Int J Adv Manuf Technol (2005) 26: 959–964
DOI 10.1007/s00170-004-2091-x

ORIGINAL ARTICLE

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Evaluation of diamond tool wear

Received: 28 May 2003 / Accepted: 9 January 2004 / Published online: 19 May 2004

Abstract The present study proposes a test protocol regarding the wear of sintered diamond tools. A set of parameters, which characterise the grade of wear, and its relationship with the cutting ability of the examined tools, are established. The proposed protocol establishes the procedure and the equipment for carrying out the tests, the features of the materials to use and the format of the report to present the results obtained. The developed test protocol indicates an universally applicable way for measurement of the wear of the diamond tool. It is an indispensable instrument for correctly carrying out the wear tests and for reliably interpreting the results. The protocol developed so far mainly regards laboratory tests, considering the slowness and precision of the measurements involved. Given the total absence of norms, this protocol could be absorbed by national and international norm establishing organisations. This protocol has also been applied to two types of tools and the results obtained have appeared reliable and replicable. The test protocol proposed in this study makes it possible to overcome the difficulties connected to the scarcity of technical data regarding the properties of the tool, which is typical in this field since the recipes for tool manufacturing are patented.

Keywords Cutting tool · Diamond sintered mill · Macro-geometric wear parameters · Test protocol · Wear

1 Introduction

The increasing demand both in the industrial field and in urban furnishing for elements in natural stone with increasingly complex geometry makes it necessary to use increasingly flexible and automatic machines, such as numerically controlled machining centres. These centres make it possible to carry out large numbers of operations by means of diamond mills. No studies on optimisation of the cutting process have been carried out for these jobs. Therefore, until now, a sometimes imperfect solution has been accepted [1, 2]. Optimisation means reducing machining costs and/or times and/or improving the quality of the products obtained by working on different factors, such as cutting strengths, tool properties, process temperatures and vibrations [3–5]. A critical point is the actual tool. Optimisation of the tool properties in relation to the wear process leads to optimisation of the whole process. The present study aims at understanding the diamond tool wear process. This behaviour has a direct influence on energy consumption and on tool life. In particular, diamond tool wear necessitates appropriate definitions and measurements. In other words, it is necessary to establish, in a clear and unequivocal way, the parameters that characterise the wear process and their measurement by means of a reliable and replicable procedure. The aim of the present study is to define a test protocol regarding wear of sintered diamond tools. The total absence of bibliographic references or norms regarding the procedures for conducting wear tests on sintered diamond tools has made it imperative to prepare an adaptable test protocol that offers a universally valid mode for carrying out the macro-geometric wear test with the aim of obtaining replicable and comparable results. It is an indispensable instrument for correctly carrying out tests and for reliably interpreting the results. It offers stone machining companies the possibility of comparing tools that producers sell as being similar, but during machining present extremely differing performances. In fact, at the present state, diamond tools available on the market are characterised solely by the specification of the material they can process, while other technical features are subject to industrial patent and, therefore, are unknown to marble and granite machining firms. This protocol could be used by tool manufacturers to evaluate the performance of their tools compared to those of competitors and at the same time to equip their supplies with information on the useful life of the tools offered. This last aspect represents a service that transformers are requesting

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with increasing insistence. The guide lines forming this protocol have been taken from existing norms for single-cut tools [6]. The protocol developed so far regards tests to be carried out in the lab, given the precision and thus the slowness of the tests involved. The protocol has allowed the development of knowledge of the wear process of diamonds, which constitute tools for machining natural stones, which in turn constitutes the basis for machining optimisation. The following paragraphs describe the properties of diamond tools used in cutting natural stones and their relationship with wear. The test protocol and its application to two types of tools are described in the following sections.

2 Wear of sintered diamond tools for machining natural stone

Diamond tools used for natural stone machining can be classified in cutting tools, such as wires, blades, disks and mills, and tools for machining surfaces, such as grinders and mills of different shapes and profiles. In both cases the tool consists of a support, a super-abrasive grit and a bound. The support is the part of the tool upon which the abrasive grit is fixed. It gives the tool the appropriate form, transmits kinetic energy from the machine rollers to the abrasive grit and absorbs the strengths created during the machining process. The super-abrasive grit has the task of removing the material. Its properties are granulometry, shape and bound matrix concentration. The granulometry expresses the measurement of the super-abrasive grit size. The form of the grit may be regular or irregular according to the quality of the actual grain. Concentration is the quantity, in weight, of the diamond grit for sector unit volume. The bound is that alloy which blocks the super-abrasive to the tool support so that it can carry out the cutting, milling, sharpening, smoothing and profiling economically and in a technically correct manner. The bound must guarantee two contrasting requisites: cutting capacity and long tool life. Finally, the bound must have wear resistance suited to the type of tool super-abrasive, such as allowing the correct protrusion in relation to the process to be carried out and the features of the material being machined, but above all it must allow the loss of worn grit to encourage replacement by new grit existing within the matrix. The metals making up the bound mixture are iron, copper, tungsten, cobalt and nickel. The diamond tool wear is the result of the wear progression of both diamond grit and tool binding. It is characterised by a sequence of steps [7, 8]. Firstly, there is a progressive increase of grit protrusion with respect to binding surface, due to binding erosion, that makes the grit come into contact with the workpiece. An emergent crystal appears on the tool surface: its cutting ability is scarce because of its small height of protrusion. A binding that is too hard would make the abrasive grit exposition so difficult the tool sector results polished before the diamond grits are completely emerged by binding. The progressive erosion of the binding makes the whole crystal appear on the surface of the tool sector. A whole crystal is a diamond grit that has a large height of protrusion and a minimum surface damage. It has the best cutting performances. Once the workpiece is contacted, the grit is rounded off so much that a plateau is generated on the grit top. It generates mechanical friction and thermal effects that polish the diamond grits. An high percentage of polished grits makes the surface of the tool sector so vitreous, to cause a less efficient cutting ability. The intermittent contact with the workpiece, caused by the tool rotation, leads to a cyclic load on the diamond grit, which deteriorates the grit ability to contrast the cutting forces and, finally, the grit breakage. This phenomenon is enlarged by the heterogeneous nature of the workpiece and by the machining vibrations. The diamond grits result is characterised by microfractures and microcracks that increase the number of cut edges on the grit surface, even if they reduce the penetration depth. Wear progression leads to a completely fragmentary particle or to a worn matrix in such a way that the diamond grit is released. The pull-out is the phenomenon due to the release of a diamond grit from binding, and to the consequent formation of a cleavage. It may accelerate tool wear, when a diamond grit is removed from the metallic binding before its useful life is completed. In this case the resulting cleavage will be very big and it will involve a considerable binding wear before a new abrasive grit emerges. Conversely, if the grit is removed from the metallic binding after its useful life is consumed, the cleavage will be less deep and less volume of binding will be consumed in order to remove a new grit. The pull-out is due to an increase either of the cutting efforts or of the cohesion power to keep fixed diamonds. New grits will emerge on the tool cutting surface and the wear cycle will begin again.

The progression of diamond tool wear consumes the diamond and the binding constituting the tool. This implies the decrease of both the weight and the diameter of the whole tool and the change of the cylindrical shape of the diamond tool. The tool moves away from its original cylindrical boundary surface. We have evaluated the consumption of a diamond mill by means of four variables that depend on the whole tool: the decrease of the tool weight, the decrease of the tool diameter, the variation in the cylindricity of the tool shape and the grinding ratio. Cylindricity is a condition of a surface of revolution where all the points of the surface are equidistant from a common axis.

These three macro-geometrical variables are directly connected with wear progression and, at the same time, they are simple to measure. They have been used to monitor the mill wear during stone machining. They have been called macro-geometric wear variables.

3 Test protocol for the macro-geometric wear of sintered diamond tools

The protocol regarding macro-geometric wear specifies the material to be machined, standard conditions of the workpiece, tool properties, the cooling fluid to be used and the cut conditions to be applied during the test. The machine that carries out the test must be of rigid structure and not tend to vibrate or bend anomalously during the test. The machine-tool for the test must have a command for continuous speed variation covering the whole range of speeds used during the actual machining. The method to be followed to achieve the test regarding tool life is the same as that used for achieving the cut operation with observations to be noted and measurements to be made. The macro-geometric wear test consists of carrying out various cutting operations in succession and interposing the measurement of the macro-geometric wear parameters between one cut and the next. The test report will contain the graph regarding the trend of the macro-geometric wear parameters in relation to the volume of removed material. Below we have the full text of the protocol.

3.1 Material to machine

Given the large number of materials used in the natural stone machining field it is not advisable to compare tests carried out on differing materials or on materials having similar properties. For this reason the properties of the materials used must be specified in a test summary according to the details given in Table 2 for the two considered granites: black Africa and Sardinian granites.

3.2 Standard conditions of the workpiece

The cutting test must involve the whole surface of the tool (i.e., the radial depth of cut must be equal to the diameter of the tool). It must be carried out on slabs having dimensions that will minimise vibrations of the work-piece during the test. The spindle and the table where the workpiece will be fixed must be stable and well-balanced. During positioning of the workpiece on the table bending of the work-piece must be carefully avoided.

3.3 Tool

Tool wear strongly depends on the materials constituting the actual tool. In the test résumé, characteristics of the tool used during the test must be specified according to indications given in the Table 3 for the two considered tools.

3.4 Cutting fluid

All cutting tests in which the cutting fluid is not a variable must be achieved using water as the cutting fluid. The cutting fluid jet must be directed onto the face of the tool and completely hit the active part of the tool. If possible, indicate jet capacity and pressure in the test résumé.

3.5 Cut conditions

For all cutting tests in which feed rate f, axial depth of cut a, and cutting speed v_t do not constitute the main test variables, cutting conditions must have the reference values shown in Table 4. If the aim of the study is to evaluate the relationship among tool wear and cutting parameters, cutting conditions must be planned on many different levels, inside the range of interest from an industrial point of view, through design of experiment techniques (DOE) techniques.

3.6 Macro-geometric wear test procedure

3.6.1 Introduction

The aim of the tool life test is to establish by means of experimental tests how one or more parameters influence the life of the cutting tools. The reason for deciding that the life of a particular cutting material is over is often different for different machining operations. The simplest case that can occur is when the tool becomes completely unusable. In the majority of cases the tool wears progressively and the machining carried out becomes less satisfactory, for instance, cut strengths increase and produce intolerable bending and vibrations. Determining the end of tool life is thus fixed for reasons of comparability.

The diamond tool wear is the result of progressive consumption of both diamond and binding. The diamond grit wear is strongly connected with the grit properties, while the binding consumption is a function of binding hardness. The micro-geometric effect is both the progressive rounding and breakage of the diamond grits, constituting the sectors layer by layer, and the erosion of binding. The macro-geometric result is the decrease of both the diameter and the weight of the tool together with the possible change of the tool cylindrical shape in time. The wear progression of a diamond tool strongly influences the tool performances and, therefore, the effectiveness and the efficiency of the stone machining. In fact, a worn tool increases the loss of the cutting ability, the amount of vibrations produced during the cutting process, the probability to have a discontinuous process and, therefore, the presence of chippings and undulations on the resulting stone product. The tool performance is a critical element for the optimisation of the stone machining.

3.6.2 Machine-tool

The machine used for the test must be of rigid structure and not tend to vibrate or bend anomalously during the test. The machine-tool must have a command for continuous speed variation covering the whole range of speeds used. Furthermore, a variable speed command allows the exact predetermination of cutting speeds and reduces the time necessary for obtaining the tool life curve.

3.6.3 Instrumentation

The following instruments are necessary for carrying out the necessary measurements and must be accurately constructed in order to be able to verify the tolerances indicated in the present instructions:

- A stopwatch to register cutting times
- An optical microscope equipped with a micrometric device for measuring the tool size
- An electronic balance with a sensitivity of 0.01 g
- An instrument for measuring cutting liquid flow (may be obtained by measuring the time necessary to empty a container having a known volume)

3.7 Procedure for tool macro-geometric wear test

The conditions vary in each single case and, therefore, the test procedure regarding tool life can only be described in general terms. The method to be followed to achieve the tool life test is the same one used to achieve good cut operations with, in addition, the necessary precautions to be taken, observations to be noted and measurements to be made.

Before beginning the test, make sure that the machine-tool, the work-piece and the tool correspond to the instructions of the present protocol.

3.8 Résumé of the test and expression of the results

In the test résumé the following results must be given:

- Changes in tool diameter with increasing volume of the removed stone
- Changes in tool weight with increasing volume of the removed stone
- Changes in tool cylindricity with increasing volume of the removed stone

4 Application example

The protocol developed has been applied to study the wear of two types of tools put on the market by a well-known producer for the machining of two types of granites (see Table 1). The cut tests have been carried out on African black granite and Sardinian granite, whose properties that must be reported according to the test protocol are given in Table 2. Linear cuts have been carried out on slabs whose dimensions are 1000 mm × 500 mm in order to allow a proper fixture on machine tool table, and with a thickness of about 30 mm for the M9Z3 mill and of about 40 mm for the M9BN. Cuts have been put at a distance assuring a complete independence among the following cuts. The parameters characterising the two types of tools are given in Table 3. Water, the cooling fluid commonly used in the machining of natural stones, has been used, directed onto the cutting zone in question by means of an appropriately positioned nozzle system and a duct inside the actual mill. The test conditions are given in Table 5. A NC 3-axis machining centre was used. It has been equipped with a continuous control chuck rotation speed and feed rate. At the end of each cut, the tool has been put off the spindle, it has been cleaned in order to remove the machining tailings, then, its diameter, weight and its cylindricity have been evaluated. The weight of the mill has been measured by an electronic balance with a sensitivity of 0.01 g. The diameter has been measured by a Leica optical microscope in six positions uniformly distributed along the tool boundary surface. The mill diameter has been considered the average value of the six realised measurements. The microscope has a resolution of 0.5 μm and a measuring uncertainty of about 2.6 μm. The diameter measurements have been used to evaluate the cylindricity, too. A couple of coaxial cylinders within which the values of the measured diameters lie has been identified. The radial distance between the two coaxial cylinders is equal to the cylindricity control tolerance value.

Table 1. Example of test protocol

Test protocol	
Material to machine	
Black Africa granite	Properties shown in Table 2
Sardinian granite	Properties shown in Table 2
Standard conditions of the work-piece	
slabs	Dimensions 1000 mm × 500 mm × 30 mm Dimensions 1000 mm × 500 mm × 40 mm
Tools	
M9Z3	Properties shown in Table 3
M9BN	Properties shown in Table 3
Cutting fluid	
water	pressure 0.2 MPa flow 10 l/min
Cut conditions	
Feed rate f	See Table 4
Cutting depth v_t	See Table 4
Cutting speed a	See Table 4
Macro-geometric wear test procedure	
Machine-tool	
NC 3-axes machining centre	
Instrumentation	
Leica optical microscope	Sensitivity 0.5 μm
Electronic balance	Sensitivity 0.01 g
Stop-watch	Sensitivity 0.1 s
Procedure for tool-wear test	
6 measurements of diameter uniformly distributed along the tool length	
weigh tool three times after each machining step	
Results résumé	
Tool diameter change vs. volume of removed stone	
Tool weight change vs. volume of removed stone	
Tool cylindricity change vs. volume of removed stone	

Table 2. Properties of the material to machine

Material properties	Sardinian granite	African black granite
Density [kg/m^3]	2608	3010
Water absorption [%]	0.25	0.05
Compressive strength [MPa]	145	180
Abrasion resistance [H$_a$]	40	65
Impact resistance [cm]	> 90	> 90
Knoop hardness [MPa]	5000	3000

4.1 Results and discussion

The study has allowed the determination of the change of the previously defined macro-geometrical variables as a function of the removed stone volume. This means to monitor the macro-geometric wear variables in time.

Figure 1 shows the trend of the mill diameter for two kinds of tools. The curves connected with the M9Z3 mill extend as far

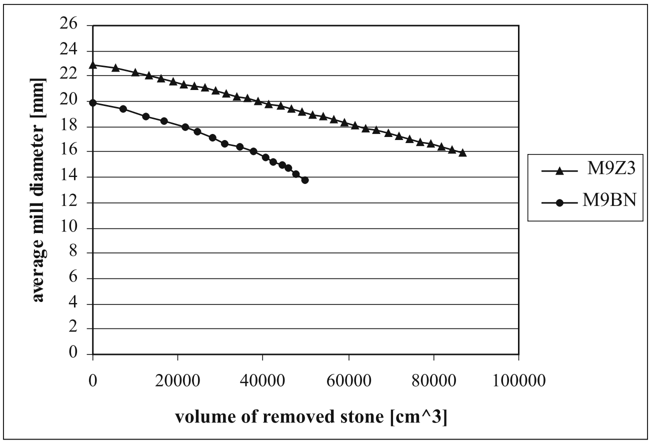

Fig. 1. Changes in tool diameter with increasing volume of removed stone

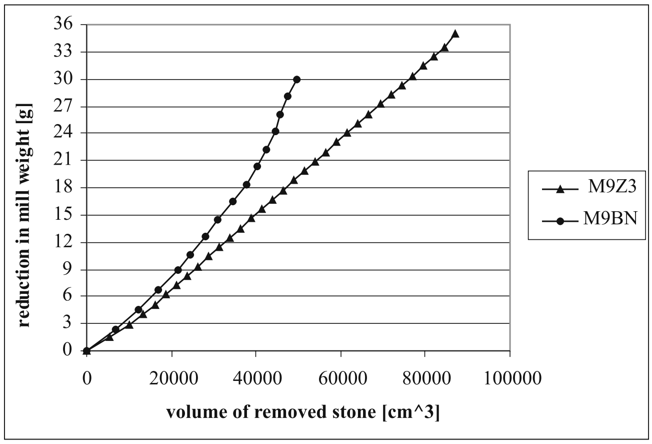

Fig. 2. Changes in tool weight with increasing volume of removed stone

Table 3. Tool properties

Tool properties	M9Z3	M9BN
Chemical composition of binder	Co-Cu-Al-Fe-Si Cu/Co = 0.285	Co-Cu-Al-Fe-Si Cu/Co = 0.51
Diamond mesh [#]	45/50	45/50
Diamond concentration [Kts/cm^3]	0.9	1.0
Tool weight [g]	238	177
Tool diameter [mm]	23	20
Sectors number	5	6
Depth of sector [mm]	35	44

Table 4. “Standard” conditions of cutting

Stone	Axial depth of cut [mm]	Cutting speed [rpm]	Feed rate [mm/min]
Granite	20 mm	5000	300
Marble	20 mm	5000	400
Granite	30 mm	4500	200
Marble	30 mm	5000	400
Granite	40 mm	4500	200
Marble	40 mm	4500	400

Table 5. Experimental plan

Test	Mill type	Process variables		
		Cutting speed [rpm]	Feed rate [mm/min]	Axial depth of cut [mm]
I	M9Z3	4500	200	30
II	M9BN	4500	200	40

as about 90 000 cm^3 of removed material and they have a linear trend. The curves to the M9BN mill arrive up to 50 000 cm^3 of the removed material and they have a curvilinear trend. The overall decrease of the mill diameter is the same for the two considered tools: it is about 6 mm. This means that the M9BN mill machines one half the amount of stone that M9Z3 removes before it breaks out. A linear trend involves a constant wear rate in time and, therefore, a progressive wear of the mill that may be easily foreseen. Figure 2 presents the reduction in weight for the two kinds of mill. A comparison between the curves is carried out to the same considerations previously emerged by the analysis of the diameter decrease. The weight decrease of the M9Z3 mill is linear, thus implying a linear wear rate and, therefore, a uniformly decreasing cutting ability. Figure 3 reports the tool cylindricity for the two kinds of mills as a function of the removed stone volume. The curves connected with the M9Z3 mill show a random and damped oscillation around the initial value of about 0.02 mm. The curves related to the M9BN mill increases strongly from 0.01 mm to 0.1 mm. This means that the cylindrical profile of the M9Z3 mill is unchanged with wear progression, whereas the M9BN mill changes its cylindrical shape very quickly due to diamond and binding consumption. The profile of the generatrix of the M9BN cylindrical boundary surface appears rounded for about 0.10 mm at the end of the wear progression (75% of the weight decrease). The trace, impressed by the mill on the stone during the machining, changes so much with the wear progression that the surface bounding the cutting

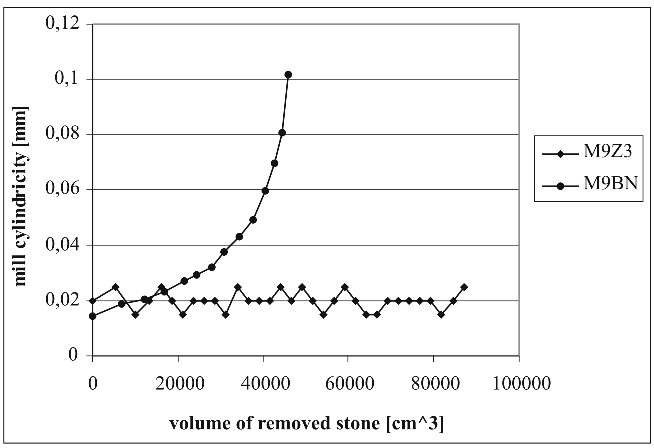

Fig. 3. Changes in tool cylindricity with increasing volume of removed stone

groove assumes a convex profile that has difficulty coupling with the other components of a paving decoration. Therefore, a high value of cylindricity involves the need of further finishing operations to reduce or to eliminate the rounded profile impressed by the worn cutting mill. Finally, all three of the considered macro-geometric variables show that the M9Z3 mill has cutting performances higher than those of the M9BN mill. It may machine a high amount of stone before breaking out. The decrease of its weight and its diameter is linear with the volume of removed granite. Therefore, it is easy to calculate the change of the mill diameter with the wear progression that is commonly used to correct the path of the mill axis for NC machining. Moreover, the cylindrical shape of the mill is unchanged with the wear progression. On the whole we can say that the protocol developed allows us to achieve results in line with the properties of the tool and allows us to compare tools having different characteristics.

5 Conclusions

The present study proposes a test protocol for the measurement of macro-geometric wear of diamond tools. In this way it is possible to obtain comparable and replicable results to characterise the wear of sintered diamond tools. The protocol specifies the material to be machined, standard conditions of the work-piece, tool properties, the cooling fluid to use and cut conditions to be applied during the test. The test report will contain the graph regarding the trend of the macro-geometric wear parameters in relation to the volume of material machined. The protocol developed has been applied to study the wear of two types of tools put on the market by a well-known producer for the machining of two types of granites.

Acknowledgement This work was carried out with funds received from the Italian M.I.U.R. (Ministry of Instruction, University and Research) within the project entitled “Stone manufacturing technologies” (COFIN01). The authors wish to thank CO.MARMI s.n.c in Cassino for supplying the stone for experimental tests.

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