A Process Planning Framework for Milling of Titanium Alloys

D. Dimitrov[1], P.J.T. Conradie[1], G. Oosthuizen[2],
[1] Department of Industrial Engineering, Stellenbosch University
[2]Department of Mechanical Engineering Science, University of Johannesburg

Abstract

Titanium alloys are being used increasingly in new generation aircraft, creating a market for high value components. It is argued that knowledge development is the key factor for South African machining suppliers to penetrate the global aerospace supply chains. This paper discusses current results of a collaborative project aiming at systematic research towards improved and more efficient utilisation of the High Speed Cutting (HSC), and particularly the High Performance Machining (HPM) technologies for selected titanium alloys. A process planning framework for milling of titanium alloys has been developed. Using as point of departure prominent tool demands, this framework combines a tool wear map approach and cost modelling that enables process planners as well as machine operators to act towards optimised machining. In this way the targeted cost minimisation and lead time shortening could be modelled and practically achieved.

Keywords

Titanium Alloys, Milling, Tool wear

1 INTRODUCTION AND BACKGROUND

The SA Titanium Industry strategy framework has been formulated with a view to deliver titanium related competencies across the entire titanium value chain, from production of titanium minerals to the manufacture of final products [1]. For that purpose the development efforts are concentrated on key technology building blocks. One of these key building blocks is targeted at the machining of titanium alloys. This is a core competence required for the production of finished products particularly for the aerospace industry as main driver of this development. Typical product examples include integral and structural parts for aircraft assemblies. In most cases, these products are machined from solid titanium metal bars or plates, or from very rough pre-forms; hence, large amounts of material typically need to be removed. The geometric and material restrictions are causally responsible for keeping the production methods and techniques as the remaining key cost factor. High demands regarding safety and quality constrain the increase in efficiency of conventional production technologies. Therefore the production of such components is rather irrational from a materials utilisation as well as a productivity point of view. In order to position South African manufacturers to competitively service local and export markets there is thus a need to develop not only a competency in machining of titanium, but also improved process chains for the production of finished parts.

2 CURRENT UNDERSTANDING OF MILLING TITANIUM ALLOYS

Titanium alloys find wide application in many industries, due to their unrivalled and unique combination of high strength-to-weight ratio and high resistance to corrosion. The machinability of Titanium (Ti) alloys is impaired by its high temperature chemical reactivity, low thermal conductivity and low modulus of elasticity [2]. The challenges in milling of this material can be divided into thermal and mechanical tool demands.

2.1 Thermal demands

The cutting tool will fail catastrophically when cutting speed (v_c) is too low due to diminished thermal softening or when it is too high due to chipping preceded by extensive crater wear.

2.1.1 Thermal load

Temperature versus v_c is usually modelled as a power law relationship, which may rise to infinity with an increase in the cutting speed [3]. This is acceptable for interpolating temperature at HPM, but for HSC the tool face temperature (T_v) may approach the melting point (T_m) of the work piece. The critical thermal load (T_c) is currently limited (around v_c = 300 m/min) in order to prevent material burn of the Ti-components, due to safety regulations [4]. For rough milling, more associated with HPM, the recommended cutting speeds range from 30-60 m/min. However for HSC, where very light radial cuts and thin chips are produced, the cutting speeds can range from 150-250 m/min.

2.1.2 Exposure time

The tool temperature is represented not solely by T_v. Of equal importance is the exposure time (τ) of the tool material to and above critical temperature (T_c) at a certain depth level below the surface. It is the volume of the cutting edge that is exposed to the degrading (e.g. T_c=800±100 °C) conditions [4]. The best balance of a high amount of heat Q_w and economic tool life (TL) is found with $a_e/Ø$ between 30 to 40% for roughing, where a_e the radial immersion and $Ø$ the tool diameter are [5].

2.1.3 *Thermal shock*

The tool is submitted to force fluctuation and cyclic heating and cooling as the tool enters and exits the work piece. The fluctuation is the temperature change defined by ΔT (≈250°C for Ti-alloys) [4], which can initiate a phenomenon known as thermal fatigue [6]. In HSC where rapid tool wear nucleates from small cracks, high transverse rupture strength (TRS) is beneficial, while in HPM where the tools are over cooled and cracks always form, high *toughness* is of particular importance [5].

2.1.4 *Climb (down)- and Conventional (up) milling*

Climb milling is normally recommended, because the instant the cutting tool enters the Ti work piece material it starts to cut, without initial sliding. While this generates less heat between the tool and work piece, more of this heat can also dissipate into the thicker chip, compared to conventional milling at the start of the cut. Rubbing occurs more frequently as flank wear V_B exceed 0.15mm [4].

2.2 Mechanical demands

The mechanical demands include the mechanical load (h_{eMax}) and the influence of different types of vibration.

2.2.1 *Mechanical load*

In milling the mechanical load (h_{eMax}) is a function of the tool diameter ($Ø$), the feed rate (f_z) and the radial immersion (a_e). The effect of the tool entering angle (κ_r) should also be considered. The friction force (F_f) between the tool and the flow of the chip along the rake face is largely influenced by the tool design and frictional phenomena, due to the periodical welding behaviour of the chip onto the tool. The three primary heat sources correlate with the cutting force components. The main shear band heat source will be the predominant heat source especially at higher cutting speeds. The secondary shear band heat source is the heat generated during the upsetting stage of cyclic chip formation, and the frictional heat source is the heat generated between the segment already formed and the rake face of the cutting tool [7].

2.2.2 *Vibration during milling*

Fluctuation in cutting forces cause tool breakage, while chatter results in very poor surface finish and reduced tool life. Catastrophic tool failure through chipping is caused by pulsating loads due to shear localization, self-induced chatter and altering cutting forces generated during the milling process [7,8].

2.2.3 *Chatter*

The chatter phenomenon does occur at standard conventional cutting speeds, although it is more distinct and destructive with higher spindle speeds (HSC) in the milling of Ti-alloys. This chattering can cause tool edge micro-chipping [2]. The stability of the milling process has been investigated using experimental, numerical and analytical methods. Deep immersions (a_p) result in very high cutting forces and severe chatter vibrations [8].

2.2.4 *Forced vibration*

Research indicates that vibration increases in response to the formation of serrated chips, which is also a consequence of low heat conductivity. This further leads to stronger variations in the cutting force components. Catastrophic tool failure during cut is a result of the forced vibration from the formation of shear localization [7,9].

3 A FRAMEWORK FOR PROCESS PLANNING OF MILLING OPERATIONS

3.1 General considerations

The process planning for milling operations starts by analysing the features of the Ti-component. Thereby, the machining strategy can be developed and the style of cutter be selected (Figure 1). Thereafter, initial cutting parameters could be set that are used to simulate (using e.g. CAD/CAM software) the cutting process of the component. Thus, the machine operator can realize the total cutting time of the component and plan its schedule replacement tool times (SRT) accordingly. At the same time he can compare these parameters with the predicted tool life (TL) from tool wear maps. If the predicted TL from the wear map is less that the SRT value, it will result in unplanned downtime. Therefore, it is essential to be ensured that the tool will cut for longer than the SRT value.

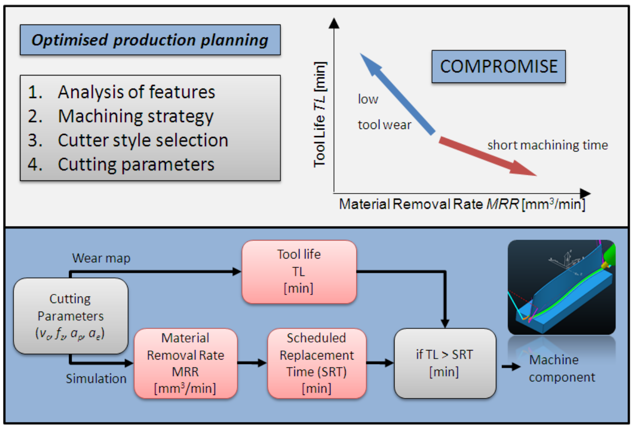

Figure 1 - A process planning framework for the milling of Ti-components – a schematic view

As a result there will always be a compromise between TL and the material removal rate (MRR). In-house trials show that the judicious choice of machining conditions, made possible using appropriately constructed wear maps, could lead to the near-ideal situation of attaining a desirable MRR (productivity).

3.2 Wear characterisation

One way to select the most suitable machining conditions is to examine the trends of tool wear with varying cutting parameters. A safe operating region can be proposed for cutting tools by superimposing possible boundaries. It is suggested that as long as the machining parameters lay within this safe zone, the tools would not suffer catastrophic tool failure (failure before SRT). Premature, catastrophic tool failure is the least desirable failure mode, because it is the most unpredictable, can be damaging to the work piece and cause costly downtime. This type of failure can be minimized through an understanding of the physical demands on the cutting tool and the effect of changing the operating conditions. Figure 2 shows the developed wear map approach for milling operations and illustrates the way remedial actions are integrated. The positive correlation in terms of wear-rate trends obtained with other work piece materials suggests that this is a viable mean to achieve the objective of developing an integrated predictive system for tool wear in metal cutting.

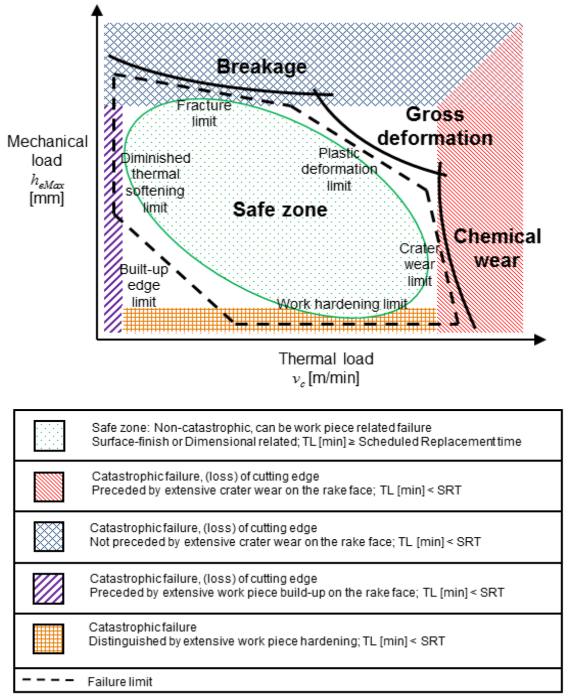

Figure 2 - Tool wear map approach – a principle view

The safe zone depicted in the failure mode diagram is a region of gradual wear associated with reliable performance. Thermal activation refers to the breakdown caused by high temperature cycling of the cutting edge between the heating and cooling stages in milling. Chemical wear is therefore caused by a reaction between the tool and the work piece during cutting. The cutting edge strength is the property that resists the breakdown of the cutting edge due to the cutting impact. Breakage by means of fracture is found when the mechanical load exceeds the physical properties of the tool material.

3.3 Cost modelling

3.3.1 Point of departure

To be able to construct an effective cost model it is of utmost importance to have a dependable mean to predict tool life and determine corresponding tooling costs. The Taylor tool life equation is one of the most famous equations for determining the tool life in machining operations and has been used extensively for cost modelling purposes. However, there are some challenges in applying the Taylor tool life equation under practical conditions, and more specifically for certain difficult to machine materials such as titanium alloys. The application of the Taylor tool life equation is discussed here along with the problems associated with it. An alternative approach is then presented to determine the tool life and the actual tooling costs.

An important part of machining economics is to determine the costs associated with the cutting tools. As cutting proceeds, the tool continuously loses value up to the point where failure occurs and the tool has no value left. This depreciation is a non-linear relationship and requires experimental work to determine the equation allowing the prediction of this tendency.

The importance of predicting the tool life and ultimately costs along this non-linear curve becomes apparent when the cost model as a whole is analysed. The major components of such a model are the costs associated with the cutting tools used and the costs associated with the work place – machine, operator, overheads etc. The work place costs elements are usually combined into one hourly rate. This cost component can be plotted as a linear function of the machining time. The tooling cost on the other hand has a non-linear relationship. The rationale behind this is that the faster a machining operation is performed (higher material removal rate), the shorter the tool life will be, and thus higher tool costs will occur. And opposite - if the machining operation takes longer (lower material removal rate), the tool life will be prolonged, resulting in lower tooling costs (Figure 3).

The practically relevant cost minimisation requires reaching a compromise between tool life and machining time. Graphically the accumulation of these two cost components will be represented by a curve over time, whose minimum will point the cost optimal duration of the machining operation. The task is therefore to determine at first the representative equation of the tooling cost, followed by a numerical differentiation of the cost sum equation as schematically shown in Figure 3.

As mentioned, determining the machining costs is very simple since it is a linear relationship between time and cost. The challenge however lies in determining a tool cost model. This cost is dependent on the tool life and therefore requires a dependable model to predict it. The Taylor tool life equation is widely used for this, but its applicability and accuracy, as discussed below, poses various problems in applying it to titanium machining processes.

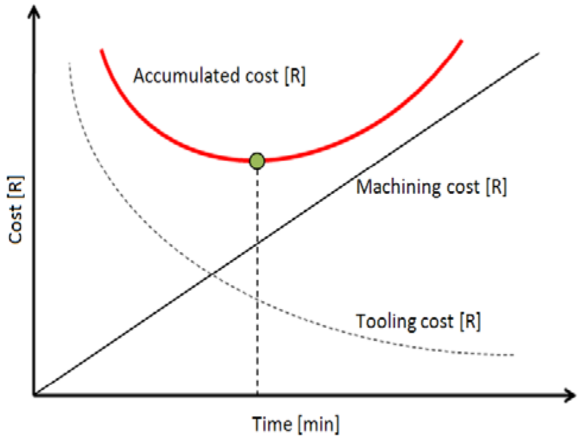

Figure 3 - Determining the cost minimum

3.3.2 Taylor's analytical model

In literature there are many forms of tool life equations, but the most famous one is the Taylor's tool life equation:

$$VT^n = C \qquad (1)$$

Here *n* is the Taylor's tool life exponent and *C* is a constant that depends on the limiting value of the flank wear (usually around $300\mu m$). The values of both these constants depend on the tool–work piece combinations and the cutting environment, and are therefore very specific in their applications. This relation was originally realised for turning operations, so to make it also applicable to other machining operations several forms of the equation have been deduced as summarized in the work of Marksberry and Jawahir [10]. With the current research the focus is on milling operations so the applicable tool life equation is:

$$T = CV_c^n f^x a_p^y a_e^u \qquad (2)$$

where *C, n, x, y* and *u* are tool life exponents that are dependent on the material of the work piece and the cutting tool or inserts. V_c is the cutting speed, *f* is the feed rate, a_p is the axial and a_e is the radial depth of cut respectively.

The problem occurring hereby is that to determine the coefficients in this equation, experiments must be conducted until failure of the cutting tool. To do the experiments for only two levels with four variables will amount to $2^4 = 16$ failure experiments. Although this is realistic for inserts, it is not economically feasible for expensive solid cutter bodies. This is still without consideration of the work piece costs. Ideally it is desired to test at three levels; however, this would amount to 81 experiments, which is also not practical. Because of the independent parameters of this model, it is not possible to make any measurements against time before the tool has failed, which makes the testing once again very expensive. To overcome this problem, models have been developed to include certain dependant parameters so that it is possible to quantify the state of the tool before it has failed. This is done by including the wear of the tool as a parameter in the tool life equation as illustrated in the work of Dos Santos et al. [11]:

$$T = Kv^R f^S a^W b^T VB_{MAX}^Z \qquad (3)$$

where *T* is the tool life, *v* the cutting speed, *f* the feedrate, *a* the radial depth of cut, *b* the axial depth of cut and *VB* the maximum flank wear of the tool. *K, R, S, W, T, Z* are constants that needs to be determined experimentally. Due to the large amount of unknowns, the parameter with the smallest influence on the tool life can be kept constant so that the equation can be simplified. In milling operations this is known to be the axial depth of cut. Simplifying and rearranging gives:

$$v = Cf^E a^F T^G VB_{MAX}^H \qquad (4)$$

where *C, E, F, G* and *H* are once again the constants that need to be determined by means of experiments. Once the applicable form of the Taylor equation is chosen, the next step is to determine the coefficients. The procedure to do this has been applied by Poulachon et al. [12] and Dos Santos et al. [11] and will be illustrated in equations (5)-(9). To transform equation (10) into a linear estimation problem, logarithms are taken on both sides of the equation to form:

$$\begin{aligned} \ln v = \ln C + E\ln f + F\ln a + G\ln T \\ + H\ln VB_{MAX} \end{aligned} \qquad (5)$$

With this form the unknowns can be determined with the use of matrix manipulations as illustrated below:

$$Y = Xb \qquad (6)$$

This equation can be set up in matrix form as shown in equation (7). It is important to note that for the estimation purposes, the preliminary coefficients have the following values: $C^* = -\ln\frac{C}{H}$; $H^* = \frac{1}{H}$; $G^* = -\frac{G}{H}$; $E^* = -\frac{E}{H}$; $F^* = -\frac{F}{H}$. N is the amount of times that cutting operations were stopped to make wear measurements. With this setup, X is known as the sensitivity matrix.

$$\begin{Bmatrix} \ln VB_{MAX1} \\ \ln VB_{MAX2} \\ \ln VB_{MAX3} \\ \vdots \\ \ln VB_{MAXN} \end{Bmatrix} = \begin{vmatrix} 1 & \ln v_1 & \ln f_1 & \ln a_1 & \ln T_1 \\ 1 & \ln v_2 & \ln f_2 & \ln a_2 & \ln T_2 \\ 1 & \ln v_3 & \ln f_3 & \ln a_3 & \ln T_3 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \ln v_N & \ln f_N & \ln a_N & \ln T_N \end{vmatrix} \begin{Bmatrix} C^* \\ H^* \\ E^* \\ F^* \\ G^* \end{Bmatrix} \qquad (7)$$

Since a different amount of experiments will be conducted, the dimensions of the matrices will not correspond. To solve this problem for calculation purposes, the following manipulation can be used:

$$X^T Y = (X^T X) b \qquad (8)$$

$$(X^T X)^{-1} X^T Y = b$$

$$b = V X^T Y \qquad (9)$$

As mentioned earlier this approach requires an extensive amount of experiments to determine all the unknowns. With titanium and its applicable cutting tools this way is particularly expensive and thus not a popular choice for use in industrial environment. According to Choragudi et al [13] another problem is that although the Taylor equation holds well for a number of common engineering and automotive metals, it is not as accurate for titanium. The Taylor approach is therefore not the best applicable mean to determine the tooling costs in titanium milling operations.

3.3.3 Proposed approach

One of the biggest challenges in tool cost modelling is to determine the value of a tool over its life time or how well it was utilized. This is more complex than simply looking at the cost of the tool and the time it was used. It is a non-linear relationship that decreases as machining time commences.

In the past extensive research has been done on the wear and its progression in certain type of tools. So there is a large amount of information available. It is general knowledge that the wear on a tool will have a direct effect on its value at any point of time during a machining operation. As a new tool the value is equal to its purchase price and at failure it is written off or equal to zero. The challenge is to determine the curve and its numerical approximation that this value will follow from new up to the point of failure. For this approach the wear is used as a starting point in developing a relationship.

Due to the correlation between the wear and the value of the tool it will have an approximately same non–linear tendency over time. The well-known shape of the tool wear curve is shown in Figure 4. Since the value of the tool will depreciate as the wear increases, there will be an inverse effect over time.

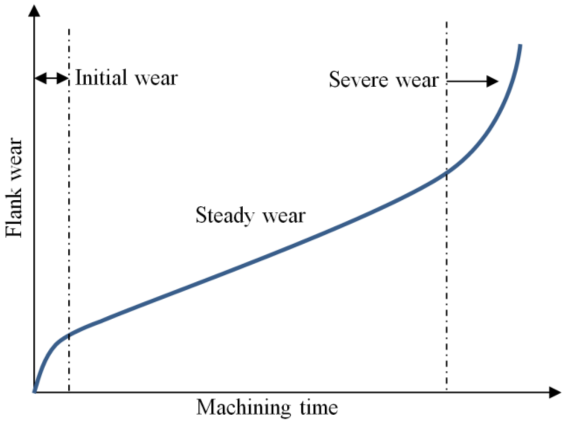

Figure 4 - Tool wear against time

The slope of the tool wear graph in Figure 4 depends on the cutting parameters applied. With more aggressive cutting parameters, the wear rate will increase and so will the slope of the graph above. With the established relation it is expected that the same will account for the slope of the tool life and tool cost.

To find a way of allocating a certain cost to the wear, a measurable parameter is needed to associate the progression of wear with. A suitable parameter is the material removed since this can be linked with the progression of time by analysing the cutting strategy and parameters. If the tool life is known for certain set of cutting parameters, the total amount of material removed can also be determined up to the point where the tool reaches its end of tool life criteria. In this way the cost per amount of material removed can be established.

It is also known that the wear increases as more material is removed, which means that a certain amount of wear corresponds to a certain amount of material removed. With these two sets of relations it is possible to establish a cost per amount of wear. As the wear increases, the value of the tool will decrease. Also as time progresses, the wear will increase and so the value of the tool will decrease. Considering these, the depreciation of the tool can in principle be illustrated as shown in Figure 5. This tendency can be well represented by an exponential equation in the form of:

$$y = Pe^{-kx} \qquad (10)$$

where *P* the value (i.e. purchase price) of the tool is and *k* represents a constant, which has to be experimentally established. This relation is most important and challenging aspect of setting up a cost model, allowing the prediction of the tooling costs. In combination with the actual machine (work place) cost it builds, as shown in Figure 3 above, the cost model base for process planning in titanium milling.

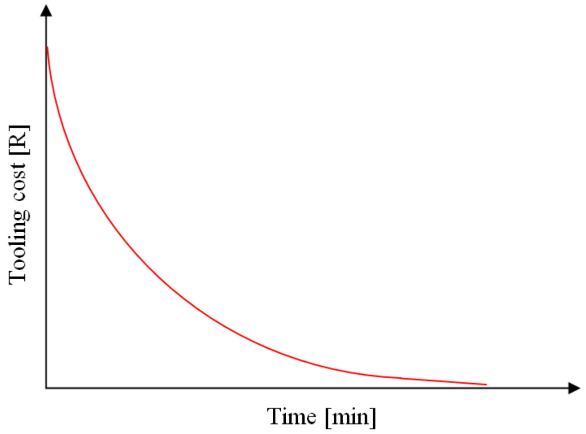

Figure 5 - Tool cost over time – a tendency view

4 CONCLUSIONS AND OUTLOOK

This paper discusses the development of a framework for process planning of milling operations for machining of some of the key materials in the aerospace industry such as selected titanium alloys. Following main conclusions can be drawn:

- Machining time cannot be considered separately from the tool wear and the work piece quality. An optimal process always will be a compromise between these conditions and requirements.
- Wear characterization maps for roughing and finishing operations in milling of Ti6Al4V components using different cutting tools with regards to material and geometry have to be developed. They can be efficient instrument in the process planning of the milling operations as well as during its execution.
- A cost model concept targeting cost minimisation of milling operations is presented. Further experimental studies towards the determination of the analytical apparatus and its validation for cost and lead time prediction are needed.

In this way the ultimate goal to create a practical tool for the development of optimised and reliable processes for machining of titanium based components shall be achieved.

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7 BIOGRAPHY

Dimiter Dimitrov obtained his PhD degree in Technical Sciences (Manufacturing Engineering) from the Technical University of Dresden. In 1999 he was appointed Professor in Advanced Manufacturing at the University of Stellenbosch, South Africa.

Pieter Conradie holds his B.Eng degree in Mechanical Engineering from the University of Stellenbosch. He is currently a Master's student in the Department of Industrial Engineering. His specific focus and area of research is the processes of Titanium machining.

Gert Adriaan Oosthuizen obtained his PhD degree from Stellenbosch University. In 2011 he became a CIRP research affiliate and was appointed as senior lecturer at the University of Johannesburg, South Africa.