The effects of lapping load in finishing advanced ceramic balls on a novel eccentric lapping machine

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Abstract: HIPed (Hot Isostatically Pressed) silicon nitride ball blanks were lapped from diameter 13.255 mm to diameter 12.7 mm by a novel eccentric lapping machine. A maximum material removal rate of 68 μm/hour has been achieved under a nominal lapping load of 43 N/ball. It was found that the material removal rate was increasing almost linearly with the lapping load within this load range. When the lapping load was higher than 43 N/ball, the material removal rate started to drop and the lapped ball roundness error started to increase. At the highest nominal lapping load of 107 N/ball, surface and subsurface damages were found on the lapped balls. Because of eccentric loading effect, the actual load on individual ball could be 25~28% higher than the nominal lapping load. The surface residual stresses of lapped balls under different lapping loads were measured, and it was found that the lapping load had less effect than previous HIP process. Rolling contact fatigue tests were conducted on balls lapped at nominal loads of 43N/ball and 107 N/ball. No failure occurred on the ball lapped at 43 N/ball after 138 million stress cycles. Ball lapped at 107 N/ball was failed after 13.3 million stress cycles with a shallow spall with flat bottom inside. This research suggests that the lapping load for advanced ceramic balls in conventional concentric lapping could be doubled from 20N/ball to 40 N/ball without degrading the surface quality of lapped balls.

Keywords: Finishing, Surfaces, Fatigue, Si_3N_4

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1. Introduction

Advanced ceramic balls (mostly made of HIPed (Hot Isostatically Pressed) silicon nitride) are now used extensively as rolling elements in hybrid precision ball bearings (with steel inner and outer rings). They have shown advantages because of thermal resistance, corrosion resistance, low density, high elastic modulus and low friction nature of advanced ceramic materials [1]. The only restriction that prevents their widespread application is the high manufacturing cost of ceramic balls. It is estimated that the surface finishing of advanced ceramic balls for high contact stress application constitutes about half of the total cost of manufacturing. Therefore finishing advanced ceramic balls with high precision bearing quality at efficiency and low cost is crucial.

In industry, ceramic balls are finished by concentric lapping and polishing with two plates placed face to face having matching concentric circular grooves on them, through several operations by gradually changing the load, plates and diamond grits sizes in the slurry. Ceramic ball surface skin produced in previous manufacturing stages which is compositionally and microstructurally different from the core of the ball has to be removed during the finishing stage. For a 12.7 mm ball, 500-800 μm stock in diameter has to be removed from ball surface. It takes weeks to finish a batch of ceramic balls.

Some research has been conducted on the finishing methods of ceramic balls, for example, Magnetic Fluid Grinding (MFG), also called Magnetic Float Grinding (Polishing), was first developed by Tani and Kawata [2] and improved significantly using a float by Kato and Umehara [3]. Three main groups involved in Magnetic Fluid Grinding of ceramic balls are Kato [4], Childs [5] and Komanduri [6]. Storlaski etc. [7] using a four-ball rolling fatigue test machine as grinding machine by replacing upper ball with a stainless cone and lower with 9 silicon nitride 6.5 mm balls, studied the grinding wear mechanism of silicon nitride in diamond slurry at relatively high speed (3,000 rpm or so). If these laboratory-scale methods can be applied to production at large scale and at low cost, are still unknown. In industry, the two plate lapping method is still the common practice for finishing advanced ceramic balls. It is recognised that the fundamental mechanism of the loose abrasive process in the two plate lapping method has received less attention and there is still great potential for further development.

A novel eccentric lapping machine was designed and prototyped in-house by the authors [8] (Fig 1). The major difference between this eccentric lapping machine and conventional concentric lapping machine is that there is an offset between the rotating axis and the centre of circular V-groove on the lower plate, and the upper plate is flat and stationary. Because of this eccentricity, the kinematics and dynamics of eccentric lapping is much more complicated than conventional concentric lapping. This eccentric lapping machine is very promising in lapping advanced ceramic balls. Two kinds of HIPed (Hot Isostatically Pressed) silicon nitride ball blanks were lapped on this machine. A lapping rate of 68 μm/hour was achieved, which is 15 times higher than conventional concentric lapping (normally 3~4 μm/hour). The polished ball surface roughness value R_a is 0.003 μm which is above grade 3 precision bearing ball specification, and ball roundness is 0.08~0.09 μm which is above grade 5 and close to grade 3 precision bearing ball specification [8].

The finishing process of advanced ceramic rolling elements constitutes two steps: lapping and polishing. In the first step – lapping, maximum material removal rate is the goal while achieving fairly good ball roundness and maintaining no consequent ball surface and subsurface damage. The second step in the finishing process is polishing, in which the ball surface roughness, roundness, dimensional and geometric accuracy are achieved. This novel eccentric lapping machine has achieved very high material removal rate of 68 μm/hour in the first step of finishing, and this was achieved with a nominal lapping load of 43N/ball. This lapping load is much higher than the ordinary lapping load of less than 20 N/ball in concentric lapping by industry and reported research [9]. Because of the eccentricity, the actual load on a lapped ball at one instant could be much higher than the nominal load. If this higher lapping load will cause the degradation of surface quality, great alteration of surface residual stresses and thus to influence the rolling contact fatigue life of the lapped balls is one of the main concern of the current study. It was found by Taguchi Methods that the material removal rate is proportional to the lapping load [10]. What is the upper limit of lapping load is another concern.

There is very limited research on the material removal rate during finishing of advanced ceramic materials in relation to engineering reliability performance. For example, Woydt and Effner using a twin-disk wear tester, studied the influences of material removal on slip-rolling wear in paraffinic oil and water [11]. They found that the wear of spherical HIP-Si_3N_4 samples was proportional to the material removal rate, whereas for cylindrical HIP-Si_3N_4, spherical and cylindrical GPS-Si_3N_4-TiN, HIP-ZrO_2 samples, in the range of material removal rate between 0.01 mm^3/s and 0.02 mm^3/s, a strong low-wear/high-wear transition occurred. No reported literature on the material removal rate or lapping load in relation to the rolling contact performance of HIPed Si_3N_4 rolling elements was found. The current study will investigate the effects of lapping load on surface residual stresses and rolling contact fatigue life experimentally.

2. Experiment

2.1 Lapping Test

The lapping test was conducted on this novel eccentric lapping machine, full details about this machine can be found on a previous publication [8]. The ball blanks were procured from the manufacturer, and some of their characteristics are listed in Table 1. Table 2 shows the summary of lapping materials. In this investigation, 8 tests were carried out with nominal lapping loads of 18N/ball, 22N/ball, 25N/ball, 31N/ball, 43N/ball, 59N/ball, 78N/ball, and 107N/ball. All the other lapping parameters were maintained the same – lapping speed 169 rpm, diamond particle size 45µm, and diamond paste/lapping fluid concentration 1g:30ml.

Before and after each lapping test, balls and lapping plates were cleaned and the diameter of each ball was measured to 1.0 µm. The diamond paste and lapping fluid were mixed according to paste concentration parameter (1g diamond paste with 30ml lapping fluid) and stirred magnetically to disperse the diamond paste fully in the lapping fluid. 5ml of lapping fluid mixture were applied to the V-groove of the lower lapping plate before each test. Each lapping test lasted one hour.

2.2 Surface Residual Stress Measurement

The surface residual stresses on the balls lapped under different lapping loads were measured by the X-ray diffraction method. Its principle is based on that when a stress is applied to a material, the inter-atomic distance in the crystal will be extended or compressed within the elastic limit of the material in proportion to the stress. A detailed description of the X-ray diffraction method can be found in reference [12].

The residual stress measurements were carried out on a Rigaku Rint 2500 X-Ray Diffractometer. Each time, three sample balls were fitted into three holes of a ball holder with the areas intended to be measured on the top and centre of each hole of the ball holder, and the ball holder was vertically fastened to a jig (Fig. 2). The jig can be moved along X, Y, Z axes and rotated around Z axis. The small gap between the sample ball and the hole was sealed with tape around the edge of the hole, in order to eliminate any clamping force applied to the sample ball.

The parameter setting of the Rigaku Rint 2500 X-Ray Diffractormeter is listed in Table 3. In order to eliminate the influences of surface roughness and surface damage from the measured values of residual stresses, balls lapped under different loads were polished at 8.82 N/ball for 24 hours (diameters were reduced by 2 µm). The depth of the measurement was about 30 µm, and this was dependent on the X-ray source which penetrated the material. The area of the measurement was a circular area with a diameter of 1 mm which was determined by the diameter of the collimator. Each ball measurement took about 30 minutes.

2.3 Rolling Contact Fatigue (RCF) Test

The Rolling Contact Fatigue (RCF) tests were performed on a Plint TE92/HS Microprocessor Controlled Rotary Tribometer configured as a high-speed rolling 4-ball machine. More detailed description about this test machine can be found in an earlier publication [13]. All tests were conducted at a maximum contact stress of 6.58 GPa and at the test machine shaft speed 10,000 rpm in fully lubricated condition using Shell Talpa 20 as lubricant oil, with HIPed Si_3N_4 ball as upper ball and three standard steel bearing balls (specification: 0.5″ ball Reference RB12.7/310995A, material: AISI 52100 bearing steel) as lower balls. Normally, tests were stopped before reaching the set time (hours) due to the failure of one lower steel ball (typically a fatigue spall). In this situation three new steel balls and fresh lubricant oil were fitted and the test continued. By changing lower steel balls, the upper Si_3N_4 testing ball could exceed the set testing time or contact stress cycles.

3. Results and Discussion

3.1 Lapping Test Results

The lapping test results are plotted in Fig 3 (material removal rate versus lapping load). The material removal rate, as defined by the decrease of lapped balls in diameter per hour, at first increased as the lapping load reached the maximum of 68µm/hour at a load of 43 N/ball. The increasing of material removal rate was almost linear with the increase of lapping load. The straight line in Fig 3 represents a slope of 15 µm/hour per kgf/ball (9.8N/ball) lapping load, which is the result of level average response analysis on lapping load parameter by Taguchi Methods in a previous study [10]. The linear increase of material removal rate with lapping load suggests that the material removal mechanism is mainly mechanical. This viewpoint is supported by a detailed surface SEM (Scanning Electron Microscope) investigation together with the comparison of less effects from different lapping fluid mixtures in another study [14].

At higher lapping loads, however, the material removal rate decreased to 55 µm/hour at a load of 59 N/ball, 25 µm/hour at 78 N/ball and 20 µm/hour at 107 N/ball. At the two highest loads (i.e., 78 N/ball and 107N/ball), the lapped ball roundness error appeared much bigger, typically 3~4 µm, some individual balls even recorded 6 µm, in sharp contrast to the balls lapped at a load of 59 N/ball or less which showed a typical roundness error of only 1~2 µm. It was assumed that at these extreme high load conditions, the balls being lapped were not rolling freely, so the material removal rate decreased and the ball roundness error increased. This assumption is from the fact that under the two extreme high lapping loads (78 N/ball and 107N/ball), strange noises came from the lapping machine and the lapping plates were hot which suggests that severe sliding wear between the balls being lapped and the lapping plates occurred. The measured lower plate rotating speed by a tachometer was 150 rpm at the load of 78N/ball and 137 rpm at the load of 107N/ball although the speed setting up was 169 rpm. At the highest lapping load of 107N/ball, the lapping machine even had difficulty to start rotating, and after one hour lapping, severe wear were found on the lapping plates.

The lapping test results suggest that the upper limit of lapping load is 43 N/ball. Although at the load of 59 N/ball, the lapped ball roundness error was acceptable, the material removal rate has dropped to 55 µm/hour, a 19% decrease from 68 µm/hour at lapping load of 43 N/ball.

3.2 Eccentric Loading Effect on the Actual Lapping Load on Individual Balls

Up to now, all the calculated lapping load are nominal, which is simply the overall lapping load divided by the number of balls being lapped. The precise solution for the load on each of the balls is achievable by considering the upper plate as a simply supported circular plate without a hole and carrying only one eccentric load [15], but this is very tedious and beyond the scope of the current study.

A rough estimation has been made to assess the eccentric loading effect. All of the lapping tests were conducted using a lapping plate with 8 mm eccentricity and a circular V-groove of 65 mm diameter. Assume in this case only three balls bearing the entire lapping load from the upper plate, evenly distributed at 0°, 120° and 240° to the centre of the circular V-groove, with the centre of the upper plate at 0° to 180° axis and 8 mm closer to Ball 1 at 0° (Fig 4). In this case, Ball 2 at 120° and Ball 3 at 240° each carry 0.286 of the entire lapping load, Ball 1 at 0° carries 0.427 of the entire lapping load. The maximum lapping load on a ball (0.427) is 28% higher than the nominal load on a ball (0.333), which is simply the entire lapping load divided by the number of balls bearing lapping load. If only two balls bear the entire lapping load, at 0° and 180°, one would be 0.623 and the other 0.377. The maximum lapping load on a ball (0.623) is 25% higher than the nominal load in this case. From these two rough estimations, it is concluded that the maximum lapping load on a ball could be 25% ~ 28% higher than the nominal load because of the eccentric loading effect.

In the lapping process (first step of finishing), diamond particles (in the size of 6μ ~ 60μ) are instantly brought into and left from between the balls and the lapping plates. In any instance, there may be only a few balls (certainly less than 15) which bear the entire lapping load. Consider an extreme condition where only three balls bear the entire lapping load. In this extreme condition, Ball 1 in Fig 4 carries 0.427 of the entire lapping load. The nominal lapping load which is simply the entire lapping load divided by 15 balls, is only 0.0667 of the entire lapping load. So under an extreme condition the maximum lapping load on a ball could be 6.4 times higher than the nominal load.

3.3 The Effects of High Lapping Load on Ball Surface and Sub-Surface Damage

The surface and sub-surface damage effects on balls lapped at the highest load of 107 N/ball were clearly revealed after polishing and fluorescent dye penetrant treatment. Fig 5 shows typical examples of surface damage observed by optical microscope. Fig 5 (a) and (b) are the same surface area under white light (a) and under ultra-violet (UV) light (b) respectively. The white fluorescent regions shown in Fig 5 (b) indicate sub-surface cracks adjacent to surface damages. This type of damage could be due to the macro-fracture caused by the excessive lapping load. A point or 'star' type feature is shown in Fig 5 (c) under white light and (d) under UV light. This type of defect is considered to be due to a point overload caused by the over-rolling of a large unbroken diamond particle. Radial cracks are formed similar to those that occur during hardness testing with a diamond indenter. Further lapping removes the dent but the cracks and sub-surface damage are revealed with UV light. No significant surface or sub-surface damage was found on balls lapped at loads 43 N/ball or less. Fig 6 (a) and (b) show the typical surface appearance of balls lapped at 43 N/ball load under white light (a) and UV light (b).

3.4 Finishing Process Induced Residual Stresses

Table 4 is the residual stress measurement results on balls lapped under different loads. The original surface residual stress from the ball blanks as procured was compressive, it was measured –149.1 MPa before polishing with a diameter of 13.255, and –117.7 MPa after polishing with a diameter of 13.253. This compressive residual stresses on the ball blank surfaces may be due to previous HIPed processes. It seems that this compressive residual stresses is concentrated near the surface layer of the ball blank and will be partly or entirely removed during the finishing process. The surface residual stress was measured –11.95MPa on a diameter of 12.703 ball lapped at a load of 13 N/ball, after a layer of 0.55 mm in diameter has been removed, assuming this light lapping load did not incur additional residual stress change. A previous investigation by Stolarski and Tobe [16] on 6.5 mm nominal diameter balls also reported that the residual compressive stress decreases as the amount of material removed grows.

The second observation is that the higher lapping load will generate higher compressive residual stresses on the balls. The residual stresses were measured on ball blanks lapped under different loads to nearly the final diameter of 12.7 mm. In order to eliminate the influences of surface profile and damage from the measured values of residual stresses, balls lapped under different loads were polished at 9N/ball for 24 hours. The results showed that there was almost a linear increase of the compressive residual stress as the lapping load increased. Under a lapping load of 13 N/ball, the residual stress was –11.95 Mpa, and at the highest lapping load of 107 N/ball, the residual stress was –142.34 MPa. The residual stress change from the lowest lapping load to the highest lapping load was only about 130 MPa.

3.5 The Effects of Lapping Load on RCF (Rolling Contact Fatigue) Performance

In the finishing process of HIPed Si_3N_4 rolling elements, maximum material removal rate (finishing rate) is desirable. This must be achieved on the condition that satisfactory surface quality is maintained to ensure long RCF (Rolling Contact Fatigue) life.

Some surface and subsurface damage occurred under the highest lapping load of 107N/ball (see Section 3.3). However, the RCF test was arranged so that there was no visible surface or subsurface damage on the rolling track, either under white light or UV light microscopy observation. This ball failed after 9 hours 51 minutes (13.3 million stress cycles). Fig. 7 shows the failure after RCF testing under microscope observation ((a) bright field, (b) dark field). The failure was a spall with a diameter of 320 μm, and the depth was 65 μm measured by microscope focus method. Compared with other fatigue spalls initiated from natural defects [17], this spall was shallow and very flat at the bottom (Fig 7 (b)).

There is a possibility that under such high lapping load the surface damage zone reached about 65 µm and the spall was initiated from the interface of this damage zone and bulk material. To validate this, the ball needs to be sectioned and etcheded to obtain the grain morphology.

The RCF test conducted on a ball lapped at the highest finishing rate (68µm/hour) (at lapping load 43 N/ball) for 102.2 hours (138 million stress cycles), showed no failure occurring on the rolling track, only small pittings and further developed scratch marks as shown in Fig 8.

The suggestion from the RCF test results is that the highest finishing rate (68µm/hour) achieved under a lapping load of 43 N/ball will not affect the RCF life; and the highest lapping load — 107 N/ball, will probably cause RCF failure. The highest lapping load is not acceptable, as it had already caused surface and subsurface damage and the finishing rate was not high either.

4. Conclusions

The effects of lapping load in finishing advanced ceramic balls on a novel eccentric lapping machine were systematically investigated by aggressive lapping test, fluorescent UV light microscopy detection, residual stress measurement, and rolling contact fatigue test. Experimental results reveal:

1. The material removal rate was almost linearly increasing with the increase of lapping load, up to a nominal lapping load 43 N/ball. The increasing slope was 15 µm/hour per kgf/ball(9.8N/ball) lapping load.
2. Under the nominal lapping load 43 N/ball, no subsequent surface and sub-surface damage on the lapped balls were found. When the nominal lapping load was higher than 43 N/ball, the material removal rate started to decrease. Under the two extremely high lapping load (78N/ball and 107N/ball), substantial surface and sub-surface damage on the lapped balls, and severe wear on the lapping plates were found. The material removal rate dropped and ball roundness error increased tremendously.
3. Although the residual compressive stress was proportional to the lapping load, lapping load induced residual stress change was relatively small. From the lowest lapping load of 13 N/ball to the highest lapping load of 107 N/ball, the residual stress change was only 130MPa.
4. Rolling contact fatigue life was greatly shortened for balls lapped under extremely high lapping load (107N/ball); Rolling contact fatigue life was not affected for balls lapped under 43N/ball.

5. It seems that a nominal lapping load 43 N/ball is the maximum applicable lapping load on this eccentric lapping machine. Taking the fact that eccentric loading was 25-28% higher than the nominal load into account, this research suggests that the lapping load in conventional concentric lapping could be doubled from 20N/ball to 40 N/ball without degrading the surface quality of lapped balls.

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List of Tables and Figures

Manufacturing Process	Directly HIPed, then rough-ground
Density (kg/m^3)	3160
Ball Diameter (mm)	13.255
Ball Roundness Variation (mm)	0.001
Surface Roughness R_a (μm)	0.202
Surface Hardness (Vikers Hardness Number, VH10)	1682
Fracture Toughness MPa m$^{1/2}$	5.3

Table 1 Some characteristics of HIPed silicon nitride ball blanks

Lapping plates	material: grey cast iron (grade 12) upper plate flat lower plate with eccentric V-groove V-groove angle 90° symmetric axis parallel to rotating axis diameter of circular V-groove 65 mm eccentricity (distance between centre of circular V-groove and rotating axis) 8 mm
Diamond Paste	Metadi II diamond paste Diamond particle sizes: 45μ
Lapping Fluid	Metadi fluid (water based) 40-6064UK

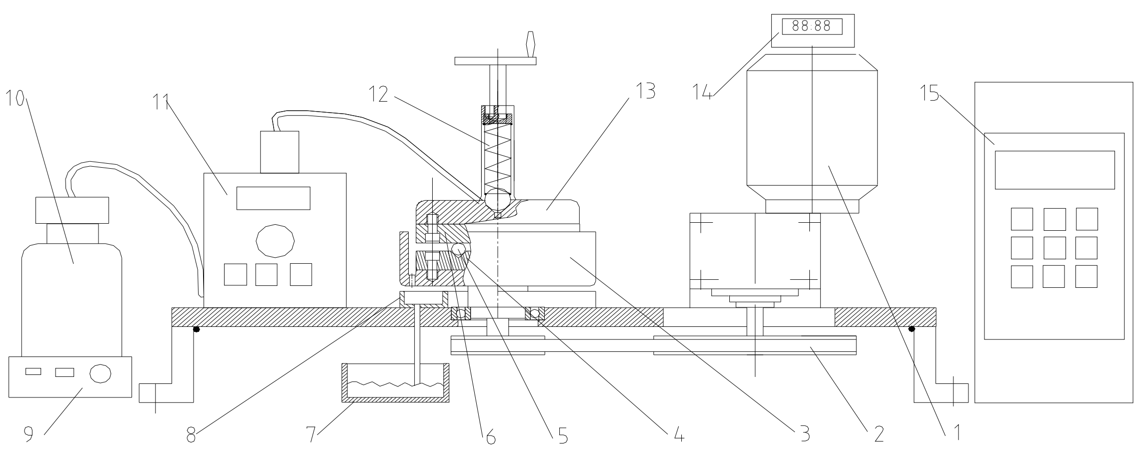
Table 2 Summary of lapping materials

X-ray source: Cr Kα1 at 40 kV and 250 mA
Collimator: 1.0 mm
Scan range: 123°~127°,
Sampling time: 100 sec.
Step angle: 0.002°
Young's modulus: 310000 Mpa
Poisson's ratio: 0.26

Table 3 Parameter setting for residual stress measurement

Description of the ball	Diameter	Residual stress value (MPa)
Ball blank as procured	13.255	-149.11(±)29.29
Ball blank polished from as procured	13.252	-117.721(±)40.69
Ball blank 106.63 N/ball lapped, then polished	12.698	-142.341(±)38.91
Ball blank 42.87 N/ball lapped, then polished	12.698	-92.1(±)50.71
Ball blank 30.97 N/ball lapped, then polished	12.704	-78.321(±)36.20
Ball blank 12.75 N/ball lapped, then polished	12.703	-11.954(±)34.21

Table 4 Residual stress measurement results on balls lapped at different loads



1 AC motor and gearbox combination   2 Pulleys and belt   3 Flange shaft
4 Lower plate 5 Ceramic ball   6 Upper plate   7 Lapping fluid collection tank
8 Lapping fluid tray   9 Magnetic stirrer 10 Lapping fluid container 11 Pump
12 Spring-loading Unit 13 Backing plate 14 Time counter   15 MicroMaster inverter

Fig. 1 Overview of the novel eccentric lapping machine system

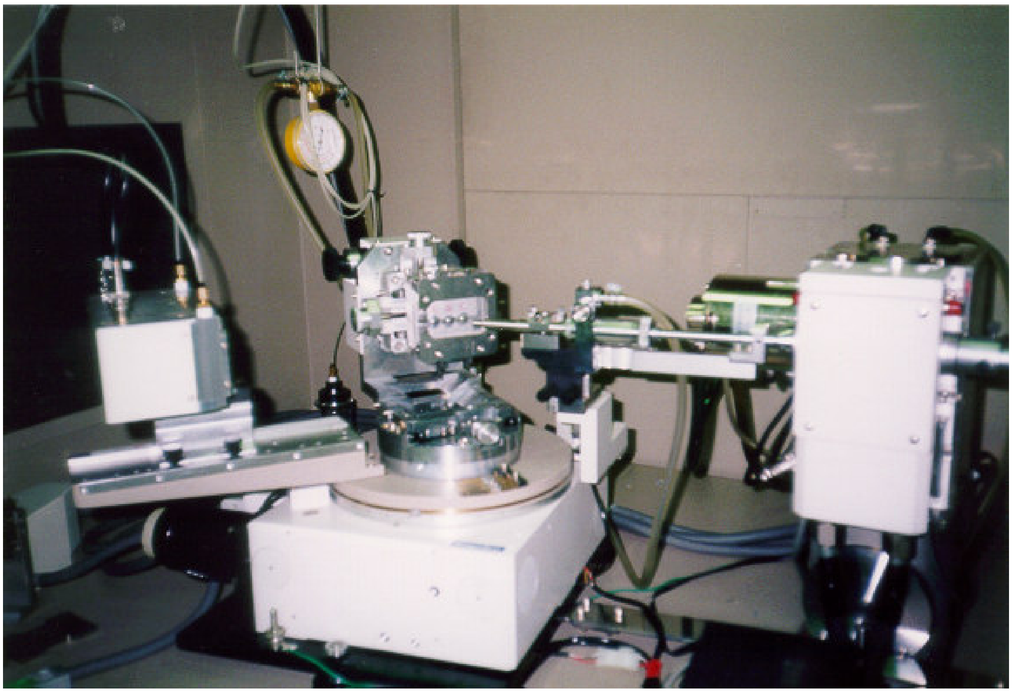


Fig.2 Residual stress measurement setting inside measuring chamber

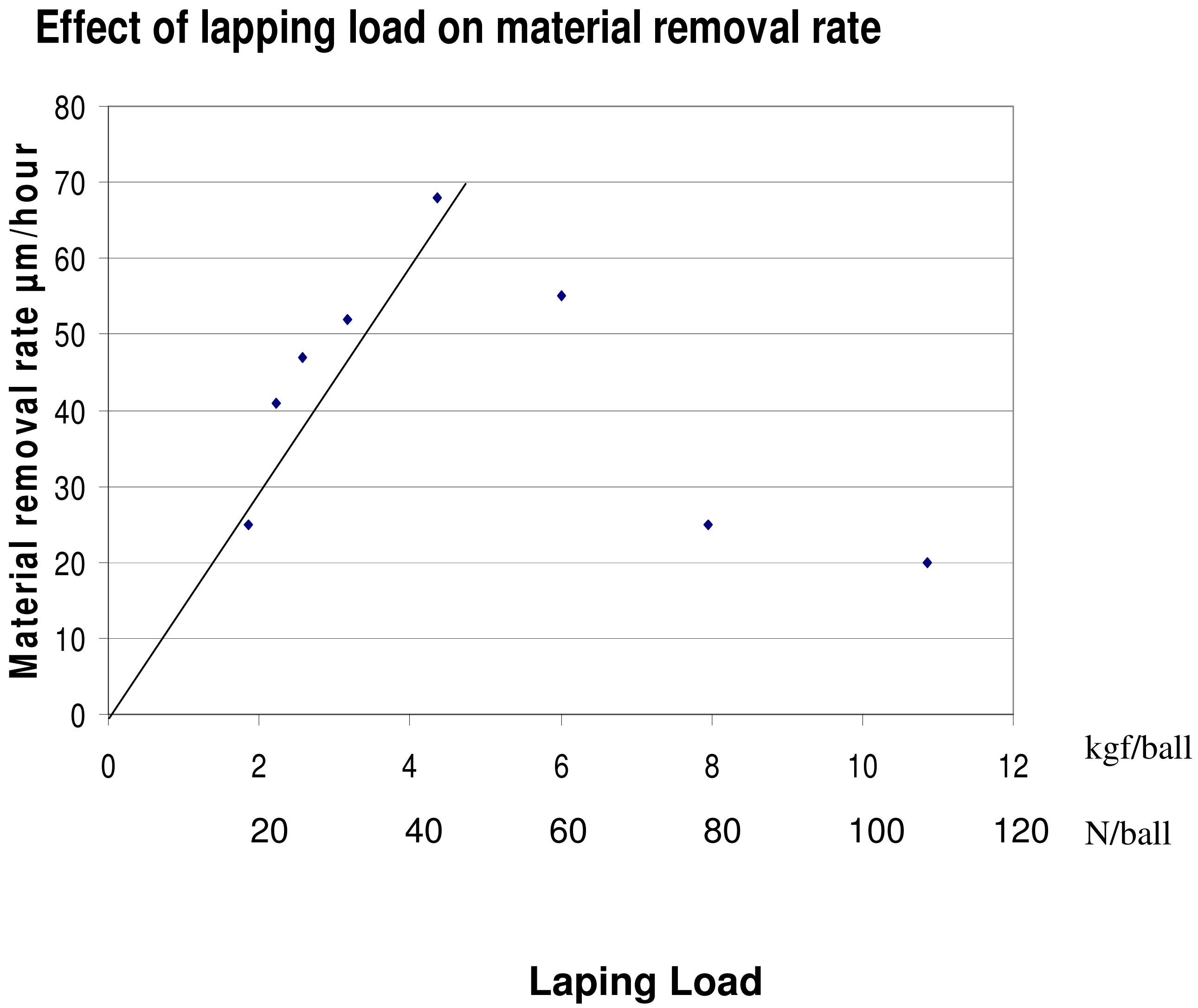


Fig 3 Material removal rate versus lapping load

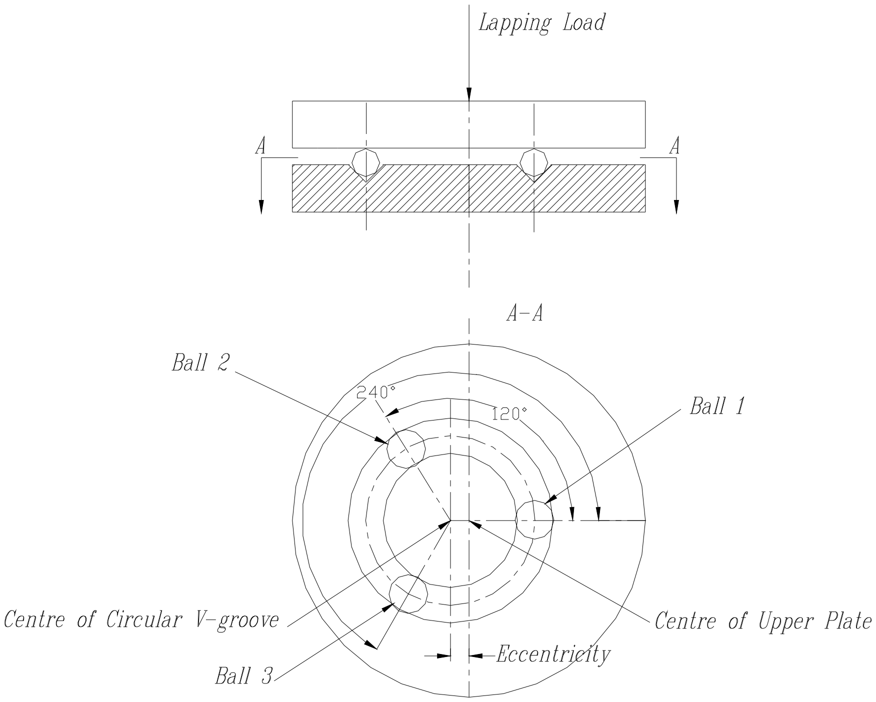
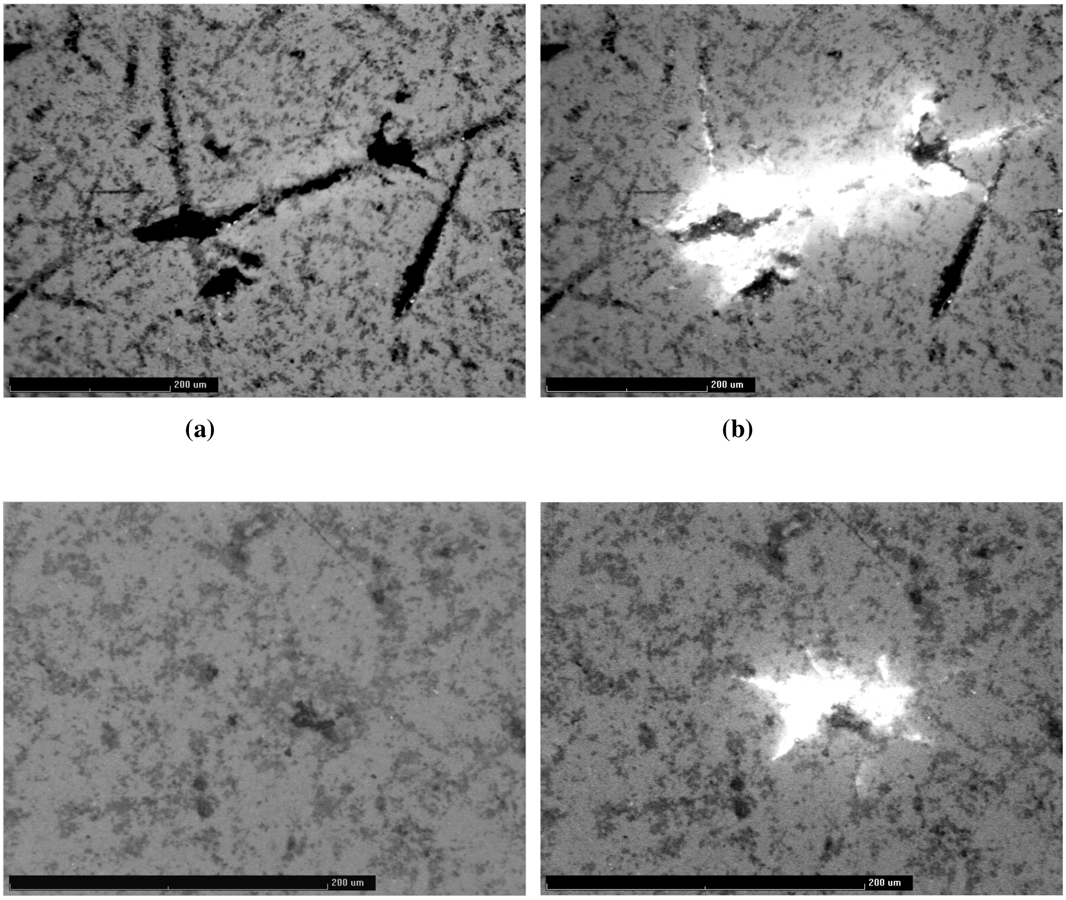


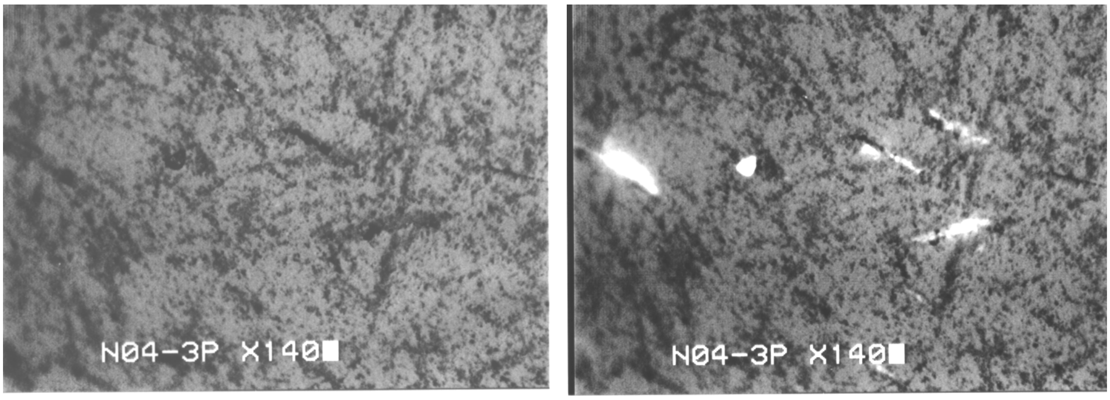
Fig 4 Rough estimation of eccentric loading effect



(a) (b)

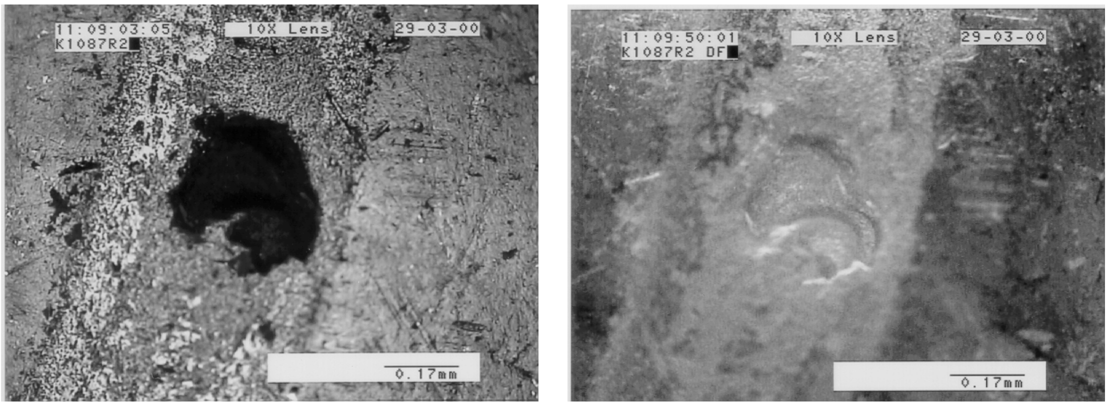
(c) (d)

Fig 5 Typical surface and sub-surface damage on balls lapped under a load of 107 N/ball



(a) **(b)**

Fig 6 Typical surface appearance of balls lapped under a load of 43 N/ball



(a) (b)

Fig 7 Ball lapped at 107 N/ball load failed after 13.3 million stress cycles RCF test

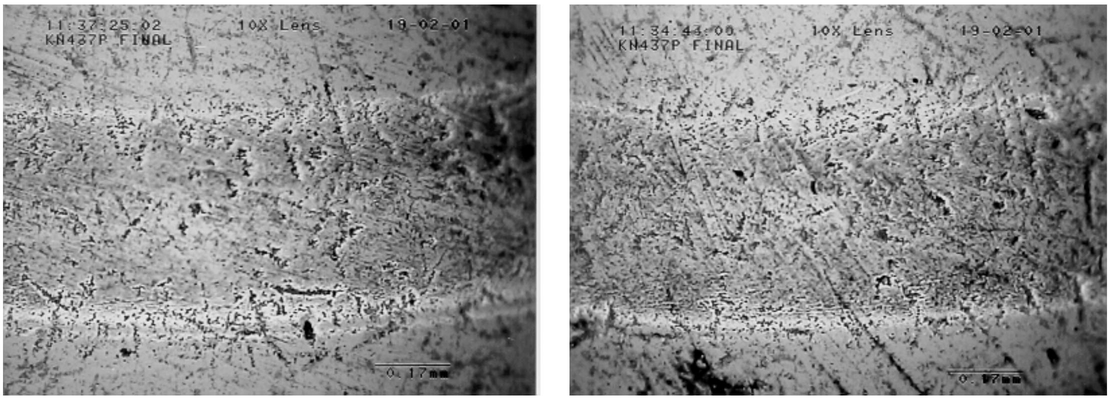


Fig 8 Ball lapped at 43 N/ball load after 138 million stress cycles RCF test