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Effects of surface roughness on the flexural strength of a hardmetal

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A detailed study to assess the effect of surface roughness on three-point flexural strength of a WC–Co hardmetal was undertaken. Eight different types of surface finish were investigated; R-parameters were determined and Weibull statistics were applied to analyse the fracture strength results. It was concluded that the highest values of rupture stress and Weibull modulus are obtained when the surfaces and the edges of the specimens are submitted to careful and gradual, step-by-step, surface-finishing operations and a 1 μm diamond paste is used as the final abrasive. Only when very fine finish is attained may the results of rupture stress then represent the intrinsic behaviour of the material.

1. Introduction

In the great majority of materials with a brittle behaviour, surface-finishing conditions must exercise some significant influence on the mechanical failure of hardmetals. In some cases, extrinsic defects (surface cracks, flaws or roughness) produced during surface-finishing operations may play a more important role in the fracture process than intrinsic defects (internal pores, grain boundaries, large grains and inclusions).

Material removal by grinding is often the only way in which tungsten carbides may be accurately shaped to final size. A grinding wheel approaches a cutting tool with an infinite number of cutting edges and it can produce surfaces to very close dimensions and a high degree of smoothness. Depending on the characteristics of the grinding wheel – type of abrasive particles, (for example, diamond particles) their grain size and relative spacing, the grade (i.e. the relative strength or holding power of the bond that holds the abrasive in place), etc. – different kinds of surfaces may be obtained. The possibility that some extrinsic flaws and stress concentrators in the surface are introduced during the grinding operation should be considered. In addition to the influence on the rupture stress of tungsten carbide workpieces, the surface flaws may also affect the scatter of rupture-stress results obtained on virtually identical testing pieces [1–3]. The objective of this investigation was to shed some light on these topics, and, therefore, as well as several specimens with a surface finish given by a D64 or a D15 grinding wheel (ISO R 565/1972), other specimens submitted to finer polishing operations have also been tested.

2. Experimental procedure

The material used in this investigation, WC (< 1 μm) –4 wt % Co, is commercially available. A low binder (cobalt) content and a very small grain size both contribute to its brittle behaviour.

Each specimen (with the geometry shown in Fig. 1) was obtained by unidirectional pressing of powder. The firm that produces the material has provided all specimens used for this research from the same batch of powder and also sintering conditions were kept constant for all the specimens. Before sintering, the longitudinal edges of the specimens were bevelled at 45 °C, using a diamond grinding wheel, and very narrow chamfers (with width $w = 0.15$ mm) were created. The final specimen dimensions after sintering were l (length) = 20 mm, b (specimen width) = 6.5 mm and h (height) = 5.5 mm.

The specimens were divided into eight groups depending on the surface-finishing procedure carried out after sintering. Each group is a set of several specimens that were submitted to identical surface-finishing operations and it will be considered, for statistical comparison among the groups, as a "subsample" of the initial "random sample" of sintered specimens. Table I summarizes each one of the surface-finishing procedures and indicates the corresponding name given to the specimens group.

In order to attain the objectives of the research two types of study were carried out: (i) surface roughness measurements and observations; (ii) flexural strength tests.

2.1. Surface roughness measurements and observations

Roughness profile R-parameters were computed by a Perthometer C5D equipped with a single-skid tracing system (RHT6-250). The tracing direction was always parallel to the longitudinal axis of the specimen, and the following R-parameters (according to DIN 4768) have been determined:

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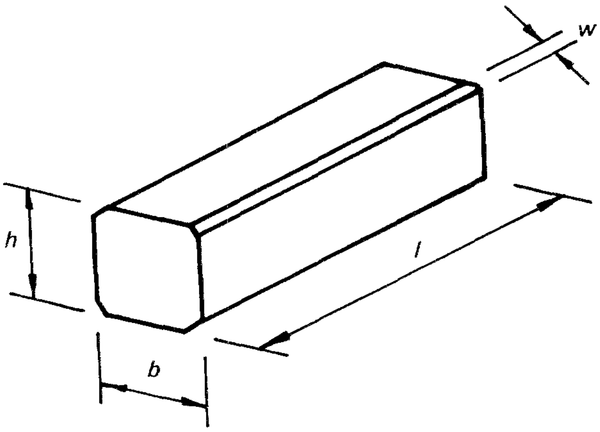

Figure 1 Specimen geometry.

TABLE I Description of surface-finishing procedures for each group of specimens

Surface-finishing procedure after sintering	Name of specimen group
None. Specimens did not suffer any surface modification after sintering, i.e. they were tested as-sintered.	Specimens AS (as-sintered)
Specimens were ground along all four longitudinal faces (not in the chamfers) using a D64 (53/63 μm mesh) diamond grinding wheel.	Specimens G64
Specimens were ground with a D15 (12/22 μm mesh) diamond grinding wheel along all four longitudinal faces, to such an extent that all chamfers were eliminated.	Specimens G15-w/c (without chamfers)
Specimens were submitted to a step-by-step "metallographical" polish along all four longitudinal faces (not in the chamfers) ending with a 15 μm diamond paste.	Specimens P15
Specimens were submitted to a step-by-step "metallographical" polish along all four longitudinal faces including the chamfers, ending with a 15 μm diamond paste.	Specimens P15-p/c (polished chamfers)
Specimens were submitted to a step-by-step "metallographical" polish along all four longitudinal faces (not in the chamfers) ending with a 6 μm diamond paste.	Specimens P6
Specimens were submitted to a step-by-step "metallographical" polish along all four longitudinal faces (not in the chamfers) ending with a 3 μm diamond paste.	Specimens P3
Specimens were submitted to a step-by-step "metallographical" polish along all four longitudinal faces, including the chamfers, ending with a 1 μm diamond paste.	Specimens P1-p/c (polished chamfers)

R_z the mean roughness depth, i.e. the mean of the five peak-to-valley values obtained from five successive sample lengths, l_e

R_{max} the maximum roughness depth, i.e. the largest of the five peak-to-valley values within the total measuring length $l_m = 5\,l_e$

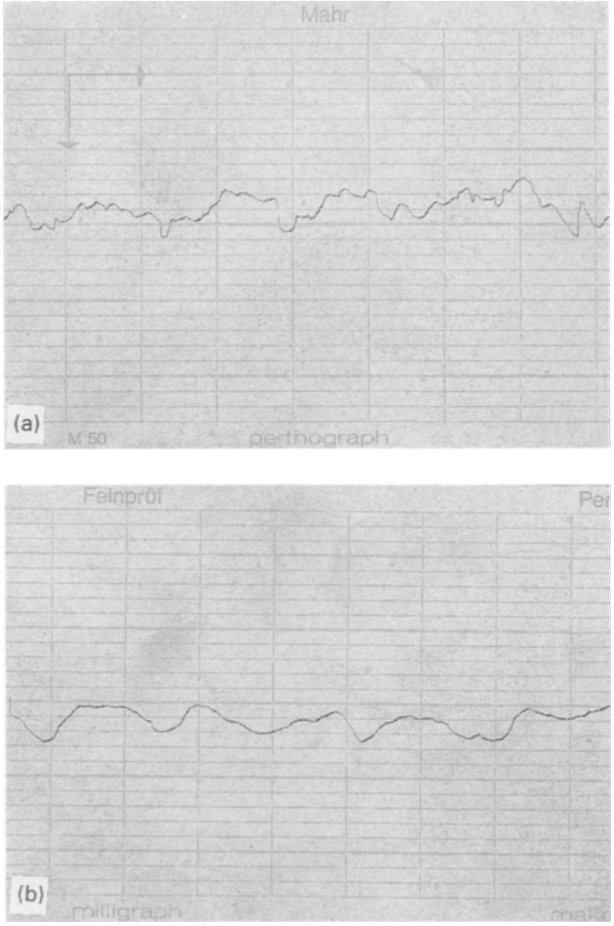

Figure 2 Examples of R profiles. (a) Specimen G64, vertical magnification × 4000, horizontal magnification × 20. (b) Specimen G15, vertical magnification × 10000, horizontal magnification × 20.

R_p the maximum levelling depth, i.e. the largest of the five "peak to mean line" values within the total measuring length, $l_m = 5\,l_e$. The "mean line" represents the so-called waviness or form of the surface and it cuts the roughness profile, R, such that the areas above and below are equal.

R_a the average roughness defined as the arithmetic mean of all values of the roughness profile R (based on the mean line) within the total measuring length, l_m, i.e.

$$R_a = \frac{1}{l_m}\int_0^{l_m} |y|\,dx \qquad (1)$$

Fig. 2 shows two examples of profiles R obtained, respectively, on G64 and G15 specimens.

For all groups of specimens, R-parameters were measured at 12 different locations on the relevant surfaces. The total measuring length, l_m, was 4.0 mm in specimens of the groups, AS, G64 and G15; $l_m = 12.5$ mm was used in all other specimens. The values of the R-parameters that are plotted in Fig. 3 correspond to the arithmetic mean of the results obtained at the 12 different locations on each type of surface finish. These mean values of the R-parameters are also indicated in Table II.

Complementary to the roughness measurements, observations of the aspect of the surfaces before and

TABLE II Roughness profile R-parameters, mean values of flexural strength and Weibull moduli for the different groups of specimens.

Specimen group	R_z (μm)	R_{max} (μm)	R_p (μm)	R_a (μm)	σ_r mean (MPa)	Weibull modulus, (m)
AS	2.79	3.31	1.88	0.380	1121	3.9
G64	1.44	1.90	1.00	0.270	1622	3.9
G15-w/c	0.55	0.70	0.40	0.100	1622	7.9
P15	0.41	0.56	0.27	0.054	1605	4.1
P15-p/c	0.41	0.56	0.27	0.054	1849	9.0
P6	0.32	0.57	0.29	0.037	Not tested	–
P3	0.32	0.47	0.21	0.036	Not tested	–
P1-p/c	0.32	0.40	0.17	0.030	1814	14.4

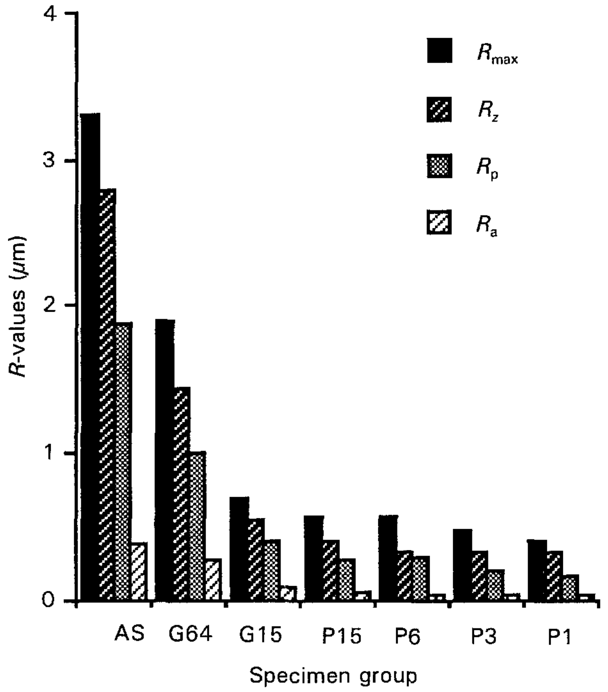

Figure 3 R-parameters versus specimen group.

after each grinding or polishing operation were carried out by optical and scanning electron microscopy (SEM). Figs 4 and 5 are examples of the final surface appearance on specimens of the groups G64 and P3.

2.2. Flexural strength tests

The flexural strength under symmetrical three-point bending has been determined in all specimens except for the groups P6 and P3. Specimens of the groups P6 and P3 were not tested because their R-values and surface appearance did not show remarkable differences compared to the specimens of the groups P15 and P1.

The span (distance between the external roller pins) of the three-point flexural jig was 15.0 mm. The tests were carried out in an Instron electromechanical testing machine using a 5 mm min^{-1} crosshead displacement velocity. Load versus displacement graphs were recorded for each specimen and flexural strength (modulus of rupture), σ_r, calculated using

$$\sigma_r = k\frac{3(F_r S)}{2(b h^2)} \tag{2}$$

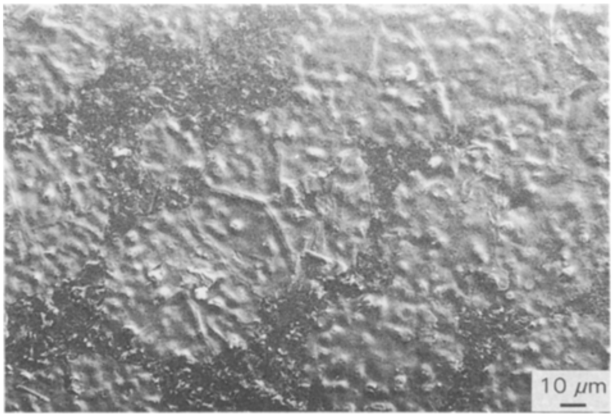

Figure 4 Scanning electron micrograph of the surface of a G64 specimen.

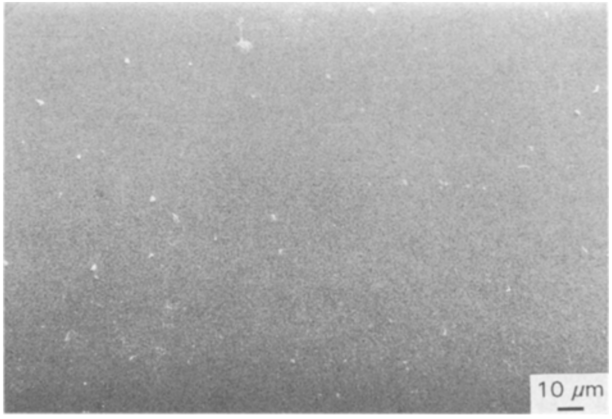

Figure 5 Scanning electron micrograph of the surface of a P3 specimen.

where k is the chamfer correction factor, F_r is the maximum recorded load, S is the span (15 mm); the dimensions (b and h) of each specimen were accurately measured before the tests. Because the width of the chamfers (w = 0.15 mm) is very small, k is considered equal to 1.0 according to ISO 3372 [4].

A theoretical analysis of errors associated with F_r readings (from the load versus displacement chart-recordings), and also with measurements of specimen dimensions, has shown that the values of σ_r may be affected by a ± 30 MPa maximum error.

SEM observations of the morphology of the fracture surface of several specimens confirmed that the source of failure (i.e. "the critical defect" responsible for the rupture of the plain specimens tested in three-point bending) was usually located at the outer surface under tension or at one of the two neighbouring chamfers. Fractographic studies carried out on the present material are described in previous work [5].

3. Results and discussion

Beside the fact that simple statistical parameters like the arithmetic mean and the sample standard deviation of σ_r-results are still used to compare the failure behaviour of brittle materials, this behaviour is better described according to the weakest link model. Assuming that the probability of failure, P_f, at a given applied stress, σ, is given by the two-parameter Weibull equation

$$P_f = 1 - \exp[-(\sigma/\sigma_0)^m] \qquad (3)$$

the assessment of the effect of surface roughness on three-point flexural strength was done through the determination of the Weibull parameters m and σ_0 for each group of specimens (or "subsample"). The method to determine m and σ_0 from each set of experimental data was based on the linearization of Equation 3 by taking double logarithms

$$\ln\ln[1/(1 - P_f)] = m\ln\sigma - m\ln\sigma_0 \qquad (4)$$

In order to apply linear regression to this equation, from which the values of m and σ_0 can be determined, it is necessary to assign to each experimental value of $\sigma = \sigma_r$ a numerical value of P_f. The experimental definition of the failure probability, P_f, was done using the following estimator

$$P_f = (i - 0.5)/N \qquad (5)$$

where i is the rank of the σ_r-value when all rupture stress results (of the same group of specimens) are positioned in increasing order and N is the total number of results, i.e. the dimension of each "subsample". In this investigation we had $N \geq 15$ for all groups of specimens, excepting the P1-p/c group where only ten specimens were tested. Among different estimators for P_f referred to in the literature, Equation 5 is usually favoured because it results in the smallest bias on the derived value of the Weibull modulus, m [6].

The display of different sets of data plotted in the same Weibull graph, as is shown in Fig. 6, allows a comparison of the failure behaviour of different groups of specimens. The "scaling" or "normalizing" parameter, σ_0, corresponds to the value of σ that causes the failure of $1 - 1/e = 0.632$ i.e. 63.2% of the specimens. The Weibull modulus, m, i.e. the slope of the straight line fit, gives an indication of the degree of scatter in fracture stress results – the higher the value of m the lower is the scatter of σ_r-results.

The values of m obtained on each group of specimens are indicated in Table II. Instead of σ_0, the (arithmetic) mean values of σ_r-results are also shown in Table II. As can be seen from these data, the refinement of the surface finish causes an increase of the mean value of σ_r, as well as an increase of the value of m, but an exception to this trend occurs with the specimens of group P15.

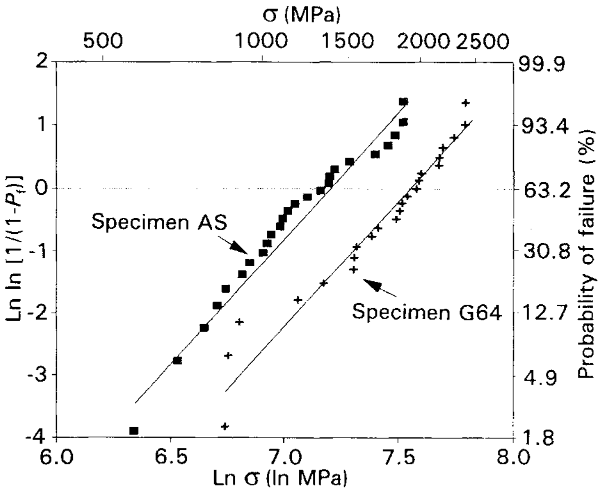

Figure 6 Weibull graph showing the results for specimens AS and G64.

The dimension of the "critical flaw", a_c, responsible for the failure of each specimen can be estimated from

$$K_c = Y\sigma_r(a_c)^{1/2} \qquad (6)$$

In order to evaluate a_c from Equation 6, we have considered $Y = 2$ and $K_c = 7.1$ MPa m$^{1/2}$. The fracture toughness value for this type of WC–Co was determined through the indentation fracture method proposed in JIS R 1607 (1990).

If the mean values of σ_r are assigned to Equation 6 for each specimen group, then the corresponding mean values of a_c can be determined. Table III shows these mean a_c-values and allows a comparison with the values of R_{max} determined by the Perthometer.

Some questions arise from the comparison between the mean a_c-values and the values of R_{max} determined by the Perthometer (equipped with the RHT 6-250 single-skid tracing system). On the one hand, for the groups AS and G64 there is a fairly good agreement between the values of a_c and R_{max}; on the other, for groups with lower roughness it was found that the theoretically determined values of a_c were larger than the measured values of R_{max}. The explanation of these discrepancies still remains open to question, but we think that the experimental technique used to measure the R-parameters has some limitations. The contact point of the stylus of the single-skid tracing system RHT 6-250 is the tip of a sphero-conical diamond. The cone has an included angle of 90 ° and its spherical tip has an nominal radius of 5 μm. Because of this radius at the tip of the diamond stylus, the pick-up cannot accurately measure the depth of many surface flaws (especially those which are sharp and narrow), and consequently the R-values that have been computed by the equipment must be smaller than the "true" values.

Returning to Table II, we can see that the m value obtained in groups AS, G64 and P15 is virtually the same (between 3.9 and 4.1). In groups G64 and P15, the mean value of σ_r is practically the same and approximately 1600 MPa. This value is clearly higher

TABLE III Mean values of a_c determined through Equation 6 and the corresponding values of R_{max}

Specimen group	R_{max} (μm)	a_c mean (μm)
As	3.31	3.2
G64	1.90	1.5
G15-w/c	0.70	1.5
P15	0.56	1.6
P15-p/c	0.56	1.2
P1-p/c	0.40	1.2

than the mean value of σ_r obtained in group AS (i.e. 1121 MPa). With the refinement of the surface finish, there is a decrease in the dimension of the "critical flaws" (see also Table III) but for groups AS, G64 and P15 the scatter of σ_r-results (or a_c-values) stays practically the same.

Comparing the results obtained for the only specimens in which the chamfers have been eliminated (specimens group G15-w/c), with the results obtained in groups G64 and P15, we can conclude that the removal of the chamfers seems to lead to a significant increase of the Weibull modulus, i.e. to a lower scatter of σ_r-results (or a_c-values). However, the mean value of rupture stress obtained in group G15-w/c is equal to the G64 and P15 mean σ_r-values. The reason for this particular behaviour of group G15-w/c has been investigated and SEM observations of the fracture surfaces have revealed that in the majority of the specimens of this group, the source of failure was located at one of the longitudinal edges at the outer surface. Consequently, the lower scatter of σ_r-results in specimens G15-w/c, with m-value close to 8, can be explained by assuming that most of the critical defects responsible for the failure of those specimens are more or less similar flaws caused by microchipping at the edges. This was not the case in specimens G64 and P15, having m-value close to 4, in which the SEM observations have revealed that the source of failure is not so predominantly located in the chamfers but it can also be positioned elsewhere at the outer surface under tension.

When considering the "mean value of σ_r, value of m", it can be seen from Table II that the best performance was obtained on specimens P1-p/c (i.e. polished with 1 μm diamond paste, not only along the longitudinal faces but also along the chamfers). However, if the accuracy (± 30 MPa) of the σ_r-results is taken into account, the mean value of $\sigma_r = 1814$ MPa obtained in the specimens P1-p/c may not show a clear difference from the mean value of $\sigma_r = 1849$ MPa obtained in specimens P15-p/c. Also the fact that "only" ten P1-p/c specimens have been tested may cause some doubt about the validity of the value $m = 14.4$. Nevertheless, the results can be justified by the clear differences between the roughness parameters of specimens P1-p/c and P15-p/c.

4. Conclusion

This investigation has shown that the flexural strength of this particular type of WC–Co clearly depends on the surface roughness of the testing pieces. SEM observations of the fracture surfaces have revealed that microchipping at the edges of the test pieces is an important source of critical flaws. When considering the "mean value of σ_r, value of m", the best performances were obtained on specimens that were polished not only along the longitudinal faces but also along the chamfers. The use of a 15 μm diamond paste as the final abrasive seems to be sufficient to approach the maximum mean value of σ_r-results (approximately 1800 MPa). Subsequent polishing operations using lower mesh diamond abrasive pastes may contribute to smoother surfaces and to higher values of the Weibull modulus, but their effect on the mean value of flexural strength is apparently slight.

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