Wear, Volume 257, Issues 1-2, July 2004, Pages 157-166.

The Influence of Specimen Misalignment on Wear in Conforming Pin on Disk Tests

I. Garcia-Prieto, M. D. Faulkner, J. R. Alcock

School of Industrial and Manufacturing Science, Cranfield University, Cranfield, Bedfordshire MK43 0AL, United Kingdom

Submission Contact Details:

Dr Jeffrey R Alcock

j.r.alcock@cranfield.ac.uk

Building 61
School of Industrial and Manufacturing Science
Cranfield University
Cranfield
Beds
MK43 0AL
United Kingdom

Tel: 01234 754185
Fax: 01234 754273

Abstract

A pin-on-disk test apparatus was modified to decrease the degree of misalignment between the pin end and the disk counterface. This was achieved by separate alignment of both pin and disk. Disk alignment was allowed by incorporating a kinematic three-ball arrangement into the disk under-face. A self-aligning pin alignment system was introduced which did not require the perpendicularity of the pin to be measured. The unmodified system had an alignment within that permitted by the ASTM G99-95a standard. However, the modified, and improved, alignment system produced significant changes in recorded wear behaviour in comparison with the unmodified system. The standard deviation of the wear data was considerably reduced and the correlation of the wear data with applied load significantly improved. The modified alignment also reduced the absolute value of wear recorded. This effect was observed for both wear volume assessed from mass change and wear volume assessed from pin height change. The reduced constraint of a misaligned pin in comparison with that of a well-aligned pin may account for the difference in these results.

Key Words

pin-on-disk, reproducibility, alignment, wear volume

Introduction: the Test Standard

The pin-on-disk testing of materials is controlled by the ASTM G99-95a [reapproved 2000] [1]standard. In this standard the recommended wear test configuration is that of a spherical ball or radius-end pin. This is run against a flat disk. Whilst the standard does leave room for other pin shapes it does not specifically describe them.

A spherical ended pin has the advantage that contact conditions can be relatively well controlled. No matter the degree of misalignment between pin axis and disk axis the initial apparent area of contact should be the same, for a given load. However, the apparent area of contact will then change during the test up to the maximum given by the pin-diameter.

A flat-ended pin has some natural advantages: it is easier to machine and easier to coat if the wear testing of coatings is required. For this reason, flat-ended pins are used in perhaps the majority of pin-on-disk tests [2,3,4,5,6,7].

However, the main disadvantage for a flat-ended pin test is the lack of controllability of the apparent area of contact. This will be dominated by the misalignment of pin and disk. The initial apparent area of contact will not be known, nor can the change in apparent area of contact with wear of the pin be easily predicted, as it can for a spherical ended system.

The ASTM G99-95a standard recommends a maximum limit of ±1° of misalignment between the pin and disk axis. However, as reported here, this leads to highly variable initial contact conditions in a flat on flat pin-on-disk test. These in turn are shown to lead to a large degree of variability in the wear test data obtained. For a controllable, reproducible, flat on flat pin-on-disk test, improved control over the pin and disk alignment is required.

This paper presents a methodology for improving alignment in a flat on flat pin-on-disk test in which the initial alignment is improved. The starting point for this work was the commonly used pivoting beam, dead weight design of pin-on-disk machine, to which minimal modifications were made. Short-duration, aggressive wear tests were used to show proof of concept. An analysis of data obtained is presented to show how the reproducibility of the data improves with the new methodology. Finally, an effect of the improved alignment system on wear volume is noted and discussed.

Introduction: Design Methodology

To reduce initial misalignment on the dead weight, pivoted pin-on-disk machine two areas were considered. First, any vertical oscillations of the disk counterface had to be reduced, and second the contact conditions, notably the angle of contact between the pin and the disk, had to be controlled.

Figure 1 shows a simplified diagram of the oscillation of the wear signal due to the disk counterface not being perpendicular to its axis of rotation [Figure 1b]. This oscillation, when the disk rotates about the drive shaft axis, can be monitored using the ‘continuous wear’ sensor on a pin-on-disk machine. It imparts what can be termed an “amplitude” of oscillation to this data. Minimisation of the disk “run-out” which causes the oscillation is essential to promoting contact conditions that are consistent throughout one disk rotation.

Expensive bearing systems and precision machining would reduce the degree of run-out. However, each time the disk was changed the run-out would also change. Hence this approach would necessitate precision machining of each disk to improve its positional repeatability. For this reason the methodology chosen here was to redesign the disk to allow its alignment to be adjustable. The experimental method would then be changed to incorporate readjustment of the disk, as required to take into account different disks.

The alignment of the flat-ended pin to the disk counterface could have been accomplished in several ways. However, the majority of solutions would have required that a measurement of ‘correct’ contact between the flat on the pin end and the surface of the disk be obtained. Instead, the method adopted was for the pin to align itself automatically without the necessity of measuring the contact conditions.

This was achieved by allowing compliance between the loading beam carriage and the pin holder. This movement was provided by a spherical seating arrangement which allowed the flat surface of the pin to move about a central point and to align itself to the disk's surface. Once the pin had attained its self-alignment the spherical seating was clamped to hold the pin rigid.

In the design the positional centre of the spherical seating was critical. If the spherical centre was coincident with the pin's flat surface, the moments exerted by the dead weight, at the pin's outer radius, would be greater than the moment from the tangential friction force. This would allow self-alignment of the pin to take place.

Experimental Method: Equipment Modification

A schematic diagram of the initial configuration of the pin-on-disk test apparatus is shown in Figure 2. The design is of the dead weight, pivoted beam type.

The removable wear disk was located on a flanged drive shaft that also provided a drive pin to ensure that the disk rotated. After the disk was placed over the drive pin, a central bolt was used to clamp the disk into position. This arrangement gave radial alignment to the disk when it was placed on the flange but did not ensure zero run-out for the disk's counterface. The flange's run-out, and any error in parallelism, between the upper and lower faces of the disk, combined to give the total run-out measured on the disk's rotating counterface. The total run-out, or wear signal 'amplitude', for the original configuration of the apparatus was measured to be 28μm at a radius of 50 mm.

The pin was secured into a pin holder. Owing to the clearance allowance within the holder the pin's axial misalignment was theoretically a maximum of 2^o out of alignment with the intended pin holder axis. However, a skilled operator using the correct pin tightening procedure could easily reduce this error to less than 1^o. The perpendicularity of the flat, on the end of the pin, to the pin axis was not controlled – except in the machining process of the pin end.

No adjustment for pin length was built into the original pin holder. Therefore, any variations in the length of the individual pin added to the error of perpendicularity relative to the disk's surface. A variation of ± 0.5 mm on the pin's overall length gave a maximum error of $\pm 0.1^o$ due to the position of the pivot on the load beam.

The estimated error of the pin alignment combined with the measured run-out on the disk would be additive in the extreme case and give a perpendicularity error of $\pm 2.3^o$, of which $\pm 2.0^o$ could be attributed to incorrect use of the pin holder itself. This error would be seen as an error on the flat to flat contact between the end of the pin and the surface of the disk. Therefore, using the initial equipment configuration, a skilled operator, minimising the pin to pin holder axial alignment error, would have little problem maintaining the contact perpendicularity error within the $\pm 1.0^o$ allowed by ASTM G99-95a. However, as is demonstrated below this 'standard' equipment configuration gave significant variations in the measured wear data.

The modified pin-on-disk configuration is shown diagrammatically in Figures 3 and 4.

The adjustment of the disk was provided by a kinematic arrangement of three radial equi-spaced balls, placed on the opposite side to the counterface surface at the extreme radius of the disk [Figure 3]. However, the disk still maintained a central clamp screw and a drive pin hole to allow it to fit on the apparatus.

One of the three balls was fixed whilst the other two could be vertically adjusted. The fixed ball gave a reference height to which the other two balls were manually adjusted. This operation was done sequentially as the disk was slowly rotated about its drive axis with the run-out monitored by a precision LVDT set at the wear radius. This kinematic arrangement was able to reduce the total run-out at a 50mm disk radius to 3.5μm. The 3.5μm oscillations were due to form imperfections of the disk's counterface itself and represented a "best case" that no further adjustment could reduce.

The pin holder [Figure 4] was modified to allow the secured pin to pivot about a spherical seating, which in turn allowed the pin to align its flat end to the surface of the disk. Once this self-alignment was complete the spherical seating was clamped so that no further movement was allowed during the test.

Experimental Method: Pin-on-Disk Test

The experimental methodology followed the ASTM G99-95a method. Changes from the standard methodology were: no disk mass loss data was measured; a continuous height measurement system was used to record height changes, which were used as one method of calculating wear loss; a flat-ended pin design, radius 5 mm, was used.

The pin-on-disk test machine used was an in-house design with a rotating disk configuration. The data recording software was written in-house. It allowed for standard wear tests and also for high data acquisition rate 'snap-shots' of data at 60 rpm.

The ASTM G99-95a test set-up and specimen weighing protocols were followed. LVDT and balance sensitivities were better than the recommended standard. The pin material was 'silver steel', composition: 1.1 – 1.2 % carbon, 0.25 – 0.45 % manganese, 0.1 – 0.25 % silicon, 0.35 – 0.5 chromium. Average hardness 257 VHN. The disk material surface was a self-adhesive medium grade silicon carbide abrasive paper [P400, Struers], mean particle size 40 μm. This was laid on the steel disk. Test duration was 300 m [300 s] at 1 ms^{-1} [254 rpm]. The tests were unlubricated.

Two sets of tests were carried out, the first with the original configuration of the apparatus and the second set using the modified pin holder and kinematic disk. Test set up details specific to the new configuration of pin-on-disk were detailed in the previous section. The same disk was used for each set of tests, the spent silicon carbide abrasive paper was replaced between tests without removing the disk from the machine, this gave a disk run-out that was consistent for each set of tests.

Experimental Method: Data Types

Below is an explanation of each data set taken or calculated from the pin-on-disk test data.

The raw data consisted of a scaled voltage signal, representing pin height in mm, from the wear LVDT taken against a time base. Two different time bases were used: 200 point per second for a 'snap shot' of the pin-disk configuration before or after the test, and one point per second during the wear test. Examples of these two data sets are shown in Figures 5 and 6 respectively. The pin track on the disk was designed such that one data per point second correlated to one data point per metre of travel. All but the first two data types, and type 6, listed below are derived from the one point per second time base.

1. Average wear signal 'amplitude': the maximum difference [i.e. run-out] in the wear LVDT height signal, in millimetres, time base 200 points per second, for one half revolution of the disk [Figure 5].
2. Average single rotation wear: change in the wear LVDT height signal, in millimetres, time base 200 points per second, after one full rotation of the disk [Figure 1b].
3. Averaged wear height data: a 10 point average trend line fitted to the wear LVDT height signal, which is collected at one data point per metre [Figure 6a]. This is a backwards average designed such that the fit line will always start at a wear height of

zero and a distance of zero. This allows comparison of data from two different tests - which will have different starting conditions with respect to their pin-disk configuration, that is a different, usually non-zero, place with respect to the ‘amplitude’ of the wear signal.

4. Average arithmetic mean deviation of the wear height data: the arithmetical mean of the wear data between time intervals of 100 s and 200 s [Figure 6b]. A centre line was superimposed on the raw data set and the deviations from the line calculated. This is mathematically equivalent to an arithmetic mean roughness.
5. Average wear calculated from pin height change: the difference in millimetres of the 10-point averaged wear LVDT height signal at the start and end of the test was taken as the height loss of a 5 mm radius cylinder. The volume loss was then calculated. There is a systematic error in this measurement as the change in height was assumed to be entirely owing to wear of the steel pin, not the silicon carbide paper. The density of the steel pins was taken as 7.68 g cm^{-3}.
6. Average wear calculated from mass loss: the difference, in grams, of the pin’s mass before and after the test divided by the density of the steel.
7. Height-wear as a fraction of mass-wear: the volume loss as calculated above from the pin-height change as a fraction of the volume loss calculated from change in mass. The fraction was calculated for each individual test, then the average fraction and standard deviation for a particular test load was calculated. If the two methods of assessing wear yielded the same results then the fraction for each load would be 1, and the standard deviation would be zero.

Results

Figures 7 to 12 present pin-on-disk test results for the unmodified pin-disk configuration.

Figures 7a and 7b show the average wear signal amplitude, at the start and end of the 300 m wear test, respectively, for the unmodified pin-disk configuration. In both cases the 20 N amplitude is the minimum. The standard deviation of the amplitude notably increases with load, even though the mean value does not. The average volume reduces for all loads after the test.

Figure 8 shows the wear height change for one rotation of the disk at the start of the test. The average appears to increase with load, though not linearly. The standard deviation at all loads is greater than 40% of the average single rotation wear value.

Figure 9 plots the variation against time of the 10-point averaged wear height for the wear tests with the unmodified pin-on-disk configuration. [The data is plotted up to maximum height change of 0.1 mm, to allow easy comparison with after modification data, Figure 15.] A wide variation in results can be observed for tests at a single load. The variation between the test specimen with the minimum change in height and that with maximum change in height in a five-test series was 0.21 mm, 0.14 mm and 0.03 mm for the 30, 20 and 10 N loads respectively. It can also be observed in Figure 9 that data from different test loads shows considerable overlap, notably between data from the 30 N and 20 N tests.

Figure 10 shows the arithmetic means of the raw wear signal deviation between 100 and 200 m. Similarly to the average wear signal amplitude results shown in Figure 7, this indicates a drop at 20 N. Again the standard deviation increases with load. At 20 N the standard deviation is greater than 50% of the average arithmetic mean value.

Figure 11 plots average wear volume loss against load. Figure 11a shows average volume loss calculated from the wear height change measurement, assuming that the height change was entirely owing to pin wear. There is a linear increase in volume of material lost with load. The absolute standard deviation also increases very significantly with load, though the increase relative to the average value is not significant. Figure 11b shows the volume loss calculated from the mass loss of the pin calculated from mass measurements before and after the test. Again there is a linear increase with load, and standard deviation markedly increases with load.

Figure 12 shows the average volume loss calculated from pin wear height reduction as a fraction of average volume loss calculated from mass loss. This is plotted as a function of load. Hence it is a comparison of the data presented in Figures 11a and 11b. Whilst the 20 N results gave an average of 1 the standard deviation is greater than 0.5. The average of the data for 30 N load average is below 1, but lies within one standard deviation of 1. However for the 10 N data, the average wear calculated from height loss is approximately one third of that calculated from the mass loss data, the average lying considerably outside one standard deviation away from 1.

Figures 13 through to 19 show test results from the modified pin-disk configuration tests.

Figures 13a and 13b show the average wear signal amplitude, at the start and end of the 300 m wear test respectively, for the modified pin-disk configuration. In both cases any variation with load in mean value lies within the standard deviation of the data. These results are in contrast to the unmodified configuration data shown in Figures 7a and 7b. Comparison with Figures 7a and 7b also indicates that the average values at the start and end of the test are significantly lower for the modified configuration. This is particularly apparent for a comparison of start of test values.

Figure 14 shows the wear height change for one rotation of the disk at the start of the test. The average increases with load, though not linearly. In comparison with the unmodified configuration data presented in Figure 8 it can be seen that the average values at each load are reduced by more than 50% by modifying the pin-disk configuration. The standard deviations are also significantly reduced.

Figure 15 shows the 10-point averaged wear height variation against time plots for the pin-on-disk tests. The range of data for each load is significantly reduced in comparison with the unmodified configuration [Figure 9] and quite consistent across the test loads. The variation between the test specimen with the minimum change in height and that with maximum change in height in a five-test series was 0.019 mm, 0.018 mm and 0.016 mm for the 30, 20 and 10 N loads respectively, i.e. there was little load dependence. In comparison the lowest variation for the unmodified configuration was 0.3 mm. There was no overlap of test data from different loads.

Figure 16 shows the arithmetic means of the raw wear signal deviation between 100 and 200 m. The average values at the three loads are consistent within their standard deviations. In comparison with data from the unmodified configuration [Figure 10] the standard deviations are significantly reduced.

Figure 17 plots average wear volume loss against load. Figure 17a shows average volume loss calculated from the wear height change measurement, assuming that the height change was entirely owing to pin wear. There is a linear increase in volume of material lost with load. The standard deviation does not vary significantly with load, unlike the data from the unmodified configuration [Figure 11a]. Figure 17b shows the volume loss calculated from the mass loss of the pin, calculated from mass measurements before and after the test. Again there is a linear increase with load, and standard deviation does not significantly vary with load. A comparison of Figure 17 and Figure 11 indicates that for both the height and mass loss data the modified pin-disk configuration produces significantly lower values of wear and significantly reduced standard deviations.

Figure 18 shows the average volume loss calculated from pin wear height reduction as a fraction of average volume loss calculated from mass loss. The 20 and 30 N averages both lie within a standard deviation of 1, whereas the 10 N average lies just outside one standard deviation from 1. The standard deviations are quite consistent across the loads and are notably smaller than for the unmodified pin-disk configuration. Of the three loads the deviation from 1 is the largest at 10 N for both the modified and unmodified configuration [Figure 12].

Discussion

It is clear that the adoption of the modified pin-disk configuration gives considerable improvement in the reproducibility of the test. A comparison of the data sets for the unmodified configuration [Figures 7 to 12] and modified configuration [Figures 13 to 18] shows a decrease in standard deviation for each data set for the modified configuration, except for the average wear signal 'amplitude' after the test [Figure 13b].

The average wear signal amplitude post-test would be expected to be relatively unchanged. This is a post-test 'snap-shot' assessment of pin-disk mismatch after the 300 s test. Figures 9 and 15 indicate that for this material couple steady state wear is reached by 100 s. Hence both the modified and unmodified configurations would be expected to have worn in by 300 s, minimising any difference owing to pin-disk misalignment. In contrast Figures 7a and 13a are an indication of the pin-disk misalignment before the test. The standard deviation of the unmodified configuration is significantly higher.

A comparison of Figures 9 and 15 also indicates that the modified configuration can produce consistent values for wear for a given load, and that the unmodified 'standard' configuration does not yield reproducible values for flat on flat contact. Again it should be emphasised that the degree of mismatch for the unmodified configuration, when used by a skilled operator, was within the limits recommended by ASTM G99-95a.

Comparison of the two data sets also indicates, again with the exception of the post-test wear signal amplitude, that the adoption of the modified configuration decreases the average value of the data set for a given load. This can be seen for the pre-test wear amplitude, the average single rotation wear at the start of the test, the arithmetic mean of the wear signal, the average volume loss calculated from height or from mass loss and in a comparison of Figures 9 and 15.

Figure 19 shows a comparison of the four volume loss data sets presented in Figures 11 and 17. It illustrates this point for the height and mass loss calculated wear data. The volume loss shows a linear relationship with load in each case. However, it is significantly greater for the unmodified configuration for both the height change and mass loss calculations.

The modified, self-aligning configuration can be thought of as the close to optimised starting alignment between pin and disk. Hence, any data point collected for the unmodified configuration will represent an assessment of wear for a relatively mismatched pin-disk configuration. Effectively, the unmodified configuration always skews the data away from that which would be obtained for the best alignment. The conclusion, therefore, is that this misalignment produces the higher wear observed. This is supported by a comparison of Figures 8 and 14 which indicates that within the first rotation of the disk the height change for the unmodified configuration is approximately double that of the modified pin-disk configuration. That these effects are artefacts of the pin-height measurement method of determining wear is ruled out by the difference between the unmodified and modified wear calculated from mass loss, as shown in Figure 19.

The above implies that initial apparent area of contact correlates with the wear of the pin. The higher misalignment will always act to reduce the apparent area of contact at the beginning of the test. An argument could be made that a relatively misaligned pin might wear at a greater rate because the lip of the pin in contact with the surface will not be as constrained by surrounding pin material as would be the case for true flat on flat contact. This lack of constraint then either changes the severity of the acting wear mechanism, or perhaps introduces a new mechanism specifically at the lip. However, no direct mechanistic evidence was obtained in support of this hypothesis.

Conclusions

A flat on flat pin-on-disk test was modified to improve the initial alignment of the pin end with the disk.

This modification in alignment affected the wear data produced. The standard deviation of the wear data was considerably reduced and the correlation of the wear data with applied load significantly improved.

The modified alignment also reduced the absolute value of wear recorded. This effect was observed for both wear volume assessed from mass change and wear volume assessed from pin height change. The reduced constraint of a misaligned pin in comparison with a well-aligned pin may account for the difference in these results.

References

[1] ASTM standard designation G 99-95a (reapproved 2000), Standard test method for wear testing with a pin-on-disk apparatus, Metals test methods and analytical procedures 03.02, ASTM International, pp 414-419, 2002.

[2] Y. Iwai, H. Yoneda, T. Honda, Sliding wear behaviour of SiC whisker-reinforced aluminium composite, Wear 181-183 (1995) 594-602.

[3] Z. Zhang, L. Zhang, Y.-W. Mai, The running-in wear of a steel/SiC_p-Al composite system, Wear 194 (1996) 38-43

[4] A. Ravikiran, M. K. Surappa, Effect of sliding speed on wear behaviour of A356 Al-30 wt.% SiC_p MMC, Wear 206 (1997) 33-38.

[5] L. Yu, S. Bahadur, O. Xue, An investigation of the friction and wear behaviours of ceramic particle filled polyphenylene sulfide composites, Wear 214 (1998) 45-63.

[6] S. Wilson, A. T. Alpas, Tribo-layer formation during sliding wear of TiN coatings, Wear 245 (2000) 223-229.

[7] T. Miyajma, Y. Iwai, Effecs of reinforcements on sliding wear behaviour of aluminium matrix composites, Wear, in press.

Wear, Volume 257, Issues 1-2, July 2004, Pages 157-166.

Figure Captions

1. a) Simplified sketch of disk rotating with perfect perpendicularity to the pin axis. b) simplified sketch of disk 'run out' as tilted disk rotates about its axis.
2. Initial pin-on-disk configuration.
3. Sketch of the kinematic disk design.
4. Sketch of the carriage and pin holder modifications.
5. An example of a 'snap shot' of the variation of LVDT signal with two rotations of the disk. Time base: 200 data points per second.
6. a) An example of wear test data generated from the variation in LVDT signal during the wear test. Time base: one data point per second. b) an example of wear height data from 50 to 250 m, showing the back average, the mean line and lines indicating the maximum and minimum deviations.
7. Average wear signal 'amplitudes' and their standard deviation at the start and end of the wear test for the unmodified configuration (a) start (b) end.
8. Average single rotation wear at the start of the wear test for the unmodified configuration.
9. 10-point averaged wear data for the unmodified pin-on-disk configuration. Key: Thick lines 30 N, medium lines 20 N; fine lines 10 N.
10. Average arithmetic mean deviation of the raw wear signal between 100 and 200 s test time for the unmodified configuration.
11. Average wear volume loss calculated from (a) pin height change (b) mass loss, for the unmodified configuration.
12. Average volume loss, calculated from pin height change, as a fraction of average volume loss calculated from mass loss, for the unmodified configuration.
13. Average wear signal 'amplitudes' and their standard deviation at the start and end of the wear test for the modified configuration (a) start (b) end.
14. Average single rotation wear at the start of the wear test for the modified configuration.
15. 10-point averaged wear data for the modified pin-on-disk configuration. Key: Thick lines 30 N, medium lines 20 N; fine lines 10 N.
16. Average arithmetic mean deviation of the raw wear signal between 100 and 200 s Test time for the modified configuration.
17. Average wear volume loss calculated from (a) pin height change, (b) mass loss, for the modified configuration.
18. Average volume loss, calculated from pin height change, as a fraction of average volume loss calculated from mass loss, for the modified configuration.
19. Wear volume from mass and height measurements for the unmodified and modified configurations.

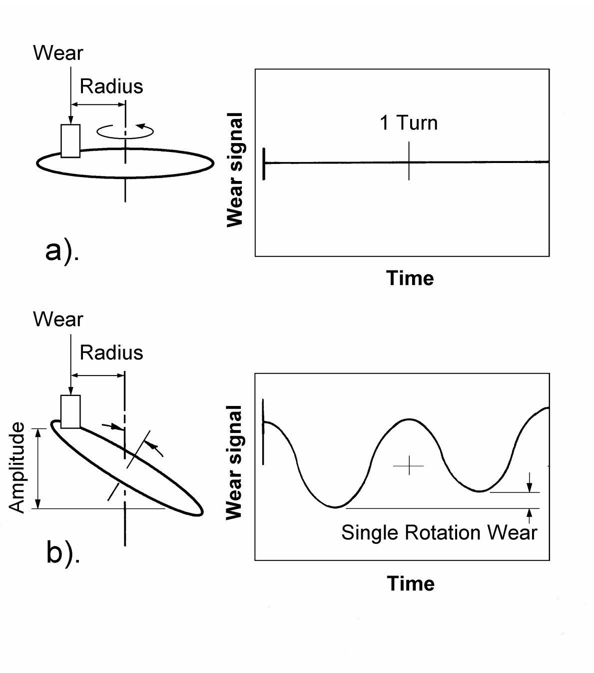

Wear
Radius
Wear signal
1 Turn
a).
Time
Wear
Radius
Amplitude
Wear signal
Single Rotation Wear
b).
Time

Fig 1

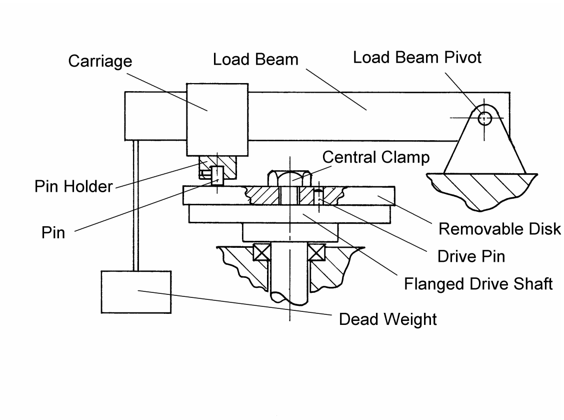

Carriage
Load Beam
Load Beam Pivot
Central Clamp
Pin Holder
Pin
Removable Disk
Drive Pin
Flanged Drive Shaft
Dead Weight

Fig 2

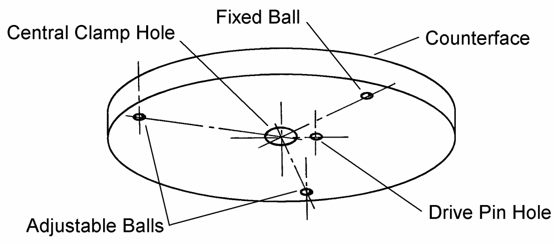

Fixed Ball
Central Clamp Hole
Counterface
Adjustable Balls
Drive Pin Hole

Fig 3

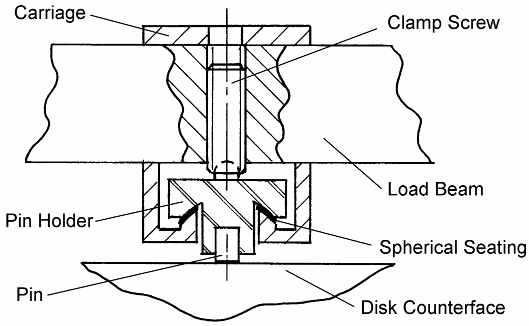

Carriage
Clamp Screw
Load Beam
Pin Holder
Spherical Seating
Pin
Disk Counterface

Fig 4

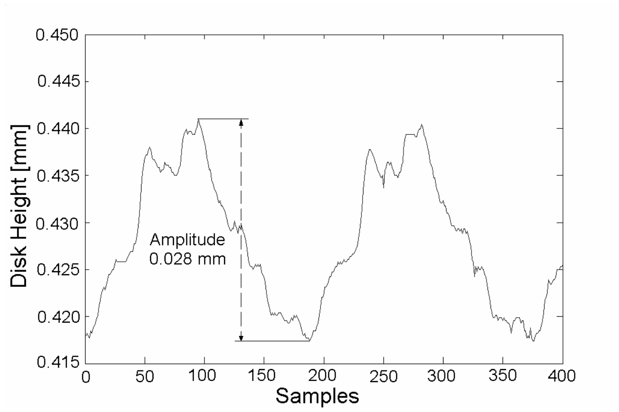


Fig 5

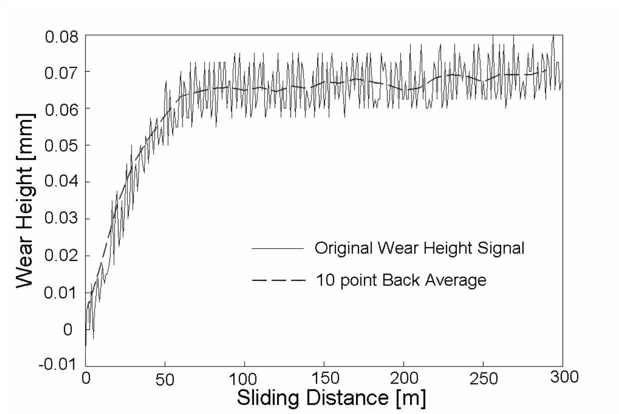


Fig 6a

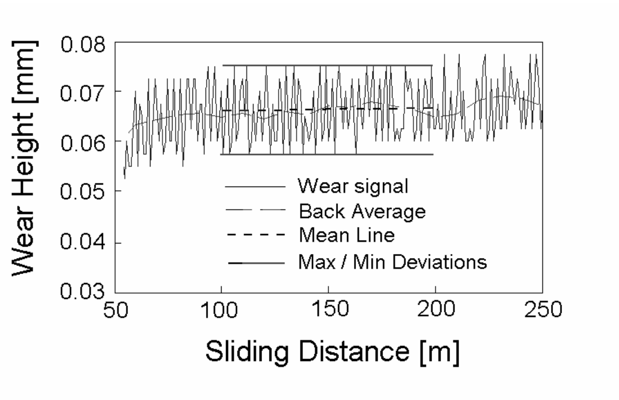


Fig 6b

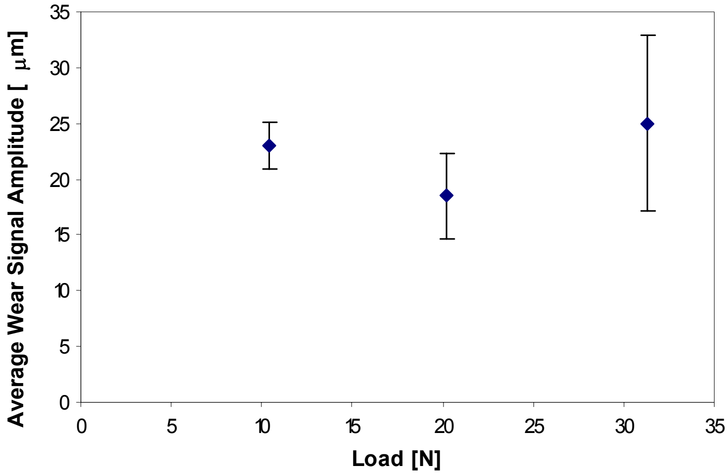

Average Wear Signal Amplitude [μm]
Load [N]
0
5
10
15
20
25
30
35

Fig 7a

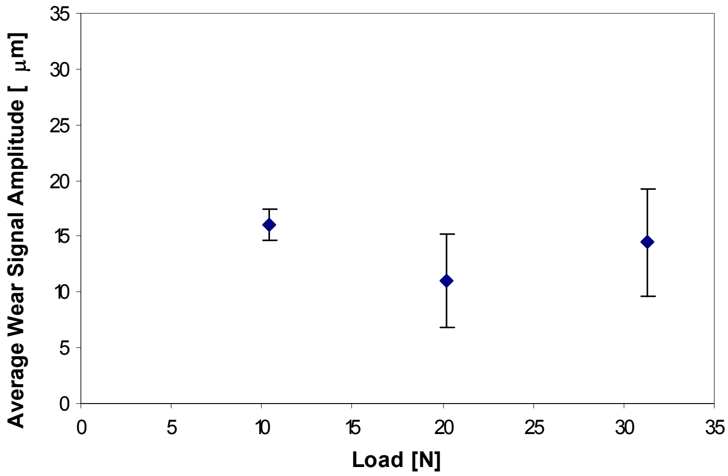

Average Wear Signal Amplitude [μm]
Load [N]
0
5
10
15
20
25
30
35

Fig 7b

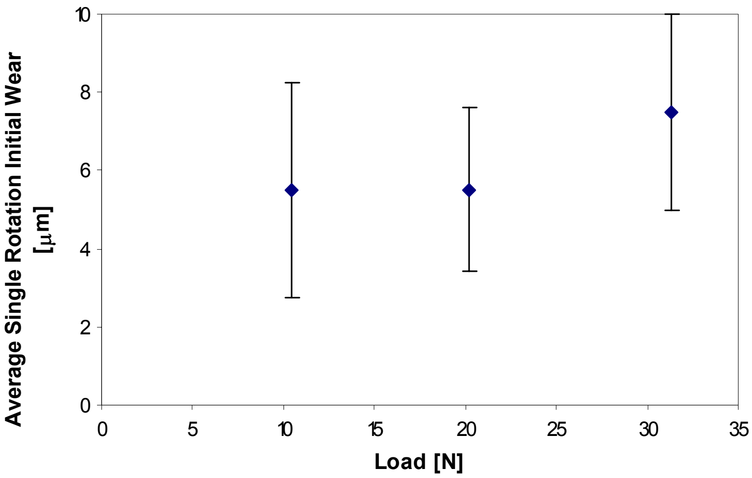


Fig 8

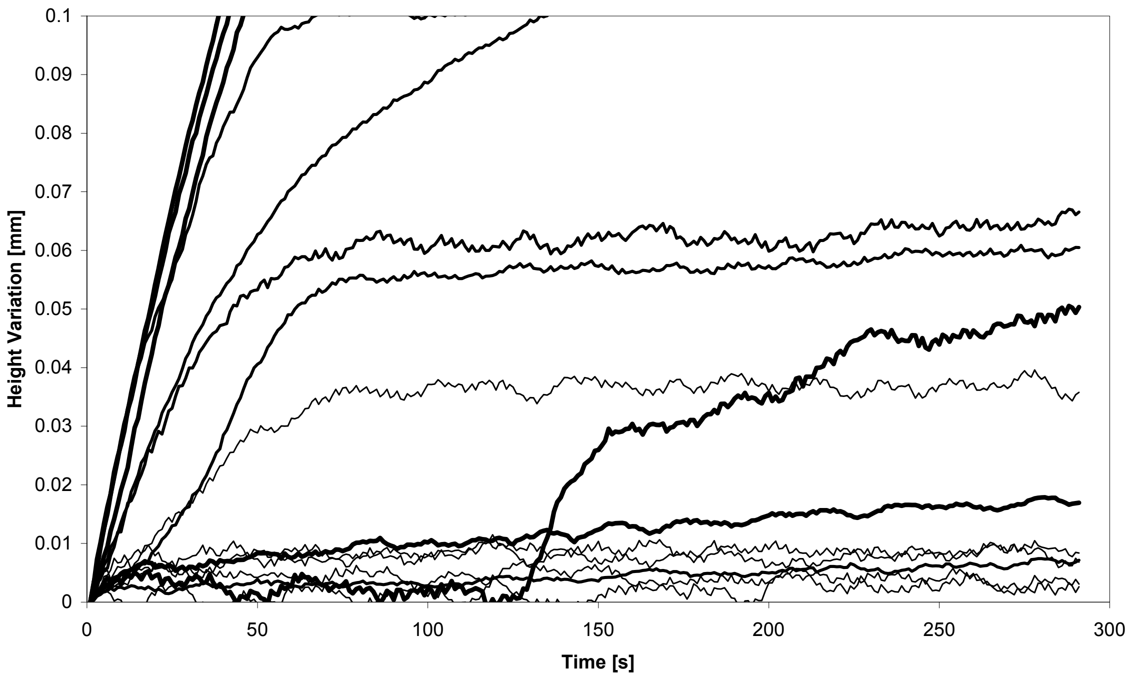
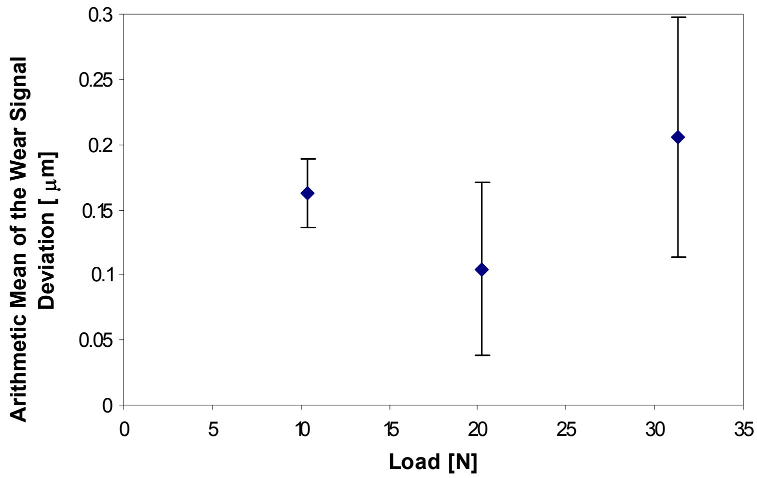


Fig 9 [See figure captions for key]



Arithmetic Mean of the Wear Signal Deviation [μm]
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
Load [N]

Fig 10

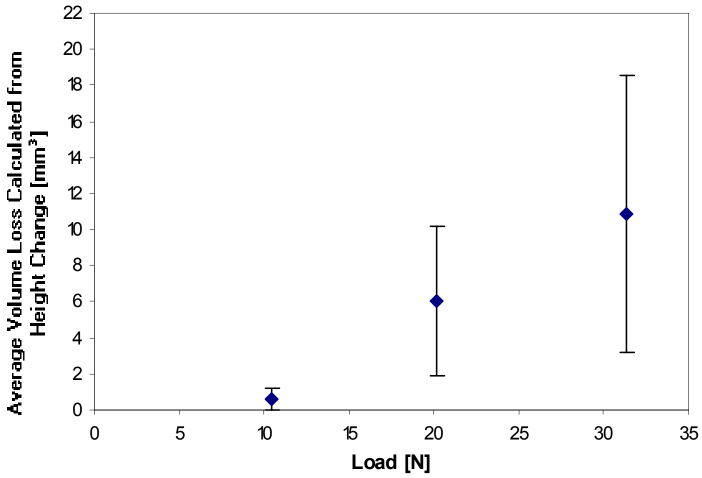


Fig 11a

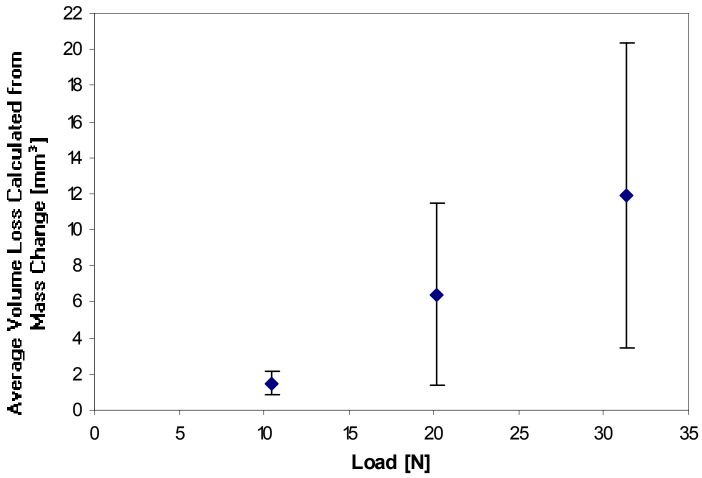
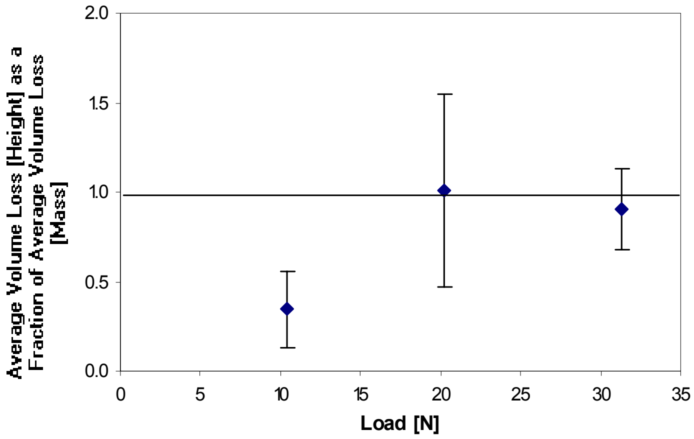


Fig 11b



Average Volume Loss [Height] as a Fraction of Average Volume Loss [Mass]
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
35
Load [N]

Fig 12

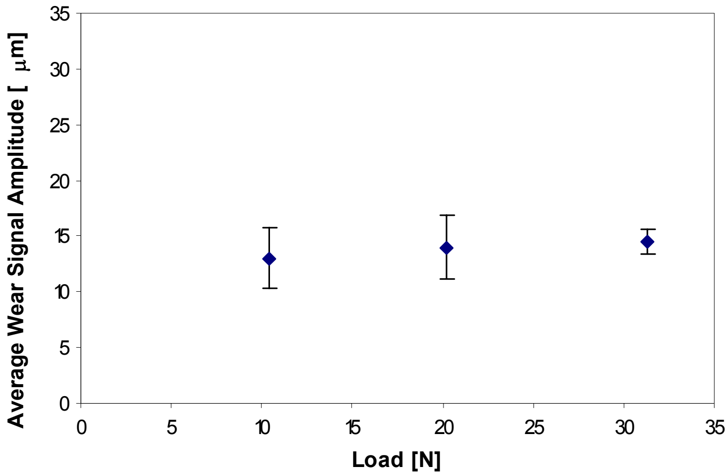


Fig 13a

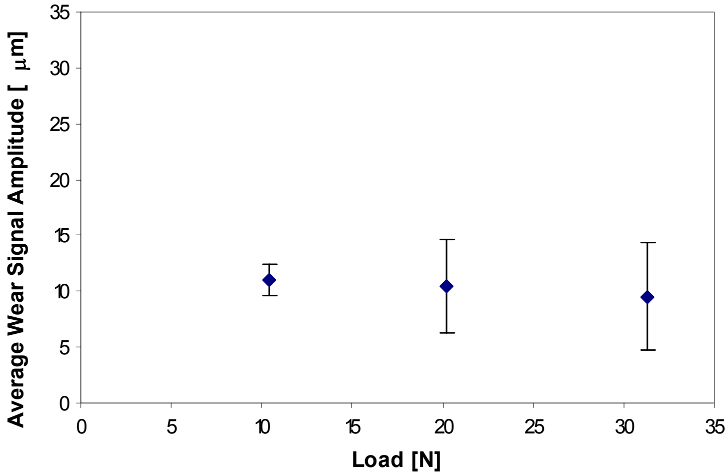


Fig 13b

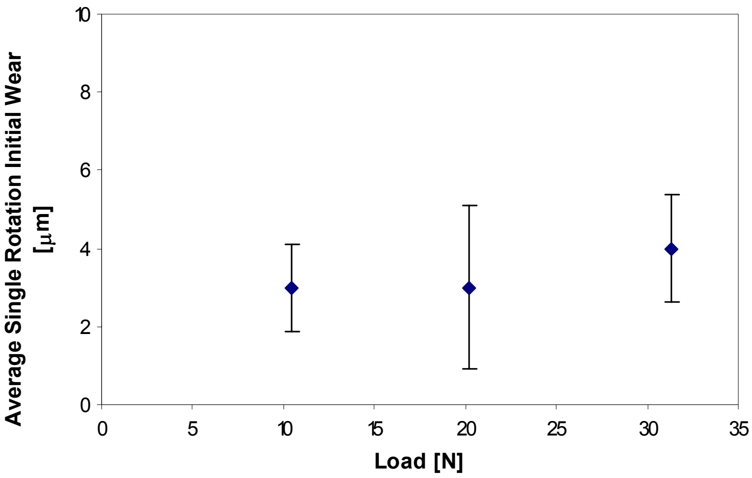


Fig 14

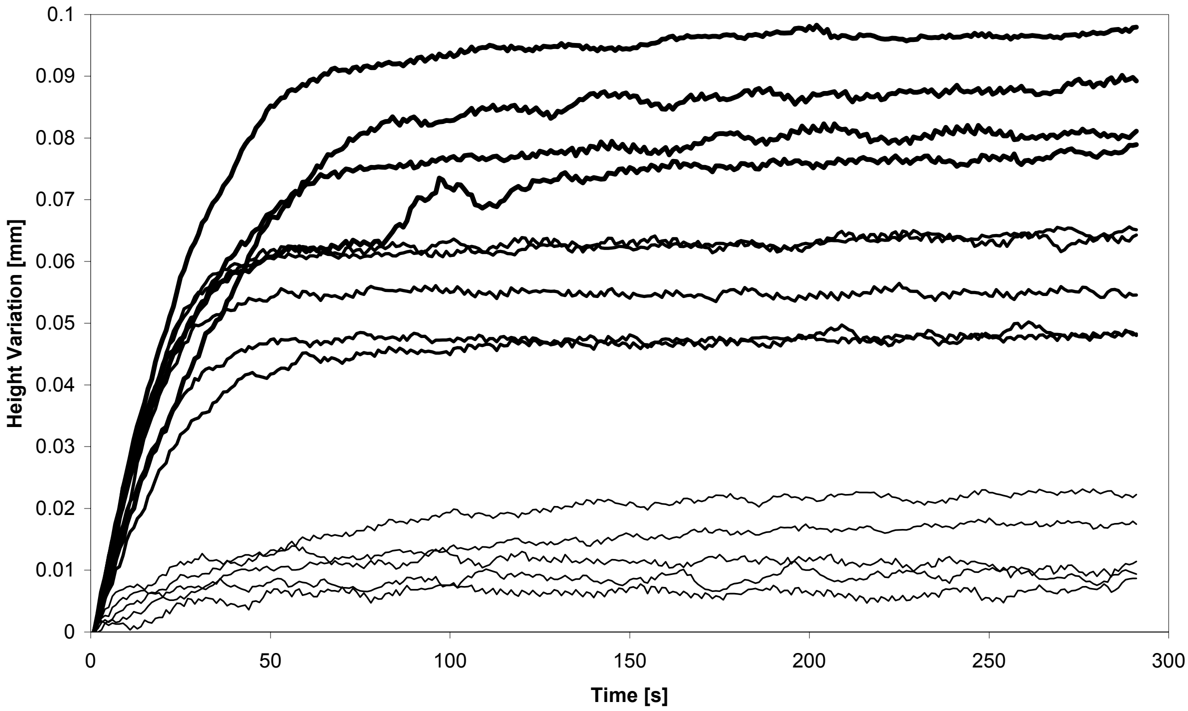
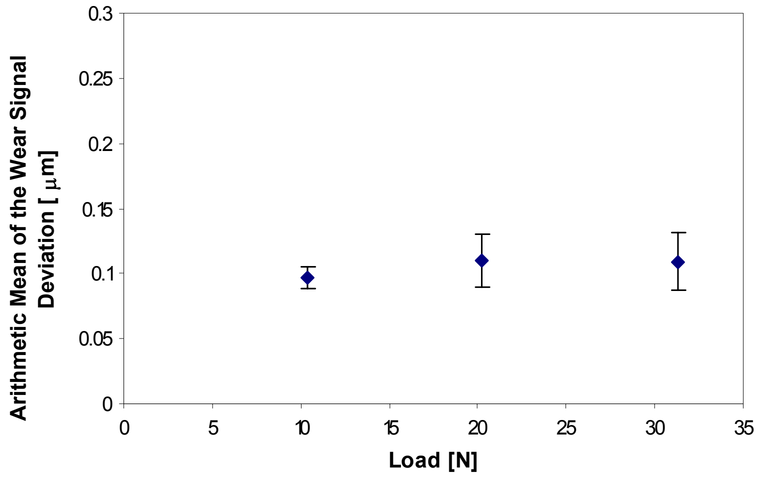


Fig 15 [See figure captions for key]



Arithmetic Mean of the Wear Signal Deviation [μm]
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
Load [N]

Fig 16

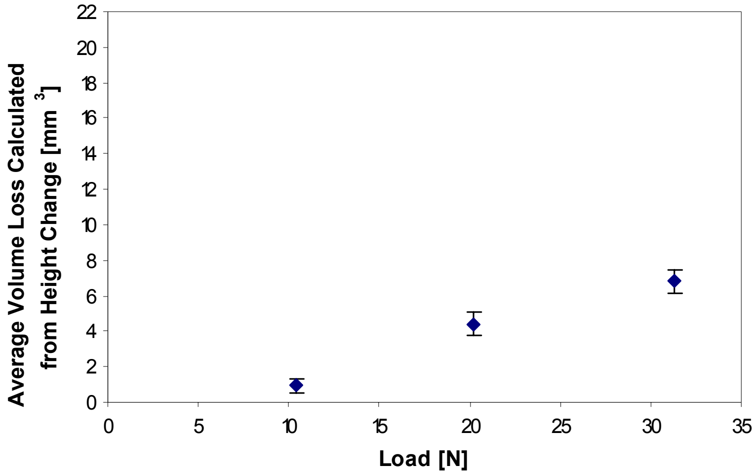


Fig 17a

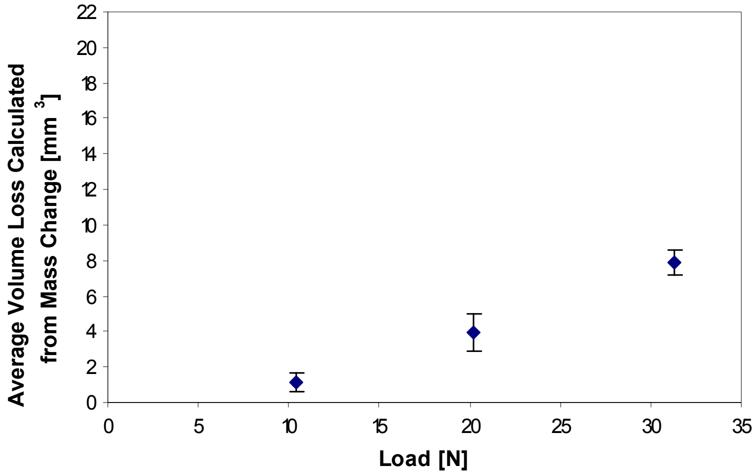


Fig 17b

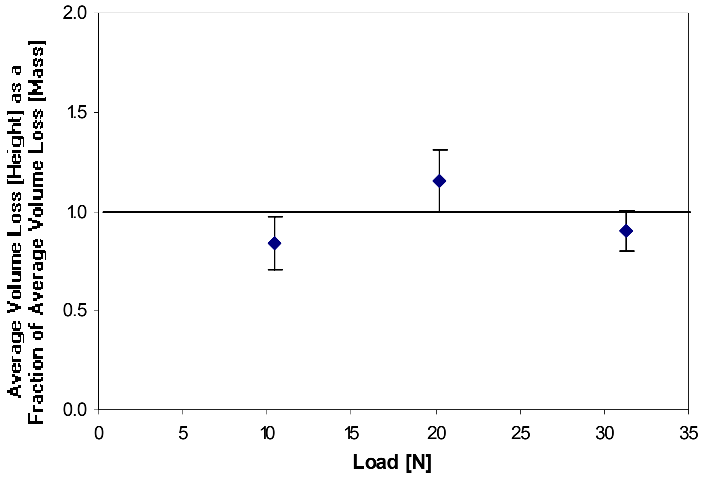

Average Volume Loss [Height] as a Fraction of Average Volume Loss [Mass]
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
35
Load [N]

Fig 18

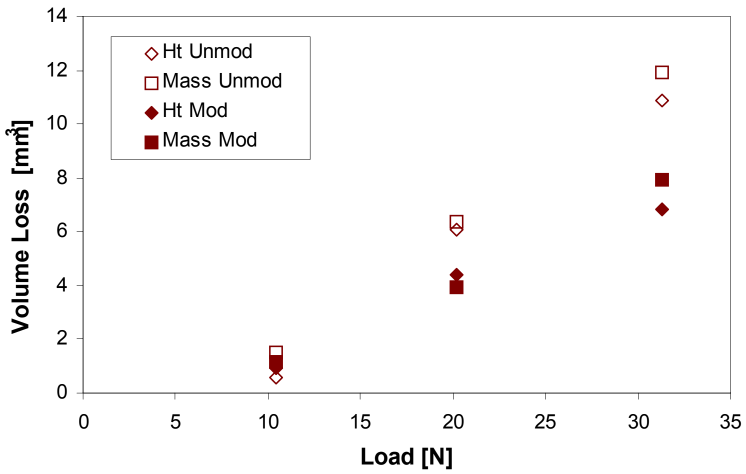

Ht Unmod
Mass Unmod
Ht Mod
Mass Mod
Volume Loss [mm3]
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
Load [N]

Fig 19