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ORIGINAL ARTICLE

Experimental research into alternative abrasive material for the abrasive water-jet cutting of titanium

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Abstract

Experimental research on high-pressure abrasive water-jet cutting of a popular titanium alloy, grade 5 (Ti6Al4V), is presented. Three types of abrasive material, garnet, olivine, and a cheaper alternative—crushed glass abrasive, were investigated. The influence of basic cutting parameters such as traverse speed and concentration of abrasive on cutting depth was shown, as was the effect of the ratio of the diameter of the water nozzle to the diameter of the focusing tube on the cutting depth. A slower traverse speed resulted in a deeper depth of cut for all abrasive materials. The variation of cutting depth became irrelevant when the concentration of the jet was increased. On basic regression analysis, the cutting depth control models were formulated. The cutting efficiency and the focusing tube wear for all abrasives were compared in order to determine the degree of effectiveness for each abrasive.

Keywords Abrasive water-jet cutting · Cutting depth · Process efficiency, titanium alloy

Abbreviations

D_c	Cutting depth; [mm]
F_a	Abrasive factor; −
N_{ID}	Nozzle internal diameter; [mm]
C_a	Abrasive concentration; [%]
S_t	Is traverse speed; [mm/s]
x	Focusing tube wear coefficient; [mg/min]
Δf	Mass loss of focusing tube; [mg]
t	Working time; [min]
SS	Sum of squares
Df	Degree of freedom
Ms	Mean square
F	Ratio of variance of a source to variance of error
ID	Internal diameter (of nozzle); [mm]

1 Introduction

Increasing prices of garnet abrasive in world markets in recent years [11, 19] have opened up the need to find cheaper alternative abrasives. The use of abrasives which are cheaper than garnet will increase the competitiveness of abrasive water-jet cutting materials. This will reduce the production costs for using this technology, especially when cutting materials which are hard to machine such as titanium alloys.

The biggest consumer of titanium alloys is the aerospace industry. This is due to their unique properties: they have a low density, high strength, high resistance to aggressive mediums, and perfect fatigue performance. Therefore, titanium parts are replacing aluminum parts in aircraft production. Titanium is now used in the most important element—the airframe of airplanes. Jet engine and airframe parts must be resistant to temperatures ranging from − 60 to + 600 °C, so aircraft engine designers are also starting to use titanium as the high-temperature performance of titanium meets this requirement. Engine parts made of titanium are mainly gears [9], discs, blades, shafts, and front fan guards to the rear end of the engine.

Unfortunately, the properties which make it suitable for practical applications generate problems during treatment. Due to its high strength, low thermal conductivity, and chemical reactivity, especially in conditions of high temperature, materials used for cutting blades significantly reduce tool life. In addition, the low Young's modulus of titanium alloys leads to spring back, which results in parts having a low-quality surface. Moreover, during turning and drilling, long continuous chips are formed and cause confusion around the cutting tool. Sheet metal processing to which turning, milling, and

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grinding [10, 28] belong is traditional methods which are harmful to the environment. They produce chips during the process and in service produce noise, vibration, dust, oil spill, evaporation of cutting fluid, etc., and may even be dangerous, for example, if the grinding wheel should break. The tools have a short operating life and the process is time and energy (electricity) consuming [13].

Only plastic processing [14, 15] and cutting with a high-pressure water jet—an advanced method of separating materials—is devoid of these disadvantages [3, 31] and provides effective treatment of titanium alloys. High-pressure water is converted to a high-speed jet inside a nozzle (Fig. 1a) and flows out of the nozzle at a speed of several hundred meters per second. It hits a stream of abrasive particles and accelerates them to high particle speed.

Adding a dry abrasive to the water jet in a special mixing chamber (Fig. 1b) increases the cutting efficiency [21, 23, 27]. As a result, it becomes possible to cut almost any material. Abrasive water-jet cutting typically aims at achieving a maximal depth of cut and a minimal roughness of the cut surface [18, 30, 34].

Typical pressure levels used by the abrasive water-jet (AWJ) system range from 400 to 600 MPa [33]. The most commonly used abrasives are garnet [25, 32] and olivine [8].

Titanium abrasive water-jet machining is the goal of many types of research around the world [12, 16, 20]. These studies concern both cutting [1, 4, 6] and drilling [5, 35] by abrasive water jet. However, most studies use garnet abrasive, which is becoming more expensive from year to year. This increases the cost of treatment since the abrasive comprises more than 80% of the cost of abrasive water-jet cutting [22].

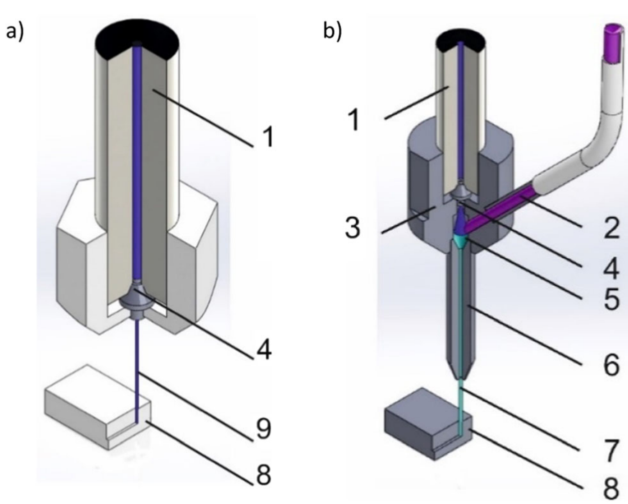

Fig. 1 **a** Water-jet cutting and **b** abrasive water-jet cutting: (1) high-pressure water inlet, (2) abrasive inlet, (3) cutting head, (4) water nozzle, (5) mixing chamber, (6) focusing tube, (7) high-speed abrasive water jet, (8) sample, and (9) high-speed water jet

2 Materials and methods

Grade 5 titanium is used as a specimen material. It is the most popular of all titanium alloys. The chemical compositions (element content) of grade 5 titanium are as follows: Al—5.50–6.75%, V—3.50–4.50%, Fe—0.25, O—0.20%, C—0.08%, N—0.05%, H—0.0125%. It gives a perfect combination of toughness and high strength (Table 1) and also has good welding properties. Resistance to fatigue and crack propagation is excellent. Like most titanium alloys, grade 5 is resistant to corrosion in natural conditions and in many industrial environments.

Garnet was used as the first abrasive material. The garnet class contains closely associated, isomorphic minerals that may grow into each other or contain a small quantity of components from other garnets which substitute for the original. Garnets are isostructural, meaning they have the same crystalline structure resulting in similar crystal shapes and properties (Table 2). Almandine ($Fe_2 + 3\ Al_2\ [SiO_4]_3$) is the most popular form of garnet used in AWJ technology [17].

Olivine was the second abrasive material to be used. Olivine is really the name for an isomorphous series between two minerals, fayalite and forsterite (Table 2). Fayalite is iron-rich Fe_2SiO_4 and forsterite is magnesium-rich Mg_2SiO_4. The two minerals form a series, where the iron and magnesium are interchangeable without having much effect on the crystal structure. Forsterite, due to its magnesium content, has a lower index of refraction, a lower density, and a lighter color than fayalite. Otherwise, they are hard to distinguish and practically each piece of the two minerals contains both magnesium and iron. They can probably only be distinguished apart by chemical analysis. For the sake of simplicity, they are frequently treated as one mineral, olivine, which is, however, still not officially accepted as a mineral.

Natural olivine concentrates are produced from crushed rocks (dunites, olivine gabbros) with different grain sizes and mineralogical purity (for example hortonolite or green olivine) and various ratios of forsterite and fayalite components for use as industrial products. The price of these products is reasonable and relatively low in comparison with alternatives. Olivine concentrates are often used in air blasting (cleaning metals, paint removal, etc.). Olivine abrasive is also

Table 1 Typical mechanical properties of titanium grade 5

Density [kg/dm^3]	4.42
Melting point [°C]	1650
Tensile strength [MPa]	950
Modulus of rigidity [kN/mm^2]	40–44
Modulus of elasticity [kN/mm^2]	105–120
Specific heat [J/kg]	560
Vickers hardness [kg/mm^{-2}]	330

Table 2 Tested abrasive material properties [17]

	Garnet	Olivine	Crushed glass
Crystal system	Cubic	Orthorhombic	Amorphous structure, glassy
Twinning	None	On {100}; on {031} as trillings	–
Unit cell	$a = 11.53$ Å	$a = 4.799$ Å; $b = 10.39$ Å; $c = 6.063$ Å	–
Habit	Crystals usually dodecahedrons or trapezohedrons; also in combination or with hexoctahedron; massive; granular	Crystals thick tabular, often with wedge-shaped terminations, small; massive, compact or granular	–
Cleavage	1; {110} parting sometimes distinct	2; {010} and {100} imperfect	None
Fracture	Conchoidal to uneven	Conchoidal	Conchoidal, very sharp, knife-like grains
Tenacity	Brittle	Brittle	Brittle
Color	Deep red to reddish-brown, sometimes with a violet or brown or brownish black hue	Greenish yellow, yellowish brown, brown	Transparent, brown, green
Hardness (Mohs)	6.5–7.5	7	5
Density	4.1–4.3	4.32	2.5

often used for AWJ cutting of metal materials and AWJ blasting. However, it is not suitable for the cutting of grained rocks [17].

Alternatives to mineral abrasives were intensively tested. They are mainly alkaline glass and glassy forms of slag or some slag containing glass matrix and Ca-Mg silicate or oxide crystals. In all cases, these materials are mostly secondary raw materials or industrial wastes.

As a third abrasive material, crushed glass was used. Na-Ca glass grit is obtained from crushed and separated waste glass products, secondary or waste materials or as industrial products. The utilization of Na-Ca glass-based abrasives in AWJC and blasting is not common. It was used only as an experimental material—tests were performed with fine glass pellets (fine droplets, balls—so called Balotine). Na-Ca glass-based abrasive has a low cutting efficiency in steel and coarse rocks because it is a brittle abrasive material [17]. The physicochemical properties of glass abrasive are shown in Table 2.

The main forming tool of the jet is the focusing tube which is the part most exposed to erosive wear [29]. In research, focusing tubes made from a special material (ROCTEC®100) were used. The ROCTEC process allows for the joining of advanced ceramic materials without the relatively soft metal binder, as in the traditional sintering technology. Removing the metallic binder and maintaining an extra-fine grain size both give optimum focusing tube performance.

The study was conducted on a test rig, using a high-pressure KMT intensifier type I50, two-axis CNC machine type ILS55 by Techni Waterjet with a computer control system, as illustrated (Fig. 2).

The maximum working pressure is 400 MPa at a flow rate of 5 dm^3/min. This allows for the use of a water nozzle with maximum ID of 0.4 mm. The cutting head used, as shown in Fig. 2, is equipped with a water nozzle ID of 0.25 mm with a focusing tube ID of 0.76 mm and a length of 75 mm and a water nozzle ID of 0.33 mm with a focusing tube with an ID of

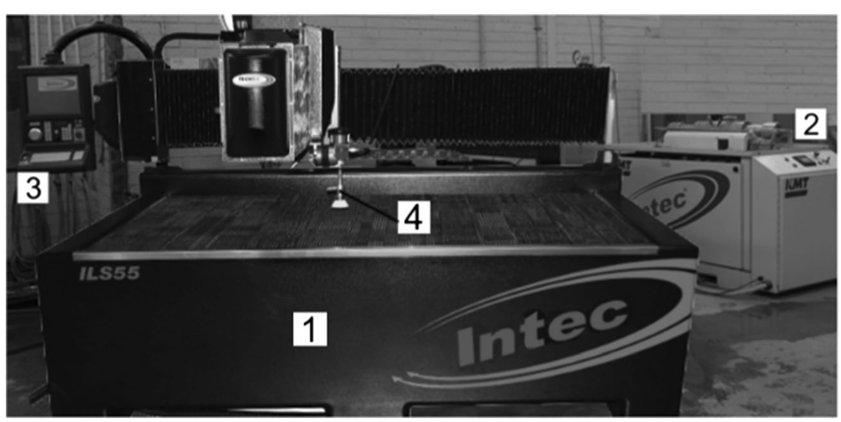

Fig. 2 Test rig: (1) cutting machine, (2) intensifier, (3) control unit, (4) cutting head

Table 3 Process parameters and levels

Symbol	Factors	1	2	3	4
N_{ID}	Nozzle ID	0.25	0.30	0.33	–
C_a	Abrasive concentration [%]	15	17.5	20	22.5
S_t	Traverse speed [mm/s]	2	4	6	–
T_a	Abrasive type	GMA80	Glass125	Olivine	–

Table 4 Independent and dependent variable of experiment

No.	Nozzle ID	Abrasive concentration	Traverse speed	Cutting depth for abrasive		
				GMA80	Glass	Olivine
	[mm]	[%]	[mm/s]	[mm]	[mm]	[mm]
1	0.25	15.0	2	25.85	20.71	22.95
2	0.25	15.0	4	15.45	14.04	14.76
3	0.25	15.0	6	10.82	9.09	9.82
4	0.25	17.5	2	27.77	22.09	23.54
5	0.25	17.5	4	16.66	14.55	15.01
6	0.25	17.5	6	11.67	10.04	10.98
7	0.25	20.0	2	29.63	23.87	26.84
8	0.25	20.0	4	17.34	14.97	15.59
9	0.25	20.0	6	12.87	10.75	11.68
10	0.25	22.5	2	28.91	23.03	24.56
11	0.25	22.5	4	16.76	14.71	14.94
12	0.25	22.5	6	11.94	10.42	10.81
13	0.30	15.0	2	28.32	22.35	24.38
14	0.30	15.0	4	17.90	14.20	16.34
15	0.30	15.0	6	12.55	11.20	11.47
16	0.30	17.5	2	30.23	23.85	26.04
17	0.30	17.5	4	18.83	14.50	16.82
18	0.30	17.5	6	13.79	11.90	12.59
19	0.30	20.0	2	32.62	25.73	29.32
20	0.30	20.0	4	20.28	15.50	17.55
21	0.30	20.0	6	15.03	12.70	13.72
22	0.30	22.5	2	31.11	24.76	26.92
23	0.30	22.5	4	19.15	14.9	16.71
24	0.30	22.5	6	14.00	12.2	12.93
25	0.33	15.0	2	29.99	23.29	25.41
26	0.33	15.0	4	18.55	16.30	17.52
27	0.33	15.0	6	13.77	11.90	13.12
28	0.33	17.5	2	31.98	24.93	27.89
29	0.33	17.5	4	20.38	17.20	18.12
30	0.33	17.5	6	15.34	12.60	14.20
31	0.33	20.0	2	34.69	26.83	30.97
32	0.33	20.0	4	22.54	18.80	19.19
33	0.33	20.0	6	16.67	13.10	15.10
34	0.33	22.5	2	32.52	25.77	28.60
35	0.33	22.5	4	20.95	17.30	18.21
36	0.33	22.5	6	15.63	12.80	14.57

1.00 mm and a length of 75 mm. The abrasive material mass flow rate was controlled manually by changing the cross section of the intake channel.

3 Test procedure

Parameters such as traverse speed, water pressure, stand-off distance, and abrasive flow rate (concentration) were varied on three levels and were selected based on our previous works [24, 25] and the works of other researchers: Alberdi et al. [1], Babu and Muthukrishnan [2], Chillman et al. [4], Hlavac et al. [7] Li and Wang [16], and Vasanth [32]. The AWJ cutting parameters with their levels are shown in Table 3.

The remaining parameters, such as pressure = 390 MPa and stand-off distance = 4 mm, are kept constant during the tests.

The design of experiment (DOE) was used to minimize the number of experiments in order to reduce cost and time. The research was carried out according to the full factorial design. The response surface method (RSM) was used with a Box-Behnken model to eliminate the non-significant factors. It consists of 36 experiments (Table 4). RSM is a combination of mathematical and statistical methods for modeling, predicting, and optimizing the independent variable on the dependent variable. It can be used in multiobjective optimization processes. In addition, it also provides a relationship between the observed responses and the process variables under consideration [2]. A polynomial equation of second order for determining the value of the regression model is:

$$y = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum_{i=1}^{k}\beta_{ii} x_i^2 \pm \varepsilon \quad (1)$$

where

y	is the corresponding response,
x_i	indicates values of the ith machining parameter,
β_0, β_i, β_{ii}	are the regression coefficients, and
ε	is the error obtained during cutting.

The effect of independent variables (control factors) on the process was made through analysis of variance—ANOVA. Based on the results shown in Table 4, the significance of machining parameters nozzle ID, traverse speed, abrasive concentration, and abrasive material on cutting depth were calculated.

4 Results and discussion

The results of the analysis of variance produce the figures given in Table 5. This analysis was carried out for a 95% confidence level ($\alpha = 0.05$). The P value of < 0.05 implies that the model factor is significant [26].

Traverse speed is the most significant factor influencing cutting depth. Meanwhile, nozzle ID respectively has a sub-

Table 5 Analysis of variance

Source	DF	Adj SS	Adj MS	*F* value	*P* value
Model	17	4491.60	264.21	589.02	0.000
Linear	5	4150.09	830.02	1850.40	0.000
Nozzle ID	1	204.39	204.39	455.66	0.000
Concentration	1	51.53	51.53	114.87	0.000
Traverse speed	1	3630.07	3630.07	8092.71	0.000
Abrasive	2	264.11	132.05	294.40	0.000
Square	3	214.63	71.54	159.50	0.000
Nozzle ID*nozzle ID	1	1.42	1.42	3.17	0.079
Concentration*concentration	1	33.58	33.58	74.86	0.000
Traverse speed*traverse speed	1	179.63	179.63	400.47	0.000
2-way interaction	9	69.68	7.74	17.26	0.000
Nozzle ID*concentration	1	0.66	0.66	1.47	0.228
Nozzle ID*traverse speed	1	0.56	0.56	1.24	0.268
Nozzle ID*abrasive	2	5.07	2.54	5.66	0.005
Concentration*traverse speed	1	6.34	6.34	14.14	0.000
Concentration*abrasive	2	1.19	0.60	1.33	0.270
Traverse speed*abrasive	2	55.85	27.93	62.26	0.000
Error	90	40.37	0.45		
Total	107	4531.97			

SS sum of squares, *DF* degree of freedom, *MS* mean square, *F* ratio of variance of a source to variance of error

Table 6 ANOVA model summary

S	R^2	R^2 (adj)	R^2 (pred)
0.669747	99.11%	98.94%	98.75%

significant effect on cutting depth. Abrasive concentration speed has the least significant influence on cutting depth.

The capability of the model was tested with an R^2 calculation. In regression, an R^2 coefficient of determination is a statistical measure of how well the regression line approximates the real data points.

Table 6 presents a standard error of the regression $S =$ 0.66769, an $R^2 = 99.11\%$ and R^2 adjusted = 98.94% and an R^2 predicted on 98.74%. Such high and little differing values show that the raw data fit very well to the regression line.

To measure multicollinearity, the variance inflation factor (VIF) was examined. VIF measures how much the variance of an estimated regression coefficient increases if predictors are correlated. If the VIF = 1, there is no multicollinearity, but if the VIF is > 1, the predictors may be moderately correlated. For most factors, there is no multicollinearity (VIF = 1.00) or any multicollinearity is slight (1.00 < VIF < 1.35).

On basis of coefficients (Table 7), the final cutting depth control models were formulated:

For GMA80 abrasive:

$$D_c = 8.47\text{-}56.0N_{ID} + 3.613C_a\text{-}8.242S_t + +163.9N_{ID}^2\text{-}0.0892C_a^2 + 0.684S_t^2 + 0.847N_{ID}\,C_a \text{-}1.33N_{ID}\,S_t \text{-}0.0531C_a\,S_t \quad (2)$$

For glass abrasive:

$$D_c = 6.63\text{-}72.0N_{ID} + 3.527C_a\text{-}7.179S_t + +163.9N_{ID}^2\text{-}0.0892C_a^2 + 0.684S_t^2 + +0.847N_{ID}\,C_a\text{-}1.33N_{ID}\,S_t \text{-}0.0531C_a\,S_t \quad (3)$$

For olivine abrasive:

$$D_c = 6.6\text{-}62.4N_{ID} + 3.541C_a\text{-}7.421S_t + +163.9N_{ID}^2\text{-}0.0892C_a^2 + 0.684S_t^2 + +0.847N_{ID}\,C_a\text{-}1.33N_{ID}\,S_t \text{-}0.0531C_a\,S_t \quad (4)$$

where

D_c is cutting depth [mm],
N_{ID} is nozzle internal diameter [mm],
C_a is abrasive concentration [%], and
S_t is traverse speed [mm/s].

Table 7 Regression coefficients

Term	Effect	Coef	SE Coef	T value	P value	VIF
Constant		17.391	0.172	101.35	0.000	
Nozzle ID	3.3697	1.6849	0.0789	21.35	0.000	1.02
Concentration	1.8628	0.9314	0.0869	10.72	0.000	1.01
Traverse speed	− 14.2733	− 7.1367	0.0793	− 89.96	0.000	1.01
Abrasive						
Glass	− 3.5709	− 1.7854	0.0916	− 19.49	0.000	1.35
GMA80	4.0787	2.0393	0.0916	22.26	0.000	1.35
Nozzle ID*nozzle ID	0.524	0.262	0.147	1.78	0.079	1.02
Concentration*concentration	− 2.509	− 1.255	0.145	− 8.65	0.000	1.00
Traverse speed*traverse speed	5.472	2.736	0.137	20.01	0.000	1.00
Nozzle ID*concentration	0.254	0.127	0.105	1.21	0.228	1.01
Nozzle ID*traverse speed	− 0.2132	− 0.1066	0.0957	− 1.11	0.268	1.01
Nozzle ID*abrasive						
Glass	− 0.683	− 0.341	0.110	− 3.09	0.003	1.35
GMA80	0.596	0.298	0.110	2.70	0.008	1.35
Concentration*traverse speed	− 0.796	− 0.398	0.106	− 3.76	0.000	1.00
Concentration*abrasive						
Glass	− 0.250	− 0.125	0.122	− 1.02	0.309	1.33
GMA80	0.394	0.197	0.122	1.61	0.111	1.33
Traverse speed*abrasive						
Glass	1.915	0.958	0.112	8.58	0.000	1.33
GMA80	− 2.337	− 1.169	0.112	− 10.47	0.000	1.33

VIF variance inflation factor

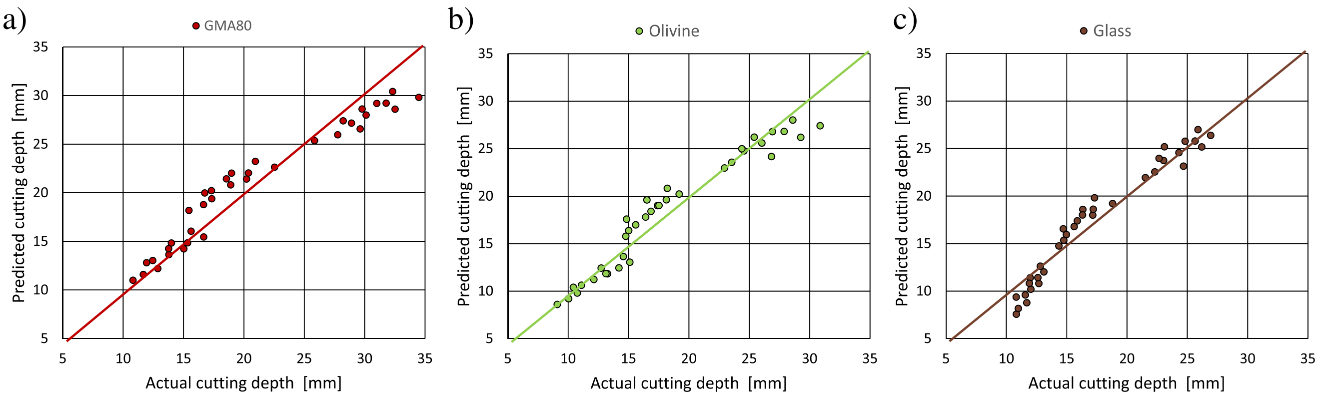

Fig. 3 Scatter plot for cutting depth for **a** GMA80 abrasive, **b** olivine abrasive, and **c** glass abrasive

The normal scatter plot of cutting depth is shown in Fig. 3. It can be concluded that the points are close to a straight line. Therefore, it suggests that the mathematical model which has been developed is satisfactory.

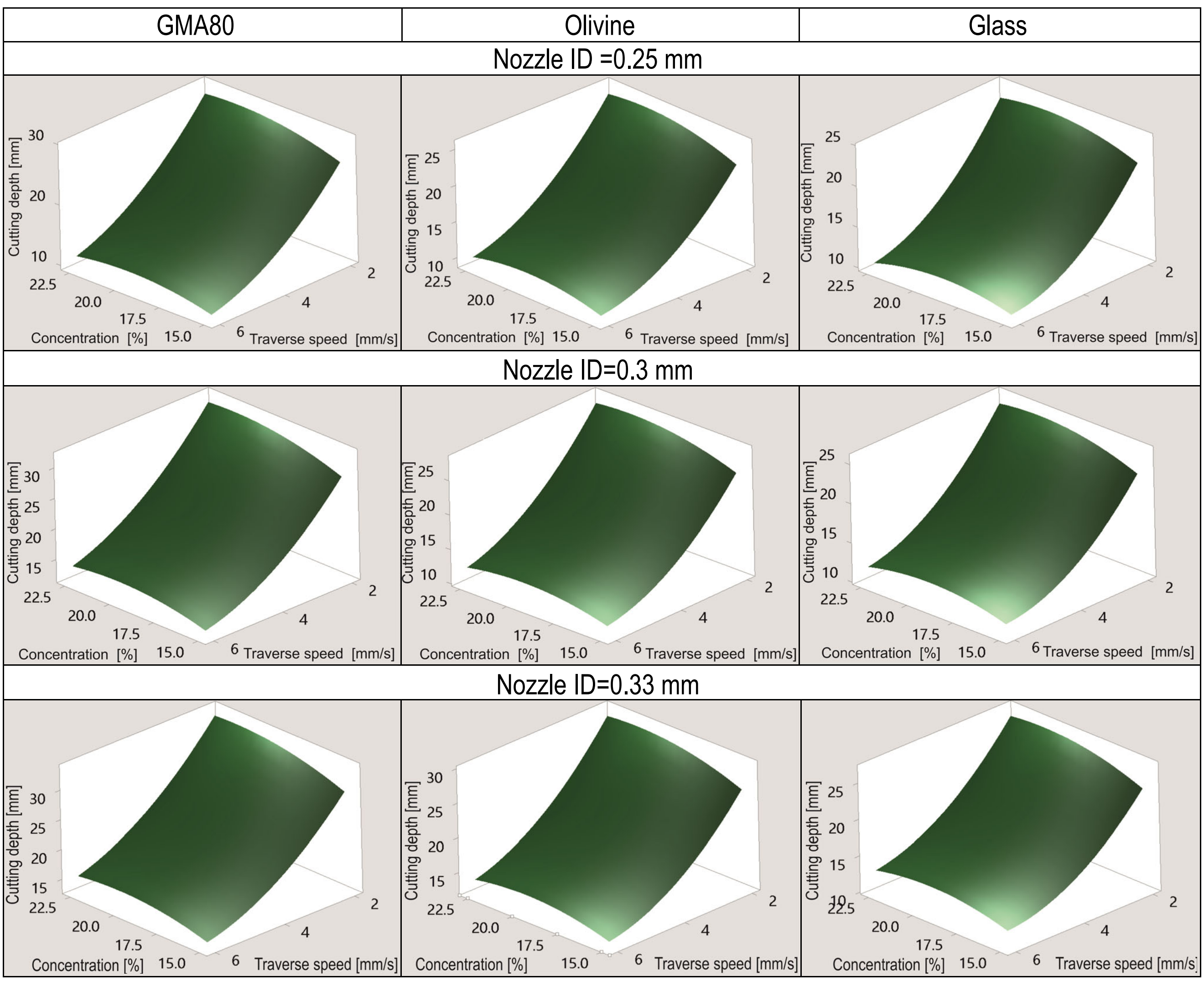

Fig. 4 Influence of traverse speed and concentration of abrasive at constant nozzle ID on titanium grade 5 cutting depth with different abrasive materials. Pressure 390 MPa

 Int J Adv Manuf Technol (2018) 97:1529–1540

4.1 The influence of abrasive concentration and traverse speed at constant nozzle ID on the cutting depth of titanium

The surface response plot of the effect of traverse speed and abrasive concentration on cutting depth for all tested abrasives is shown in Fig. 4. The increase in traverse speed leads to a reduction in the cutting depth value. On the basis of the analysis of variance (Table 5), traverse speed is the most dominating parameter on cutting depth value. A low traverse speed (2 mm/s) allows more abrasive grains to cut the machining material. A large number of abrasive grains provide a lot of cutting edges, and this leads to an increase in material removal rate. Thus, the cutting kerf becomes deeper.

The maximum cutting depth for an abrasive concentrate equal to 20% can be observed. Above this value, water is not able to provide maximum velocity to abrasive grains. An additional adverse factor is an interaction (impact) between the abrasive grains, which also negatively affect the total energy of the abrasive water jet. Decreasing the abrasive concentration results in a decrease in cutting depth due to a smaller number of abrasive grains and hence a smaller number of cutting blades. The nature of this relationship was observed with all nozzles for all types of abrasives tested.

4.2 Influence of nozzle ID and traverse speed at constant abrasive concentration nozzle ID on cutting depth of titanium

The surface response plot of the effect of traverse speed and nozzle ID on cutting depth for all tested abrasives (Fig. 5) shows that cutting depth is at the minimum for a high traverse speed and low nozzle ID. From the ANOVA (Table 4), the water nozzle ID is a less significant parameter than traverse speed on controlling the surface roughness.

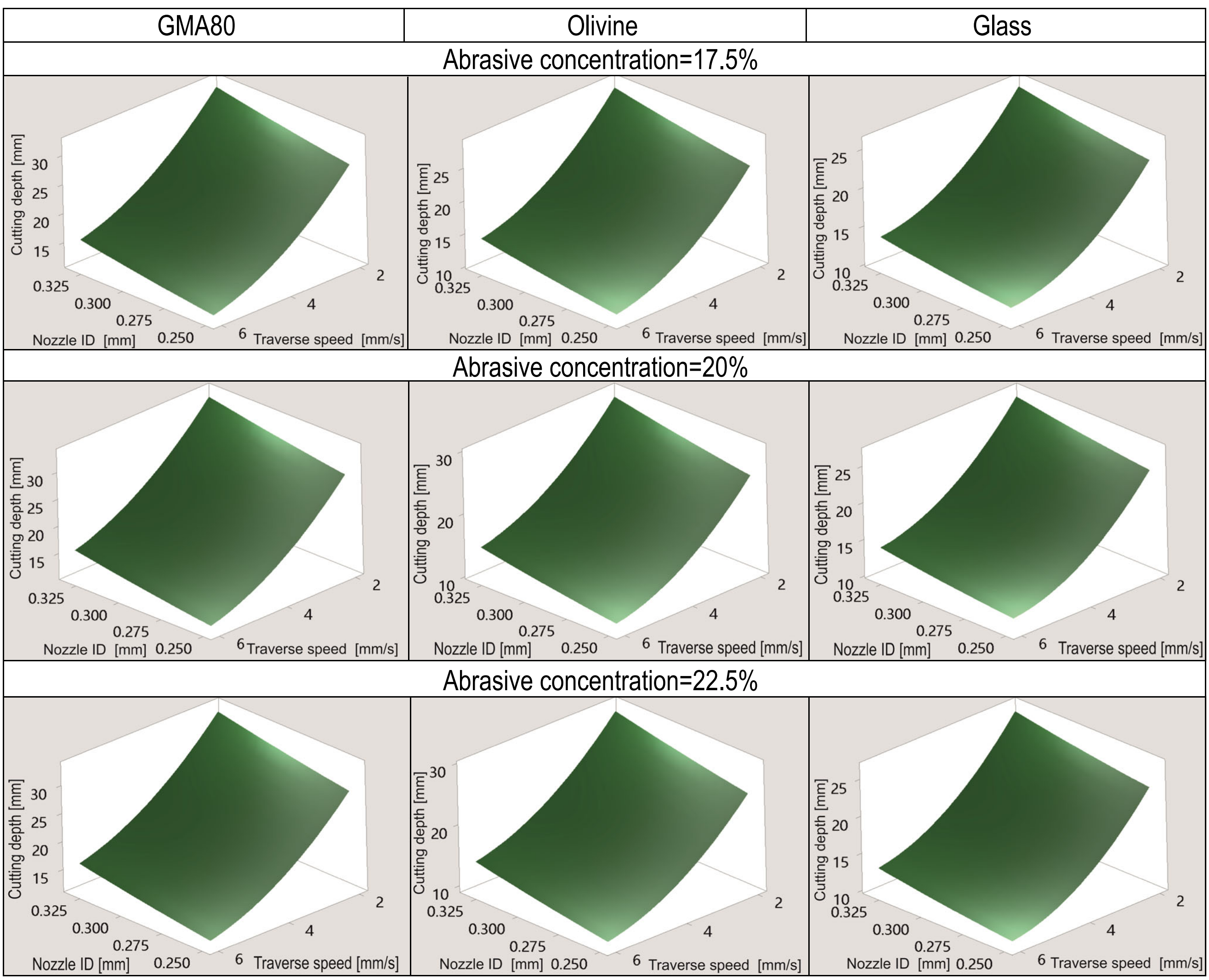

Fig. 5 Influence of traverse speed and nozzle ID at constant concentration of abrasive on titanium grade 5 cutting depth with different abrasive materials. Pressure 390 MPa

The biggest cutting depth is achieved for the nozzle with the largest ID and at the lowest traverse speed. Also in this case, the nature of this relationship was observed with all nozzles for all types of abrasives tested.

4.3 Influence of abrasive concentration and nozzle ID at constant traverse speed on cutting depth of titanium

The surface response plot of the effect of nozzle ID and abrasive concentration on cutting depth for all tested abrasives is shown in Fig. 6. Also in this case, the maximum cutting depth for an abrasive concentrate equal to 20% can be observed. The increase in traverse speed leads to a reduction in the cutting depth value. The greatest cutting depth is achieved with the largest nozzle and optimality (from the cutting depth point of view), equal to a 20% abrasive concentration. In this case too, the nature of this relationship was observed with all nozzles for all types of abrasives tested.

4.4 Abrasive efficiency

The results of these titanium cutting tests have allowed us to compare the efficiency of high-pressure abrasive water-jet treatment with a variety of abrasives. As a basis for comparison, a widely used abrasive, garnet was selected. It was excised according to the formula:

$$f_x = \frac{D_x}{D_g} \tag{5}$$

where

f_x is x abrasive material efficiency factor,
D_x is cutting depth achieved using x abrasive material [mm], and

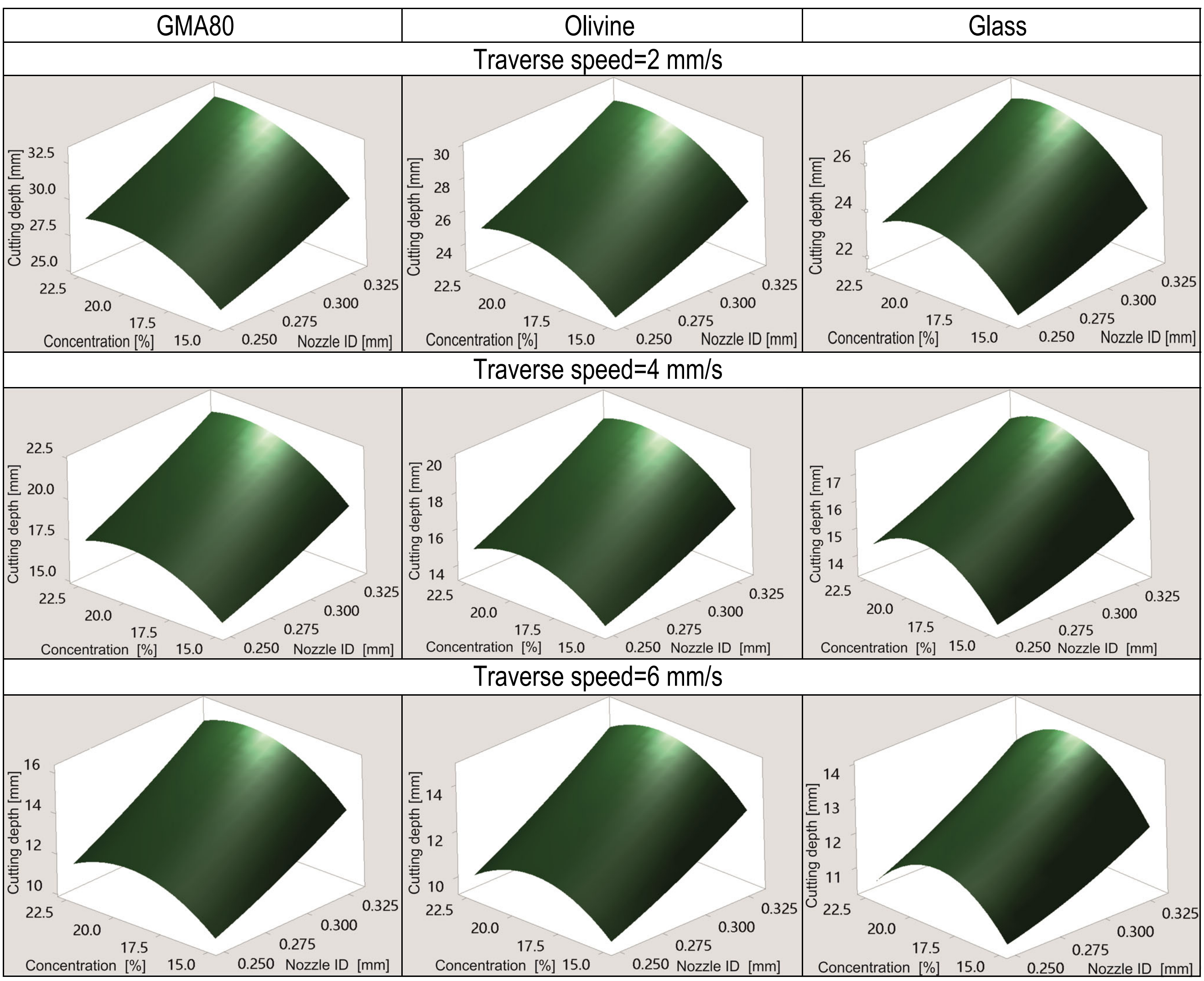

Fig. 6 Influence of concentration of abrasive and nozzle ID at constant traverse speed on titanium grade 5 cutting depth with different abrasive materials. Pressure 390 MPa

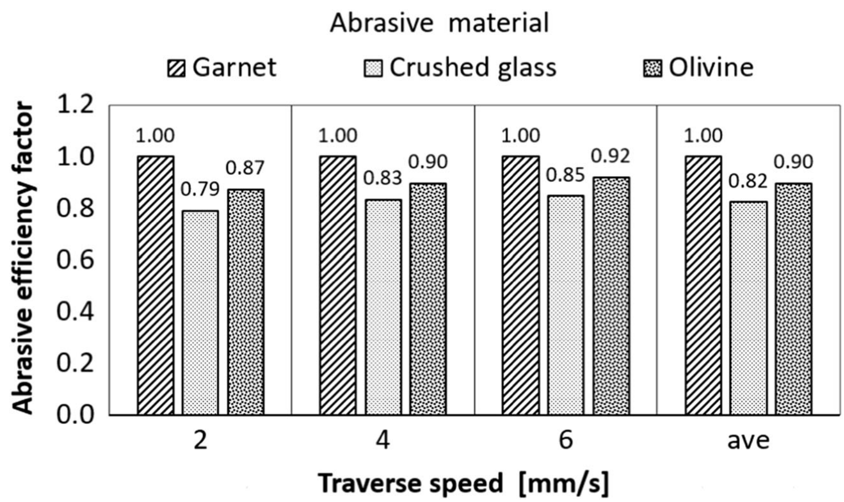

Fig. 7 Comparison of the abrasive material efficiency factor for testing abrasive

D_g is cutting depth achieved using garnet abrasive material [mm].

Figure 7 presents the graphic illustration of Eq. (5). The relationship between the abrasive materials tested and traverse speed on the efficiency factor can be observed for olivine and crushed glass in relation to garnet. The efficiency factor for olivine abrasive material reaches a value near 0.89 over the whole range of traverse speeds tested. For crushed glass, the abrasive efficiency factor reaches a value from 0.80 to 0.85 (average 0.82).

In addition to the maximum cutting depth, square cut efficiency was used. It is calculated according to the equation:

$$E_S = D \times S_t \quad (6)$$

where

E_S is the square cut efficiency [mm^2/s],

S_t is the traverse speed [mm/s], and

D is the cutting depth [mm].

On the basis of Eq. (6), sample times for 1000 mm cut of the 5-mm thick titanium, with the optimum abrasive flow rate (20%) using water nozzles with diameters of 0.25, 0.30, and 0.33 mm, were determined (Fig. 8). The shortest cutting time was achieved using a garnet abrasive. For olivine, the average cutting time increases by 11% and for glass abrasive by 24%.

4.5 Focusing tube wear

In parallel with the study of the depth of cut, research focusing on tube wear at work was conducted. A definite focusing tube durability coefficient was used. It was determined as the ratio of mass loss over time:

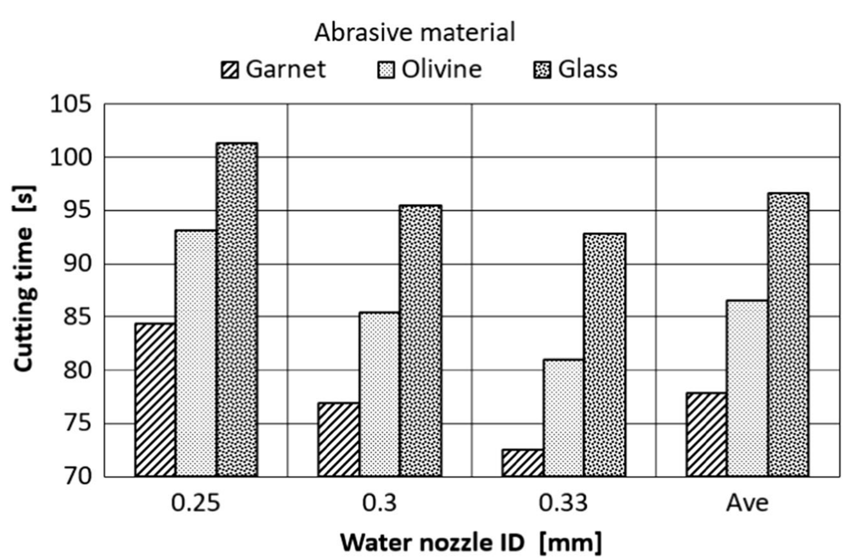

Fig. 8 Cutting time of the 1000-mm titanium grade 5 material ≠ 5 mm for testing abrasives

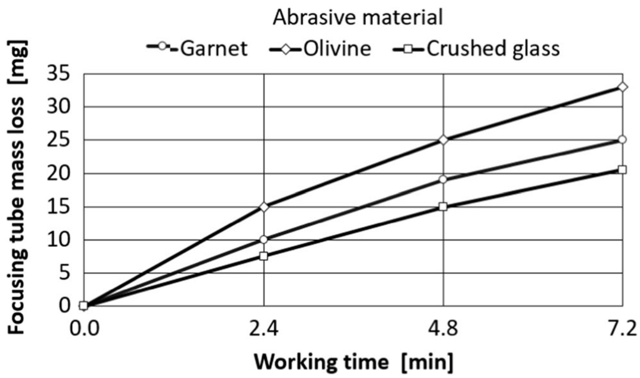

Fig. 9 Wear of focusing tube. Tube material: ROCTEC100; abrasives: garnet, olivine, and glass

$$x = \frac{\Delta f}{\Delta t} \quad (6)$$

where

x is the focusing tube wear coefficient [mg/min],
Δf is the mass loss of the focusing tube [mg], and
Δt is the working time [min].

Figure 9 shows the wear of focusing tubes as a function of the amount of GMA garnet, crushed glass abrasive, and olivine which flowed through the focusing tube. Wear in time is similar and proportional for all tested abrasives, but less for glass abrasives and greater for olivine.

Abrasive wear is most affected by the abrasive properties and especially the hardness of the grains. Among the abrasive materials tested, the smallest hardness, equal to 5 on the Mohs scale, is characterized by crushed glass. The grains of garnet and olivine have a similar hardness, equal to 7 on the Mohs scale. This is confirmed by the results of the study. The biggest wear coefficient of the focusing tube was reached for olivine—4.58 mg/min. Garnet abrasive reached a wear coefficient equal to 3.47 mg/min and crushed glass abrasive gave the lowest value, equal to 2.85 mg/min.

5 Conclusion

This experimental study led to the following conclusions being drawn:

- A slower traverse speed resulted in a deeper depth of cut over the whole examined area.
- Increasing the abrasive concentration in the jet from 15 to 20% results in an increase in cutting depth. A continued increase of abrasive concentration beyond this value actually results in a small decrease in cutting depth.
- For all abrasives, the optimum abrasive concentration in the jet is 20%.
- The garnet abrasive material gave the greatest cutting depth.
- The use of olivine abrasive material resulted in a slight decrease (average 0.9) in the maximum cutting depth.
- Crushed glass caused even less effect (average 0.82).
- Olivine caused the greatest abrasive wear of the focusing tube (4.58 mg/min).
- Garnet abrasive achieved a wear coefficient equal to 3.47 mg/min
- Crushed glass abrasive caused the smallest value of wear coefficient, equal to 2.85 mg/min.

Abrasive water-jet machining is one of the most advanced machining processes. This process can be used for machining any material without structural changes to the surface and surface properties.

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