13th International Research/Expert Conference
”Trends in the Development of Machinery and Associated Technology”
TMT 2009, Hammamet, Tunisia, 16-21 October 2009

MECHANICAL MICROMACHINING OF OXIDE CERAMICS

Roberto Calzavarini
Giovanna Gautier di Confiengo
ISTEC-CNR Strada delle Cacce, 73, Torino Italy

Barbara Previtali,
Rebaioli, Lara
DIMEC, Politecnico di Milano,
via La Masa 34,
Milano Italy

Luca Settineri,
DISPEA, Politecnico di Torino
C.so Duca degli Abruzzi, 24,
Torino Italy

ABSTRACT

In the last decade there has been a great interest in product miniaturization, intended as the constant technological trend of producing smaller devices for any application, with no detriment for functionality or for efficiency. Such trend affects any manufacturing sector, from aerospace to cars, medical and optical applications. The present paper is focused on the mechanical micromilling of a peculiar ceramic material, which is Zirconia Toughened Allumina (ZTA), which founds increasing interest for biomedical applications. The experimental activity consisted of micromilling tests, conducted on presintered and green materials, by means of a dedicated micromill. As output variables, part surface quality was analyzed in terms of surface roughness and surface damage. Results show that the most affecting factors on the part surface quality are material conditions (green or presintered) and milling approach (up milling or down milling). Parameters traditionally affecting surface quality, such as cutting speed and feed, are in this case less influent than expected.

Keywords: Micromachining, Ceramic materials, Surface quality

1. INTRODUCTION

In the last decade there has been a strong interest in miniaturization of products, and this tendency has involved every manufacturing sector, from aerospace, to automotive, optical, medical and electronic. To produce miniaturized goods, there is a need for innovative manufacturing technologies, able to produce small dimension objects with the desired specifications in terms of dimensional and geometrical tolerances, surface quality and residual stresses [1]. With the term micromanufacturing technologies, we intend the processes, machines and tools for the creation of parts with sizes ranging from 1 to 999 μm and with and accuracy of the order of 1 μm [1,2]. There exist several kinds of micromanufacturing technologies, among which those using chemical agents, electrochemical phenomena, or high energy-density beams, such as laser or electron beam [3,4]. An important class of micromanufacturing technologies is mechanical micromachining, which applies in miniaturized form the same techniques than in the macro- version, but using very small tools and very precise machines designed using specific criteria [5]. Interaction between micro tools and materials and consequently the state of the produced surfaces is probably the main issue to be solved in the production of high quality microproducts. Micromilling is on of the most versatile microtechnology, able to obtain a wide range of surfaces. With the reduction of mill and chips sizes, there appear to be negative effects due the fact that the cutting edges interact with one or few grains at each pass, therefore the material is presented to the tool as highly inhomogeneous. Therefore there exist the risk of having relatively high, variable and difficult to predict cutting forces and relatively high surface roughness with possible surface damages [6].

Ceramic materials are desirable in miniaturised products due to their intrinsic characteristics of high hardness, durability, thermal and corrosion resistance. They find application in the medical as well in the optical and mechanical fields [7]. Ceramics, however, are intrinsically fragile and this strongly limits their application as structural materials. Therefore, several toughened ceramics have been developed in the recent past, in the attempt to overcome or mitigate the problem. Among these, Zirconia Toughened Alumina (ZTA) finds increasing interest as structural material for biomedical applications, raising the need for shaping processes able to yield the desired characteristics, especially in terms of surface quality, even in the case of machining of micro features. Micro machining of ceramics, however, presents some difficulties, mainly due to the interaction with the tools. Ceramics are intrinsically inhomogeneous and fragile, therefore the common chip removal models do not apply. Chip separation follows a fragile mechanism and the generated surface often shows a unacceptable damage level [8]. For this reason, ceramic machining, at macro and micro level, often occurs at the green or presintered stage. In this paper, the first results of an experimental activity on the mechanical micromilling of Zirconia Toughened Allumina are presented, conducted on presintered and green material. As output variables, part surface quality was analyzed in terms of surface roughness and surface damage. Results show that the most affecting factors on the part surface quality are the material conditions (green or presintered). Parameters traditionally affecting surface quality, such as cutting speed and feed, are in this case less influent than expected.

2. EXPERIMENTAL SET UP

Workpiece material is a composite 84% Al_2O_3 + 16 % ZrO_2. Green samples have been prepared by Cold Isostatic Pressing (CIP), with a pressure of 2500 kg/cm2 for 1-2 minutes, after linear pressing at 500 kg/cm2. Presintered samples have been prepared with the same procedure, followed by a presintering at a temperature of 1100 °C for 1 hour. Sample shape is parallelepipedal, with sizes 33x33x11 mm (see Figure 1).

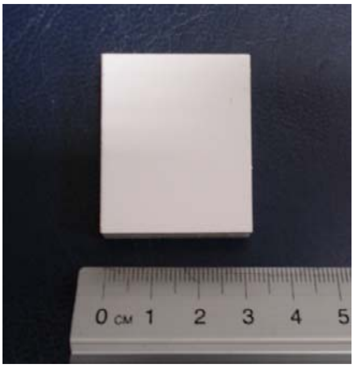


Figure 1. Sample used for the machining tests.

Table 1. Parameters used in the cutting tests.

Test number	Number of teeth	Cutting speed (m/min)	Feed per tooth (mm/tooth)
1	2	50	0.00942
2	2	75	0.00628
3	2	50	0.00942
4	2	50	0.014
5	2	50	0.00942
6	2	50	0.00471
7	2	50	0.00942
8	2	25	0.00942
9	4	25	0.00471
10	4	75	0.00157
11	4	25	0.014
12	4	75	0.00471
13	4	50	0.00707

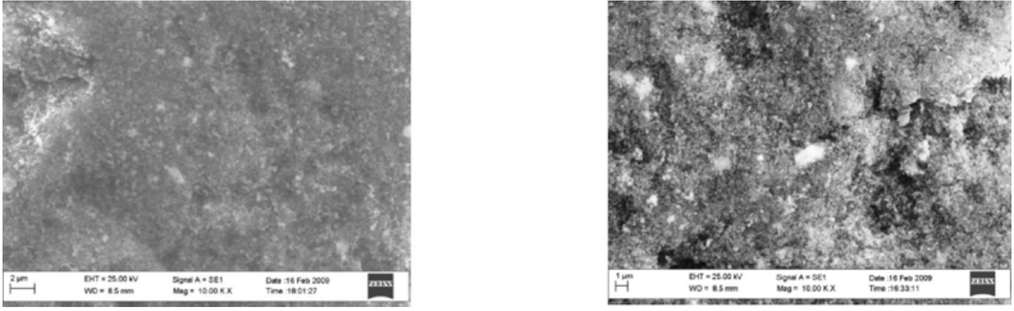
The tests have been conducted with the following procedure:

- Study of the sample surfaces before machining: measure of roughness (Ra), HV microhardness, SEM observation of the surfaces to evaluate presence of porosity, cracks, etc..
- Milling tests;
- Study of the surfaces of the machined part: measurement of Ra, Rsk and Rku and SEM observations to evaluate modification of the surface integrity occurred during machining.

For the roughness measurements, a Form Talysurf 120 instrument has been used, and 6 repetitions for each test have been carried out, while hardness Vickers was measured with a DURIMET instrument, with a 500 g weight. Surface integrity has been observed by a ZEISS EVO 50 XVP Scanning Electron Microscope. The milling machine usd for the cutting experiments was a Kern Evo Ultra Precision CNC Machining Centre, while the tools were ISO K20 cylindrical mills, for semi-finishing (2 teeth) and finishing (4 teeth) operations, with a diameter of 0.5 mm. An up-mill contouring operation has been carried out, with cutting speed of 25, 50 and 75 m/min, feed velocity of 300, 600 and mm/min and feed per tooth correspondingly ranging from 0.00157 to 0.014 mm/tooth, for a total of 13 tests. Radial and axial depth of cut where both 0.25 mm, while mill axis has been kept perpendicular to the part surface. A complete overlook of the different cutting tests with the corresponding parameters is shown in Table 1.

3. RESULTS AND DISCUSSION

Hardness measurements gave the following results: green ZTA, 7 HV, presintered ZTA 165 HV. Suchbig difference in the hardness values is due to the bonds that presintering creates inside the materialand makes the presintered samples much easier to handle without breakage risks. Volume loss due to presintering was negligible. SEM observation of the surfaces of green and pre-sintered samples show a substantial difference,being the surface of presintered samples much more homogeneous (see figure 2).



(a) (b)

Figure 2. SEM images of the surfaces of a presintered (a) and green (b) sample before machining.

In Tables 2 and 3 the measured roughness parameters Ra, Rsk and Rku are reported, for the different cutting tests, for the green and presintered samples. The roughness values have been measured in the directions parallel and perpendicular to the feed. From the observation of such Tables, it can be stated that Ra values of the presintered sample are often lower than those of the green sample. Values measured in the direction perpendicular to the feed show values of one order of magnitude higher than those measured in the direction parallel to the feed. Dispersion is generally not negligible. Distribution of craters and surface irregularities makes the results of the roughness measurements quite dispersed. No apparent correlation with cutting speed is observed, while a feed increase means an increase in Ra, especially when measured in the direction perpendicular to the feed in the case of the green samples. Results appear to be independent on the number of teeth of the mill. Measurements of Rsk and Rku indicate that the obtained surface has a good load bearing capabilities (Rsk < 0), but low peaks'density, (Rku > 3), typical of the machining of brittle material.

4. CONCLUSION

In this paper, the first results of an experimental activity on the mechanical micromilling of Zirconia Toughened Allumina are presented, conducted on presintered and green material. As output variables,part surface quality was analyzed in terms of surface roughness and surface damage.

Results show that the most affecting factors on the part surface quality are the material conditions (green or presintered). Parameters traditionally affecting surface quality, such as cutting speed and feed, are in this case less influent than expected. In the case of the green samples, feed has limited, but not zero, influence of Ra, especially when this is measured in the direction perpendicular to the feed.

Masurement of Rsk and Rku, indicate a typical machined surface of a brittle material.

Further work is needed to examine other surface quality indicators, and to explore the surface characteristics of the material after sintering.

Table 2. Roughness values measured on the surface of the green samples after machining.

Test number	Ra (std.dev.); // feed	Ra (std.dev.); ⊥ feed	Rsk; // feed	Rsk; ⊥ feed	Rku; // feed	Rku; ⊥ feed
1	0.34 (0.03)	0.89 (0.049)	-0.88	-0.20	4.72	5.63
2	0.36 (0.29)	0.50 (0.012)	-1.40	-0.93	7.57	6.61
3	0.30 (0.10)	0.69 (0.042)	-1.17	-1.36	6.30	9.33
4	0.46 (0.70)	0.49 (0.117)	-1.24	-1.49	8.20	8.26
5	0.31 (0.19)	0.42 (0.012)	-1.41	-1.02	8.16	7.58
6	0.29 (0.65)	0.51 (0.025)	-1.47	-0.50	10.79	4.26
7	0.29 (0.33)	0.45 (0.063)	-1.21	-0.21	6.18	4.97
8	0.28 (0.06)	0.51 (0.023)	-1.31	-0.45	6.61	4.26
9	0.27 (0.09)	1.07 (0.048)	-0.55	0.22	3.04	3.01
10	0.30 (0.04)	0.37 (0.066)	-1.02	-0.93	5.02	9.22
11	0.29 (0.31)	0.58 (0.110)	-0.75	-0.52	4.20	5.16
12	0.31 (0.01)	0.67 (0.029)	-1.25	-0.21	7.51	5.14
13	0.34 (0.02)	0.45 (0.040)	-1.14	-0.13	7.01	7.20

Table 3. Roughness values measured on the surface of the presintered samples after machining.

Test number	Ra (std.dev.); // feed	Ra (std.dev.); ⊥ feed	Rsk; // feed	Rsk; ⊥ feed	Rku; // feed	Rku; ⊥ feed
1	0.89 (0.03)	0.80 (0.553)	-2.57	-2.13	20.45	12.01
2	0.16 (0.26)	0.55 (0.177)	-2.18	-0.75	15.97	5.86
3	0.06 (0.02)	0.46 (0.129)	-1.26	-2.89	0.72	18.81
4	0.28 (0.56)	0.52 (0.211)	-1.77	-3.48	11.59	21.52
5	0.61 (0.92)	0.44 (0.053)	-2.27	-3.40	13.22	19.81
6	0.05 (0.02)	0.38 (0.095)	-0.50	-2.48	4.43	17.78
7	1.11 (1.21)	0.87 (0.230)	-3.92	-3.79	36.18	15.20
8	1.50 (3.52)	0.62 (0.192)	0.13	-1.30	45.54	9.89
9	0.17 (0.24)	0.73 (0.095)	-0.51	-2.19	6.18	15.47
10	0.16 (0.02)	0.91 (0.135)	-1.40	-1.84	12.21	8.79
11	0.04 (0.03)	0.97 (0.030)	-4.46	-0.70	5.94	6.67
12	0.74 (0.91)	0.67 (0.261)	-1.47	-3.34	6.22	16.13
13	0.05 (0.02)	0.57 (0.677)	-0.59	-4.03	4.29	25.00

5. REFERENCES

[1] Masuzawa T.: State of the Art of Micromachining, Annals of CIRP, 49/2, pp. 473-488, 2000.

[2] Takacs M., Vero B., Mészaros I.: Micromilling of Metallic Materials, Journal of Material Processing Technology, 138, pp. 152-155, 2003.

[3] Vollertsen F., Hu Z., Niehoff H.S., Theiler C.: State of the Art in Micro Forming and Investigations in Micro Deep Drawing, Journal of Materials Processing Technology, 151, pp. 70– 79, 2004.

[4] Ho K.H., Newman S.T.: State of the Art Electrical Discharge Machining (EDM), International Journal of Machine Tools and Manufacture, 43, pp. 1287-1300, 2003.

[5] Bissacco G., Hansen H.N., De Chiffre L.: Micromilling of hardened tool steel for mould making applications, Journal of Materials Processing Tech., 167/2-3, pp. 201-207, 2005.

[6] Pérez H., Vizán A., Hernandez J.C., Guzmán M.: Estimation of cutting forces in micromilling through the determination of specific cutting pressures, Journal of Materials Processing Tech., 190/1-3, pp. 18-22, 2007.

[7] Harsányi G.: New types of reliability problems in porous ceramic based microdevices, Materials Chemistry and Physics, 44/1, pp. 85-89, 1996.

[8] Venkatachalam S., Li X., Liang S.Y.: Predictive modeling of transition undeformed chip thickness in ductile-regime micro-machining of single crystal brittle materials, Journal of Materials Processing Tech., 209/7, pp. 3306-3319, 2009.