International Journal of Machine Tools & Manufacture 67 (2013) 28–34

Contents lists available at SciVerse ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Analytical and experimental investigations on thread milling forces in titanium alloy

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ARTICLE INFO

Article history:
Received 6 August 2012
Received in revised form
17 December 2012
Accepted 18 December 2012
Available online 28 December 2012

Keywords:
Thread milling
Titanium alloy
Cutting forces
Design of experiments

ABSTRACT

This study deals with the thread milling process that is considered a complex machining technique due to its elaborated tool geometry and its tridimensional tool trajectory. It needed advanced research on the threading process which has not been much studied. Previous studies focused on geometrical modeling or mechanistic modeling of the thread milling process. There is a need for a better understanding of parameter effects to accomplish a model that tends to be more realistic and includes local parameters. This investigation does the analysis of thread milling parameters: thread geometry, cutting conditions and tool angles, which can be applied to the tool optimization. The cutting forces and torque were measured and representative values of its variation were calculated and analyzed as response of the experiments. A geometrical analysis and an analysis of variance were employed for determining the influence of the factors and based on the results, it is proposed a physical understanding of the process.

1. Introduction

Threaded pieces are needed for wide applications in industry and it can be manufactured in a variety of ways, applying the two basic principles: plastic working or metal cutting. Threads produced by plastic deformation have higher strength than the machined ones but does not guarantee high accuracy or precision as in tapping and thread milling, the cutting methods. Especially for brittle or special materials that cannot be produced by plastic working.

As an example, materials for medical solutions, as titanium alloys and smart material alloys, require the manufacturing process with controlled proprieties and precision either for internal and external threads. There are very few papers exploring thread milling forces on titanium alloys although it has been widely used for medical and dental implants [1–3].

Internal thread cutting can be produced by tapping tools in machining center or by turning tools in lathe, in these cases feed velocity can be very high because it is proportional to the thread pitch, cutting velocity and tool diameter. Breakage of a thread-cutting tool can impact significantly the productivity of the process [4]. When compared to form tapping [5] or cut tapping, a broken tool in thread milling is easier to evacuate without damaging the workpiece, so it is a good alternative for high cost parts. While tapping requires a given tool for producing a specific thread dimension, thread milling can produce threads in bigger diameters and special threads.

For cut tapping there are some researchers dedicated to develop models for the process: mechanistic models for the prediction of tapping torque including identification of faults typical of a tapping operation (as misalignment, runout and tooth breakage) [6,7], unified-generalized mechanics of a cutting model, as it is called in [8], and experimental studies, as in [9] that used the electrical current signal of the spindle motor for diagnosis.

The study on thread milling cutting forces was first developed by Araujo et al. [10]. A mechanistic force model was created from a linear thread cutting experiment where the referential frames were superposed and independent from the tool trajectory. The feed velocity in the vertical direction was neglected. After mechanistic calibration, the model was applied in a helical path by rotating force basis and it was validated. Fromentin and Poulachon [11,12] developed a geometric local analysis for thread milling considering the envelope tool profile, an analytical formulation of the cutting edges and a more precise calculation for uncut chip thickness. It is pointed out a concern on interesting local cutting edge aspects, including flute angle, and how it reflects on the cutting area and cutting force components. The present study includes some changes on geometrical analysis if it is compared to the previous ones [12]. Those geometrical and phenomenological hypothesis have to be validated by experimental analysis.

In 2012, Sharma et al. [13] developed a model adding the vertical feed to the simulation. Another important improvement in the force

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http://dx.doi.org/10.1016/j.ijmachtools.2012.12.005

model concerns on the calibration that takes into account the local normal rake angle in the cutting edge is considered [12].

The technique of designs of experiments (DOE) and analysis of variance (ANOVA) is widely used to optimize parameters of machining processes due to its capacity to identify the most influential factors on the process, as presented in [14,15] for end milling analysis.

The main goal of this paper is to achieve the understanding of global forces, based on experiments and its relation to geometrical parameters. The present study is focused on the thread milling of titanium alloy Ti_6Al_4V and the following parameters are studied: flute angle, rake angle, thread diameter, depth of cut and feed rate. A geometrical analysis is presented and it defines criteria to characterize the thread milling conditions. A specific experimental set-up was developed for measuring cutting force, acquiring tool position and computing forces in different referential frames needed for mechanical analysis. From data analysis the paper proposes some modifications on its analysis and it opens further possibilities for tool optimization and mechanistic force modeling.

2. Process analysis

The basics of thread milling processes and tool sequences are described in previous articles [10,13,16,17]. The thread machining begins positioning the tool on the center of a drilled hole, followed by a penetration strategy to the bulk. There are basically three penetration strategies [18]: straight penetration, quarter revolution penetration and half revolution penetration (HRP), which is used in Fig. 1a. After the penetration, the tool is said to be in "full machining" (FM) and the tool axis trajectory describes a r_{tt} radius circle in the XY projection plane inside the drilled hole. The internal threads studied in this article are metrical, right hand, one tool pass is used and the cutting begins with the tool in the lower part of the hole, ending in the top after producing the helical trajectory. The total tool displacement in FM for z is one thread pitch P [19]. After the cutting, the tool retracts from the thread surface to the center of the hole and after outside the workpiece.

2.1. Thread milling parameters

The thread milling parameters are presented in order to clarify and unify the nomenclature from published articles. In full machining, the tool has two important engagement parameters related to circular trajectory: radial depth of cut r_{doc} and radial penetration r_p, shown in Fig. 1b. Radial penetration is calculated using the nominal thread diameter D and the minor diameter of the internal thread D_1 [19], and for the most common case is described in [12] as

$$r_p = \frac{D - D_1}{2}. \tag{1}$$

For this case, the radial depth of cut is written as a function of the thread pitch and the tool diameter D_t, defined by Fromentin and Poulachon [12] by

$$r_{doc} = \frac{P(80.\sqrt{3}D - 75.P)}{256(D - D_t)}. \tag{2}$$

The instantaneous axial depth of cut a'_{doc} reduces (in FM) from the initial axial depth of cut a_{doc} down to $(a_{doc} - P)$, as the tool goes up and z increases.

Feed per tooth f_t takes into account the helical trajectory used by the CNC command. It can be projected to the XY plane $f_{t_{xy}}$ and calculated as a function of the angular thread pitch $p_\theta = P/2\pi$ [12]:

$$f_{t_{xy}} = \frac{f_t}{\sqrt{\left(\frac{p_\theta}{r_{tt}}\right)^2 + 1}}. \tag{3}$$

For each pitch profile to be manufactured, the tool cutting edge presents three orientations: upper, front and lower cutting edge, as presented in [12]. The maximum uncut chip thickness $t_{c_{max}}$ on front cutting edge has close relation to the cutting force. In thread milling it is calculated as an approximated function of the radial depth of cut and tool diameter, as follows:

$$t_{c_{max}} \approx 2 f_{t_{xy}} \sqrt{\frac{r_{doc}}{D_t}\left(1 - \frac{r_{doc}}{D_t}\right)}. \tag{4}$$

2.2. Cutting continuity

Cutting continuity is an important property for end milling and thread milling that reduces the instantaneous cutting force and the amplitude of its variation that contributes for vibrations and a possible fatigue fracture. The flute angle λ_{st} contributes directly to the cutting continuity. The flute in contact with the cylindrical surface defines, in the XY plane, an flute engagement angle δ, presented by Tlusty and MacNeil [20]. For end milling using constant a_{doc}, it is calculated by

$$\delta = \frac{2 a_{doc} \tan(\lambda_{st})}{D_t}. \tag{5}$$

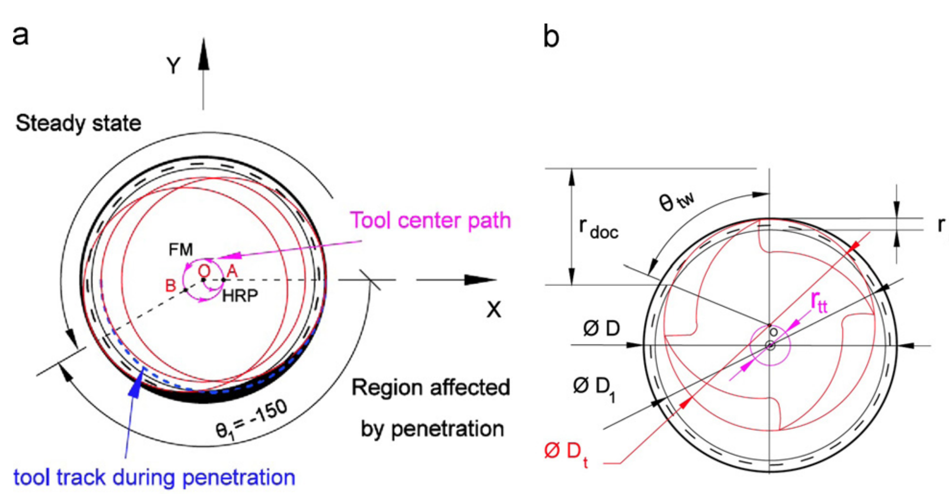

Fig. 1. Thread milling process in aerial view: (a) analysis of penetration on steady state and (b) geometrical parameters.