Tool Wear in Milling of Medical Grade Cobalt Chromium Alloy

-Requirements for Advanced Process Monitoring and Data Analytics

Eamonn Ahearne, Szymon Baron, Shane Keaveney, Denis Dowling and Gerry Byrne School of Mechanical and Materials Engineering, University College Dublin, Ireland

Abstract

Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Computer Numerical Control (CNC) are platform technologies in high end manufacturing. However, the machining process on the CNC Machine Tool is generally the main source of loss of component accuracy, precision and extraneous effects on surface finish and integrity. Moreover these "losses", and therefore costs, only increase in cutting processes due to the inherent modes and mechanisms of progressive and catastrophic tool wear.

In high end manufacturing sectors, these losses are also exacerbated by the use of "difficult-to-cut (DTC)" materials while more stringent specifications apply and higher levels of process capability are demanded. The use of Cobalt Chromium (Co-Cr-Mo) alloys in the Medical Device sector is indicative of the many challenges. However, notwithstanding the importance of the application, there are few publications on the fundamental mechanisms in cutting this alloy, other than by the present authors.

This paper builds on our research to date by reporting some preliminary results on tool wear progression in CNC milling of the Co-Cr-Mo alloy conforming to ASTM F75. It also assesses the feasibility of real time tool wear monitoring on a Mori Seiki NMV1500 CNC Machining Centre using the MTConnect communication standard. The results obtained through MTConnect are provided by embedded sensors within the machine tool and are correlated with a laboratory piezoelectric dynamometer. The results from both methods, obtained at two cutting speeds, are also related to observed tool wear progression and the cumulative volume of material removed. The results are discussed in terms of the potential and limitations of using of MTConnect and the machine tools embedded sensors, for monitoring of the process and the onset of tool wear.

Keywords: Biomedical materials, five axis machining, CAD-CAM-CNC, tool wear, process monitoring.

1 INTRODUCTION

Medical grade cobalt chromium molybdenum, Co-Cr-Mo, alloys possess a unique combination of mechanical and physio-chemical properties that qualify them as a biocompatible material for class 3 medical devices. An example of their use is shown in figure 1 where the orthopedic implant components labelled 1 & 3 are typically made from a Co-Cr-Mo alloy. The critical properties of the alloy for the demanding in vivo environment include: strength, stiffness, hardness, wear resistance (in the case of the ASTM F75 variant) and "bio-compatibility" [1, 2].



Figure 1: Components for Total Knee Arthroplasty

In order to realize the required complex component geometry and high precision tolerances imposed by strict international standards, device manufacturers rely on a platform "business process" that involves the use of Computer Aided Design (CAM) and Computer Aided Manufacturing (CAM) technologies and, critically, multi-axis Computer Numerically Controller (CNC) machine tools. However, in high end manufacturing, the overall capability of this "process chain" is often determined by the core cutting process and the fundamental mechanisms that result in thermal errors, deflections, vibrations, and notably tool wear.

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The effect of tool wear, the subject of the present paper, is to change the tool geometry and thereby directly affect the dimensional accuracy and surface finish and, potentially, the surface integrity of the component. This is particularly critical in multi-axis machining of freeform surfaces with an extended kinematic chain and greater potential for Abbe type errors [3]. Likewise, tool wear reduces the cutting (energy) efficiency resulting in higher cutting forces and therefore higher local-global temperatures often with adverse effects on surface finish and integrity [4].

2 MOTIVATION

The general objective of our programme of research is the development of an understanding of the fundamental mechanisms of material removal and tool wear in cutting, and specifically milling, of Co-Cr-Mo alloys. The goal for our partners is a significant reduction in related costs based on scientifically-informed and engineered improvements. An adopted strategy for expediting this goal is the development of an advanced process monitoring system and data analytic techniques. This paper reports on the feasibility of using machine tool embedded sensors, accessed using the MTConnect communication standard, for that purpose.

3 LITERATURE REVIEW

(A) Fundamental Mechanisms in Cutting Co-Cr-Mo Alloys

There was limited research in the public domain on the fundamental mechanisms in cutting of Co-Cr-Mo alloys before 2015. However, that topic has been the focus of our UCD research group since the paper presented at the 2015 MTTRF conference [5]. That paper described the composition, micro-structure and properties of the broader class of Co-Cr-Mo alloys and assessed these alloys as "difficult-to-cut (DTC)" materials. The alloys were assessed both in "theory", with reference to the definition of a DTC

material, and by experiment, where a specific Co-Cr-Mo alloy (ASTM F1537) was compared with medical grade titanium Ti-6AI-4V (F136) in a full factorial milling experiment. Subsequently, supported by our industry partners, it was decided to conduct more fundamental studies involving orthogonal cutting of Co-Cr-Mo allov variants (ASTM F1537 and F75). The objective was to determine the cutting force coefficients, and correlate measured force component levels with chip morphology, as a function of the basic parameters; cutting speed (v_c) and undeformed chip thickness (h). A number of papers have been published in that regard [6-8] for ASTM 1537 while a most recent paper (submitted for publication) reports results for the Co-Cr-Mo ASTM F75 variant. Thus, our research to date has improved understanding of the fundamental mechanisms in cutting, determined the functional relationships between cutting forces and the most basic parameters and thereby enabled macro-mechanics modelling of more complex cutting processes including determination of the torgues and power in milling following state-of-the-art approaches [9].

(B) Fundamental Mechanisms of Tool Wear

However, with due regard to the limited number of publications on cutting of Co-Cr-Mo, none have been found to date specifically on the mechanisms of tool wear. Moreover, the interest here is in tool wear in milling involving interrupted cutting.

The progressive loss of cutting tool material as a result of the conditions generated in the primary, secondary and the tertiary shear zones in the cutting process is known as the tool-wear [10]. When the micro-geometry of the tool cutting edge degrades to some limit because of progressive wear, or catastrophic breakage occurs, the tool must be replaced. Cutting tools experience various forms of wear such as: flank, notch, crater wear and edge chipping. The tool wear patterns are formed through a combination of wear mechanisms which include: adhesion, abrasion, oxidation, diffusion and fracture wear [12]. The relative contribution of each wear mechanisms however depends on the mechanical and physio-chemical properties of the tool-work including, for example, chemical affinity of the materials, oxidation resistance, the presence of hard abrasive carbides etc. [12]. In machining, tool wear is a significant consumable cost but it also affects a wide range of other key performance indicators. In this regard the tool-wear is one of the main considerations when defining a material as DTC noting that there is much subjectivity in the definition of what constitutes a DTC material and designating materials accordingly [5].

Although wear of the cutting tools is generally an inherent phenomenon in the cutting process, a range of solutions can be utilized in order to extend the life of the cutting tool and/or increase the material removal rates [5, 11]. These advances (in general) have included: the use of cemented carbides since 2nd half of the 20th century which allowed for increased production rates, the use of high temperature resistant coatings (such as TiAIN or TiN) which further extended the life of the cutting inserts and also the development of extremely hard and temperature resistance cutting tools with tipped edges from polycrystalline cubic boron nitride [11, 13] as examples. In general the relationship between the tool life and the cutting conditions can be described by Taylor equation, given below. This idealized model can be significantly limited by a range of factors such as operating parameters, toolpath, machine

configuration and the tool and workpiece characteristics. Often the tool-wear phenomenon presents a unique problem given the configuration of the manufacturing process [11-13].

$$C = v_c T^n$$

A turning tool-wear experiment carried out in UCD [in press] has shown that the wear of a Tungsten Carbide tool will result in a progressive increase in the cutting tool edge radius (r_b) in oblique cutting of Co-Cr-Mo, ASTM F75. This was correlated with an increase in the magnitude of the forces measured by the dynamometer as shown in figure 2. This observation would indicate that, under similar cutting conditions in milling, the progressive wear of the cutting tool would require an increased torque at the spindle and power consumed by the axis drive motors.



Figure 2: An Increase of the Force Component due to Tool-Wear in Oblique Turning of Co-Cr-Mo.

(C) Smart Manufacturing Developments

The multiple mechanisms of tool wear and the absence of models and predictive methods for application specific sets (tool-material-coolant-machine) indicates the nature of the challenge which can only be addressed by major breakthroughs. More recently, it has been advocated that the era of Industry 4.0 or digital manufacturing (DM) may contribute to the deconvolution of the inherent complexity of processes [14] in the future. In particular the development of ascribed disruptive technologies such as new smart sensors, the Internet-of-things (IOT), advanced data analytics and cloud computing [14].

Clearly these developments suggest a strategy for the present project now advocated by our industry partners and involving the development of application specific sensors, process-machine monitoring strategies and the deployment of advanced data analytics techniques. The principle is to follow a systematic progression in "levels of intelligence" as depicted in figure 3. In that regard the UCD Insight Centre for Advanced Data Analytics, is now part of a new collaborative project with our industry partners defined to progress towards the indicated goal. The concept follows from our recent collaboration with the late eminent colleague, Professor David Dornfeld, who pioneered this in the MTTRF and CIRP community and actively supported collaboration between LMAS at UC Berkeley and UCD.

In the industrial domain also, progressive CNC machine tool manufacturers are leading the new era of DM with related machine tool developments. In this regard DMG Mori are indicative with new machine tool offerings such as the Ultrasonic 20 which is a platform machining center that can combine several technologies of relevance to the present challenge. These technologies include: active ultrasonic modulation of the tool, high speed spindle, high precision 5-axis capability, the incorporation of i4 sensor systems and also the functionality and performance of the new Celos control software [15].



Figure 3: Roadmap for Process Control [14].

4. SPECIFIC OBJECTIVES

The following are the specific objectives of the research reported in this paper

1. To investigate the modes of tool wear in milling of Co-Cr-Mo, ASTM F75 and characterise its progression, comparing it with the mode of wear found in the reported study of the partners manufacturing process chain

2. To examine the effects of cutting speed on tool wear but also forces / power.

3. To assess the capability of the embedded machine tool sensors to measure mechanical motor power levels in milling of the Co-Cr-Mo alloy, over a typical working range. Of particular interest is the capability to measure the change in measured loads as tool wear progresses.

The last objective will inform decisions on the need for additional sensors / sensor systems such as installed power monitoring or embedded force sensors etc. It is also opportune in the context of the due change in the excellent facilities awarded by the MTTRF and the appropriate selection of a machine tool platform.

With due regard to this background and the stated objectives of the research, this paper now reports in order on; the manufacturing process analysis undertaken on the production line in our industry partners plant, the experimental set-up and methodology to realize the indicated objectives on the Mori Seiki NMV 1500 in UCD, the results and analysis from the experimental programme and finally a discussion and conclusions with respect to the stated objectives.

5. MANUFACTURING PROCESS ANALYSIS

The research reported here follows a systematic study of the manufacturing process or value stream in the DePuy Synthes plant, Carriigaline Co Cork in Ireland. The main objective was to identify and characterize the chronic modes and causes of tool wear during normal production, working closely with the operators and process engineers to set aside tools adjudged to be due for change as per normal procedures, noting that the decision to change a tool is entirely the responsibility of the machine operator. This study extended over several weeks and operators were asked to document the decision criteria applying to each tool change. Most of the study was also conducted in the presence of the UCD Researcher and in all cases basic production data including machine and process parameters were recorded.

In total, a sample size of over 67 tools was obtained for microscopic examination and characterization back in UCD. © 2016 The Proceedings of MTTRF 2016 Annual Meeting

From that study two predominant modes of tool wear were identified. One chronic mode of tool wear of was characterized as progressive edge wear reducing the effective edge radius. The wear mode is adjudged to be similar to the type described by Shaw in [12] as "nose wear", noting however the generality of this classification given the context of the study here on a specific DTC alloy

6. EXPERIMENTAL SET-UP AND METHODOLOGY

The experiments were all run on a state-of-the-art Mori Seiki 5-axis Machining Centre NMV1500 DCG, as shown in figure 4, with design characteristics that include: high stiffness "box-in-box" structure, "through center of gravity" dual axis drives, high precision form accuracy (<5 μ m) and up to 60,000 RPM spindle speed.



Figure 4: Mori Seiki NMV1500 DCG Machining Centre.

The fixed parameters for the experiments are as shown in table 4. The detailed specifications for the parameters are ordered by tool, work and process with inset pictures for illustration. The work material, in bar form, was orientated in relation to the tool as shown in figure 5 which also shows the feed direction relative to the Mori Seiki machine co-ordinate system and designated directions on the Kistler dynamometer. A basic one-way surface milling tool path was followed with a width of cut 2.4 mm (30% step-over) and a depth of cut of 2 mm.

The bespoke workpiece fixture (with rigidity in the XY plane estimated to be 675 kN/mm) was mounted onto the Kistler type 9257b three component, piezoelectric dynamometer. This is shown in the inset pic. (b) of table 4. The complete assembly was mounted on the Mori Seiki table as also shown. The dynamometer is connected to a Kistler amplifier type 50019 with three channels monitoring the F_{x_1} , F_y and F_z components. A Kistler Type 8762A5 accelerometer with a useful frequency range of 20 Hz-5.5 kHz was mounted on the fixture and its output connected to standalone charge amplifier. The amplifiers outputs were connected to a NI DAQ PAD 6251 data acquisition system with Labview software with sampling rate of 30 KHz.

The measurements of the axes and spindle powers, from the machine's embedded sensors, were accessed using the MTConnect communication standard. However, compared with the dynamometer, the data acquisition 'sampling rate' via MTConnect was determined by the machine tool and was typically less than 5Hz. The record of the data accessed through MTConnect was stored as a string in a text file for post-processing.

#	Experimental Parameters		Value		Figures
Tool Related					
1	Tool Make & Code		Flately Engineering 081469N		
2	Tool Type		8mm x R2mm x 6FLT		
3	Tool Diameter		8 mm		
4	No. of Flute	es	6		(Alterna
5	Tool Materi	ol Material		K 30	
6	Tool Coatin	ol Coating		Tiain	
7	Axial Rake	9	45 °		1111
8	Radial Rak	е		0 °	
1 0	Corner Radius			2 mm	
Work Related					
1	Material Properties	See table 2			
2	Stock Shape- Dimension s	Round bar ¢60mm			Co-Cr-Mo WORKPIECE FIXTURE
3	Fixture Design & Set-up	See pic.			DYNAMOMETER
Process / Fixed Parameters					
1	Depth of Cu	epth of Cut		2 mm	
2	Width of Cut / Stepover		2.4 mm (30%		
3	Milling Direction		Down-milling		
4	Coolant Type		Fusch Ecocool Ultralife A		31.4
5	Coolant Flow Rate / Nozzle		1.1 l/min		
6 7	No. of Nozzles Set-up		8 See pic.		

Table 4: Fixed Experimental Parameters

For the direct comparison between the dynamometer and power measurements, a set of test runs were undertaken at two levels of cutting speed, 20 and 60 m/min, ensuring max chip thickness (*h_c*) of 15 μ m for 30% tool step-over. The max chip load is given by: $h_c = \frac{v_{ft}}{N_c n}$

where V_{ft} is the feed speed (ms⁻¹), N_c is the tool speed (revs.s⁻¹), *n* is the number of tool flutes [12].

Following removal of each 2mm depth of material, the cutting tool was removed from the machine and inspected using a Keyence VHX-2000 series optical microscope. A new tool was used for each test run and this procedure was repeated until the tool breakage or severe edge wear was observed.

Data recorded by LabView was analyzed with the use of DiaDem software. Prior to inspection and analysis of the force measurements, each channel was filtered using a digital low-pass filter of 3.5 kHz corresponding to the

dynamometer's natural frequency [16]. The charge amplifier's charge leakage was also offset using the tool idle level as the reference zero point. For every incremental depth of cut, an average and upper ¼ of F_x , F_y and F_z were evaluated from the steady state cutting for every 3rd and 3rd last pass. This allowed for an accurate plot of the force vs. volume of material removed. The data recorded via the MTConnect HTTP terminal was stored as a single string of text, separated by a delimiter. MS Excel was used to filter and process the string of text for required information (X-Load, Y-Load, Z-Load, and Spindle-Load).



7. EXPERIMENTAL RESULTS

Figures 6 shows source measurements for the three force components, recorded by the dynamometer in one pass of the cutting tool. The high sampling rate enables the isolation of single engagements as shown in the inset pic. This is simply confirmed by calculation of the time interval between engagements.

Figure 7 shows a plot of the mean force in the feed direction (F_x) as the cumulative volume of material removed increases. At 60 m/min a tool breakage event was preceded by the onset of a higher amplitude cyclic force (F_x) variation as shown in figure 8. A cursory inspection of the force profiles showed that the force in the feed direction (F_x) had the most systematic increase with volume of material removal and was therefore used for further analysis in terms of the research objectives.



Figure 6. Typical Plot of The Force Record one Pass of The Cutting Tool as Recorded by the Dynamometer.



Figure 7: The Plot of an Average and the Max. of Force in Steady State Cutting vs Volume of Material Removed.

Thus, at 20 m/min, a steady increase was observed in the feed force component, corresponding to a progression in tool edge wear characterised on Keyence inspection as "nose wear" with reference to the typology of Optiz as described in [12]. There was also a near-continuous (along the cutting edge) defect type described (pending further examination) as "delamination" noting the presence of a so-called "Fire" coating on the tools.



Figure 8: The Characteristic Pattern of F_x Associated With The Tool Breakage

This systematic wear type correlates with the observations from the manufacturing process analysis as reported in section 5. The new tool and the different wear modes associated with each cutting speed are shown on Figure 9.



Figure 9: New Tool and Observed Modes of Tool-Wear at Different Cutting Speeds.

The analysis of the load profile on the axis drive motors, as recorded via MTConnect, did not show any systematic variation with tool wear. However, the profile of the spindle

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load increased systematically with the volume of material removed at 20 m/min as shown in figure 10 (the X-axis "index" represents individual data points).



Clearly, the sampling rates for the embedded sensors obtained through MTConnect are lower by orders of magnitude than the data obtained by the dynamometer (and data acquisition system). Furthermore, the data points were not "output" at regular intervals but were "sampled" as indicated by a status bit shown on the machine's HMI.

Finally, figure 11 shows the variation in spindle load over the life of the two tools tested at 60 m/min; the spindle load is higher for the second (repeat) tool. Here, the second tool (R2) shows a higher overall average and progressively increasing spindle load. Inspection of the corresponding dynamometer measurements showed the aforementioned characteristic pattern (figure 8) indicating tool breakage upon initial tool entry.



Figure 11: Plot of the Spindle Loads Over the Life of the Tools Tested at 60 (m/min).

8. DISCUSSION

The discussion that follows relates back to the three specific objectives as defined in section 4 in the context of the obtained results.

(1) Three characteristic modes of tool wear / failure have been identified in this research including; progressive "nose wear", an ascribed "delamination" mode and gross tool fracture mode. These modes and rate of tool wear, subject to further evaluations, corresponded to the modes found in the manufacturing process analysis reported in section 5. This generally validates the set up in UCD for future research showing that it emulates the process in our partner's plant.

(2) The results showed a "not unexpected" difference in the tool life at the two speeds in line with the classical Taylor power law. However, at the high speed, the tool failure mode was more macro-fracture notwithstanding that the feed forces were comparable (including a repeat at the higher speed). Further investigation is planned including SEM examination and fractography.

(3) It was also shown that, for the specific range of conditions examined, the measurements from the embedded machine sensors, obtained through MTConnect, can provide an indication of progressive tool wear. The spindle load measurements correlated with the feed force measurements (comparing figures 7 and 10) noting however the higher sensitivity of the former. Moreover, due to low and varying sampling rates, the use of the spindle motor load would be limited to monitoring of the progressive modes of wear. Thus it is clearly also not suitable for sensing high frequency phenomena such as tool engagements, segmented chip formation etc.

However, the capabilities enabled by MTConnect for process monitoring and are not only in the monitoring of spindle loads but also in the monitoring of multiple parameters including axis positions, velocities, acceleration etc as well as a myriad of machine status levels. In terms of the objective here, these capabilities will in the future, enable correlation of locally varying forces and power with the fundamental parameters in cutting (chip load, tool speed, depth and width of cut) during normal operations by referencing the planned tool path-time codified in the CAM programme.

There are also other "higher level" strategies for improved process monitoring to exploit the DM era. One strategy for the machine tool manufacturers would involve "design for monitoring"; a strategy already in the focus of the industry as evidenced in recent machine tool designs.

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