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Surface Finish and Mechanical Properties of Commercial Aluminas

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Abstract

In this work the influence of two different grinding procedures, longitudinal and planetary, on the mechanical properties of two commercial aluminas has been investigated. In order to check if the technological history, as a consequence of the grinding procedures, can be reduced and/or eliminated, the investigation has been extended also to sample batches in which the surface subjected to tensile stress was finished by lapping. The experimental results, discussed in terms of machining parameters, have been analysed from the point of view of roughness, microstructure and flexural strength. In addition, an extensive microscopic examination of fracture surfaces has been performed in order to establish the relationship between failure, pre-existing flaws and machining induced surface damage. © 1996 Elsevier Science Limited.

Introduction

The increasing interest in advanced ceramics, as a potential substitute for traditional materials, results from their particular properties such as high surface hardness and flexural strength, low friction, high wear resistance, high temperature resistance and chemical stability. However, the intrinsic brittleness, high stiffness, low fracture toughness and poor impact resistance of these materials limit their extensive use. These peculiar properties make dense ceramics difficult to machine and where possible, machining processes should be avoided. Ceramic material can be removed by mechanical, thermal or chemical action. Mechanical methods are most commonly used and are widespread.[1] The finishing processes are necessary to attain the design dimensions and tolerances and can be critical. The processes employed, however, often induce flaws which have a negative influence on the mechanical strength of the piece. A variety of mechanisms are involved during machining brittle materials: elastic/plastic deformations, phase transformations, microcracking, crack propagation, dislocations and sliding phenomena. Grinding and lapping with diamond abrasives are widely employed machining procedures for finishing ceramic components and represent the major contribution to processing costs. For this reason, research and development of net shape forming technologies continues to be of prime importance. Even though much progress has been made in this respect, machining to achieve very close tolerances along with surface finishing are often required for items such as human prostheses, bearings, thread guides, seals and laser ceramics.

The surface finishing processes often result in serious damage in the form of both residual stresses, tensile and compressive, and surface and sub-surface cracks. In particular grinding procedures induce compressive stress near the surface.[2] These deleterious effects can be reduced by optimising the machining parameters, such as grit size of the abrasive, wheel bond, wheel speed, cooling lubricant fluid, downfeed and abrasive steps. There are several procedures which can be used to remove surface and sub-surface flaws and reduce the consequent stress concentrations after grinding, such as lapping, annealing, oxidation, chemical etching, surface compression and flame lapping.[3] Lapping and annealing, probably the most common post-machining procedures, lead to improved properties by removing the worst surface damage produced by the previous steps and relieving the residual stresses through healing of sub-surface flaws and crystallisation of glassy phases, where present. The residual stresses can sometimes increase flexural strength but often contribute to a general decrease in strength. In some materials such as zirconia ceramics, the increase in volume and distortion of the microstructure that occurs as a result of the tetragonal → monoclinic phase transformation induces a residual stress field which produces a toughening effect.

One of the most important factors in determining the residual strength of machined ceramic materials concerns the microstructure. The effects of the machining rate and grinding procedure (such as the surface finish and flexural strength) as well as the grinding force necessary to produce a given result are influenced considerably by the grain size and porosity of the material being processed.[4]

The material removal, the mechanism of which is controlled by brittle fracture, can generate widespread damage at the surface of ceramic materials thus compromising their mechanical properties and integrity.[5] The mechanism of material removal, as a consequence of surface finishing processes, combined with the residual stresses, contributes to the development of flaws, which in turn may have a considerable effect on the strength.[6] The interaction of abrasive grains with the surface of ceramic materials is considered similar to the effects induced by a sliding indenter.[7,8] In particular when a sharp indenter is pressed into a ceramic surface, a critical load value exists, at which lateral and radial cracks develop, responsible for material removal and loss of strength, respectively.[9] A plowing abrasive grain produces a more complex system of cracks,[10,11] the overlapping of which leads to a reduction in strength as well as anisotropic strength behaviour.

The objective of the present work was to study: (i) the effects of two different procedures of grinding machining on the flexural strength of two commercial alumina ceramics, (ii) the effect of lapping on the flexural strength of materials, initially ground in the same way, (iii) the influence of the microstructure of the materials tested on the machining procedure and the final strength behaviour, and (iv) the role of pre-existing defects such as porosity, agglomerates and grain size, and machining-induced surface damage on flexural strength.

Experimental Procedure

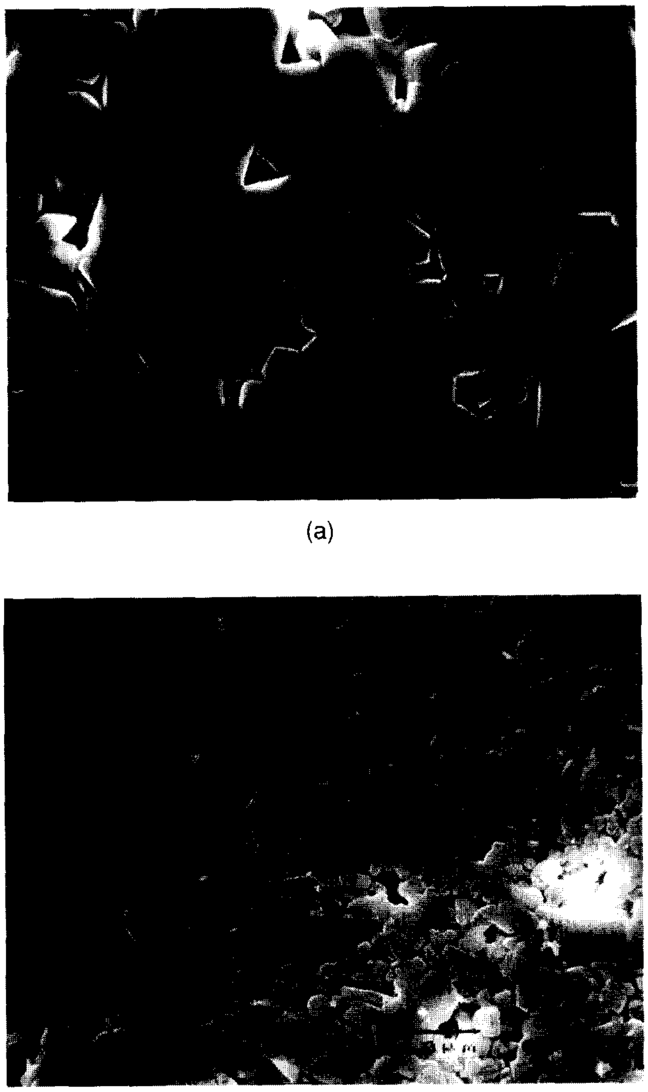
Two commercial alumina ceramics, commonly employed in Italy, with different microstructures, referred to from now on as alumina A and alumina B were investigated. Their main physical-mechanical characteristics are reported in Table 1.

Alumina A is a compacted material, characterised by a dishomogeneous microstructure with small slightly elongated grains and occasional large grains, more than 10μm in size (Fig. 1(a)). Alumina B is a low purity alumina, 90wt%, with many intrinsic defects, characterised by the presence of agglomerates and porosity; the grains are very small and elongated, with average dimensions grouped in a narrow range (Fig. 1(b)). Reported in Fig. 2 are the histograms of the grain size distribution of both alumina ceramics, obtained with the Graftek Optilab (version 2.1) software after digitising the images in order to count the grains and automatically measure the geometric parameters. Elaboration of the data was carried out with a base of at least 150 grains for each material, including minimum and maximum grain size, shape factor, area of each grain together with other morphological characteristics. SEM examinations of fractured surfaces of the two materials show, for alumina A, a small amount of round

Table 1. Physical-mechanical characteristics of the materials

Characteristic	*Alumina A*	*Alumina B*
Density (g/cm^3)	3·70	3·57
Al_2O_3 content (wt%)	95·0	90·0
Average grain size (μm)	4·2	1·8
E (GPa)	320	265
HV_{20} (GPa)	10·78	9·98
K_{IC}* (MPam$^{0·5}$)	5·67	3·17

*Vickers indentation technique (Anstis *et al.* formula).



(a)

(b)

Fig. 1. SEM micrograph showing the thermal etched surface of (a) alumina A, and (b) alumina B; ├─┤ is 1·5μm.

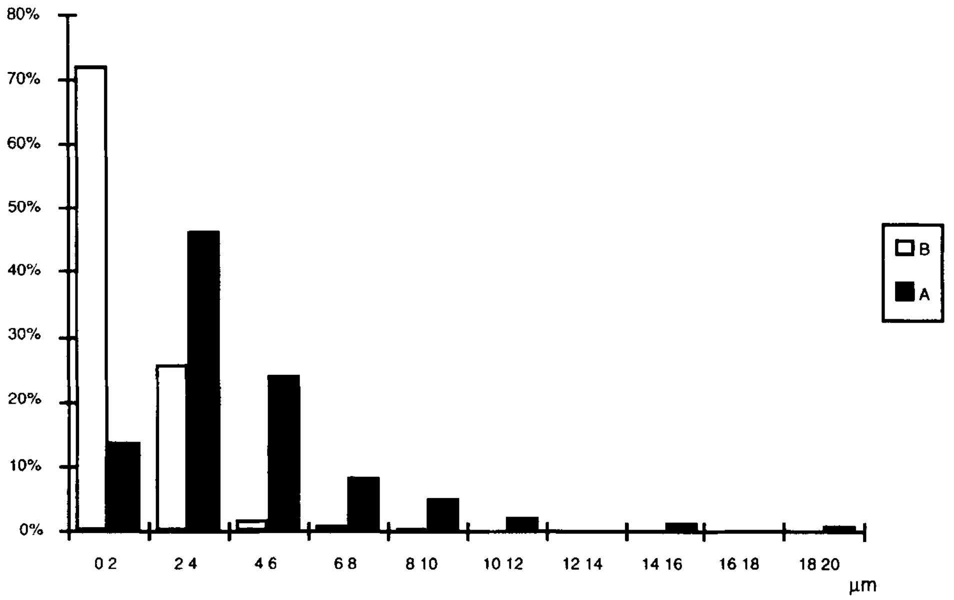
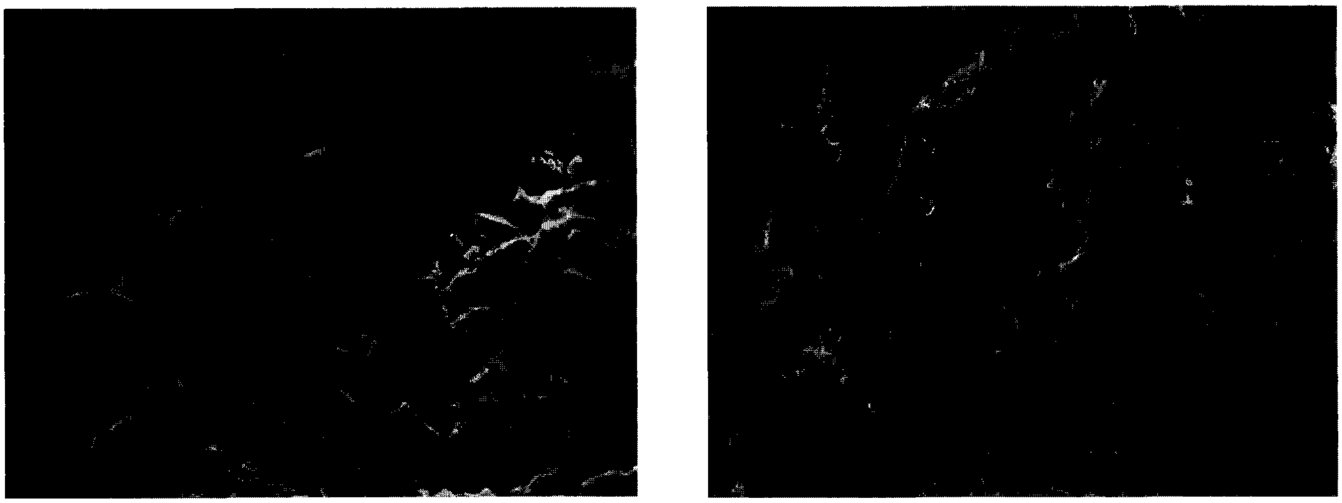


Fig. 2. Grain size distribution of the two alumina ceramics.

and mainly transgranular pores (Fig. 3(a)); while for the alumina B the porosity is always very low and is mainly due to elongated cavities connected with the starting powder agglomerates (Fig. 3(b)).

Test pieces in the shape of rectangular bars (2·0×2·5×25·0mm^3, edge cut and tolerance ±0·2mm) were prepared from commercially available samples of the two aluminas supplied in the form of plates. The longitudinal edges of the test pieces were chamfered at approximately 45° to a distance of 0·12±0·03mm as measured along the face or side of the test piece. For each material, two batches of 25 specimens were wet-ground using in the first machining steps diamond abrasive mounted in a matrix of soft metal. The final steps were performed on two different grinding tool machines, equipped with two grinding wheels of different geometry with diamond abrasive mounted in a matrix of organic resin: (i) M1, longitudinal grinding method, on a Tacchella (Italy) surface grinder, and (ii) M2, planetary grinding method, on a Brother (Japan) surface grinder. The grit of abrasive diamond particles, the bonding matrix of the grinding wheels, and the cut depth were kept constant. The two grinding procedures are illustrated schematically in Fig. 4(a) and (b). The parameters chosen for the grinding procedures M1 and M2, summarised in Table 2, are industrial parameters commonly adopted for machining ceramic materials. Furthermore, for each material, another two batches of samples (each batch consisting of 25 specimens) were prepared according to the aforementioned grinding conditions and then lapped on the surface to be subjected to tensile stress, using an orbital lapping tool machine, equipped with a 230mm in diameter lapping disk. Lapping was carried out at 110rpm, using a 3µm



(a) (b)

Fig. 3. SEM micrograph showing the fractured surface of (a) alumina A, and (b) alumina B.

diamond polishing paste, and a specific normal force $Fn = 49{\cdot}1$MPa. The lapping operations were carried out following the machining procedures specified in the final draft of En 843-11 regarding: *Advanced technical ceramics — Monolithic ceramics — Mechanical properties at room temperature — Part 1: Determination of flexural strength.*

The surface roughness of the ground and lapped samples was measured with a profilometer Hommel Tester T2000 (Germany), equipped with a stylus tip radius of less than 5μm.

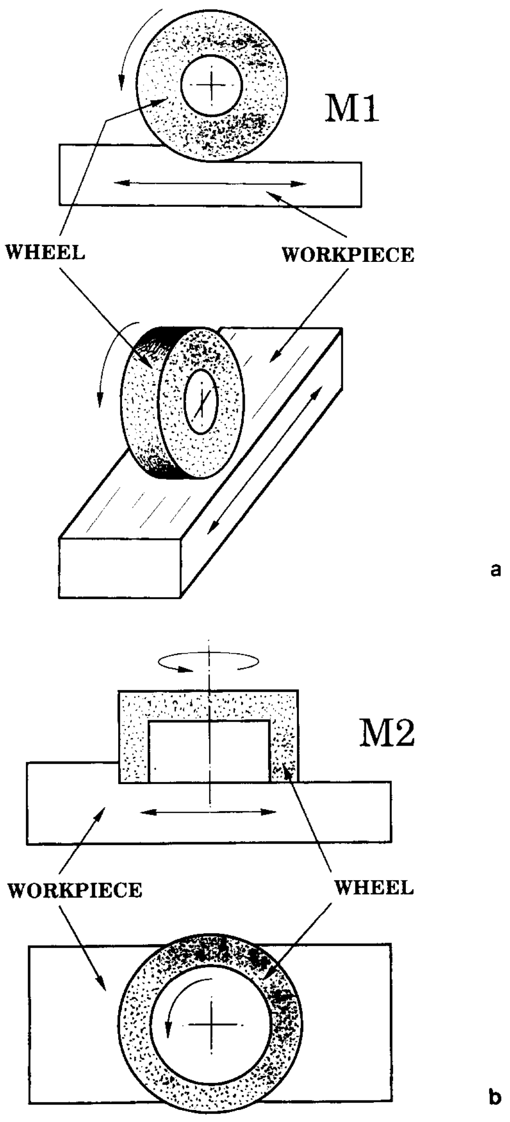


Fig. 4. Schematic view of the experimental set-up (a) M1, and (b) M2.

Table 2. Grinding parameters and procedures

Grinding parameter	*Grinding procedure*	
	M1	*M2*
Wheel revolutions (rpm)	1750	6000
Wheel grit (μm)	63–74	63–74
Cut depth (mm)	0·002	0·002
Table feed (mm/min)	15 000	2000

The flexural strength was evaluated by breaking all the samples in a four point bending fixture with an outer roller span of 20mm and an inner roller span of 10mm at a crosshead rate of 0·5mm min^{-1}, using a J&J M30K (UK) testing machine. Analysis of the fracture data involved calculating the average flexural strength values, the corresponding standard deviations and Weibull's modulus via the method of least squares linear regression which provides a less precise but conservative estimate. The Weibull's estimator used in the present investigation was $P_n = (i - 0{\cdot}5)/N$.[12]

In order to recognise the failure origin and the role of pre-existing and machining-induced flaws, the fracture surfaces of most of the halved bar pieces after the flexural strength test were observed with a scanning electron microscope JEOL T330 (Japan).

Results and Discussion

The values of average and maximum surface roughness (R_a and R_m, respectively) of the differently ground sample batches are reported in Table 3. For the same alumina, the two grinding procedures M1 and M2, do not affect the surface roughness. The R_a values are more linked to the microstructural features rather than the machining parameters, larger grain size led to higher R_a values.[7,13]

Lapping drastically reduces the surface roughness and for both aluminas the mean roughness values become closer. The maximum roughness values R_m, are essentially unchanged, because they correspond to the depth of pre-existing porosity of the materials, uncovered by the machining process.

Reported in Table 4 are the average flexural strength data, their standard deviations and the respective Weibull's moduli.

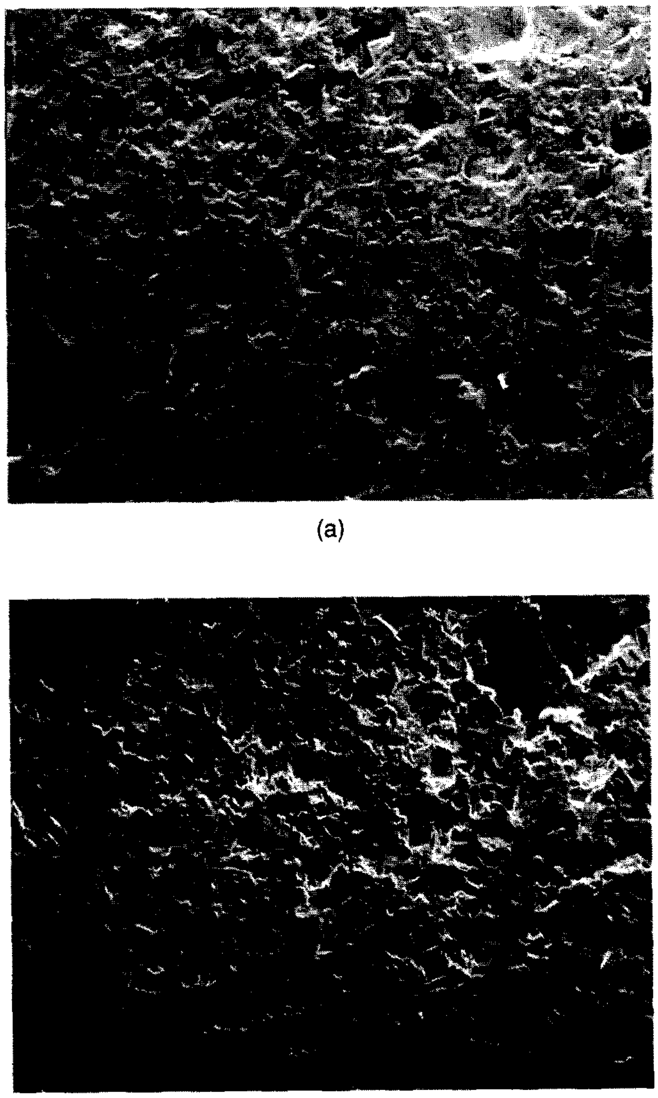
For alumina A, the passage from longitudinal grinding procedure M1, to planetary grinding procedure M2, results in a significant increase in flexural strength, about 13%, while there is a slight decrease in Weibull's modulus. The surface of the alumina, ground following the M1 grinding procedure, shows numerous rather large cavities due to

Table 3. Surface roughness, average R_a and maximum R_m values

Machining procedure	*Alumina A*		*Alumina B*	
	R_a (μm)	R_m (μm)	R_a (μm)	R_m (μm)
M1	0·60±0·02	8·29	0·38±0·02	5·52
M1 + Lapping	0·18±0·06	7·23	0·18±0·01	4·52
M2	0·59±0·05	6·67	0·42±0·02	9·16
M2 + Lapping	0·12±0·04	5·84	0·19±0·02	4·83

Table 4. Flexural strength and Weibull's modulus of differently machined aluminas

Machining procedure	*Alumina A*		*Alumina B*	
	σ (MPa)	m	σ (MPa)	m
M1	226·1±17·8	15·0	263·9±32·5	9·4
M1 + Lapping	292·8±20·2	17·3	285·5±35·5	9·6
M2	255·1±23·0	13·4	254·4±28·0	10·8
M2 + Lapping	278·1±26·0	13·0	262·4±24·1	13·1

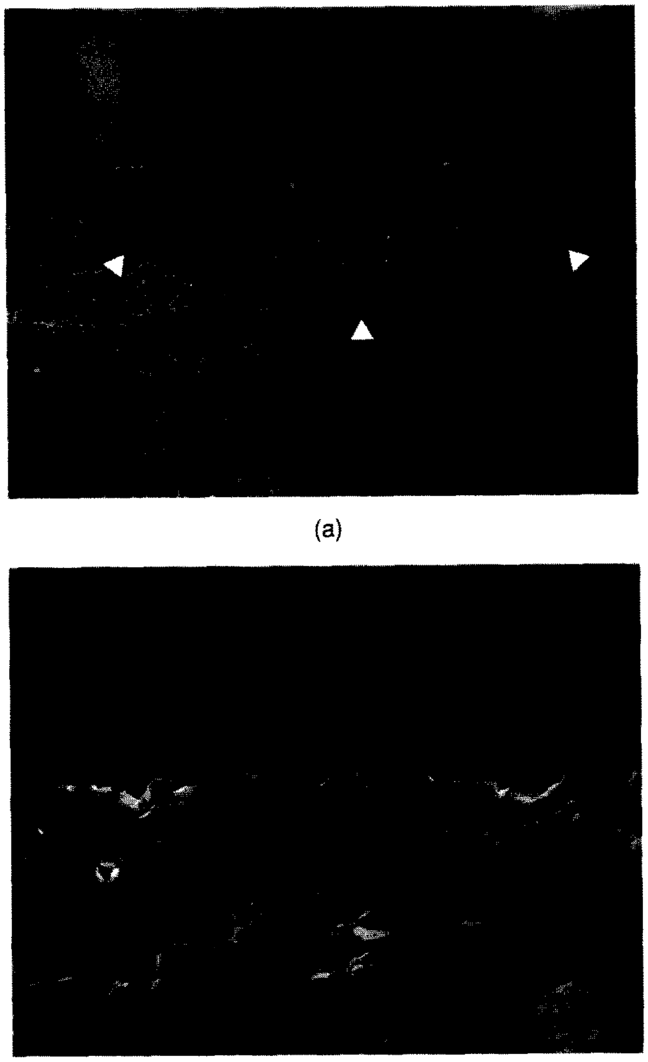

(a)

(b)

Fig. 5. SEM micrograph of alumina A, (a) surface, ground following the M1 procedure, and (b) surface, ground following the M2 procedure; ⊢⊣ is 6μm.

grain pullout (Fig. 5(a)). The observations of the fractured surfaces reveal that the fracture origin of many bars, ground following the M1 grinding procedure, is due to these surface defects created by grain pullout (Fig. 6), whose sharpened morphology contributes to weaken the mechanical strength. Furthermore, these kinds of defects can interact with deleterious effects on the strength (Fig. 7(a) and (b)).

Fig. 6. SEM micrograph of the failure origin for a bend bar of alumina A, M1 grinding procedure; ⊢⊣ is 2μm.


(a)

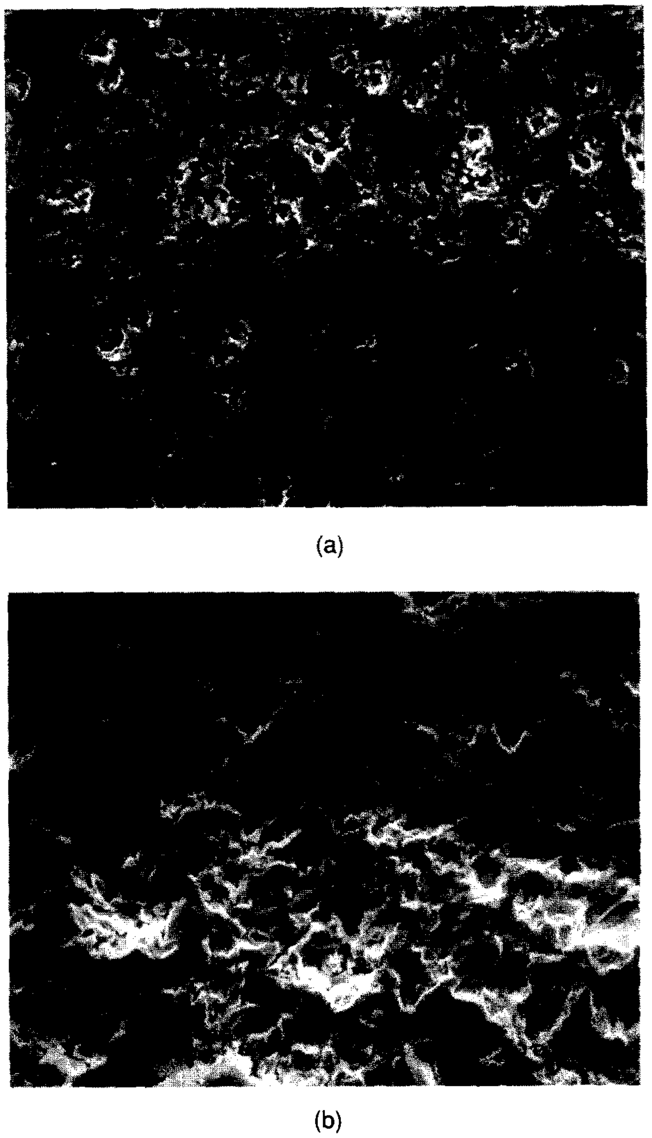
(b)

Fig. 7. SEM micrograph of (a) mirror area in a fractured bar of alumina A, M1 grinding procedure, and (b) magnification of (a) showing the failure origin.

When M2 grinding procedure was used, the surface of the alumina A test pieces (Fig. 5(b)), even though rather rough, does not present the

Fig. 8. SEM micrograph of a fracture surface of alumina A, M2 grinding procedure. The cracked grain acted as failure origin.

Fig. 9. SEM micrograph of a surface of alumina A ground following the M2 procedure and subsequently lapped.



(a)

(b)

Fig. 10. SEM micrograph of alumina B ground following the M2 procedure, (a) surface, and (b) magnification of (a).

cavities caused by grain pullout, but rather small microcracks inside the grains. The surface shows plastically deformed areas, also involving large grains. These transgranular cracks, caused by grinding, are smaller than the cavities induced by grain pullout, are more numerous and result in increased flexural strength (Fig. 8). Nevertheless these flaws determine larger data scattering, as seen from the Weibull's modulus. Lapping after grinding determines, for both the grinding procedures, a substantial improvement in flexural strength and, for the M1 grinding procedure only, an increase and reduced scattering in the Weibull's modulus. All the large defects caused by the two grinding procedures are almost completely eliminated by polishing. On the lapped surface, which is very smooth as seen in Fig. 9, only some small pits still remain.

For the fine grained alumina B, there is only a slight decrease in flexural strength with the M2 grinding procedure, about 4%, and the Weibull's modulus does not vary considerably. The fine grained material has a smoother surface than alumina A (Fig. 10(a)). The mechanism of material removal, acting in both the M1 and M2 grinding procedures, was always accompanied by plastic deformations. The presence of significant amounts of silicate and glassy phase, less hard and more easily deformable than alumina, can explain this behaviour. The surfaces of the ground bars were covered by a layer of plastically deformed material (Fig. 10(b)), which partially hides the many structural defects of the material, porosity and agglomerates. Microscopic examination of fracture surfaces showed that these pre-existing flaws were the failure origin for most of the samples, as seen from Fig. 11(a) and (b). The two grinding procedures do not significantly affect the flexural strength and the data scattering of alumina B. The flaws introduced by grinding are not larger than

(a)

(b)

Fig. 11. SEM micrograph, (a) defects present inside the alumina B, and (b) fracture surface of a bar of alumina B, ground following the M1 procedure, the porosity acted as failure origin.

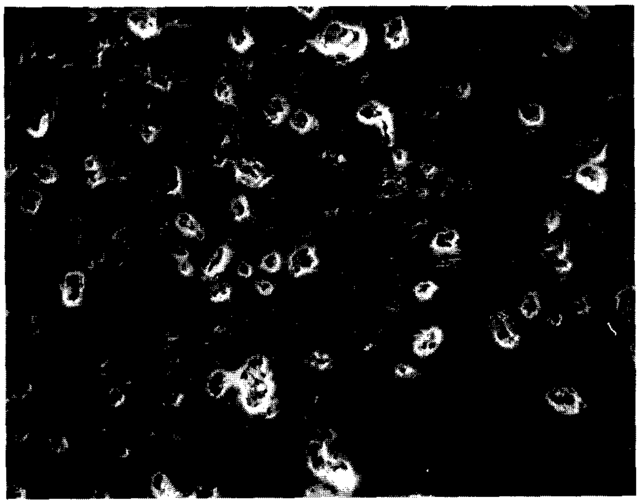


Fig. 12. SEM micrograph of a surface of alumina B ground following the M1 procedure and subsequently lapped.

the pre-existing microstructural defects and, as is well known, the extent of strength reduction depends on the ratio of the size of the pre-existing flaws to that of the flaws produced by the machining process.

Although the lapping process reduces the surface roughness (Fig. 12), it does not affect the bending strength and Weibull's modulus. This is in agreement with the previous behaviour, since, for this alumina, the intrinsic defects, are not caused by the differing grinding, the main cause of failure. Therefore in this case, lapping was not a significant machining process as regards the flexural strength behaviour. The relationship between the machining process employed for the two alumina ceramics, and their bending strengths is of particular interest.

For the coarse-grained and more pure material, alumina A, the different grinding procedures are able to introduce flaws that negatively affect the mechanical behaviour of the material. It is evident that the choice of grinding procedures can be very important in controlling the residual strength. Longitudinal grinding introduces larger machine-induced flaws that lead to lower values of flexural strength. As a result of minimised machining defects, alumina A reaches its higher strength values when the surface is polished.

For the less pure and fine grained material, alumina B, the choice of machining procedure does not play a significant role in controlling the mechanical performance. This less hard material presents, under grinding, a higher plastic deformation which prevents the development of large induced flaws. In these conditions, the pre-existing and concurrent larger flaws control the strength more than damage to the surface caused by machining.

Conclusions

In the present work the influence of two different grinding procedures on the mechanical behaviour of two commercial alumina ceramics was evaluated. Furthermore the effects of the grinding procedures on the fracture strength and surface roughness of the aluminas were estimated via a post-machining lapping process. The following observations can be made on the basis of the results obtained:

- The roughness measurement of the ground surfaces is not sufficient to evaluate the machining quality. Roughness values are more closely linked to the type of material than to the machining procedure.
- The two alumina materials investigated had very different responses to the grinding procedures chosen. For alumina A, the M2 grinding

procedure (planetary grinding) caused an increase in flexural strength, about 13%, while for alumina B the mechanical strength was only slightly affected by the two grinding procedures.

- The microstructure, grain size, agglomerates and porosity, can play a significant role in the material removal mechanism. When the pre-existing flaws are predominant and/or of the same size as those induced by machining, the grinding procedures have very little effect on the flexural strength, as seen from alumina B, and thus should be chosen on the basis of the costs. Furthermore, because in the case of alumina B, the finishing process (lapping) does not lead to a significant improvement in the flexural strength, the necessity for this final and expensive machining process should be carefully evaluated on the basis of the designated use of the components.
- The purity of the material, in particular the presence of glassy phases, can influence the material removal mechanism. Glassy phases always favour plastic deformations and can reduce the induced damage. Furthermore they can also heal, during a subsequent annealing process, induced sub-surface flaws, in particular median cracks.
- The lapping procedure can improve the flexural strength by removing the grinding-induced damage, as shown from alumina A, for the case that the concurrent pre-existing defects are smaller in size than the grinding-induced flaws.
- The previous points can be very important from an industrial point of view. The machining costs, the effective advantages of a machining procedure, a more correct application of ceramic components, the performances and the microstructure of the material all should be well known *a priori* in order to choose the best machining parameters to adopt.
- As a function of the specific application and the intrinsic characteristics, the machining procedures should be chosen such that the required surface condition is achieved with a minimum in machining costs and loss in strength.

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