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Procedia Engineering 132 (2015) 433 – 439

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

Estimation of Thermal Effects in Dry Drilling of Ti6Al4V

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Abstract

This work focuses on the dry drilling of titanium alloy Ti6Al4V. The main objective is establishing a methodology to quantify the heat generated in the material, and the heat fluxes towards it during a machining process. For the thermal effects determination in the machined material, a tridimensional finite element model of drilling was developed. The numerical model was validated experimentally. From the thermal distributions obtained numerically, the heat that acts on the material due to the action of the edges of the tool it is determined.

Keywords: Thermal effects; drilling; experimental; Ti6Al4V.

1. Introduction

There are several works focused on modeling the thermal phenomena in machining processes [1-5], both analytically and numerically. One of the most complex aspects in drilling processes is the quantification of the heat generated, as well as the determination of heat fluxes among piece, chip, tool, cutting fluid and environment [6].

Titanium alloys are often used in applications of high responsibility, so it is necessary to verify the damage produced in the material during machining. Thermal damage is particularly important due to the high reactivity of these materials at high temperatures.

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doi:10.1016/j.proeng.2015.12.516

This work focuses on the dry drilling of titanium alloy Ti6Al4V. The main objective is establishing a methodology to quantify the heat generated in the material and the thermal fluxes towards it during machining. Afterwards this methodology will be described, indicating the results when applied to specific machining conditions.

In order to validate the numerical model and get information necessary to the thermal fluxes to the material, the evolution of the axial force and torque is experimentally obtained during the drilling process.

2. Numerical Model and validation tests.

For the determination of thermal effects in the machined material during a drilling process a tridimensional finite element model was developed. The numerical model was created using the DEFORM 3D TM v.6.1 software.

2.1. Cutting conditions

This work has been developed in relation to the dry drilling of Ti6Al4V alloy using 6mm diameter twist drills with 140 ° point angle. The tool is TiAlN coated carbide. The cutting parameters considered were: Cutting speed 50 m/min and feed 0,07mm/rev.

2.2. Numerical Model

The tool was modeled as a rigid solid type with the thermal properties equivalent to the WC-carbide. The friction law for the tool-material interaction was defined following the Coulomb law, with a friction coefficient of 0.6 (suitable to simulate friction on TiAlN coated tools).

The tool was meshed using tetrahedral elements with a maximum density in the area close the cutting edges, being the element size of that region about 0.07mm. In order to save computational time, the elements size progressively increases up to 0.3mm in the areas far from the cutting edges. The total number of elements necessary for the tool mesh is about 100,000.

DEFORM3DTMv.6.1 includes information determined experimentally that related the stress, strain and strain rate with different temperatures, which constitutes the characterization of the material to be drilled (Ti6Al4V). For the final simulation, a plastic behavior of the material to be drilled was used since no convergence was obtained when an elasto-plastic behavior was established.

The material to be machined was modeled as discs with a fix diameter of 9mm and thickness ranging from 2mm to 10mm.

Meshing tridimensional numerical models requires a huge amount of elements. In drilling processes, the active length of the edges and the machining length to be simulated are very high, therefore this problem has a huge importance. For the workpiece, a mesh with tetrahedral elements and with higher element density was used in a cylindrical zone of diameter 6.5mm. The size of the elements in that region ranges from about 0.13mm to minimum size of about 0.01mm. To obtain the desired distribution of elements was used certain weighting factors base on temperature, strain, strain rate and stress fields. The total number of elements required for the material mesh was roughly 200,000. Although the mesh was too coarse far from the tool edges, the element sizes of 0.01mm close to the edges allowed proper modeling of the chip formation,. Therefore, the model is not valid for modeling the interaction of the drill bit with the new created surface. Only is considered the simulation corresponding to the first revolutions of the drill bit (entry point of the drill bit and some posterior revolutions).

Moreover, it was set a steady convection coefficient of 0.02 N / (mm · s · ° C) in the upper and lower surfaces of the workpiece and on all surfaces of the tool.

2.3. Experimental model validation:

To validate the numerical model and to obtain information concerning the heat fluxes towards the material, through holes in Ti6Al4V plates 14mm thick were performed (the machine used in the test was a machining center Kondia mod. B-500). During the tests the evolution of axial force and torque was measured using a dynamometer Mod. Kistler 9124B.

Figure 1 shows the evolution of these magnitudes along the drilling process for the cutting conditions considered in this work (cutting speed of 50m/min and feed of 0.07mm/rev).

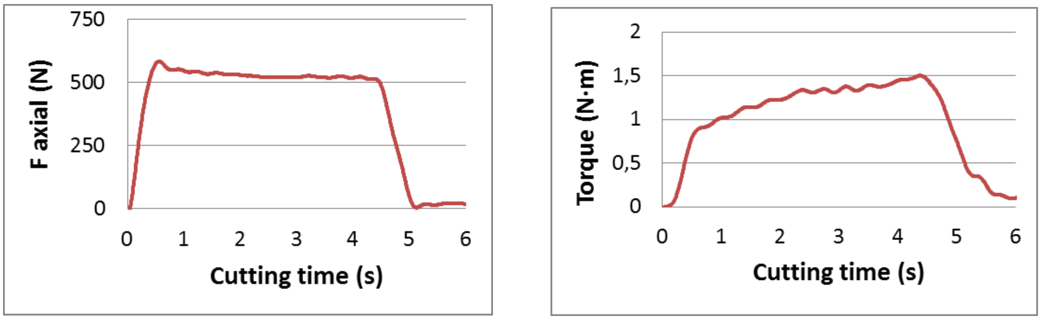

Fig 1. Evolution of the axial force and torque during drilling (cutting speed of 50m/min and feed of 0.07 mm/rev).

In both graphs an initially sharp growth corresponding to the entry point of the bit is observed. Subsequently, the axial force is moderately reduced due to increasing of the material temperature during the drilling process. However, the torque continues rising (although more slowly) due to increases on the friction of the drill with the hole wall.

To validate the numerical model should be considered the experimental values corresponding to the first revolutions of the drill subsequent to the entry in its entirety from the tip of the drill bit. Table 1 shows the numerical and experimental values and their difference. It is noted that the numerical model correlates well with the experimental results.

Table 1. Experimental validation of the numerical model

	Experimental	Numerical	Error
Axial Force (N)	540	510	5.6%
Torque (N·m)	0.9	1	11.1%

3. Determination of the heat fluxes that affect the material

In a drilling process with a twist drill, the condition in which the chip is formed varies along the edges of the tool due to the cutting geometry and the variable cutting speed. The edges of the twist drills are divided into chisel edge, cutting lips and leading edges. To determine the thermal fluxes towards the material, the edges were divided into eight sections:

- Chisel edge: it was divided into two sections (sections 1 and 2) of 0.42 mm length.
- Cutting lips: it was divided into 5 sections (sections 3 to 7) of 0.5 mm length.
- Leading edges: One single section (section 8) whose length is considered equal to 2 times the feed per edge to consider the increment of the active edge length due to the effect of the material deformation in the cutting area.

It is considered that the thermal effects on the material are constant along each section. Thus, it is possible to perform the thermal analysis in the central positions of each section.

The amount of heat that acts on the material due to the action of the cutting edges of the tool is determined from the corresponding increase in temperature.

The analysis of thermal distribution at the bottom of the hole (see Figure 2) shows that in the central area of the bottom of the hole, the material temperature is practically homogenous and it increases during the process.

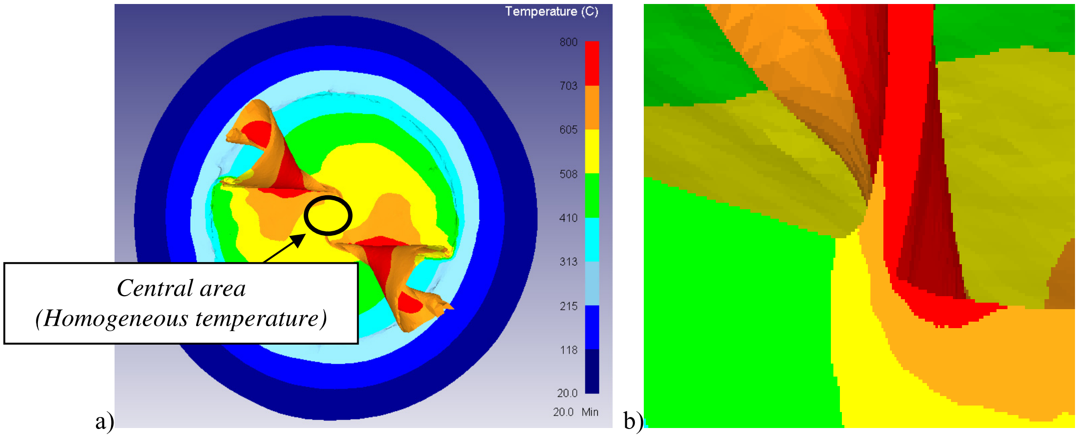

Fig. 2. a) Thermal distribution for the drill bottom material. b) Thermal distribution for a material section orthogonal to the edge.

3.1. Heat determination corresponding to the edge sections 2 to 8

In Figure 3 the material temperature increment due to the center point of the third section action is shown (the behavior is similar for the other sections, except for the section 1). Each curve corresponds to a given depth from the machined surface up to 0.15mm.

It is noted that a certain distance ahead of the edge (called X), the material is not affected by machining, being the initial temperature similar for different depths represented. For the case shown in Figure 3, X = 0.3mm.

The maximum temperature is reached in the material of the machined surface at the instant in which the contact with the tool (corresponding to the value distance = 0.3mm in figure 3) is lost. The temperature increment due to the machining action is smaller for deeper regions. At a certain depth designated as Y, the material is not affected thermally by the action of the edge. For the studied conditions (see Figure 3) Y = 0.15mm.

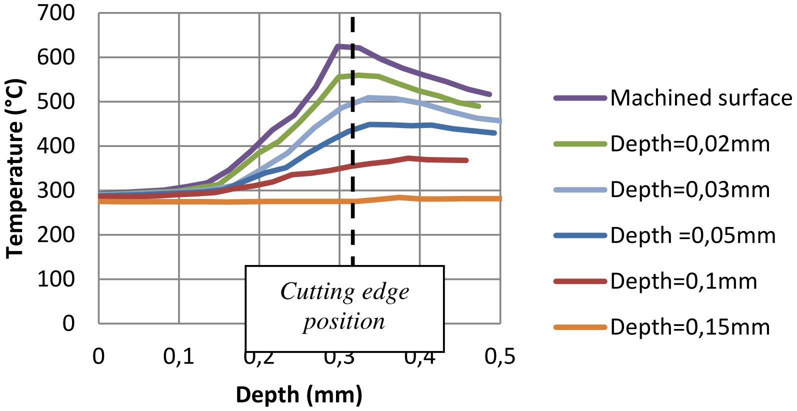

Fig. 3. Temperature increase of the material due to the action of the tool (corresponding to the center point of the edge in section 3).

To determine the heat which acts on the material, it is considered a control volume defined by:

- In the cutting direction: Material from the cutting edge position to a forward position the X value.
- In the feed direction: Material from the machined surface to the depth Y.
- In the edge direction: Length edge section analyzed (called L).

In a differential increment of time (dt) an amount of material with length (dX), height Y and depth and L enters the control volume. Being the cutting speed Vc,, can be written:

$$Vc = dX/dt; \qquad \text{(Eq. 1)}$$

At the same differential of time, the same amount of material (dimensions dX · Y · L) leaves the control volume, but at higher temperature.

Therefore, due to the action of the edge, a differential heat (dQ) enters the control volume:

$$dQ = \int_0^Y dX \cdot dY \cdot L \cdot \Delta T \cdot C_{calorif.}\,; \quad \text{(Eq. 2)}$$

Being ΔT the temperature variation throughout the control volume of the material located at a depth Y and Ccalorif the heat capacity of the material.

By operating the equations 1 and 2 it is obtained:

$$\dot{Q} = \frac{dQ}{dt} = V_c \cdot L \cdot \int_0^Y \Delta T \cdot C_{calorif.} \cdot dY\,; \qquad \text{(Eq.3)}$$

Being $\dot{Q}$ the heating power that acts on the upper surface of the control volume due to the action of the edge.

To get the heating power from Eq.3 the temperature variations will be determined from the numerical model, dividing the material in layers of Y / n thickness:

$$\dot{Q} = V_c \cdot \frac{Y}{n} \cdot L \cdot \sum_{i=1}^{n} \left(\Delta T_i \cdot C_{calorif.} \right) \qquad \text{(Eq. 4)}$$

Being ΔTi the increase in material temperature of the i-th layer

Eq.4 expression is applicable to all edge sections less the closest to the axis of the drill. However, when applying the methodology described to all edge sections indicated, there are areas of the material whose temperature is increased due to the action of the edge and that effect has not been considered. Specifically, in the areas in which the direction of the edge change (intersection of the leading edges with the cutting lips and the intersection of the cutting lips with the chisel edge) Analyzing the magnitude of those material volumes not considered is seen that this effect is only significant in relation to the heating power corresponding to the leading edge (section 8), which should be increased by approximately 60% over the one obtained using Eq. 4. Furthermore, some of the heat that affects the material due to the leading cutting edge is dissipated also in the opposite direction to the feed movement of the drill. Therefore, the heating power corresponding to the section 8 is still slightly higher. It is estimated that the heating power corresponding to the section 8 is about twice the one obtained by applying the expression Eq.4.

3.2. Determination of the heat corresponding to the edge Section 1 (central area of the bit)

The analysis of the temperature distribution in the material closest to the axis of the drill indicates:

- The temperature for the material is homogeneously located at the same depth. It is not produced a precise heating due to the passage of the edge.
- The material temperature increases progressively with the cutting process.
- Temperature gradients appear essentially in the direction of the axis of the hole so thermal fluxes only go in that direction. Therefore, it is considered that the material below the edge Section 1 is being heated due to the heat that reaches by its upper surface, by the action of the tool.

It is called Vinitial the volume of material that is under Section 1 of the edge at a moment defined by a cutting time (tc). It is called Vfinal the volume of material that remains under Section 1 in an instant (tc+Δtc). The heat that has reached the material during Δtc time can be determined from the corresponding temperature incremnet of the material. During the cutting time considered is removed part of the material in the form of chip (Velim.). In the calculation should be included the heat that arrive to the material due to the action of the edge before being eliminated in the form of chips. For calculating the heat that acts on the material, it is considered the temperature of the material volume (Velim.) as the average temperature of the material from the bottom of the drill along the drilling time (Δtc). This average temperature will be called Taveragebottom. Therefore, the heating power is obtained by applying the expression:

$$\dot{Q} = \frac{dQ}{dt} = \frac{Q}{\Delta t_c} = \frac{\int_0^{Vfinal} C_{Caloríf.} \cdot T_{final} \cdot dV + \int_0^{Ve\lim.} C_{Caloríf.} \cdot T_{averagebotom} \cdot dV - \int_0^{Vinicial} C_{Caloríf.} \cdot T_{initial} \cdot dV}{\Delta t_c} \qquad \text{(Eq. 5)}$$

Being Tfinal and Tinitial temperatures in the moment (tc+Δtc) and (tc) in the differential of material volume (dV).

3.3. Application of the methodology described in a particular case

The following heat fluxes are obtained using the methodology described for the simulation corresponding to 18 revolutions of the drill so the total entry of the bit tip plus 5 revolutions more has been considered. Has been chosen this moment for the following reasons:

- The temperature in the material is representative of which is achieved during the process.
- Enough wall of the hole have been formed so the effect of the leading cutting edge of the drill bit on the walls can be determined.

For the determination of the heat corresponding to the closest section to the axis of the drill (section 1) has been considered the material temperature increment corresponding to 1/3 revolutions of the tool (□tc equal to 0.008 seconds). To determine the heat corresponding to sections 2-8 has been applied the expression Eq. 4 taking into account layers of Y / n = 0.01mm thickness.

In Table 2, the corresponding heating powers for each section of the edge are given (for the conditions described). The relative heating values are also indicated per unit of edge length (expressed in W / mm).

Table 2. Heating power which acts on the material along the drill edge

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8
Heating Power (W)	0.02	6.23	41.03	54.84	36.58	39.08	44.73	19.80

It is noted that the heating powers which acts on the material due to the action of the edges is higher in 7 and 8 sections (maximum distance from the axis of the drill and thus maximum cutting speed). High heating values are also obtained in the central zone of the edge (section 4).

4. Conclusions

In this paper have been described the main features of a three-dimensional numerical model of an experimentally validated drilling process. Taking into account the thermal distributions obtained numerically, it has established a methodology to determine the heat that acts on the material due to the action of the edges of the tool. The methodology has been described for dry drilling processes of the Ti6Al4V alloy, but is directly applicable to any drilling process.

Acknowledgements

The authors acknowledge the financial support for this work to the Ministry of Economy and Competitiveness of Spain under the Project DPI2014-56137-C2-2-R.

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