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Analysis Of Strain Hardening And Surface Quality In Machining Of Titanium Alloys, Experimental And Simulation-Based Approach

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Abstract
In this experiment, strain hardening and surface integrity during the dry turning of the Ti-6Al-4V alloy are investigated by the effect of tool flank wear and cutting parameters. The study examined carbide inserts with three degrees of flank wear carried out in machining trials (1 mm, 1.5 mm and 2 mm). All the machining trials were arranged based on an L27 Taguchi orthogonal array which considers different cutting speeds, feed rates and depths of cut. Effects of surface flank wear and cutting parameters on work-hardening and surface integrity (measured by surface roughness, micro-hardness and microstructure) of titanium alloys were examined. According to the results, supporting surfaces that had been worked more on the sides were clearly harder. Because of stronger plastic deformation on the tool–work piece boundary, more strain hardening took place in the top layer. Research confirmed that tool wear, in particular wear in the critical region, is important in changing surface features.

Keywords: *Work-Hardening; Surface Integrity; Ti-6Al-4V; Tool Flank Wear; Turning.*

INTRODUCTION

Titanium alloys are known as difficult-to-machine materials. The difficulties of machining titanium are numerous and dependent on the specific types of titanium alloys (Pramanik 2014). The (high-temperature, strain, and strain-rate) deformation process in machining situation is complicated and fundamentally distinct from the deformation behavior of ordinary metals like steel and aluminum, etc. (Pramanik, Islam et al. 2013). The specified alloy, Ti-6Al-4V, combines 4% vanadium and 6% aluminum with the remainder of titanium, making it a particularly extensively utilized titanium alloy globally. This alloy, which is a grade 5 titanium alloy, possesses superior qualities compared to pure titanium. Preserves the fundamental qualities of titanium, including thermal characteristics or rigidity, through exhibiting considerably more strength than pure titanium (Komanduri and Reed Jr 1983, Joy, Prakash et al. 2020). Several research studies on Ti-6Al-4V have elucidated techniques to improve machinability by using tool wear and ideal machining environments (Rao and Shin 2002). Nevertheless, this metal alloy is extremely difficult to machine due to insufficient thermal conductivity, comparatively high chemical activity, low elastic modulus, and the high strength concentration at elevated temperatures (Madyira, Laubscher et al. 2013). Strain hardening, often known as work hardening, is a critical factor in assessing the plastic deformation of metallic substances. Work-hardening properties are closely related to, toughness of materials, and deformability of materials, ductility , and strength (Wang, Liu et al. 2014). Numerous factors influence the level and characteristics of work hardening, followed by the most significant determinants being material qualities such as cutting condition temperature , or strain rate (Pervaiz, Rashid et al. 2014). A high-quality turning surface can enhance strength qualities, including thermal resistance, resistance to corrosion, and fatigue (Neşeli, Yaldız et al. 2011). The quality of surface machined Ti-6Al-4V is directly influenced by work hardening. The hardened surface created after machining may lead to fluctuations , emergence of residual stresses and surface roughness (Harun, Burhanuddin et al. 2022). The surface roughness corresponds to a technological extent of crucial importance or an indicator of the state of the surface, which has numerous regulated or unregulated process parameters, including cutting condition, cutting circumstances, quality of materials, machine vibrations, tool wear, tool characteristics, etc.

(Simunovic, Svalina et al. 2016) . The physical interaction between the work piece and tool which generates thermo-mechanical stresses, concluding in significant plastic deformation of the subsurface layer of the machining specimens. These alterations induce preformation of work hardening and microstructural modifications, which influence the service quality and efficiency (Jafarian 2019, Parida 2019) . Surface integrity is considered an important factor for determining surface quality (Jafarian, Mohseni et al. 2020). The surface integrity (SI) of a machined work piece encompasses microstructure, surface roughness, work hardening phase transformation, and residual stress. This is crucial for the service efficiency with operational lifespan for the main components (Zha, Qin et al. 2024). By using the Taguchi technique as an effective instrument for the construction of superior quality systems. It offers a straightforward, effective, and methodical strategy to enhance quality, cost, and designs for performance (Yang and Tarng 1998).Tool wear and surface finish are critical aspects of machining processes, as they directly influence product quality, manufacturing efficiency, and operational costs (Benardos and Vosniakos 2003). A further significant factor that adversely impacts the performance of the turning operation is referred to as flank wear. The flank wear controlled the surface roughness with geometrical precision regarding the final product, which are affected by cutting environments and cutting tool insert geometry. Consequently, for assurances of surface roughness and low flank wear, optimization of machining is required in the geometric parameters of the turning process (Senthilkumar, Ganapathy et al. 2014). Consequently, Ti6Al4V has been the subject of numerous studies, mostly concentrating on machinability evaluation, experimental and computational analyses, along with modelling and optimization investigations (Younas, Jaffery et al. 2021).

(Che-Haron and Jawaid 2005) Noted the highest layer exhibited a work hardening phenomenon, as its hardness value exceeded that of the work piece material. The investigation also demonstrated how the hardness levels reduce below the surface layer, therefore, of the maturation of Ti6Al4V. (Wang, Liu et al. 2014) investigated the work hardening characteristics of Ti–6Al–4V by high-temperature compression examination and identified various levels of work hardening. (Patil, Jadhav et al. 2016) examines how dry machining Ti6Al4V affects the surface texture concerning the machined work piece. By changing the feed rate and cutting speed but maintaining cut depth, the particular team checked how the variation affected the subsurface deformation. (Samsudeensadham, Mohan et al. 2021) studied the impact of machining parameters in dry machining of Ti-6Al-4V alloy, emphasizing the role of depth of cut and feed rate on cutting power, temperature, and surface roughness.

The current investigation focuses on critically analyzing the investigation of surface work hardening done by a limited level of tool flank wear (between 1 and 2 mm) on certain aspects of the surface integrity for grade 5 titanium alloys. To review the wear behavior of the coated tool at an unexpected level and the impact on the Ti-6Al-4V alloy, produced hardness, surface roughness, microstructure, and residual stress were examined. The operation is done under dry conditions and uses CVD (coated carbide) tools. Optimizing turning process parameters, including cutting speed, depth of cut, feed, work piece hardness and nose radius on surface integrity and number of passes using the Taguchi method to give the best association of turning operating parameters that provide maximum hardness and minimum surface roughness.

2. Experimental Procedure

2.1 Work Materials

To investigate the unique aspect of surface integrity since turning the Ti-6Al-4V alloy, 27 tests were performed on the solid cylindrical samples having a diameter of 9 mm and a length of 70 mm, in accordance with ASTM E8/E8M, as seen in Fig. 1. The chemical composition and mechanical properties of the metal, as measured and received, are presented in Tables 1 and 2.

TABLE 1. Chemical Composition of Ti-6Al-4V titanium alloy (wt.%) as measured.

Element	Ti	Al	V	Fe	Mn	Mo	Zr
(wt.%)	%90.79	% 6.25	%3.36	% 0.07	%0.03	% 0.02	% 0.01

TABLE 2. Mechanical properties of Ti-6Al-4V titanium alloy as received.

Work Material (MPa)	Elongation (GPa)	Tensile strength (MPa)	Hardness (Vickers)	Yield strength
Ti-6Al-4V (Annealed)	16	994	349	903

2.2 Tool Materials Specification

For this research, carbide inserts covered with chemical vapor deposition (CVD) were used to examine the impact of tool geometry, including nose radius, rake angle, and relief angle, as illustrated in Fig. 2. The inserts were fixed on tool holders PSDNN 2525 M12 (ISO standard). The inserts were P10/K15C, including a multi-layer composition of titanium compound and aluminum oxide, produced by TIZIT PLANSEE, with the (ISO Specification) SNMG 120416-EN (90 square-shaped insert).

2.3 Machining Test

Turning tests were performed under dry conditions. A HARRISON M450 lathe machine, employed for turning, was used, having a power output of 7.9 kW with a peak rotational speed of 2000 rpm. All the cutting tests were performed under dry cutting conditions on a Ti6Al4V work piece. The cutting parameters are specified in Table 3.

2.4 Selection of Orthogonal Array and Design of Experiments

Machining experiments were performed under dry cutting conditions. The selection of array for the experiments is the L27 (3^3) orthogonal array. Five process parameters, with each having three levels, have been established as control factors. The selected control parameters are material hardness (HV) (A), cutting speed (B), feed rate (C), depth of cut (D), and (tool flank wear) (E). The DOE Taguchi Orthogonal Array L27 is configured in Minitab 21 to be applied as the experimental design, as represented in Table 4.

TABLE 4. L_{27} Orthogonal arrays.

Run	A	B	C	D	E
1.	1	1	1	1	1
2.	1	1	1	1	2
3.	1	1	1	1	3
4.	1	2	2	2	1
5.	1	2	2	2	2
6.	1	2	2	2	3
7.	1	3	3	3	1
8.	1	3	3	3	2
9.	1	3	3	3	3
10.	2	1	2	3	1
11.	2	1	2	3	2
12.	2	1	2	3	3
13.	2	2	3	1	1
14.	2	2	3	1	2
15.	2	2	3	1	3
16.	2	3	1	2	1
17.	2	3	1	2	2
18.	2	3	1	2	3

19.	3	1	3	2	1
20.	3	1	3	2	2
21.	3	1	3	2	3
22.	3	2	1	3	1
23.	3	2	1	3	2
24.	3	2	1	3	3
25.	3	3	2	1	1
26.	3	3	2	1	2
27.	3	3	2	1	3

TABLE 3. Machining conditions used in the experiment.

Parameters	Level 1	Level 2	Level 3
Cutting Speed (Vc), m/min	31.4	50.2	62.8
Feed Rate (f), mm/rev	0.04	0.23	0.45
Depth of Cut (a_p), mm	0.2	0.3	0.4

FIGURE 1. Machined tensile samples with a cutting length of 70 mm and a diameter of 9 mm

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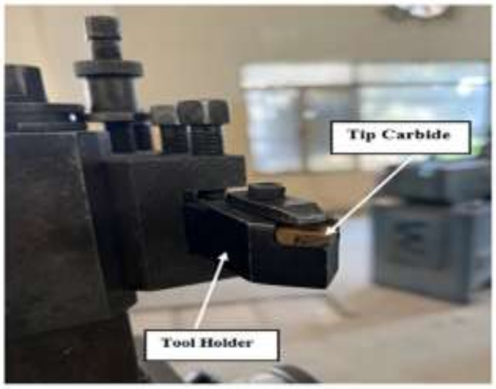


Figure 2. Tool holder clamping a carbide insert.

3. RESULTS

To investigate the effect of three different levels of tool flank wear on surface hardness and surface roughness as a work-hardening mechanism, the following section shows the results of experiments that involved dry turning Ti-6Al-4V alloy under various cutting circumstances. Surface hardness, tool flank wear (VB), and surface roughness (Ra) were the main things that were measured. Table 5 shows a summary of the experimental findings.

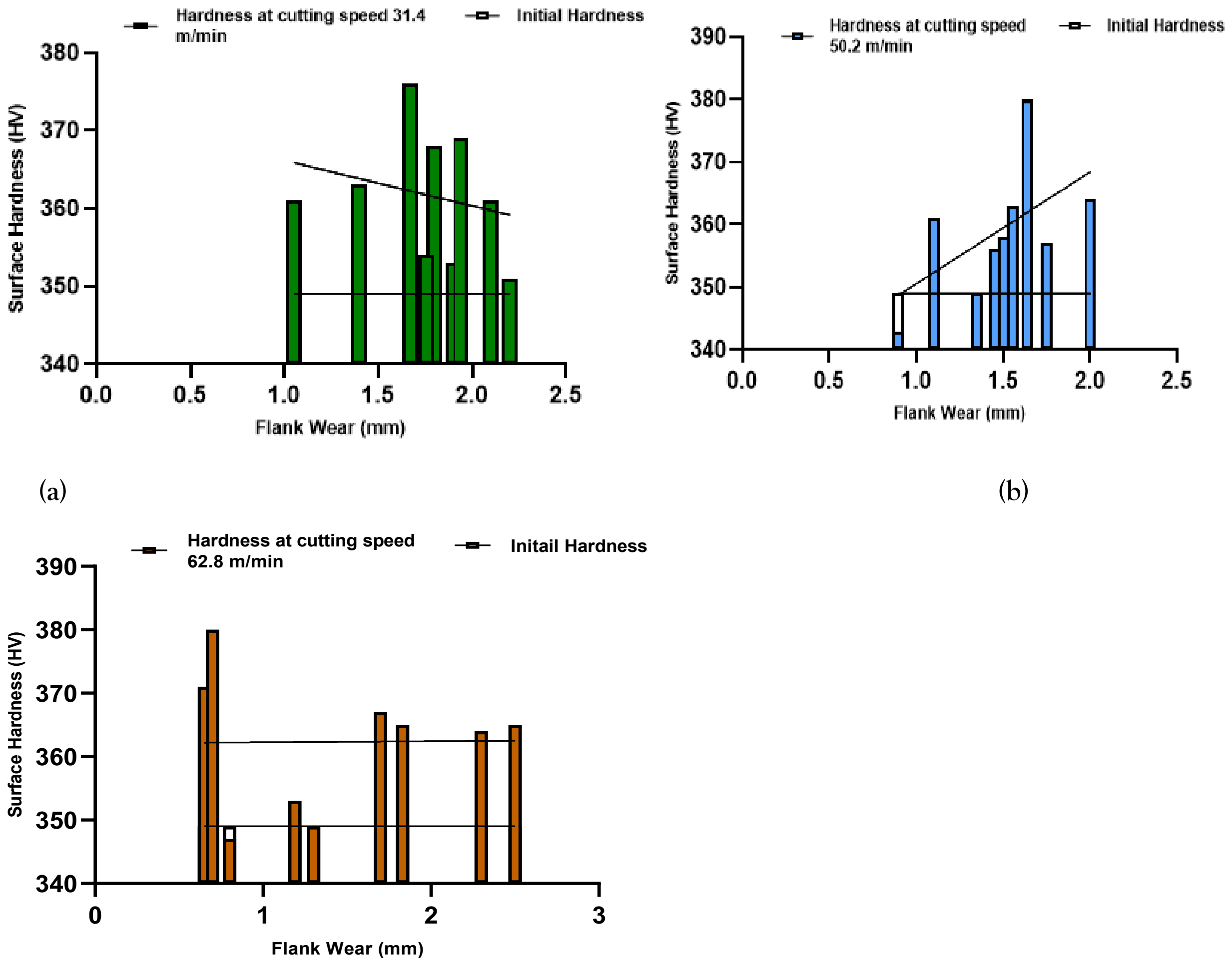
No.	Material	Cutting Speed (Vc), m/min	Feed Rate (f), mm/rev	Depth of Cut (a_p), mm	Hardness (HV)	Roughness (μm)	Tool Flank Wear
1.	Ti-6Al-4V	31.4	0.04	0.2	376	0.95	1.7
2.					353	1.02	1.9
3.					361	1.59	1.05
4.		50.2	0.23	0.3	349	1.39	1.3
5.					361	0.74	1.1
6.					364	1.01	2
7.		62.8	0.45	0.4	367	0.84	1.7
8.					365	1.08	1.8
9.					347	1.04	0.8
10.	Ti-6Al-4V	31.4	0.23	0.4	363	0.89	1.4
11.					361	0.93	2
12.					368	0.70	1.8
13.		50.2	0.45	0.2	356	0.76	1.5
14.					363	1.66	1.6
15.					380	1.40	1.6
16.		62.8	0.04	0.3	365	0.73	2.5
17.					364	1.28	2
18.					349	0.97	1.3
19.	Ti-6Al-4V	31.4	0.45	0.3	351	1.16	2.2
20.					354	0.76	1.7
21.					369	1.03	1.9
22.		50.2	0.04	0.4	358	0.77	1.5
23.					357	0.90	1.8
24.					343	0.90	0.9
25.		62.8	0.23	0.2	371	0.87	0.7
26.					380	1.39	0.7
27.					353	0.99	1.19

Table 5. Provides a summary of the results of hardness, tool flank wear, and roughness for 27 turning tests on Ti-6Al-4V.

3.1 Results of Surface Hardness

One of the parameters utilized to describe the surface integrity of a material is hardness. As it measures of work hardening mechanism, it measures the resilience of the material to plastic or elastic deformation, and failure (Wang, Liu et al. 2014).The results were plotted in three separate graphs (Flank Wear vs. Surface Hardness) as shown in Figs. 4 (a, b and c), each representing one cutting speed. The interpretation of these graphs is as follows: At 31.4 m/min, all measured surface hardness values were consistently above the initial material hardness (349 HV reached to 351 HV and 376). This means that the mechanism of improving surface hardness by using a high level of flank wear was done successfully. Maximum surface hardness is 376

HV at 1.67 mm flank wear. The minimum surface hardness of 351 HV at 2.2 mm flank wear is needed to prevent rubbing during higher levels of flank wear, which prolongs the duration that the work piece and tool are in contact with increases frictional heat. At 50.2 m/min, surface hardness ratings were typically too high; instead, some were far lower than the original hardness. The specimen that was the hardest to obtain had 1.64 mm of flank wear and 380 HV. The sample with the least amount of wear on the flank had 0.9 mm and 343 HV. Due to increased cutting speeds and tool wear, the relationship between hardening and thermal softening gets more convoluted. The surface hardness was between 347 HV and 380 HV at the highest speed, which was 62.8 m/min. Certain values were greater than others, whereas a few were within or below the original hardness. This finding illustrates that reducing flank wear intensifies thermal softening. The material was hardest when the flank wear was 0.7 mm and the softest while the flank wear was 0.8 mm (380 HV and 347 HV respectively).



(a)

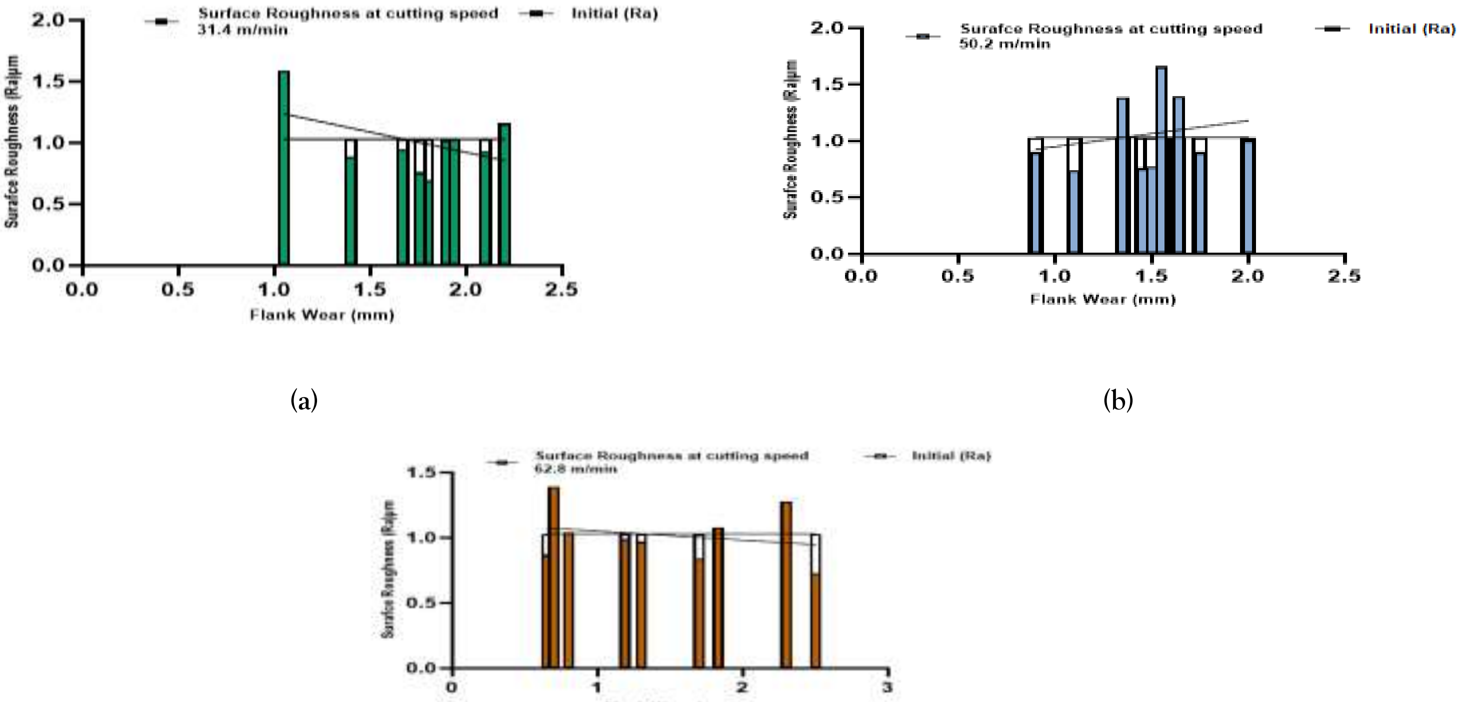
(b)

(c)

FIGURE.4 Effect of tool flank wear on surface hardness at (a) Vc=31.4 m/min, $(f) =$ 0.04,0.23,0.45 , $(a_p) =$ 0.2 ,0.4, 0.3. (b) $V_c = 50.2$ m/min , (f)=0.23,0.45,0.04, $(a_p) =$ 0.3,0.2,0.4.(c) $V_c = 62.8$ m/min , $(f) =$ 0.45,0.04,0.23, (a_p) = 0.4,0.3,0.2

3.2 Results of Surface Roughness

A parameter that characterizes the surface integrity is the surface roughness (Sahu, Andhare et al. 2018). The correlation between surface roughness (Ra) and tool flank wear (VB) was systematically examined at three cutting speeds: 31.2, 50.2, and 62.8 m/min, through dry turning of Ti-6Al-4V, as shown in Figs. 5 (a, b, and c). At 31.4 m/min, the values of surface roughness varied between 0.70 and 1.59 µm. The majority of results remained similar to or even below the initial roughness. At a flank wear of 1.05 mm, the roughness attained its peak at 1.59 µm. This variability was mainly due to prolonged edge formation or adhesion phenomena during the initial stages of wear. At a speed of 50.2 m/min, the roughness exhibited significant variation (0.74–1.66) µm. The maximum Ra of 1.66 mm at the flank of 1.55 mm occurred when the flank reduced to 1.55 mm, indicating that the edge deteriorated and the crater eroded. The higher temperatures while dry cutting induced friction and enhanced micro-chipping. Flank wear attained its maximum at 2.5 mm at a speed of 62.8 m/min, even though surface roughness remained within a more limited range of (0.73–1.39) µm. This transpired due to the rapid removal of material, which resulted in plastic deformation that refined the surface, despite the significant deterioration of the tool edge.



(a)

(b)

(c)

Figure 5. Effect of tool flank wear on surface roughness at (a) V_c =31.4 m/min, (f) = 0.04,0.23,0.45, (a_p) = 0.2,0.4,0.3. (b) V_c =50.2 m/min, (f) = 0.23,0.45,0.04, (a_p) = 0.3,0.2,0.4 (c) V_c =62.8 m/min, (f) = 0.45,0.04,0.23, (a_p) = 0.4,0.3,0.2.

4. DISCUSSION

The findings indicate that the ability to use tool flank wear at a certain level is a facility to improve surface hardness of hard-to-machine titanium alloy Ti-6Al-4V with a distinct correlation between tool flank wear and surface hardness/roughness across inconsistent cutting speeds. When the cutting speed was low (31.4 m/min), the surface hardness was mostly above the baseline (349 HV), reaching a peak of 376 HV at 1.67 mm flank wear according to (Arrazola, Garay et al. 2009) as tool wear rises, friction at the interact between the tool and the work piece rises, leading to more plastic deformation with an increased formation of hardened layers on the surface. This suggests that moderate tool wear at low speeds results in increased plastic deformation without significant heat generation, hence improving surface hardness. A minimum hardness of 351 HV at 2.2 mm flank wear indicates that increased wear prolongs contact time and frictional heat, potentially decreasing hardness significantly. At a moderate speed of 50.2 m/min, hardness exceeded 380 HV at a flank wear of 1.64 mm, indicating that plastic deformation and localized thermal effects from heightened friction-assisted work hardening. The minimum value of 343 HV at 0.9 mm flank wear indicates reduced deformation while the tool remains sharp. At a speed of 62.8 m/min, the maximum hardness of 380 HV at 0.7 mm flank wear shows significant plastic deformation. The discarded data (347 HV at 0.8 mm) indicate that thermal softening occurs more frequently at elevated cutting speeds, suggesting that excessive heat reduces hardness. At all speeds, surface roughness commonly obtained was more severe as the tool was carried out. More inconsistent tool contact happens when the flank wear is higher, leading to more damage to the surface. At medium flank wear, roughness was lower slightly, which suggests that consistent tool contact smoothed issues through slightly. Some experiments showed that roughness decreased significantly at higher cutting rates because the heat made the material softer, which made cutting easier. Nevertheless, at high speeds, the results were impacted significantly since the wear behaviors occasionally remained the same.

5. CONCLUSION

The results of surface work hardening done by a limited level of tool flank wear between 1 and 2 mm on titanium alloys (Ti-6Al-4V) under dry conditions with (CVD) coated cemented carbide are given below and form the basis for the conclusions:

- Surface hardness improved by increasing flank Wear at a flank wear of 2.0 mm, the highest Vickers hardness values were shown, proving that higher wear creates more plastic deformation and strain-hardened surfaces.
- Changes in surface integrity were mainly caused by flank wear. By an increase of flank wear, there was an increase of contact area among the work piece and tool, which caused higher friction, more heat and greater stress on the tool. All of which improved the hardness of the surface.
- Cutting parameters from test samples greatly influenced both surface roughness and hardness. Increasing feed rates resulted in rougher surfaces. However, moderate cutting speed and feed rates made for a smooth surface and gave the best results without major damage to the surface.
- Using the Taguchi method helped improve machining conditions. Analysis of variance (ANOVA) determined which parameters were the most significant, and the proper combination of settings was set to enhance surface hardness without going beyond the allowed surface roughness.
- Using worn tools (tool flank wear) to specific levels in testing provided important information on the interaction between the tool wear and the characteristics of machined titanium. It is especially important in places where tools wear out as a result of the machining process.

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