
General paper

INTERRELATION ANALYSES OF MECHANICAL PROPERTIES
IN COMMERCIAL CERAMICS USING CATALOGED DATA

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Abstract: Under conditions specified in this work, mechanical properties of commercial alumina, silicon carbide, silicon nitride and zirconia ceramics were selected from published manufacturers' catalogs. Numerical data of the selected properties for materials of 254 kinds in total were finally compiled in a computer-readable database. Interrelations among these properties were analyzed by using the database, and analyzed results were discussed. The selected properties of Young's modulus, linear thermal expansion coefficient, bending strength, Vickers hardness and fracture toughness were correlated with an apparent porosity derived from the theoretical and bulk density. Relationships of the selected properties to the porosity were fitted to exponential functions, and a good fitness was confirmed in most of the cases with a few exceptions. In general, every mechanical property tended to decrease with increasing the porosity. Although the hardness variation with respect to the bending strength was expressed by a proportional relationship for alumina and silicon carbide, a power relation was more adequate for silicon nitride and zirconia. The relation between the fracture toughness and the bending strength was fitted to a power function. In this case, a good fitness was identified for silicon carbide and zirconia, though a poor correlation was found for alumina and silicon carbide. A specific crack length, which was used to modify a fracture mechanics criterion for small cracks, was well correlated with the bending strength by a power function.

Key words: Ceramics, Interrelation analysis, Porosity, Young's modulus, Linear thermal expansion coefficient, Bending strength, Vickers hardness, Fracture toughness, Database of cataloged data

1. INTRODUCTION

Ceramic materials are expected as candidate materials for high-performance structural components, though they have a disadvantage of large scatter in strength characteristics. From a statistical design aspect, especially, it is desired that databases on strength or its related mechanical properties of ceramics shall be constructed in a computer-readable style. It should be specially mentioned that two excellent databases on ceramic strength have already been established or published [1, 2]. Their contents, however, are mainly compiled by using data obtained in research works. A lot of data, which appear in manufacturers' catalogs of ceramics, are also important to understand the state of the arts because ceramic materials in such catalogs are practically used.

Recently, catalogs of ceramic materials from thirty-four Japanese manufacturers were collected by the 136th Committee, Japan Society for the Promotion of Science, so that a databook on properties of engineering ceramics could be published for the convenience of mechanical design. Ceramic materials, which have been picked out as structural ones in the collection activity, are as follows; 103 kinds of alumina, 20 of sialon, 39 of silicon carbide, 51 of silicon nitride and 48 of zirconia. Their mechanical properties were selected from cataloged data, and summarized in a databook [3]. Extensively stored data for various kinds of ceramic materials as in the databook enable us to have a lot of information about interrelations among their mechanical properties.

In this work, data as stated above were further selected under specified conditions, and compiled in a computer-readable database. By using the database, interrelations among selected mechanical properties were systematically analyzed to gain useful knowledge for mechanical design and/or material processing. Analyzed interrelations were also discussed.

2. TARGETS OF INVESTIGATION

2.1. Mechanical Properties as Targets

Mechanical properties included in the aforementioned databook [3] are as follows; bulk density, porosity, Young's modulus, hardness, fracture toughness, bending strength, compressive strength, linear thermal expansion coefficient, thermal conductivity, thermal shock resistance and maximum temperature to be used. Among these properties, six characteristics of bulk density, Young's modulus, hardness, fracture toughness, bending strength and linear thermal expansion coefficient, which are measured at room temperature, are selected for targets of investigation by considering the following situation. To clarify an interrelation among some properties, there should be somewhat many data on the properties. The six parameters as mentioned above can be often referred to
the databook for all ceramics, while the others including
the porosity are seldom seen in the databook.

It is noted that the porosity is one of the im-
portant parameters which directly reflect sintering
conditions of ceramics including additives used in processing.
Therefore, it is worth while investigating interre-
lations of mechanical properties to the porosity from
an aspect of material processing. Since the porosity
is a normalized parameter, it is also efficient to dis-
cuss its correlation to one of mechanical properties
in a relative comparison among ceramics with differ-
ent density. As stated above, however, the porosity
is rarely found in the databook. Consequently, an ap-
parent porosity \( p_{\text{ap}} \) is introduced in this work to be
related with other mechanical properties. The ap-
parent porosity is defined by using the bulk density \( \rho \)
as

\[
p_{\text{ap}} = 1 - \left( \frac{\rho}{\rho_{\text{th}}} \right),
\]

where \( \rho_{\text{th}} \) is the theoretical density of a ceramics un-
der consideration. The theoretical density to be used
in Eq. (1) is 3.98Mg/m\(^3\) for alumina, 3.50Mg/m\(^3\) for
silicon carbide, 3.40Mg/m\(^3\) for silicon nitride, and
6.10Mg/m\(^3\) for zirconia [4].

2.2. Construction of Database

A database on the aforementioned mechanical
properties of commercial ceramics was constructed us-
ing cataloged data from the databook [3] as well as
some data of several ceramics which have been pub-
lished by the author et al. [5-10]. The database
was compiled in a format of MS-Excel (the registered
trademark of Microsoft Corporation) work-sheet so
that interrelations among mechanical properties could
be analyzed on a personal computer. It is noted that
the database does not include all of cataloged ceramic
materials. An essential condition for a material to be
included in the database is that the bulk density of the
material is certainly described, provided that at least
one of Young’s modulus, hardness, fracture toughness,
bending strength and linear thermal expansion coef-
ficient should be also given for the material. For the
present, sialon was excluded from the database due to
the following reason. Twenty kinds of sialon were very
few in analyzing mutual relations between mechanical
properties, and five manufacturers producing sialon
ceramics were too limited, as compared with cases in
other four ceramics (see Table 1).

Numbers of material kinds and manufacturers for
each ceramic material, which is finally investigated in
this work, are listed in Table 1.

3. INTERRELATION ANALYSES AND DIS-
CUSSIONS

3.1. Relationships of Elastic Properties to
Porosity

Properties associated with elastic deformation
treated in this work are the Young’s modulus \( E \)
and the linear thermal expansion coefficient \( \alpha \). Since \( \alpha \)
is related to a thermal stress, the parameter is also
important in mechanical design. In this section, these
two properties are correlated to the apparent porosity.

3.1.1. Relation between Young’s modulus and
porosity

Figure 1 shows the Young’s modulus \( E \) correlated
with the apparent porosity \( p_{\text{ap}} \). Spriggs [11] stated
that the dependency of Young’s modulus on the poros-
ity is expressed as

\[
E = E_0 \exp(-b_E p_{\text{ap}}),
\]

where \( E_0 \) and \( b_E \) are constants. Approximated curves
depicted in Fig.1 are fitted to Eq.(2) by the least
squares method. Note that each curve in the figure
is drawn as an extrapolated curve out of a given data
range in order to be able to see the whole trend of the
correlation. This drawing style of extrapolated curves
is the same in the following figures.

Values of \( E_0 \) and \( b_E \) for each ceramic material are
listed in Table 2, where \( R \) is a correlation coefficient
in the fitting. It is revealed that the Young’s modulus
decreases as increasing porosity. When the Young’s
modulus is compared for a fixed apparent porosity in
Fig.1, it is found that the order of increase in the mod-
ulus is as follows; silicon carbide, alumina, silicon ni-
tride and zirconia. The same order is seen in the order
of \( E_0 \)-values in Table 2.

3.1.2. Relation between thermal expansion co-
efficient and porosity

The relation between the linear thermal expansion

coefficient $\alpha$ and the apparent porosity is shown in Fig. 2. By analogy to the Young’s modulus, the relation is approximated by an exponential function;

$$\alpha = \alpha_0 \exp(-b_\alpha p_{ap})$$

(3)

where $\alpha_0$ and $b_\alpha$ are constants. A curve fitted to Eq. (3) for each material is depicted in Fig. 2. The constants in Eq. (3) and the correlation coefficient are summarized in Table 3. The value of $\alpha_0$, which implies the thermal expansion coefficient of a material without porosity is found to be larger in the order of zirconia, alumina, silicon carbide and silicon nitride. It is also suggested that oxide ceramics have much larger thermal expansion coefficient than non-oxide ceramics.

In general, $\alpha$ tends to decrease as increasing the porosity. As compared with the case of Young’s modulus, however, the correlation coefficient is found to be very low, and the variation of $\alpha$ with respect to the porosity is not so remarkable. Although the relation between them was also fitted to a linear function, the correlation coefficient was almost equal to that in fitting by Eq. (3) for each material.

3.2. Relation between Bending Strength and Porosity

Bending strength $\sigma_b$ correlated with the apparent porosity is shown in Fig. 3. It is known that the relation of the strength to the porosity is also approximated by an exponential function [8, 12, 13]. So, curves in the figure are fitted to a function;

$$\sigma_b = \sigma_0 \exp(-b_\sigma p_{ap})$$

(4)

where $\sigma_0$ and $b_\sigma$ are constants. In Fig. 3, it is difficult to see a relative trend among ceramic materials, excepting alumina which shows the lowest strength. Table 4 presents values of $\sigma_0$ and $b_\sigma$ for each ceramic material. The constant $\sigma_0$ means the strength of a material with no porosity. Since the strength $\sigma_0$ for zirconia, silicon nitride, silicon carbide and alumina is larger in that order, it is suggested that the strength is generally higher in the same order as above when it is compared for a fixed porosity.

In general, $\alpha$ tends to decrease as increasing the porosity. As compared with the case of Young’s modulus, however, the correlation coefficient is found to be very low, and the variation of $\alpha$ with respect to the porosity is not so remarkable. Although the relation between them was also fitted to a linear function, the correlation coefficient was almost equal to that in fitting by Eq. (3) for each material.

Table 3. Parameters fitted for exponential relation between thermal expansion coefficient and porosity.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha_0$ (10^-6/K)</th>
<th>$b_\alpha$</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina</td>
<td>7.54 x 10^-6/K</td>
<td>0.319</td>
<td>0.38</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>4.32 x 10^-6/K</td>
<td>0.290</td>
<td>0.18</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>3.22 x 10^-6/K</td>
<td>0.313</td>
<td>0.31</td>
</tr>
<tr>
<td>Zirconia</td>
<td>9.32 x 10^-6/K</td>
<td>1.46</td>
<td>0.37</td>
</tr>
</tbody>
</table>

For instance, the most popular loading mode in bending test is three- or four-point bending type using square-section specimens. In this case, the ratio $(\sigma_{4pb}/\sigma_{3pb})$ of four-point to three-point bending strength of specimens with the same shape is estimated as $[2/(m+2)]^{1/m}$ [15], where $m$ is the shape parameter in two-parameter Weibull distribution function. As the shape parameter $m$ is ranging from 10 to 20 in ordinary ceramics [ex. 14], the ratio of $(\sigma_{4pb}/\sigma_{3pb})$ for the two extreme $m$-values are calculated as 0.84 for $m = 10$ and 0.89 for $m = 20$. The result suggests that the influence of bending mode on strength scatter is not so large. As another factor, the loading rate also affects ceramic strength [ex. 16]. The differ-
ence in loading rate yields a larger scatter of strength in alumina, especially, which is more sensitive to the loading rate compared with other ceramics [ex. 14]. This may be related to a smaller \( R \)-value in alumina.

3.3. Hardness Related with Other Properties

The Vickers hardness \( HV \) is only considered in this work, though there are various types of hardness in the databook [3]. The hardness \( HV \) is the same as Vickers hardness number defined for metallic materials in ASTM Standard [17].

3.3.1. Relation between hardness and porosity

Figure 4 presents the Vickers hardness correlated to the apparent porosity. It is not well known what kind of function is available for fitting the relation between \( HV \) and \( \rho_{ap} \). As one of trials, a function similar to Eq. (4) is applied for the relation by considering a linear relationship of the hardness to the tensile strength, which is confirmed in metallic materials [ex. 18].

\[
HV = HV_0 \exp (-b_H \rho_{ap}) \tag{5}
\]

where \( HV_0 \) and \( b_H \) are constants. It is clarified that variations of the hardness with respect to the porosity in alumina and silicon nitride are well fitted to Eq.(5). Values of \( HV_0 \) and \( b_H \) for alumina and silicon carbide are shown in Table 5.

On the other hand, relations for silicon nitride and zirconia cannot be well fitted to Eq.(5), i.e., the correlation coefficient is around or less than 0.3. This may be attributed to the fact that hardness data for these materials are restricted only in a short range of porosity less than 0.1. In Fig.4, relations for silicon nitride and zirconia are presented by horizontal lines, levels of which are equal to mean values of hardness for the two ceramic materials. In Table 5, the mean hardness shown in Fig.4 is listed as values of \( HV_0 \) for silicon nitride and zirconia.

3.3.2. Relationship of hardness to strength

It is known that the Vickers hardness \( HV \) in metallic materials is proportional to the tensile strength \( \sigma_B \) or the flow stress \( \sigma_{flow} \) such as \( HV \approx 0.3 \sigma_B \) [18] or \( HV \approx 0.3 \sigma_{flow} \) [19], where \( \sigma_B \) or stress is in MPa. By analogy, the bending strength \( \sigma_b \) instead of the tensile strength \( \sigma_B \) is applied in correlating the hardness. Figure 5 indicates the relation between the hardness and the bending strength, in which the relation of \( HV = 0.3 \sigma_b \) is drawn with a dot-dash-line. The hardness variations for alumina and silicon carbide can be approximated by a similar proportional relation;

\[
HV = C_H \sigma_b \tag{6}
\]

where \( C_H \) is 4.3 for alumina and 4.2 for silicon carbide.

On the other hand, no proportional relationship is identified for silicon nitride and zirconia. In these materials, a saturated tendency of the hardness appears in a region of higher strength. In approximating relations for silicon nitride and zirconia, a power function is adopted as the best fitting one of asymptotic functions such that the hardness converges to 0 as the strength reduces to 0. The curves for silicon nitride and zirconia in Fig.5 are expressed by

\[
HV = HV' (\sigma_B)^q \tag{7}
\]

where \( HV' = 457 \) and \( q = 0.183 \) with a correlation coefficient of \( R = 0.48 \) for silicon nitride, and \( HV'_0 = 341 \) and \( q = 0.187 \) with \( R = 0.54 \) for zirconia.

Although a proportional relation is confirmed in alumina and silicon carbide, the proportional coefficient \( C_H \) is much larger than 0.3 which is expected in metallic materials. In ceramic materials, especially, it should be noted that the tensile strength \( \sigma_B \) is less than the bending strength \( \sigma_b \) due to the size effect as described in Sec.3.2. The relation of \( \sigma_B \) to \( \sigma_b \) is
estimated by the next equation [20],

\[ \sigma_b = f(m) \sigma_0, \]  

(8)

where \( f(m) \) is a function of \( m \); \( f(m) = [2(m+1)^2]^{1/m} \) for three-point bending and \( f(m) = [4(m+1)^2/(m+2)]^{1/m} \) for four-point bending, respectively. Since the value of \( f(m) \) calculated for \( m = 10 \) and \( m = 20 \) ranges from 1.25 to 1.73, the proportional coefficient \( C_H \) is found to become much larger by combining Eq. (8) with Eqs. (5) and (6). Consequently, it is concluded that the same proportional relation as in metallic materials is not expected in ceramic materials even if the tensile strength is replaced by the bending strength. This is caused by a larger resistance for plastic deformation in ceramics compared with metallic materials.

3.4. Interrelation Analyses from Fracture Mechanics Aspects

In this section, fracture mechanics parameters derived from mechanical properties in the database are investigated in their interrelations.

3.4.1. Relation between fracture toughness and porosity

The fracture toughness \( K_C \) is correlated with the porosity in Fig. 6. There are various procedures to evaluate the fracture toughness \( K_C \) of ceramics [ex. 2], and evaluated \( K_C \)-values depend on the procedure. However, evaluating methods of \( K_C \) were not always specified in catalogs. In spite of a possible variation in \( K_C \)-value, Fig. 6 shows that the toughness tends to decrease as increasing the porosity.

\[ K_C \propto \sqrt{E/\gamma_C}. \]  

(9)

The Young's modulus is expressed by an exponential function of the porosity as seen in Sec. 3.1. It is also known [23] that the relation of the fracture energy to the porosity can be reasonably approximated by

\[ \gamma_C = \gamma_0 \exp(-b_e p_{ap}), \]  

(10)

where \( \gamma_0 \) and \( b_e \) are constants. Therefore, Eqs. (2), (9) and (10) yield another exponential relation of \( K_C \) with respect to the porosity as

\[ K_C = K_{CE} \exp(-b_K p_{ap}), \]  

(11)

where \( K_{CE} \) is a constant proportional to \( \sqrt{E/\gamma_0} \), and \( b_K = (b_E + b_e)/2 \).

Curves in Fig. 6 are fitted to Eq. (11), in which \( K_{CE} \) and \( b_K \) are listed in Table 6. As seen in the table, the toughness \( K_{CE} \) of a material with no porosity becomes higher in the order of zirconia, silicon nitride, silicon carbide and alumina. As compared with cases of silicon nitride and zirconia, the fitness by Eq. (11) is not good for alumina and silicon carbide as shown in Table 6. The poor fitness for these materials may be ascribed to their data concentrating in a restricted region of porosity around 0.1.

The toughness in a range of low porosity is efficient in actual, because it is suggested that the fracture mechanics approach cannot be applied for porous ceramics [8]. It should be noted, however, that a large scatter of \( K_C \) is seen in a region of low porosity.

Table 6. Parameters fitted for exponential relation between fracture toughness and porosity.

<table>
<thead>
<tr>
<th>Material</th>
<th>( K_{CE} )</th>
<th>( b_K )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina</td>
<td>4.00</td>
<td>1.94</td>
<td>0.29</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>5.27</td>
<td>2.69</td>
<td>0.40</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>7.57</td>
<td>4.08</td>
<td>0.83</td>
</tr>
<tr>
<td>Zirconia</td>
<td>8.19</td>
<td>3.11</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Fig. 6. Relation between fracture toughness and porosity.

The relation between the toughness and the porosity will be discussed. Based on the Griffith criterion [21], the energy release rate \((K_C)^2/E\) is proportional to the fracture energy \( \gamma_C \) which is later modified by Orowan [22]. The proportional relationship leads to

\[ K_C \propto \sqrt{E/\gamma_C}. \]  

(9)

The Young's modulus is expressed by an exponential function of the porosity as seen in Sec. 3.1. It is also known [23] that the relation of the fracture energy to the porosity can be reasonably approximated by

\[ \gamma_C = \gamma_0 \exp(-b_e p_{ap}), \]  

(10)

where \( \gamma_0 \) and \( b_e \) are constants. Therefore, Eqs. (2), (9) and (10) yield another exponential relation of \( K_C \) with respect to the porosity as

\[ K_C = K_{CE} \exp(-b_K p_{ap}), \]  

(11)

where \( K_{CE} \) is a constant proportional to \( \sqrt{E/\gamma_0} \), and \( b_K = (b_E + b_e)/2 \).

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<th>( b_K )</th>
<th>( R )</th>
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<tbody>
<tr>
<td>Alumina</td>
<td>4.00</td>
<td>1.94</td>
<td>0.29</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>5.27</td>
<td>2.69</td>
<td>0.40</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>7.57</td>
<td>4.08</td>
<td>0.83</td>
</tr>
<tr>
<td>Zirconia</td>
<td>8.19</td>
<td>3.11</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Fig. 7. Relation between fracture toughness and bending strength.

3.4.2. Relation between fracture toughness and bending strength

Ceramic materials with higher levels in both toughness and strength are preferable to mechanical applications. Now, the relation between the fracture toughness and the bending strength is investigated. Figure
7 indicates their correlation. Although a higher toughness is confirmed for materials with higher strength, the toughness seems to be saturated even if the strength is improved.

The relations are fitted to a power function;

\[ K = K_{CP} (\sigma_b)^s \]  \hspace{1cm} (12)

where \( K_{CP} \) and \( s \) are shown in Table 7. In this case, too, a poor fitness by Eq. (12) is seen for alumina and silicon carbide. This result may be owing to strength data limited around 500MPa in these materials.

Table 7. Parameters fitted for power relation of fracture toughness versus bending strength.

<table>
<thead>
<tr>
<th>Material</th>
<th>( K_{CP} )</th>
<th>( s )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina</td>
<td>1.27</td>
<td>0.179</td>
<td>0.23</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>0.689</td>
<td>0.276</td>
<td>0.33</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>0.190</td>
<td>0.518</td>
<td>0.78</td>
</tr>
<tr>
<td>Zirconia</td>
<td>0.613</td>
<td>0.360</td>
<td>0.74</td>
</tr>
</tbody>
</table>

3.4.3. Specific crack length

It is reported [5, 9, 10, 24-28] that fracture originating from a small flaw of size \( a \) in ceramics occurs at a lower stress than the estimated strength of \( \sigma_f = K_C/\sqrt{l} \); \( l \) is an equivalent crack length defined as \( l = a M_o^2 \) [5]. The multiplication factor \( M_o \) for \( K \)-estimation is determined by a crack geometry and/or a loading mode [ex. 29-32]. To deal effectively with the overestimation of \( \sigma_f \) for small cracks, the simplest and efficient procedure [9, 26] was proposed such as

\[ \sigma_f = \frac{K_C}{\sqrt{l + l_o}}. \]  \hspace{1cm} (13)

The parameter \( l_o \) is a specific crack length which is determined to express a central trend in dispersed experimental results for the relation of \( \sigma_f \) versus \( l \).

Although Eq. (13) is convenient from an engineering aspect, \( l_o \) must be determined experimentally through a tedious fractographic observation [ex. 9, 10]. To settle the problem, a reference crack length \( l^* \) was proposed to be used in estimating \( l_o \) as follows [10].

\[ l^* = \frac{1}{\pi} (\frac{KC}{\sigma_f})^2, \]  \hspace{1cm} (14)

where \( K_C \) and \( \sigma_f \) are cataloged fracture toughness and mean strength of a material under consideration. Figure 8 shows the relation between the length \( l_o \) determined experimentally and the reference crack length \( l^* \). A good correlation is found between the two length parameters for various materials and loading modes. A curve in Fig.8 is fitted to the following function with a correlation coefficient of \( R = 0.98 \).

\[ l_o = 6.09 \times 10^{-2} (l^*)^{1.87}. \]  \hspace{1cm} (15)

Equation (15) enables us to estimate the specific crack length \( l_o \) by using cataloged data. For instance, the specific crack length \( l_o \) evaluated by using Eqs.(14) and (15) is correlated with the bending strength in Fig.9. In this case, the best fitting was observed in the relation of \( l_o \) to \( \sigma_b \) by using a power function as

\[ l_o = L_o (\sigma_b)^n, \]  \hspace{1cm} (16)

where \( L_o \) and \( n \) are listed in Table 8.

![Fig.8. Relation between specific and reference crack length parameters.](image)

![Fig.9. Relation between specific crack length and bending strength.](image)

Table 8. Parameters fitted for power relation between specific crack length and bending strength.

<table>
<thead>
<tr>
<th>Material</th>
<th>( L_o )</th>
<th>( n )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina</td>
<td>2.15 \times 10^8</td>
<td>-2.74</td>
<td>0.87</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>2.77 \times 10^7</td>
<td>-2.42</td>
<td>0.88</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>3.55 \times 10^4</td>
<td>-1.26</td>
<td>0.90</td>
</tr>
<tr>
<td>Zirconia</td>
<td>1.87 \times 10^7</td>
<td>-2.14</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Consequently, a value for \( l_o \) can be obtained by the following three options: the combination of Eqs. (14) and (15) for given cataloged data, Eq.(16) for a given strength, or the combination of Eqs.(4) and (16) for a given porosity. Equation (13) and \( l_o \) evaluated as above will be applicable in estimating the fracture strength when the dominant flaw in a ceramic component is detected by a nondestructive inspection and so on. As stated above, however, it is noted that the
specific crack length \( l_0 \) represents an average variation in a dispersed relation of \( \sigma_f \) versus \( l \). The crack length \( l_0 \) to be applied in the above estimation must be multiplied by a factor such as \( \xi > 1 \) so that \( \xi l_0 \) can describe the lower bound of scatter in the relation.

4. CONCLUSIONS

In this work, commercial ceramics and their mechanical properties in manufacturers' catalogs were selected under specified conditions. Materials to be investigated were alumina, silicon carbide, silicon nitride and zirconia. Mechanical properties of bulk density, Young's modulus, linear thermal expansion coefficient, bending strength, Vickers hardness and fracture toughness were selected to be compiled in a computer-readable database. The database included the properties for 98 kinds of alumina, 43 of silicon carbide, 60 of silicon nitride and 53 of zirconia.

By using the database, interrelations among mechanical properties were analyzed and discussed. The properties of Young's modulus, thermal expansion coefficient, bending strength, Vickers hardness and fracture toughness were correlated with an apparent porosity calculated using the theoretical and bulk density. Their relations with respect to the porosity were fitted to exponential functions. A good correlation to the porosity was identified in most of cases, excepting the thermal expansion coefficient for all ceramics and the hardness for silicon nitride and zirconia. Every mechanical property tended to decrease with increasing the porosity, though the thermal expansion coefficient was not so sensitive to the porosity. Although the hardness variation with respect to the bending strength was expressed by a proportional relationship for alumina and silicon carbide, a power function was more adequate for silicon nitride and zirconia. The relation between the fracture toughness and the bending strength was fitted to a power function. In this case, a good fitness was confirmed for silicon carbide and zirconia, though a poor correlation was seen for alumina and silicon carbide. A specific crack length, which was used to modify a fracture mechanics criterion for small cracks, was well correlated with the bending strength.

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