УДК 621.95.01 **doi: 10.20998/2078-7405.2019.91.13**

Ildiko Maňkova, Marek Vrabel,
Ladislav Kandráč, Košice, Slovakia

EVALUATION OF CHIP MORPHOLOGY WHEN DRILLING TITANIUM ALLOY

Abstract: *Chip formation within a hole making processes plays an important role in selection of proper machining parameters. Understanding of this phenomenon is also important in relation to wear behaviour or machined surface integrity parameters like roughness, residual stresses and many others. Proposed study aims to compare different shapes and forms of chips produced when drilling titanium alloy Ti-6Al-4V with solid carbide tool by various cutting conditions. The effect of cutting edge radius and side clearance angle on chip formation process was also considered within this work. Experimental data has confirmed strong relationship between drilling parameters and evaluated variable.*
Keywords: *drilling experiments; tungsten carbide; titanium alloy; types of chips; chip morphology; machining parameters.*

1. INTRODUCTION

Chip evacuation from machined hole still represents one of the fundamental difficulties of the drilling process. A better understanding of chip formation while machining titanium and its alloys enables the identification of optimal machining conditions contributing to higher productivity, increased component quality and lower production costs from the perspective of extended tool life [1]. Constricted space in the drill flutes causes chip accumulation especially when machining ductile materials such as titanium. Such a material tends to generate continuous helical chips [2]. The major disadvantage of the helical chip formation is degradation of the finished surface by scratches generated when chips are transported away from the cutting zone. According to Sharif and Rahim [3] straight carbide (uncoated WC-Co) remains the best tool in turning, milling, drilling when compared to coated carbide tools. The tool material and its geometry as well as process parameters during high-throughput drilling of Ti-6Al-4V were extensively investigated by Li et at. [4]. They concluded that higher cutting speed resulting to higher productivity was achieved using commercially available WC-Co spiral point drill in comparison to conventional HSS twist drill. However, there is a lack of research articles in the field of hole making titanium alloy aimed to study effect of tool geometry (clearance angle) and micro geometry (cutting edge radius) on resulting chip morphology. Mikó et al. [7] in their research paper optimized finishing process within twist drill production to ensure desired cutting edge radius for given tool. Durakbasa and Bas [15] evaluated relationship between nanometrological parameters of the high precision cutting tools and surface roughness after machining.

Slodki et al. [9] investigated chip form during orthogonal machining of titanium and steel alloys with respect to cutting parameters and cutting fluid conditions. Other difficulties related to machinability of titanium and its alloys were summarized by Neslušan and Czán [10].

Li et al. [4], Rahim et al. [5], Zhang et al. [8] and Kim et al. [6] investigated that the same chip morphology, a continuous chip with three regions of initial spiral cone followed by the steady-state spiral cone and folded long ribbon chip, could be seen in all Ti drilling tests, as shown Figure 1 and Figure 2. Zhang et al. [8] and Kim - Ramulu [6] concluded that the characteristic of the chip formation in twist drilling of titanium based alloy is different from other metals categorized the Ti chips into three types: continuous chip, continuous chip with built-up edge, and discontinuous chip. The distinctive features of Ti chip can be described as serrated, shear-localized, discontinuous, cyclic and segmented.

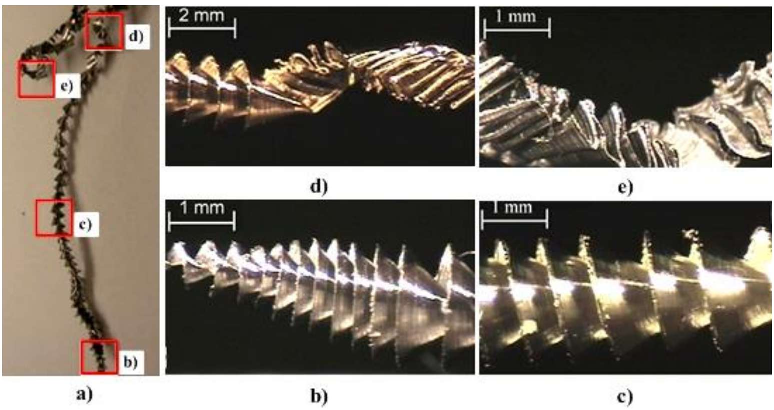

Figure 1 – Chip morphology of Ti-6Al-4V at v_c = 18.3 m/min and f = 0.051 mm: a) whole chip, b) initial spiral cone, c) steady-state spiral cone, d) transition between spiral cone and folded long ribbon, and e) steady-state folded long ribbon [4]

Li et al. [4] mentioned that after drilling, the Ti chip could be entangled around two flutes of the drill and bent by the tool holder. This is called chip entanglement, which is due to the difficulty for smooth chip ejection. An example of the chip generated by WC/Co Spiral drill at 18.3 m/min cutting speed and 0.051 mm/rev feed in dry drilling is shown in Figure 1 a). The close-up view of the initial spiral cone, generated at the start of drilling from the beginning of contact to whole diameter penetrate into the work piece, is illustrated in Figure 1 b). After this step, the steady-state spiral cone chip morphology, as shown in Figure 1 c), was generated. Due to the increased resistance to eject the chip, the spiral cone was changed to folded ribbon chip morphology. Close-up view of the chip transition region and the folded ribbon chip are shown in Figures 1 d) and e), respectively. Under the same MRR (156 mm^3/s), the best drill life and surface finish results were achieved at 91 m/min peripheral cutting speed and 0,102 mm/rev feed using the WC–Co spiral point drill.

Rahim et al. [5] studied that the most of the chips were discontinuous based from the significant formed of saw tooth. In general, the formation of saw tooth in machining titanium alloys is due to the instability of thermoplastic at primary shear zone. In this experiment, periodic chips formation was obvious probably due to the selected cutting speeds which fall within the high speed range.

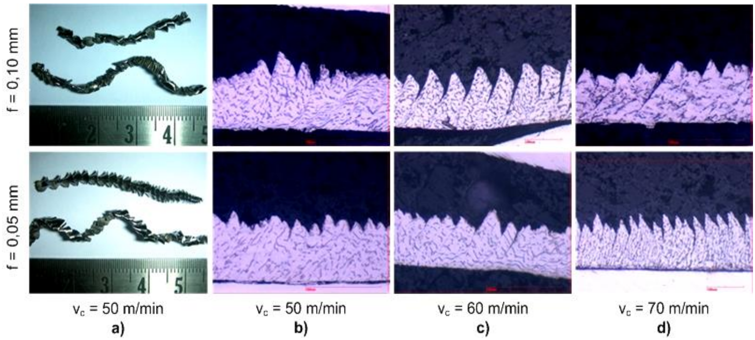

Figure 2 – Chip shape and saw tooth chip formation of Ti-6Al-4V:
a) chip shape v_c = 50 m/min, b) SEM sample v_c = 50 m/min,
c) SEM sample v_c = 60 m/min, d) SEM sample v_c = 70 m/min [5]

Fig. 2 shows the long folded wavy type chips and long curly type chips were produced at feed f = 0.05 mm and they were slightly longer than at feed f = 0.1 mm. In contrast, short folded wavy type chips were produced for feed f = 0.1 mm. The average chip segmentation ratio tends to decrease with increase in cutting speed from 50 m/min to 70 m/min

Based on this literature review proposed study focuses on research related to the evaluation of chip morphology with regard to cutting conditions (feed, cutting speed) and tool geometry parameters in drilling titanium alloy Ti-6Al-4V with solid carbide twist drill. Furthermore, graphical matrix with various types of morphologies was created for easier identification of undesirable chip form with respect to studied variables.

2. EXPERIMENTAL CONDITIONS

The drilling experiments were conducted on a 3 axis Mazak Nexus 410 A-II vertical machining centre with maximum spindle revolution 12 000 rpm.. The machine tool has maximum spindle motor output 11 kW. It is equipped with Mazatrol Matrix Nexus controller. The machining experiments were carried out using Agip Aquamet 4 HS – BAF cutting fluid supplied with high pressure to enhance the capability of chip evacuation from cutting zone The cutting data used for the experiments are contained in Table 1.

Uncoated straight tungsten carbide WC/Co twist drills with diameter of 8.2 mm with various geometries were employed to perform experimental testing. Due to superior wear resistance and thermal stability is tungsten carbide still preferable choice in machining titanium or nickel based alloys. Cutting tools were supplied by ProTech Service Company. To ensure cutting edge sharpness, a new twist drill has been used for each test within experimental work. The workpiece material used in the all experiments was a forged bar of an alpha – beta titanium alloy Ti-6Al-4V with diameter of 300 mm and thickness of 31.5 mm.

Table 1 – Taguchi orthogonal array L16 for drilling experiments

Exp No	$\mathbf{v_c}$ [m/min]	**f** [mm/rev]	**α** [˚]	**Exp** No	$\mathbf{v_c}$ [m/min]	**f** [mm/rev]	**α** [˚]
1	25	0.05	7	**9**	60	0.05	15
2	25	0.1	7	**10**	60	0.1	15
3	25	0.15	15	**11**	60	0.15	7
4	25	0.2	15	**12**	60	0.2	7
5	40	0.05	7	**13**	90	0.05	15
6	40	0.1	7	**14**	90	0.1	15
7	40	0.15	15	**15**	90	0.15	7
8	40	0.2	15	**16**	90	0.2	7

Chemical compositions and mechanical properties of the work piece material are summarized in Tab. 2 and 3.

Table 2 – Nominal chemical composition of the Ti-6Al-4V alloy

Elements	Ti	Al	V	Fe	O	N
Ti6Al4V (%)	Bal.	6.01	3.87	0.18	0.14	0.006

Table 3 – Mechanical properties of the test sample

Tensile strength Rm (MPa)	**Yield strength Re** (MPa)	**Modulus elasticity** (GPa)	**Hardness** (HRc)	**Elongation at fracture A5** (%)
900	830	114	36	14

A series of cuts at various combinations of cutting speeds of 25, 40, 60 and 90 m/min, feed rates of 0.05, 0.1, 0.15 and 0.2 mm/rev, clearance angles of 7˚ and 15˚ as well as cutting edge radii of 20 and 30 µm (Figure 3) to show their effect on chip formation process.

It is well known that the cutting tool edge geometry significantly influences many fundamental aspects such as cutting forces, chip formation, cutting temperature, tool wear, tool life and other characteristics like surface roughness and surface damage [11].

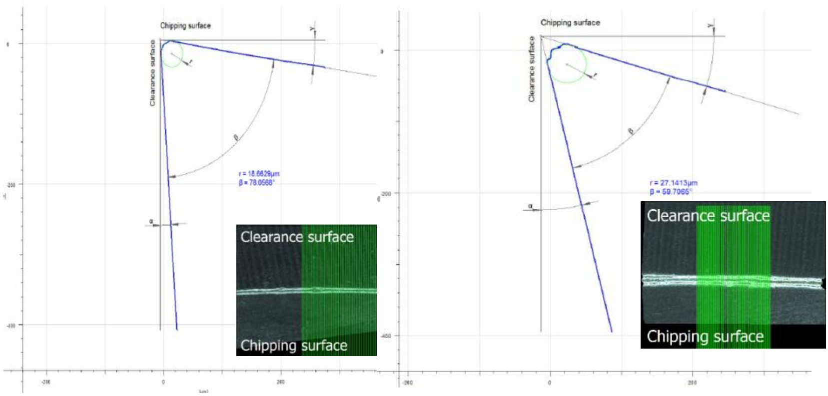

Figure 3 – Representative cutting tool geometries used in experiments
a) 20µm b) 30µm cutting edge radius, respectively

Wyen and Wegener [12] evaluated the effect of cutting edge radius on selected variables in orthogonal machining of titanium alloy. They stated that a large cutting edge radius causes a large deformation of material in front of cutting edge radius as well as more energy is needed for the plus of deformation. Taguchi orthogonal array (OA) L16 was used to conduct experiments. According to Kivak et al. [13], Taguchi method compared to traditional experimental designs makes use of a special design of OA to examine the quality characteristics through a minimal number of experiments.

3. RESULTS AND DISCUSSION

Different types of chips obtained from drilling tests were collected and are shown in Figure 4 after each cut with a new tool. Green line in Figure show acceptable chip form red line show undesired chip morphology in drilling. According to form and morphology of resulting chips can be stated that chip formation in process of hole making plays an important role in evaluating and proper selection of cutting conditions (v_c, f) that have significant impact on their formation as well as for chip evacuation from cutting zone. The adhesion of the titanium during machining generates an increase in friction between the chip and the tool rake face, resulting in a thicker chip. This could also explain the increase in tool wear and also possibly the increase in cutting force. Hence, chip formation processes are significantly affected by the conditions of the tool. According to Li et al. [4] the balance of cutting speed and feed is essential to achieve long drill life and good hole surface roughness in high throughput drilling Ti-6Al-4V titanium alloy with fine-grained WC–Co tool material

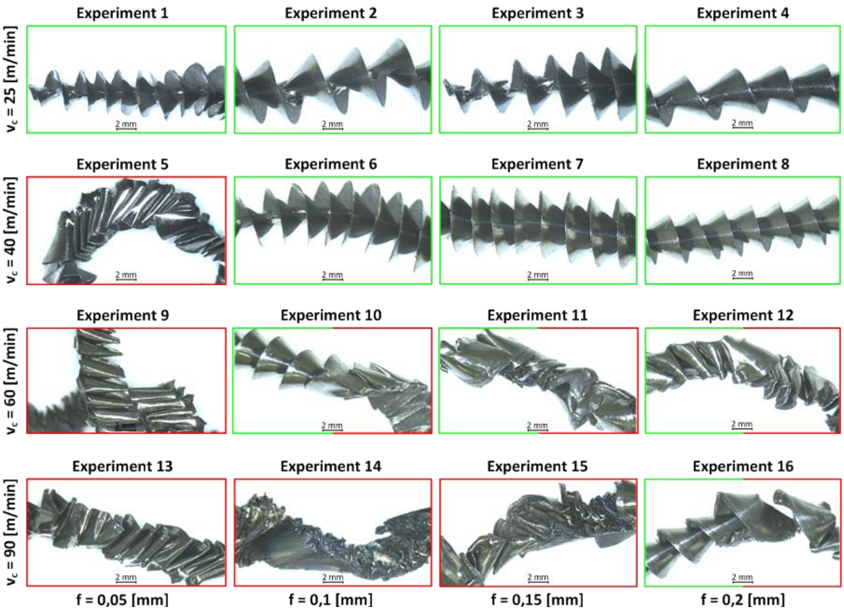

Figure 4 – Various types of chip morphology from drilling tests

Spiral cone shape represents favourable chip morphology in drilling titanium. Such a morphology was observed when drilling with lower cutting speed (v_c = 25 m/min) and all feed rates used (f = 0.05, 0.1, 0.15, 0.2 mm) as well as with v_c = 40 m/min and f = 0.15, 0.2 mm, stage 1 and 2, respectively as shown in Figure 5.

On the other side, when machining with higher cutting speeds (v_c = 60 and 90 m/min) become chip ejection from the drilled hole more difficult and chip morphology has changed from spiral cone to folded ribbon shape. When machining with higher cutting speeds v_c = 60 and 90 m/min and all feed rates employed becomes chip transfer from cutting zone more complicated and difficult.

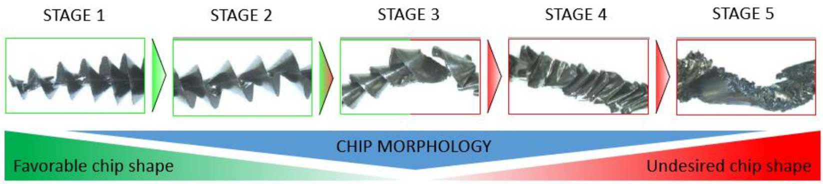

Figure 5 – Different stages of chip evaluation

In stage number 3 and 4, the steady spiral cone has changed to the so called folded ribbon chip morphology, which is undesired chip shape in drilling operation and causes problems with its evacuation. On the other hand, in machining with inappropriately selected cutting parameters (higher than tool manufacturer´s recommendation) and insufficient cooling, phenomenon of adhered chip in the area of tool-chip interface can occurs.

Figure 6 – Welded chip on cutting tool - experiment No 15

Armendia et al. [14] in their work concluded based on previous research that adhesion is a typical feature in titanium machining because of both the high temperatures generated and its chemical reactivity with most of the tool materials. Adhered work piece material results to severe deformation and increases resistance to eject the chip from hole machined, see Figure 6. Chip morphology in Stage 5 (welded chip) is absolutely unacceptable for drilling due to unpredictable process behaviour.

4. CONCLUSIONS

Chip morphologies examined from drilling titanium alloy Ti-6Al-4V with WC/Co uncoated carbide tool have proven strong relationship with cutting condition employed as expected. Furthermore, phenomenon of adhered chip and severe tool wear occurs when machining with higher cutting parameters mainly cutting speed (v_c = 60 and 90 m/min). Cone spiral chip has change to folded ribbon shape in cutting speed higher than 40 m/min. Influence of feed rate is less significant when compared to influence of the cutting speed. This can be explained by increasing temperature which tends to adhere work piece material to cutting tool a thus worsens chip evacuation from cutting zone. Effect of cutting edge radius and clearance angle on deformation process is also considered within this article, but within macro scale observation no significant effect of tool geometry on chip formation was found. Micro scale research including SEM represents excellent topic for the future work.

ACKNOWLEDGEMENTS

The authors greatly appreciate the support of project VEGA 1/0219/18 "Development of intelligent monitoring system for zero-defect production of irreplaceable parts."

References: **1.** *Palanisamy S., McDonald S. D., Dargush M. S.* (2009) Effect of coolant pressure on chip formation while turning Ti6Al4V alloy. Int. J. of Mach. Tools and Manufacture (49):73-743**.** **2.** *Brinksmeier E., Pecat O., Rentsch R.* (2015) Quantitative analysis of chip extraction in drilling of Ti6A64V. CIRP Annals – Manufacturing Technology (49): 93-96**.** **3.** *Sharif S., Rahim E. A.* (2007) Performance of coated and uncoated carbide tools when drilling titanium alloy – Ti6Al4V. Journal of Material Processing Technology (185): 72 – 76. **4.** *Li R., Hegde P., SHih A. J. (2007)* High-throughput drilling of titanium alloys. *Int. J. of Mach. Tools* and Manufacture (47): 63 – 74. **5.** *Rahim E.A., Kamdani K., Sharif S.:* Performance evaluation of uncoated carbide tool in high speed drilling of Ti6Al4V. (2008), J Adv Mech Des Sys Manuf vol. 2, pp. 522–531. **6.** *Kim D. - Ramulu, M. - Pedersen, W.:* Machinability of titanium/graphite hybrid composites in drilling. In: Transactions of NAMRI/SME. Vol. 33, 2005, pp. 445-452. ISSN 1047-3025. **7.** *Mikó B., Palásti – Kovács, B., Sipos S., Drégelyi – Kiss Á.* (2015) Investigation of cutting edge preparation process in drilling. Inter. Journal of Machining and Machinability of Materials (6): 529 – 542. **8.** *Zhang P.F., Churi N.J., Pei Z.J., Treadwell* **C.:** Mechanical drilling processes for titanium alloys: A literature review. (2008), Machining Science and Technology vol. 12, No. 4, pp. 417-444. ISSN 1532-2483. **9.** *Slodki B., Struzikiewicz G., Slusarczyk L.* (2016) Influence of cutting fluid conditions and cutting parameters on the chip form in turning of titanium and steel alloys. Key Engineering Materials (686): 74 – 79. **10.** *Neslušan M., Czán A.* (2001) Obrábanie titánových a niklových zliatin. 195 pp., EDIS Žilina, ISBN 80-7100-933-4**. 11.** *Dogra M., Sharma V. S., Dureja J.* (2011) Effect of tool geometry variation on finish turning – A Review. Journal of Engineering Science and Technology Review (4): 1- 13. **12.** *Wyen C. F., Wegener K.* (2010) Influence of cutting edge radius on cutting forces in machining titanium. CIRP Annals – Manufacturing Technology (59): 93-96. **13.** *Kivak T., Samtas G., Cicek A.* (2012) Taguchi method based optimisation of drilling parameters in drilling of AISI 316 steel with PVD monolayer and multilayer coated HSS drills. Measurement (45): ISSN 1547-1557. **14.** *Armendia M., Garay A., Iriarte L. M., Arrazola P. J.* (2010**)** Comparison of the machinabilities of Ti6Al4V and TIMETAL 54M using uncoated WC – Co tools. Journal of Materials Processing Technology (210): 197 – 203. **15.** *Durakbasa N. M., Bas G.* (2013) Surface Roughness Investigation of the Cutting Edge of the High Precision Cutting Tools Enabled by Micro and Nanometrological Measurements. Proceedings of the XXVII. microCAD International Scientific Conference. ISBN 978-963-358-018-9; 5 pages.

Ільдіко Манкова, Марек Врабел,
Ладіслав Кандрач, Кошіце, Словакія

ОЦІНКА МОРФОЛОГІЇ СТРУЖКИ ПРИ СВЕРДЛІННІ ТИТАНОВИХ СПЛАВІВ

Анотація. *Формування стружки в процесах виготовлення отворів грає важливу роль у виборі правильних параметрів обробки. Розуміння цього феномена також важливо по відношенню до поведінки зносу або параметрів цілісності оброблюваної поверхні, як шорсткість, залишкові напруги і багато інших. Пропоноване дослідження націлене на порівняння різних форм і розмірів стружки під час свердління титанового сплаву Ti-6Al-4V твердосплавними свердлами в різних умовах різання. Вплив радіусу заокруглення різальної крайки і заднього кута на процес стружкоутворення також було розглянуто в рамках даної роботи. Експериментальні дані підтверджують тісний взаємозв'язок між режимами свердління і параметрамі, що оцінюються. Експерименти проводилися з використанням спіральних свердел з вольфрамо-кобальтового твердого сплаву, без покриття, діаметром 8,2 мм і з різною геометрією. Для виключення впливу зносу, використовувалися кожного разу нові свердла. Морфологія стружки, досліджена під час свердління титанового сплаву Ti-6Al-4V твердосплавним інструментом без покриття WC / Co, довела, як і очікувалося, тісний зв'язок із існуючими умовами різання. Крім того, явище прилипання стружки і сильного зносу інструменту виникає при обробці з більш високими параметрами різання, в основному зі швидкістю різання (Vc = 60 і 90 м / хв). Конічна спіральна стружка має форму складчастої стрічки при швидкості різання більше 40 м / хв. Вплив швидкості подачі менш істотний в порівнянні з впливом швидкості різання. Це можна пояснити підвищенням температури, при якій матеріал заготовки прилипає до ріжучого інструменту, що погіршує видалення стружки із зони різання. Вплив радіусу ріжучої крайки і заднього кута на процес деформації також розглядається в цій статті, але при спостереженні в макромасштабі не було виявлено суттєвого впливу геометрії інструменту на формування стружки. Мікромасштабні дослідження, включаючи SEM, представляють відмінну тему для майбутньої роботи.*

Ключові слова: *експерименти з свердління; карбід вольфраму; титановий сплав; типи стружки; морфологія стружки; параметри обробки.*