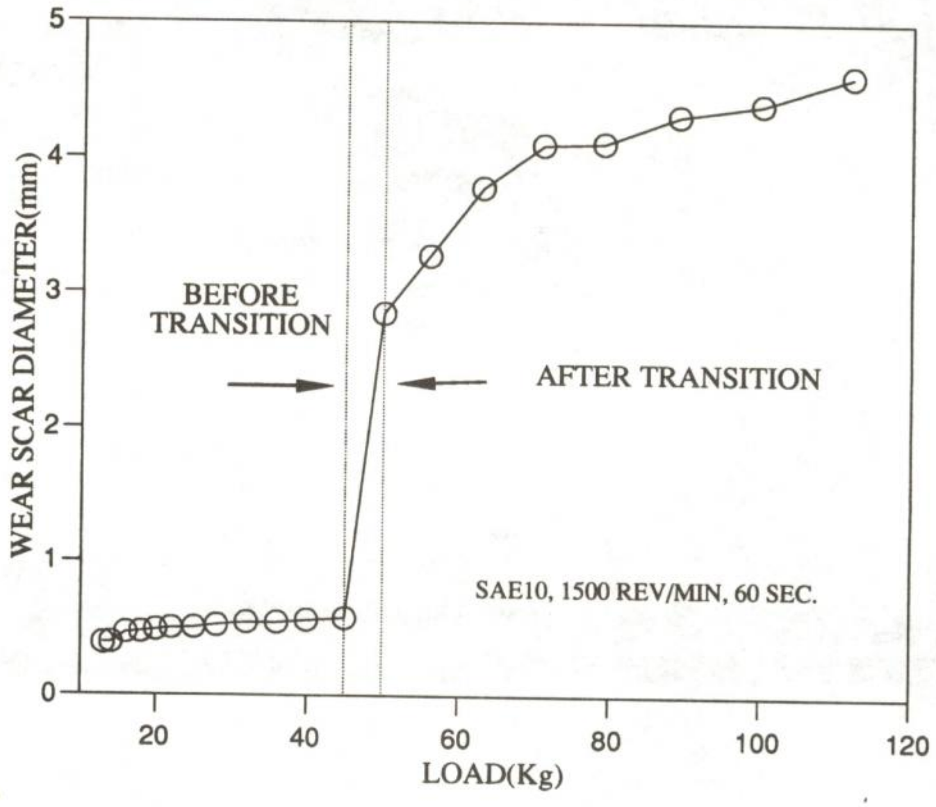


FIGURE 5 PQ INDEX VS LOAD

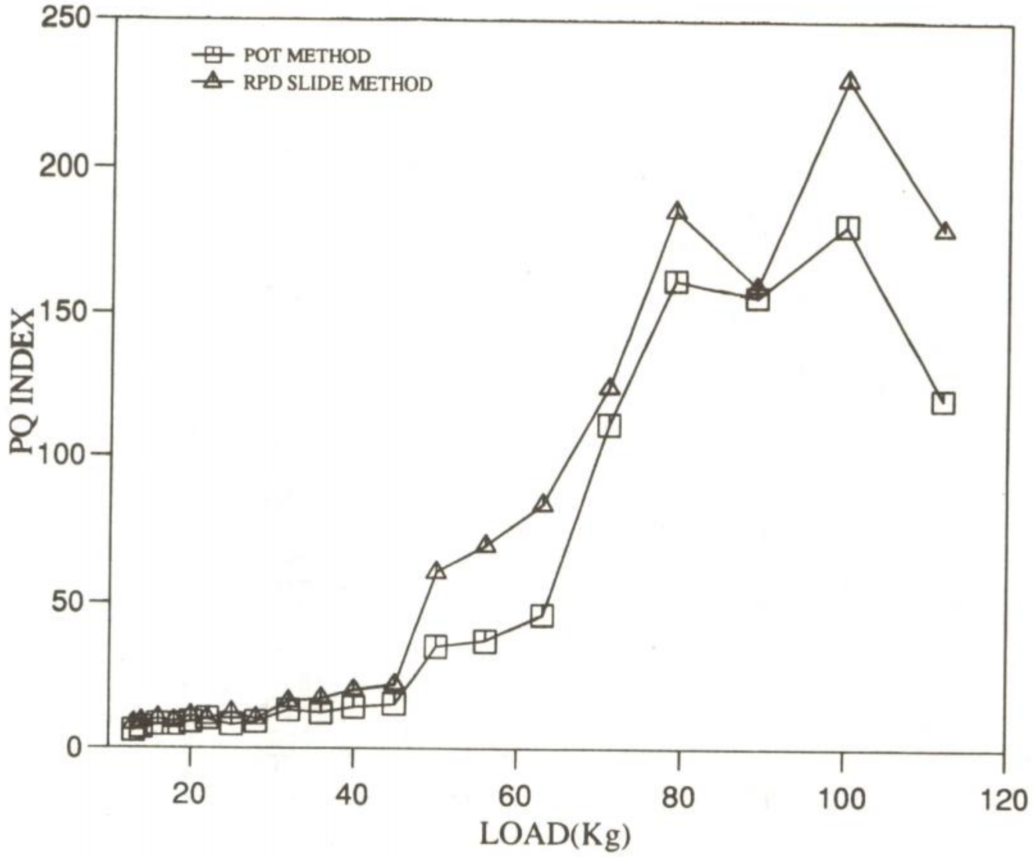


FIGURE 6 COEFFICIENT OF VARIATION VS ROUNDNESS FACTOR

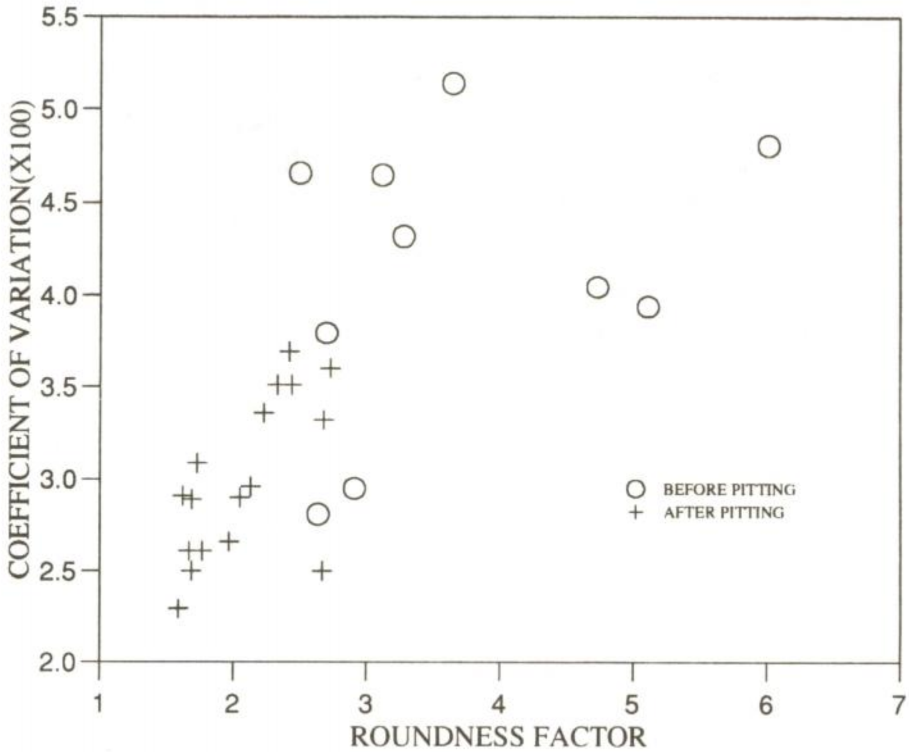


FIGURE 7 KURTOSIS VS ASPECT RATIO

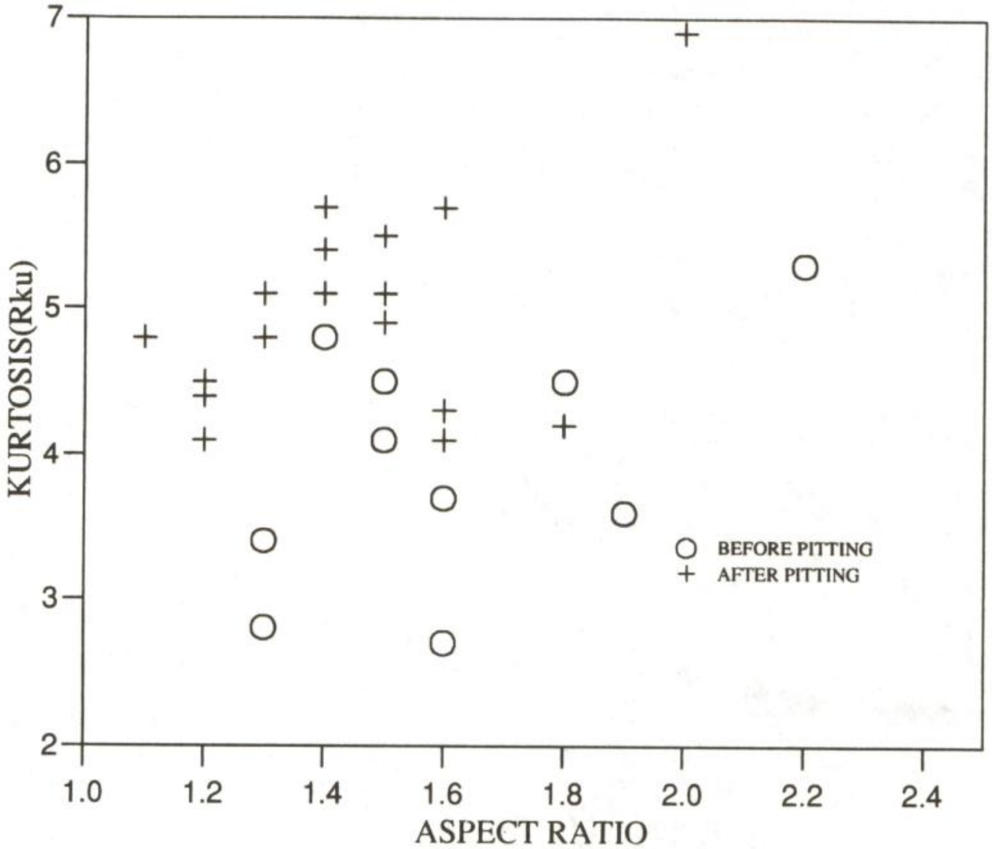


FIGURE 8 SOA READING VS LOAD

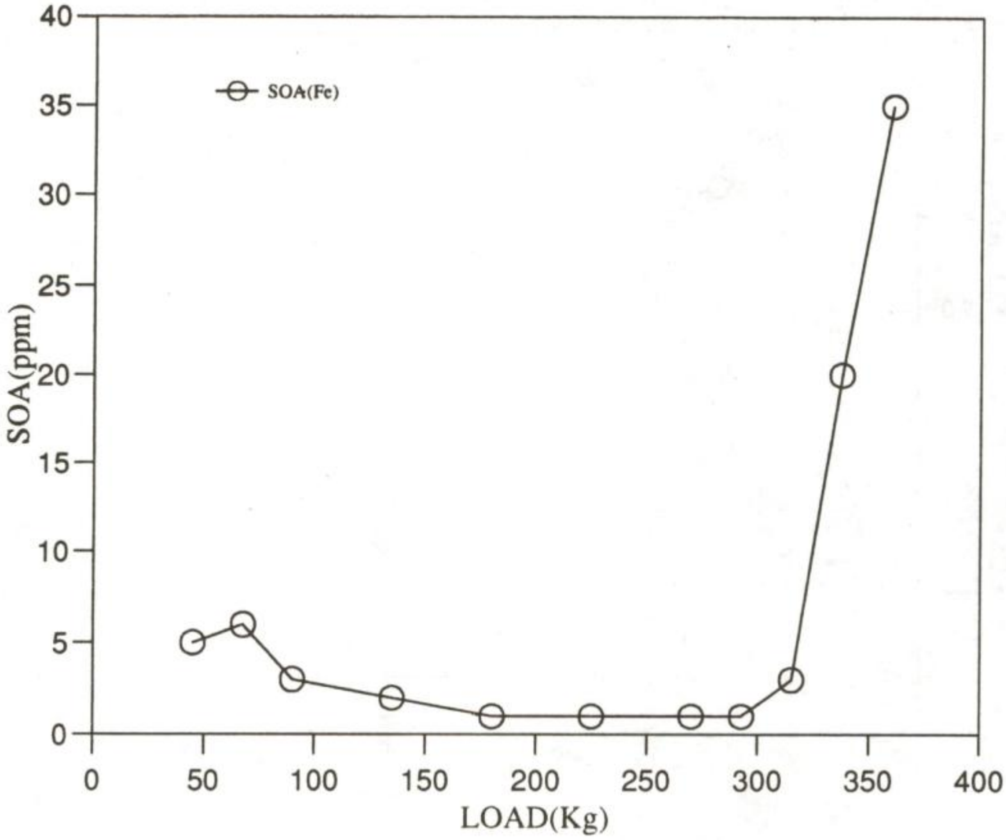


FIGURE 9 PQ INDEX VS LOAD

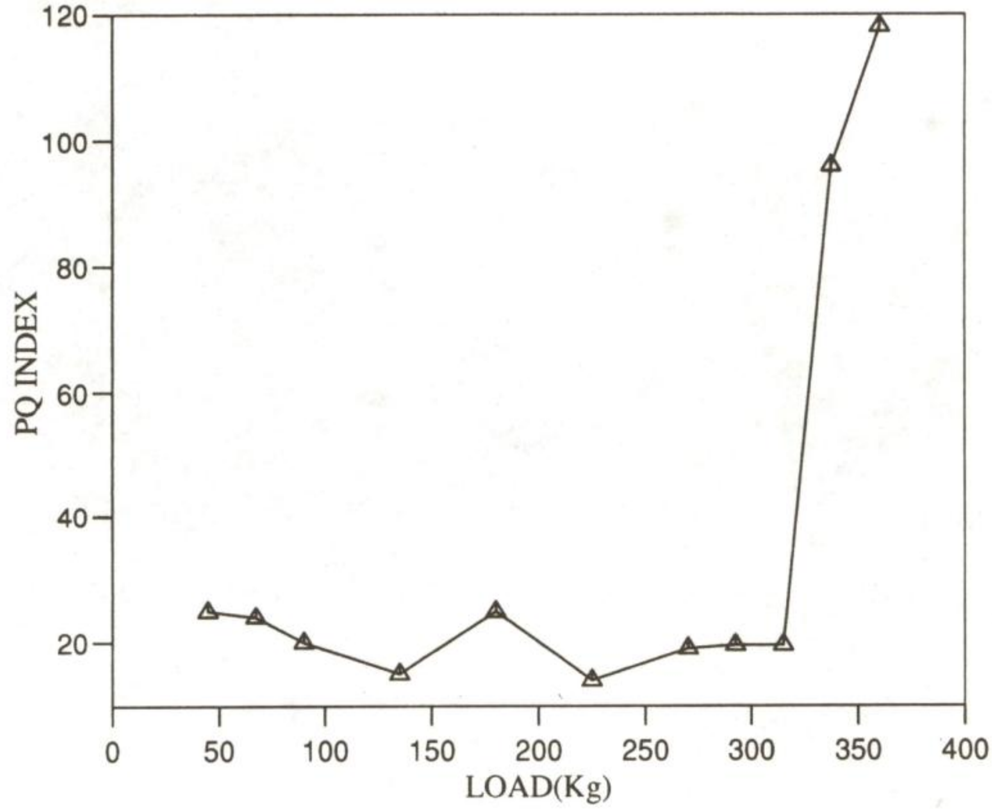


FIGURE 10 DR VS LOAD

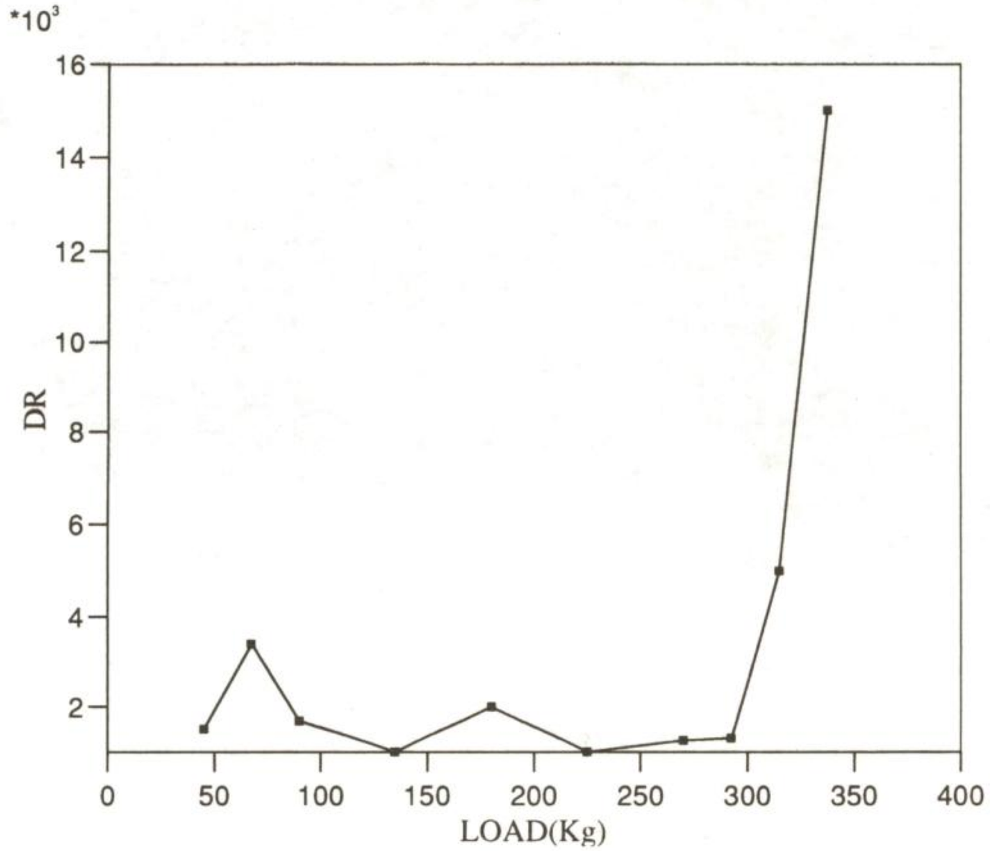


FIGURE 11(a) PARTICLES FROM BEFORE TRANSITION PERIOD

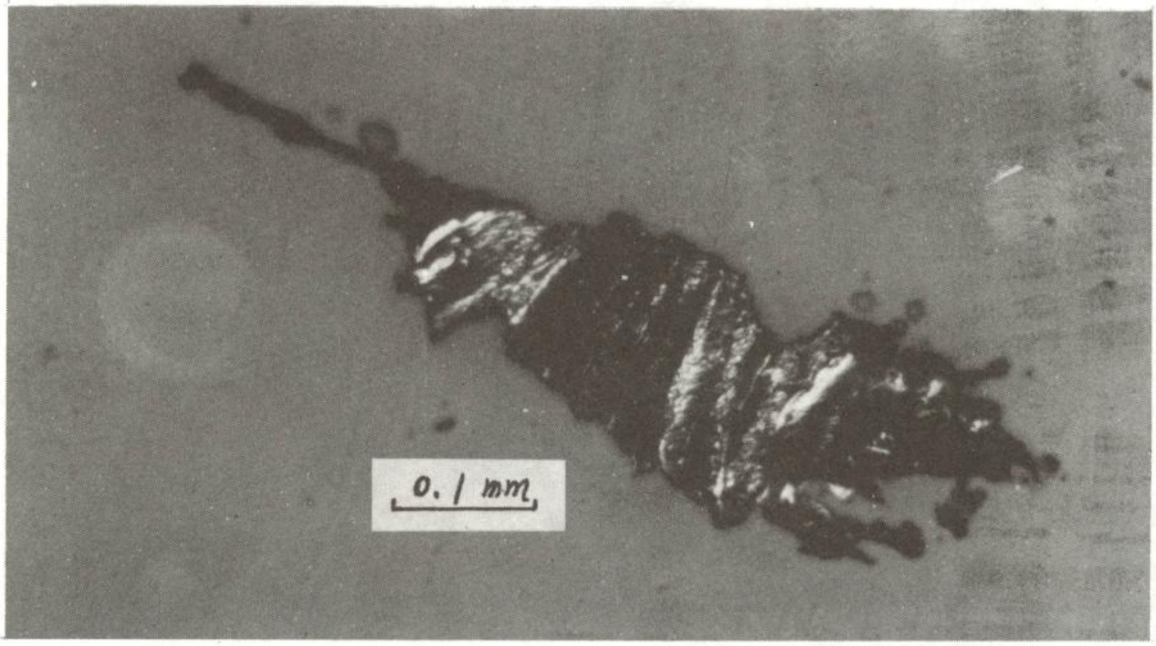


FIGURE 11(b) PARTICLES FROM AFTER TRANSITION PERIOD

FIGURE 11 PARTICLES - 4 BALL SCUFFING TESTS(BEFORE AND AFTER TRANSITION PERIOD)

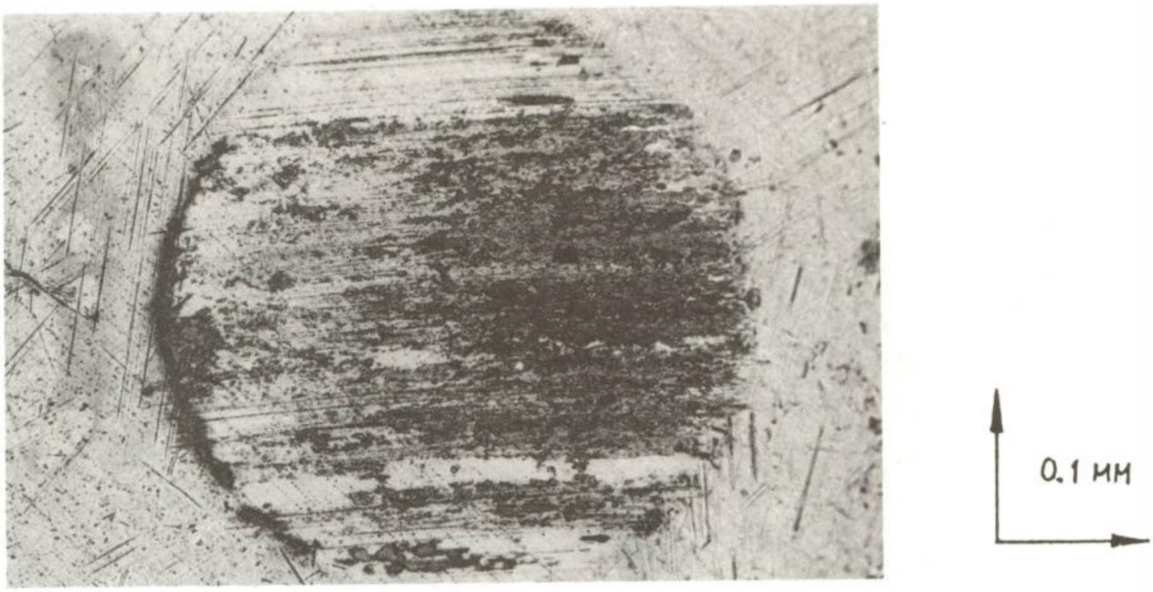


FIGURE 12(a) WORN SURFACE FROM BEFORE TRANSITION PERIOD

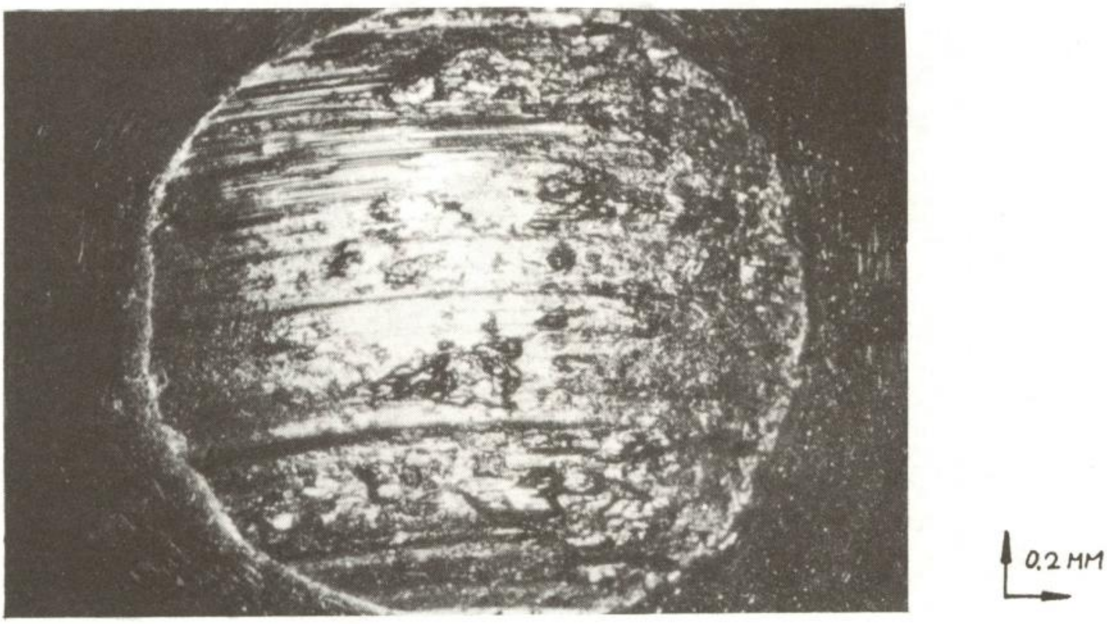


FIGURE 12(b) WORN SURFACE FROM AFTER TRANSITION PERIOD

FIGURE 12 WORN SURFACES - 4 BALL SCUFFING TESTS(BEFORE AND AFTER TRANSITION PERIOD)

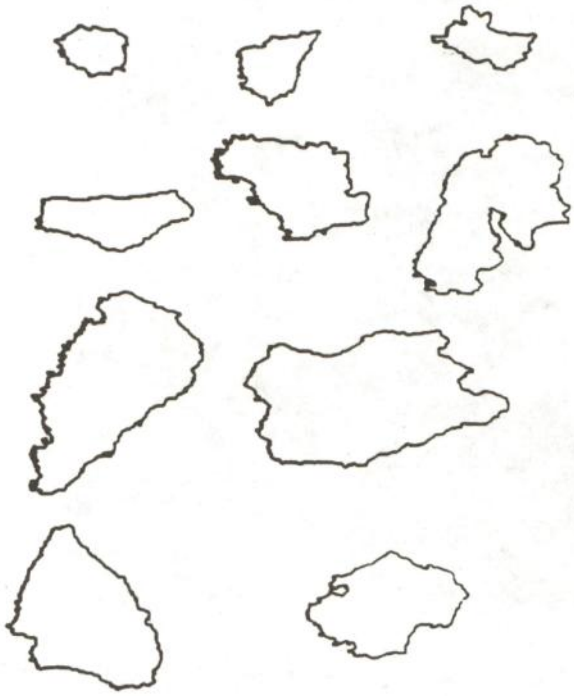


FIGURE 13(a) PARTICLES FROM BEFORE PITTING PERIOD

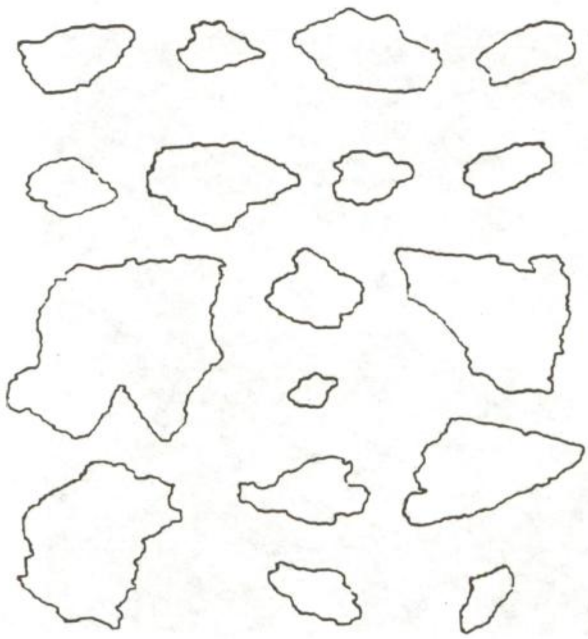


FIGURE 13(b) PARTICLES FROM AFTER PITTING PERIOD

FIGURE 13 PARTICLE IMAGES - 4 BALL PITTING TESTS(BEFORE AND AFTER PITTING PERIOD)