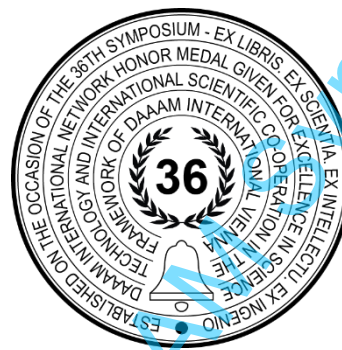


FLANK WEAR PROGRESSION OF A GROOVING INSERT DURING TURNING OF Ti-6Al-4V AT INCREASING CUTTING SPEEDS

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Abstract

Turning of the Ti-6Al-4V titanium alloy is characterised by intense and often unpredictable tool wear, driven by its low thermal conductivity, high chemical reactivity and pronounced tendency toward built-up edge formation and edge chipping. This paper investigates the flank wear behaviour of a grooving insert with a rounded nose radius across a range of cutting speeds, in order to establish how far cutting speed can be raised without a loss of edge stability. Turning tests were carried out with a X61 0602-315 L G8330 grooving insert at cutting speeds of 100, 120 and 150 m/min, while feed and depth of cut were kept constant. Flank wear VB was measured at regular intervals with a digital microscope. The results show a systematic increase of the wear rate with cutting speed, consistent with established machining theory, and no brittle edge failure at any of the tested speeds. The rake face showed adhered titanium and a crater at the tool nose, most pronounced at 150 m/min. Overall, the results confirm that the rounded-nose geometry provides an edge stable enough to allow turning of Ti-6Al-4V at cutting speeds of up to 150 m/min while maintaining a predictable, gradually progressing flank wear.

Keywords: titanium alloy; Ti-6Al-4V; turning; flank wear; cutting speed; tool wear

1. Introduction

Titanium alloys, and Ti-6Al-4V in particular, are used extensively in the aerospace and medical industries thanks to their high strength-to-weight ratio, excellent corrosion resistance and biocompatibility [1]. Despite this, titanium alloys are universally regarded as difficult-to-machine materials: the machinability index of Ti-6Al-4V is only about a fifth of that of a free-cutting steel, and lower still after solution treatment and ageing [1]. This poor machinability results from a specific combination of physical, thermal and chemical properties rather than from any single dominant cause.

The most significant factor is titanium's low thermal conductivity, roughly $6.5\text{--}7.5\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, about six times lower than that of structural steels [1, 2]. Heat generated during chip formation is therefore poorly dissipated into the chip and workpiece. Instead, the cutting tool itself absorbs up to about 80 % of the generated heat, and cutting-edge temperatures can locally reach up to $1100\text{ }^{\circ}\text{C}$ [2]. Because the chip-tool contact length on the rake face is roughly a third shorter than

when machining steel, this heat load is concentrated in a very narrow zone directly at the cutting edge, producing steep thermal gradients and severe local mechanical stress [1, 2].

A further defining feature of machining titanium alloys is the tendency to form a segmented, saw-tooth chip over a wide range of cutting conditions, in contrast to the continuous chip typical of steel [8]. The chip is divided into segments of low internal deformation joined by narrow, heavily sheared bands in which the flow stress drops sharply, which is why titanium chips break comparatively easily even though chip formation itself is inherently cyclic [8]. Two explanations have been proposed for this behaviour: one attributes it to thermoplastic instability, in which localized softening in the primary shear zone outpaces strain hardening because heat cannot be conducted away quickly enough [8]; using a quick-stop technique, however, Vyas and Shaw observed that a crack instead initiates at the free surface of the chip and propagates toward the cutting edge along the plane of maximum shear stress, pointing to a fracture-controlled rather than a purely thermal mechanism [9]. Whichever mechanism dominates, the cyclic nature of chip segmentation subjects the cutting edge to a correspondingly cyclic mechanical load, which is a further reason why edge robustness against chipping is critical when selecting a tool geometry for this alloy.

Titanium's high chemical reactivity at elevated temperature promotes adhesion and diffusion between the chip and the tool material, leading to the formation and cyclic tearing of a built-up edge; this process regularly results in surface damage and in micro-chipping of the cutting edge [1]. At temperatures above roughly 600 °C, diffusion of atmospheric oxygen and nitrogen into the machined surface, combined with intense plastic deformation, also produces a hardened subsurface layer that accelerates notch wear on the next pass [1]. Finally, the comparatively low elastic modulus of titanium alloys, about 115 GPa at room temperature and falling further with temperature, makes the workpiece prone to elastic deflection and spring-back under the cutting force, which promotes friction on the tool flank and can lead to chatter and dimensional inaccuracy unless a rigid setup and a suitable tool geometry are used [1].

This low elastic modulus has a particularly direct effect on flank wear. In the tertiary deformation zone, where the tool flank rubs against the freshly machined surface, the actual shear plane deviates from the nominal cutting plane because the workpiece material elastically deflects and springs back after the cutting edge has passed. Ezugwu notes that, because titanium alloys have a markedly lower elastic modulus, about 100-130 GPa, than steel, this springback and the resulting rubbing against the tool flank are more pronounced, which accelerates flank wear [1]. Schaal et al. confirmed experimentally that this elastic recovery increases with cutting speed for titanium, in contrast to aluminium alloys, where it decreases, and linked greater recovery directly to higher flank wear and a higher feed-direction force component [10]. This mechanism offers a further explanation, alongside the crater-wear behaviour discussed below, for why flank wear can be expected to grow more rapidly at higher cutting speeds.

The robustness of the cutting edge against this kind of damage is strongly influenced by its micro- and macro-geometry. Wyen and Wegener showed that increasing the cutting-edge radius raises cutting and feed forces when turning titanium, but that a larger radius also makes the edge substantially more resistant to chipping [4]. A related effect is expected from the tool's nose radius: turning trials on Ti-6Al-4V by Sykora and Syrovatka confirmed that geometric parameters such as the nose radius and the depth-of-cut ratio have a marked effect on the resulting force components and, by extension, on edge loading during turning of this alloy [5]. This suggests that a rounded-nose insert geometry, rather than a sharp-nosed one, should tolerate a wider range of cutting speeds before edge chipping becomes the limiting factor. Titanium alloys are conventionally machined at comparatively low cutting speeds, so verifying the cutting edge's strength at elevated speeds provides a practical basis for selecting parameters in subsequent machining trials.

The aim of this paper is to establish, experimentally, how far the cutting speed can be raised when turning Ti-6Al-4V with a rounded-nose grooving insert before edge stability is lost. Flank wear VB was tracked over cutting time at three cutting speeds, and the resulting wear curves are used to judge whether the wear progression remains gradual and predictable, or whether it is instead interrupted by chipping or fracture of the cutting edge.

2. Materials and methods

The workpiece material was Ti-6Al-4V round bar, 28 mm in diameter. Due to the limited clamping length of the counter-spindle of the machine tool used, the bar was cut to a length of 300 mm and clamped in hard jaws so that the overhang did not exceed 80 mm, in order to avoid deflection and run-out. The chemical composition of the alloy, as specified by AMS, is given in Table 1.

Al	C	Fe	H	N	O	V	Y	Ti
5.5-6.75	0.08 max.	0.3 max.	0.015 max.	0.05 max.	0.2 max.	3.5-4.5	0.005 max.	balance

Table 1. Chemical composition of Ti-6Al-4V per AMS specification (wt.%) [11]

Testing was performed on a DMG MORI CTX BETA 1250 TC 4A turn-mill centre, offering a variable spindle speed up to 5 000 rpm and flood-coolant delivery at a pressure of up to 100 bar. Flood coolant was applied throughout testing, since an effective cooling and lubrication strategy has a considerable influence on tool wear when machining difficult-to-cut titanium-based alloys [6].

A grooving insert, type X61 0602-315 L G8330, was used in an external holder P61.SFL-2525M-06, intended for external circumferential grooving under stable to moderately unstable conditions. The insert has a rounded nose and a non-constant chamfer between the major and minor flank, visible in Figure 1. According to the manufacturer's specifications, the insert features a clearance angle α_o of 7° , a rake angle γ_o of 15° , and a 0.13 mm rake-face chamfer. The cutting-edge radius r_n was measured at approximately $14\text{ }\mu\text{m}$.

The insert is a PVD-coated, submicron-grain WC-Co carbide grade (ISO P25–P40 / M20–M35), suitable for ISO P, M, K and, with coolant, S material groups.

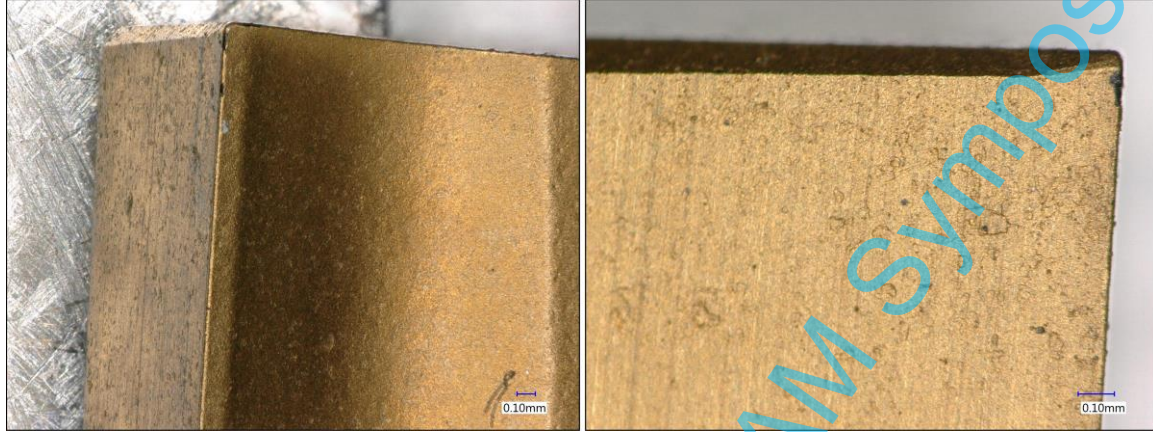


Fig. 1. Unused insert prior to testing: (a) rake and flank faces, showing the facet on the rake face and the chamfer between the major and minor flank; (b) corresponding flank face

The workpiece was machined by face turning, which removes an equal volume of material with every pass, unlike longitudinal turning where the removed volume changes with diameter. Keeping the chip volume constant has been shown to result in a more uniform load on the cutting tool [13].

Each facing pass ran from the bar's initial diameter of 28 mm to an end diameter of 10 mm, left as a stub to avoid the impractically high spindle speeds.

Three tests were run at increasing cutting speed while feed and depth of cut were kept constant, as shown in Table 2; the speed was raised between tests only while the wear progression from the previous test remained gradual and free of brittle edge failure. The end-of-test criterion was a fixed number of passes, so that the volume of material removed between measurements was identical for every test. Flank wear was recorded with a KEYENCE VHX-6000 digital microscope after every 20 passes, and the flank wear width VB was evaluated in accordance with the criteria defined by ISO 3685 [7].

Flank wear was evaluated in line with the wear-land classification defined by ISO 3685, which distinguishes wear at the tool nose VBC, notch wear VBN, wear along the straight section of the major cutting edge VBB, and the corresponding maximum flank wear VBBmax, while crater wear on the rake face is described separately by its width KB, mean distance KM, distance from the cutting edge KF and depth KT [7]. In the present tests, the straight-section flank wear VBB was tracked, since it developed as a continuous, clearly bounded wear land in every test and could be measured repeatably with the microscope's built-in dimensioning tool, as illustrated for the three cutting speeds in Figure 3.

Parameter	Test 1	Test 2	Test 3
Cutting speed v_c [m/min.]	100	120	150
Feed f [mm/rev.]		0.1	
Depth of cut a_p [mm]		0.25	

Table 2. Cutting conditions of the turning tests

3. Results

In all three tests, the insert developed a typical, measurable flank wear land, which made a direct evaluation of VB possible. Figure 2 shows the flank wear VB plotted against cutting time for the three cutting speeds, together with micrographs of the wear land captured after the first 20 passes and again at the fourth measurement point of each test, illustrating how the wear land visibly grows between these two points at each speed. Flank wear increased steadily with cutting time in every test, and no brittle edge failure – chipping or fracture – occurred at any of the tested speeds. Figure 3 shows the corresponding flank wear land at the end of each test, confirming visually that the flank wear remained regular and free of chipping even at the highest cutting speed.

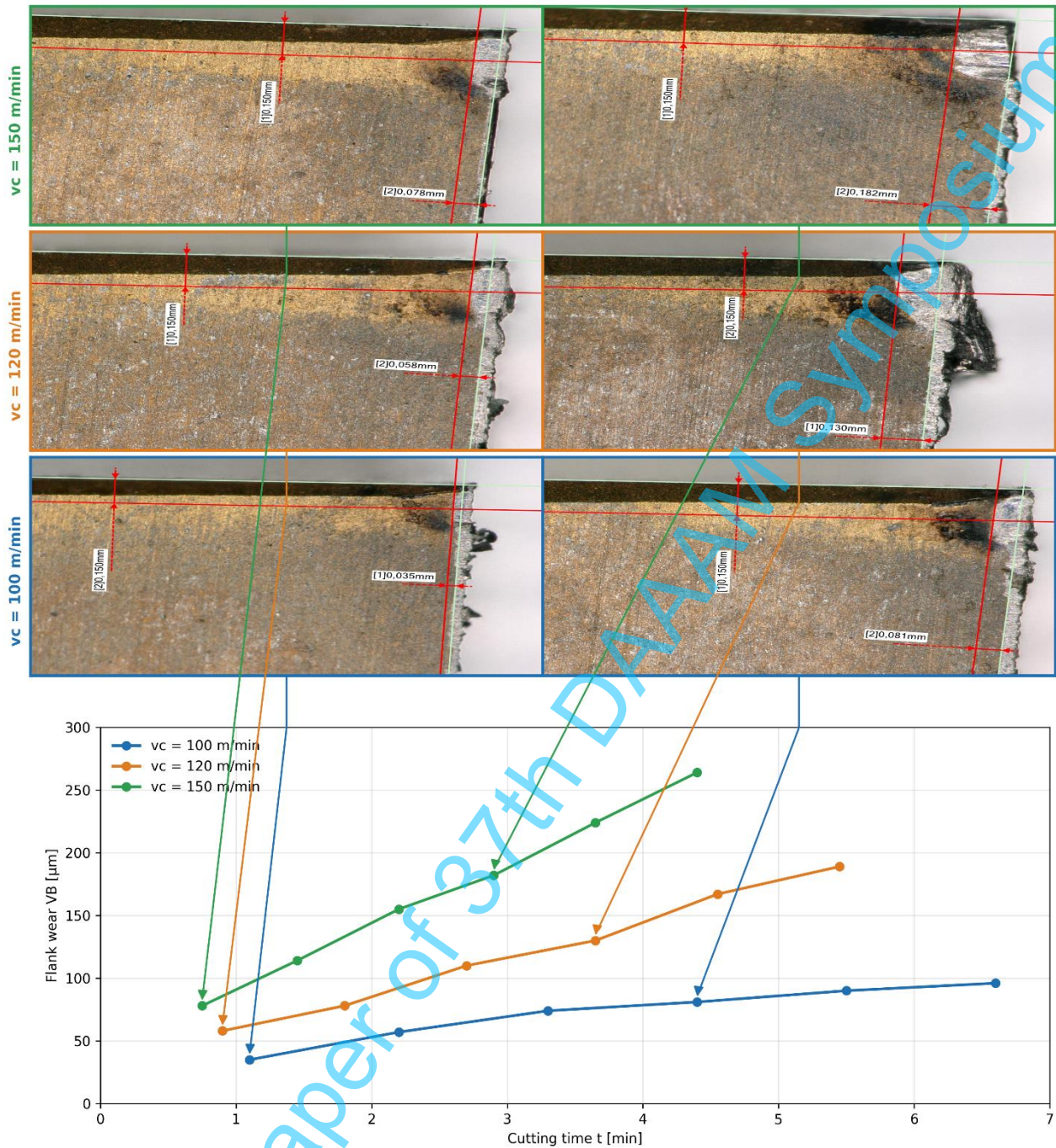


Fig. 2. Flank wear VB as a function of cutting time for $v_c = 100, 120$ and 150 m/min

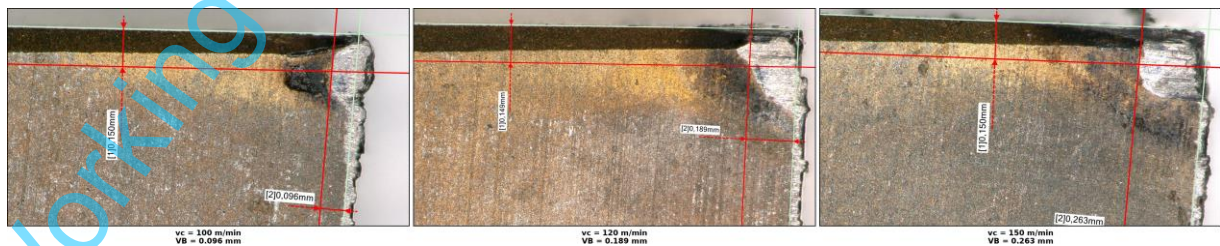


Fig. 3. Flank wear land at the end of each test (KEYENCE VHX-6000 digital microscope), showing a regular, chipping-free wear scar at $v_c = 100, 120$ and 150 m/min, respectively

4. Discussion

According to the classical model of tool flank wear, wear progresses through three characteristic stages: an initial, comparatively rapid break-in period caused by the running-in of the freshly ground cutting edge, a steady-state period in which wear increases at an approximately constant rate, and a final failure region in which wear accelerates sharply as the tool approaches the end of its useful life [12].

The measured wear curves in Figure 2 follow this pattern for the first two stages. At $v_c = 100$ m/min the transition is clearly visible: VB rises comparatively quickly over the first two measurement intervals before settling into a slower, near-constant rate for the remainder of the test. At $v_c = 120$ and, in particular, $v_c = 150$ m/min this transition is less distinct, and VB instead increases at a comparatively high, roughly constant rate throughout the test; this is consistent with a shorter, less pronounced break-in period at the higher cutting temperature generated at these speeds. None of the three tests reached the third, rapidly accelerating failure region, which agrees with the test methodology, since testing was deliberately stopped after a fixed number of passes while the wear progression remained gradual, rather than continued until tool failure. The higher wear rate recorded at $v_c = 120$ and 150 m/min compared with $v_c = 100$ m/min is therefore attributable to a steeper steady-state slope, not to an earlier onset of the failure region.

The results follow the trend expected from cutting-tool theory and from related turning studies on this alloy: flank wear grows markedly faster as cutting speed increases [1, 7]. At $v_c = 100$ m/min wear developed slowly and steadily; at $v_c = 120$ m/min the growth rate was clearly higher. At $v_c = 150$ m/min flank wear increased fastest, reaching the highest recorded values within the shortest cutting time.

Across the full speed range, wear developed gradually, without the sudden edge damage that carbide tools can suffer under comparable cutting conditions [3]. This indicates that the rounded-nose geometry of the tested insert, together with its non-constant flank chamfer, provides an edge robust enough to avoid chipping across this speed range, consistent with the edge-robustness benefit reported for larger cutting-edge and nose radii on this alloy [4, 5]. Because a stable, gradual wear progression was observed even at the highest tested speed, a cutting speed of up to 150 m/min can be recommended for turning Ti-6Al-4V with this insert geometry, while still allowing a sufficient number of wear measurements to be taken before the tool reaches the end of its useful life.

The rake face was also inspected with the digital microscope at every measurement point. At all three cutting speeds, titanium adhered to the rake face along the cutting edge. At the nose, a crater with a local loss of tool material developed directly adjacent to the cutting edge. It grew with cutting time, and its extent increased with cutting speed, being most pronounced at $v_c = 150$ m/min (Figure 4). This agrees with the crater wear typical of cemented carbide tools in machining titanium alloys, driven by adhesion and diffusion at high cutting temperatures [1], [3]. Unlike chipping, the crater developed progressively over several measurement intervals, and no sudden fracture of the cutting edge occurred within the tested number of passes.

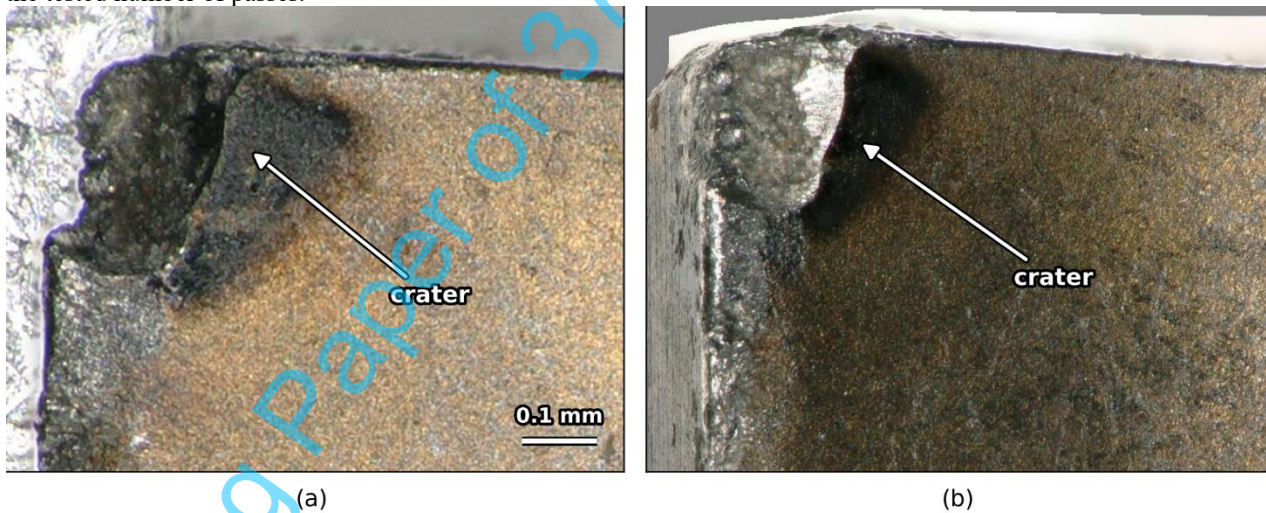


Fig. 4. Rake face at the tool nose at the end of the test at $v_c = 150$ m/min (KEYENCE VHX-6000 digital microscope): (a) top view; (b) 3D view, showing the crater adjoining the cutting edge

Several limitations of this study should be noted. Only one insert geometry, one feed and one depth of cut were tested, and only flank wear was measured quantitatively; crater wear on the rake face was assessed only visually, without measuring the crater depth KT. Because the tests were stopped after a fixed number of passes, the final stage of accelerated wear was not reached and tool life could not be determined. The conclusions are therefore limited to the tested insert and cutting conditions.

5. Conclusion

Turning of Ti-6Al-4V is limited by intense tool wear and a tendency toward edge chipping, which is why the alloy is usually machined at low cutting speeds. The aim of this study was to determine how far the cutting speed can be raised with a rounded-nose grooving insert, type X61 0602-315 L G8330, so that a sufficient number of wear measurements can be taken without fracture of the cutting edge. Face-turning tests were carried out at cutting speeds of 100, 120 and 150 m/min with constant feed and depth of cut, and the flank wear VB was measured with a digital microscope after every 20 passes in accordance with ISO 3685.

In all three tests, the insert developed a typical flank wear land, which allowed the wear to be measured and evaluated reliably. The wear progression agrees with machining theory: flank wear grew faster with increasing cutting speed, and the highest values were reached at 150 m/min. The wear remained gradual at all tested speeds, and no chipping or fracture of the cutting edge occurred. On the rake face, titanium adhered along the cutting edge at all speeds, and a crater with a local loss of tool material developed at the tool nose, most pronounced at 150 m/min. The test therefore confirmed the assumption that, with a rounded tool nose, cutting speeds of up to 150 m/min can be used while still allowing a sufficient number of wear measurements to be taken before the edge fails.

These results served as the basis for designing a more robust main experiment on turning Ti-6Al-4V, in which the cutting speed range verified here was used to set the cutting parameters [14].

6. Acknowledgments

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7. References

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