FRACTURE INDENTATION TOUGHNESS TESTING IN HARDMETALS

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Abstract. *This paper describes an experimental and numerical study of the Vickers indentation testing of hardmetals specimens. Indentation testing is commonly used for surface hardness measurement of different materials. This method is quite versatile and several new applications for it have been proposed. However, the implementaion of some of these techniques and many of their results still raise questions among researchers. These include the evaluation of fracture toughness in hardmetal materials, which present a mechanical behaviour between a plain brittle ceramics and a more ductile metals. These materials are frequently used to manufacture cutting tools for which very high surface hardness and also compression and wear strength are expected. These peculiar mechanical properties of those materials are difficult to evaluate through conventional testing techniques. Amongst these limitation, the experimental results of hardness and fracture toughness agrees well with results found in the literature. Strong levels of residual tensile stresses were observed close to the specimen surface and the indentation tip regions.*

On the order hand, the numerical analysis was implemented by three dimensional finite element model using the commercial solver MARC™. Hardness values predicted by this model were compatible with those obtained experimentally. In this analysis, the maximun principal stress field was used to locate the most expected areas for crack formation during the Vickers indentation testing.

Keywords: *Indentation Testing, Fracture Toughness, Numerical Analysis*

1. INTRODUCTION

Indentation testing is commonly used for surface hardness measurement of different materials (Souza, 2000). The Vickers essay consists of a 136º pyramidal diamond indenter, Fig 1. This testing method is quite versatile and several research works have proposed new applications for it. These include the evaluation of different mechanical properties of materials, for example, elasticity modulus (*E*) and fracture toughness (K_{IC}) (Niihara, 1983; Zeng and Chiu, 2001).

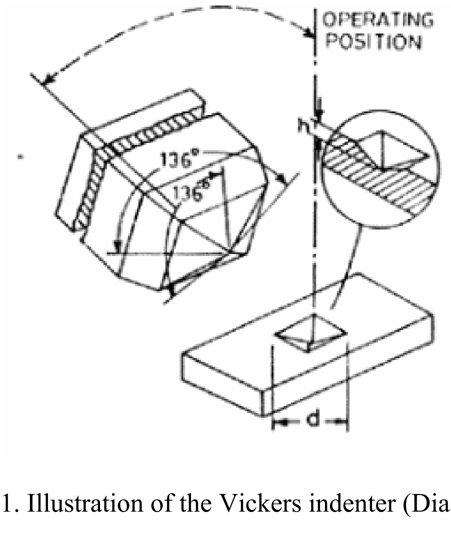

Figure 1. Illustration of the Vickers indenter (Dias, 2004)

However, the implementation of some of those techniques and many of their results still raise questions among researchers (Pontom and Rawlings, 1989; Schubert *et al.*, 1998). Difficulties are particularly acute when materials like tungsten carbide with cobalt (WC-Co), which present a mechanical behaviour between a plain brittle ceramic and a more ductile metal, are tested (Laugier, 1985). WC-Co is a material frequently used in cutting tools manufacturing, such as ISO SNMA 120408 HIP carbide tools, for which very high surface hardness and also compression and wear strength are expected (Trent, 1984; Sandvik, 2000). These peculiar mechanical properties bring difficulties to evaluate those materials through conventional testing techniques. Consequently, several proposals able to evaluating the mechanical properties of these tools based on non-conventional techniques have been presented in the literature (Densley and Hirth, 1998; Szutkowska, 1999). Among these, the Vickers indentation testing is one of the most used techniques to evaluate the fracture toughness of tungsten carbide and similar materials, nevertheless, the application of Vickers testing presents some limitations and drawbacks. Considering those limitations, the diversity of empirical equations that are available to calculate fracture toughness based on two main models of crack nucleation and propagation is one of the most important, Fig. 2. During the Vickers indentation testing of WC-Co, the surface radial cracks that can be usually observed are considered to be Palmqvist cracks (Niihara, 1983).

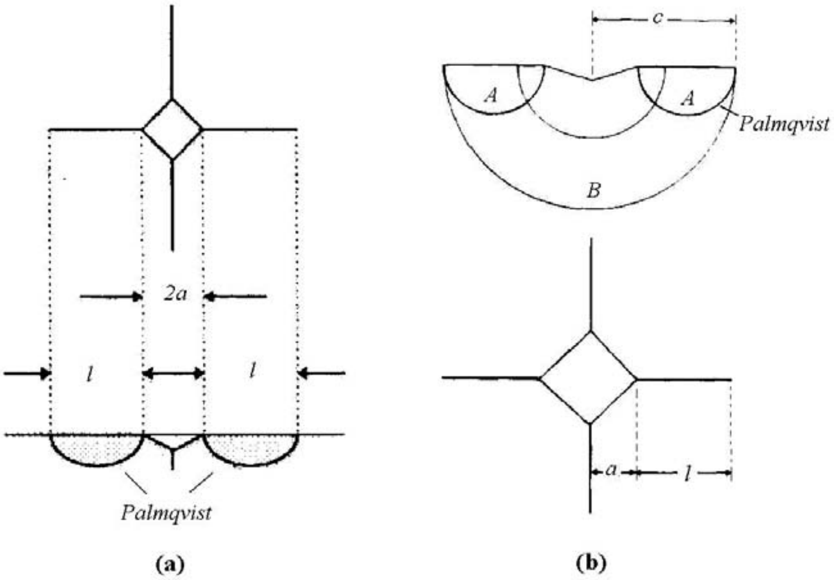

Figure 2. Models of crack nucleation and growth during Vickers indentation testing: (a) Palmqvist (Niihara, 1983); and (b) radial-median (Laugier, 1985)

Numerical modelling can contribute to solve some limitations of the experimental analysis of Vickers indentation testing. Such approach can estimate the material strain and stress fields around the indentation, and so help to sort out areas with more favourable conditions for crack nucleation and propagation during the test, and, which allow a better understanding of the test. In the last ten years, some attempts of numerical indentations testing modelling of different materials using finite element analysis have been performed (Dias *et al.*, 2005). However, even this approach has presented some shortcomings related to several factors including the need of higher computer performance and the lack of adequate criteria to characterize crack nucleation and propagation.

In this article was experimentally determinated the Vickers hardness and indentation fracture toughness of a WC-Co machining insert by indentation techniques. Experimental values of hardness and fracture toughness for the sample of a 120408 HIP cutting tool, which contains tungsten carbide with 6% cobalt, were presented. Scanning electronic microscopy to evaluate the distribution of tungsten carbide in the cobalt matrix for the GC 415 specimen.

This work also presents a numerical simulation of Vickers indentation testing of tungsten carbide with cobalt (WC-Co) using three dimensional finite element models. This approach was trigged by the difficulties to evaluating the experimental stress and strain fields developed in the material during the loading and unloading cycles of the indentation test. Those fields are key factors in the nucleation and growth of cracks during the indentation testing of low toughness materials and should be considered when analyzing these processes. In this paper, the stress fields obtained by numerical simulation, the predicted sites for cracking nucleation and the hardness values and were used in comparison with the experimental data and also with results reported in the literature.

2. HARDNESS TESTING

The experimental testing was performed in a Heckert hardness machine using a Vickers pyramidal diamond indenter. The procedure was according to the DIN 50133 standard (1972). Additionally, the insert surface of the sample was prepared by polishing to obtain a mirror-like finishing with minimal residual stresses (Ávila, 2003). In sequence, the scanning electronic microscopy was used to evaluate the distribution of tungsten carbide in the cobalt matrix.

A load of 588 N was slowly applied to the insert surface by the indenter with a penetration speed of about 0.001-0.02 mm/s during thirty seconds. After this interval, the indenter was removed from the testing surface and the indentation dimensions were measured with an optical microscope (Souza, 2000). The results from these tests were used as part of the numerical model validation of the developed in this work. They were also taken into consideration to establish some characteristics of the model.

Fracture toughness was determined from the indentation test results by using two semi-empirical equations for Palmqvist cracks. Equation (1) was formulated by Niihara (1983) and modified by Szutkowska (1999) and Eq. (2) was proposed by Shetty (1985).

$$\left({}^{K_{IC}\phi}\Big/_{Ha^{1/2}} \right)\left({}^{H}\Big/_{E\phi} \right)^{2/5} = 0{,}035\left({}^{l}\big/_{a} \right)^{-1/2} \tag{1}$$

$$K_{IC} = 0{,}0937\left(HW\right)^{1/2} \tag{2}$$

Where K_{IC} is the fracture toughness, H is the hardness, E is the elasticity modulus, a is the half length of the indentation diagonal, l is the half size of the Palmqvist surface crack, Fig. 2, ϕ is the restriction factor proposed by Szutkowska (1999) and P is the indenter force and $W = P/4l$.

3. NUMERICAL MODELING

The numerical simulation was developed on commercial finite element software MARC™ (2005). This software is considered to be very efficient to perform numerical analysis of systems that are characterized by high strain and stress gradients and by non linear behaviour. The characteristic of Vickers essay allowed simulating the load application in the specimen during testing by imposing a displacement on the indenter, which made possible a better control during the indentation cycle. In the present work, a displacement of 0.02 mm was adopted based on results of the experimental tests performed on 120408 HIP (Dias, 2004). The penetration and load removal phases of the test were modelled using three hundred interaction steps for each phase. In order to reduce the model processing time, only one quarter of both specimens and indenter were modelled, Fig. 3.

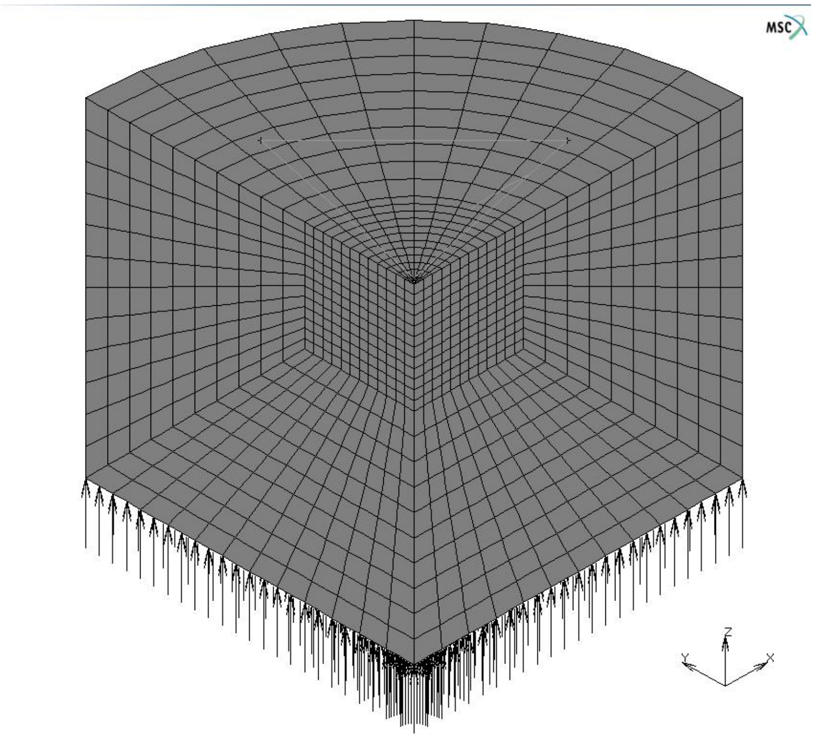

Figure 3. Numerical model of the specimen and indenter

This specimen was modelled as a circular plate using brick three-dimensional eight nodes elements, Fig 3. To represent this plate, 4752 elements and 5715 nodes were used. The base of this plate was constrained in the indentation direction (z-axis). Boundary conditions linked to the problem symmetry were applied in the directions of the x and y axes (Dias *et al.*, 2005). The sample was considered as an isotropic, homogeneous material with Young modulus of

619.5 MPa and Poisson coefficient of 0,28 (Trent, 1984). The Vickers indenter was modelled by rigid plate forming a pyramid with an angle of 136º between its opposing faces.

The elastic-plastic behaviour was represented by Eq. (3)(Dias *et al.*, 2007), where σ_e, ε_e, ε'_e, m, n e σ_o are, respectively, the effective stress, the effective strain, the effective strain rate, the hardening coefficient, the strain rate sensitivity coefficient and the yielding limit. Table 1 presents the mechanical properties which were adopted in the present work based on data from the literature for the WC-6Co carbide tools (Trent, 1984; Zeng and Chiu, 2001).

$$\sigma_e : \max\left[\left(B + A\varepsilon_e^m \dot{\varepsilon}_e^n\right), \sigma_o\right] \tag{3}$$

Table 1 – Mechanical properties of ISO SNMA 120408 HIP (Trent, 1984; Zeng and Chiu, 2001).

σ_o (MPa)	σ_{TR} (MPa)	A (MPa)	B	n	m
5760	3750	18060	0	0	0.244

Where σ_o is a yield limit, σ_{TR} is a transversal rupture stress, A and B are constant of Eq. (3)

4. RESULTS AND DISCUSSION

Figure 4 shows the scanning electronic microscopy of the specimen. Despite the fact of cutting tools manufacturer guarantees the presence of an uniform distribution of tungsten carbide in the cobalt matrix (Sandvik, 2000), it was possible to verify a non uniform distribution. This absence of uniformity could result on unlike experimental values of K_{IC}.

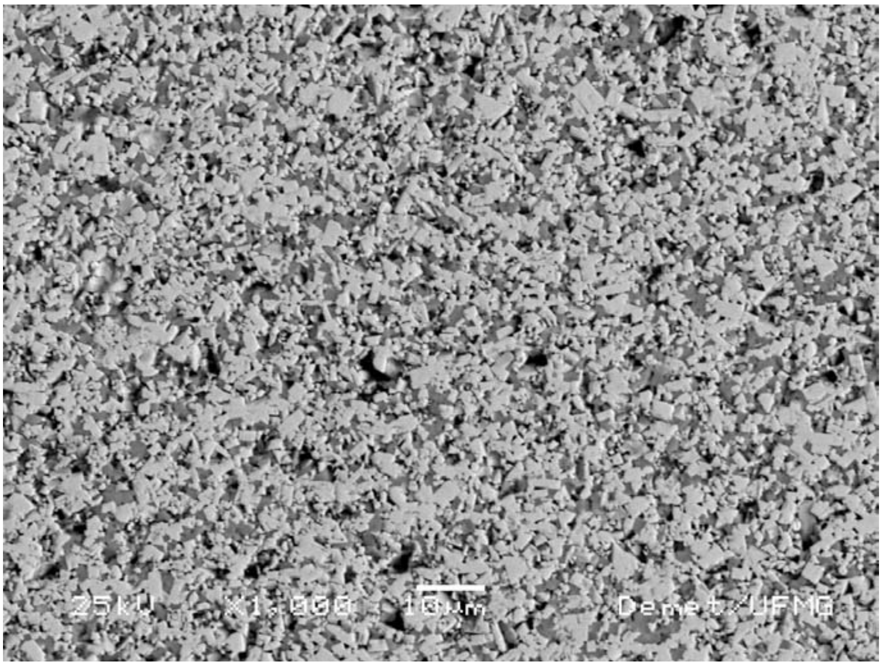

Figure 4. Surface micrographs (1000x) of GC 415 cutting tool specimen

Table 2 shows the experimental results obtained for the hardness testing of 120408 HIP specimens. The mean hardness value (18,97 GPa) was about 5,4 % higher than the experimental ones found in the literature. The ratio between the crack and indentation diagonal lengths (l/a) was inside the range of 0.25-2.5 what characterize them as Palmqvist radial cracks (Niihara, 1983; Pontom and Rawlings, 1998; Schubert *et al.*, 1998).

Fracture toughness (K_{IC}) was evaluated from hardness testing results using Eq. (1) and Eq. (2). In these calculations, it was employed the data from Tab. 1 and Tab. 2 which the restrain factor (ϕ) suggested by Szutkowska (1999).

Table 3 presents the values of K_{IC} found in the present work and compare them with the value of 10MN/m$^{3/2}$ obtained in the literature using bending testing (Trent, 1984). Although the K_{IC} found in the present work through Eq. (1) deviate around 29% from this value, it may be expected that the used preparation procedure did not form residual stresses on the surface of the tested specimen.

A surface hardness value of 20.5 GPa was obtained by the numerical simulation of the 120408 HIP specimen indentation testing. This hardness value was about 8,1 % higher than the experimental ones. This result suggests that the present simulation represented adequately the global behaviour of the Vickers indentation testing.

Table 2. Experimental results obtained in the Vickers hardness testing

Force	Hardness (GPa)	Indentation diagonal length ($2a$)	Radial cracks (l)	Ratio (l/a)	$\phi = H / \sigma_o$
588 N	18,74	328,80 μm	314,30 μm	1,91	3,25
	18,74	325,90 μm	207,15 μm	1,27	3,25
	18,62	328,50 μm	289,00 μm	1,76	3,23
	18,62	327,60 μm	275,35 μm	1,68	3,23
	19,56	319,30 μm	259,95 μm	1,63	3,40
	19,56	319,30 μm	302,90 μm	1,90	3,40

Table 3. Fracture toughness of 120408 HIP specimens obtained from indentation testing and comparison with bending testing value

Equation	K_{IC} (MN/m$^{3/2}$)	Difference (%)
"Eq. (1)" (Szutkowska, 1999)	12,88 MN/m$^{3/2}$	28,8
Eq. (2) (Shetty, 1985)	9,48 MN/m$^{3/2}$	5,5

Figure 5 shows the maximum principal stress distribution predicted by the numerical model by the end of the test in the plane that includes the indentation diagonal. This distribution was similar to other results described in the literature for similar materials (Dias *et al.*, 2005). It was used to predicted, considering Rankine's criterion, regions along this plane where conditions for crack nucleation were reached, Eq. (4).

$$\sigma_1 \geq \sigma_{TR} \tag{4}$$

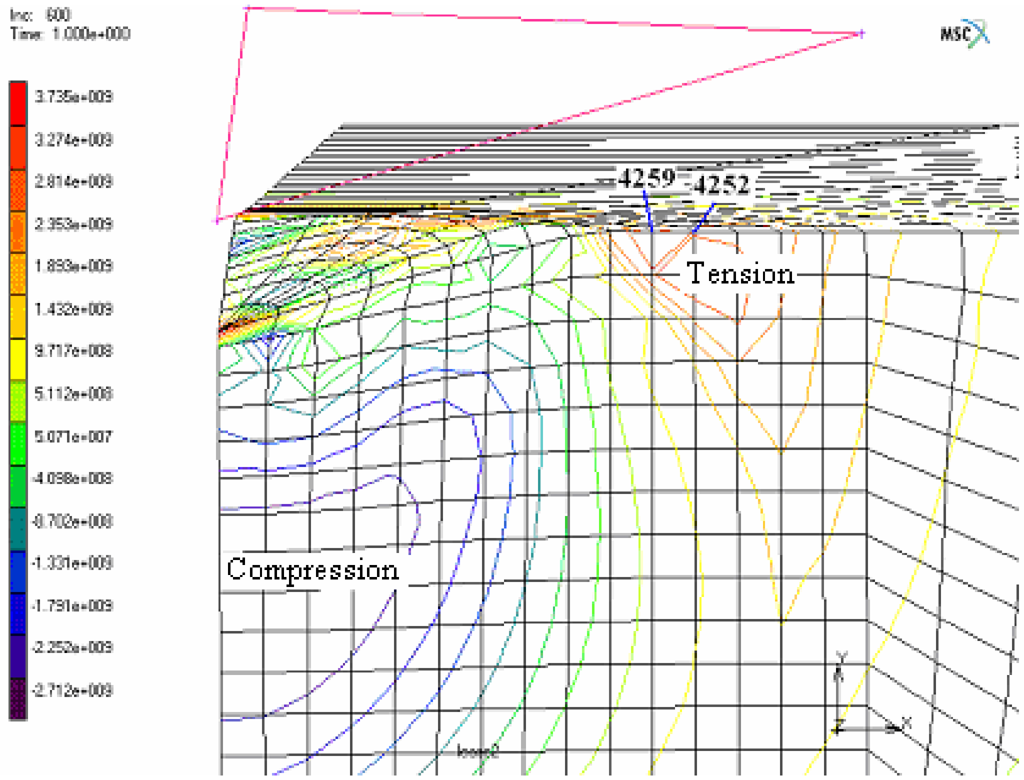

Figure 5. Distribution of highest principal stress (GPa) in the plane that contains the indentation diagonal

In the numerical analysis, a residual tension stress field could be observed close to the specimen surface and just after the end of the indentation. The location of this region agreed with results of both experimental tests and numerical simulations found in the literature (Niihara, 1983; Szutkowska, 1999; Dias *et al.*, 2005). On the other hand, a region of compression stresses was observed just below the indentation. In this way, crack nucleation and propagation is not expected in this region.

Two nodes (4259 and 4252) of the model were chosen to demonstrate the evolution of stress distribution during the indentation test in the region close to the indentation tip, where the maximum tensile stresses were observed, Fig. 6. This figure indicates the build up of high tensile stresses in this region confirming that it is really critical from the point of view of Rankine's criterion, Eq. (4).

These results indicated the presence of strong stress gradients and high tension stresses in the region next to the indentation and around indenter diagonal direction. These results confirmed that this is a region prone to the formation of crack, i.e., Palmqvist type cracks. In this region, it can also be observed that the predicted maximum principal stress can have a value nest to the measured transversal rupture stress (σ_{TR}) of 120408 HIP, Table 1, which also can support the formation of cracks in this region.

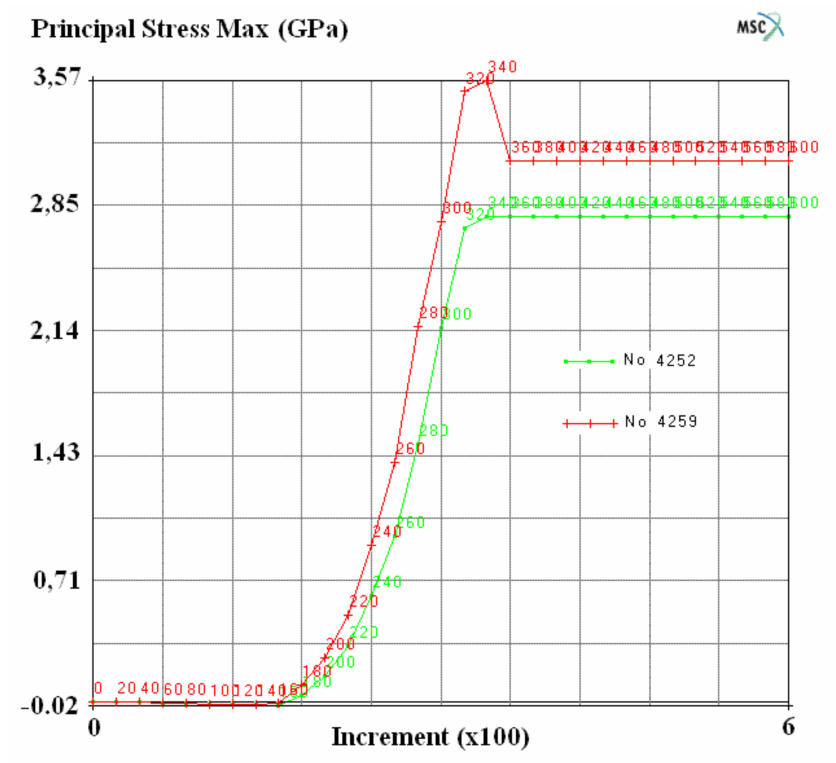

Figure 6. Evolution of the highest principal stress during the simulation of two selected points

5. CONCLUSIONS

This work presented experimental and numerical results of indentation testing of cutting carbide tools (WC-Co). Fracture toughness of this material was evaluated experimentally by the indentation testing using two semi-empirical equations.

The procedure used in the preparation of the surface of the specimen looked to be adapted and guarantees a low cost preparation. The experimental values of superficial hardness and fracture toughness were in accordance with the values informed by the manufacturer of cutting tool 120408 HIP specimens. Likewise, the analysis of the micrography of the sample surface showed a non-uniform distribution of the WC in the matrix of Cobalt. This distribution may have been the cause of the difference of 28,8% in the value of fracture toughness when using the experimental methodology proposal by Szutkowska (1999).

The 3D finite element (FE) model developed in the present work was able to represent adequately the general behaviour of the Vickers indentation testing and also some qualitative aspects of the stress field around the indentation.

The formation residual stress field was also shown. Moreover, predicted maximum principal stress values in the region around indenter diagonal direction were higher than the rupture stress of 120408 HIP cutting tool and so could support the formation of Palmqvist cracks in this region. These numerical results indicate that the failure mechanism in those specimens was agree with the model proposed by Niihara (1983) and modified by Szutkowska (1999).

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