Influential Parameters in Plunge Milling for Titanium Alloy Ti-6Al-4V

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Abstract. Plunge milling is an interesting production mean for machining deep workpieces. It is identified as a process potentially able to afford significant gains in productivity during the roughing phases, especially in the case of workpieces made of hard materials. Within this paper, a study of cutting forces in plunge milling of titanium alloy Ti-6Al-4V is conducted. Several types of inserts provided by manufacturing tools suppliers with various cutting angles, type of chip breaker and nose radius, are exploited along with different cutting parameters. The results show the influence of the geometrical parameters and cutting parameters on the cutting forces, and give various information to establish next the optimal trajectories of the tool during plunge milling operations on titanium alloys, according to the type of workpieces.

Keywords: Plunge milling · Cutting forces · Titanium alloy Ti-6Al-4V

1 Introduction

When working in deep slots and cavities with traditional milling, tool bending and vibrations are usually encountered. These problems are generally solved by reducing cutting parameters. However, using this solution causes a loss of productivity, especially during roughing phases. As a better alternative, plunge milling can be employed [1]. This technique involves a series of successive plunges (axially) into the stock, each time separated by a radial offset as presented in Fig. 1. The benefit of plunge milling is that the cutting forces change from radial to axial, leading to more stability, particularly required when using a long tool assembly and machining difficult-to-cut materials like titanium alloys. Thus, cutting parameters can be increased and less time will be needed to remove the excess material.

Most of the previous works related to cutting forces in plunge milling were conducted on materials other than titanium alloys such as stainless steel [2], magnesium alloys [3], aluminum alloys [4] and they were mainly concentrated on the effect of cutting parameters. On the other hand, plunge milling cutting forces in the case of titanium alloys are little addressed [5] and their analysis didn't take into account the effect of geometrical parameters represented by cutting angles, type of chip breaker, edge radius and nose radius. Therefore, our work focuses on studying the influence of cutting parameters and geometrical parameters on plunge milling operation applied on

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titanium alloys. The experimental procedure is described in paragraph 2. An analysis of cutting forces in accordance with cutting and geometrical parameters is then carried out in paragraph 3. Finally, a conclusion is given in paragraph 4.

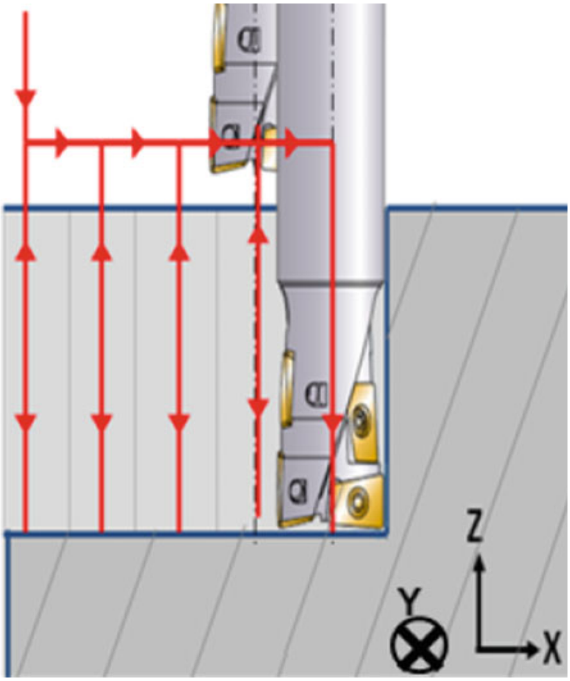

Fig. 1. Plunge milling principle

2 Experimental Protocol

2.1 Material

The studied material Ti-6Al-4V is one of the most commonly used titanium alloys. The composition of this alloy and its properties are presented in Table 1 and Table 2 [6].

Table 1. composition of Ti-6Al-4V

Element	Al	V	N	C	H	Fe	O	Ti
Percentage	6	4	<0.05	<0.1	<0.015	<0.3	<0.2	Balance

Although titanium is as strong as steel, it is about 40% lighter in weight, which, along with its high strength and exceptional corrosion resistance makes it an essential structural metal for aerospace field [7]. However, machinability of titanium alloys is considered as an important issue [8, 9]. In fact, titanium and its alloys have a low

Table 2. Properties of Ti-6Al-4V

Property	Minimum value	Maximum value	Units
Density	4.429	4.512	g/cm^3
Elastic limit	786	910	MPa
Young's modulus	110	119	GPa
Ductility	0.05	0.18	
Thermal conductivity	7.1	7.3	W/m K

modulus of elasticity and a high elastic limit, which causes the problem of spring back during machining. Also, because of the relatively low thermal conductivity of titanium alloys, the intense heat produced during machining is absorbed by the cutting tool which eventually wears more rapidly. Added to that, the feed speed and cutting speed required when machining these metals are generally low, which leads to a low material removal rate. Therefore, an optimum choice of the cutting conditions and tool is essential.

2.2 Cutting Tools

The cutting tools are chosen from the plunge milling products proposed by recognized manufacturing tools suppliers. The first tool is a 32 mm diameter Mitsubishi AJX milling cutter and the second tool is a 33 mm diameter Mitsubishi AQX milling cutter (Fig. 2). Several types of inserts with differences in macro and the micro-geometries are used in order to analyze the influence of those parameters on the process. The cutters are designed for roughing, and the grades of the inserts are adapted for machining titanium alloys.

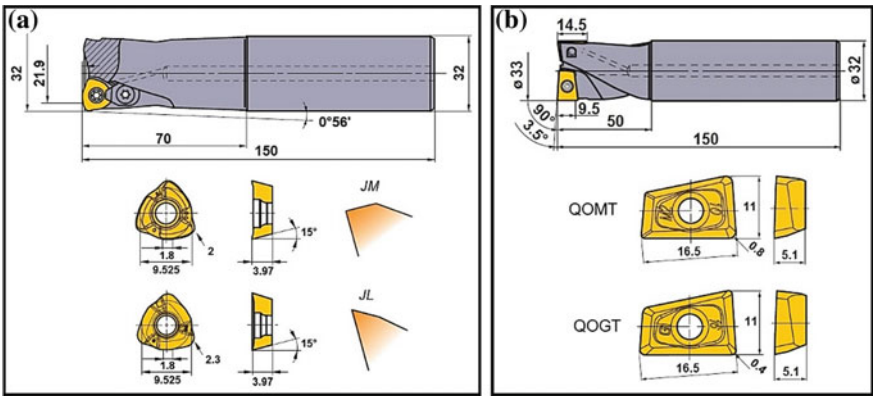

Fig. 2. Cutting tools: Mitsubishi AJX (**a**); Mitsubishi AQX (**b**)

Cutting angles and edge radius of the cutters are obtained with a profile projector and the 3D optical measurement system Alicona (Table 3). Kr is the angle between the main cutting edge of the insert and the tool displacement, γ1 and γ2 are the effective axial cutting angles (γ1 = γn1 + γp and γ2 = γn2 + γp), and fz* is the limit of fz which defines the zone where only γ1 is active (Fig. 3).

Table 3. Geometrical parameters of cutting tools

	Mitsubishi—JL	Mitsubishi—JM	Mitsubishi—QOGT	Mitsubishi—QOMT
rε (mm)	2.3	2	0.4	0.8
rβ (μm)	21	27	35	70
Kr °	103	115	86	86
αn °	17	18	12	17
βn °	54	57	59	64
γn1 °	5	−19	19	−1.5
γn2 °	19	15		9
γf °	−6	−6	0	0
γp °	7	7	6	6
γ1 °	12	−12	25	4.5
γ2 °	26	22		15
fz*	0.27	0.19		0.22

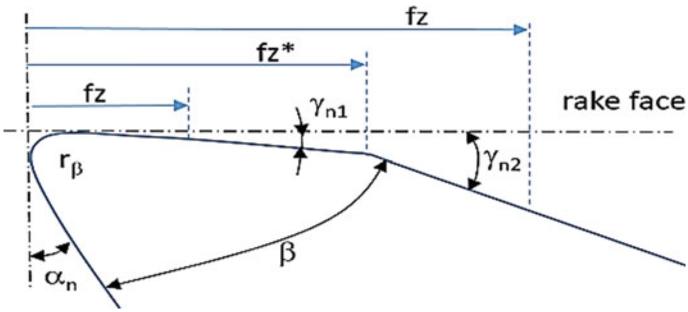

Fig. 3. Geometrical parameters of the insert

2.3 Experimental Procedure

A DMU 85 monoBLOCK 5-axis CNC machine is used to perform full width cut plunge milling tests on titanium alloy Ti-6Al-4V blocks, with lubrication and only one insert. Different values of cutting speed Vc, feed per tooth fz and radial offset ae (Table 4) are used in order to analyze the influence of these parameters on cutting forces. The cutting depth is 10 mm and cutting forces are given by a Kistler six-component force measurement plate 9257B.

Table 4. Cutting parameters

Vc (m/min)	fz (mm)	ae (mm)
50	0.1	2
60	0.15	3
70	0.2	4
80	0.25	5
	0.3	

The measured forces are the three orthogonal components of cutting force Fx, Fy and Fz. These forces are then converted into the rotating reference of the cutter in order to obtain the tangential Ft, radial Fr and axial Fa forces using the Eqs. (1–3) based on the angle of engagement of the insert θ in the chip area and entry angle θ_e (Fig. 4). During tests, one of the cutting parameters is changed for each plunge, in order to evaluate its influence on cutting forces.

$$F_t = F_y \cdot \cos\theta - F_x \cdot \sin\theta \quad (1)$$

$$F_r = F_x \cdot \cos\theta + F_y \cdot \sin\theta \quad (2)$$

$$F_a = F_z \quad (3)$$

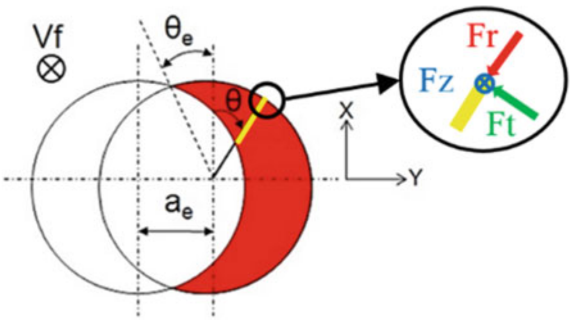

Fig. 4. Chip area for full width cut plunge milling

3 Results and Discussion

The analysis is based on the maximum value of forces. The tangential force and the axial force are maximum in the position θ = 90° (Figs. 4 and 5). Although the radial force reaches its peak before θ = 90°, its value in this position is still close to the maximum. In fact, the highest stress applied on the tool is at the position θ = 90°, due to there is a maximum chip area. Accordingly, all the forces are considered in that position. Mitsubishi AJX tools will be referred as JM and JL and Mitsubishi AQX tools as QOGT and QOMT.

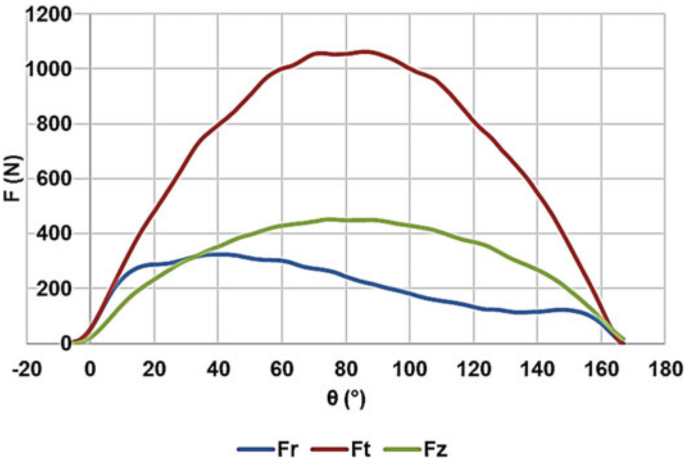

Fig. 5. Test conducted with AQX—QOGT tool using Vc = 60 m/min, fz = 0.2 mm and ae = 5 mm (Low-Pass Filter 150 Hz)

3.1 Influence of Cutting Speed

With a feed per tooth fz = 0.2 mm and a radial offset ae = 3 mm, tests with different values of cutting speed Vc from 50 to 80 m/min are conducted (Fig. 6).

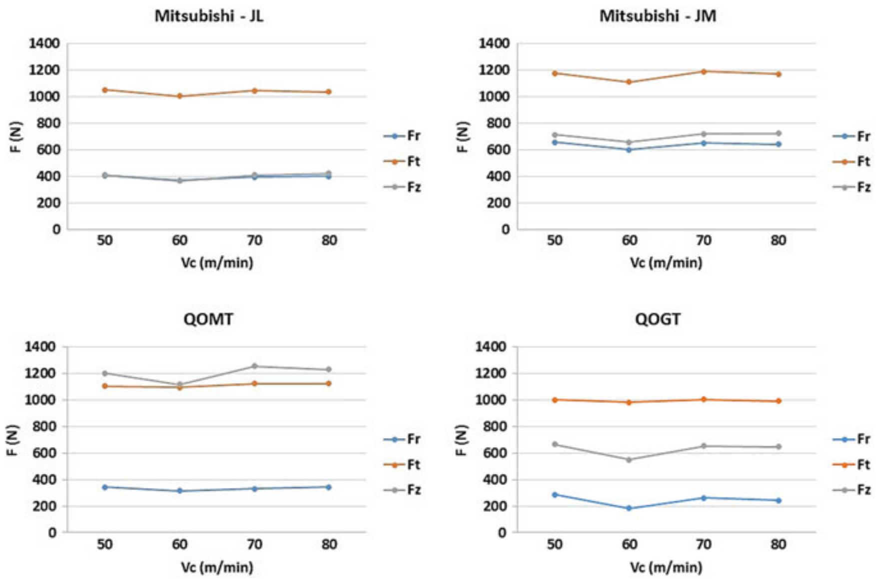

Fig. 6. Influence of cutting speed on cutting forces

For cutting speed Vc = 60 m/min, the cutting forces are minimum and from this value, the cutting speed almost has no effect as we obtain a small increase and then a stabilization. In fact, for that value of cutting speed, the thermal softening is sufficient to cut the material with minimal force and energy. After that, even with greater cutting speed (70 and 80 m/min), a stable cutting process is maintained and the cutting forces almost remain the same. However, cutting speed is considered a very important parameter in terms of the cutting tool life as found in previous works [5, 10].

3.2 Influence of Feed Per Tooth

Tests are carried out with a cutting speed Vc = 60 m/min, a radial offset ae = 3 mm and several values of feed per tooth fz from 0.1 to 0.3 mm (Fig. 7).

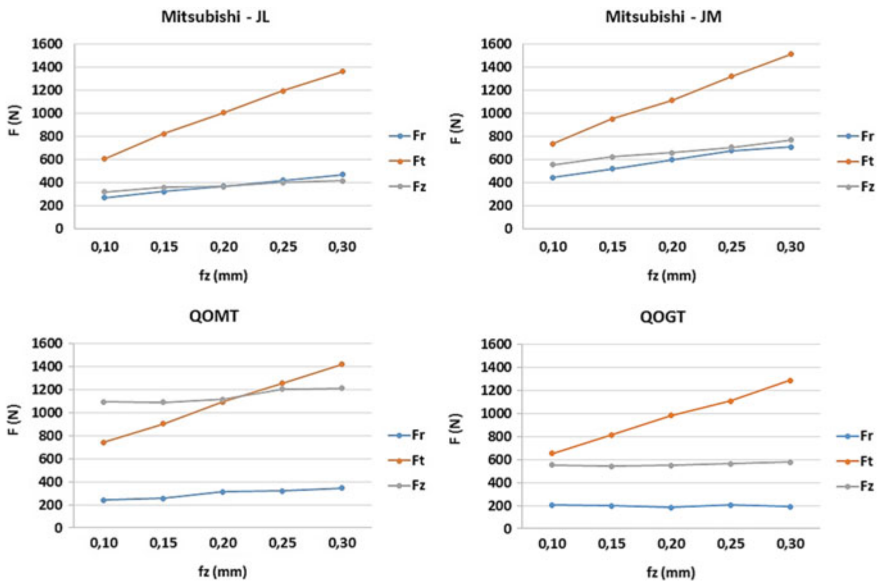

Fig. 7. Influence of feed per tooth on cutting forces

Feed per tooth affects mostly the tangential force which increases almost linearly with this parameter. The dependency of radial and axial forces on the feed per tooth is lower. Indeed, since this parameter represents the height of the maximum cutting section, it indicates the engaged part of the insert nose radius (Fig. 8). When the feed per tooth increases (from fz1 to fz2), that part expands, which induces a raise of both of the forces especially for tools with higher insert nose radius and edge radius.

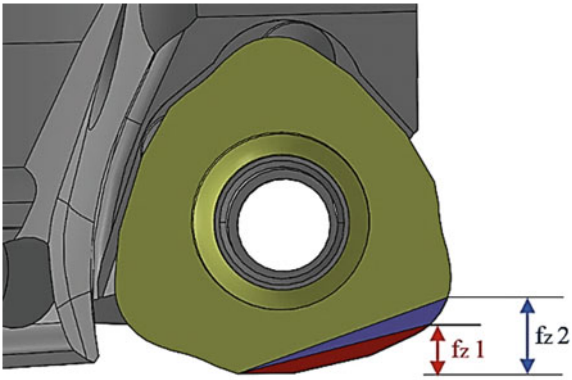

Fig. 8. Dependency of the engaged part of the insert nose radius on feed per tooth (AJX tool)

3.3 Influence of Radial Offset

Different values of radial offset ae from 2 to 5 mm are tested while using a cutting speed Vc = 60 m/min and feed per tooth fz = 0.2 mm (Fig. 9).

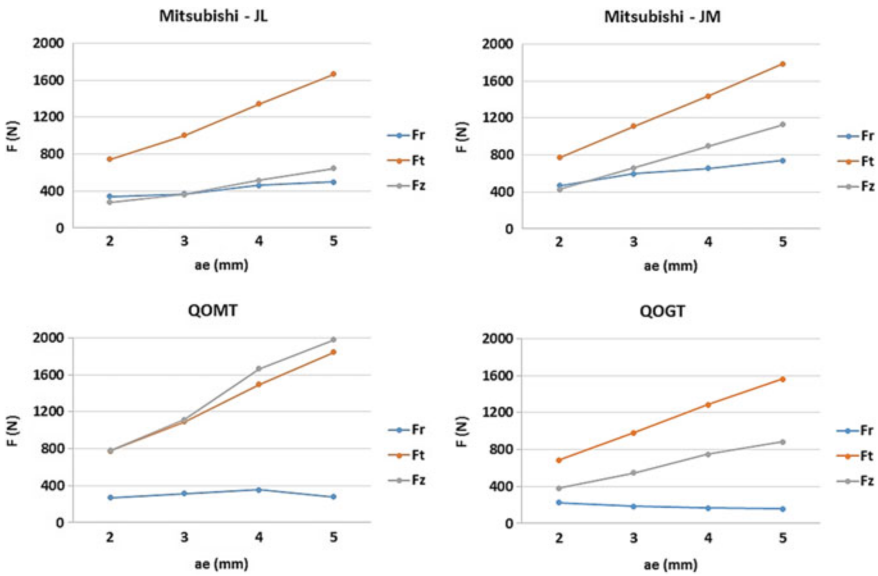

Fig. 9. Influence of radial offset on cutting forces

A quasi-linear increase of the tangential force is obtained when radial offset increases. Besides, a similar behavior is shown by the axial force. The main cause is that when the radial offset increases, the engaged part of the insert becomes larger, resulting in a quasi-linear increase of the axial force. About the radial force, two different behaviors are obtained: for Mitsubishi—JM/JL, a rise of the force is obtained with the increase of radial offset. However, with Mitsubishi AQX, we have a compensation between the components of the force through the main cutting edge, the nose radius and a part of the vertical edge, (Fig. 10) resulting in a little increase and then a decrease of the radial force for QOMT, and a progressive reduction of the effort for QOGT. The two different behaviors are directly related to the cutting edge angle Kr. If this angle is greater than 90°, we have the continuous increase of the radial force. If it is less than 90°, we obtain the compensation between the components of the force.

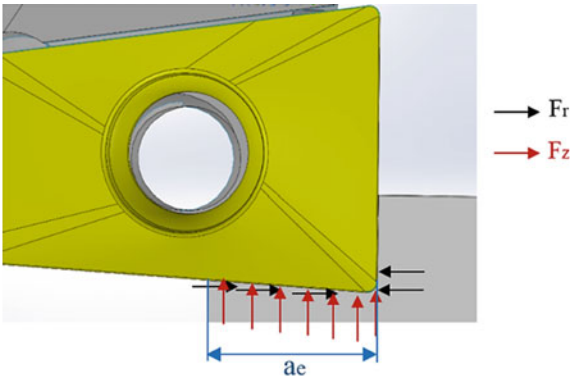

Fig. 10. Representation of radial offset and cutting forces (Mitsubishi AQX tool)

3.4 Influence of Geometrical Parameters

Based on the variation of the maximum forces (Figs. 6, 7 and 9) and the geometrical data of the tools (Table 3), several interpretations are made.

Tangential force is strongly influenced by the axial rake angle as it decreases with the increase of this parameter. In fact, for example with the AJX tool, for feeds per tooth up to fz = 0.25 mm (Fig. 7), the axial rake angle is mainly given by $\gamma 1$ (JM: −12°, JL: 12°), and the insert JL exhibits then the lowest tangential forces. Edge radius of the insert $r\beta$ (QOGT: 35 µm, QOMT: 70 µm) has also an impact on tangential force which is reduced when the tool is sharper, particularly for low feeds per tooth.

Axial force is heavily dependent on the sharpness of cutting edge ($r\beta$) and effective axial cutting angle γ. In fact, the edge radius of QOMT insert is twice as large as that of QOGT insert, and the axial force given by QOMT tool is almost twice that of QOGT tool. In addition to that, the cutting angle $\gamma 1$ of JM insert is negative (JM: −12°, JL: 12°), resulting in much higher axial force compared to that of JL tool, almost its double.

Radial Forces are heavily influenced by the cutting edge angle Kr, mainly whether it is more or less than 90°. We can see that the tools JL and especially JM (with Kr > 90°) create significant radial forces, which increase when enlarging the engaged part of the insert. But QOGT and QOMT tools generate less radial efforts, which also evolve differently when machining more material (Fig. 9). Besides, radial forces are strongly dependent on nose radius rε too. The laterally engaged part of the insert is greater with using larger nose radius, which engenders higher radial forces. Finally, radial rake angle γf (−6° for JM/JL against 0° for QOGT/QOMT) influences also radial forces, as a negative γf makes the tool blunter and increases the cutting forces.

4 Conclusion

The influence of diverse parameters on plunge milling of titanium alloy Ti-6Al-4V is investigated. Based on the analysis of elementary tests of z-axis milling with different cutting tools, the following conclusions can be drawn:

- Plunge milling provides a minimal radial force, which results in less vibrations and more stability during machining titanium alloys. Besides, radial forces can be minimized by using an insert with a cutting edge angle equal to or less than 90°, a zero radial rake angle, and small edge radius and nose radius.
- On cutting parameters, the radial offset is the most influential on cutting forces. The feed per tooth has a less influence, but considerably important in particular on the tangential and radial forces. While the dependency on cutting speed is relatively low. A good choice of these parameters is essential in order to assure an excellent productivity with acceptable levels of cutting forces.
- The geometrical parameters represented by cutting angles and edge preparation, are very important to have a better behavior of the cutting tool during plunge milling.
- With the inserts JL/JM/QOGT, the tangential force is the highest cutting force. In order to have axial forces of the same order as tangential forces, inserts with high edge radius like QOMT have to be used.
- When using plunge milling for roughing very deep pockets, we can use a tool with a reduced sharpness like AQX – QOMT tool, to have higher axial forces and low radial forces, which results in a better stability during the process.
- The continuation of the study will be related to the wear according to cutting and geometrical parameters, in order to make the best choice of the tool when roughing a specific workpiece made of titanium alloy.

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