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Wear and Strength of Mg-PSZ, Worn on Hardened Steel

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Abstract

Wear tests were performed with a Mg-PSZ/stavax couple using a strip-on-disk configuration. The centre sliding velocity was 1·4 m/s, the normal pressures used were 0·09 MPa, 0·13 MPa and 0·23 MPa and the testing times were 20 h, 70 h and 200 h. Tests were done under ambient conditions and with water as a lubricant. Polished as well as ground Mg-PSZ surfaces were used. The strength of the Mg-PSZ, the surface roughness of the Mg-PSZ and the wear volumes of the Mg-PSZ and the stavax were measured. The worn surfaces of the Mg-PSZ were examined with optical microscopy using interference contrast and with scanning electron microscopy. The strength of the material was found to be independent of testing time. It was concluded that the influence of the mechanical and/or thermal interaction between the Mg-PSZ and the steel on the residual stress layer was the strength-determining factor. Testing under ambient conditions caused more residual stress and thus a higher strength than testing with water as a lubricant. The relation between wear volume W_v and time t could be described by $W_v = c_1 t$ and the relation between wear volume and load P by $W_v = c_2(P - P_c)$. The R_a of worn surfaces was found to be independent of normal pressure. A wear mechanism, incorporating adhesion of the stavax on the Mg-PSZ and delamination of the Mg-PSZ, was derived from observations of the worn surfaces and of the wear debris.

Die Mg-PSZ/stavax-Werkstoffkombination wurde mittels der Streifen/Scheibe-Anordnung auf ihr Verschleißverhalten untersucht. Die Geschwindigkeit im Mittelpunkt der Scheibe war 1·4 m/s, die verwendeten Drücke betrugen 0·09 MPa, 0·13 MPa und 0·23 MPa und die Versuchszeiten lagen bei 20 h, 70 h und 200 h. Die Tests wurden sowohl unter normalen Umgebungsbedingungen als auch mit Wasser als flüssigem Medium durchgeführt. Es wurden sowohl polierte wie auch grob geschliffene Mg-PSZ-Oberflächen verwendet. Bei den Versuchen wurden die Festigkeit und die Oberflächenrauhigkeit des Mg-PSZ sowie die abgetragene Menge an Mg-PSZ und stavax gemessen. Die geschädigten Oberflächen des Mg-PSZ wurden am Lichtmikroskop mittels des Interferenzverfahrens und am Rasterelektronenmikroskop begutachtet. Die Festigkeit des Materials hing nicht von der Versuchszeit ab. Aus den gewonnenen Daten wurde geschlossen, daß die mechanische und/oder thermische Wechselwirkung zwischen dem Mg-PSZ und dem Stahl auf die zurückbleibende, geschädigte und unter Spannung stehende Schicht den entscheidenden Einfluß auf die Festigkeit darstellt. Tests unter Normalbedingungen verursachten höhere zurückbleibende Spannungen und ergaben somit eine höhere Festigkeit als die in Wasser durchgeführten Versuche. Für Abrieb W_v und Zeit t ergab sich die Beziehung $W_v = c_1 t$ und für Abrieb und Belastung P $W_v = c_2\ (P - P_c)$. Der R_a-Wert der geschädigten Oberflächen hing nicht vom Belastungsdruck ab. Wie sich aus den Oberflächen- und Abriebsuntersuchungen schließen läßt, setzt sich der Verschleißmechanismus

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aus einer Adhäsion des stavax auf dem Mg-PSZ und einer Ablösung des Mg-PSZ zusammen.

On a conduit des essais de résistance à l'usure avec un couple Mg-PSZ/stavax en utilisant une configuration lamelle-sur-disque. La vitesse de glissement au centre était de 1·4 m/s, les pressions normales mises en jeu de 0·09, 0·13 et 0·23 MPa et les durées d'essai de 20, 70 et 200 h. Les expériences étaient réalisées sous conditions ambiantes et avec de l'eau comme lubrifiant. Des surfaces de Mg-PSZ polies ou dégrossies étaient utilisées. On a mesuré la résistance mécanique et la rugosité de surface de la Mg-PSZ ainsi que les volumes d'usure de la Mg-PSZ et du stavax. Les surfaces usées de la Mg-PSZ ont été examinées par microscopie optique avec contraste d'interférence et par microscopie électronique à balayage. On a établi que la résistance mécanique du matériau est indépendante de la durée de l'essai. On en a conclu que l'influence de l'interaction mécanique et/ou thermique entre la Mg-PSZ et l'acier sur la couche de contraintes résiduelles est le facteur déterminant la résistance. Les essais réalisés sous conditions ambiantes conduisent à davantage de contraintes résiduelles et donc à une résistance plus élevée par rapport aux essais réalisés avec de l'eau comme lubrifiant. La relation entre le volume d'usure W_v et le temps t peut être décrite par $W_v = c_1 t$ et la relation entre le volume d'usure et la charge P par $W_v = c_2(P - P_c)$. Le R_a des surfaces usées est indépendant de la pression normale. A partir des observations sur les surfaces usées et sur les débris d'usure, on a pu déduire un mécanisme d'usure incorporant l'adhésion du stavax sur la Mg-PSZ et la délamination de la Mg-PSZ.

1 Introduction

One of the most interesting applications of ceramics is as wear-resistant materials. Partially stabilized zirconia (PSZ), in particular Mg-PSZ, is a commercially available ceramic often mentioned[1-6] as a material suitable for such an application. In many of these applications, wear is not the only relevant property. The relative brittleness of ceramics makes the strength behaviour of the material during wear also of importance. No information whatsoever is available on this point. Therefore, tests were done on commercially available Mg-PSZ to relate strength and wear conditions.

The phase transformation tetragonal⇒monoclinic in zirconia, which is of crucial importance to the mechanical behaviour of Mg-PSZ as described in Refs 7–10, also influences its wear behaviour significantly. Again hardly any specific information with regard to wear is available. The dilatation associated with this phase transformation results in a layer of compressive stresses at a ground or worn surface. These compressive stresses will have a closing effect on surface flaws, thus increasing the strength.

To investigate the influence of wear on strength, wear tests were performed using a strip-on-disk configuration. The strip, Mg-PSZ, was sized to dimensions which made it suitable for three-point bend testing after the wear testing. The disk was a hardened steel, also denoted as stavax.

Two types of wear-test series were performed: one series under ambient conditions with polished Mg-PSZ surfaces, and one series with water as a lubricant with ground Mg-PSZ surfaces. Additional tests were done with ground Mg-PSZ under ambient conditions and with polished Mg-PSZ with water as a lubricant. A wear mechanism, derived from the observations on the worn surfaces and the wear debris, is proposed. The results from this study are compared to the results from earlier studies mentioned in the literature.[2-6,11]

2 Experimental

2.1 Material characterization

The density of the commercially available Mg-PSZ was determined from the weight and dimensions of seven samples. Young's modulus and Poisson's ratio were determined with the pulse-echo method, also on seven samples. The fracture toughness of the material was measured under dry conditions (at a dew point of −40°C) with three-point bend tests on twenty single-notched samples and with the double cantilever beam (DCB) method on three samples. The fracture toughness was also determined from seven single-notched samples which were broken in tap water. Ten single-notched samples which had lain in tap water for 200 h at 30°C were taken out of the water and the fracture toughness of these samples was measured at a dew point of −40°C. The strength of the Mg-PSZ was determined from three-point bend tests both on ten samples with polished surfaces and on 36 samples with ground surfaces. Vickers hardness was measured with a Leitz hardness tester at a load of 2·0 N on a polished surface. The microstructure of the material was visualized, after polishing as described in Section 2.2, by thermal etching (6 h at 1100°C) and by etching with HF. The disk was made of a steel, also denoted as stavax, and thermally hardened, at a maximum temperature of 1000°C for 1 min. The Vickers hardness of this steel disk was measured with the Leitz hardness tester at a load of 5·0 N. The density was calculated from the dimensions and the weight of a disk. The chemical composition and other mechanical properties of this material were taken from the data supplied with this material.

2.2 Sample preparation

Samples were prepared by sawing and grinding. Grinding was done with a diamond wheel, containing diamonds with a diameter of 46 μm (D46) and with water cooling. The grinding wheel rotated in the same horizontal plane as the surface which was to be ground. The rotation axis of the grinding wheel was orientated orthogonal to this surface.

The worn surfaces were either initially polished, or initially ground as described in Section 2.1.

Polishing was done with a diluted soap solution on a tin disk, initially with diamond powder of 4–7 μm, and in the last step with diamond powder of 2–4 μm. A layer of at least 30 μm[12] was removed by polishing from the surface of the samples to remove the residual stress layer caused by the grinding.[12–15] A polished surface is, however, not expected to be entirely stress free.

The Mg-PSZ samples were sawn as illustrated in Fig. 1. This particular shape made it possible to perform the wear tests on the Mg-PSZ and to obtain afterwards ten samples of 15 × 3 × 1 mm suitable for a three-point bend test. This test will be described in Section 2.5. The ten surfaces of 15 × 1 mm were worn tangentially to the rotation direction of the steel disk. The grinding marks on the ground samples used in the wear tests were orientated perpendicular to the length direction of the three-point bend samples.

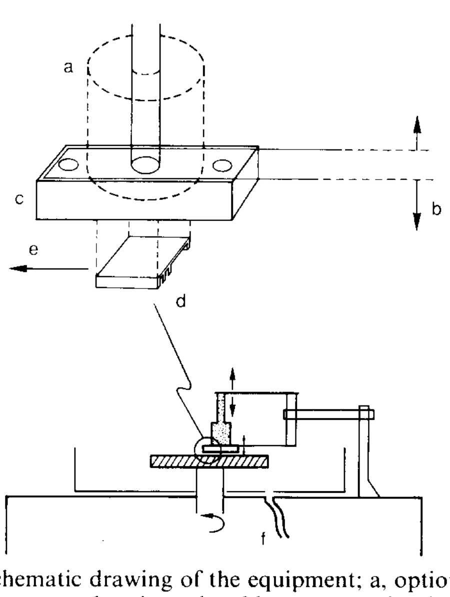

Fig. 1. Schematic drawing of the equipment; a, optional extra weight; b, a metal strip only able to move in the vertical direction, c, the steel holder to which the Mg-PSZ cam, d, is attached; e indicates the sliding direction of the disk and f is the tube used to remove residual lubricant.

The steel disk was polished after each measurement. This assured that every test started with the same surface conditions for the disk. The hardness of the disk, about 6·5 GPa, was checked with Vickers hardness measurements at a normal load of 5·0 N on an unworn part of the disk before or after each test.

2.3 The wear testing instrument

A schematic drawing of the wear testing apparatus is shown in Fig. 1. It is based on a common polishing table, with the steel disk attached to it. The Mg-PSZ is glued to the centre of a steel block of about 50 × 20 × 20 mm. A brass cylinder, and when needed extra weights to vary the normal pressure, are screwed on top of the centre of this block. The line through the centre of gravity of the cylinder and the centre of gravity of the Mg-PSZ is normal to the steel disk. This pile of Mg-PSZ, steel and brass is kept in position by two strips of metal, which enable the pile to move only in the vertical direction.

2.4 Testing conditions

The wear tests were performed in air at room temperature and humidity conditions. The sliding velocity was kept constant at 1·2 m/s for the inner specimen and 1·5 m/s for the outer specimen. Before testing, the Mg-PSZ and the disk were cleaned ultrasonically in ethanol, washed in ethanol and dried in blown hot air. Improvement of this procedure is limited by practical problems, especially because of the large size of the steel disk. Also, the testing in air makes a more complicated cleaning procedure less useful. Three different loads were used, 14 N, 19 N and 34 N, resulting in a normal stress of 0·09 MPa, 0·13 MPa and 0·23 MPa, respectively. At each load, tests were done at three different time intervals, 20 h, 70 h and 200 h. Three tests were done twice to investigate the reproducibility of the measurements.

Tests were performed under ambient conditions and with water as a lubricant. The lubricant was applied to the disk at a constant velocity of 2 ml/min, in front of the contact between the steel disk and the Mg-PSZ.

2.5 Wear measurements and surface observations

The worn surfaces of two or three Mg-PSZ samples for each test condition were examined in the sliding direction with a profile tracer, a Taylor-Hobson

(Leicester, UK) Talysurf. The results were digitally processed, and presented as roughness, R_a, values. The R_a values of the steel were measured after three tests with the same equipment.

After each wear test, the ten samples of $15 \times 3 \times 1$ mm were removed from their bases by sawing. The dimensions of each sample were measured and they were broken in a three-point bend test with the worn surface under tension. The three-point bend tests were performed at a dew-point of -40°C, using a span width of 12 mm and a strain rate of about 1·2%/min.

The wear testing instrument was primarily designed to relate wear conditions to strength which explains the shape of the Mg-PSZ sample. Wear volumes were, however, also determined. Probably because of the relatively long total edge length in comparison with the area loaded, it is difficult to make a comparison with other measurements done on more conventional instruments. The weight of a Mg-PSZ sample was measured before and after each test. From the weight difference and the density, the wear volume of Mg-PSZ was calculated. Also, the height of each sample at various positions was measured before and after each wear test. This also gives an estimate for the wear volume of Mg-PSZ. With these wear volumes, a wear coefficient, K, can be calculated according to

$$K = W_v/Px$$

where W_v is the wear volume, P is the normal load and x is the sliding distance.

The wear track of the steel disk was measured with a profilometer. Profiles were measured at various enlargements, depending on the size of the tracks, at intervals of 30° and/or 90°. The wear volume was calculated from the radii of the tracks and the average area from the profiles.

The worn surfaces were observed with optical microscopy using interference contrast (InCo), and with scanning electron microscopy (SEM). Some of the surfaces were qualitatively analysed with energy dispersive element analysis by X-rays (EDAX). A polished and a worn Mg-PSZ surface were observed with scanning acoustic microscopy (SAM). The wear debris from various tests was collected, and observed with SEM and qualitatively analysed with EDAX.

3 Results

The characteristics of the Mg-PSZ and the steel are given in Table 1. The microstructure of the Mg-PSZ shows a grain size of about 50 μm. After etching with HF ellipsoidal precipitates with a length of about 0·3 μm are seen. These precipitates, either monoclinic or tetragonal, are characteristic for this material (see, for example, Ref. 16). The phase of these precipitates cannot be determined with SEM, but the precipitates with a length of about 0·3 μm are probably monoclinic, since etching with HF enhances the transformation, and tetragonal precipitates of this size are not stable.

Table 1. Characteristics of the Mg-PSZ and the steel[a] used

Material	*Mg-PSZ*	*Steel*[a]
Chemical composition (wt%)	Mg, 2·5	C, 0·38 Si, 0·8 Mn, 0·5 Cr, 13·6 V, 0·3
Density (g/cm^3)	$5·73 \pm 0·01$	6·7
Young's modulus (GPa)	$195 \pm 3·0$	215
Poisson's modulus	$0·324 \pm 0·005$	
Vickers hardness (GPa)	12 ($P = 2$ N)	5·8–6·8 ($P = 5$ N)
Strength (three-point bend test) (MPa)		
Polished	761 ± 33	
Ground D46	915 ± 56	
Fracture toughness (MPa m$^{1/2}$)		
DCB	$10·3 \pm 0·2$	
Three-point bend test	$11·5 \pm 1·1$	
Measured in water	$7·5 \pm 0·2$	
After 200 h in water	$11·9 \pm 0·9$	
Roughness, R_a (μm)		
Polished	0·025	0·001
Ground D46	0·21	

[a] Also denoted as stavax.
All results given as $X \pm S$ stand for the average X and the sample standard deviation S.

Table 2. Results of the wear tests performed under ambient conditions on initially polished surfaces for Mg-PSZ

Time (h)	*Load (N)*	$\sigma_{3pb} \pm S$ *(MPa)*	R_a *(μm)*		*Mg-PSZ*		*Stavax*	
			Mg-PSZ	*Steel*	W_v *(mm³)*	*K (m²/N)*	W_v *(mm³)*	*K (m²/N)*
Ground D46		915 ± 56	0·21		—		—	
Polished		761 ± 33	0·025					
20	14	797 ± 22	0·099		3	2·1E − 15	7	5·0E − 15
70	14	779 ± 7[a]	0·161		16	3·2E − 15	13	2·6E − 15
200	14	795 ± 31	0·100		50	3·5E − 15	28	2·0E − 15
20	19	774 ± 22	0·194		—		24	1·3E − 15
70	19	770 ± 38	0·275		10	1·5E − 15	126	1·9E − 14
200	19	768 ± 24	0·059		—		240	1·3E − 14
20	34	802 ± 19	0·209		—		—	
20	**34**	**830 ± 19**	**0·327**	**0·047**	**125**	**3·6E − 14**	**117**	**3·4E − 14**
70	34	795 ± 51	0·064		—		118	9·8E − 15
70	**34**	**807 ± 27**	**0·213**	**0·064**	**115**	**9·6E − 15**	**59**	**4·9E − 15**

[a] One sample was not included for the calculation of the average, because the strength of this sample deviated extremely from the other samples, probably due to an exceptionally large inherited flaw. Strength values determined with a three point bend test are given as σ_{3pb}. The number $xE - y$ stands for $x \cdot 10^{-y}$. All results given as $X \pm S$ stand for the average X and the sample standard deviation S. The results written in bold type are the results of the reproducibility tests.

The quantitative results of the various tests are summarized in Tables 2, 3 and 4. The material loss after testing for 200 h at $P = 34$ N under ambient conditions was too large to perform the required measurements. It seems reasonable to conclude from the data that the test condition, and not the initial surface preparation, is the main cause of differences between the results of the two complete test series.

3.1 Roughness after wear testing

The tests done with water as a lubricant show a decrease in R_a with increasing time after 200 h, where the average R_a is 0·02 μm. The scatter around the average values for one time interval at various loads decreases with increasing time. The data from the tests done under ambient conditions show that the R_a values at various loads approximate an average of about 0·1 μm. The scatter around this average decreases with increasing time. The R_a of surfaces worn under ambient conditions is higher than the R_a of surfaces worn with water as a lubricant. No relation is found between R_a and normal load.

3.2 Strength after wear testing

After a period of running in, the strength of the Mg-PSZ does not vary significantly with time, at least

Table 3. Results of the wear tests performed with water as a lubricant on initially ground surfaces for Mg-PSZ

Time (h)	*Load (N)*	$\sigma_{3pb} \pm S$ *(MPa)*	R_a *(μm)*		*Mg-PSZ*		*Stavax*	
			Mg-PSZ	*Steel*	W_v *(mm³)*	*K (m²/N)*	W_v *(mm³)*	*K (m²/N)*
Ground D46		915 ± 56	0·21		—		—	
Polished		761 ± 33	0·025					
20	14	838 ± 50	0·11		0·2	1·4E − 16	1	7·1E − 16
70	14	784 ± 26	0·094		3	6·1E − 16	53	1·1E − 14
200	14	790 ± 107	0·005		6	4·3E − 16	183	1·3E − 14
20	19	767 ± 19	0·17		2	1·0E − 15	26	1·4E − 14
70	19	740 ± 23	0·046		5	7·5E − 16	94	1·4E − 14
200	19	747 ± 19	0·017		4	2·1E − 16	120	6·3E − 15
20	34	715 ± 45	0·11		4	2·1E − 15	21	6·1E − 15
70	34	718 ± 29	0·075		12	1·0E − 15	108	9·0E − 15
200	34	719 ± 26	0·034		20	5·8E − 16	163	4·8E − 15
200	**34**	**733 ± 26**	**0·041**	**0·059**	**15**	**4·4E − 16**	**101**	**2·9E − 15**

Strength values determined with a three point bend test are given as σ_{3pb}. The number $xE - y$ stands for $x \cdot 10^{-y}$. All results given as $X \pm S$ stand for the average X and the sample standard deviation S. The results written in bold type are the results of the reproducibility tests.

Table 4. Results of the wear tests done to compare the different test conditions and the different initial surface preparations

Time (*h*)	*Load* (*N*)	$\sigma_{3pb} \pm S$ (*MPa*)	R_a (*μm*)	*Mg-PSZ* W_v (*mm*^{3})	*Mg-PSZ* *K* (*m*^{2}/*N*)	*Stavax* W_v (*mm*^{3})	*Stavax* *K* (*m*^{2}/*N*)
Ambient conditions, ground Mg-PSZ							
172	14	812 ± 31	0·304	26	2E−15	242	2E−14
200	19	777 ± 42	0·314	38	2E−15	350	2E−14
70	34	813 ± 28	0·128	122	1E−14	80	7E−15
With water as a lubricant, polished Mg-PSZ							
200	14	791 ± 46	0·004	2	1E−16	3	2E−16
70	19	774 ± 43	0·019	3	4E−16	33	5E−15
70	34	792 ± 30	0·011	8	7E−16	75	6E−15
200	34	766 ± 41	0·015	26	8E−16	243	7E−15

Strength values determined with a three point bend test are given as σ_{3pb}. The number $xE-y$ stands for $x \,.\, 10^{-y}$. It is concluded that the test condition is the dominant factor and not the initial surface preparation.

until 200 h of testing. The strength after wear with water as a lubricant is less than the strength after testing under ambient conditions at $P = 34$ N.

The relations between load and strength are illustrated in Figs 2 and 3. The data from the tests done with water as a lubricant are shown in Fig. 2. Starting with a ground surface, which has a strength of about 915 MPa, the strength decreases with increasing load. Starting with a polished surface, there is a slight increase in strength at $P = 14$ N and a decrease in strength at higher loads. The strength at $P = 34$ N of initially ground Mg-PSZ is significantly less after wear with water as a lubricant than the strength of initially polished or ground Mg-PSZ worn under ambient conditions. The strength of initially polished Mg-PSZ after wear with water as a lubricant lies between the results of the tests done under these two conditions.

The data from the tests done under ambient conditions are shown in Fig. 3. The strength at $P = 19$ N is clearly less than the strength at $P = 34$ N. All strength values are larger than the strength of polished Mg-PSZ and less than the strength of ground Mg-PSZ.

3.3 Wear volume

The relation between wear volume and time, excluding some extreme results explained by the anomalous sample shape, is approximately linear, according to

$$W_v = c_1 t$$

with W_v as wear volume, c_1 as a constant and t as time. The relation between wear volume and load is also approximately linear, according to

$$W_v = c_2(P - P_c)$$

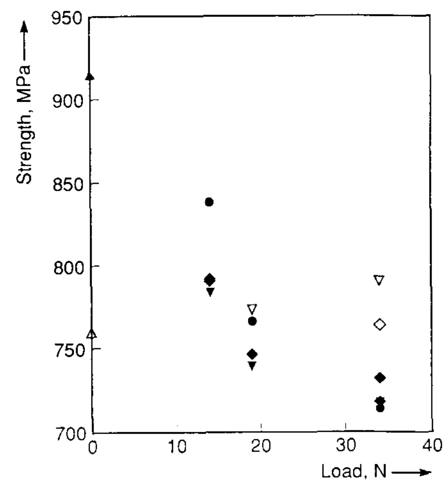

Fig. 2. Strength–load curve, showing the three-point bend strength of polished or ground Mg-PSZ after testing with water as a lubricant; polished: △, 0 h; ○, 20 h; ▽, 70 h; ◇, 200 h; ground: ▲, 0 h; ▼, 70 h; ◆, 200 h. See text for explanation.

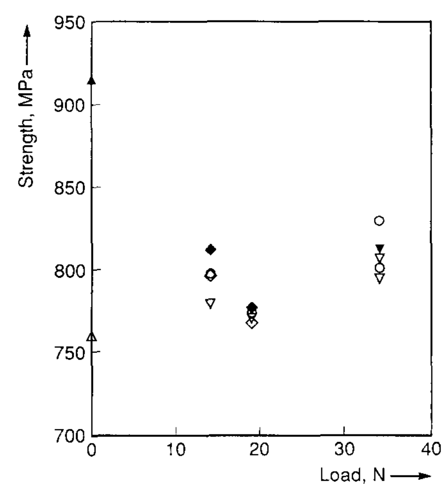

Fig. 3. Strength–load curve, showing the three-point bend strength of polished or ground Mg-PSZ after testing under ambient conditions; polished: △, 0 h; ○, 20 h; ▽, 70 h; ◇, 200 h; ground: ▲, 0 h; ▼, 70 h; ◆, 200 h. The strength at $P = 34$ N is higher than the strength at $P = 19$ N and higher than the strength of a polished surface. See text for further explanation.

with P as load and c_2 and P_c as constants. The values of these constants depend on testing conditions. A critical load P_c is suspected, below which there is hardly any wear.

3.4 Wear surface

The most essential observations from the wear surfaces and the wear debris are given in Figs 4–10. The observed phenomena occur more or less on most of the worn surfaces. The wear condition, ambient or with water as a lubricant, determines the relative frequency of the characteristics of the wear surface. No influence of load or time interval is observed.

Two mechanisms (adhesion and abrasion) are found on samples worn under each condition. Gradual transitions between these mechanisms, as shown in Fig. 4, are found, but under each condition one mechanism dominates. The wear surface of the Mg-PSZ after wear under ambient conditions is mainly covered with steel (adhesion). Metallic film transfer is usually observed in the literature on wear of ceramic/steel couples.[3,4] An example of such a surface is shown in Fig. 5. The wear surface after wear with water as a lubricant is mainly abrasive, with patches of steel adhered to the ceramic. This steel is mainly located at the boundary of a sheet of Mg-PSZ which is still attached to the bulk material Observing a surface worn with water as a lubricant with interference contrast shows the preferential wearing of grain boundaries under these conditions (Fig. 7). This is also observed after testing a Mg-PSZ/Mg-PSZ couple in an acetic acid buffer solution.[5] The 'slip-stream' marks in Figs 6 and 7 are

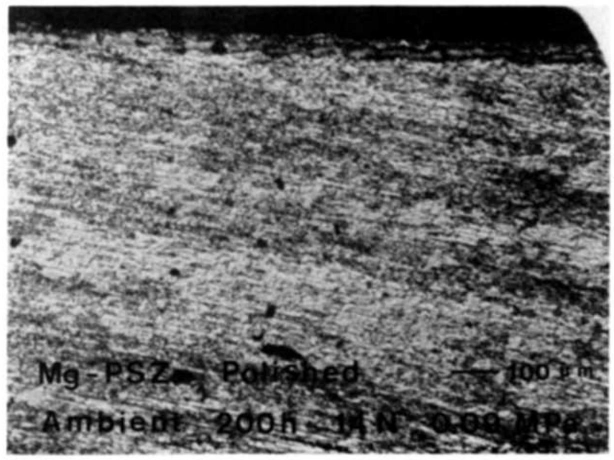

Fig. 5. Wear surface of initially polished Mg-PSZ after testing for 200 h, at a normal load of 14 N, equivalent to 0·09 MPa, under ambient conditions. The shown surface is characteristic for the adhesion dominating during wear under ambient conditions. Photograph taken with InCo.

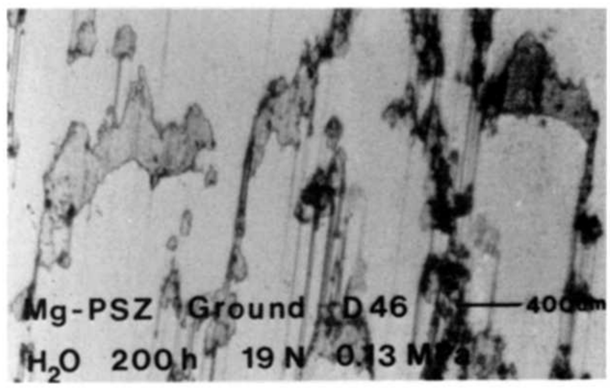

Fig. 6. Wear surface of initially ground Mg-PSZ after testing for 200 h, at a normal load of 19 N, equivalent to 0·13 MPa, with water as a lubricant. The adhered patches of steel and the 'slip-stream' marks are characteristic for wear with water as a lubricant. Sliding is from top to bottom. Photograph taken with InCo.

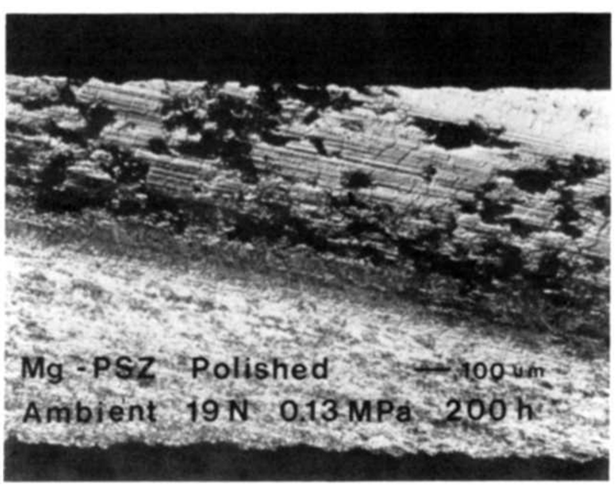

Fig. 4. Wear surface of initially polished Mg-PSZ after testing for 200 h, at a normal load of 19 N, equivalent to 0·13 MPa, under ambient conditions. A transition between the two characteristic wear surfaces is visible. Adhesion is the dominant mechanism during testing under ambient conditions. Photograph taken with interference contrast (InCo).

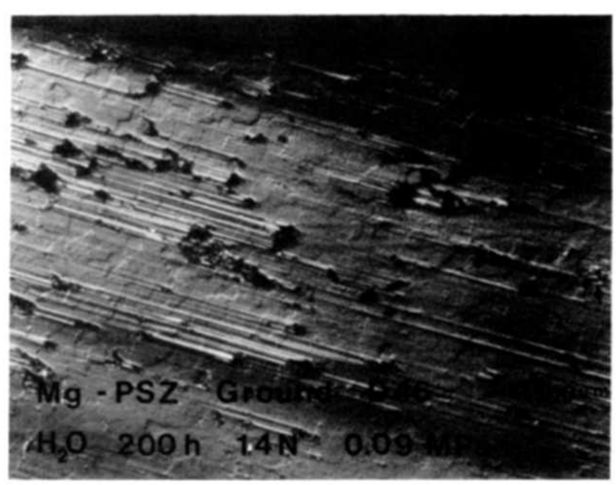

Fig. 7. Wear surface of initially ground Mg-PSZ after testing for 200 h, at a normal load of 14 N, equivalent to 0·09 MPa, with water as a lubricant. The 'slip-stream' marks, the clearly visible grain boundaries and the steel patches are characteristic for a surface worn with water as a lubricant. Sliding is from right to left. Photograph taken with InCo.

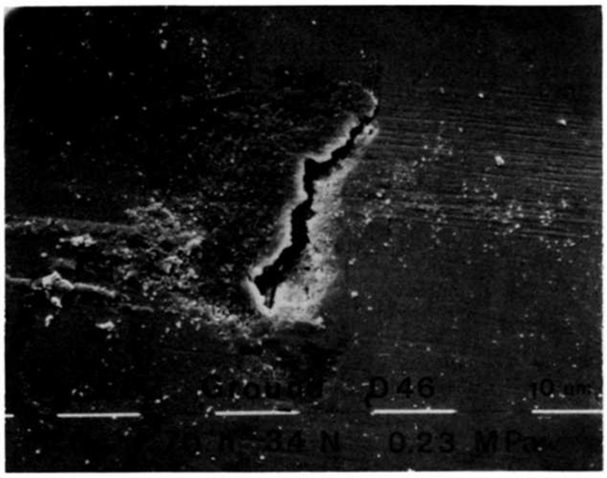

Fig. 8. Wear surface of initially ground Mg-PSZ after testing for 70 h, at a normal load of 34 N, equivalent to 0·23 MPa, with water as a lubricant. This surface shows clearly the perpendicularly oriented microcracks. Sliding is from right to left. Photograph taken with SEM.

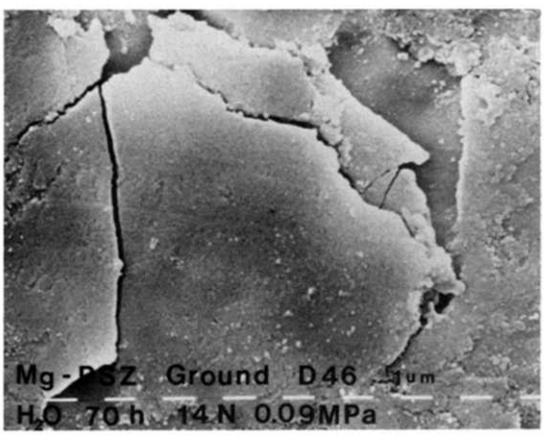

Fig. 9. Wear surface of initially ground Mg-PSZ after testing for 70 h, at a normal load of 14 N, equivalent to 0·09 MPa, with water as a lubricant. This surface shows the delamination and fracture of the Mg-PSZ. Sliding is from right to left. Photograph taken with SEM.

Fig. 10. Wear debris, Mg-PSZ and steel. The figure shows a sheet, containing Mg-PSZ on the visible surface (determined with EDAX) surrounded by oxidized steel spheres.

characteristic for surfaces worn with water as a lubricant. Microcracks, shown in Fig. 8, are often associated with adhered steel, and preferentially located at grain boundaries. Most of the surfaces show the delamination of sheets, as illustrated in Fig. 9.

The wear debris consists of oxidized steel spheres and thin sheets (Fig. 10). The composition of the sheets, examined with EDAX, is found to be either mainly steel, mainly Mg-PSZ, or steel and Mg-PSZ both in significant quantities.

4 Discussion

4.1 Roughness

The average R_a value and the scatter around the average for the tests done with water as a lubricant, and the scatter around the average for the tests done under ambient conditions are time dependent. This means there is still a time effect after 200 h which influences the local contact situation. A variation in load, resulting in an increase in the number of contact points rather than a change in shape and size of the contact points explains why the R_a is independent of load. The R_a values for the tests done with water as a lubricant on ground and polished Mg-PSZ are approximately equal, but they are significantly lower than the R_a values from the tests done under ambient conditions. This shows that the environmental test conditions, and not the initial surface preparation, will eventually determine the local contact situation.

4.2 Strength

The independence of the strength of Mg-PSZ from testing time indicates the continuous development of a residual stress layer during steady-state wear. After a period of running in, equilibrium is reached between the removal of material from the surface and the continuous development of a residual stress layer.

The strength data at $P = 14$ N and 19 N are about equal after wear under the two different conditions. At $P = 34$ N the strength of Mg-PSZ is significantly less after sliding with water as a lubricant compared to the strength after sliding under ambient conditions. This is explained by assuming that the residual stress layer developed due to sliding with water as a lubricant is smaller than the residual stress layer developed during sliding under ambient conditions. This difference is caused by a difference in friction coefficient or because of the higher temperature under ambient conditions. The closure effect on flaws is thus greater under ambient conditions at a load of 34 N than under conditions with water as a lubricant at the same load. Whether there is a difference in flaw size due to the different test conditions is still to be investigated. The fracture toughness measurements show that the fracture toughness is smaller when tested in water, but this does not result in a measurable decrease in strength afterwards. The strength after testing with water as a lubricant at $P = 34$ N is less than the strength of polished Mg-PSZ. This is consistent with observations made by scanning acoustic microscopy, which show a thinner residual stress layer after the mentioned wear test than after polishing.

The strength after testing under ambient conditions at $P = 34$ N is higher than the strength at $P = 19$ N. This indicates that the residual stress layer is enhanced by the stronger mechanical interaction. Under more severe conditions a higher strength should be reached.

4.3 Wear volume

The calculated value for the wear coefficient K is in most cases higher after testing under ambient conditions than after testing with water as a lubricant. The relative difference in these values of K are comparable to the differences given in Ref. 2. The influence of a decrease in fracture toughness due to the presence of water is not measurable. The calculated K is usually higher for the steel disk than for the Mg-PSZ, also as in Ref. 2, except for a few tests done under ambient conditions.

The relation between wear volume and time is approximately linear. This is in accordance with e.g. Archard's law.[17] The wear volume–load relation shows a threshold point, P_c, as discussed in Section 3.4, above which the wear volume suddenly increases. Since wear of Mg-PSZ is associated with lateral cracks, a change in wear mechanism at $P = P_c$ from wear by plastic deformation to wear by fracture is likely.

4.4 Wear mechanism

In Fig. 11, the characteristics of the proposed wear mechanism are illustrated. The mechanism is based on the results of the tests done under ambient conditions but, with adjustments, it is also applicable to wear with water as a lubricant. The difference in wear rate, expressed in the volume data, for these two conditions is probably explained by the different friction coefficients. More friction under ambient conditions results in more stress, and thus in higher stress concentrations.

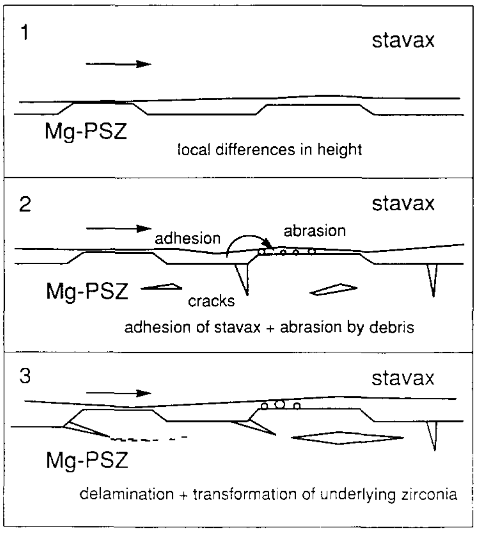

Fig. 11. Schematic illustration of the wear mechanism. See text for explanation.

At steady-state wear, there will be a certain surface topography on the Mg-PSZ (Fig. 11(1)). Plastically deforming steel will adhere to the Mg-PSZ, mainly in 'valleys' (Fig. 11(2)). The 'hills' are abraded by debris. This debris causes the 'slipstream' marks located behind the adhered patches. The stress pattern developed due to the sliding causes lateral and vertical cracks. In the third step, Fig. 11(3), the cracks grow, and sheets of Mg-PSZ delaminate. The sheets resulting from this delamination are found in the wear debris collected afterwards.

These observations correspond to the observations given in Ref. 6, where surface-initiated subsurface microcracks and plate-like debris particles are mentioned. The Mg-PSZ underneath the delaminated Mg-PSZ will transform to monoclinic zirconia. Under steady-state wear, there will thus be a continuous cycle of the removal of transformed material from the surface, and the transformation of the material which had been underneath this sheet. This transformation and the accompanying residual stress is thus restricted to thin layers at the surface. This will enhance the development of lateral cracks. The thickness of the sheets found in the wear debris is of the same order of magnitude as the thickness of the part of the residual stress layer which contains the largest stress.[12] Also, the development of subsurface lateral cracks is predicted in Ref. 11, where a mixed mode (shear and compression) stress state is used to model the sliding of brittle materials. In Refs 18–21 the stress state during sliding is used to predict delamination wear.

During wear with water as a lubricant, the R_a of the Mg-PSZ is of the same order of magnitude as the R_a of the steel. There will thus be less adhesion of steel to the Mg-PSZ, which corresponds with the above-mentioned observations.

4.5 Further considerations

The differences in hardness and yield stress for Mg-PSZ and the used steel are interesting. A polished Mg-PSZ surface models a situation free of residual stress. The hardness of polished Mg-PSZ is about 12 GPa, giving an estimate for the overall flow stress of 4 GPa. The critical transformation stress which is the onset of plastic deformation, however, is about 1·1 GPa[12,22,23] in a triaxial stress state. This value could be less in a biaxial stress state, but the exact relation between stress state and critical transformation stress is not yet clarified.[12] The hardened steel has a Vickers hardness of about 6·5 GPa. A rough estimate for the yield stress of the steel is given by one third of the hardness, although it could become significantly less under ambient conditions due to the increase in temperature. In Ref. 6, wear tests are described between PSZ and steel under ambient conditions at loads of 5–40 kg (50–400 N) and at velocities of 1 m/s and 4 m/s. The observations done on the surface of the PSZ are comparable to the observations described in this report. In Ref. 6, the high temperature and high plastic deformation at the PSZ/metal interface are mentioned.

The polished Mg-PSZ is thus the first material to yield due to the phase transformation. This plastic deformation influences the initial stages of the wear process, in particular the number and shape of contacts points. This results in a change in local pressure.

Gradually, as a consequence of the phase transformation, the Mg-PSZ is strain hardened. The critical transformation stress, responsible for initial yield, is 1·1 GPa, but for complete transformation a stress of probably more than 3·5 GPa is required in an equibiaxial stress state.[12] If thermal effects are neglected, the strain hardening will raise the yield stress of the Mg-PSZ, until it is equal to the yield stress of the steel. After this point, the local pressure is assumed to remain constant, at a level close to the yield stress of the steel. This will also hold for other wear couples with Mg-PSZ. This consequence has to be verified experimentally.

Finally, in a steady-state situation, the partly transformed surface of Mg-PSZ will deform the steel surface plastically. The patches of steel adhered on the Mg-PSZ are examples of plastically deformed steel.

An initially ground Mg-PSZ surface will then initially plow through the steel, until the residual stress layer on the Mg-PSZ caused by grinding is removed. The wear conditions will then determine the residual stress profile as described in Section 4.4.

A problem connected to the relation between residual stress and wear is the relation between the phase transformation and the process which causes the transformation. The transformation can occur due to the temperature increase, due to the normal load or due to the transverse force. It is assumed that the influence of thermal energy during lubricated tests can be neglected. The lubricants are supposed to be active as cooling liquids. The temperature at the contact points during tests under ambient conditions seems to be high enough to cause the transformation, but it is not known what the temperature rise is quantitatively, and more importantly, it is not known how far the temperature rise goes into the heat-insulating material.

The normal force of the load is supposed to have no significant contribution to the transformation. The overall pressure is far less than the critical transformation stress. Incidental interactions between the Mg-PSZ surface and loose debris particles are assumed to be negligible, although they could well be the cause of the 'slip-stream' marks shown in Figs 5 and 6.

The tangential forces caused by the lateral movement between the two materials are supposed to be the main cause of the phase transformation. It is thus interesting to investigate the relation between friction and residual stress.

5 Conclusions

(1) The roughness of worn Mg-PSZ is independent of the load. This indicates an increase in the number of contact points with increasing load, and not a change in shape and size of contact points.
(2) The R_a of Mg-PSZ worn with water as a lubricant decreases to 0·02 μm after 200 h. The R_a of Mg-PSZ worn under ambient conditions approaches an average of 0·1 μm after 200 h. The scatter around average R_a values decreases with increasing time under both conditions.
(3) The environmental conditions determine the wear behaviour of the Mg-PSZ at the local contact points after a period of running in. The influence of the initial surface preparation is negligible after a period of running in.
(4) The strength of Mg-PSZ is independent of wear time after a period of running in.
(5) The residual stress layer is the strength-

dominating factor after polishing, grinding and wear, all three as described in this paper.

(6) The wear volume is approximately linear with time.

(7) There is a threshold load in the wear volume–load retention. This threshold load could indicate the transition of wear by plastic deformation to wear by fracture.

(8) The following wear mechanism is proposed for the steady state situation:

—Adhesion of steel on the partly transformed surface of the Mg-PSZ, in the lower parts of the surface topography of the Mg-PSZ, either in large quantities (ambient conditions), or in smaller amounts (with water as a lubricant).

—Abrasion of the higher parts of the surface topography of the Mg-PSZ caused by the wear debris.

—The development of perpendicular and lateral cracks in the Mg-PSZ.

—The delamination of sheets of either Mg-PSZ, steel or Mg-PSZ plus adhered steel and the transformation of underlying zirconia.

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