COMPARING THE PERFORMANCE OF MICRO-END MILLS WHEN MICRO-MILLING OF ADDITIVE MANUFACTURED TI-6AL-4V TITANIUM ALLOY

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The objective of this work is to compare the performance of uncoated micro-end-mills and their effect on micro-milling of the Ti6Al4V titanium alloy that had been manufactured in the technology of Additive Manufacturing (AM). In this work, two different geometries of square-end micro-mills with two and fourcutting fluteshave been used. The effective tool geometry at the real micro-machining is rather problematic, because most of the tools are just down-scaled dimensions of standard cutters, so the cutting geometries might not be working well for all dimensions. The Ti6Al4V titanium alloy was made in technologyof Direct Metal Laser Sintering (DMLS). Micro-milling tests were done with use of high precision 5-axis KuglerTM micro-milling centre under dry cutting conditions. The performances were evaluated in terms of surface topography, burrs formation, surface integrity and tool wear.

KEYWORDS

micro-milling, additive manufacturing, surface integrity, micro-end mills

1 INTRODUCTION

Micro-milling is one of the most progressive manufacturing technologies that are emerging nowadays, since it permits to produce low-size piecesof complex shapes and high geometrical accuracy in a wide range of materials like hardened steel, alumina, copper, titanium and their alloys, plastics and silicon [1,2]. However, micro-machining becomes challenging when machining difficult-to-cut but useful alloys, such as e.g. Ti6Al4V. The reasons for their use can be foundin their properties, for example the excellent biocompatibility, human allergic respose, corrosion resistance, high ratio between the strength and mass (density around 4.4 g/cm^3), osseous-integration, making it suitable for manufacturing e.g. human implants [3,4].

One of the modern technological processesis manufacturing the Ti6Al4V with the use of powder metallurgy, so the alloy can be prepared using so-called Additive Manufacturing (AM) technologies, e.g. the ElectronBeam Melting (EBM) and the Direct Metal Laser Sintering (DMLS). It is possible to produce very complex structures and to reduce a material waste employing these AM technologies.Only thin layers of material have to be removed from those surfaces so high geometrical accuracy of the parts can be achieved. The cutting conditions and cutting tools should be chosen very carefully and can be significantly different from those used for machining the wrought Ti6Al4V alloy [5,6,7].

In this work, the two different geometries of square-end micro-mills of 0.3 mmdiameter were used for machining of the DMLS Ti6Al4V alloy at a slotting operation. The machined surfaces were evaluated in terms of surface topography, surface defects and burrs, showing that the geometry of the micro-mills had a significant impact on the overall process.

2 MICRO-MILLING EXPERIMENTS

2.1. Material

The workpiece material was the Ti6Al4V titanium alloy, produced by the DMLS technology. A martensitic microstructure is produced with this technology due to significant temperature gradientsin the workpiece during the fabrication process [8]. After the DMLS process the workpiece should undergo a heat treatment, consisting of heating-up the material above its β-transus temperature, and then cooling down in a specific rate to obtain a final microstructure, consisting of α and β coarse lamellae. The typical microstructure after the heat treatment is shown in Fig. 1.

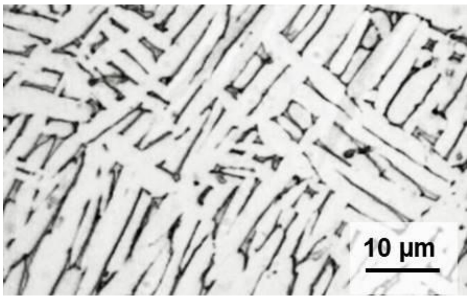

Figure 1. A lamellar microstructureof the DMLS Ti6Al4V material (after heat treatment).

Consequently, the workpiece was ground using sand papers (grit sizes P100,220,400 and 600) and polished with a dispersion of silica to ensure the top surface flatness without affecting the sub-layers.

2.2. Design of experiments

The micro-milling experiments were carried outonthe 5-axis high precision micro-milling machine MicromasterKuglerTM, equipped with two spindles, a mechanical (10,000 – 60,000 RPM) and the air bearing (20,000 – 180,000 RPM), with built-in eddy current sensor, which is able to measure and compensate the spindle axis expansion online.

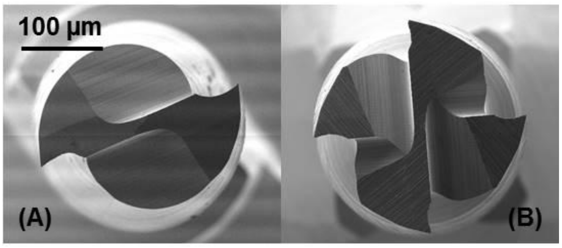

Figure 2. SEM images of the (A) two fluted and (B) four fluted flat-end-square micro-mills.

Two tested cutting micro-mills are shown in Fig. 2. The tool A was a two-fluted solid tungsten carbide tool,uncoated, the tool B was a four-fluted tool, the same material quality K10. The diameters of both tools werethe same (0.3 mm).

The full immersion slotting under dry lubrication condition was used as milling strategy. A stream of compressed air (0.3 MPa) was used to facilitate the removal of the chips from the cutting zone. The width of the slot was defined by the diameter of the tool, the depth of cut was set constant for all the experiments (30 µm), and the length of the slot was also constant (25 mm).A full factorial design of experiments with two factors (cutting speed and feed per tooth) with two and four levels respectively was used. Each experiment was repeated twice. The factors with their levels are reported in Table 1.

Table 1. Cutting conditions used in the micro-milling experiments

Tool A (2 fluted)				
v_c (m/min)	63	149	-	-
f_z(µm)	0.1	0.5	1.5	3.0
Tool B (4 fluted)				
v_c (m/min)	58	154	-	-
f_z(µm)	0.1	0.5	1.5	3.0

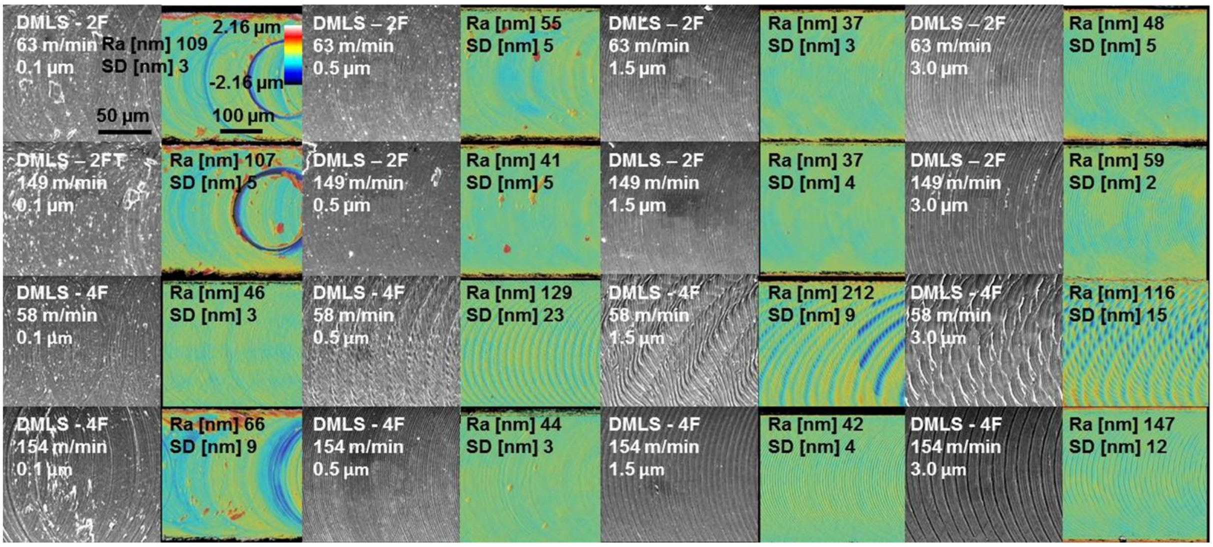

Figure 3. Surface topographies characterized using SEM and a confocal optical profiler (2F: two-fluted tool; 4F: four-fluted tool)

3 RESULTS

3.1. Surface topography

The machined surface topography was evaluated using both theFeiQuanta Scanning Electron Microscope ™ (SEM) and theSensofar™ PLµNeox confocal optical profiler. The instrument was equipped with the 100x magnification lens characterized with a field of view of 127x97 µm^2 and the vertical resolution of 5 nm. The profile average roughness was evaluated on the basis of the ISO 4288 standard. Depending on the expected mean width of the profile elements, a cut-off λc value of 0.08 mm was used to filter the profiles. Ten values of the profile roughness, at different randomized locations along the sampled length, were taken and their means and standard deviations wereassessed.

The surface scans of the slot bottoms can beseen inFig. 3 that compare pictures acquired using the SEM and the profiler. When using the four-fluted tool it was evident that the feed per tooth affectedthe surface topography more than the magnitude of the speed (except of the results for cutting speed 58 m/min). It is evident that the lowest values of the feeds affected the surface significantly; the increasing feeds per toothhelped to make the surfacetracks smoothly. In the case of four-fluted tool and cutting speed of 58 m/min, the SEM pictures clearly confirm that the machined surface was strongly deteriorated by some unexpected tool vibrations. The profile roughness (Fig. 4)turned out to be a function of the cutting conditions.If the data for the lowest cutting speed of the four-fluted tool are excluded, the other results were in agreement with the available literature data [9]. When adopting the lowest feed per tooth, the profile roughness was quite high, as a consequence of the ploughing regime that prevails over shearing one. It is due to the fact that the material is mainly plastically deformed rather than cut, as the criterion of the minimum uncut chip thickness was not respected [4,10].

Regarding the four-fluted tool and the lowest cutting speed, the surfaces were perturbed by vibrations and, therefore, also the profile roughness value was much higher, as can be seen in Fig. 5. Anyway, the roughness value for the lowest feed per tooth was lower than expected, whatwas on contrary to the previous effect of ploughing phenomenon. More investigations are needed to understand this peculiar behaviour.

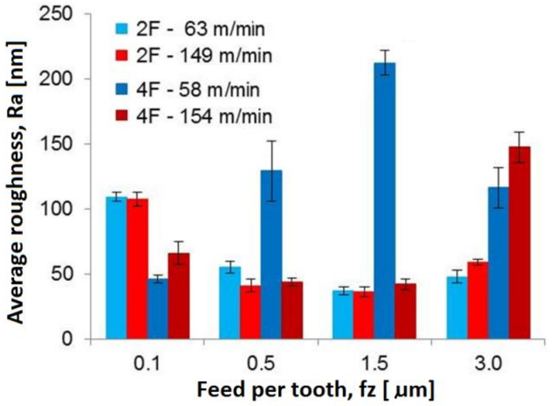

Figure 4. Average roughness as function of the cutting conditions (2F: two-fluted tool; 4F: four-fluted tool)

3.2. Burrs analysis

The burrs represent unwanted protrusions of material during the machining process due to passive loading and may affect the part required properties [11]. Moreover, in micromachining burr formation is one of the main limiting factors, as their dimensions are comparable to those of the machined workpieces failing the capability to meet the part desired geometry and tolerances [12–14].

In this work, the burrs were qualitatively analyzed using the SEM. The burrs formed at the top surface of the micro-milled slots can be seen in Fig. 5. The reported images show that there are significant differences in the burrs shape and size as function of the tested cutting conditions. There is an evident influence of the feed per tooth, because incensements of the feed per tooth cause that the burrs are consequently minimized,regardless the geometry of the tool. On the contrary, the effect of the cutting speed in the milling was observed as a minor factor. On the other hand, the differences of the burrs amount when using the two different tools can be highlighted.The extent of burrs when milling with the four-fluted tool was lower,especially for the lowest values of the feed per tooth, comparing to the results for two-fluted tool.

3.3. Surface defects

In order to evaluate the surface integrity the surface defects were evaluated - Fig. 6. For the lowest value of the feed per tooth, due to the prevailing ploughing phenomenon, the surface is highly deteriorated and different types of defects (side flow of workpiece material, released particles from built-up edges, pores) are superimposed together. At increasing the feed per tooth, mainly chips debris and some smeared material can be found, especially for the highest value of the feed per tooth.

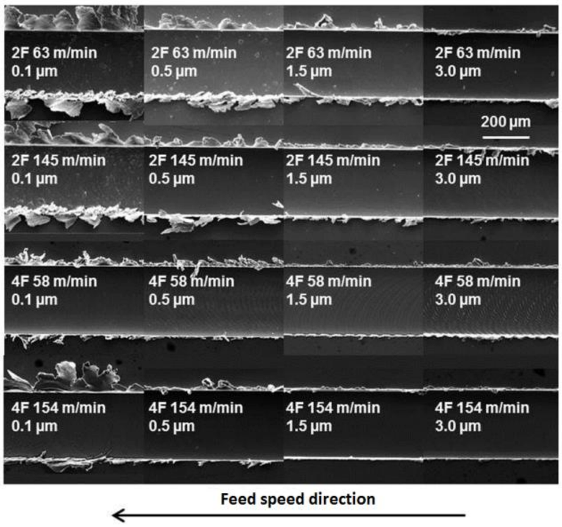

Figure 5. SEM analysis of the burrs (2F: tow-fluted tool; 4F: four-fluted tool, cutting speed, feed per tooth)

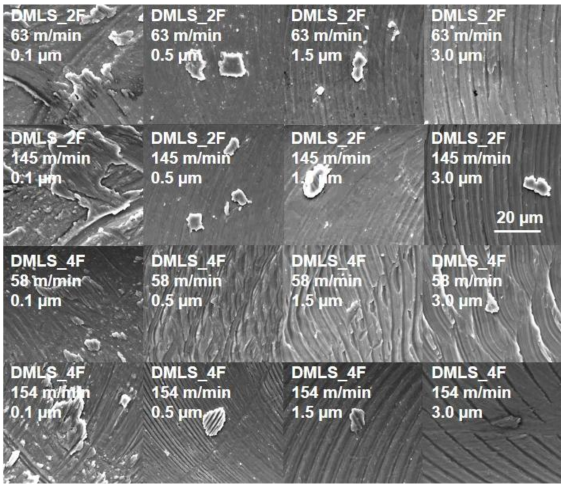

Figure 6. Surface defects at the slot bottom (2F: two-fluted tool; 4F: four-fluted tool, cutting speed, feed per tooth)

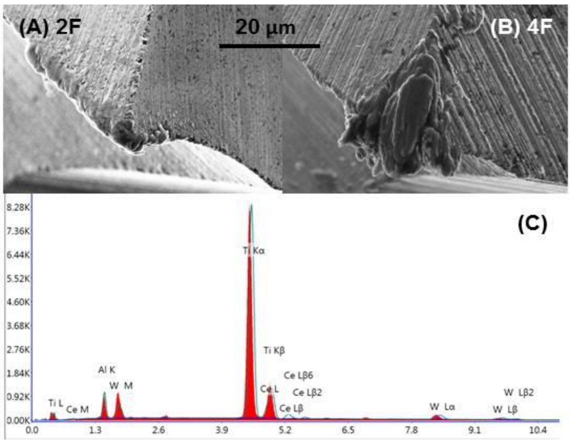

Figure 7. Adhesion of the workpiece material to the cutting edge, EDS spot analysis confirming the workpiece material

3.4. Tool wear

All the tools were inspected before and after the micro-milling experiments in order evaluate their wear. After the testing, the adhesion of the workpiece material as built-up-edge to the tool has beenfoundand cutting edge micro-chipping also. A comparison of the two-flute and the four-flutetools after machining at the lowest cutting speed and intermediate feed per tooth (1.5 µm) can be seen in Fig. 7: the material adhesion to the cutting edge is evident, as proved with the EDS analysis, regardless of the tool geometry. Plastic deformation of the tips, abrasive wear and built-up-edgescreated preferably anchoring at the worn places have been found.

4 CONCLUSIONS

The cutting performances of two-fluted and four-fluted flat square end micro-mills when machining of DMLS Ti6Al4V have been evaluated in this work.

The two-fluted milling tool produced a better quality and more consistent results than the four-fluted tool. However, the feed per tooth has been found as the most important cutting parameter affecting the machined surface roughness and burr formation.Astrong effect ofthe tool vibrations on the machined surface was found also due to use of higher cutting speeds (149-154 m/min).

The lowest feed per tooth (0.1µm) produced large and discontinuous burrs on both sides of the slots for both tools due to side flow of material, while the surface machined at the highest feeds (3 µm)appeared almost burrs free. However, the four-fluted tool produced certainvolume of burrs also; mostly at the lowest feed per tooth than the two-fluted tool.

The tool wear was characterized mainly by the adhesion of the workpiece material to the tool edges andproduction of built-up-edges. This observation was found at both milling tools, just the extent of the adhered material seemed to be slightly more evidentat the two-fluted tool.

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REFERENCES

[Aramcharoen 2009] Aramcharoen, A., Mativenga, P. T. Size effect and tool geometry in micromilling of tool steel. Precis Eng 2009;33:402–7. doi:10.1016/j.precisioneng.2008.11.002.

[Aurich 2009] Aurich, J. C. et al. Burrs—Analysis, control and removal. CIRP Ann - Manuf Technol 2009;58:519–42. doi:10.1016/j.cirp.2009.09.004.

[Câmara 2012] Câmara, M. A. et al. State of the Art on Micromilling of Materials, a Review. J Mater SciTechnol 2012;28:673–85. doi:10.1016/S1005-0302(12)60115-7.

[Cheng 2013] Cheng, K., Dehong, H. Micro cutting: fundamentals and applications. New York: John Wiley & Sons, 2013,185-221.

[Facchini 2010] Facchini, L. et al. Ductility of a Ti-6Al-4V alloy produced by selective laser melting of prealloyed powders. Rapid Prototyp J 2010;16:450–9. doi:10.1108/13552541011083371.

[Filiz 2007]Filiz, S. et al. An experimental investigation of micro-machinability of copper 101 using tungsten carbide micro-endmills.Int J Mach Tools Manuf 2007;47:1088 100. doi:10.1016/j.ijmachtools.2006.09.024.

[Li 2011] Li, P. et al. Design of micro square endmills for hard milling applications. Int. J. Adv. Manuf.Technol 2011, 60:9-12. doi:10.1007/s00170-011-3330-6.

[Masuzawa 2000] Masuzawa, T. State of the Art of Micromachining, CIRP Ann. - Manuf. Technol., vol. 49, no. 2, pp. 473–488, 2000.

[Mian 2010] Mian, A. J, Driver, N., Mativenga, P. T. A comparative study of material phase effects on micro machinability of multiphase materials. Int J AdvManufTechnol 2010;50:163–74. doi:10.1007/s00170 009-2506-9.

[Murr 2009] Murr, L. E. et al. Microstructure and mechanical behavior of Ti-6Al-4V produced by rapid-layer manufacturing, for biomedical applications., J. Mech. Behav. Biomed.Mater., vol. 2, no. 1, pp. 20–32, Jan. 2009.

[Özel 2011] Özel, T. et al.. Experiments and finite element simulations on micro-milling of Ti–6Al–4V alloy with uncoated and cBN coated micro-tools. CIRP Ann – ManufTechnol 2011;60:85–8. doi:10.1016/j.cirp.2011.03.087.

[Thepsonthi 2013] Thepsonthi, T, Özel, T. T. Experimental and finite element simulation based investigations on micro-milling Ti-6Al-4V titanium alloy: Effects of cBN coating on tool wear. J Mater Process Technol 2013;213:532–42. doi:10.1016/j.jmatprotec.2012.11.003.

[Traini 2008] Traini, T. et al. Direct laser metal sintering as a new approach to fabrication of an isoelastic functionally graded material for manufacture of porous titanium dental implants., Dent. Mater., vol. 24, no. 11, pp. 1525–33, Nov. 2008.

[Tsipas 2014] Tsipas, S. A, Gordo, E., Jiménez-Morales, A. Oxidation and corrosion protection by halide treatment of powder metallurgy Ti and Ti6Al4V alloy. Corros. Sci. 2014, 88:263-274 DOI: 10.1016/j.corsci.2014.07.037.

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