The testing of cemented carbide tools: the development of a test based on the diametrical compression test
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I Introduction

Cemented carbide is a most suitable and for that one of the most important tool materials. It is available in many compositions and qualities.

The application of cemented carbides - also for constructive purposes - is continuously increasing, mainly by its resistance to wear.

However, particularly in the field of cutting as regards the considerable variations in cutting force and the high temperatures, brittle behaviour of carbide tools is a big problem. For this reason the need is felt for a practical, reliable and theoretically justified test method for the measurement of strength and toughness behaviour - also in relation with thermal load - which also instigates an effective classification of the different carbides.

Of the classic test methods many have specific drawbacks when applied to brittle behaving materials. As regards the bending test the state of the surface in particular has a great influence on the measurable stress for fracture. In the tensile test, clamping and lining of the test specimen form problems. In both cases the manufacturing of the test specimen takes special - and therefore costly - care.

The ring test provides an ideal uniaxial state of stress, but the manufacture of a great number of accurately ground and well tolerated cemented carbide rings would make experiments intricate and costly. As the measurement of the resistance against thermo shock is also to be included, the diametrical compression test remains as the method of choice.

II The experimental set up.

For testing cemented carbide tool materials standard throw away type inserts of the type SNUN 120312 have been used. Two diagonally opposed corners of the square bits are ground flat till the resulting faces attain a length 0.1 D, D being the length of the diagonal.

The test piece is now placed upright, the two small faces touching,
between the dies of an adapted pillar die set (see Fig. 1). The die faces consist of a superior K40 carbide, enclosed as inserts in shrink rings. The application of this material in prestressed state allows the testing of most cemented carbide qualities by resisting normal stress up to 80 x 10^3 bar. In order to obtain a stress distribution between the contact faces as uniform as possible, copper shims with a thickness of 0.05 mm are fitted between. For the measurement of the relative resistance to thermo shock (RTS), a heat flux is applied by conducting a heavy pulse of electric current through the specimen. For this purpose two adapted spot welding electrodes are clamping on both sides the centre of the upright standing test piece. (See Fig. 2).

III The stress distribution in the square test bit.

The stress distribution in the diagonally loaded square specimen is comparable to the one in a diametrically loaded disk. The stress distribution in a disk, as experimentally verified by Hondros 1), can therefore to a certain extent be applied to a square shaped specimen. The results of a stress analysis (plane stress), made with the aid of the finite element method (ASKA-TRIM elements) is given below. The uniform stress on the small ground faces, \( \sigma_p = 3.9 \times 10^3 \text{ N/mm}^2 \), represents a bulk load of 20000N. The principal stresses across the diagonals are given in Table 1 and Figure 3.

For the computation of the transverse stress in the centre of a disk it holds:

\[
\sigma_{1y} = \frac{2 F}{\pi D t}
\]  

(1)

in which:  
\( F = \sigma_p \times 0.1 D \times t \)  
\( D = \text{length of the diagonal} \)  
\( t = \text{thickness of the test piece} \).

When \( F = 20000 \text{N} \), it follows that  
\( \sigma_{1y} = 2.483 \times 10^2 \text{ N/mm}^2 \).

The corresponding value for a square test piece follows from Table 1:  
\( \sigma_{1y} = 2.523 \times 10^2 \text{ N/mm}^2 \).

From this it follows that, with respect to the centre of a square test piece, \( \sigma_{1y} \) can be computed with the help of Eq. (1).

As for the stresses in the \( Y \)-direction it can be defined:

\[
\sigma_{2y} = - K \sigma_{1y}
\]  

(2)

In Table 2 the \( K \)-values are given for different positions between the centre and the edge of the specimen.
The strain is maximum in transverse direction. In a state of plain stress it equals:

$$\varepsilon_{1y} = \frac{1}{E} (\sigma_{1y} - \nu \sigma_{2y})$$

(3)

By defining the effective stress for failure:

$$\sigma_e = E \varepsilon_{1y}$$

(4)

follows with Eqs. (2) and (3):

$$\sigma_e = (1 + \nu K) \sigma_{1y}$$

(5)

IV Criterion for fracture.

It is assumed that failure occurs when the maximum elastic strain reaches a critical value called the ultimate uniaxial strain (U.U.S.)\(^2\)\(^3\). The corresponding load is defined as \(F_{\text{max}}\). For the computation of the critical strain it is necessary that the stresses which correspond to the location where fracture is initiated are known. This location in turn is influenced by the following phenomena.

a) The changing \(\sigma_e\) along the loaded diagonal.

Starting point is the failure being initiated at the specific location along the loaded diagonal where the ultimate uniaxial strain is first reached. The maximum value of the transverse tensile strain \(\varepsilon_{1y}\) occurs for a \(\frac{d}{D}\) ratio of about 0.55 (see Table 2), which would predetermine the most dangerous location outside the centre, quite near the bi-compressive zone of the specimen.

b) The possibility of plastic flow.

The occurrence of plastic flow will delay fracture. Adopting the Tresca criterion for the effective stress for plastic flow \(\tilde{\sigma}\), one arrives at:

$$\tilde{\sigma} = \sigma_{1y} - \sigma_{2y} = \sigma_{1y} (1 + K)$$

(6)

Brittle fracture will not be preceded by plastic flow if:

$$\frac{\sigma_e}{\sigma_f} = \frac{\varepsilon_{1y} E}{\sigma_f} > \frac{\tilde{\sigma}}{\sigma_y}$$

(7)

where \(\sigma_y\) is the yield stress and \(\sigma_f\) stands for rupture strength in the uniaxial case. This condition can also be written as:

$$\frac{\sigma_f}{\sigma_y} < \frac{1 + \nu K}{1 + K}$$

(8)
For $v = 0.3$ and $3.6 < K < 180$ (see Table 2) the plastic flow constraint factor, i.e. the right hand part of Eq. (8), takes values between 0.30 and 0.45. From this it would occur that a slight preference exists for brittle action to take place in the centre of the specimen.

However, from experimental results of Doi \textsuperscript{4}) it follows that the composites which have a $\lambda_{av}$ value$^\text{m)}$ exceeding 0.1 $\mu$m (i.e. most ISO P- grades and some M- grades$^{5)}$) meet the condition $\sigma_f / \sigma_y > \approx 0.45$.

This means that for these grades no part of the material along the loaded diagonal is excluded from plastic flow and that therefore it cannot be expected that the small change in constraint of plastic flow along the loaded diagonal has a dominating influence.

c) The influence of isostatic stress.

It is known that the strength of brittle materials is isostatic stress dependent; strength decreases with an increasing value of the isostatic stress ($\sigma_i$). As regards cemented carbides, Fig. 4 shows this dependency for two different compositions. From the results obtained by Shaw \textit{et al.} \textsuperscript{2)} it would appear that the influence of isostatic stress on the effective stress for failure ($\sigma_e$) decreases with an increasing percentage of cobalt. Although it is believed that the difference between the 6% and the 12% cobalt grades, as is occurring for negative values of $\sigma_i$, is partly caused by an underestimation of $\sigma_e$ in the latter case, the shown tendency certainly cannot be ignored. See section a): a high cobalt content causes the $\lambda_{av}$ value to exceed 0.1 $\mu$m and the location of fracture initiation to shift outside the centre of the disk. This in turn results in an increased $\sigma_e$-value.

The isostatic stress follows from:

$$\sigma_i = \frac{1}{3} (1 - K) \sigma_1$$  \hspace{1cm} (9)

In the compression test $\sigma_i$ shows a minimum at the centre thus giving a tendency of fracture initiation to take place at this location.

As regards the location of fracture initiation it can be concluded that the change in $\sigma_e$ has to compete with both the occurrence of constraint of plastic flow and the influence of isostatic stress on U.U.S.. As it is not yet possible to quantify the influence of Loth last mentioned mechanisms, it may be clear that one can in no way be conclusive. Only in the case of

$^\text{x)}$ $\lambda_{av}$ = mean free path between the grains.
fracture initiation at the centre of the specimen, the effective stress for fracture is known. In the case of a square bit this stress may then be calculated from the equation:

\[ \sigma_e = (1 + 0.3 \times 3.6) \left( \frac{2F}{\pi D t} \right) \times 4.2 \frac{F}{D t} \]  

(10)

Further on it is shown that the location of fracture initiation does no longer correspond to the centre of the specimen when the cobalt content is exceeding about 12%.

V Measurement of the relative resistance to thermo-shock (R.T.S.)

When a sudden heat flux is applied to the centre of the specimen which simultaneously is in diagonal compression, the added thermal stresses cause the resulting stresses to be maximum at the edge of the heated zone (See Fig. 5). The point of failure is realised when at the edge:

\[ \text{U.U.S.} = \frac{1}{E} \left( \sigma_{1F} + \sigma_{1T} \right) - \nu \left( \sigma_{2F} + \sigma_{2T} \right) \]  

(11)

From this it can be shown that the relative resistance to thermo shock is 6):

\[ \text{R.T.S.} = \frac{U.U.S.}{k} = \frac{\phi L (1 + \nu)}{2 (1 - \frac{F_{\text{min}}}{F_{\text{max}}})} \]  

(12)

where

- \( \phi \) = heat flux
- \( L \) = characteristic length
- \( \nu \) = Poisson ratio
- \( k \) = thermal coefficient of conductivity
- \( \alpha \) = thermal coefficient of expansion
- \( F_{\text{min}} \) = minimum load for failure with assistance of thermal load.

For standardized test conditions, Eq.(12) can be simplified to:

\[ \text{R.T.S.} = \frac{A}{1 - \frac{F_{\text{min}}}{F_{\text{max}}}} \]  

letting \( A < \text{R.T.S.} < \infty \)  

(13)

(A = constant)

By placing the electrodes at different positions along the loaded diagonal, \( F_{\text{min}} \) will take different values. It is thus possible to determine the location where under pure mechanical load fracture will start. This point is indicated by the smallest appearing value of \( F_{\text{min}} \).
VI Statistical evaluation of test results

Weibull statistics

It is shown empirically\(^7\) that the probability \( F \) for brittle fracture taking all values \( \sigma \leq \sigma \), answers the following equation:

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

(14)

where \( \sigma_0 \) = characteristic stress
\( m \) = Weibull slope
\( \sigma \) = a stochastic variable.

from Eq.(14) it follows that:

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

(15)

b) If \( \sigma = \sigma_0 \) then \( F = 1 - \frac{1}{e} = 0.632 \)

By using Weibull probability paper where \( \log \sigma \) is taken as the horizontal axis and \( \log \ln \left(\frac{1}{1 - F}\right) \) as the vertical axis, the relation between rupture strength and the corresponding probability \( F \) can be determined easily. In using this statistical method the following procedure is used:

1) The measured values of \( n \) tests are tabulated according to their magnitude (\( \sigma_1 \cdots \sigma_n \)).
2) With the aid of the median rank formula\(^8\)

\[
F_j = \frac{j - 0.3}{n + 0.4} \quad (j = 1, 2, 3, \ldots n), \quad (16)
\]

the corresponding values of \( F \) are computed.
3) \( \sigma_j \) is put against \( F_j \) on Weibull probability paper
4) The best fitting straight line is characterized by:

\[
m = \text{directional coefficient}
\]

\[
\sigma_0 = \text{stress value corresponding with a probability of failure of 0.632}
\]

Experiments

Four carbide qualities have been tested e.g., according to ISO definition, the grades \( P \) 10, \( P \) 40, \( K \) 10 and \( K \) 20.

The average dimensions of the inserts are: length of diagonal \( D = 17.2 \) mm and thickness \( t = 3.2 \) mm. Therefore the transverse stress in the centre of the specimen at failure can be expressed as:

\[
\sigma_x = \frac{2 F_{\text{max}}}{\pi D t} = 1.15 \times 10^{-2} F_{\text{max}}
\]
The obtained $\sigma_x$ values have been worked out with the help of Weibull probability paper. (See Figs. 6, 7 and 8). Both the K 10 and P 40 grade also have been tested for thermo shock, the electrodes being clamped at as well as off the centre of the diagonal. (See Figs. 7 and 8). Some numerical values are given here:

<table>
<thead>
<tr>
<th>Grade</th>
<th>P 10</th>
<th>P 40</th>
<th>K 10</th>
<th>K 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Co</td>
<td>11</td>
<td>16.5</td>
<td>8.5</td>
<td>10</td>
</tr>
<tr>
<td>$H_v$ (kgf/mm$^2$)</td>
<td>1550</td>
<td>1400</td>
<td>1850</td>
<td>1500</td>
</tr>
<tr>
<td>$\sigma_{F=0.5}$ (N/mm$^2$) (i)</td>
<td>354</td>
<td>335</td>
<td>430</td>
<td>325</td>
</tr>
<tr>
<td>m</td>
<td>19</td>
<td>20</td>
<td>17</td>
<td>24</td>
</tr>
<tr>
<td>$\sigma_{FT}$ (ii)</td>
<td>1500</td>
<td>2100</td>
<td>1400</td>
<td>1800</td>
</tr>
<tr>
<td>$\sigma_{F=0.5}$ (iii)</td>
<td>--</td>
<td>--</td>
<td>227</td>
<td>317</td>
</tr>
<tr>
<td>R.T.S.</td>
<td>--</td>
<td>--</td>
<td>2.1A</td>
<td>40.6A</td>
</tr>
</tbody>
</table>

(i) For pure mechanical load  
(ii) Transverse rupture strength according to manufacturers specifications  
(iii) Combined with thermo shock

In view of the substantial difference in magnitude, it is to be noticed that no systematic deviation exists with regard to the various grades between the values of $\sigma_{F=0.5}$ and $\sigma_{FT}$. The difference in magnitude of both quantities is due to size- and stress gradient effects and, more important, because of the ultimate uniaxial stress being a poor strength criterion. The variance is at least partly caused by deriving the compression test results from the state at the centre of the specimen. Actually the location of fracture initiation may lie anywhere in a region along the loaded diagonal. The effect is demonstrated by the results in the Figs. 7 and 8. The different results are matched by different positions of the electrodes while keeping the heat flux constant. For the K 10-grade with a 2.5% Co content, the highest sensitivity to fracture is obviously occurring at the centre of the bit. For the P 40 grade (16.5% Co) however, the most dangerous location is outside the centre, where the transverse tensile stress $\sigma_{1y}$ reaches values differing from $\sigma_x$ (Eq. 17).
For the U.S. the difference between actual and calculated values is amplified. This gives a firm base to the objections as made in section IV with regard to the diametrical compression test. The application of a small heat flux will induce fracture at a predetermined location and thus remedy problems as in the case where the U.S. is concerned.

Acknowledgments

The authors make grateful acknowledgment to Prof. P.J. Gielisse, University of Rhode Island for his many valuable suggestions on this project. Thanks are also due to Mr. W.D.G. Bosma for his appreciated help in realizing this report.

References

8) Report SP 30 of the Statistical Dept. of the Mathematical Centre Amsterdam.
Fig. 1. The diagonal-compression test rig

Fig. 2. Electrodes and clamping device.

Fig. 4. The variation of effective stress for failure with isostatic stress.
(After Shaw et al.2)
Fig. 3. Stress distribution across the diagonals of a diagonally loaded square specimen.

Table 2

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>K</td>
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<td>-5.02</td>
<td>-12.3</td>
<td>180</td>
<td>12.6</td>
<td>6.9</td>
<td>4.96</td>
<td>4.06</td>
<td>3.65</td>
<td>3.56</td>
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<tr>
<td>node number</td>
<td>( \sigma_{1x} ) (N/mm(^2))</td>
<td>( \sigma_{2x} )</td>
<td>node number</td>
<td>( \sigma_{1y} ) (N/mm(^2))</td>
<td>( \sigma_{2y} )</td>
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<tr>
<td>1</td>
<td>( 2.50 \times 10^2 )</td>
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</table>

In node number 1: \( \sigma_{2x} = \sigma_{2y} \); \( \sigma_{1x} = \sigma_{1y} \)

Table 1

![Fig. 5. Transverse stress distribution for combined mechanical and thermal load.](image-url)
Fig. 6. Compression test results (no thermal load) of four carbide grades.

Fig. 7. Compression test results. Influence of thermal load and position of the electrodes (K 10-grade).
Fig. 8. Compression test results. Influence of thermal load and position of the electrodes (P 40-grade).