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Paper

DETERMINATION OF MACHINABILITY AND ABRASIVE CUTTING PROPERTIES IN AWJ CUTTING

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ABSTRACT

Modern abrasive waterjet machines require precise parameter settings to meet the ever-increasing precision demand. Machinability and abrasive index are two important parameters for abrasive waterjet cutting. The latest software uses a cutting model that takes the inputs of machinability, abrasive index, and other process parameters to predict the jet behavior so that compensation can be made to improve the part accuracy. The methodology to determine the values of machinability and abrasive index is becoming more crucial than ever. Improper methodology can lead to large discrepancy in the data of machinability and abrasive index as well as cutting results. This paper will present a methodology in determining machinability and abrasive index.

Note: This version contains corrections of the mistakes in the version published in the conference proceedings.

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1. INTRODUCTION

In the 1990s' abrasive waterjet machines experienced a revolution that started with the integration of a cutting model with CNC control software. The cutting model greatly simplified an originally complicated operation to a very simple one: the operator only needs to enter the thickness and machinability of the workpiece material and the software will automatically set proper cutting speeds along the tool path. This not only greatly improves the user-friendliness of abrasive waterjet cutting but also enhences the part accuracy significantly. Abrasive waterjet machines soon started to emerge in machine shops, working hand-in-hand with other traditional and non-traditional machine tools and have since become the fastest growing sector of the machine tool industry.

In today's state-of-the-art abrasive waterjet machines, much more sophisticated cutting models are used in the control of cutting speed as well as taper compensation (see Zeng et al. (1999), Olsen et al. (2003), Zeng et al. (2005),and Olsen & Zeng (2006)). These cutting models use the settings of process parameters such as material machinability and thickness, quality requirement, curvature of tool path, water pressure, orifice diameter, mixing tube diameter, abrasive material and mesh size, as well as abrasive flow rate, etc. to predict the proper cutting speed as well as taper error and make fine adjustments along the tool path. Some reference values of material machinability and abrasive cutting property for a limited number of materials are already available in the literature (e.g. Zeng et al. (1992) & Zeng et al. (1999)). A small number of manufacturers of abrasive waterjet machines also provide their own versions of machinability and abrasive cutting property of an expanded list of materials for their end users. Table 1 and Figure 1 show two different versions of machinability, used by OMAX Corporation and Flow International Corporation, for a dozen of engineering materials. It appears that there is a factor of 24 between these two versions of machinability, i.e. machinability used by OMAX is roughly 24 times of that used by Flow.

Table 1. Material Machinability Used by OMAX and Flow

Material	Flow	OMAX
Tungsten Carbide	1	0.1
Inconnel	2.95	83.6
Tool steel	2.98	67.7
SS 304	3.19	80.8
SS 316	3.24	82.5
Mild Steel	3.42	81.3
Titanium	4.15	108.3
Brass 360	5.55	160
Al 6061	8.62	219.3
Plate Glass	16.54	385
Nylon	17.91	435.4
Lexan/Plex	18.8	435

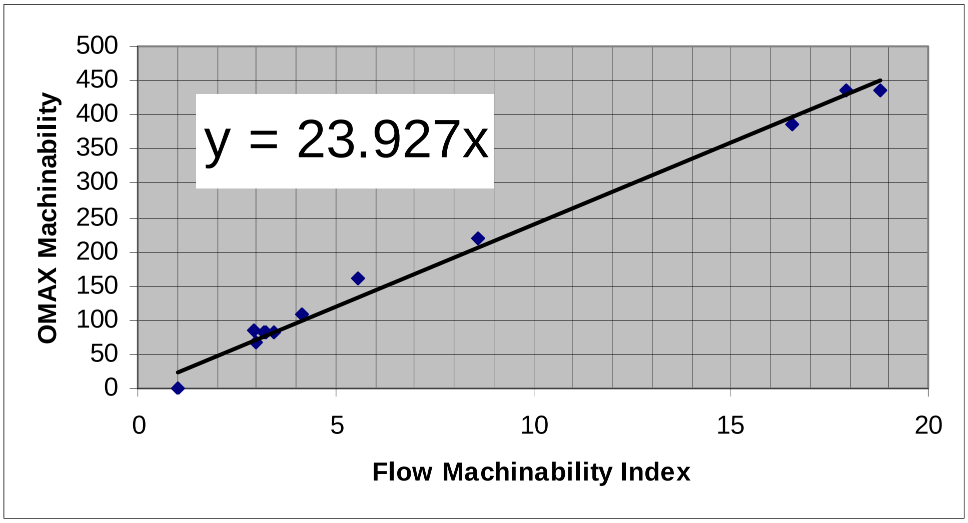


Figure 1. Relation between the two versions of machinability used by OMAX and Flow.

The existing data are good enough for a majority of common cutting applications. However as the technology expands into a wider market, the users frequently come across with new materials with undetermined machinability. Even though the end users can perform their own tests to determine machinability and abrasive cutting properties by using the method suggested by the author previously (Zeng, 1992), lack of an industry-wide standard and guidance often discourages so-doing. Modern abrasive waterjet machines require high accuracy in parameter settings in order to meet the ever-increasing accuracy demand. A well-defined standard in determining the machinability and abrasive cutting properties will be very helpful in meeting these requirements. If different versions of machinability provided by equipment manufacturers are determined by using the same standard, the end users will benefit from industry-wide information sharing. This paper attempts to address these issues.

2. DEFINITION OF MACHINABILITY AND ABRASIVE INDEX

What is machinability? If a search is done, one will find many different versions of definition for machinability. For traditional machining, machinability is often related to tool life, power requirement, and surface integrity (see Avallone & Baumeister III (1987), Section 13.4). A definition used previously by the author (Zeng, 1992) is re-phrased here: Machinability is a quantified kinetic response of a workpiece material subjected to a certain machining operation and condition.

A modeling study of abrasive waterjet cutting of metals was done by Hashish (1984), based on a cutting and deformation wear theory. A cutting model was derived as follows:

$$h = \frac{M_a \cdot P_w}{MD \cdot u \cdot (1 + \frac{M_a}{M_w})^2} (\frac{2 \cdot (1-c)}{\pi \cdot \varepsilon} + \frac{c \cdot \alpha_1}{4 \cdot \sigma_f}) \qquad (1)$$

where h is the depth of cut; M_a and M_w are abrasive and water mass flow rates; P_w is water pressure; MD is the diameter of the mixing tube; u is the traverse speed of the nozzle; σ_f and ε are, respectively the flow stress and specific energy (for deformation wear) of the workpiece material; c is the assumed portion of the jet involved with cutting wear; a_1 is the impact angle at top of kerf. A later model by the same author (Hashish, 1989) accounted for the effects of abrasive particle roundness, the threshold velocity of erosion, and the coefficient of friction. Even though the later model has a high theoretical value in understanding the contributing factors in material removal mechanism, its complexity unfortunately limits its practical use.

A physical model of abrasive waterjet cutting has been previously derived by the author (Zeng, 1992 or Zeng et al., 1992), based on an elasto-plastic erosion theory of ceramics. In this model, the depth of cut is expressed by:

$$h = \left(\frac{\eta \cdot C_v \cdot C_y}{1 + \frac{M_a}{M_w}}\right)^2 \cdot \frac{C_0 \cdot M_a \cdot P_w}{\rho_w \cdot MD \cdot u} \left(\frac{2 \cdot f_w \cdot \beta \cdot a \cdot \sigma_f \cdot \alpha^2}{3 \cdot \gamma \cdot E} + \frac{\alpha}{\sigma_f}\right) \qquad (2)$$

where η, C_v, and C_y are the momentum transfer efficiency in the abrasive waterjet nozzle, orifice coefficient, and compressibility coefficient (Hashish, 1989); r_w is water density; C_0 is an unknown factor that accounts for all other variables that were not included in the modeling (such as abrasive material and size, standoff distance, etc.). All but one (a) variables inside the second parenthesis are material parameters. This model was derived for crystalline ceramic materials, but was generalized to apply to both brittle and ductile materials. The first term inside the parenthesis is associated with material removal due to network cracking and the second term is associated with material removal due to plastic flow. For brittle materials the first term will dominate while for ductile materials the second term will. This model is only valid for small values of the particle incident angle (a). In abrasive waterjet cutting, abrasive particles strike at the curved cutting front of the target material at glancing angles, and therefore the value of a is assumed to be small and a constant.

Agus et al. (1996) proposed a model that accounts for the interaction between abrasive and rock that is being cut. A parameter called Specific Erosion, E_s, is defined to be the ratio between cutting rate (traverse speed, u, times depth of cut, h) and abrasive flow rate. Their model links the Specific Erosion to abrasive properties with a material and machine constant, K, as follows:

$$E_s = K \cdot P_r \qquad (3)$$

where K accounts for the characteristics of the rock and jet parameters (such as water pressure and flow rate, etc.) and P_r represents the combined effects of abrasive properties.

$$P_r = H_p^a S^b \rho_p^c d_p^d R_v^e \qquad (4)$$

where H_p is the Knoop hardness, S the shape factor deviation from a sphere, r_p the particle density, d_p the mean particle diameter, and R_v the volume percentage of abrasive in the jet.

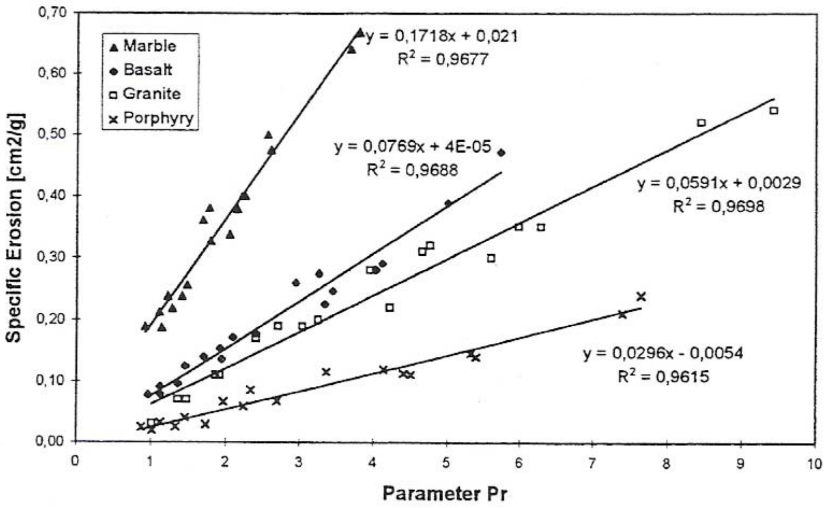


Figure 2. Correlation lines of specific erosion as a function of parameter P_r (Agus et al., 1996).

Abrasive waterjet cutting tests were done with three different types of abrasive (garnet, quartz sand, and copper slag) and four different types of rock (granite, marble, basalt, and porphyry). Test data were curve-fitted to find the correlation between specific erosion and the abrasive parameter P_r (see Figure 2). The different slopes of the correlation lines reflect the different characteristics of the four materials (i.e. the values of K). Based on regression of experimental data, it was found that the value of K as well as the coefficients a and b in equation (4) are functions of workpiece material hardness. The regression yielded:

$$E_s = K_1 \cdot H_r^{-0.87} H_p^{0.15 \cdot H_r + 0.45} S^{-0.38 \cdot H_r + 2.55} \rho_p^{-0.2} d_p^{0.1} R_v^{-0.5} \qquad (5)$$

where H_r is the Knoop hardness of rock and K_1 is a system constant, depending on machine setups such as water pressure and flow rate, etc. By using the definition of the Specific Erosion defined by Agus et al. (1996), equation (5) can be rewritten as:

$$h = \frac{M_a \cdot K_1 \cdot H_r^{-0.87} H_p^{0.15 \cdot H_r + 0.45} S^{-0.38 \cdot H_r + 2.55} \rho_p^{-0.2} d_p^{0.1} R_v^{-0.5}}{u \cdot \rho_p} \qquad (6)$$

Another analytical model was proposed by Singh et al. (1994) to incorporate the effect of abrasive properties.

$$h = \sum_i \frac{\delta v_i \cdot N_i}{u \cdot \chi \cdot MD} \qquad (7)$$

where χ is a factor accounting for irregularity of kerf, N_i the ith particle, and δv_i the individual particle volume removal, calculated by:

$$\delta v_i = f_m(\sigma_m, \gamma_m, \ldots) \cdot g_p(\sigma_p, \alpha_i, \varphi_i, \ldots) \cdot (1 - k_i) \cdot (E_{a,i} - E_{c,i}) \qquad (8)$$

where $f_m(\sigma_m, \gamma_m, ...)$ and $g_p(\sigma_p, \alpha_i, \varphi_i, ...)$ are, respectively, functions of workpiece material properties and abrasive properties; k_i is a fraction of energy that is not used in material removal; $E_{a,i}$ and $E_{c,i}$ are, respectively, the kinetic and critical energy of an individual particle.

It is worthy to point out that all the above four models have a common structure in terms of the material effect --- the material effect can be represented with a single parameter. This single parameter would replace the combined effects of all the parameters inside the parenthesis in equations (1) and (2) or the value of H_r^{-087} in equation (6) or the function $f_m(\sigma_m, \gamma_m, ...)$ in equation (8). A natural choice for the name of this parameter is machinability for abrasive waterjet cutting, N.

Among the five abrasive parameters in equation (4), the particle size and the volume percentage of abrasive, are really process parameters, instead of abrasive parameters. A new parameter, Abrasive Index F_a, is introduced to represent the combined effects of the three true abrasive parameters, H_p - the Knoop hardness, S - the shape factor deviation from a sphere, and r_p - the particle density. This Abrasive Index also represents the function $g_p(\sigma_p, \alpha_i, \varphi_i, ...)$ in equation (8).

In a similar manner, a Nozzle Index (F_n) is introduced to represent the combined effects of η (momentum transfer efficiency in abrasive waterjet nozzles) and C_v (orifice coefficient) in equation (2).

There are some unknown variables that are not yet accounted for (e.g. standoff distance, nozzle alignment, etc.). Their combined effect is represented by a factor F.

Using these newly defined parameters, equation (2) is rewritten as follows: (here h represents material thickness, and u separation speed)

$$u = F \cdot F_n \cdot F_a \cdot N \cdot \frac{M_a \cdot P_w}{MD \cdot h \cdot (1 + \frac{M_a}{M_w})^2} \qquad (9)$$

If equation (9) is a perfect model, it could be used to define material machinability (N). Realizing that no perfect model exists, equation (9) is generalized to the following form that assembles a perfect model:

$$u = F \cdot F_n \cdot F_a \cdot N \cdot f(P_w, OD, MD, M_a, AM, h) \qquad (10)$$

The fact that water mass flow rate M_w is a function of pressure P_w and orifice diameter OD has been used in this generalization. Also included in this generalization is the effect of abrasive mesh size (AM).

Therefore material machinability in the abrasive waterjet cutting is defined by:

$$N = \frac{u}{F \cdot F_n \cdot F_a \cdot f(P_w, OD, MD, M_a, AM, h)} \quad (11)$$

Similarly abrasive index is defined by:

$$F_a = \frac{u}{F \cdot F_n \cdot N \cdot f(P_w, OD, MD, M_a, AM, h)} \quad (12)$$

The significance of equations (10)-(12) is that all the contributing factors are considered while the modeling error is minimized. Even the unknown factor F is important because it says that there might be some unknown factors that can affect the test result even if you have controlled the other known factors. A repeatability study done by the author provides some supporting evidences to this statement. In this study, eight sets of separation cutting tests were done using the test method (4) described in section 4.1 by the same operator. All the eight sets of tests were done with the following fixed parameters: water pressure, orifice, mixing tube, abrasive material/mesh size/flow rate, and stand-off distance. Each set of tests was done with a new mixing tube and used these three materials: 10 mm (0.4”) thick Absolute Black granite, 25 mm (1”) thick aluminum 6061-T6, and 25 mm (1”) thick steel A36. Each set of tests was conducted on the same day, but the eight sets of tests lasted a few days. Even though these eight sets of tests were done at namely the same conditions, the results are different. The deviations of the separation speeds from the average values are plotted in Figure 3. The data variation is as much as 23% for the granite sample, probably because a more subjective separation criterion (“chipping free”, see section 4.1, test method (4)) was used. The data variation for the two metals is less. Standard deviation is 7.5% for granite, 4% for aluminum, and 5% for steel.

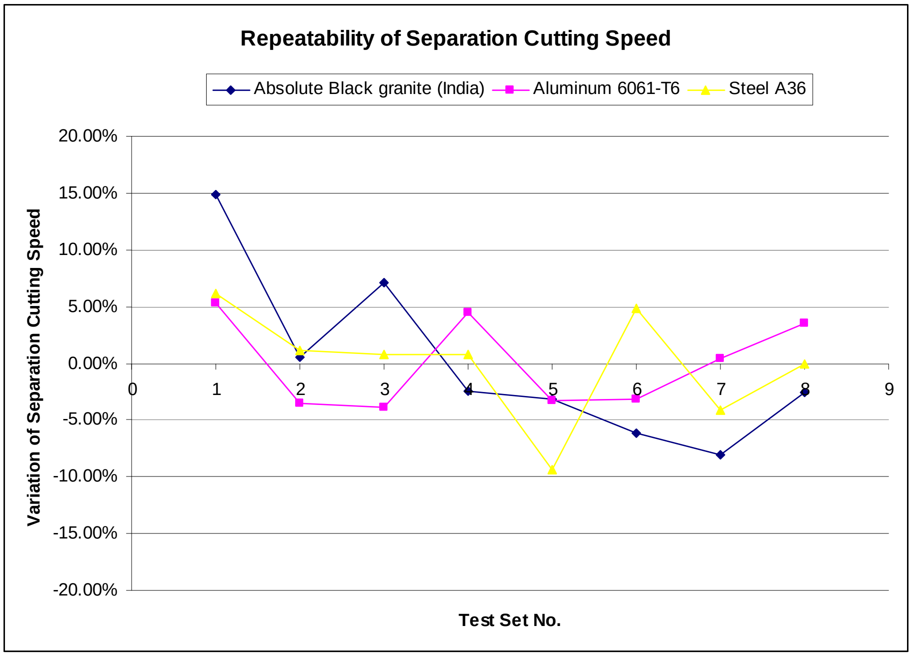


Figure 3. Variation of separation cutting speeds under namely same conditions.

3. DETERMINATION OF MACHINABILITY AND ABRASIVE INDEX

A general method to determine machinability and abrasive index has been previously introduced by the author (Zeng, 1992). Even though this general method is relatively easy and straight forward, it does depend on the accuracy of the model and in some cases it may not be applicable. In this section several methods to determine machinability and abrasive index will be discussed. All of these methods are practical and applicable in laboratory or in field. Selection of a particular method is based on the priority of accuracy, time, cost, and material availability.

Method (1): Two tests with the same process settings --- most accurate

To determine machinability two tests are done with the same nozzle and exactly the same process parameters (pressure, orifice, mixing tube, abrasive flow rate, and abrasive mesh size). Therefore the values of the nozzle index F_n and the process parameters P_w, OD, MD, M_a, AM are the same. Two different materials are used in these two tests. One is the subject material, of which the machinability N_1 is to be determined. The other material is used as the "bench mark" reference material with a known machinability N_0. According to Agus et al. (1996), the effects of abrasive hardness and shape factor depend on workpiece material hardness, as evidenced in equation (6). To have the same value of abrasive index F_a, not only should the abrasive used for both tests be the same, but the reference material should be close to the subject material in terms of hardness and erosion characteristics as well. For example, if the subject material is steel, the reference material should be also steel. If the subject material is stone, don't use metal for the reference material. In this method, these two materials should also have exactly the same thickness (i.e. the same value of h). To minimize the impacts of other unknown factors these two tests should be done on the same setup (same orifice and mixing tube, same pressure and abrasive flow rate, etc.), one after another, so that the value of F is kept the same (hopefully). An even better practice is to test the reference material before and after testing the subject material. The data average of the two reference tests represents the data for the reference material.

In this method the value of the denominator in (11) is the same, thus the machinability of the subject material can be calculated by:

$$N_1 = N_0 \frac{u_1}{u_0} \qquad (13)$$

where u_0 and u_1 are the separation cutting speeds of, respectively, the reference material and the subject material from the two tests. The definition of separation cutting speed and the way to determine it will be covered in the next section.

Similarly, to determine abrasive index, two tests will be done on two different abrasive materials, one subject and one reference (with the known abrasive index F_{a0}). These two abrasive materials should have the same mesh size. The testing workpiece material and other process settings should be the same. The abrasive index of the subject abrasive F_{a1} can be calculated by:

$$F_{a1} = F_{a0} \frac{u_1}{u_0} \qquad (14)$$

Method (2): Two tests with slightly different process settings --- slightly less accurate

Sometimes it is not practical to have the same process settings for the two tests as described in method (1). For example, the subject and reference materials often come in different thickness. In this case, equation (10) cannot be applied directly to calculate machinability and abrasive index. However if the process settings for the two tests are close, an existing cutting model can be used as an approximation of the perfect model. A concept of Data Proximity Model is thus introduced.

The Data Proximity Model is defined as a model that is accurate if applied at the proximity of a calibrated data point.

The author's choice of such a Data Proximity Model is based on a cutting model that has been used extensively in this industry and described by Zeng et al. (1999). This existing cutting model is used to substantiate the function $f(P_w, OD, MD, M_a, AM, h)$ in equation (10). The effect of abrasive size, expressed by $d_p^{0.1}$ in equation (6), is also incorporated into this model in the format of $AM^{-0.1}$ (considering that mesh size AM is inversely proportional to the particle diameter d_p). The Data Proximity Model is thus expressed by the following equation:

$$U = F \cdot F_n \cdot F_a \cdot N \cdot \frac{C \cdot P_w^{1.833} \cdot OD^{1.580} \cdot M_a^{0.394}}{Q^{1.15} \cdot h^{1.15} \cdot MD^{0.711} \cdot AM^{0.1}} \qquad (15)$$

Note that a quality index Q is also introduced. When Q=1, the cutting speed U becomes the separation cutting speed u. C is a scaling constant, depending on the unit system being used and scaling of the factors F, F_n, F_a, and N. For metric unit system (U: mm/min, P_w: MPa, M_a: kg/mm, OD, MD, h: mm), the author uses $C = 4.1981\text{x}10^{-5}$. For English unit system (U: inch/min, P_w: kpsi, M_a: lb/min, OD, MD, h: inch), $C = 4.272\text{x}10^{-4}$.

To determine machinability two tests are done with similar process settings and two different materials, one subject material and one reference material with a known machinability N_0. The machinability of the subject material is calculated by:

$$N_1 = N_0 \cdot \frac{F_0}{F_1} \cdot \frac{F_{n0}}{F_{n1}} \cdot \frac{F_{a0}}{F_{a1}} \cdot \frac{U_1}{U_0} \cdot \frac{(\frac{Q_1}{Q_0})^{1.15} \cdot (\frac{h_1}{h_0})^{1.15} \cdot (\frac{MD_1}{MD_0})^{0.711} \cdot (\frac{AM_1}{AM_0})^{0.1}}{(\frac{P_{w1}}{P_{w0}})^{1.833} \cdot (\frac{OD_1}{OD_0})^{1.580} \cdot (\frac{M_{a1}}{M_{a0}})^{0.394}} \qquad (16)$$

Similarly the abrasive index of the subject abrasive can be calculated by:

$$F_{a1} = F_{a0} \cdot \frac{F_0}{F_1} \cdot \frac{F_{n0}}{F_{n1}} \cdot \frac{N_0}{N_1} \cdot \frac{U_1}{U_0} \cdot \frac{(\frac{Q_1}{Q_0})^{1.15} \cdot (\frac{h_1}{h_0})^{1.15} \cdot (\frac{MD_1}{MD_0})^{0.711} \cdot (\frac{AM_1}{AM_0})^{0.1}}{(\frac{P_{w1}}{P_{w0}})^{1.833} \cdot (\frac{OD_1}{OD_0})^{1.580} \cdot (\frac{M_{a1}}{M_{a0}})^{0.394}} \qquad (17)$$

Even though these two equations appear complex, they can be greatly simplified if most of the process settings are the same. In the simplest case, these two equations boil down to equations (13) & (14). For quality index Q, it is best to keep it to be 1, i.e., separation cutting speed is to be determined in the two tests. However if separation cutting test is not practical and a slower cut is made instead, judgment must be made to determine the Q value of the slower cut by comparing the cut surface to the standard five Q levels (see Figure 4) as described by Zeng et al. (1999).

Figure 4. Sample of five quality levels.

Method (3): One test --- less accurate

This method is similar to the general method the author initially introduced. If for some reasons it is not practical to do two tests, this method can be used to estimate the machinability and abrasive index with a lower accuracy. Equation (15) is used to calculate machinability and abrasive index as follows:

$$N = \frac{U \cdot Q^{1.15} \cdot h^{1.15} \cdot MD^{0.711} \cdot AM^{0.1}}{F \cdot F_n \cdot F_a \cdot C \cdot P_w^{1.833} \cdot OD^{1.580} \cdot M_a^{0.394}} \qquad (18)$$

$$F_a = \frac{U \cdot Q^{1.15} \cdot h^{1.15} \cdot MD^{0.711} \cdot AM^{0.1}}{F \cdot F_n \cdot N \cdot C \cdot P_w^{1.833} \cdot OD^{1.580} \cdot M_a^{0.394}} \qquad (19)$$

The values of F and F_n can be set to 1 for lack of information. To further simplify the calculations, a set of process parameters (P_w, OD, MD, M_a, AM) can be pre-defined. A certain type of abrasive is pre-selected for the test of machinability. Likewise, a certain workpiece material is pre-selected for the test of abrasive index. As a result, the above two equations can be simplified to:

$$N = C_1 \cdot U \cdot Q^{1.15} \cdot h^{1.15} \qquad (20)$$

$$F_a = C_2 \cdot U \cdot Q^{1.15} \cdot h^{1.15} \qquad (21)$$

where C_1 and C_2 are pre-defined constants:

$$C_1 = \frac{MD^{0.711} \cdot AM^{0.1}}{F \cdot F_n \cdot F_a \cdot C \cdot P_w^{1.833} \cdot OD^{1.580} \cdot M_a^{0.394}} \qquad (22)$$

$$C_2 = \frac{MD^{0.711} \cdot AM^{0.1}}{F \cdot F_n \cdot N \cdot C \cdot P_w^{1.833} \cdot OD^{1.580} \cdot M_a^{0.394}} \qquad (23)$$

Method (4): No test --- least accurate

Sometimes it is impossible to do even a single test. For example, a job quotation has to be made prior to getting the material or the material is limited or too expensive to do tests on. In these cases, estimate of machinability has to be made. These estimates are usually made based on similarity of materials. For metals, similarity in hardness is often used as the foundation for estimation. Table 2 and Figure 5 show that machinability appears to have a certain degree of correlation with hardness. If an educated guess has to be made based on the knowledge of Rockwell B (R_b) hardness, the following curve-fitting relation can be used:

$$N = \left(\frac{1919}{R_b}\right)^{1.4474} \qquad (24)$$

However, it should be noted that some metals (e.g. Copper C110, Titanium 6Al-4V, and Aluminum 2024) do not follow this relation.

Table 2. Correlation between material machinability and its R_b hardness

Material	Machinability	Rockwell B
Tool Steel (M2)	67.7	91.1
Stainless Steel 304	80.8	85.7
A36 Mild Steel	81.3	69.5
Stainless Steel 316	83.1	77.5
Inconel® 625	83.6	91.1
Invar 36	93.3	73.2
Brass 360	160.4	58.2
Aluminum 6061	219.3	54.7
Copper C110	102.8	35.0
Titanium 6Al-4V	108.3	109.0
Aluminum 2024	215.3	68.0

(*Note: Inconel® is a registered trademark of Special Metals Corporation).*

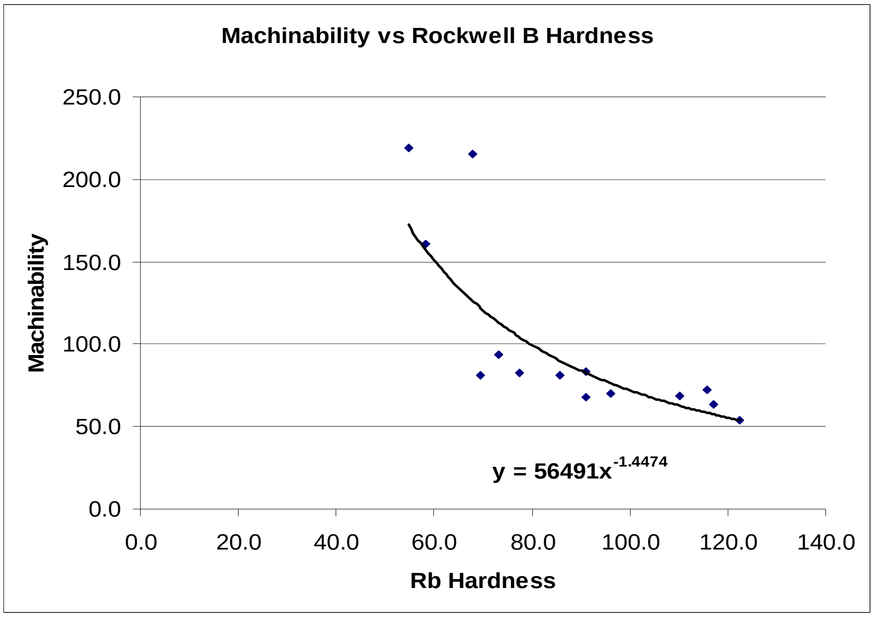


Figure 5. Correlation between machinability and hardness.

4. TESTING METHODOLOGY AND DATA

4.1 Testing Methodology

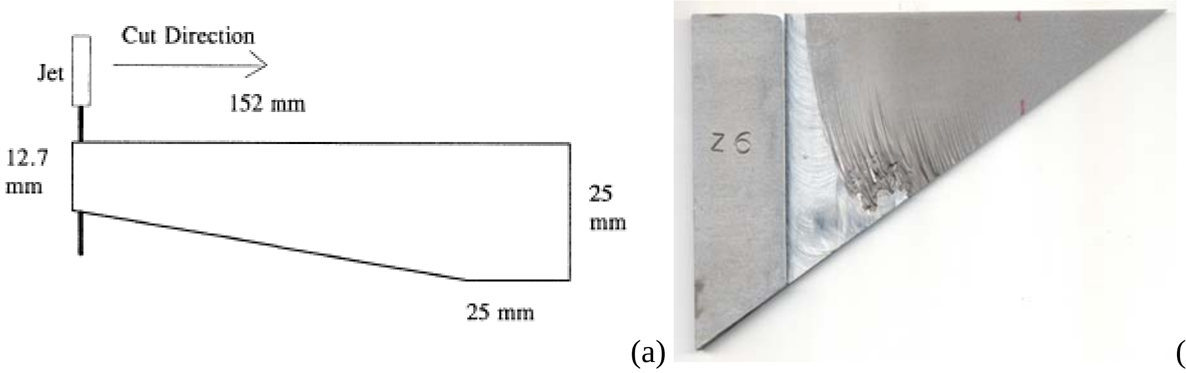
To use methods (1) to (3) in section 3 to determine machinability and abrasive index, testing is needed to determine separation speed or depth of cut or the value of Q. There are several methods to run the tests to determine separation speed or depth of cut. If the depth of cut is determined, method (1) in section 3 will not be applicable, but methods (2) and (3) will be. For all these methods, equation (15) can be used to make an initial guess of the cutting speed or depth of cut to speed up the testing.

Test Method (1): Determine depth of cut with a fixed cutting speed

In an earlier study by the author (Zeng, 1992), tests were done by making non-through cuts on the sample materials and then the depth of cuts were measured by inserting a fine needle into the kerf. Often one test cut was made and then multiple measurements were done along the entire length of the cut. With this method there is no need to run many trial cuts. However, because a typical abrasive waterjet cut has peaks and valleys along the bottom of the kerf, the measurements of depth of cut depend on where the fine needle lands on. Even though taking average over multiple measurements is helpful in obtaining statistically meaningful data, the depth of cut obtained in this measurement method tends to be larger than the depth of cut for complete separation. In another word the cutting speed calculated with this method tends to be too aggressive. To ensure that the measured depth of cut above all of the peaks (therefore a complete separation), the sample can be cut open to expose the peaks and valleys and then measurement is done on the top of the highest peak. Doing this will improve the accuracy, but will make the test more costly and less practical to do in the field.

Test Method (2): Determine depth of cut with a fixed cutting speed

A more popular method is to run test cuts on a wedge block (i.e. varying depth of cut) at fixed cutting speeds (see Figure 6 (a), Singh et al, 1994). Then the depth of cut is measured at the end of kerf (see Figure 6(b), courtesy of Barton Mines Company). This method requires making wedge blocks out of the subject material to be tested, which is not always feasible and practical. Because the end point location of the kerf is affected by the jet fluctuation the consistency and accuracy of this method are also questionable.



(a) (b)

Figure 6. Test cuts on a wedge block.

Test Method (3): Determine separation speed with a linearly varying cutting speed

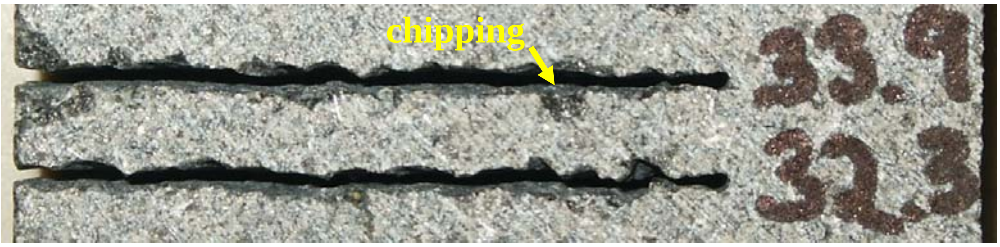
A logical twist of method (2) is to make test cuts on a flat sample with linearly varying cutting speed. The separation speed is calculated by matching the speed proportion to the through-cut proportion. This method is more practical because it does not require special preparation of the sample materials. However it does not get rid of the end point variation caused by jet fluctuation either. To minimize the impact of the end point variation, a relatively long cut and thus a large sample part is required.

Test Method (4): Determine separation speed with discrete cutting speeds

The author’s choice of the testing method is to make multiple trial cuts on a flat part with discrete cutting speeds until the separation speed is found according to a certain separation criterion. The cut is 50 mm (2”) long. After the first cut is made, the cutting speed is adjusted up or down to make the next cut. The testing is completed if two speeds are found, which are different by 5% or less, one separating the material and the other not. The separation criterion is that the sum of width of any remaining “bridges” at the bottom of cut is less than 1.6 mm (1/16”) --- this is called “bridging free” criterion. Figure 7 (a) shows two test cuts on a piece of 25 mm (1”) thick 6061-T6 aluminum. The cut at 353 mm/min (13.9 ipm) is considered “separated” because it is “bridging free” while the other cut at 360 mm/min (14.2 ipm) is not. The author has found that this method produces the most consistent results among all the five methods discussed here, even though the testing takes a little more time. To speed up the testing, a binary search scheme can be used to pick the test speed. For example if a cut-through speed S1 and a nonthrought speed S2 are found, then the average of these two speeds can be used for the next trial. The separation speed will be found with an error of ξ (typically 5%) after n trials (2^n= (S1-S2)/S1/ ξ).

For brittle materials (stones, ceramics, glass, etc.), if the "bridging free" criterion is used, the bottom portion of the cut surface may suffer from defects due to a blow-out effect of the jet --- the bottom edge of the material is blew out instead of being cut. These defects include chipping along the bottom edges or a significantly wider kerf. The separation cutting speed thus obtained tends to be too aggressive such that the cutting speeds at higher Q values end up with bad surface quality. In these cases, a "chipping free" criterion is more appropriate. This criterion says that a cut that is considered "separated" should not have any chipping or significantly wider kerf in length exceeding 1.6 mm (1/16"). Figure 7 (b) shows the bottom view of two test cuts on a piece of 10 mm (0.4") thick Absolute Black granite. The cut at 820 mm/min (32.3 ipm) is considered "separated" because it is "chipping free" while the other cut at 861 mm/min (33.9 ipm) is not. The "chipping free" criterion is more subjective and thus the data may be less consistent.

(a) Aluminum 6061-T6 --- "bridging free"



(b) Absolute Blake granite --- "chipping free"

Figure 7. Separation criterion: (a) "bridging free" and (b) "chipping free".

Test Method (5): Determine Q value with a fixed cutting speed

In this method, only one through cut is made on the test part with a fixed cutting speed that is slower than the separation cutting speed. Then the cut surface is compared to a standard five-quality bar (Figure 4) to estimate the value of Q. Method (2) or (3) in section 3 can then be used to determine machinability and abrasive index. This method can be used when the test material or time is limited for multiple test cuts. However a lower accuracy should be expected from the test results because the judgment of Q value is subjective.

4.2 Data of Machinability and Abrasive Index

The test method (4) in section 4 and the analytical method (1) in section 3 have been used by the author to determine the machinability of a variety of engineering materials and the abrasive index of several abrasive materials. The values of machinability are presented in Figure 8 and the values of abrasive index in Table 3. As a disclaimer, the author does not guarantee these values be perfectly accurate. The only way to know if a particular value of machinability or abrasive index is accurate or not is to use it. Having good results from many different applications will give you the confidence. If not it may be necessary to conduct your own tests by following one of the methods discussed earlier.

5. CONCLUSIONS

The methodology to determine machinability and abrasive index in abrasive waterjet cutting is defined. Testing methods and data are also presented. The information provided in this paper will facilitate the technology developers or the end users to determine material machinability and abrasive index accurately and efficiently by choosing a proper method. The author hopes this will promote knowledge exchange which benefits the end users in the end.

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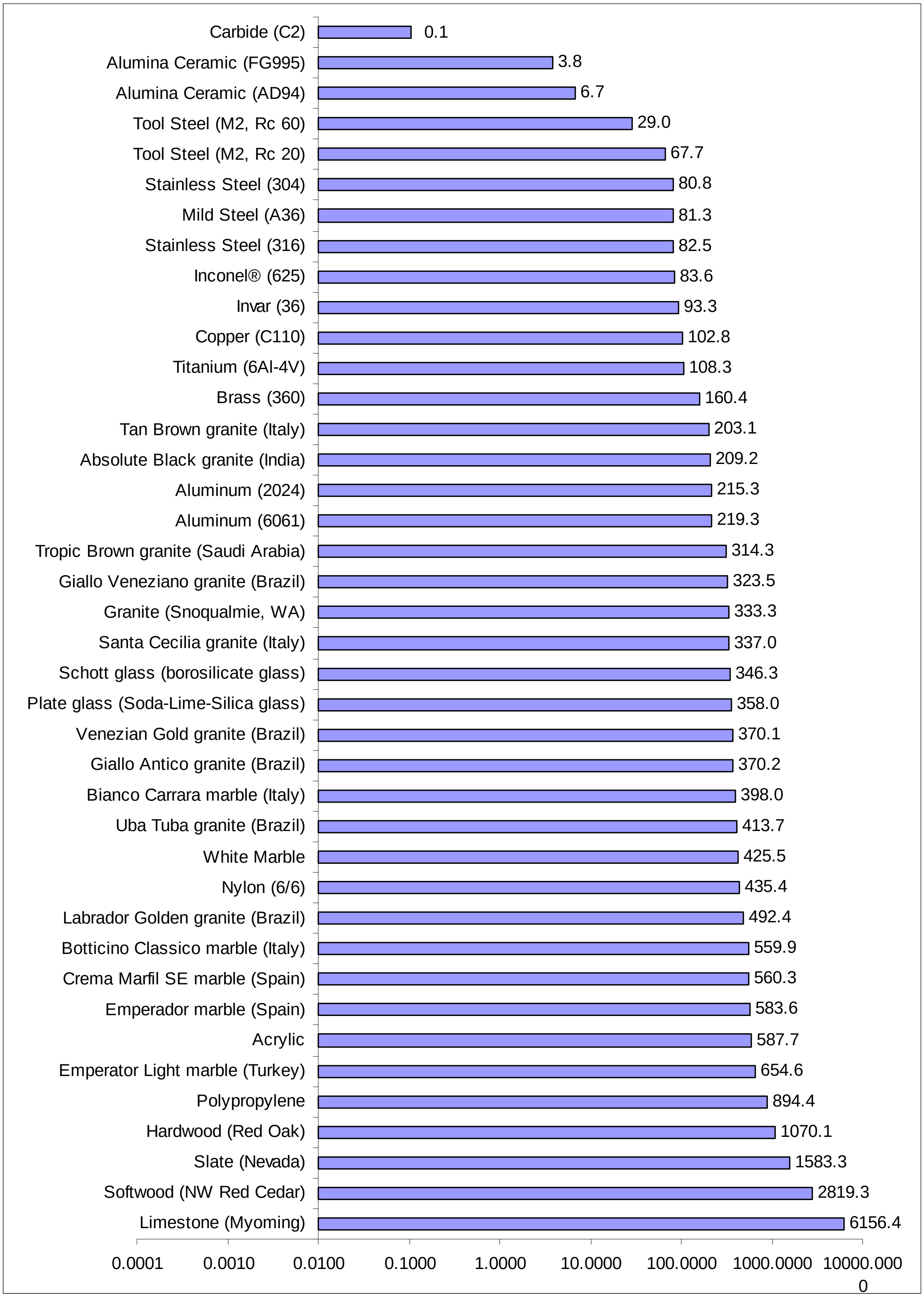

Figure 8. List of machinability.

Table 3. Abrasive Index

Abrasive	**Cutting Granite**	**Cutting Aluminum**	**Cutting Steel**
Barton HPX garnet	1.00	1.00	1.00
Barton HPA garnet	1.02	0.95	0.95
Olivine	0.22	0.85	0.81
Crushed Glass (VitroGrit®)	0.01	0.83	0.46
Glass Beads (Ballotini Impact Beads)	0.06	0.30	0.14
Aluminum Oxide (Blastite BT)	1.31	1.11	1.21
Silicon Carbide	1.18	1.02	1.12

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