Manufacturing of Femoral Heads from Ti-6Al-4V Alloy with High Speed Machining: 3D Finite Element Modelling and Experimental Validation


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Titanium alloys are used for the manufacturing of femoral heads for orthopaedic implants. Poor machinability of these materials, especially at high speeds, creates the need for more detailed investigations on this subject. The at hand study analyzes the construction of 3D Finite Element Method (FEM) models pertaining to the manufacturing of femoral heads made from Ti-6Al-4V. For this purpose a commercial FEM programme is employed, specialising in machining modelling, namely AdvantEdge. The validation of the model is provided through experiments on actual femoral heads cut in a CNC lathe at high cutting speeds. Comparison between experimental and numerical results on cutting forces and chip morphology exhibits a good agreement, indicating the success of the proposed models. These 3D models can be used for realistically estimating the influence of cutting conditions on the final product, without performing time and money consuming experiments.

Keywords: Femoral Heads, High Speed Machining, Titanium alloys, FEM Modelling, Chip Morphology

1 Introduction

Orthopaedic implants used in replacement surgeries around the world, including hip and knee joints, are in the number of millions; knee replacement surgeries only in the USA are estimated to exceed 300,000 annually [20]. The importance of this sector is not only because of the size of the market it appeals to but also of its impact on human lives, the conditions of which are undoubtedly improved after surgery. However, the manufacturing of femoral heads, hip and knee joints is quite challenging because of the complicated shapes of the implants and the specialised products required for some patients, but also because of the materials used for this task, i.e. metals such as titanium alloys and ceramics. These materials are preferred due to their bio-compatibility and endurance as implants. However, they require manufacturing processes for the production of precision components such as machining and powder metallurgy that impose difficulties in many cases.

Titanium alloys are materials that exhibit properties that make them ideal for orthopaedic implants. They possess a combination of favourable mechanical properties such as high strength, with low material density and high corrosion resistance. These characteristics are vital for implants that will be fitted for many years inside a human body. Titanium alloy implants are manufactured by machining although the poor machinability of this material is documented. Cutting tools used in the machining of titanium alloys are reported to prematurely fail due to low thermal conductivity of the material that increases the temperature at the tool-workpiece interface, its tendency to weld to the cutting tool due to chemical reactivity and its high strength maintained at elevated temperatures [9]. Chattering due to machining forces is another source of tool wear [28]. For increased accuracy at high speeds in metal machining, hard turning is usually employed [17]. However, for titanium alloys machining it is recommended to apply straight tungsten carbide tools at cutting speeds below 1 m/s and for High Speed Machining (HSM) it is necessary to suppress the cutting heat as much as possible while dissipating it quickly [21]. The manufacturing of complex shapes as the femoral heads by HSM, as well as the HSM of titanium alloys has been investigated and reported in the literature [11, 13]. Machining titanium and its alloys at high cutting speeds is preferable; an important advantage of HSM is the high material removal rate achieved, which is a function of the cutting speed as well as the undeformed chip cross-section, leading to higher productivity.

In the present paper the manufacturing of titanium alloy femoral heads with HSM is performed. The alloy studied in the present paper is Ti–6Al–4V, one of the most important Ti alloys, which is used in more than 50% of all commercial Ti applications for structural components employed in the aerospace, nuclear, chemical and biomedical industry. The aim of the paper is to present 3D Finite Element Method models for the machining of femoral heads that can be used for further studies of this complicated and challenging task. A commercial FEM programme is selected for this purpose, while model validation is achieved through the comparison of the numerical results of the FEM analysis with the experimental data collected during the process.

2 Experimental

Two femoral heads were cut for the experimental procedure. The selection of the cutting variables was made according to the literature for titanium cutting, more specifically cutting speed was selected to be constant at 140 m/min, a speed that leads to high speed machining for titanium [22]. The depth of cut was also selected to be constant for both implants at 0.5 mm. The only variable that changed during processing was feed rate, which took the values of 0.15mm/rev and 0.21 mm/rev for each implant, respectively. The cutting conditions are tabulated for the cutting of both femoral heads in Table 1. The workpiece material was titanium Ti-6Al-4V alloy, with hardness 35HRC, and properties as shown in Table 2. The Ti alloy workpiece was processed in a CNC lathe OKUMA Lb 10H, see Figure 1a, with maximum 10,000 rpm and
movement accuracy in both axes 0.1μm. The cutting tool used was a coated tool from SECO with specification DNMG 110404 - M3 with TP 2000 coated grade. This cutting tool has rhombic shape with cutting edge angle 55° and is intended for general turning on steels and alloyed steels, as it is coated with four layers of Ti (C, N) + Al₂O₃ + Ti (C, N) + TiN. The rake angle mounted in the toolholder was γ=−5° and inclination angle was λ_s=−9.5°. The tool cutting edge angle was κ=93°.

**Tab.1 Cutting conditions for the two femoral heads**

<table>
<thead>
<tr>
<th>Cutting variables</th>
<th>1st Cutting</th>
<th>2nd Cutting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed, v (m/min)</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Feed, f (mm/rev)</td>
<td>0.15</td>
<td>0.21</td>
</tr>
<tr>
<td>Depth of cut, d (mm)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Tab. 2 Workpiece Material Properties**

<table>
<thead>
<tr>
<th>Material Properties of Titanium Alloy Ti-6Al-4V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td><strong>Mechanical</strong></td>
</tr>
<tr>
<td>Hardness, Rockwell C</td>
</tr>
<tr>
<td>Tensile Strength, Ultimate</td>
</tr>
<tr>
<td>Tensile Strength, Yield</td>
</tr>
<tr>
<td>Elongation of Break</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
</tr>
</tbody>
</table>

Cutting forces were measured through analog data measurement equipment and a dynamometer was adjusted on the tool. In order to avoid false measurements during the experimental procedure due to abnormal local conditions, two tests for each experiment were held and an average value was adopted. The cutting forces were measured in all three directions, namely x, y and z axis, with a Kistler 9257A dynamometer, a three-component piezoelectric platform. The force data were recorded by a specifically designed, very compact multi-channel microprocessor controlled data acquisition system with a single A/D converter preceded by a multiplexer; in Figure 1 the experimental setup can be observed. Furthermore, the chips were gathered at the end of each experiment so that they may be compared to the chips from the simulation.

**Fig. 1** Experimental procedure: (a) the CNC Lathe which was used, (b) the microprocessor and data recorder, (c) during the procedure, (d) inside the cabin, where the device to support the (d1) workpiece prior to machining and (d2) the dynamometer are depicted, (e) the experimental results of forces versus tool position and (f) the final femoral head.
3 Finite Element Modelling

Numerical modelling and especially FEM is widely used for the analysis and the prediction of the cutting performance in machining operations. The advantage of the method is that it can provide several difficult-to-measure data on variables such as temperatures, plastic strains, strain rates, and stresses. Simulations of metal machining using the finite element method have a background of about three decades; worth mentioning is an early pioneering work of Usui and Shirakashi [30]. The first models that appeared on the simulation of metal machining, and the majority of the work performed so far, pertain to two dimensional orthogonal cutting strain models. So far three types of analysis have been proposed, namely Eulerian, Lagrangian and the newer Arbitrary Lagrangian-Eulerian (ALE) analysis. In the Eulerian approach the finite element mesh is spatially fixed and the material flows through it in order to simulate the chip formation. The computational time in such models is reduced due to the few elements required for modeling the workpiece and the chip and is mainly used for simulating the steady state condition of the cutting process with continuous chip [6, 8, 25, 26]. The elements do not undergo severe distortion since the mesh is a priori known but experimental data must be known before the construction of the model in order to determine the chip geometry.

Although the Eulerian formulation is still utilized by some researchers, the Lagrangian formulation has been proposed. In this approach the elements are attached to the material and the undeformed tool is advanced towards the workpiece. For the analysis two techniques may be employed, i.e. the implicit and the explicit time integration technique, allowing for non steady state problems to be faced. A disadvantage of the method is connected to the large mesh deformation observed during the simulation. Due to the attachment of the mesh on the workpiece material, the mesh is distorted because of the plastic deformation in the cutting zone. For the formation of the chip, a chip separation criterion in front of the tool edge is applied. There are a lot of criteria proposed so far; Black and Huang have performed an evaluation on some of them in their work [5]. The proposed chip separation criteria are geometric or physical, involving critical distance between the tool and the workpiece, critical values of e.g. stress or strain, or even crack propagation criteria. A lot of Lagrangian formulation non steady state plain stress analysis models have enriched the relative literature [15, 18, 23, 32]. Note that, the arbitrary Lagrangian-Eulerian formulation (ALE), a method that aims to combine the advantages of the two methods mentioned above, has also been utilized lately. More on the FEM modeling of machining processes can be found in the work of Markopoulos [19].

Looking at the literature for metal cutting with FEM, it may be concluded that a large part of them describe the simulation results of the chip formation process during orthogonal machining [10, 24, 29]. Furthermore there are also papers that describe the stresses [2, 16], thermal distortions [27], tool wear [31] and of course cutting forces [3, 4] during machining. Predicted results may not only vary with input data but also with the applied software and so the choice of the software is important. In all the aforementioned projects, commercial software like MSC.Marc, Abaqus, Deform 2D/3D, Nike, AdvantEdge etc. was utilized.

For the purposes of this paper, commercial FEM software specific for machining operations was chosen to simulate the metal cutting process, namely AdvantEdge™ supplied by Third Wave Systems. This software package was built from the start with metal cutting operations in mind, allowing simulation of turning, drilling, milling, micro machining, etc. in either two or three dimensions. AdvantEdge is a Lagrangian, explicit, dynamic code which can perform coupled thermo-mechanical transient analysis. The program applies adaptive meshing and continuous remeshing for chip and workpiece, allowing for accurate results. The program menus are properly designed so that model preparation time is minimized. Furthermore, it possesses a wide database of workpiece and tool materials commonly used in cutting operations, offering all the required data for effective material modeling. The commercial FEM code employed makes the implementation of the latest developments very easy, reduces the model construction time and enhances the reliability of the models.

The models provided are 3D high speed turning models for Ti-6Al-4V machining. They were chosen to be so in order to have the ability to make a more accurate comparison between the experimental and the numerical results, especially for the chip morphology. The cutting conditions used in the experimental work, as tabulated in Table 1, were also used as input to the FEM models, for the purpose of comparison of results.

The success of a machining model greatly relies on the implementation of an adequate workpiece constitutive model [14]. For instance, of interest is the way thermo-mechanical coupling is considered. In cutting processes heat generation originates from the two deformation zones, i.e. the primary and the secondary, due to inelastic and frictional work. The heat is conducted into the tool and chip and transferred away from the chip to the environment or the cutting fluid by convection. This is usually modelled with material and tribological models that are functions of mechanical and thermal behavior with strain, strain rate and temperature. The associated strain hardening and thermal softening, two mechanisms that act contradictory the one to the other, need to be accounted for. In the present analysis, the constitutive model of the workpiece material is governed by the Power Law described by the following equation:

\[
\sigma(\varepsilon^p, \dot{\varepsilon}, T) = g(\varepsilon^p) \cdot \Gamma(\dot{\varepsilon}) \cdot \Theta(T)
\]  \hspace{1cm} (3.1)

where \(g(\varepsilon^p)\) is strain hardening, \(\Gamma(\dot{\varepsilon})\) is strain rate sensitivity and \(\Theta(T)\) is thermal softening.

The strain hardening function \(g(\varepsilon^p)\) is defined as:

\[
g(\varepsilon^p) = \sigma_0 \left(1 + \frac{\varepsilon^p}{\varepsilon_p^0}\right)^{\lambda/\eta}, \text{ if } \varepsilon^p < \varepsilon_p^0
\]  \hspace{1cm} (3.2)
\[ g(\varepsilon_p) = \sigma_0 \left( 1 + \frac{\varepsilon_p}{\varepsilon_{0p}} \right)^{\frac{1}{n}} \text{, if } \varepsilon_p \geq \varepsilon_{cut} \]  

(3.3)

where \( \sigma_0 \) is the initial yield stress, \( \varepsilon_p \) is the plastic strain, \( \varepsilon_{0p} \) is the reference plastic strain, \( \varepsilon_{cut} \) is the cut-off strain and \( n \) is the strain hardening exponent.

The rate sensitivity function \( \Gamma(\dot{\varepsilon}) \) is provided as:

\[
\Gamma(\dot{\varepsilon}) = \left( 1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left( 1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{\frac{1}{n}} \text{, if } \dot{\varepsilon} \leq \dot{\varepsilon}_i
\]

\[
\Gamma(\dot{\varepsilon}) = \left( 1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left( 1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{\frac{1}{n}} \text{, if } \dot{\varepsilon} > \dot{\varepsilon}_i
\]

(3.4)

(3.5)

where \( \dot{\varepsilon} \) is strain rate, \( \dot{\varepsilon}_0 \) is reference plastic strain rate, \( \dot{\varepsilon}_i \) is strain rate where the transition between low and high strain rate sensitivity occurs, \( m_1 \) is the low strain rate sensitivity coefficient, \( m_2 \) is the high strain rate sensitivity coefficient.

The thermal softening function \( \Theta(T) \) is defined as:

\[
\Theta(T) = c_0 + c_1 T + c_2 T^2 + c_3 T^3 + c_4 T^4 + c_5 T^5, \text{ if } T < T_{cut}
\]

\[
\Theta(T) = \Theta(T_{cut}) - \frac{T - T_{cut}}{T_{melt} - T_{cut}}, \text{ if } T \geq T_{cut}
\]

(3.6)

(3.7)

where \( c_0 \) through \( c_5 \) are coefficients for the polynomial fit, \( T \) is the temperature, \( T_{cut} \) is the linear cut-off temperature and \( T_{melt} \) is the melting temperature. Material’s thermo-mechanical properties are taken from the software’s database.

The cutting tool is modelled as a rigid body with the geometrical characteristics described in section 2. AdvantEdge allows for up to three coating layers for the cutting tools. For the DNMG cutting tool, three layers, namely TiN, Al₂O₃ and TiC are considered. The coating layers are important for the thermal analysis that is also of interest in the present study, besides the cutting forces. The predicted cutting forces from the FEM model are compared with the measured ones, while a comparison of the chips produced in each case is also provided. Additionally, the simulations can provide more results such as the temperature distribution on the cutting tool and within the workpiece, which are essential in order to understand the physical phenomena taking place during the process. The length of the simulations is held on more than a full rotation, namely 400°, in order to obtain richer results.

### 4 Results and discussion

In this paragraph the results of the numerical simulation are presented. Additionally, these results are compared with the experimental ones in order to evaluate the cutting process and draw useful conclusions. Furthermore, FEM analysis gives a view of the critical temperatures that are developed on the workpiece / tool contact surface and the plastic deformation of the workpiece and tool. In the following Figures 2 and 3, the temperatures of the cutting tool and the workpiece, and the plastic deformation of the workpiece, for both experimental procedures, are presented.

![Fig. 2 Cutting temperatures and plastic strains with cutting speed v = 140 m/min, feed rate f = 0.15 mm/rev and depth of cut d = 0.5 mm](image)

Fig. 2 Cutting temperatures and plastic strains with cutting speed \( v = 140 \text{ m/min}, \) feed rate \( f = 0.15 \text{ mm/rev and depth of cut } d = 0.5 \text{ mm} \)
Through the experimental procedure and with the use of the dynamometer, all the three components of the forces that acted on the tool, namely the cutting force \( F_H \), thrust force \( F_V \) and resultant force \( F_A \), were measured. According to the model analysis, the same three force components were calculated by the proposed model. The results indicate, however, that only cutting force and resultant force were quite good, in comparison to experimental forces. The thrust force was incomparable to the experimental one. The failure to accurately predict all force components is attributed to two different reasons. In the first case, it is argued and backed-up with experiments that the discrepancies between modelling and experimental results lay with the materials and the conditions and not with the failure of software to simulate machining. It is agreed that cutting and thrust forces are not correctly predicted at the same time, the latter being underestimated [7]. In the second case, the discrepancies are attributed to inadequate workpiece material or contact conditions modelling. The workpiece material modelling may not work well at high stresses, strain rates and temperatures as the ones encountered in machining. The evaluation of friction models has been the topic of some publications and many approaches have been proposed [19] but the subject remains controversial. In a work by Filice et al. [12], five different friction models were analyzed and the investigators concluded that mechanical result, e.g. forces, contact length, are practically insensitive to friction models, as long as the “correct” friction coefficient is applied. It is worth noticing that Arrazola and Özel [1] used a FEM model to measure the influence of friction models on several parameters and concluded that thrust forces are more affected by friction modelling than cutting forces.

From the comparison of the forces of the first cutting procedure, which is present in Figure 4, the mean value of the cutting force \( F_H \) is 252.4 N, when from the finite element analysis was predicted at 265 N, which has a discrepancy of about 4.8 % giving a very good prediction. Furthermore, the mean value of the resultant force \( F_A \) from the experimental procedure is 72 N, when from the analysis was predicted at 89 N, with a discrepancy close to 19 %. For the second cutting procedure, which is also present in Figure 4, the mean value of the cutting force \( F_H \) is 320.2 N and the predicted one is 339.4 N, which gives a discrepancy of about 2.7%. Moreover, the mean value of the resultant force \( F_A \) from the experimental procedure is 107.8 N, when from the analysis was predicted at 93.6 N, with a discrepancy close to 13.2%.
The chip morphology varies according to the cutting conditions, as can be seen in Figure 5 (a) and (b). For the first experiment the chip is formatted in continuous linear type. The simulation also predicts the chip in the same way with experimental results. For the second experiment the chip has discontinuous form, which also is well predicted by the modeling simulation. The reason for the different type of chip is the use of lower feed rate at 0.15mm/rev, which leads the tool to a smaller movement velocity and breaks the chip to small pieces.

Fig. 5 Chip morphology when processing Ti-6Al-4V with cutting speed 140m/min, depth of cut 0.5mm and feed rate (a) 0.15mm/rev and (b)0.21mm/rev

5 Conclusion

To summarize this paper, the model of High Speed Turning of femoral heads from titanium alloy Ti-6Al-4V with coated carbide tools is able to predict cutting forces and chip morphology. In order to present more realistic results, the simulation was performed with three dimensional models. These models require more computer power and take more time to run but on the other hand can provide more results. The models have proved to predict well the morphology of the chip produced by the HSM. The force modeling also provided reliable results for the cutting and the resultant forces. Furthermore, it is possible to exploit the capabilities of the software used to calculate other parameters such as temperatures in the workpiece and the tool. The models can be used in the future for the analysis of manufacturing of femoral heads by titanium alloys.

References