

SURFACE FINISH WHEN THREADING TITANIUM-BASED ALLOY UNDER DRY MACHINING

Siti Hartini Hamdan, Ahmad Yasir Md Said and John Rizal Biki

Faculty of Mechanical and Manufacturing,
University Kuala Lumpur Malaysia France Institute,
43650 Bandar Baru Bangi, Selangor, MALAYSIA.

E-mail: sitihartini@mfi.unikl.edu.my, yasir@mfi.unikl.edu.my

ABSTRACT

This paper discusses the quality of surface finish when threading titanium-based alloy under dry condition. The quality of surface finish was studied at various cutting parameters and at the two extreme stages of the machining process, i.e. at the beginning and end of the process. The objective is to evaluate the effect of a worn-out tool on the quality of surface finish. PVD-coated carbide tools were used in this study. Experiments were conducted at two cutting speeds, 35 and 55 m/min, two depths of cut, 0.2 and 0.25 mm, and a constant pitch of 2.0 mm. The tool wear and the quality of surface finish were inspected visually by microscope. The tool's flank wear was measured gradually and machining was stopped when the flank wear reached the rejection criterion of 0.3 mm. The microstructure beneath the machined surface was also evaluated. It was found that, at the beginning of machining, there was only a feed mark on the surface finish. When the machining was prolonged until the tools reached the rejection criterion, a bad surface finish was produced. Metal debris, surface cavities and a boundary crack were observed. Results show that machining with a worn-out tool can cause microstructure alteration beneath the machined surface. The selection of cutting parameters and monitoring of tool wear are crucial in order to obtain a good surface finish. Characterization of the surface finish with respect to the threading process under a dry condition would ultimately help in the development of suitable parameters for machining titanium-based alloys.

Keywords: Surface finish; microstructure; dry machining.

INTRODUCTION

Titanium and titanium alloys present several excellent properties such as very high strength-to-weight ratio, excellent corrosion resistance, light weight and the ability to maintain their properties at extremely high temperatures [1-6]. Research on the surface integrity and surface finish of titanium alloys is becoming more significant for the aerospace industries as it is used to produce high quality machined surface components and requires high accuracy [7-9]. Lubrication improves the machinability of the workpiece material, increases productivity by reducing tool wear and extends the tool life. However, the cutting fluids are seriously toxic [10]. As discussed by Elmagrabi et al. [1] and Ginting and Nouari [11], their absence means high friction and a high cutting temperature at the tool-workpiece interface and significantly affects both the tool wear and the tool life. Dry machining then becomes an ideal solution but poses a greater challenge to manufacturing engineers due to the high temperatures generated during

machining [10, 12]. Higher cutting temperatures reduce the yield strength of the workpiece material, making it more ductile. These results reduce the cutting forces and hence improve the machinability of the material [13]. It is ecologically desirable and considered as a necessity for manufacturing industries in the near future [14]. According to Daymi et al. [15], the surface integrity is the critical parameter on which the machined components' performance, reliability, and service life rely. There are two aspects to surface integrity, i.e. surface topography characteristics and subsurface layer characteristics. As studied by Daymi et al. [15], the surface topography comprises surface roughness, waviness, form errors, and flaws. The nature of the surface layer has a strong influence on the mechanical properties of the part. When machining any component, it is first necessary to satisfy the surface integrity requirements. Surface integrity produced by a metal removal operation includes the nature of both surface topography and surface metallurgy [15-18]. Some of the categories of metallurgical surface damage produced during machining include micro-cracks, micro-pits, tearing, plastic deformation of feed marks, and re-deposited materials. Therefore, control of the machining process is essential to produce components of acceptable integrity [3, 7]. It is known that titanium alloys have poor machinability due to generation of a high cutting temperature, short chip tool contact length and low elastic modulus. During machining of titanium alloy, very high cutting temperatures are generated close to the cutting edge of the tool. A large proportion (about 80%) of the heat generated is conducted into the tool because it cannot be removed with the fast flowing chip or into the workpiece due to the low thermal conductivity of these materials [19]. A higher cutting speed also results in rapid cratering and/or plastic deformation of the cutting edge. This is due to the temperature generated, which tends to be concentrated at the cutting edge closest to the nose of the inserts. The rapid tool failure and chipping at the cutting edge result in a poor surface finish of the machined surface. This causes not only higher surface roughness values but also higher micro-hardness values and severe microstructure alteration [20]. The surface finish tends to become smoother towards the end of the tool life. This is probably due to deformation on the flank face or adherence of the workpiece material at the tool nose. Increasing the cutting speed leads to higher roughness values [20]. The present work focuses on the surface finish of threaded titanium alloy Ti-6AL-4V using a coated carbide tool under a dry machining condition.

Table 1. Thread cutting parameters.

Specimen No	Diameter	Tags	Tool condition	Pitch (mm)	Depth of cut /run (mm)	Cutting speed, v (m/mm)	Rotary spindle speed (rpm)
1	22	A1	New	2	0.2	35	507
2	22	B1	New	2	0.25	35	507
3	22	C1	New	2	0.2	55	796
4	22	D1	New	2	0.25	55	796
5	22	A2	Worn	2	0.2	35	507
6	22	B2	Worn	2	0.25	35	507
7	22	C2	Worn	2	0.2	55	796
8	22	D2	Worn	2	0.25	55	796

EXPERIMENTAL SET-UP

Machining

The experiments were carried out on a HAAS SL-10 CNC lathe machine, which was controlled by a Fanuc Haas controller. Throughout the experiments, the pitch was kept constant at 2.0mm, and the depth of cut was set at 0.2 and 0.25 mm. The cutting speed employed during the machining tests was 35 and 55 m.min⁻¹, while the spindle speeds were adjusted at 507 and 796 rev.min⁻¹. The machining experiments were carried out in a dry cutting condition. The cutting conditions used are given in Table 1.

Workpiece Materials

Titanium alloys are available in several different grades. Most of the grades are of alloyed type with various additions of, for example, aluminium, vanadium, nickel, ruthenium, molybdenum, chromium or zirconium. Titanium alloy Ti-6Al-4V is a widely used grade as it offers high strength, depth hardening ability and elevated temperature properties up to 400°C. The workpiece material used in the thread machining was a titanium alloy Ti-6Al-4V, the composition of which is given in Table 2. A rod with ϕ 38mm was cut using a band saw to a length of 140mm. The rod was turned to ϕ 22mm and faced to 120 mm length by using a conventional lathe machine. The thread was then produced under dry machining based on the required cutting parameters. The material was then to be divided into smaller portions, as illustrated in Figure 1. Carbide coated with PVD aluminium titanium nitride (AlTiN) was used as the threading insert. The thread dimensions were M22 x 2.0 sharp 60° V (see Figure 2).

Table 2. Chemical composition of the titanium alloys [21].

Work material	Chemical composition							
	Ti	Al	V	Fe	O	C	N	H
Ti – 6% Al – 4% V	Balance	6	4	0.3	0.2	0.1	0.05	0.0125

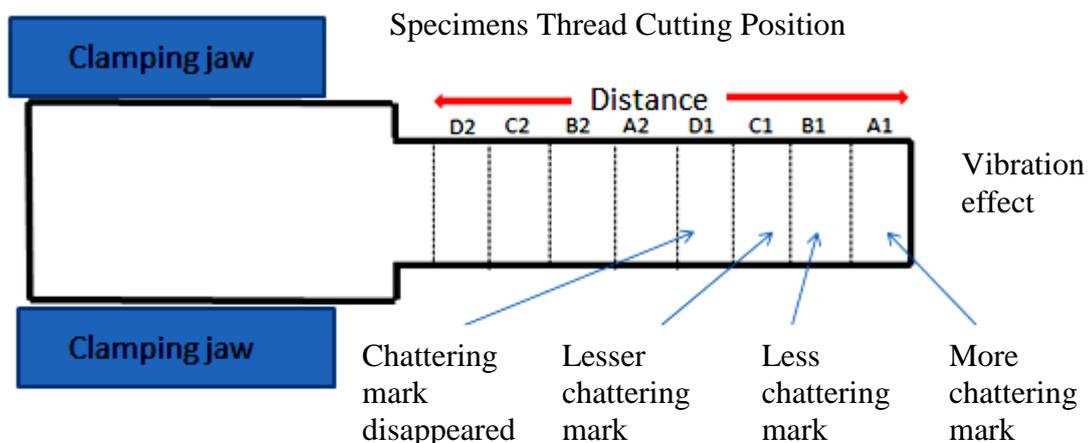


Figure 1. Workpiece clamping position.

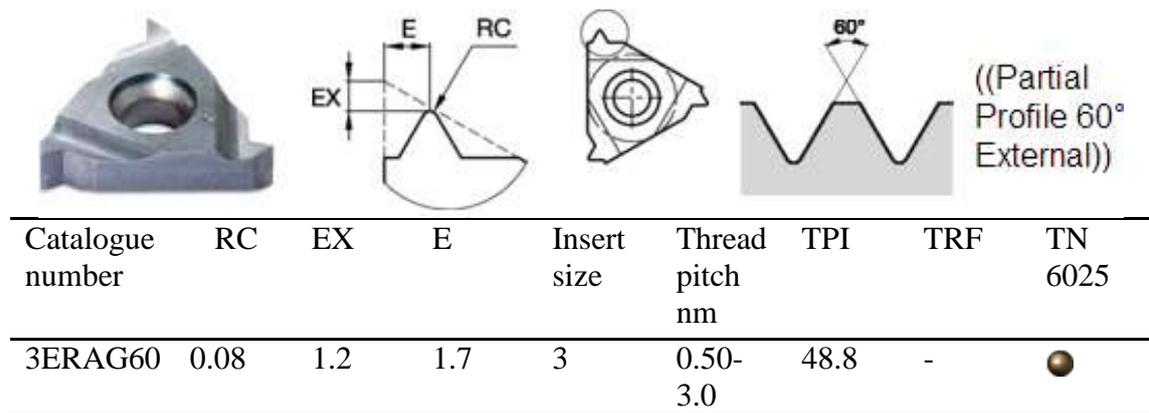


Figure 2. Cutting tool geometry specification.

RESULTS AND DISCUSSION

Surface Finish

The variation in surface texture for each specimen can be seen via optical microscope. From the experiments, two types of surface pattern were identified, consisting of feed marks and chattering marks. The phenomenon known as “chatter” happened during the cutting operation, where several types of vibrations influence the chip flow-rate and final work surface. Compared to free and forced vibrations, self-excited vibrations are more detrimental to the finished surfaces and cutting tools and this may result in large amplitudes of relative motion between the cutter and workpiece [22]. The feed mark reflects the depth of cut on the thread, where a greater depth of cut produced a rougher feed mark. A smoother thread surface can be obtained by providing 0.5mm or less depth of cut for the finishing cut. The chattering mark was caused by the workpiece’s clamping position during the cutting process. The greater the distance from the clamping point, the clearer the chattering mark produced on the specimen as the workpiece tends to chatter. Figure 1 shows the workpiece’s clamping position during the studied specimen production. The chattering marks gradually disappear when the specimen gets closer to the clamping point.

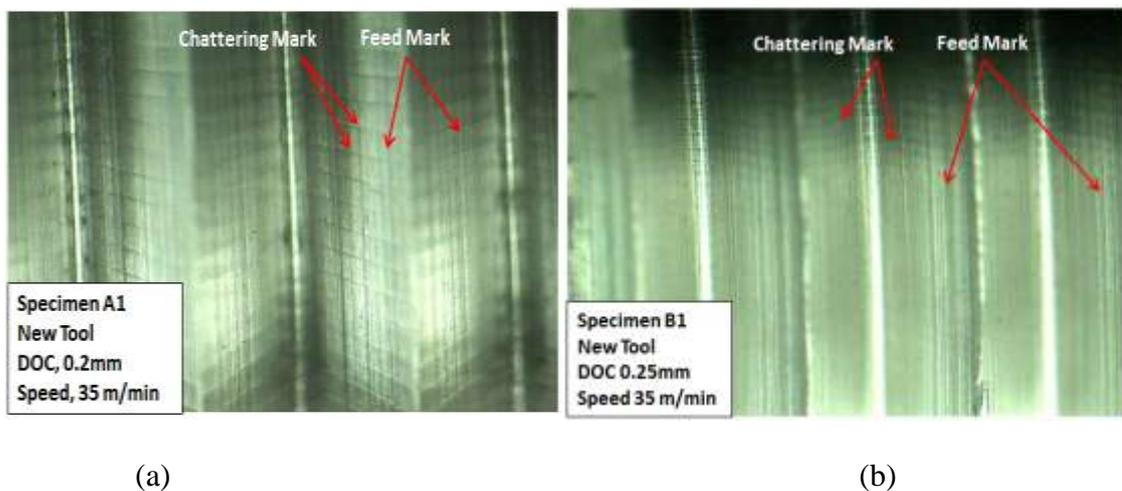


Figure 3. (a) Chattering mark and feed mark clearly visible-50x; (b) Feed mark clearly visible and chattering mark gradually disappearing -50x.

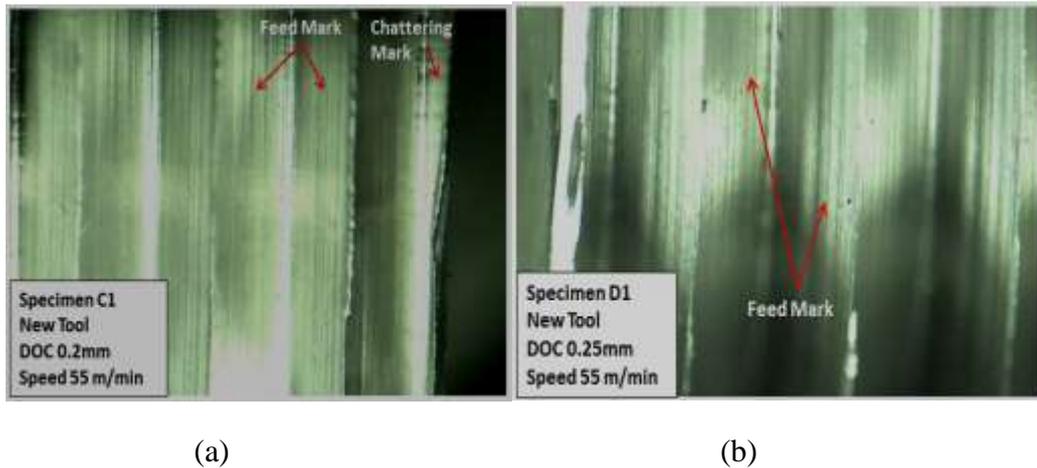


Figure 4.(a) Chattering mark prone to disappear but feed mark clearly visible -50x
(b) Chattering mark totally disappears but feed mark clearly visible- 50x.

No critical surface damage was found on specimens produced by the new tool, as can be seen in Figure 3 and Figure 4. Only slight differences can be visually spotted between specimens A1, B1, C1 and D1 which were respectively produced by the new tool. In general, the surface roughness of the machined component decreased with the increase in cutting speed [21]. This proves that the variable cutting parameters that were set to generate variation in the thread surface texture were not effectively achieved. Greater differences in the range of depth of cut and cutting speed should be set for better results. A feed mark appeared to be relatively clear on each specimen as it approached the clamping point. A chattering mark was clearly visible on specimen A1. However, it gradually disappeared on specimen C1. The surface finish tends to become smoother towards the end of tool life. This is probably due to deformation on the flank face or adherence of the workpiece material at the tool nose [20]. The visuals were focused randomly on the roots of the thread and no other damage pattern was found.

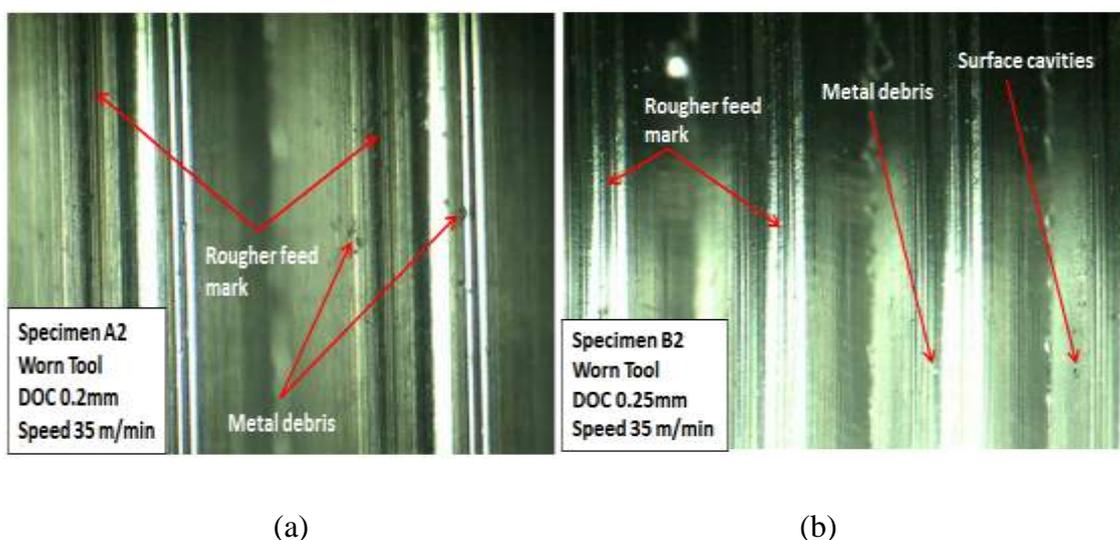


Figure 5. (a) Surface damage produced by worn tool - 50x; (b) The existence of surface cavities and other damage - 50x.

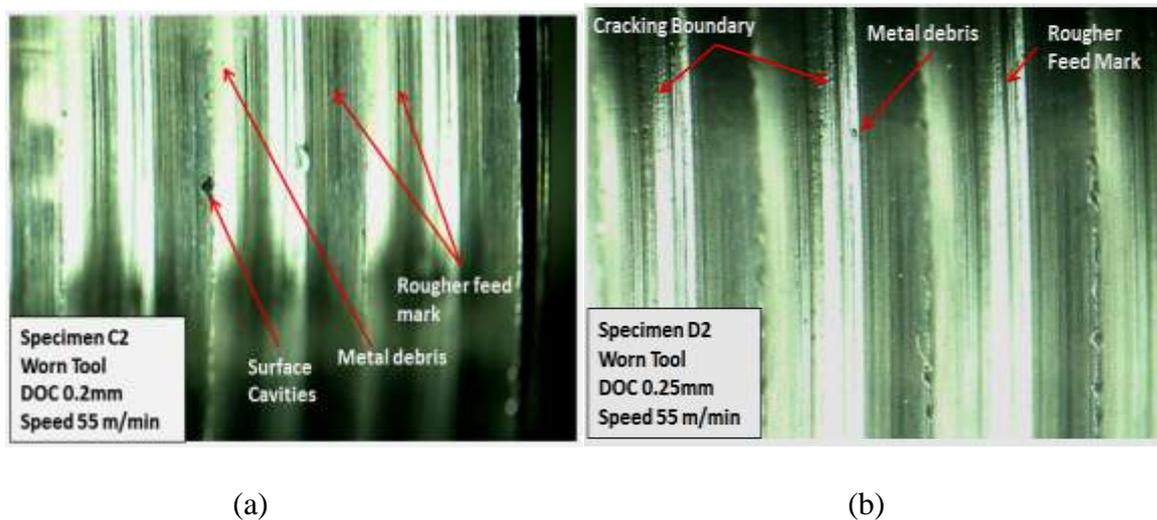


Figure 6. (a) Larger surface cavities and other damage spotted- 50x; (b) Cracking boundary and other damages spotted-50x.

Visual optical observation on specimens produced by the worn tool revealed several types of surface texture damage, as shown in Figure 5 and Figure 6. Machining of the titanium alloy with the nearly worn tools tends to increase the hardening rate of the surface layer [20]. Other than a rougher feed mark, damage in the form of metal debris, surface cavities and a cracking boundary was also spotted. The assumption is that the worn tool was not cutting effectively, but tends to rub the material surface, especially for a difficult-to-machine material like titanium alloy. When the cutting tool became dull, this meant that the nose radius became bigger, and the change in the nose radius corresponds to the feed marks on the machined surface [7]. The rubbing action provides high cutting pressure which causes the workpiece to tend to move away from the cutting tool. In addition, a freshly cut surface may be burnished by a dull cutting tool, and hence work-hardened at the machined surface [23]. Furthermore, extreme undissipated heat generated at the cutting edge encourages the accumulation of sheet-material on the tool surface. This process is usually known as galling and is related to adhesion wear. This condition is part of a factor that contributes to the abovementioned surface damage.

CONCLUSIONS

The findings of the surface texture analysis prove that the surface produced by a new tool is much better than with a worn tool. The rougher feed mark on the specimen produced by the worn tool was caused by the ineffective cutting edge. Uneven cutting contact along the worn tool's nose leaves a scratch mark and a rough feed mark surface. The absence of coolant might also be a factor that affects the surface texture, as there was no lubricant agent to smooth the cutting process. The effect of variable cutting parameters such as depth of cut and cutting speed for both the worn and new tools was not clearly seen via the optical microscope. All the damage was caused by the physical condition of the tool. However, the effect of variable cutting parameters can be found in microstructure alteration analysis.

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