Proposal for cooperative research on testing and classification of cemented carbide tool materials

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PROPOSAL FOR COOPERATIVE RESEARCH ON TESTING AND
CLASSIFICATION OF CEMENTED CARBIDE TOOL MATERIALS

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P.C. VEENSTRA

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### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Significance</th>
<th>Recommended Unit</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Function of the thermal diffusivity</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>a</td>
<td>Exponent</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>b</td>
<td>Exponent</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>Constant</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>c</td>
<td>Specific heat</td>
<td>$J/°C.Kg$</td>
<td>$L^2T^{-2}$</td>
</tr>
<tr>
<td>d</td>
<td>Diameter of the disk</td>
<td>$m$</td>
<td>$L$</td>
</tr>
<tr>
<td>$d_1$</td>
<td>Average particle size</td>
<td>$\mu m,m$</td>
<td>$L$</td>
</tr>
<tr>
<td>E</td>
<td>Young's modulus of elasticity</td>
<td>$N/m^2$</td>
<td>$L^{-1}M T^{-2}$</td>
</tr>
<tr>
<td>$F_r$</td>
<td>Applied load</td>
<td>$N$</td>
<td>$L M T^{-2}$</td>
</tr>
<tr>
<td>$F_f$</td>
<td>Ultimate load</td>
<td>$N$</td>
<td>$L M T^{-2}$</td>
</tr>
<tr>
<td>$F_{min}$</td>
<td>Minimum load for failure (with applied heat flux)</td>
<td>$N$</td>
<td>$L M T^{-2}$</td>
</tr>
<tr>
<td>$F_{ij}$</td>
<td>Expected fraction of a series of specimen to fail at the stress $\sigma_j$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>Volume percentage of carbide grains</td>
<td>$%$</td>
<td>$L$</td>
</tr>
<tr>
<td>h</td>
<td>Equivalent chip thickness</td>
<td>$mm$</td>
<td>$L$</td>
</tr>
<tr>
<td>K</td>
<td>Maximum shear stress on the shear plane; $\sigma = \sigma_1/\sigma_3$</td>
<td>$N/m^2$</td>
<td>$L^{-1}M T^{-2}$</td>
</tr>
<tr>
<td>$K_t$</td>
<td>Thermal diffusivity of tool material</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>k</td>
<td>Thermal coefficient of conductivity</td>
<td>$J/m.°C.s$</td>
<td>$L M T^{-3}$</td>
</tr>
<tr>
<td>L</td>
<td>Length of thermal path</td>
<td>$m$</td>
<td>$L$</td>
</tr>
<tr>
<td>l</td>
<td>Mean free path between grains</td>
<td>$\mu m,m$</td>
<td>$L$</td>
</tr>
<tr>
<td>m</td>
<td>Constant indicating the Weibull slope</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n</td>
<td>Number of tests</td>
<td>$N/m^2$</td>
<td>$L^{-1}M T^{-2}$</td>
</tr>
<tr>
<td>p</td>
<td>Isostatic stress</td>
<td>$N/m$</td>
<td>$L^{-1}M T^{-2}$</td>
</tr>
<tr>
<td>$R_t$</td>
<td>Resistance to thermo-shock</td>
<td>$N/s$</td>
<td>$L M T^{-3}$</td>
</tr>
<tr>
<td>$R_{tj}$</td>
<td>$j^{th}$ Grade of resistance to thermo-shock</td>
<td>$N/s$</td>
<td>$L M T^{-3}$</td>
</tr>
<tr>
<td>$S_t$</td>
<td>Sensitivity to thermal stress</td>
<td>$s/m^2$</td>
<td>$L^{-2}T$</td>
</tr>
<tr>
<td>T</td>
<td>Time of cutting period; tool live</td>
<td>$s$</td>
<td>$T$</td>
</tr>
<tr>
<td>t</td>
<td>Time of cooling period; thickness of disk</td>
<td>$s;m$</td>
<td>$T;L$</td>
</tr>
<tr>
<td>V</td>
<td>Volume of maximum loaded area</td>
<td>$m^3$</td>
<td>$L^3$</td>
</tr>
<tr>
<td>$V_T$</td>
<td>$V$ of transverse-strength test specimen</td>
<td>$m^3$</td>
<td>$L^3$</td>
</tr>
<tr>
<td>$V_t$</td>
<td>$V$ of tensile-strength test specimen</td>
<td>$m^3$</td>
<td>$L^3$</td>
</tr>
<tr>
<td>v</td>
<td>Cutting speed</td>
<td>$m/s$</td>
<td>$L T^{-1}$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Significance</td>
<td>Recommended Unit</td>
<td>Dimension</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------</td>
<td>------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Mass density</td>
<td>Kg/m$^3$</td>
<td>M L$^{-3}$</td>
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<tr>
<td>$\gamma_0$</td>
<td>Rake angle</td>
<td>o</td>
<td>1</td>
</tr>
<tr>
<td>$\varepsilon_f$</td>
<td>Ultimate uniaxial strain for failure</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\varepsilon_{fT}$</td>
<td>Ultimate uniaxial strain in bending</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>Thermal strain</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>Cutting temperature</td>
<td>$^\circ$C</td>
<td>-</td>
</tr>
<tr>
<td>$\theta_1$</td>
<td>Transit temperature for friction controlled wear</td>
<td>$^\circ$C</td>
<td>-</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Thermal coefficient of expansion wear</td>
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<td>-</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Coefficient of friction</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson's ratio</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma_1, \sigma_2, \sigma_3$</td>
<td>Principal stress</td>
<td>N/m$^2$</td>
<td>L$^{-1}$ M T$^{-2}$</td>
</tr>
<tr>
<td>$\sigma_e$</td>
<td>Effective stress</td>
<td>N/m$^2$</td>
<td>L$^{-1}$ M T$^{-2}$</td>
</tr>
<tr>
<td>$\sigma_0$</td>
<td>Characteristic fracture stress</td>
<td>N/m$^2$</td>
<td>L$^{-1}$ M T$^{-2}$</td>
</tr>
<tr>
<td>$\sigma_j$</td>
<td>Rupture strength of $j^{th}$ specimen</td>
<td>N/m$^2$</td>
<td>L$^{-1}$ M T$^{-2}$</td>
</tr>
<tr>
<td>$\sigma_{fT}$</td>
<td>Ultimate rupture strength in bending</td>
<td>N/m$^2$</td>
<td>L$^{-1}$ M T$^{-2}$</td>
</tr>
<tr>
<td>$\sigma_{ft}$</td>
<td>Tensile rupture stress</td>
<td>N/m$^2$</td>
<td>L$^{-1}$ M T$^{-2}$</td>
</tr>
<tr>
<td>$\sigma_{Y0}$</td>
<td>Maximum normal stress on the rake during cutting</td>
<td>N/m$^2$</td>
<td>L$^{-1}$ M T$^{-2}$</td>
</tr>
<tr>
<td>$\sigma_\theta$</td>
<td>Thermal stress</td>
<td>N/m$^2$</td>
<td>L$^{-1}$ M T$^{-2}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Heat flux ; shear angle</td>
<td>J/m$^2$ s ; o</td>
<td>M T$^{-3}$ ; 1</td>
</tr>
</tbody>
</table>
PROPOSAL FOR COOPERATIVE RESEARCH ON TESTING AND CLASSIFICATION OF CEMENTED CARBIDE TOOL MATERIALS.

1. A fracture criterion for "brittle" materials.

Many research workers and manufacturers of cemented carbides and ceramics have attempted to find a fracture criterion for brittle behaving materials. Generally they adopted a maximum stress criterion but they were unable to indicate accurate failure criterion in terms of stress.

Using a statistical approach, in the case of concrete specimen in uniaxial compression, Hatano \(^1\) showed that failure could be formulated in terms of ultimate uniaxial strain.

Recently, also Shaw et al. \(^2\) came to the conclusion that the maximum tensile strain criterion is a reliable tool for predicting brittle fracture. However, measurement of small strain is substantially more difficult than the measurement of load. Subsequently the ultimate strain is preferentially derived from

\[
\varepsilon_f = \frac{\sigma_f}{E}
\]

There is more evidence for \(\varepsilon_f\) being an adequate toughness parameter for "brittle" materials. From the results of Gurland and Parikh \(^3\) it can be derived that, to a good approximation, a linear relation exists between the ultimate strain in bending and the impact strenght (unnotched) after Charpy (See Fig. 1). This holds for various WC-Co alloys as long as plastic deformation plays a minor role, which is the case when the percentage of WC is greater than 60. The transverse rupture strength does not show such a relationship with impact strength.

Another point is, that within each of the series P, M and K, the interpretation of I.S.O. classification might be based on, amongst others, the ultimate uniaxial strain (See Fig. 2).

It thus appears that \(\varepsilon_f\) may satisfy as a criterion for fracture toughness of cemented carbides when the carbide contents exceeds 60%.
Fig. 1
The relation between impact strength and fracture toughness $\varepsilon_{ft}$ in bending.

Fig. 2
The interpretation of I.S.O. classification based on fracture toughness $\varepsilon_{ft}$ and the sensitivity to thermal stresses $S_t$. 
2. The resistance to thermal shock of "brittle" materials.

Apart from the type of load and the state of stress there are a number of material properties affecting brittle behaviour of materials like ceramics and cemented carbides. Especially in the case of cutting tools the sensitivity to thermal stresses contributes to early failure. A representative quantity for the thermal stress sensitivity may be derived as follows.

If the thermal strain is defined by

\[ \varepsilon_\theta = \lambda \Delta \theta \]

then the thermal stress of a clamped tool-bit can be expressed by

\[ \sigma_\theta = \lambda E \Delta \theta \]

Let the thermal load be characterized by a flux \( \phi \) per unit of area then analog to Ohm's law

\[ \frac{\Delta \theta}{L} = \frac{\phi}{k} \]

where \( k \) is the thermal coefficient of conductivity.

Subsequently, the thermal stress can be derived from

\[ \sigma_\theta = \frac{\lambda E}{k} \phi L \]

In this equation the thermal stress sensitivity \( S_t \) is represented by \( \frac{\lambda E}{k} \). Fig. 2 shows that on the average this quantity increases with decreasing code-number in the case of the I.S.O. P-series. This means that for this series low fracture toughness and high sensitivity to thermal stresses go together. Contrary to this is the behaviour within the K-group where a low fracture toughness is compensated by a low sensitivity to thermal stresses. (The values of the different quantities used have been calculated from material specifications of a well known make of carbide inserts.)

The resistance to thermo-shock can be derived from

\[ \sigma_f = \varepsilon_f E = \frac{\lambda E}{k} \phi L \]
and can be written as

\[ R_T = \varepsilon f \frac{k}{\lambda} \]

3. The relation between fracture toughness and the material parameters.

Examining experimental results obtained by Gurland and Parikh it has been observed that a pure exponential relationship exists between fracture toughness in bending \( \varepsilon f_T \) and the mean free path between the carbides, i.e. the average value of the thickness of the matrix layer (See Fig. 3).

Fig. 3
The mean free path versus fracture toughness after results from Gurland and Parikh.

Fig. 4 shows that this behaviour can be confirmed for a number of current types of carbide tool materials. (The values depicted in this figure have been calculated from the specifications given by the manufacturer; the values of the mean free path have been calculated from the average particle size \( d_1 \) and the composition of the material \( G \), whilst assuming cubic grains.)
From Fig. 4 the following conclusion can be drawn:

1. Fracture toughness is mainly controlled by
   a) The mechanical properties of the binder
   b) The mean free path between the grains.

2. The mechanical properties of the carbides (TiC, TaC, NbC, CrC₂ and WC) do not have a significant influence on fracture toughness (observe P10 and P30, P40 and M40).

The conclusions are of course restricted to situations where the stresses are tensile and the influence of plastic deformation is negligible.

The lower strength for smaller values of the mean free path $l$ is apparently a result of positive isostatic stresses which are generated in the thin layers of binder material between the grains. (See also Section 4 ($k_f = k_f(p)$) and reference 15).

The orthodox standard test methods such as the uniaxial tensile test and the different bending tests have proven to be completely unsatisfactory when applied to "brittle" materials like cemented carbides. The tensile test is a very poor choice for testing brittle materials due to gripping difficulties and the great influence of misalignment on stress distribution. Results from bending tests are equally frustrating by showing great scatter. In this case the large stress gradient with the maximum tensile stress at the surface together with the, for brittle materials characteristic, sensitivity to surface conditions are responsible for this.

In particular with respect to cemented carbide tool inserts, the form and size of the specimen available are not suited for either the tensile or the bending test.

Recently, Shaw et al.\textsuperscript{2)} reported from a diametrical compression test applied to brittle materials. This indirect tensile test, also called the Brazilian test, was first introduced in 1953 by Carniero and Barcellos for testing concrete and is based upon the phenomenon that a tensile stress is acting across the loaded diameter of a diametrical loaded disk. Except for the regions quite near the strip loadings, this normal stress is uniformly distributed over the loaded diameter (See Fig. 5) and is equal to

\[ \sigma_3 = \frac{2F}{\pi dt} \]

where \( F \) is the applied load, \( d \) the diameter and \( t \) the thickness of the disk. In addition to this tensile stress, substantial compressive stresses are also present. In the region of the load the stress condition is biaxial compressive which means that the material there can resist much greater stresses. In this the Brazilian test is very attractive since this means that fracture initiates internally rather than at the outer surface. The fact that compression shows a minimum at the centre of the disk specimens may explain why the specimens rupture at the centre.

At the same time however, these compressive stresses affect the test results and this influence has to be evaluated when the results are to be compared with those from different tests. The ultimate uniaxial ten-
sile strain can be plotted versus the isostatic stress $p$. Since the
disk test provides for only one single point in this curve, the need
for different tests shows up. The disk test provides for

$$\varepsilon_f = \varepsilon_3 = \frac{1 + uK}{E} \sigma_3 = \frac{\sigma_3}{E} = \frac{(1 + uK) 2F_f}{\pi dt}$$

$$p = -\frac{2}{3} \sigma_3 = -\frac{4}{3} \frac{F_f}{\pi dt}$$

where $u = 0.3$ and $K = -\sigma_1/\sigma_3$ ($\sigma_1$ and $\sigma_3$ are principal stresses; at
the centre $K = 3$).

It is suggested to investigate the possibility of using specimens with
elliptical form instead of circular ones in order to find different
points of the curve.

Since square inserts are most frequently used, it seems very interesting
to investigate the possibility of applying the principle of the disc test
to this type of specimen.

The influence of isostatic stress is clearly demonstrated in Fig. 6. The
graph shows results for two different grades as obtained by Shaw et al.
Positive isostatic stresses were obtained by using accurately machined
thin walled rings ($t = 1.25$ mm). A pressure was exerted on the inside
surface of the ring by an expanding balloon. This method is considered
to be too complicated and too expensive to serve as a standard test.
Fig. 6 shows that more "brittle" materials undergo a greater change in strength with hydrostatic stress than more "ductile" compositions. When compared with the uniaxial tensile test and the bending tests, the disk test shows relatively little scatter and is therefore a most suitable test method. The disk test may also be used as a method for measuring the relative resistance to stresses caused by thermo-shock.

When a heat flux is lead through the specimen, the minimum force which causes fracture, $F_{\text{min}}$, can then be related to $R_t$. For a fixed value of $\phi L$, the relative resistance to fracture can be taken from

$$\sigma_f = \sigma_0 + \sigma_{F_{\text{min}}}$$

$$\varepsilon_{fE} = \frac{\lambda E}{k} \phi L + \frac{2(1 + vK)}{\pi dt} F_{\text{min}}$$

$$\frac{\lambda}{\varepsilon_{fE} K} = \text{Const.} \left(1 - \frac{2(1 + vK) F_{\text{min}}}{\pi dt \sigma_f} \right) = \frac{1}{R_t}$$
Fig. 7 Principle of the set-up for testing the relative resistance against thermoshock.

Tests should be carried out for various temperatures in order to establish the influence of temperature on the mechanical and thermomechanical properties. If this influence proves to be significant, which is to be expected for grades containing a low % of Co and - still more important - a high Ti-C content\textsuperscript{12}, fracture toughness and thermal stress sensitivity should be measured at temperatures which are representative for cutting.

5. Evaluation of test results.

5.1 Statistics

Scatter in results is inherent to fracture tests, in particular when "brittle" materials are involved. Compared with the averaging of such results, a better use of the data can be made by applying statistics. In the case of brittle fracture Weibull extreme value statistics have often been applied successfully (See also Shaw \textit{et al.}). According to Weibull, the fraction $F$ of a series of specimen that fails at a certain stress can be estimated from the empirical formula:

\[
F = 1 - \exp\left(-\frac{x}{\sigma_0}ight)^n
\]
where \( \sigma_0 \) is a constant for the test series to be called the characteristic fracture and \( m \) is also a constant for the series called the Weibull slope. Rearranging the equation above, it will be found that

\[
\log \ln \left( \frac{1}{1-F} \right) = m (\log \sigma - \log \sigma_0)
\]

For analyzing test results it is convenient to use Weibull's special kind of probability paper. Weibull paper is ruled with \( \log \ln 1/(1-F) \) as ordinate and \( \log \sigma \) as abscissa. When plotted on this paper, the experimental data usually show a straight line having a slope \( m \). The value \( \sigma_0 \) is found when \( F = 0.632 \). Using a normal frequency distribution, the value of \( F \) (median rank) belonging to the \( j \)th rank number may be calculated from

\[
F_j = \frac{j - 0.3}{n + 0.4} \quad (\%)
\]

where \( n \) represents the number of tests made.

In the case of a sample size 5, the values are ordered to

<table>
<thead>
<tr>
<th>Rank no (No of broken specimens at ( \sigma_j ))</th>
<th>Rupture strength ( \sigma_j )</th>
<th>Rank (%) ( F_j )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \sigma_1 )</td>
<td>12.95</td>
</tr>
<tr>
<td>2</td>
<td>( \sigma_2 )</td>
<td>31.38</td>
</tr>
<tr>
<td>3</td>
<td>( \sigma_3 )</td>
<td>50.00</td>
</tr>
<tr>
<td>4</td>
<td>( \sigma_4 )</td>
<td>68.62</td>
</tr>
<tr>
<td>5</td>
<td>( \sigma_5 )</td>
<td>87.06</td>
</tr>
</tbody>
</table>

A low slope indicates a large variability in the test results. For
"brittle" materials the value of $m$ is reported to be 20 or less (compared with ductile materials: $m \approx 40$), which indicates that it is inadvisable to recommend the mean strength as rupture strength. The equation

$$F_j = 1 - e^{-\frac{\sigma_j^m}{\sigma_0}}$$

offers a convenient way of predicting the early-failure stress belonging to the $j$th rank.

More detailed information can be found when consulting the references 5), 6), 7).

5.2 Size effects.

It is a wellknown fact that in the case of "brittle" materials the probability of an early failure increases with increasing size of the area of maximum stress. This effect has to be taken into account when using different specimen sizes, different types of tests or when test results are applied to actual conditions.

It may be clear that, being a result of the distribution of imperfections, the influence of the size of the loaded area decreases with increasing area. Weibull statistics may also be used to estimate the effects of specimen size and stress distribution on fracture toughness. In that case, it is assumed that a specimen fails when a certain critical stress (tensile) is exceeded. Putting forward a uniform distribution of the imperfections, the area or volume involved is estimated by considering the space over which the effective stress is within 10% of the critical value corresponding to the earliest failures ($F = 1\%$).

$$\sigma_e = (1 + uK) \sigma_3$$

To obtain a sizewise equivalent, the effective stress has to be calculated according to

$$\sigma_e V^{1/m} = \text{Constant}$$
Thus the size effect depends upon the Weibull slope $m$. Additional to the size effect, results from transverse rupture tests are substantially affected by a stress gradient effect. This effect causes transverse rupture tests to give higher values of rupture strength than results from for instance tensile tests. One can compensate this effect by extending the above equation to

$$\frac{\sigma_{fT}}{\sigma_{ft}} = \left( (m + 1)^{2} \frac{V_t}{V_T} \right)^{1/m}$$

5.3 The influence of isostatic stress.

The influence of isostatic stress has already been mentioned in a previous section. The results of Fig. 6 show that this influence is significant. Subsequently, results from different tests involving different states of stress should only be compared after being modified to the same isostatic stress. A same problem has to be solved when test results are applied for predicting brittle failure of carbide tools under cutting conditions. This, in fact, involves a number of tests to be carried out for different values of the intermediate stress (see the suggestions made in section 4).

6. Cutting tests.

The real significance of any definition of fracture toughness with respect to brittle failure of cutting tools lies in the existence of a relation between this definition and the cutting conditions involving chipping and failure, and not in the least in the possibilities to find such a relation. At present where no analysis for tool failure is available, one is restricted to an empirical approach. A first remark which has to be made is, that the method of dimension analysis might successfully be applied here for finding the system parameters, especially in the case of interrupted cutting. Since fracturing is a mechanical problem, in the case of cutting clearly
assisted or sometimes dominated by thermo-dynamic effects, a logic first step would seem the translation of cutting conditions into interface temperatures and stress distributions. It was Hara\(^8\) who found an experimental relation between the normal stress on the rake face and the cutting temperature at one side, and chipping of cemented carbide tools in continuous cutting at the other. This relation is shown in Fig. 8.

![Figure 8](image)

**Fig. 8**
An experimental fracture criterion in reference to interface temperature and normal stress.

The left parts of the curves shown in Fig. 8 suggest a significantly decreasing probability of chipping with increasing temperature. The author tends to believe that the left part of such a curve is merely controlled by a pure mechanical mechanism whilst the right part is dominated by thermal stress. In the region of very high temperatures, plastic failure may also play an important role.

Reason for this way of thinking is that for lower temperatures (= lower cutting speeds) the coefficient of friction decreases with increasing temperature which, with the aid of the Mohr circle, can be translated into the situation of a greater part of the tool-wedge being under compressive stresses (See also Ellis and Barrow\(^9\)). As a result of a favour-
able influence on the mechanical conditions of contact between chip and tool, an increasing temperature leads to lower tensile stresses and subsequently to less chipping.

This way of thinking is confirmed by the general experience that "sticky" work materials cause more chipping than less adhesive ones. It is known that beyond a certain temperature, friction conditions do not longer change substantially with temperature whilst thermal stresses become more and more significant. From this, the right part of the curves can be explained.

It thus seems that low-temperature effects should better be separated from high-temperature effects in the sense as is depicted in Fig. 9. The actual significance of these relations, however, has to be confirmed by experiments.

![Fig. 9 Preliminary proposal for treating results from continuous cutting tests.](image)

It has been mentioned before, that both $\varepsilon_f$ and $R_t$ are functions of the isostatic stress $p$, which particularly in the case of "brittle" grades means that an accurate evaluation of results will only be possible if the boundary stress conditions of the tool are known. This implies that an elaborate cutting model must be available. It is therefore suggested that as a first approach the influence of $p$ should be neglected.
It is further suggested to adopt the Primus version of the normal stress on the rake \(^{10}\) as a representative value for the load of the tool.

\[ \sigma_{\gamma_0} = K(1 + \sin 2(\phi - \gamma_0)) \]

where \(K\) is the maximum shear stress on the shear plane.

Beyond the B.U.E. region, the temperature can be calculated with the equation

\[ \theta_c = C h^a \nu^b \]

in which \(h\) is the equivalent chip thickness in \(\text{mm}\) and \(\nu\) the cutting speed in \(\text{m/s}\). \(C, a\) and \(b\) are constant for one combination of tool and work material. (e.g. For C45N/P20 and a rake angle of \(6^\circ\) : \(C = 873, a = 0.11\) and \(b = 0.29\)).

When applying stress and temperature as independent variables, it should be expected that one single curve covers both various work materials and various tool geometries.

A more direct correlation between cutting variables and characteristic properties of tool materials seems possible when examining the equation for the cutting temperature. Experiments show that \(b/a \approx 3\) which means that the cutting temperature is preponderantly related to the cutting speed, whilst the normal stress on the rake is dominantly dependent upon the feed. It thus seems a fair possibility that toughness behaviour during cutting can be represented sufficiently in the way as is shown in Fig. 10. In that case however, one pair of curves will cover only one combination of tool and work material.

Apart from the need to estimate tool life from statistical results, one must be able to recognise phenomena which do, and phenomena which do not belong to one particular mechanism. This in fact means that there is a need for classification-of-failure diagnoses.

The interrupted cut introduces periodic changes in temperatures and forces.

As to the cutting force, at the onset of each cut, this force will gradually increase until a maximum value is reached; no overshoot in force can take place since cutting is a complete irreversible process (i.e. \(dU = 0\)). Subsequently, the influence of mechanical impact does not exist.
Also thermal fatigue is probably of secondary importance. In the case of interrupted cutting, the influence of temperature-time effects can be explained as follows.

The highest compressive stresses will occur during the first few cuts, when the mechanical load is simultaneously assisted by substantial thermal expansion. It is quite possible that during these first cuts plastic deformation of the tool material takes place. With increasing cutting time, the average tool temperature rises, which in continuous cutting will result in lower temperature gradients in the tool near the cutting edge. However, a complication arises with the existence of the cooling period which causes a wave propagating effect of the heat in the tool, as a result of which tensile stresses are generated near the rake face when

- the surface temperature on the rake drops below the average temperature of the tool,

and when

- plastic deformation has taken place during one of the first cuts.
In both cases, the probability of the stresses becoming tensile increases with time.

From the foregoing it may be evident that the interrupted cut introduces the following parameters:

- the duration of the idle period (t)
- the cooling medium, etc.
- the cutting time (T)
- the thermal diffusivity of the tool material \((K_t)\)
- the phase-shift between force and temperature during entry of the cutting edge into the work.

As to the last point, since it is to be expected that, when plotted versus time, both force and temperature will gradually approach some maximum value, one can neglect the influence of the phase-shift if the "switch-on"-time is smaller than the time for one cut. Generally, this condition will be met.

Any kind of forced cooling such as the application of cutting fluids etc. substantially reduces tool life of "brittle" tools like carbides and cermets. Therefore, when testing tool materials, cooling conditions must be standardized. This in fact means that cutting in air at room temperature is the most practical choice. Another requirement is, that during one test the machining process must never be interrupted for a period exceeding the idle period of the tool.

Cutting time is important, seeing that an increase of the average cutting edge temperature will increase the probability of tensile stress at the end of the idle period. Realizing that the admissible cutting time before failure is the definition for tool life \(T\), it is sensible to consider this quantity as the dependent variable. However, the non-stationary solution of the temperature distribution \(\theta(x,t)\) of a body, at one side extended to infinity, which at the time \(t = 0\) is being exposed to a heat source of constant temperature \(\theta\) sounds:

\[
(\theta(x,t) - \theta) - (\theta_{t=0} - \theta) \frac{k}{c \gamma} \frac{t}{x^2} = \epsilon
\]
where \( k/c\gamma \) stands for the thermal diffusivity \( K_t \) and \( A = A(K_t) \). Whilst the above equation represents a gross approximation to the actual temperature distribution, it is evident that the (average) cutting edge temperature is a function of \( K_t \). Therefore it is proposed to choose \( K_t \) instead of \( T \) as the independent variable. Apart from the cutting temperature and the resistance to thermal stresses \( R_t \), the length of the cooling time seems most important. Subsequently it is expected that for interrupted cutting the relations between the different quantities will approach those depicted in Fig. 11. For the moment it is suggested to adopt the tool life criterion for brittle failure as has recently been proposed by König:

\[
\frac{\text{length of chipped edge}}{\text{length of active cutting edge}} = 1
\]

Fig. 11 Proposal for evaluation of cutting test results (interrupted cut).

As a result of the sticking effect on the rake, exit conditions may also have a significant influence on tool life. This influence can be minimized by carrying out the tests concerning the interrupted cut in down milling.

It is also known that a cutting edge radius smaller than a certain
critical value will give rise to much scatter in tool life. This influence on test results is ruled out by giving the carbide inserts a standard treatment by which the size of the radius becomes larger than the critical value. Test results can be plotted on Weibull paper with log ln 1/(1-F) as ordinate and log T as abscissa. The applicable tool life can be estimated from the best fitting straight line, for instance for F = 1 %. The plot of Fig. 10 may serve as an aid for choosing the cutting conditions concerning the cutting tests with interrupted cut.

7. Enumeration.

Being subject for discussion in the first place, the previous sections suggest the need for the following investigations:

1) Classification-of-failure diagnoses.

2) The existence of reliable relations between both fracture toughness $\epsilon_f$ and the resistance to thermal stress $R_t$ and tool failure in continuous cutting.

3) The significance of the resistance to thermal stress $R_t$ and the thermal diffusivity $K_t$ with respect to brittle failure during interrupted cutting.

4) The influence of temperature on mechanical and thermal properties of cemented carbides.

5) The application of the disk test as a standard toughness test for carbide inserts, giving special attention to the possibility of

- testing specimens of square form
- investigating the influence of the hydrostatic stress on fracture toughness
- measuring the mechanical and thermo-mechanical properties at different temperatures.

Cooperative work on the items 2) and 3) requires extensively standardized test conditions, which have first to be agreed upon.
When cutting temperature is applied as independent variable, some additional problems have to be solved. It proves to be impossible to collect sufficient data on cutting temperature from literature. Our laboratory could accept to perform experiments using the Gottwein method in order to find the values of $C$, $a$ and $b$ for various tool materials against C45N.

Possibly, this activity could be extended with the worthfull help of other cooperative members. Reference $^{13}$ provides for data concerning the thermo-electric characteristics of a number of carbide grades (Sandvik) and the steel C45N. Furthermore, it is proposed to use the equivalent chip thickness rather than the feed as a cutting variable, since the Gottwein-temperature is uniquely determined by the former quantity, independent on the particular geometry chosen. A list of feeds, cutting geometries and corresponding equivalent values can be provided by our laboratory (14).

Since the temperature serves only as a reference, there is no concern for the possible systematic errors own to the Gottwein method.

In the mean time one could perform cutting experiments in order to find direct relations of the kind as is depicted in the Figs. 10 and 11, whilst borrowing the mechanical and thermal specifications of the different tool materials from literature. In this stage any influence of temperature on the thermo-physical and mechanical properties should be neglected.

Simultaneously, the importance of classification-of-failure methods has to be evaluated.
LITERATURE


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