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Effect of tool wear on quality in drilling of titanium alloy Ti6Al4V, Part I: Cutting Forces, Burr Formation, Surface Quality and Defects

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Abstract: Titanium's Ti6Al4V, alloy is an important material with a wide range of applications in the aerospace industry. Due to its high strength, machining this material for desired quality at high material removal rate is challenging and may lead to high tool wear rate. As a result, this material may be machined with worn tools and the effects of tool wear on machining quality need to be investigated. In this experimental paper, it is shown how drills of various wear levels affect the cutting forces, surface quality and burr formation. Furthermore, it is shown that high cutting forces and high plastic deformation, along with high temperatures that arise in cutting with worn tools may lead to initiation of microscopic cracks in the workpiece material in proximity of the drilling zone.

1 Introduction

Despite excellent properties, manufacturing products out of titanium alloys is challenging, since thermal, chemical and mechanical properties of these alloys make various processing methods difficult and expensive. In metal cutting, because of chemical reactivity, titanium alloys show weld tendency with tools which can result in chipping and pre-mature tool failure. In addition, low thermal conductivity of titanium causes temperature rise and built-up-edge [1]; furthermore, the tool-chip contact length is considerably shorter in machining of titanium alloys compared to steels and cast irons; this creates a high stress region close to the cutting edge and brings the high temperature zone on the rake face very closer to the cutting edge [2]. Finally, titanium's lower modulus of elasticity - almost half of steels- increases the risk of chatter vibrations during machining.

In applications of titanium alloys, fatigue life is a critical requirement; therefore properties such as surface finish, microstructure, microhardness and residual stresses are considered in surface integrity study of machined titanium parts. The heat generated during cutting combined with low thermal conductivity of the titanium alloys, which restricts heat dissipation, raises the temperature which speeds up diffusion and may cause microstructural modifications and phase transformations [3]. In addition, the large concentrated machining loads, induce plastic deformation, micro-cracking, tearing and residual stresses as surface and sub-surface alterations [3]. The surface integrity is particularly important in drilled holes since the material around a hole already experiences a primary stress concentration due to the existence of the hole in comparison to the bulk material. Because of this stress concentration, several aerospace incidences have occurred due to the cracks that had initiated around fastener holes [4, 5].

Burr formation at the entry and exit of a hole is a common problem in drilling operations. In titanium drilling, burr formation at the drill exit is a major concern; since burrs interfere with the mechanical assembly of parts and can cause jamming and misalignment; furthermore, burrs can reduce fatigue life of components by causing stress concentration at hole edge [5]. The exit burr problems are more critical in drilling of multi-layered metal-composite laminates; in those applications deburring operations may need costly disassembly of laminates [6, 7].

Effects of drill geometry in burr formation in drilling of Ti-6Al-4V are studied by Dornfeld *et al.* [7]; where changing the cutting speed from 6 to 10 m/min, and feed rate from 0.05 to 0.2 mm/rev in wet cutting had slight effect on the thickness and height of the formed burrs; while point geometry of the drill significantly affected the burr height and thickness.

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Cantero *et al.* [8] studied different cutting strategies affecting the tool temperature in dry drilling of Ti6Al4V with TiN coated fine grain straight carbide grades and noted important changes detected by microhardness measurements and SEM-EDS analysis that pointed to microstructural changes while having limited tool wear and high hole quality in terms of dimensions, surface roughness and burr height.

In this paper, the effect of varying levels of tool wear on burrs and surface quality is studied. Since rubbing of the worn tool flank and rounded cutting edge increases friction force and frictional heat generation, which in turn leads to higher temperatures and faster wear; a cutting force measurement is performed to provide an understanding of machining energy consumed at different levels of tool wear. Furthermore, the cutting forces could be used as reliable indicators for monitoring tool wear; therefore it is important to evaluate sensitivity of cutting forces and torques to wear to setup proper thresholds for monitoring systems.

So far an overview of effects of tool wear on burr formation and defects has been given. In section 2, the experimental setup to investigate the effects of tool wear is presented, and in section 3, the results in terms of cutting forces, burr morphology and internal cracks are presented. The effects of tool wear on subsurface grain structure and hardness will be presented in the second part of this paper.

2 Experimental method and material

The material used for the experiment was α-β titanium alloy, Ti6AL4V (ASTM grade 5 titanium). Three separate rectangular plates, 120 mm (L) × 72 mm (W), with a thickness of 3.15 mm were prepared for horizontal cutting (HC), vertical cutting (VC) and vertical dry cutting (VDC) respectively. Distance between hole-centers was 11 mm, and a machined steel backing plate with a grid of 9 mm holes was used behind the titanium plates to prevent buckling of titanium plates due to large axial drilling forces. Uncoated solid carbide twist drills (SECO SD29-8.0-312244-T EDP 00000) with artificially created wear levels ranging from 0.0 mm flank wear (new tool) to 1.0 mm flank wear (extremely worn tool), at the interval of 0.2 mm were used in this experiment.

The experiments were conducted in two different conditions. In HC and VC series, high pressure cutting fluid is supplied through the flank face of the drill to the cutting zone, with a cutting speed of 35 m/min at the drill periphery. The difference between HC and VC series is the configuration of the five axis machine tool performing the cutting and the slight difference in cutting fluid and chip evacuation due to the gravity. In the second condition, VDC (Vertical Dry Cutting), dry drilling was performed with lower cutting speed of 20 m/min at the drill periphery. The feed per tooth is kept 0.05 mm for all cutting conditions and all cutting parameters are listed in Table 1. Drilling at each condition is repeated at least seven times with each tool wear level. Cutting forces are measured with a Kistler 9255B type dynamometer. Furthermore, a spindle power sensor was used for indirect inductive power measurement of the power consumed in spindle's motor.

Table 1: Cutting parameters

	HC and VC	VDC
Cutting speed (m/min)	35	20
Feed per tooth (mm/tooth)	0.05	
Spindle speed (rev/min)	1393	796
Cooling method	Coolant Cimcool Cimtech A32, 7%	Dry cutting

2.1 Measurement

Six tools were ground in such a way to represent flank wear of 0, 0.2, 0.4, 0.6, 0.8 and 1.0, wear level 0 indicating an intact tool at the corner of the cutting edge (Figure 1), representing the predominant wear form of carbide tools in drilling of titanium alloys, where the corner wear is significant due to higher speed at the periphery of the drill in comparison to the inner sections of the drill's edge. Other parts of the cutting geometry such as tool center point are presented in Figure 2.

3 Results

In this section cutting forces, the burr formation at the entry and exit and surface condition at different wear levels in wet and dry conditions are presented.

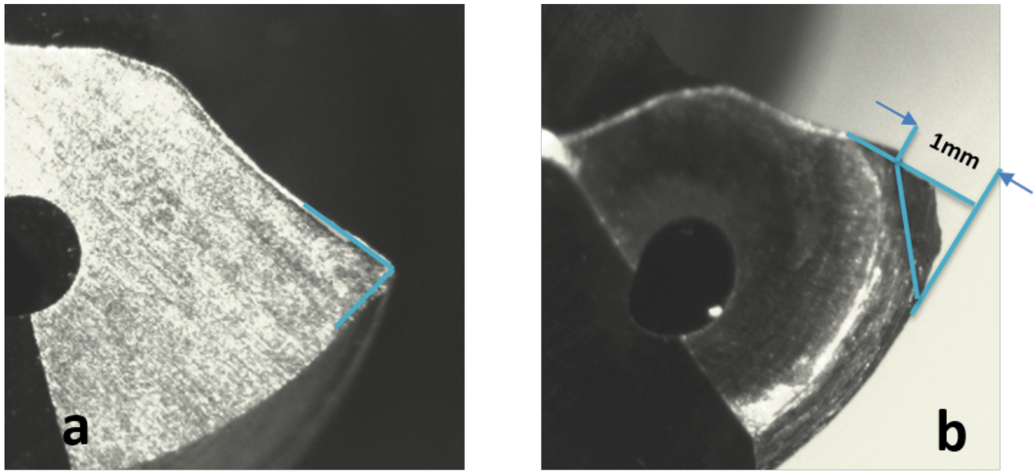

Figure 1: Tool wear measurement at the cutting lip: a) new tool with no wear with level 0.0, b) worn tool with wear level 1.0 mm

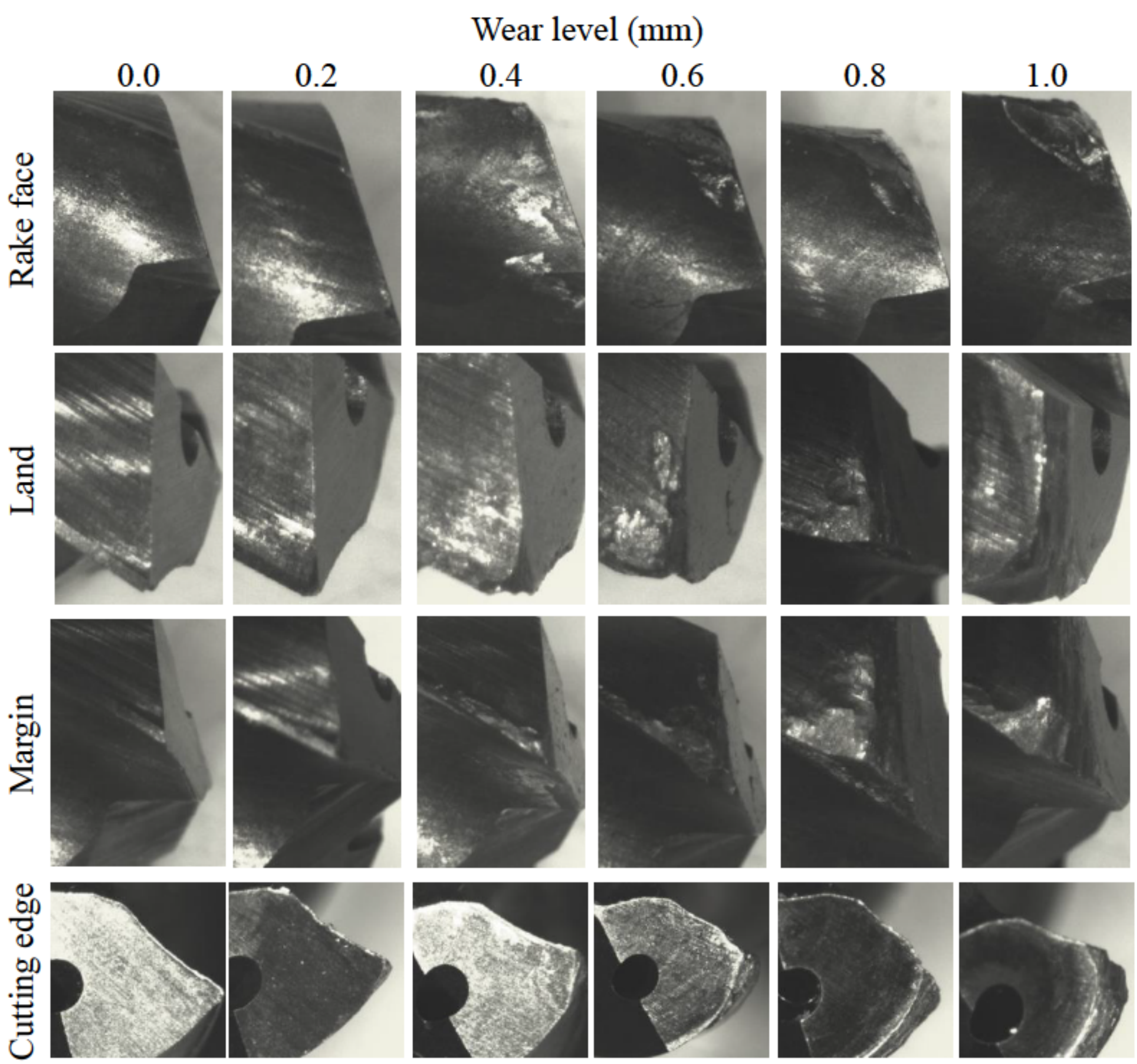

Figure 2: Tool geometry for different wear levels

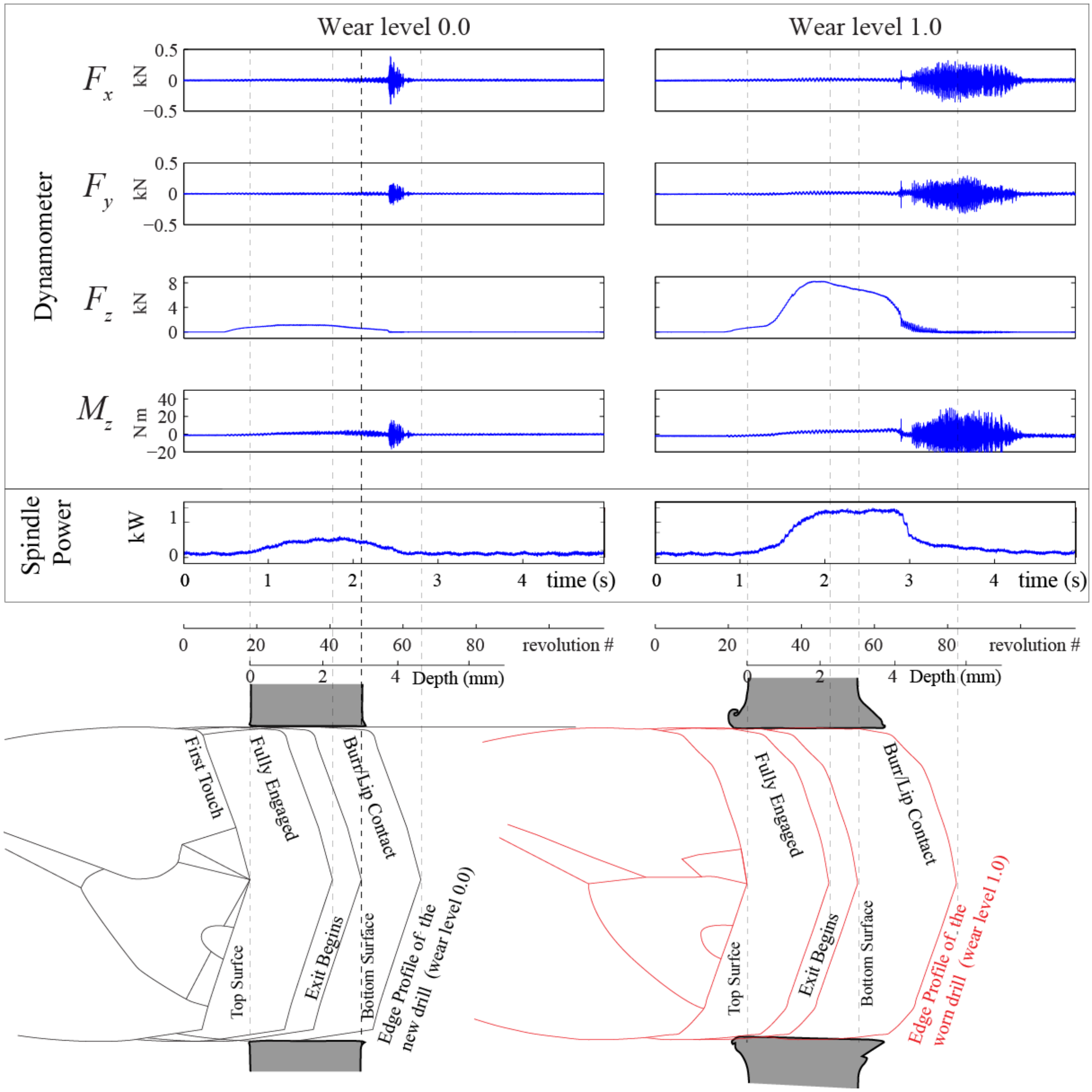

Figure 3: Raw measurements in VC condition for the new drill (wear level 0) and highly worn drill (wear level 1.0)

3.1 Cutting Forces

Cutting forces in axial (F_z) and lateral (F_x, F_y) directions, along with cutting torque (M_z), measured by the table dynamometer are shown in Figure 3. The spindle power, measured by the spindle power sensor mounted around the electric power supply cables of the spindle is also included in Figure 3. Lateral forces F_x and F_y originate from imperfections of the twist drill and are rather small and only become notable during the exit of the drill through the hole when the drill's margin hits the burrs. These burrs, as will be shown in following section, are longer with worn drills; therefore this phase is more notable for the worn drill. The axial forces for the new and worn drills are similar in the beginning of the cut, until the cutting extends outside of the tip regions of the drills (which are rather identical for new and worn drills, and reaches close to the worn corner region of the drill, where a very large axial force, close to 8 kN is needed to sustain the feed rate of the tool. the increase of spindle power and torque are small compared to the axial force and only in the torque measured by the dynamometer one can note a large amplitude oscillation in the burr-contact region.

Figure 4 summarizes the changes in the peak to peak values of the force and power measurements for all cut-

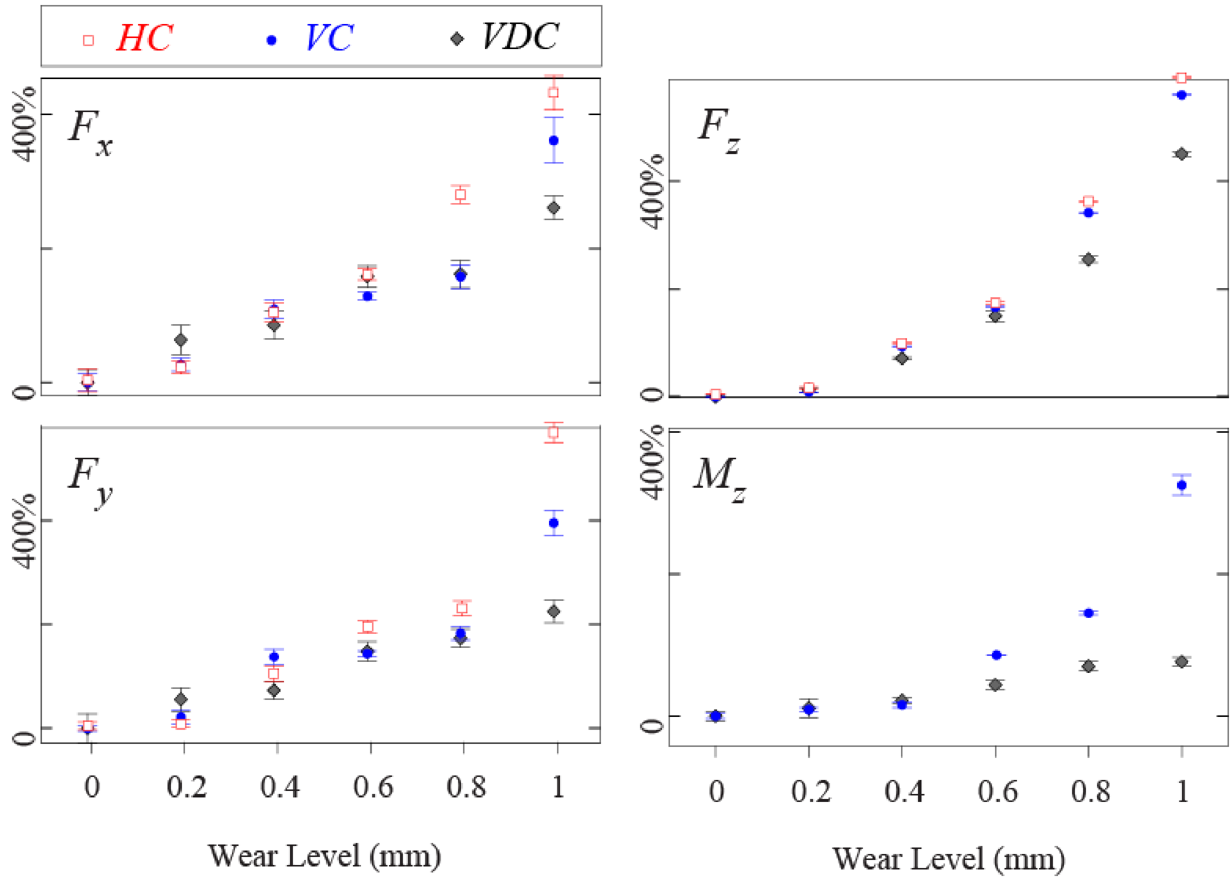

Figure 4: Changes in the peak to peak value of the cutting force and torque signals for various tool wear levels compared to the average of the new tool

ting conditions, versus the average peak to peak values of those measurements for new tools, which shows increasing of these measurements, up to 400%. Parameters such as axial force, also have a very small standard deviation, across repeated drilling tests.

3.2 Burr morphology

Rolled back burrs, similar to those in Figure 5a-5c, are observed at the hole entry for both dry and wet cutting conditions. As the wear level increases, the the tip of the burr rolls back more and the profile becomes curlier and wider for all cutting conditions. The burr formed at exit has a different form and it is outside shape is similar to a cone attached to a cylinder. The length of exit burr increases too as the wear level increases as shown in Figure 5. At the hole exit, burr is more uniform, comparatively thinner but longer. In dry cutting (VDC), when the wear level of the tool ranges from 0.6 to 1.0 mm (see Figure 5f), the burr is long and it is formed by the shape of the backing plate used in the drilling experiments, as if the hot workpiece material is formed around the larger hole in the steel backing plate.

Burr height is selected as a simple variable for quantification of burr geometry. Figure 6 shows evolution of burr height versus tool wear in HC, VC and VDC conditions at the drill entry and drill exit. In general, burr height increases with the increase of tool wear due to the higher temperature and higher forces in drilling. Furthermore, burr height at the drill exit is higher compared to the drill entry for almost all of the samples.

The height of the burr at the drill entry is almost same for all cutting conditions (VC, HC and VDC); in contrast, at the drill exit, this height is considerably larger for the dry condition.

The formation of exist-burr is explained by the fact that at exit, after the initial rupture of the surface by the drill tip, a transition is made from chip formation to burr formation as the remaining material is pushed to the sides of the hole, rather than being cut. High wear level increase cutting forces and power input (as shown in the previous section) and generates more heat, leading to higher work-

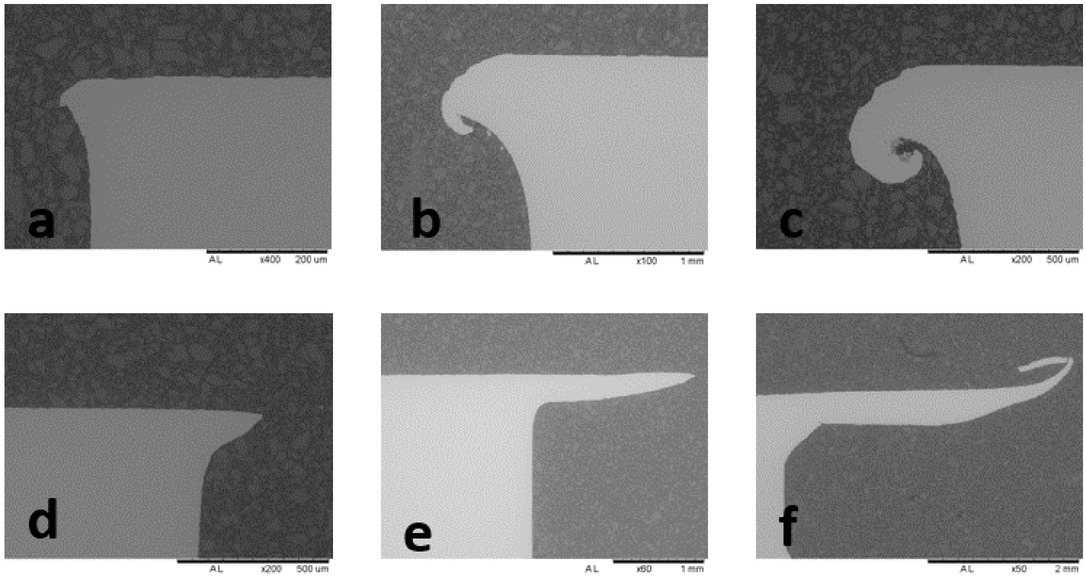

Figure 5: Burr formation at hole entry (top row) and hole exit (bottom row) for VDC with tool wear from 0.2 (a and d) to 0.4 (b and e) to 0.8 (c and f). Feed direction is from left to right

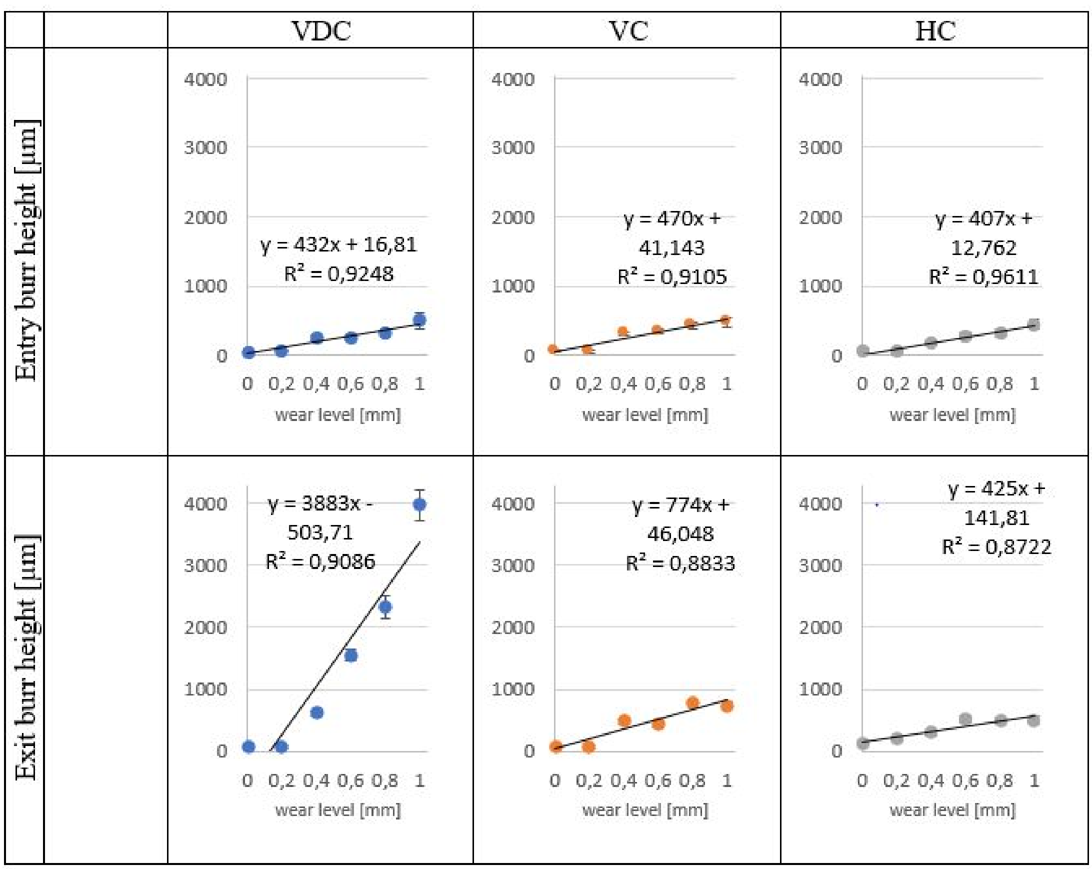

Figure 6: Burr height versus tool wear at hole entry and hole exit for dry (VDC) and wet (VC and HC) conditions

piece temperature in the cutting zone which softens the material ahead of the drill [9]. Moreover, larger axial forces with worn drills, as shown in the previous section cause large plastic deformation at drill entry and exit where

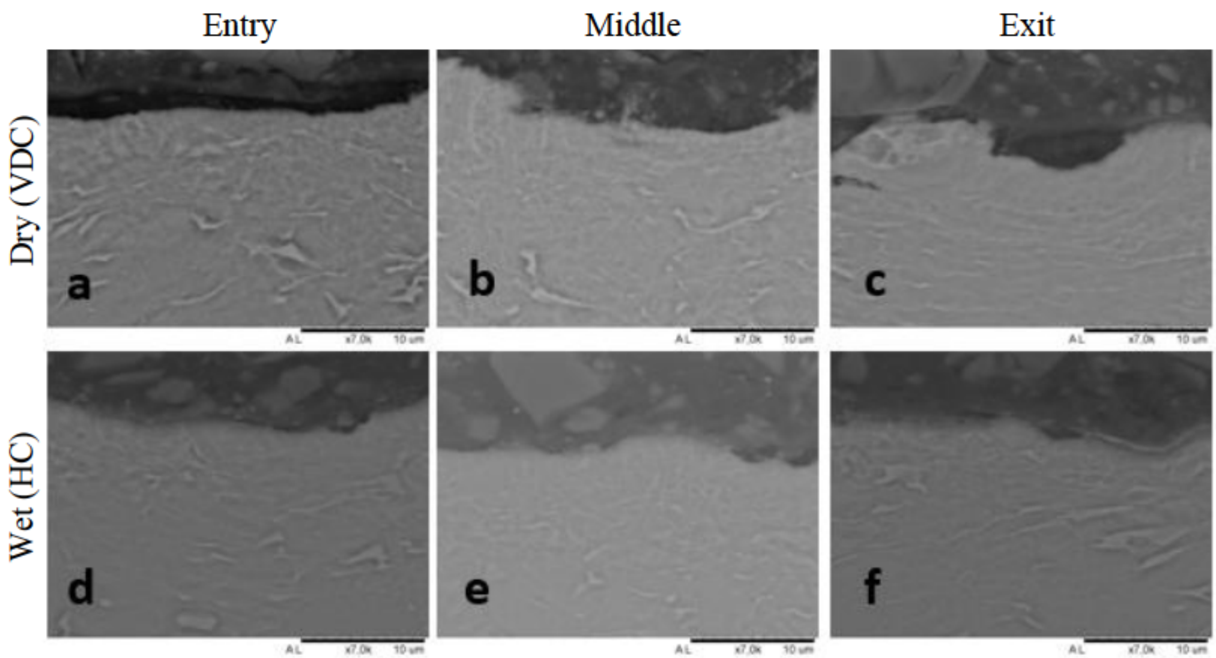

Figure 7: SEM micrograph of surface defects at ×7000 magnification for VDC and HC with 0.4 wear level: a, b and c correspond to hole entry, middle and hole exit for VDC; and d, e and f for the HC respectively

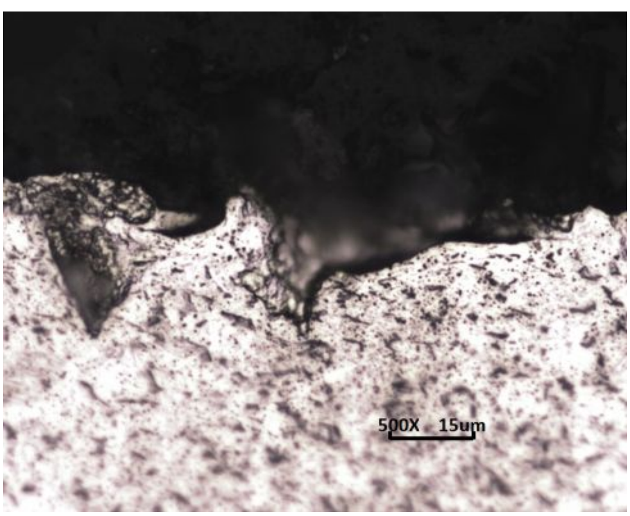

Figure 8: a defective surface for dry cutting using tool wear level 0.8 mm

workpiece material is unsupported, and results in notable burr height. These phenomena are more pronounced in dry drilling, which lead to considerably large exit burrs, as shown in Figure 6.

3.3 Surface quality

Smoothness of the machined surface is investigated qualitatively by study of metallographic samples and interface between the workpiece and Bakelite with 7000× magnification. With dry cutting the roughness increases considerably (Figure 7). Very defective surfaces are noticed for dry cutting at the tool wear levels 0.8 and 1.0 mm. As an example, Figure 8 shows a rough cross section from drilling with worn tool (wear level 0.8) in dry cutting condition.

3.4 Internal Cracks

In dry cutting, fractures are also observed at the hole exit when tool wear level exceeded 0.8 (Figure 9). Excessive plastic deformation due to large axial force and torsion, along with decreased strength of the base material at high temperatures is considered the source of tearing of the machined layer, as damaged tool flank rubs against the workpiece and softens it. The drilling with a worn tool, in a mechanism similar to a friction-stir-welding process creates considerable plastic deformation; both in the axial direction (as evidenced by the orientation of the grains), and also in the tangential directions. When plastic deformations become larger than the ultimate plasticity of the material, cracks are initiated and grown as evidenced in Figure 9. These fractures are found to be initiated from the exit burrs, which points to the importance of burr removal and hole exist chamfering or filleting to remove such defects, in addition to careful prevention of drilling with worn tools.

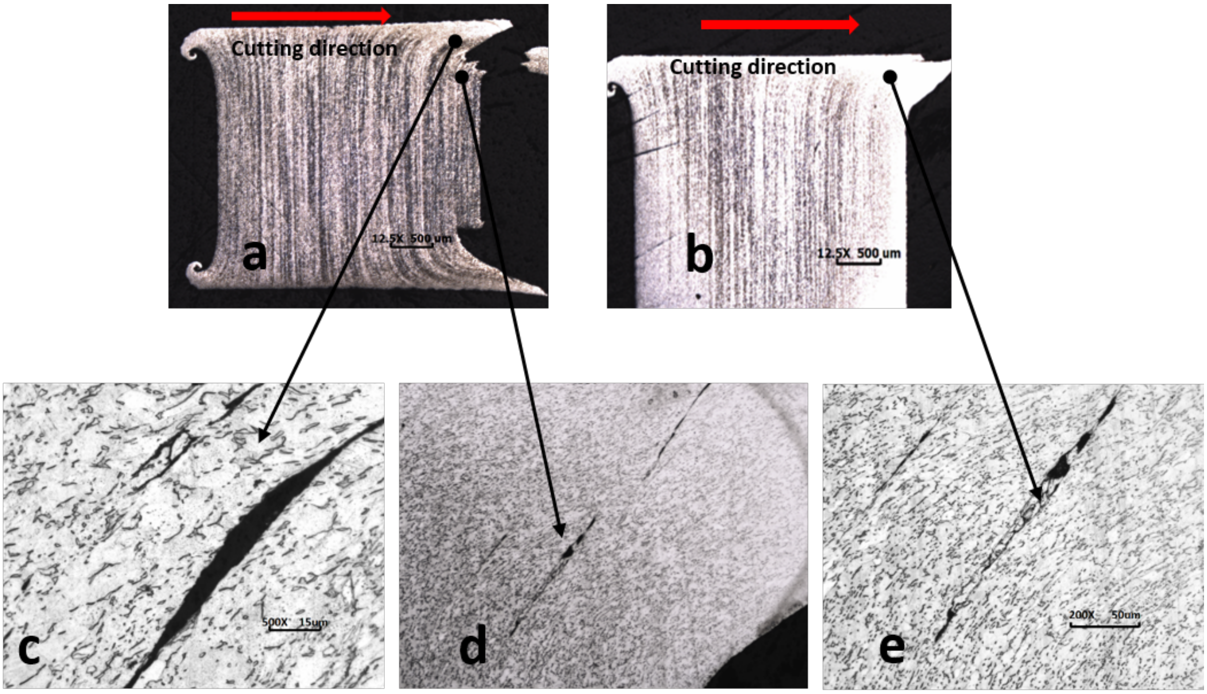

Figure 9: Fracture and tearing of the surface observed at the hole exit for VDC produced by tool wear level 0.8 mm (a) and 1.0 mm (b)

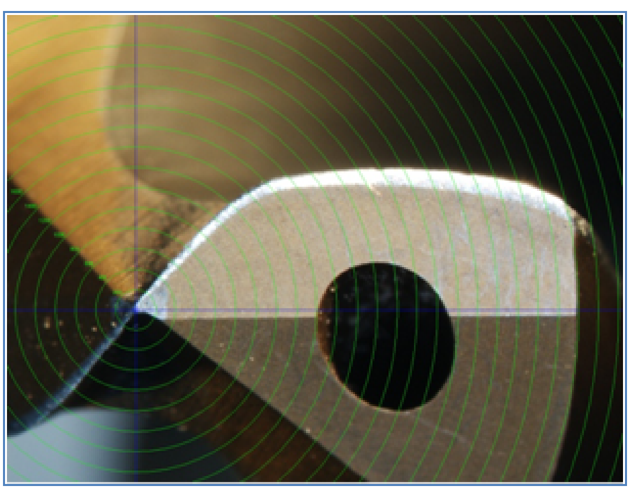

Figure 10: Wear pattern of a drill bit in the radial direction

4 Discussions

In this section we discuss several critical issues related this work, which are not apparent in the presented results.

First, the measurement of forces, Fx and Fy, is still important even theoretically they sum to be zero during drilling. This is because in a practical drilling operation, there is never a complete balance between the lateral forces. There is always some level of "wander" behavior of the tool, in particular in the early stages before the full depth of cut has been reached. This paper is investigating the possible methods of measuring and predicting hole quality and therefore, it was assumed that there might be some correlation between the forces in the plane (the lateral forces) and the hole quality in terms of, among others, "burr formation".

Secondly, the actual wear phenomenon in drilling is quite complicated, without showing a uniform wear pattern on the cutting edge of the drill bit. It is known that **the real tool deterioration** (wear progression) is different from the emulated wear lands, used in this investigation at different levels ranging from new to 1,0 mm maximum wear land. In the chart and picture shown in Figures 10 and 11, the wear land as function of radial position from the center of the drill can be seen from a large number of production tools (drills) measured after use under similar conditions. It can be seen that the wear progression is almost linear over large sections of the cutting edge. However, at the periphery of the drill, the wear rate increases and causes the wear land width to occasionally almost reach the 500 micron level (a recommended maximum value ranges from 200 to 300 micron).

Consequently (due to the increased wear on the corner edges), the burr heights at the hole entrance as well as hole exit increases. The impact on part integrity is obvious but needs to be quantified and the consequence needs to be described. Therefore, the need for the method develop-

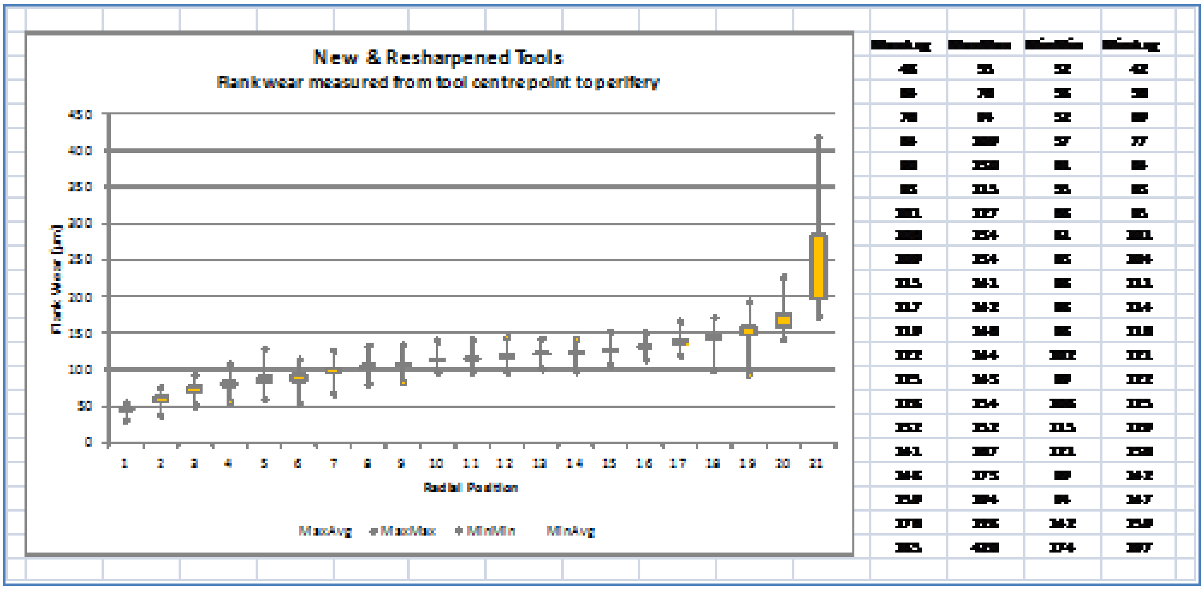

Figure 11: The measured wear versus the radial position, corresponding to Figure 10

ment that led to the pre machined wear levels used as described in this paper. The advantage by such method is to be able to study the impact from tool wear in a repeatable and robust set-up, rather than exactly resemble the real drilling operation. However, with the specific aim to focus on the most important part of the tool with respect to the achieved part integrity and not necessarily add to much attention to the intermediate parts of the cutting edge.

Thirdly, burrs are the reminiscences of plastically formed material that for some reason have not been possible to cut away. Most often due to lack of support structure to maintain high enough forces to be able to rupture the work material rather than bend and deflect from the cutting tool. In drilling there are (at least) two types of burrs, at the entrance of the hole and at its exit. The entrance burr, and its effect on the integrity of the part (hole), is normally mitigated by a traditional bevel or corner rounding process. The exit burr, is however a bit more difficult to address. The same physics apply for the exit burr as for the entrance burr. However with the difference that the tool and consequently the work material is much warmer and thus it is even more difficult for the tool to cut. In particular in the latter phase of the cutting action where the tool is about to break through the work piece it is also much warmer than at the entrance and more easily form artifacts plastically. In particular if chipping occurs, the material close to what will remain as the hole wall will then be extruded in various degrees and subsequently form a burr. Depending on the state of the cutting tool and thermal properties of the work piece material, the burr will reach different heights but more importantly, from an integrity point of view, the radial depth of impact on what remains as the “hole wall” will be different. Thus, the burr not only requires an extra de-burring operation after the hole is machined, but also defines the size of the bevel or corner rounding to be done subsequently. This effect has also been shown in Figure 9 (among all other data).

5 Conclusions

The tool wear has a significant effect on formation of the drilled holes, in terms of cutting forces, burr formation, surface and internal defects.

Trust forces and side forces increase drastically (close to 400%) with worn drills while the cutting torque and power increase in a smaller range of about 70% with worn drills.

Severe plastic deformation of the machined surface is observed at the drill exit of with dry cutting, especially when drilled hole is produced with wear level 0.6 and above. At the initial stages of wear, *i.e.* wear level up to 0.2 mm, deformation is significantly lower and there is little difference between wet and dry conditions. Entry burrs are rolled back but the exit burr is uniform which takes the shape of the backing plate. In dry cutting burr is considerably large at the drill exit when tool wear exceeds 0.4 mm. Surface is more uneven in dry cutting compared to the wet cutting and in dry cutting with wear levels of 0.8 and 1.0 mm both surface tearing and internal cracks are observed.

Future investigations with measurement of the tool and the workpiece temperature during drilling at different radial positions and development of finite element models for reliable prediction of temperature, stress and deformation fields in machining with worn drills can further clarify the nature of damages caused by worn drills.

References

[1] Kalpakjian, S., S.R. Schmid, and C.-W. Kok, Manufacturing processes for engineering materials. 2008: Pearson-Prentice Hall.

[2] Trent, E.M. and P.K. Wright, Metal cutting. 4 ed. 2000, Boston, MA: Butterworth-Heinemann.

[3] Che-Haron, C.H. and A. Jawaid, The effect of machining on surface integrity of titanium alloy Ti–6% Al–4% V. Journal of Materials Processing Technology, 2005. 166(2): p. 188-192.

[4] Wanhill, R., Milestone case histories in aircraft structural integrity. Comprehensive structural integrity (Vols. 1–10, pp. 61–72). Elsevier, 2003.

[5] Davidson, D.A., Surface condition impacts part performance: Burrs, edges can negatively influence function of components. Metal finishing, 2007. 105(2): p. 22-31.

[6] Saunders, L.K.L., A finite element model of exit burrs for drilling of metals. Finite elements in analysis and design, 2003. 40(2): p. 139-158.

[7] Dornfeld, D., et al., Drilling burr formation in titanium alloy, Ti-6AI-4V. CIRP Annals-Manufacturing Technology, 1999. 48(1): p. 73-76.

[8] Cantero, J., et al., Dry drilling of alloy Ti–6Al–4V. International Journal of Machine Tools and Manufacture, 2005. 45(11): p. 1246-1255.

[9] Kundu, S., S. Das, and P.P. Saha, Optimization of drilling parameters to minimize burr by providing back-up support on aluminium alloy. Procedia Engineering, 2014. 97: p. 230-240.