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# The influence of environmental fluids and temperature on the cut-surface morphology of single-crystal silicon

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Single-crystal (Cz) silicon wafers [(1 0 0) p-type] were cut in air, deionized (DI) water and ethanol, at room temperature, 150 and 200° C by a diamond impregnated dicing wheel using a specially designed apparatus. The effects of environmental fluids and temperature on the cut surface morphology were examined by scanning electron microscopy (SEM). The SEM investigation showed that gouging and ploughing is predominant when silicon is cut in DI water or ethanol. Debris size analysis showed that the mean diameter of the volume distribution (*MV*) of debris formed in ethanol at room temperature was 9.5 $\mu$m while that formed in air was 1.3 $\mu$m. The surface morphology is significantly different at 150 and 200° C as compared to room temperature, i.e. the width of individual wear tracks varied from 0.8 $\mu$m for room temperature to 1.6 $\mu$m for 200° C.

## 1. Introduction

Abrasive cutting is used extensively in the machining of glasses, ceramics and semiconductors [1, 2]. Abrasive cutting is generally understood to result in damage due to contact of the surfaces. The geometry and chemistry of the sliding bodies, load, speed, temperature and environmental fluids influence the damage formed in abrasive cutting [3, 4].

Abrasive cutting is currently being used in the semiconductor and solar photovoltaic industry. In the semiconductor industry, single-crystal silicon boules are cut into wafers by abrasive cutting with diamond- or silicon carbide-impregnated wires or circular blades [5]. To increase the cutting efficiency and minimize the damage in the cut surface it is desirable to understand how the environmental fluids and temperature affect the cut surface morphology.

In this paper we summarize the results of the high-speed cutting of single-crystal silicon in air, DI water and ethanol at room temperature, 150 and 200° C using a specially designed experimental apparatus in which the cutting variables, such as feed rate, depth of cut, fluids, temperature, cutting speed and load can be controlled.

## 2. Experimental procedure

Single-crystal (Cz) (1 0 0)p-type silicon samples cut from wafers 101.6 mm in diameter were used in this study. The surfaces of the sample which were rectangular with dimensions 0.5 × 15 mm × 50 mm were polished to semiconductor industry standards, dipped in HF and rinsed in DI water prior to mounting in a fixture for cutting. A schematic diagram of a specially designed experimental apparatus for the high-speed cutting is shown in Fig. 1. The apparatus consists of a diamond impregnated dicing wheel mounted on the shaft of a d.c. motor. The motor speed is controlled by a microprocessor and the speed is monitored by a magnetic pick-up and digital readout. The silicon is mounted on a heatable stage. The stage may be positioned by microprocessor-controlled stepper motors so that the feed rate and depth of cut may be prescribed. The sample stage is also recessed so that the silicon may be immersed in fluids during the cutting. The stage is mounted on a load cell the output of which is read on a bridge amplifier and meter (BAM).

The silicon was abraded by an industrial diamond impregnated dicing wheel (Series 401, Micro Automation, Fremont, California) in air, DI water and ethanol at room temperature at the following abrading conditions: the wheel speed was 1000 r.p.m., the feed rate was 0.3 mm sec$^{-1}$, and the depth of cut was 0.127 mm. The blade length and thickness of the wheel were 0.51 to 0.64 and 0.020 to 0.025 mm, respectively.

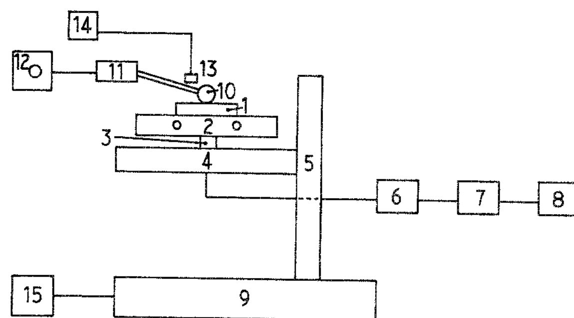


*Figure 1* Schematic diagram of the experimental apparatus. 1 – specimen, 2 – heatable specimen stage, 3 – load cell, 4 – translation mechanism, 5 – elevation mechanism, 6 – transducer, 7 – BAM, 8 – *x–y* recorder, 9 – table, 10 – cutting wheel, 11 – d.c. motor, 12 – speed controller, 13 – magnetic pick-up, 14 – digital readout and 15 – microprocessor controller.

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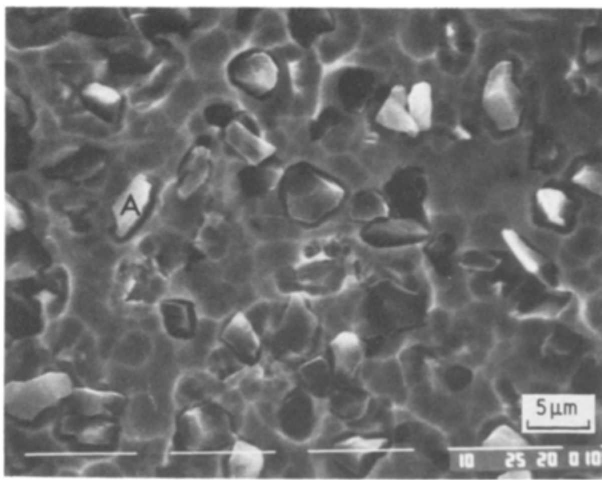



*Figure 2* SEM micrograph of the cutting wheel blade showing the embedded diamond grits (A: diamond grits).

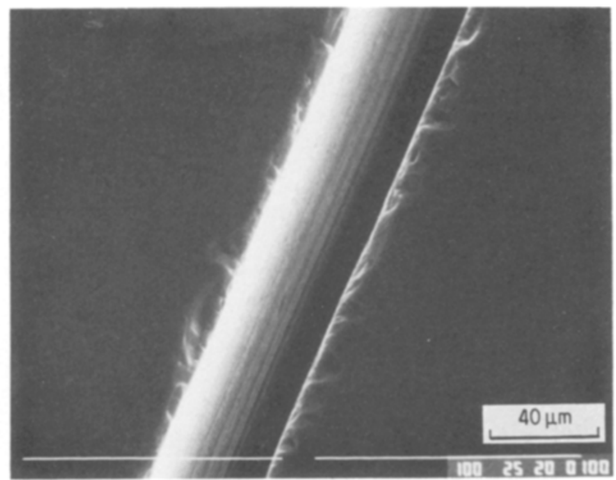



*Figure 3* SEM micrograph of a single groove formed in air at room temperature.

The o.d. surface of the wheel was examined by the SEM. Fig. 2 shows an example of a typical area of the blade surface. The average diamond diameter is 5 $\mu$m. The silicon samples were abraded at three different temperatures: room temperature, 100 and 200° C without any fluids in contact with the silicon. The temperature of the silicon was measured by a alumel–chromel thermocouple that was impressed on the silicon surface. Fig. 3 shows SEM micrograph of a single groove which was produced at the previously described conditions. The width of the groove is determined by the blade thickness. The cut surfaces were examined and the width of individual wear tracks were measured by SEM. The analysis of the debris size distribution was accomplished by a Microtrac particle size analyser (Leeds and Northrup Instruments, Chicago, Illinois). It utilizes the theory of low-angle, forward scattering light from a laser beam projected through a stream of particles. The amount and direction of light scattered by the particles is measured by an optical filter. These measurements are analysed by a microcomputer, which determines the particle size distribution.

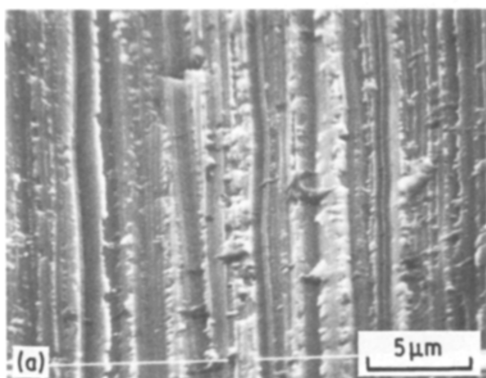
## 3. Results

### 3.1. Room temperature cutting

SEM micrographs of a cut surface abraded in air at room temperature are shown in Fig. 4. The grooves appear to be composed of individual scratches, each most likely a result of a single diamond traversing the surface and, each scratch possesses evidence of plastic flow (ploughing) indicated by the raised ridges found at the edges of the grooves [6]. The SEM micrographs shown in Figs 5 and 6 are of the cut surfaces formed in DI water and ethanol using the same cutting parameters to obtain the surface shown in Fig. 4. These surfaces appear smoother with large pits as compared to the surfaces cut in air.

The load on the silicon was monitored by the load cell. The load is related to the plunge rate (feed rate) and depth of cut. Fig. 7 shows the variations of load as a function of the depth of cut at room temperature and, as can be seen in this figure there is considerable variation of the load as the blade traverses the sample. This fluctuation is due to the change in silicon deformation mode. The load was 0.083, 0.167 and 0.333 N when the depth of cut was 0.127, 0.254 and 0.381 mm, respectively. Load is very important in the deformation mode. At high loads damage is by cracking and at low loads damage is by plasticity [7, 8].

Surface morphology is related to debris size and distribution. The debris generated by cutting in air, DI water and ethanol at room temperature was analysed and the results are shown in Fig. 8. As can be seen from Fig. 8, the mean diameter of the volume distribution ($MV$) of debris formed in ethanol at room temperature was 9.5 $\mu$m while that formed in air was 1.3 $\mu$m.



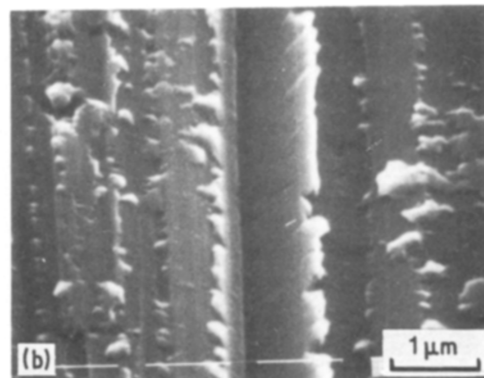




*Figure 4* SEM micrographs of the cut surface of silicon abraded in air at room temperature.

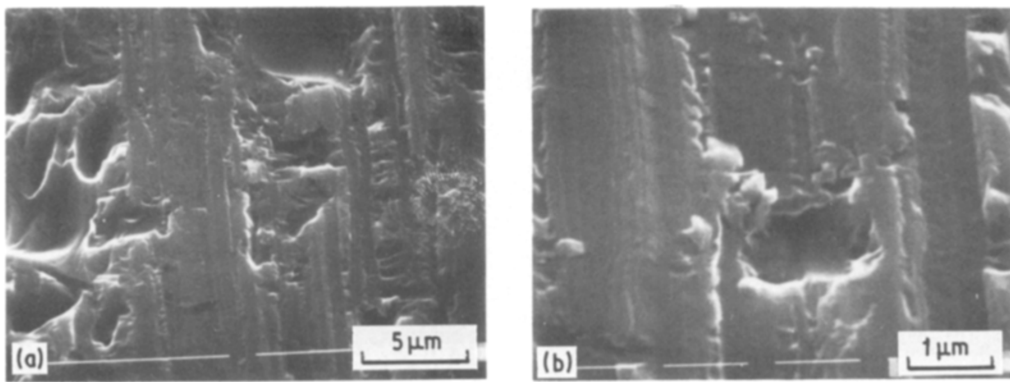



*Figure 5* As Fig. 4, but in DI water.

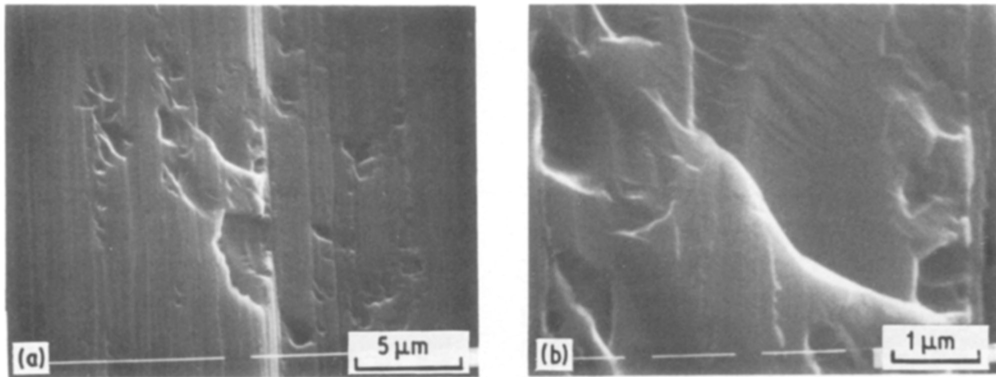



*Figure 6* As Fig. 4, but in ethanol.

## 3.2. Elevated temperature cutting

The surface morphology of the silicon abraded at 150 and 200° C is shown in Figs 9 and 10, respectively. As can be seen, the surface morphology changes from the type seen at room temperature. The width of the individual wear tracks varies from 0.8 $\mu$m for room temperature to 1.6 $\mu$m for 200° C. Each wear track displays evidence of ploughing with the scooped-out material being plastically deformed and cracked. The level of plasticity on the surfaces and the increase in the width of the wear track with such a small change in temperature is surprising since plasticity is not expected in silicon below 600° C [9]. The debris size distribution of silicon cut at 100° C is shown in Fig. 11. At 100° C the size was smaller than that at room temperature. The load was measured at 150° C as shown in Fig. 12. As can be seen in Fig. 12, as temperature increases, the peak load increases, which means that the deformation mode is changed at high temperatures. The load measured at room temperature and 150° C was 0.118 and 0.176 N, respectively.

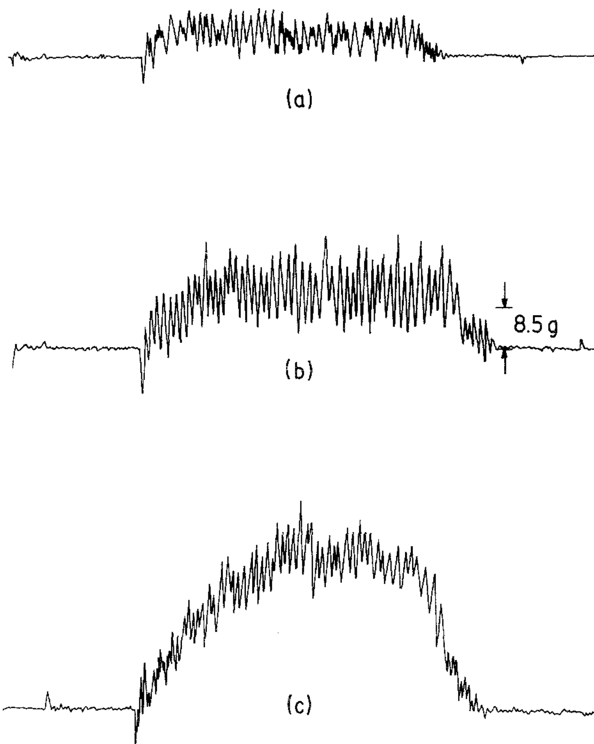



*Figure 7* Variations of load as a function of the depth of cut at room temperature (a) 0.127 mm, (b) 0.254 mm, (c) 0.381 mm.

## 4. Discussion

There is considerable controversy about the deformation mode of silicon at low temperatures. Several workers have shown that low temperature deformation such as abrading, grinding and indentation has resulted in dislocations [6, 10]. Stickler and Booker [10] performed fine abrasions on a rotating cloth pad using 6 $\mu$m diamond particles in a slurry with kerosene as a lubricant at abrasion pressure of 1.96 N cm$^{-2}$. Their transmission electron microscopy (TEM) work showed that the damage consisted of single dislocations and chipped and cracked material. They suggested that dislocations generated near the surface have different mobilities than those in the bulk and this causes an extra degree of freedom compared with dislocations formed in the bulk materials, and hence can form more readily. Puttick and Shahid [8] have reported that, when silicon was indented at room

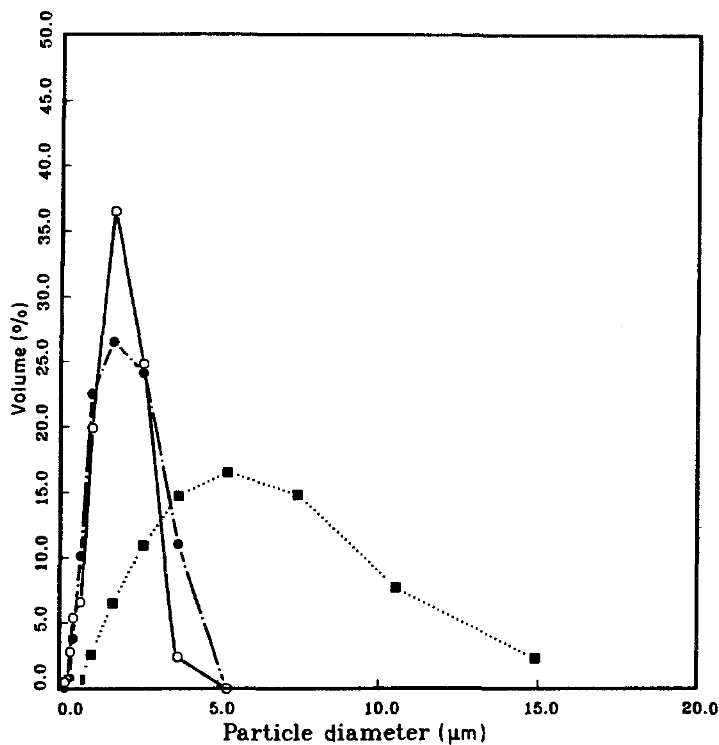


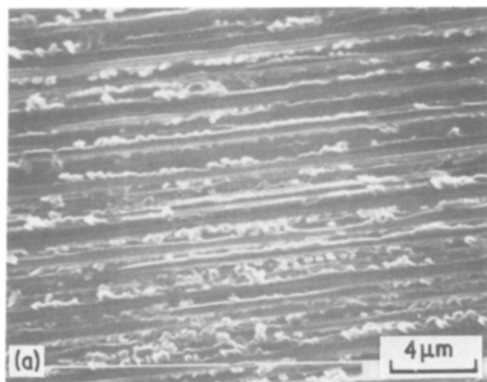

*Figure 8* Debris size distribution in different fluids at room temperature. (○) air; (●) DI water; (■) ethanol.

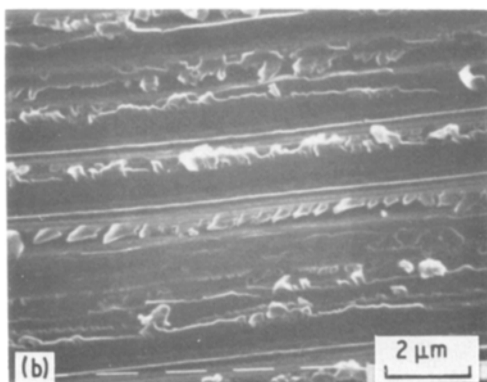
temperature under very low loads between 0.003 and 0.03 N, dislocation loops were formed. Lee *et al.* [11] have shown that indentation damage mode changes with load and Lee and Danyluk [12] have observed that loads below 0.98 N produce plasticity at the expense of median cracks. On the other hand, bending experiments have shown that silicon crystals deformed plastically with a sharp yield-point above about 600° C [9] and tensile tests also showed that silicon single-crystals deformed plastically at temperatures above 900° C [13]. It is perhaps surprising that silicon deformed plastically when it is cut up to 200° C because dislocations are not usually considered to be mobile in silicon below 600° C [9]. A possible explanation for this is as follows. Our load measurement shows the load is below 0.49 N which is in the low load range. The contact temperature in our elevated speed experiments is not yet known, however, an isothermal temperature increase of 200° C used in these experiments and contact temperature can induce plasticity as can be seen in Fig. 10. Also there has been some suggestion that space charge fields are related to the deformation mode. If stress fields are smaller than the extent of the space charge field, then plasticity will dominate while cracking will dominate if the stress field extends beyond the space charge field. If this is the case, as temperature and extent of space charge field increase, plasticity is expected to increase.

## 5. Conclusions

The results of this study can be summarized as follows:

1. Environmental fluids in contact with (1 0 0)p-type single-crystal silicon affect the deformation



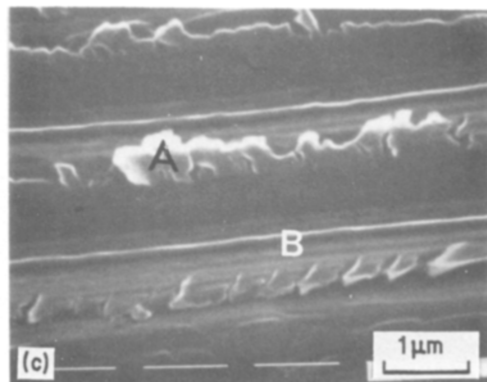
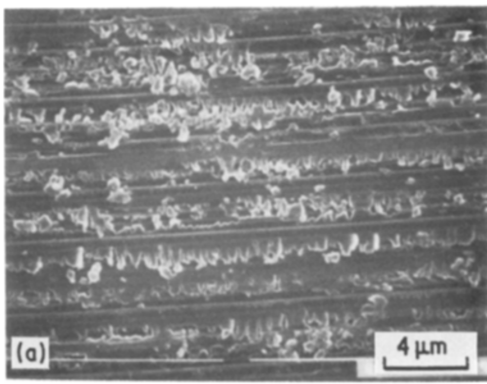
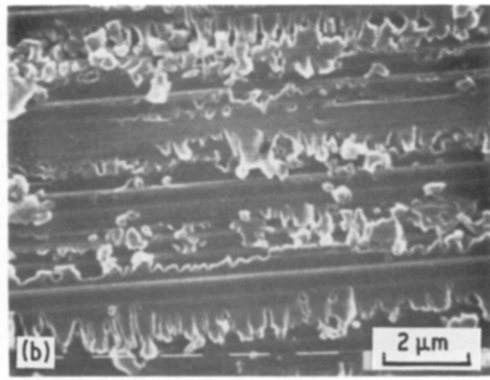




*Figure 9* Scanning electron micrographs of silicon cut at 150° C (A: ploughed ridge; B: groove track due to a single diamond).



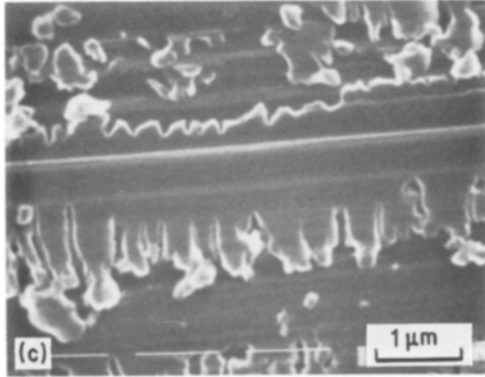




*Figure 10* Scanning electron micrographs of silicon cut at 200° C.

mode. Gouging and ploughing is predominant when cutting is done in DI water and ethanol as compared with cutting in air.

2. The mean diameter of the volume distribution (*MV*) of the debris is 1.3 $\mu$m in air and 9.5 $\mu$m in ethanol.

3. As the temperature increases silicon deforms more plastically. The width of the wear tracks was 0.8 $\mu$m for samples cut at room temperature and 1.6 $\mu$m for samples cut at 200° C.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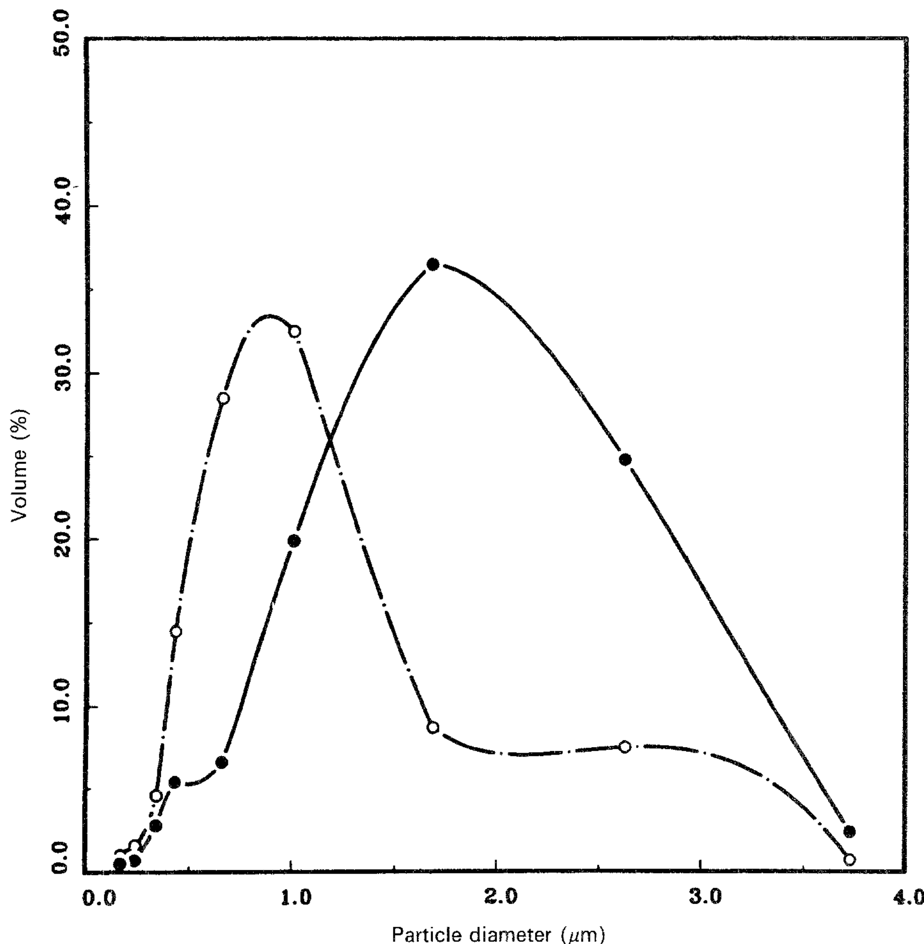


*Figure 11* Debris size distribution at room temperature and 100° C.

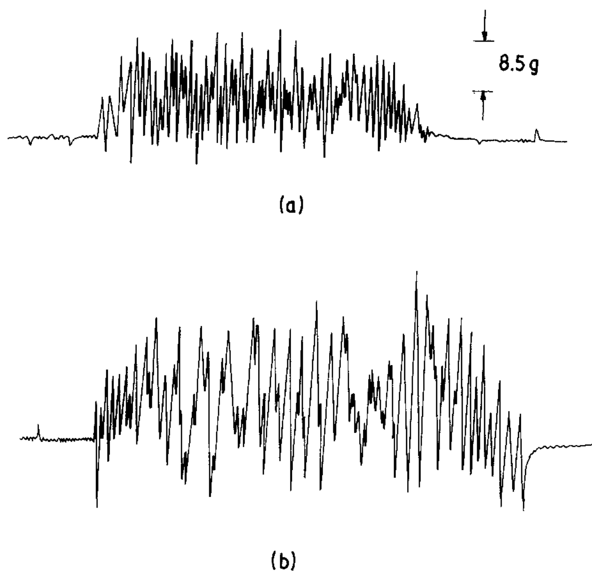


*Figure 12* Result of load measurement at room temperature (a) and 150° C (b).

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