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Effect of tool wear on quality in drilling of titanium alloy Ti6Al4V, Part II: Microstructure and Microhardness

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Abstract: Drilling of Ti6Al4V with worn tools can introduce superficial and easily measured features such as increase of cutting forces, entry and exit burrs and surface quality issues and defects. Such issues were presented in the part I of this paper. In part II, subsurface quality alterations, such as changes of the microstructure and microhardness variation is considered by preparing metallographic sections and measurement, mapping of the depth of grain deformation, and microhardness in these sections. Drastic changes in the microstructure and microhardness were found in sections drilled with drills with large wear lands, particularly in the dry cutting tests. These measurements emphasize the importance of detection of tool wear and ensuring coolant flow in drilling of holes in titanium components.

1 Introduction

The α-β titanium alloy Ti6Al4V is the most commonly used titanium alloy, accountable for over 45-60% of the total titanium production [1]. Since the utilization of titanium alloy is usually associated with the need of great reliability, for instance in the aerospace industry, the surface integrity parameters are critical, as surface defects can act as stress raisers and reduce the fatigue strength [1–4]. Koster and Field, in milling tests on beta rolled Ti6Al4V, showed that peripheral milling with dull end-mills considerably reduces the fatigue strength [5]. They demonstrated that during the various metal machining operations, a wide range of Ti6Al4V fatigue strengths can be achieved because of the alteration induced in the surface of the material and not due to the changes in surface roughness. Residual stresses influence the fatigue performance when the surface roughness R_a is between 2.5 to 5 μm [4].

Subsurface microstructural changes in various machining operations on titanium alloys are discussed by serval researchers. Hughes *et al.* [6] noted the microstructural changes in turning of Ti6Al4V which consisted of deformed boundaries and elongated grains. In drilling of Ti6Al4V connecting rods, Reissig *et al.* [7] also noted subsurface grain deformation. In dry milling of titanium alloy Ti6242S, Ginting and Nouari [8] also observed a deformed layer under the machined surface which they explained by the high cutting pressure at elevated temperatures. They found that the deformation level was increasing linearly with increasing depth of the milled surface which they attributed to the increase in temperature versus depth, due to reduced coolant supply. Ginting and Nouari [8] reported a microhardness value decrease of 8% compared to the bulk material hardness under the machined surface which gradually increased to 8% higher than the bulk material hardness in the subsequent sub-surface. This was explained as a result of the thermal softening and work hardening respectively. In contrast, in finish turning of Ti6Al4V with PCD tools in presence of conventional and high pressure coolant supply, Ezugwu *et al.* [9] noticed minimal or no plastic subsurface grain deformation. They also observed hardened sub-surface thus higher hardness with conventional coolant but a softened sub-surface with high pressure coolant [9].

In addition to the cutting of titanium in presence of coolant, dry cutting condition is investigated considering the excessive temperature rise in dry drilling [10, 11]. Depending on the cutting speed and tool, the cutting temperature can be as high as 1215°C in dry machining [12]. In dry drilling of Ti6Al4V Cantero *et al.* [13] observed increase of hardness up to 420 HV compared to the base hardness of 330 HV and microstructural changes such as the absence of β phase close to the machined surface. They explained this observation by the formation of hard ‘alpha case’ due

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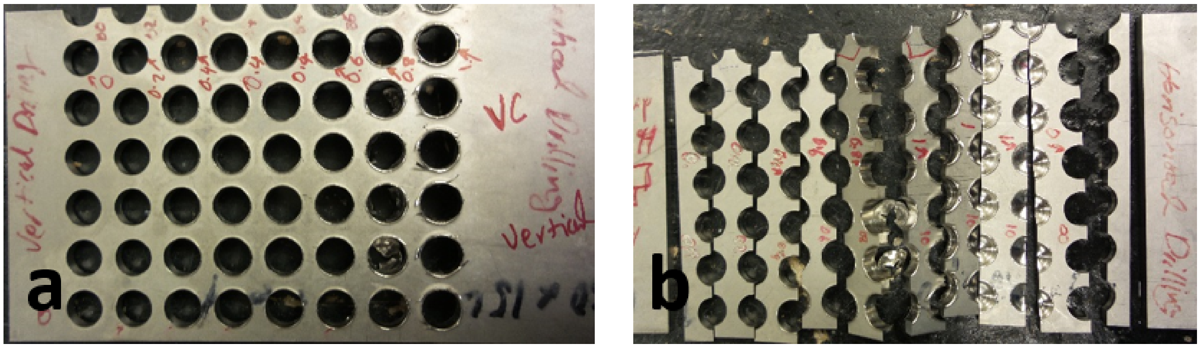

Figure 1: Photographic views of a) drill holes for VC b) after being sectioned of the holes

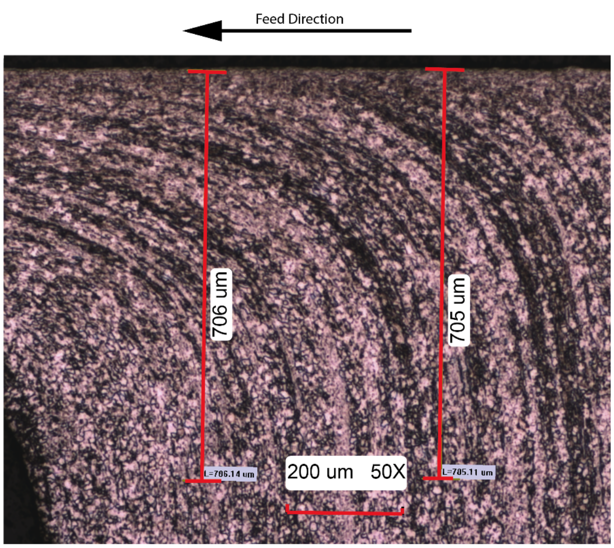

Figure 2: Grain deformation beneath the drilled hole for VDC with wear level 0.8 at the end of the drilled hole showing depth of grain deformation of 706 μm

to heating of the titanium alloy in oxygen or nitrogen rich environment since these elements are known to stabilize the alpha phase [14]. Cantero *et al.* [13] also reported that the hardness value in the drill exit is slightly higher than that of the middle of the hole for the same depth mainly because of the elevated temperature and stress. In end milling of Ti6Al4V with TiAlN coating using cutting fluid, while Sun and Guo [15] did not observe any phase transformation, they noted the deformation and reduction of β phase near the end milled surface with the increased cutting speed. They believed this was caused by thermal and mechanical loads applied to the workpiece during milling. Furthermore, Che-Haron and Jawaid found a very thick deformed layer in the case of a worn tool while turning of Ti6Al4V in dry conditions [16], they also recorded a higher hardness region just beneath the machined surface up to 100 μm associated with the work hardened surface layer [16] and they found a lower subsurface hardness than the bulk material at the distance between 100-200 μm; which was attributed to over-aging of the material.

Subsurface hardness alterations has been also studied by other researchers. Sun and Guo [15] reported an increase of microhardness value in the top layer of 68-80% compared to the bulk material, explained by the strain hardening effect induced by surface deformation and a subsequent layer with lower hardness than the bulk material, explained by surface softening. In contrast, Warren and Guo [17] explained the observed low microhardness value by the 'edge effect' during micro indentation, *i.e.* a measurement technique error, rather than metallurgical or mechanical surface softening. However, Moussaoui *et al.* [18] explained the softened region under the machined surface as a result of diffusion of vanadium from the β phase to α phase.

While the mentioned research sheds light on the effect of cutting conditions on the subsurface properties, the effect of tool wear of various levels and coolant presence in cutting speeds commonly used in industrial applications has not been discussed widely. In this paper the effect of tool wear and application of cutting fluid on micro hardness and micro-structural alterations in drilled holes in Ti6Al4V is systematically studied.

After an overview of the sample preparation, microstructural analysis and measurement protocol in section 2, results in term of microstructure alterations and microhardness alteration are presented in section 3 with discussion and conclusions presented in sections 4 and 5.

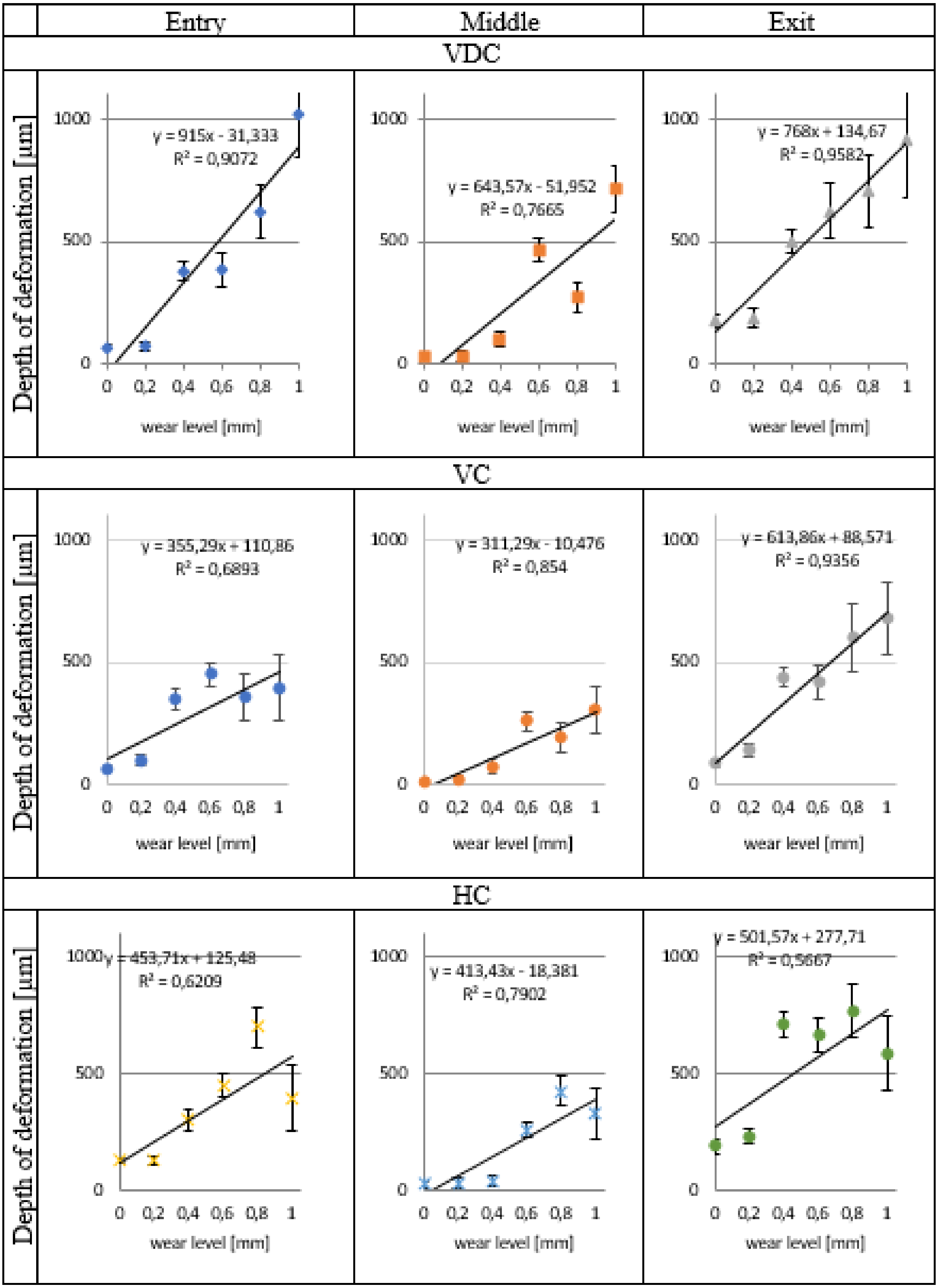

Figure 3: Depth of the deformation under the machined surface at hole entry, middle and hole exit for VDC, HC and VC

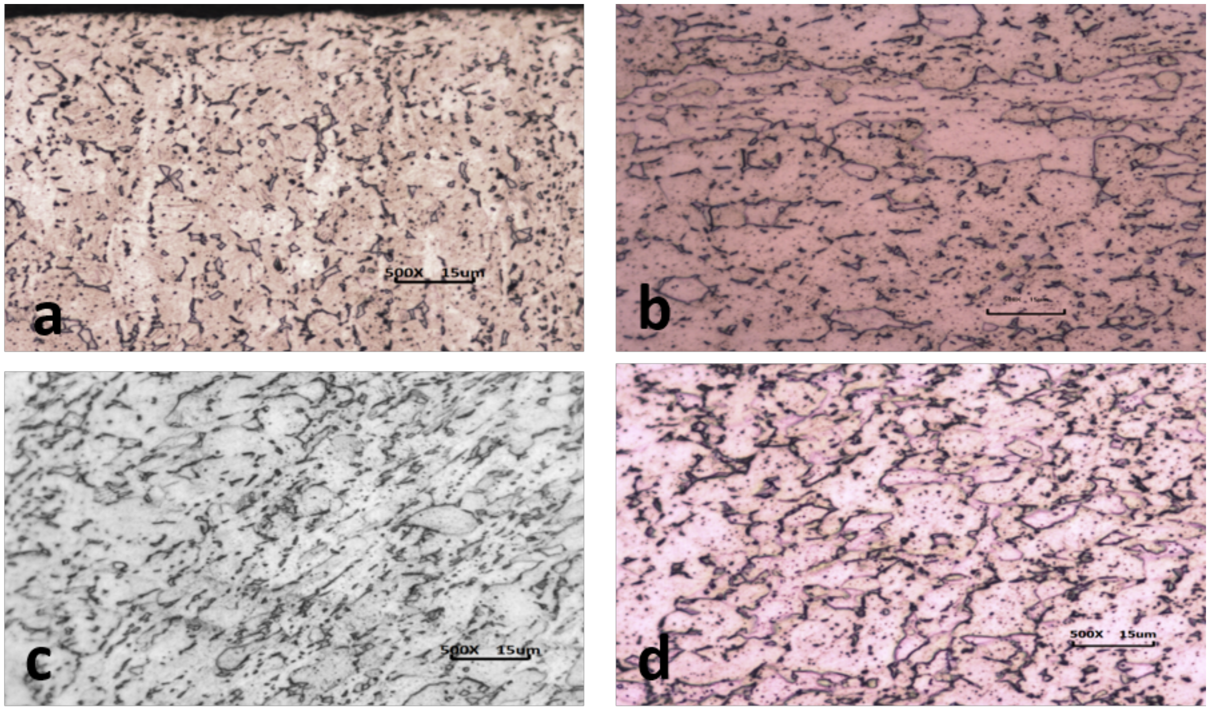

Figure 4: Micrograph showing microstructure at various zones beneath the drilled hole for VC using wear level 0.6 at 500× magnification, a) at hole entry b) middle of the drilled hole c) hole exit and d) bulk

2 Experimental method and material

Details of the workpiece and cutting conditions are presented in the part I of this paper and will not be repeated here, instead an overview of metallographic sample preparation and microstructural analysis is presented.

In order to examine the machined subsurface characteristics, all workpiece plates after drilling (Figure 1a) were cut at planes passing the axis of each hole (Figure 1b) using a precision cutter and cleaned by ultrasonic cleaning before mounting. The specimens were mounted and ground with SiC papers and were polished with diamond compounds and then they were etched for 7-10 seconds with Kroll's reagent prior to the microstructure observation.

Microstructure analysis was carried out using an Olympus BX60M optical microscope and Hardness test was performed on the cross-sectional planes of the drilled holes using a Shimadzu Vickers microhardness tester with a load of 1.961 N (200 gm) and loading time of 15 seconds. In addition, specimens were examined using a Hitachi TM 3000 Scanning Electron Microscope (SEM) and chemical composition was analyzed using an BRUKER Quantax 70 Energy Dispersive Spectrometry (EDS) system to investigate the possible chemical composition changes (if any) of the aluminum (Al) as α stabilizer and vanadium (V) as β stabilizer. Spectra taken from a region beneath the hole surface at the hole entry, middle of the drilled hole and hole exit were compared with those taken from the respective regions far from the machined surface (bulk region).

Depth of the grain deformation was measured quantitatively, using an optical microscope at the hole entry, middle and at hole exit. Microhardness measurements were taken in the radial direction from the machined surface at the hole entry, middle and hole exit.

3 Results

In this section, microstructural alteration and microhardness profile are compared for drilled samples in HC (with coolant, horizontal drilling), VC (with coolant, vertical drilling) and VDC (dry vertical drilling) conditions. Detailed description of these cutting operations are presented in the part I of this paper. Analysis of sub-surface layer, in terms of microstructure alteration, microhardness alteration and chemical composition analysis is presented with respect to the pre-determined wear levels of the tool in following subsections.

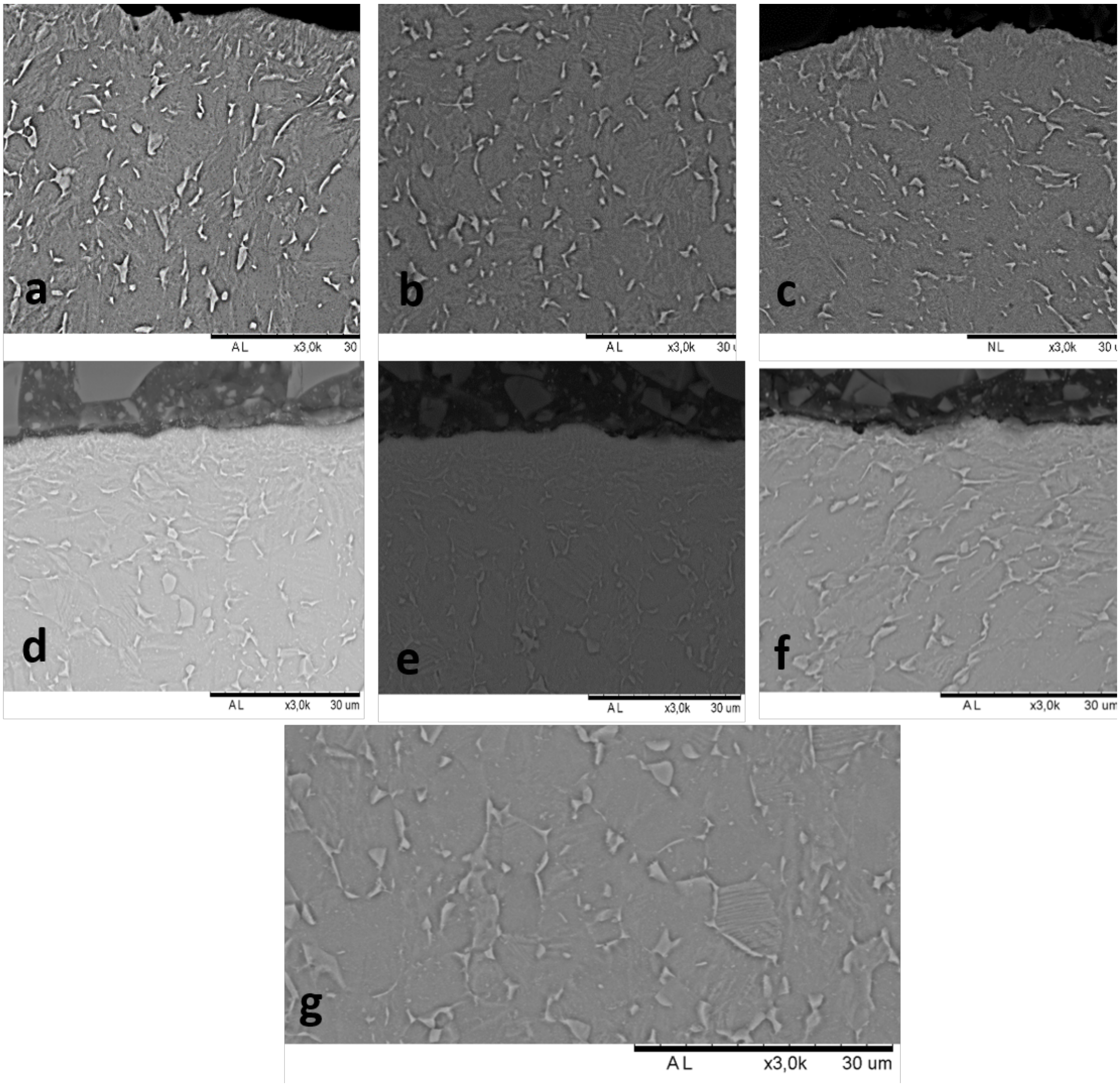

Figure 5: SEM image showing different grain direction and β diffusion at hole entry (a), middle (b), and hole exit (c) for VDC with wear level 0.8 mm; and at hole entry (d), middle (e), and hole exit (f) for VC compared to bulk material (g)

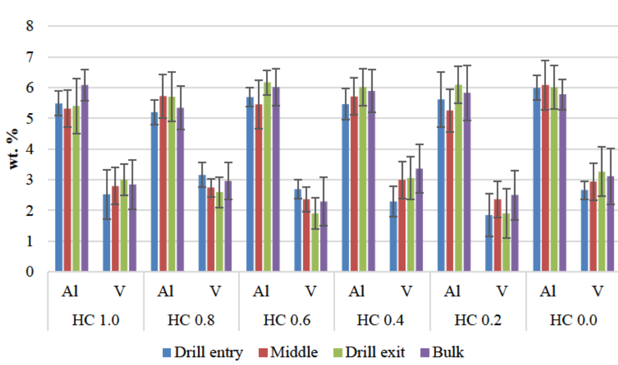

Figure 6: Al and V content hole entry, middle, hole exit and bulk material of the horizontal cutting (HC) with wear levels of 1.0, 0.8, 0.6, 0.4, 0.2 and 0.0 mm

3.1 Microstructure alteration

Depth of plastically deformed layer is selected as the measure of microstructure alteration (see Figure 2). This depth is measured for VDC, HC and VC at hole entry, middle and exit and it is presented in the Figure 3. As this figure shows, the depth of the deformed zone is not uniform along the drilled hole and for the all cutting conditions (VDC, HC and VC), deformation at the hole exit is higher than those of hole entry and middle of the drilled hole.

The differences in deformation depth between hole entry, middle and exit are not significant up to the wear level 0.2 mm. As the wear level exceeds 0.4 mm, deformation depth increases significantly. In case of dry condition (VDC), the deformation depth while using tool with wear

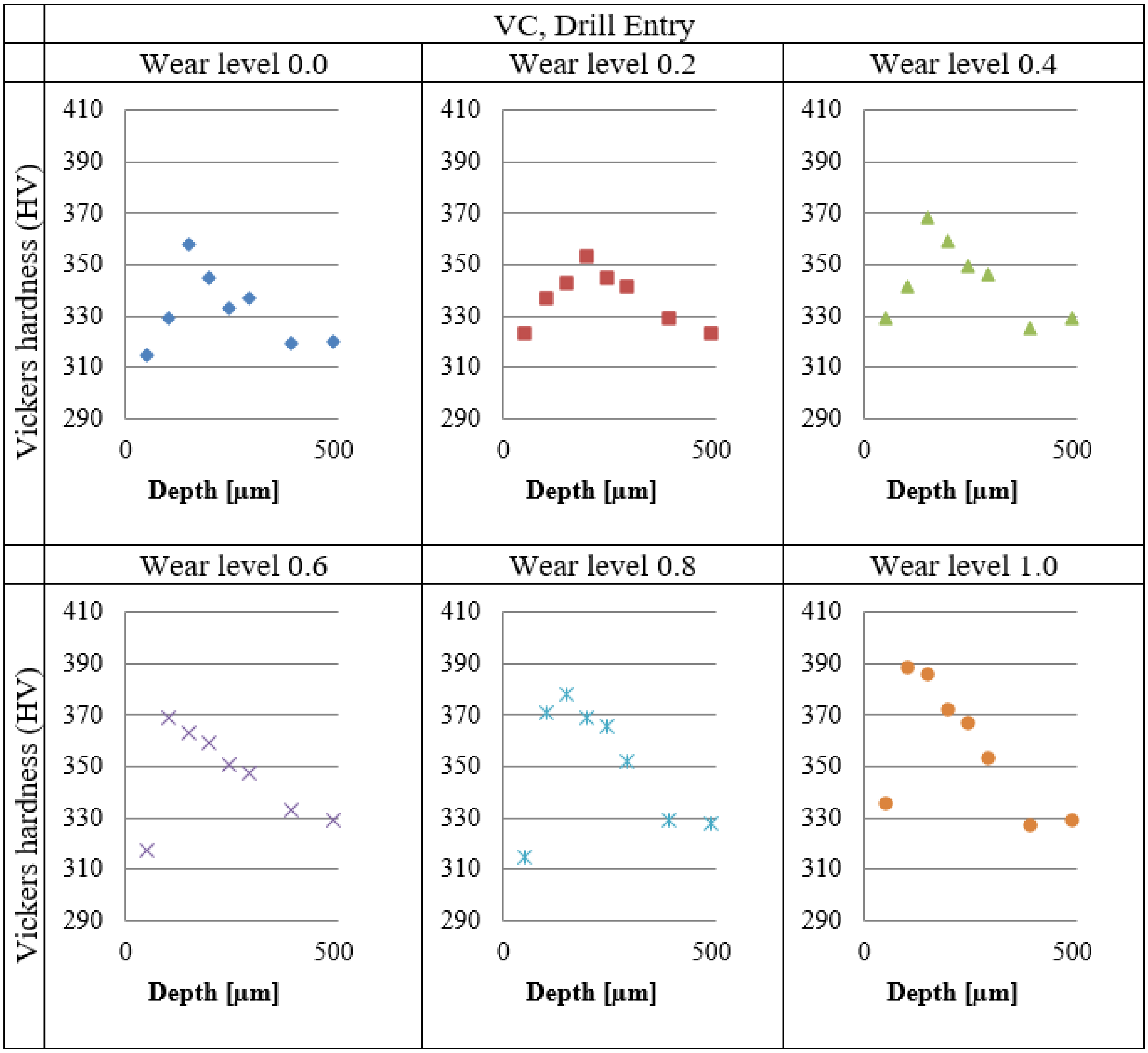

Figure 7: Microhardness at the drill entry for VC

level 1.0 mm is as high as 1.0 mm at hole exit compared to the 0.68 mm for VC and 0.59 mm for HC.

Higher magnification (500×) optical microscope micrographs of the microstructure just beneath the machined surface are presented in Figure 4. In these micrographs, a strong distortion in microstructure is observed at the end of the drilled holes where the grains are oriented in the cutting feed direction.

Figure 5 presents SEM micrographs of the holes machined with drill of wear level 0.8 mm in VDC and VC cutting conditions which shows that the volume of the β phase decreases and even disappears underneath the machined surface at hole exit with this wear level; such transformation however is negligible in case of wet cutting conditions (HC and VC). Furthermore, at drill exit in dry condition, (Figure 5c), the grains of the subsurface layers are elongated towards the cutting direction indicating severe plastic deformation.

To investigate the reasons for reduction of β phase close to the hole surface, aluminum (Al) and vanadium (V) contents are measured at the hole entry, middle of the hole and hole exit using EDS. Two or three points were chosen at each zone and the averaged value is presented just beneath the drilled surface. Al and V contents in the respective bulk material region are also measured. Figure 6 summarizes results of average Al and V content at different zones with error bars for horizontal cutting (HC). No significant differences have been observed between the region close to the machined surface and the bulk material irrespective of the depth of the drilled hole. Furthermore, the

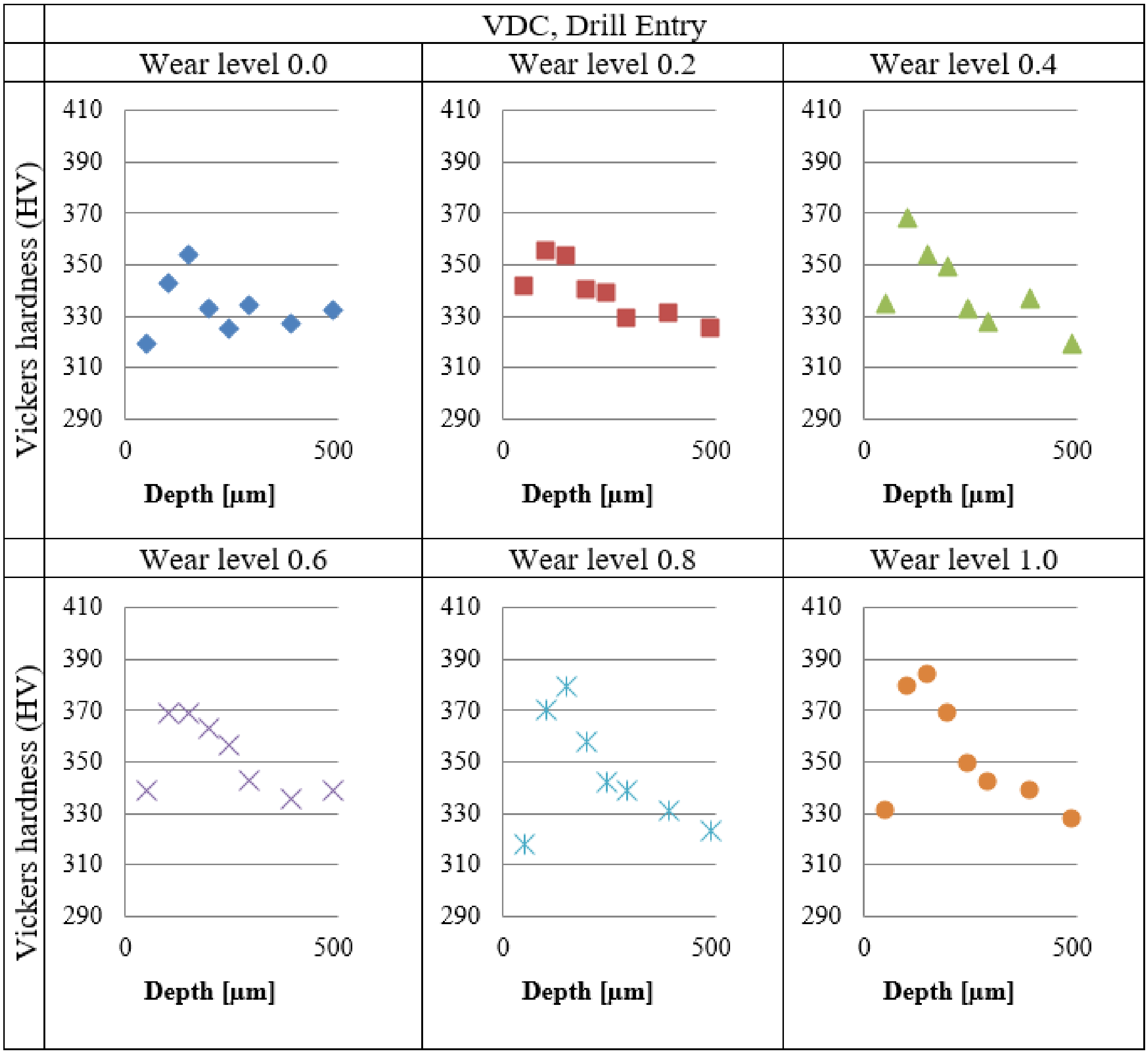

Figure 8: Microhardness at the drill entry for VDC

low vanadium content is probably due to the etching effect as the aluminum and vanadium content of the un-etched samples are slightly higher than etched samples.

3.2 Microhardness alteration

Three different 'zones' are selected and in each 'zone', three different rows with a distance of 50 µm apart from each other are selected for the measurement. A radial depth up to 500 µm is investigated, with 50 µm between the first 6 indentation and 100 µm between the last two indentations. The average result for each depth from the machined surface is recorded and plotted.

The results in terms of microhardness versus the depth beneath the machined surface at the entry, middle and end of the drilled hole for VC and VDC samples produced by tools having different wear levels are depicted in Figures 7-12. Results for HC are excluded for brevity.

Figures 7-12 show an identical trend for all three zones with a lower microhardness value 50 µm from the machined surface, where the microhardness values are even lower than the bulk material, then the microhardness increases at 100-150 µm from the machined surface. Microhardness values lower than the bulk material immediately under the machined surface, are probably due to limited support for the tested material at the edge of the surface, known as 'edge effect' as described by Warren *et al.* [17].

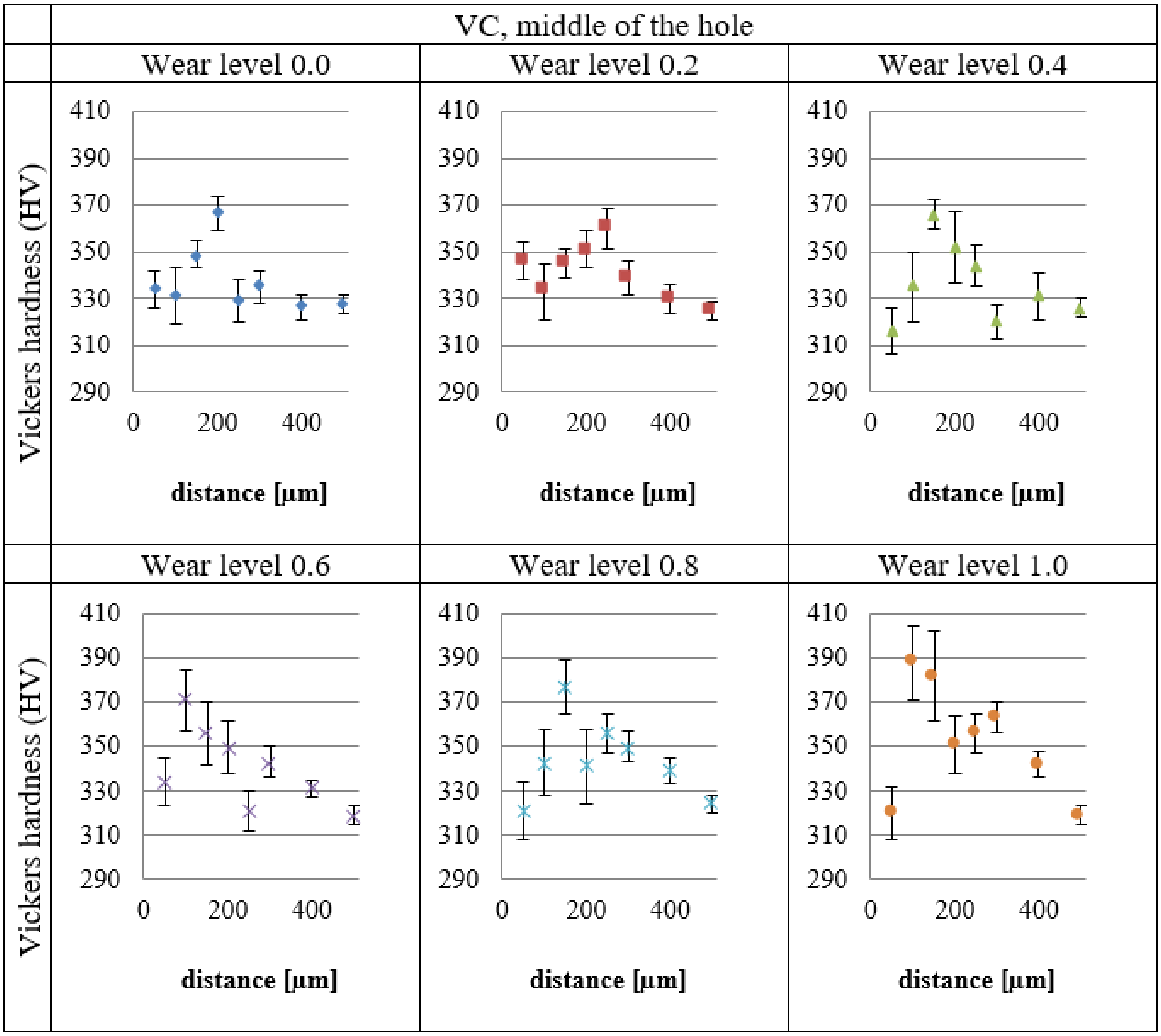

Figure 9: The microhardness value at the middle of the holes (VC)

Only notable difference in hardness between different cutting conditions is the distance at which the hardness is maximum; which varies from sample to sample depending on the cutting condition and tool wear level. As the distance from the machined surface increases further, the hardness reduces and approaches the level of the base material. Again, the distance at which the measured hardness value approaches the hardness of the base material varies greatly depending upon the tool wear and cutting condition.

Microhardness distribution for vertical dry drilling using a tool wear level of 0.4 mm at three different zones is shown in the Figure 13. This shows an identical trend for all three 'zone's with a lower microhardness value at the very beginning, which increases drastically at a depth around 100-150 µm from the machined surface. Vickers hardness values of 368, 384 and 380 are found from a distance respectively 100, 150 and 150 µm for three different zones.

4 Discussion

According to Figure 3, deformation is the lowest in the middle of the drilled hole, in contrast to the result found in [7], where Reissig *et al.* observed a linear increase in deformation, started at the hole entry all the way to the hole exit. This is probably because of the larger volume of the workpiece to which the heat can dissipate and the uniform thrust force in the middle of the hole.

Figure 5 shows the reduction of β phase close to the hole surface. The aluminium and vanadium content are measured and compared to the bulk material close to the

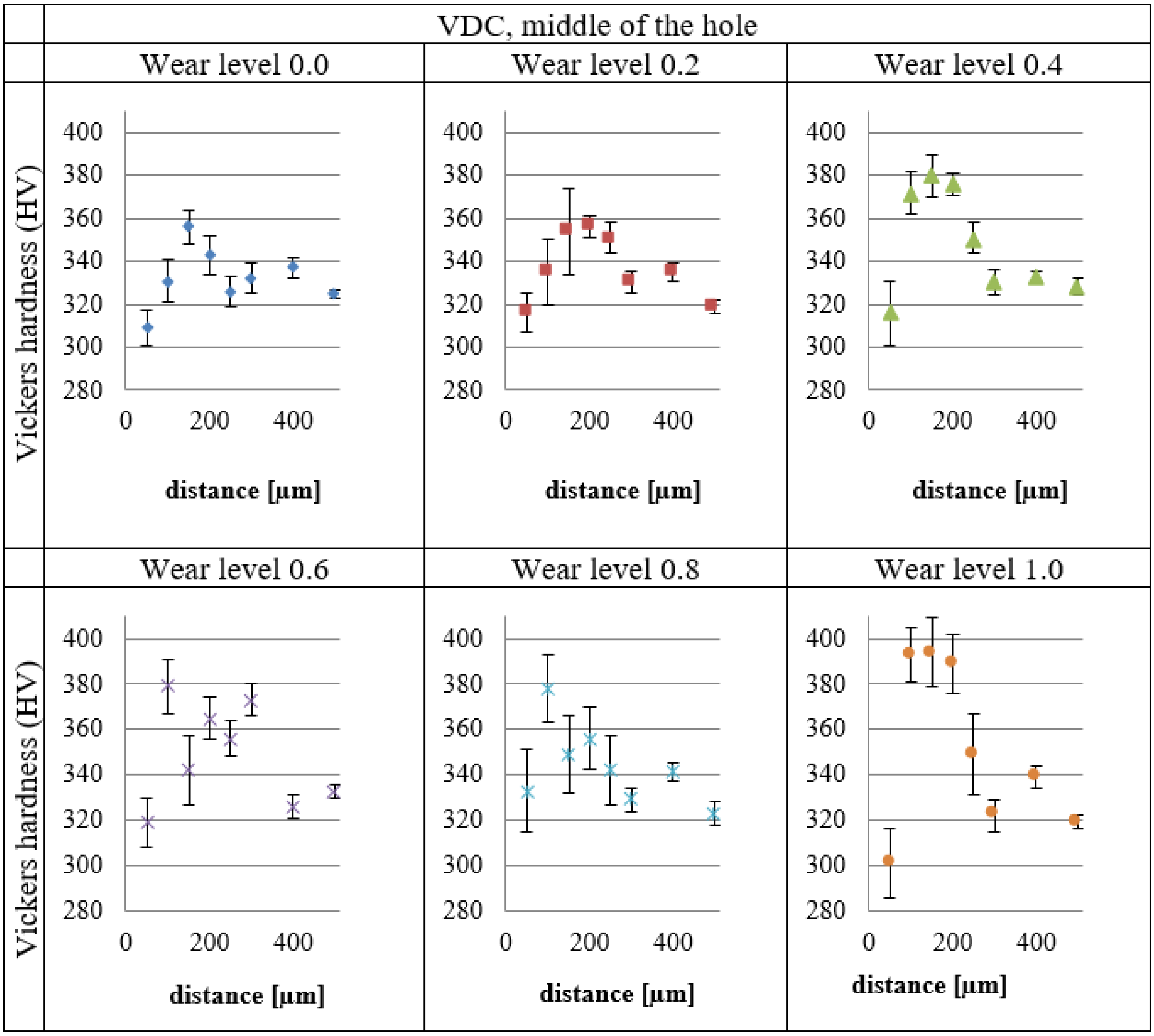

Figure 10: The microhardness value at the middle of the holes (VDC)

hole surfaces, to investigate possible diffusion of these elements. This could be explained by a hypothesis [19] that β phase decomposition is in this case a diffusionless transformation, *i.e.*, a transformation occurs without any chemical composition changes. However, this explanation differs from the findings of Reissig *et al.* [7] suggesting a low feed rate is likely to cause the chemical composition changes in drilling of Ti6Al4V. A likely explanation for increase of hardness is creation of alpha phase due to presence of oxygen and nitrogen in atosphere as noted by Cantero *et al.* [13].

Figures 8-12 depict the microhardness variations beneath the holes surface. The microhardness variation for the soft and harder zones is affected by machining process and can be related to the recrystallization and grain size [16]. In general, the hardness values are significantly higher, where the microstructures are heavily deformed and lower for less deformed microstructure; however, while the grain deformation is considerably higher in cutting with a worn tool in the dry condition, the microhardness changes are rather of similar magnitude for the wet and dry conditions.

The higher hardness maybe explained by the work hardening of the deformed layer beneath the machined surface up to some certain distance [6] and presence of oxygen and nitrogen elements that encourage transformation into α titanium with higher hardness [13]. However, lower microhardness at just below the machined surface (at around 50 µm) is probably because of the over-aging of the titanium alloy as a result of very high cutting temperature produced at the local surface [16] and also as manifestation of the 'edge effect' as described by Warren *et al.* [17].

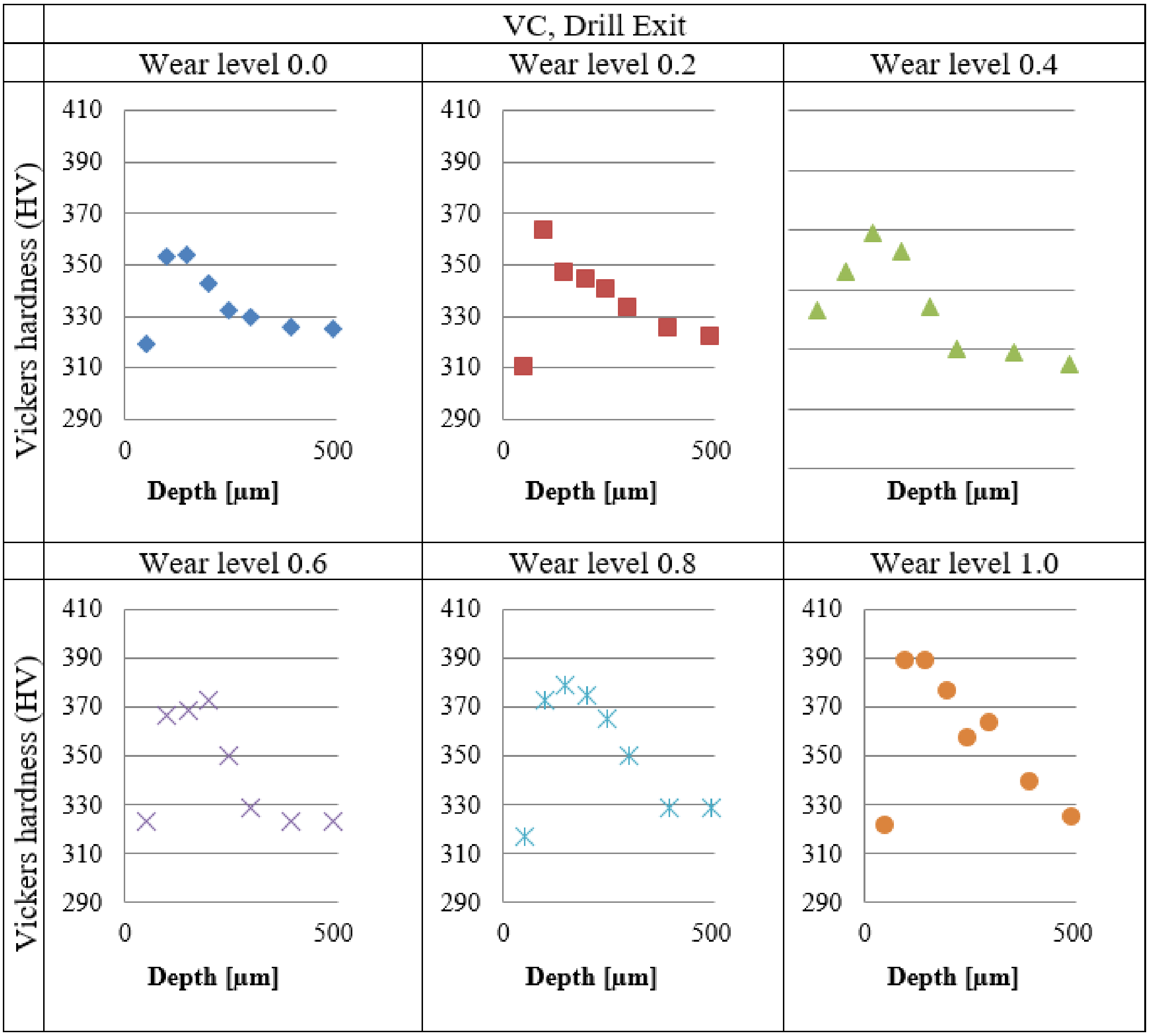

Figure 11: Microhardness at the drill exit for VC

5 Conclusions

The influence of tool wear on the grain deformations and microhardness alteration is significant. Some of the key findings are summarized below:

1. Significant difference is observed between dry cut and wet cut in terms of microstructural alteration. This difference is more pronounced when the tool wear reached 0.6 mm and above.
2. No significant change in chemical composition is noticed underneath machined surface compared to the bulk material in various regions such as drill entry, middle of the drill hole and drill exit.
3. Microhardness alteration follows an identical trend for all cutting conditions and wear levels. Microhardness values are lower (in same case even below the bulk material hardness value) just beneath the surface of the drilled hole at a distance up to 50 µm in the radial direction from the drill hole and reaches highest at the distance in between 100 to 200 µm which is up to 20% higher than the bulk material hardness and then approaches to the bulk material hardness as the radial distance increases.
4. Sub-surface microhardness varies slightly along the hole's length. It is highest at the drill exit and comparatively higher at the drill entry than the middle of the hole.

A more detailed numerical or experimental investigation of the temperature and deformation fields during

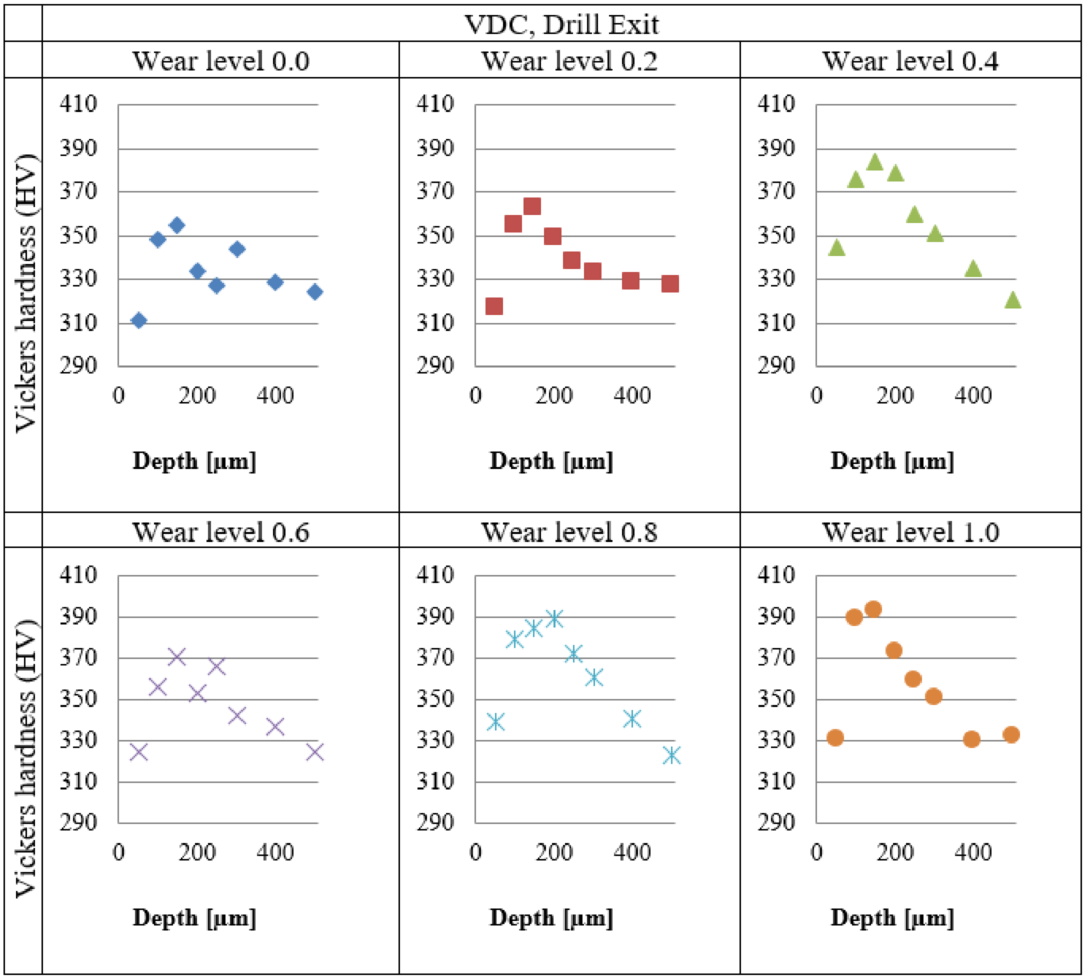

Figure 12: Microhardness at the drill exit for VDC

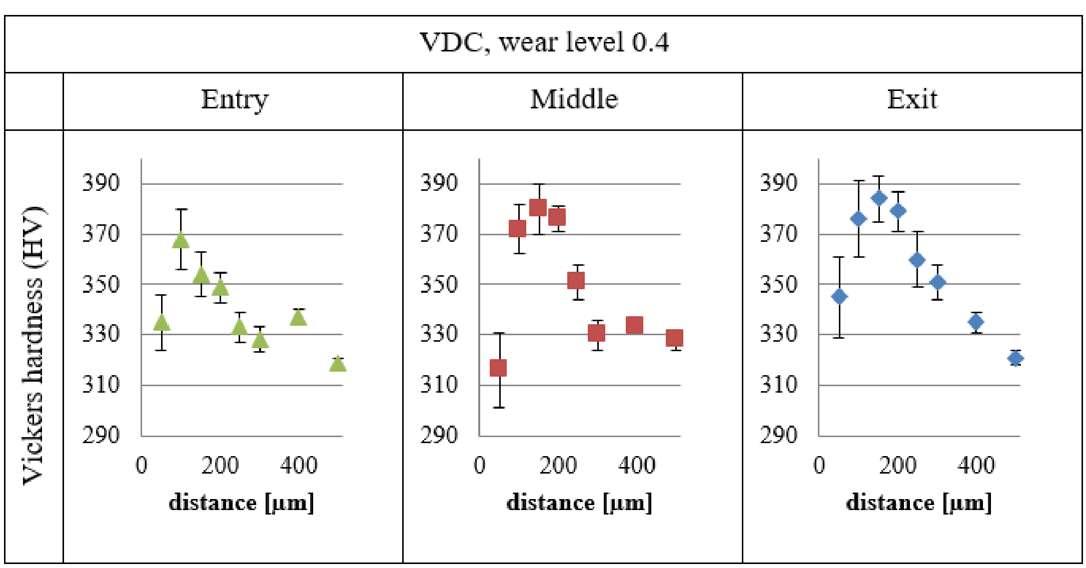

Figure 13: Microhardness value beneath the machined surface at the hole entry, middle and at the exit for vertical dry drilling using the tool wear level 0.4

drilling is expected to shed more light on some aspects such as the hardness change mechanisms.

References

[1] Ezugwu, E., J. Bonney, and Y. Yamane, An overview of the machinability of aeroengine alloys. Journal of materials processing technology, 2003. 134(2): p. 233-253.
[2] Ezugwu, E. and Z. Wang, Titanium alloys and their machinability—a review. Journal of Materials Processing Technology, 1997. 68(3): p. 262-274.
[3] Arrazola, P.-J., et al., Machinability of titanium alloys (Ti6Al4V and Ti555. 3). Journal of Materials Processing Technology, 2009. 209(5): p. 2223-2230.
[4] Koster, W. Effect of residual stress on fatigue of structural alloys. in Practical Applications of Residual Stress Technology, Conference Proceedings, Indianapolis, Indiana. 1991.
[5] Koster, W. and M. Field. Effect of Machining Variables on the Surface and Structural Integrity of Ti. in Proceedings of the North American Metalworking Research Conference. 1973.
[6] Sharman, A., J. Hughes, and K. Ridgway, The effect of tool nose radius on surface integrity and residual stresses when turning Inconel 718™. Journal of Materials Processing Technology, 2015. 216: p. 123-132.
[7] Reissig, L., et al., Investigation of near surface structure in order to determine process-temperatures during different machining processes of Ti6Al4V. Scripta Materialia, 2004. 50(1): p. 121-126.
[8] Ginting, A. and M. Nouari, Surface integrity of dry machined titanium alloys. International Journal of Machine Tools and Manufacture, 2009. 49(3): p. 325-332.
[9] Ezugwu, E.O., et al., Surface integrity of finished turned Ti–6Al–4V alloy with PCD tools using conventional and high pressure coolant supplies. International Journal of Machine Tools and Manufacture, 2007. 47(6): p. 884-891.
[10] Bordin, F.M. and R.P. Zeilmann, Effect of the cutting edge preparation on the surface integrity after dry drilling. Procedia CIRP, 2014. 13: p. 103-107.
[11] Ezugwu, E., Key improvements in the machining of difficult-to-cut aerospace superalloys. International Journal of Machine Tools and Manufacture, 2005. 45(12): p. 1353-1367.
[12] Nabhani, F., Machining of aerospace titanium alloys. Robotics and Computer-Integrated Manufacturing, 2001. 17(1): p. 99-106.
[13] Cantero, J., et al., Dry drilling of alloy Ti–6Al–4V. International Journal of Machine Tools and Manufacture, 2005. 45(11): p. 1246-1255.
[14] Donachie, M.J., Titanium: a technical guide. 2000: ASM international.
[15] Sun, J. and Y. Guo, A comprehensive experimental study on surface integrity by end milling Ti–6Al–4V. Journal of Materials Processing Technology, 2009. 209(8): p. 4036-4042.
[16] 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.
[17] Warren, A. and Y. Guo, On the clarification of surface hardening by hard turning and grinding. Transactions of NAMRI/SME, 2006. 34: p. 309-316.
[18] Moussaoui, K., et al., Influence of milling on surface integrity of Ti6Al4V—study of the metallurgical characteristics: microstructure and microhardness. The International Journal of Advanced Manufacturing Technology, 2013. 67(5-8): p. 1477-1489.
[19] Li, R., et al., Metallurgical analysis and nanoindentation characterization of Ti–6Al–4V workpiece and chips in high-throughput drilling. Materials Science and Engineering: A, 2008. 472(1–2): p. 115-124.