International Journal of Natural and Engineering Sciences 9 (2): 25-31, 2015
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Investigation of Cutting Parameters of Drilling Ti6Al4V Using Finite Element Analysis

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Received: April 13, 2015
Accepted: May 26, 2015

Abstract

The high strength, low weight ratio and outstanding corrosion resistance of Ti6Al4V led to wide range of applications which demand high levels of reliable performance in aerospace, automotive, chemical plant, power generation and other major industries. Ti6Al4V also has numerous applications in the medical industry. The biocompatibility of Ti6Al4V is excellent, especially when direct contact with tissue or bone is required. However, these alloys are notoriously difficult to machine owing to several inherent properties of the material. Drilling is one of the most widely used machining technique in industry and there are lots of studies to investigate in both academic and industrial area. Predictions of important process variables such as temperature, cutting forces and stress distributions play significant role on designing tool geometries and optimizing cutting conditions. Researchers find these variables by using experimental techniques which are time consuming and expensive. As an alternative, Finite Element Modelling (FEM) becomes main solution. Heat generation during a drilling process has a major influence on the tool life and workpiece material behavior that are significantly affected by cutting conditions (cutting speed, feed rate). In this study, the effect of cutting conditions on temperature generated in drilling process was investigated by means of finite element simulations using DEFORM-3D. Variation of temperature on Ti6Al4V workpiece was examined with respect to change in feed rate (0.2, 0.3, 0.4 mm/rev) and cutting speed (2000, 3000 rpm) cutting conditions. In all of these simulations, workpiece material has 1 mm height, 2 mm radius cylindrical shape and 10 mm length WC drill bit, designed using Catia program, were used.

Keywords: *Computer Aided Design, Finite Element Analysis, Drilling,* Ti6Al4V

INTRODUCTION

In almost all machining processes, a wedge shaped tool or a number of tools make contact with the work-piece and remove the material in the form of chips. The process of chip formation is not known properly. In most of the references on machining [1-2], a single shear plane model is described which is based on the assumption that material removal takes place through shear over a very narrow zone. This model suffers from a number of drawbacks; infinite strain rate, unrealistically high shear strain, unrealistic behavior of the work material, improper accounting for the resistance of the work material to cut, unrealistic representation of the tool–work-piece contact, inapplicability for cutting brittle work materials, incorrect velocity diagram, incorrect force diagram and inability to explain chip curling. Actually the machining process is so complex that no existing physics-based model seems to describe the process properly.

Drilling is one of the most important and basic operation for producing cylindrical holes is machined components, it is a cutting process that uses a drill bit to cut or enlarge a hole of circular cross-section in solid materials [3]. The drill bit is a rotary cutting tool as shown in Figure 1. The bit is pressed against the workpiece and rotated at rates from hundreds to thousands of revolutions per minute. This forces the cutting edge against the workpiece, cutting off chips from the hole as it is drilled. Drilling may affect the mechanical properties of the workpiece by creating residual stresses around the hole opening and a very thin layer of highly stressed and disturbed material on the newly formed surface. An approximate importance of the many variables in determining the drilling energy requirements was used to rank parameters from most important to lower importance as: workpiece material properties, feed rate, cutting speed, drilling diameter, drill depth (drilling time), helix angle, coolant, chisel edge angle, drill wear, geometry and set-up.

The use of computational techniques is increasing day by day in the machining industry. Process modeling and optimization with the help of computers can reduce expensive and time consuming experiments for manufacturing good quality products. Metal machining processes involve large deformation of elasto-plastic materials due to applied loads. The material is deformed till fracture, in order to remove material in the form of chips. The physical behavior of the work-piece during the processes is modeled in the form of differential equations and boundary and initial conditions. One of the well-known mathematical techniques to solve differential equations and boundary and initial conditions is the Finite Element Method (FEM).

FEM has a wide use in modeling metal cutting. Klamecki (1973) has developed one of the first FE models for metal cutting processes using a Lagrangian elasto-plastic three-dimensional model to date has been limited to the early stages of chip formation [4]. Komvopoulos and Erpenbeck (1991) introduced a criterion of separation chip using the argument of the tolerance criterion distance to investigate the chip formation [5]. Ceretti et al. (2000) has developed a model of cutting eliminating elements have reached a critical value of accumulated damage. With the developments of hardware and commercial FE codes, limitations of modeling and computational difficulties have been overcome to some extent, many researchers focused on particular topics of cutting metals [6]. Muhammad et al. (2010) a 3D model of drilling process of AISI 1010 steel was presented. The simulations were performed on a close to real model and the results were validated using experiments. It was concluded that increase in feed and speed affected the thrust force and torque [7]. Özel (2006, 2007, and 2009) used FEM to study the effects of different models of friction on the results of cutting [8-10]. Also, Muhammad et al. (2011, 2012) presented the effect of changing drilling parameters for machining of Ti-alloys at elevated temperatures. Comparatively less forces were recorded when drilling at elevated temperature compared to the same set of parameters but at room temperature [11–12].

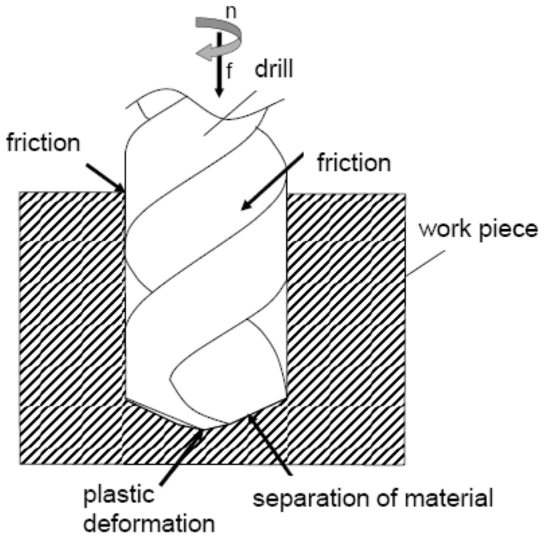

Figure 1. Drilling operation (n: tool rotation, f: feed rate)

Finite Element Analysis (FEA)

FEA has now become an integral part of Computer Aided Engineering (CAE) and is being extensively used in the analysis of many tedious real time engineering problems. Many powerful software tools and packages are available promoting its widespread use in industries. FEM is a computational technique which is employed for achieving approximate solutions for boundary value problems in engineering. Concisely stated, a boundary value problem is a mathematical problem that requires the satisfaction of a differential equation everywhere within a known domain of independent variables and also the specific conditions on the boundary of the domain via one or more dependent variables.

FEA consists of three main steps, namely, pre-processing, solution, and post processing. Pre-processing (i.e. model definition) includes definition of the geometric domain of the problem, the element type(s) to be employed, the material properties of the elements, the geometric properties of the elements (length, area, etc.), the element connectivity (mesh of the model), the physical constraints (boundary conditions), and the loadings. The solution comprises the governing algebraic equations in matrix form, computes the unknown values of the primary field variable(s), and gathers the findings. The computed results are then employed to determine the additional and the derived variables such as reaction forces, element stresses, and heat flow with the help of a back substitution step. In post processing, analysis and evaluation of the results.

Several FE techniques are available today for accurate and efficient modelling of the machining process: material and geometrical non-linear analysis, mesh rezoning techniques, element-separation for chip formation modelling, element separation criteria, tool wear modelling, residual stress prediction, etc. The types of analysis are: 2-D and 3-D; material and geometrical non-linearity; thermomechanical; thermoelastic–plastic; thermo–viscoplastic; elasto–plastic; viscoplastic; rigid–plastic; large deformation; ALE thermomechanical; Eulerian; adaptive remeshing.

Deform-3D

DEFORM-3D is a powerful process simulation system designed to analyze the three-dimensional flow of complex metal forming processes as shown in Figure 2. It is a practical and efficient tool to predict the material flow in industrial forming operations without the cost and delay shop trials. Typical applications include closed die forging, open die forging, machining, rolling, extrusion, heading, drawing, cogging, compaction and upsetting [13].

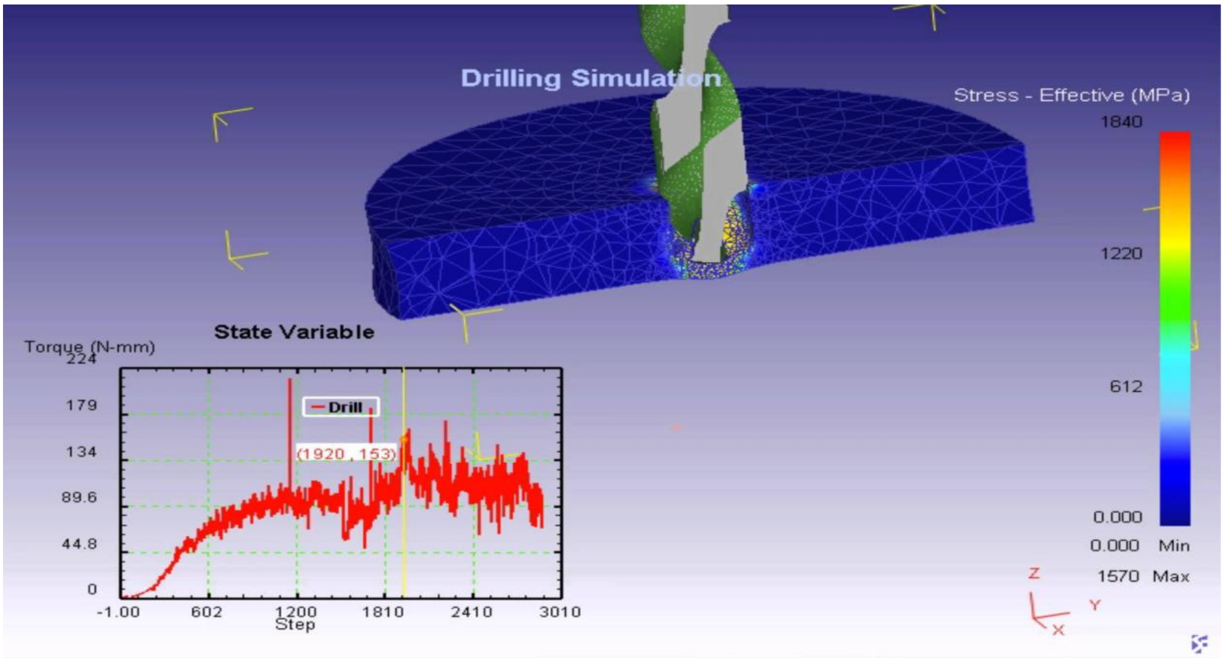

Figure 2. Drilling simulation using DEFORM-3D

Based on the FEM, DEFORM has proven to be an accurate and robust solution in industrial applications for more than two decades. The simulation engine is capable of predicting large deformation material flow and thermal behavior with astonishing precision. Drilling is one of the newest and complex applications that DEFORM have been applied to. Because; drilling is a high speed, three-dimensional operation with complex tool and chip geometries. The mathematical theory and modeling that DEFORM applies is a result of years of academic and industrial development. Although it has achieved reliable results in many applications, there are many areas for improvement in the application of the program, especially in drilling.

Ti6Al4V

Ti6Al4V, also known as grade 5, Ti-6Al-4V or Ti 6-4, is the most commonly used titanium alloy. It has a chemical composition of 6% aluminum, 4% vanadium, 0.25% iron, 0.2% oxygen and the remainder titanium. It is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties. Among its many advantages, it is heat treatable. Over 70% of alloy grades melted are a sub-grade of Ti6Al4V, its uses vary in many aerospace and engine component uses and also major non-aerospace applications in the marine, offshore and power generation industries in particular [14].

Generally, Ti6Al4V is used in applications up to 400^0C. It has a density of roughly 4420 kg/m^3, Young's modulus of 110 GPa, and tensile strength of 1000 MPa. By comparison, annealed type 316 stainless steel has a density of 8000 kg/m^3, modulus of 193 GPa and tensile strength of only 570 MPa [14]. Ti6Al4V is the alloy most commonly used in wrought and cast forms. Most properties are affected by the microstructure, which is determined by the thermo-mechanical history. It is highly resistant to general corrosion in sea water. Ti6Al4V has excellent biocompatibility, especially when direct contact with tissue or bone is required. Ti6Al4V's poor shear strength makes it undesirable for bone screws or plates. It also has poor surface wear properties and tends to seize when in sliding contact with itself and other metals. Surface treatments such as nitriding and oxidizing can improve the surface wear properties. Application areas of Ti6Al4V are aircraft structural components (Figure 3.) and biomedical implants (Figure 4.).

Experiments are not effective and accurate way of determining heat and stress distributions involved in drilling operations due to various reasons. This study offers more accurate and effective way of determining heat and stress distribution in drilling operations by taking advantage of computers and most recent finite element analysis algorithms. After determination of these quantities, factors effecting the heat generation and temperature distribution like the properties of workpiece, rotational speed of the drill, the applied force and the geometry of the drill bit are optimized in order to minimize heat generation.

Heat generation during a drilling process has a major influence on the tool life and workpiece material behavior that are significantly affected by cutting conditions (cutting speed, feed rate). In this study, the effect of cutting conditions on temperature generated in drilling process was investigated by means of finite element simulations using DEFORM-3D. Variation of temperature on Ti6Al4V workpiece was examined with respect to change in feed rate (0.2, 0.3, 0.4 mm/rev) and cutting speed (2000, 3000 rpm) cutting conditions. In all of these simulations, workpiece material has 1 mm height, 2 mm radius cylindrical shape and 10 mm length WC drill bit, designed using CATIA, were used.

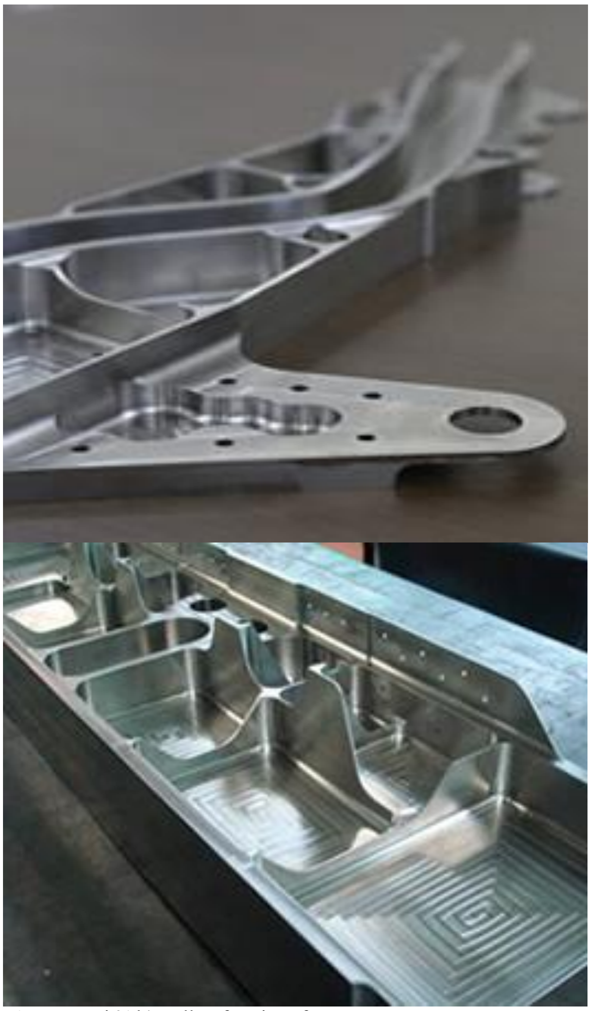

Figure 3. Ti6Al4V alloy for aircraft structure components

Figure 4. Orthopedic implants made from Ti6Al4V

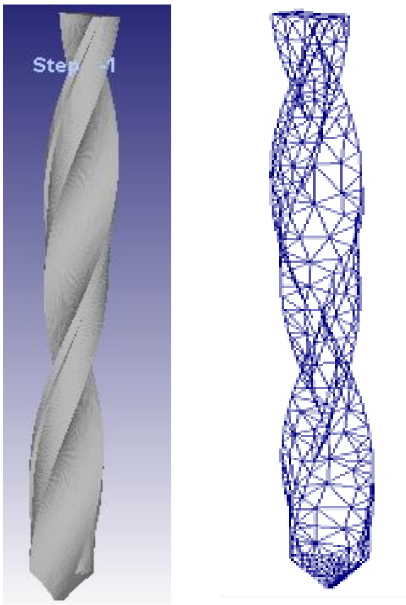

Figure 4. 3D designed and FEM of a drill

MATERIAL AND METHODS

In metal cutting, FEA is one of the state-of-the-art tools to study the process zone and tool-workpiece interaction zone. FE models have a great value for understanding of the cutting processes by reducing traditionally and expensively used experimental methods.

Modeling of drill bit geometry

The most commonly used drill is the conventional conical point drill, and surgical drills mainly originate from this type of drill with minor revisions. After modeling bone material, drill bit geometry modeled using 3D CAD software CATIA and transferred to the FEA software DEFORM, as shown in Figure 4. The geometry of the drill bit has an effect on the amount of heat generated. The significant parameters that describe the geometry of a drill include the drill radius, point angle, helix angle, web thickness, and cone angle. The diameter of the drill bit used in simulation is modeled 3.2 mm. The drill bit used in this study was made of WC.

Creating Workpiece features

Thermomechanically coupled 3D FE models were developed using DEFORM 3D [13], to investigate deformation processes in drilling operations. Due to unavailability of sufficient computational power and memory storage in the past as well as the complex drill-workpiece interaction, most of the drilling simulations were performed with a certain level of simplification such as reducing the three-dimensional problem to a two-dimensional formulation, by assuming the cutting lips as a combination of small elementary cutting tools performing an orthogonal cutting operation or considering one cutting lip of the drill bit. In our FE simulations, a deformable workpiece has 1 mm height, 2 mm radius cylindrical primitive shape.

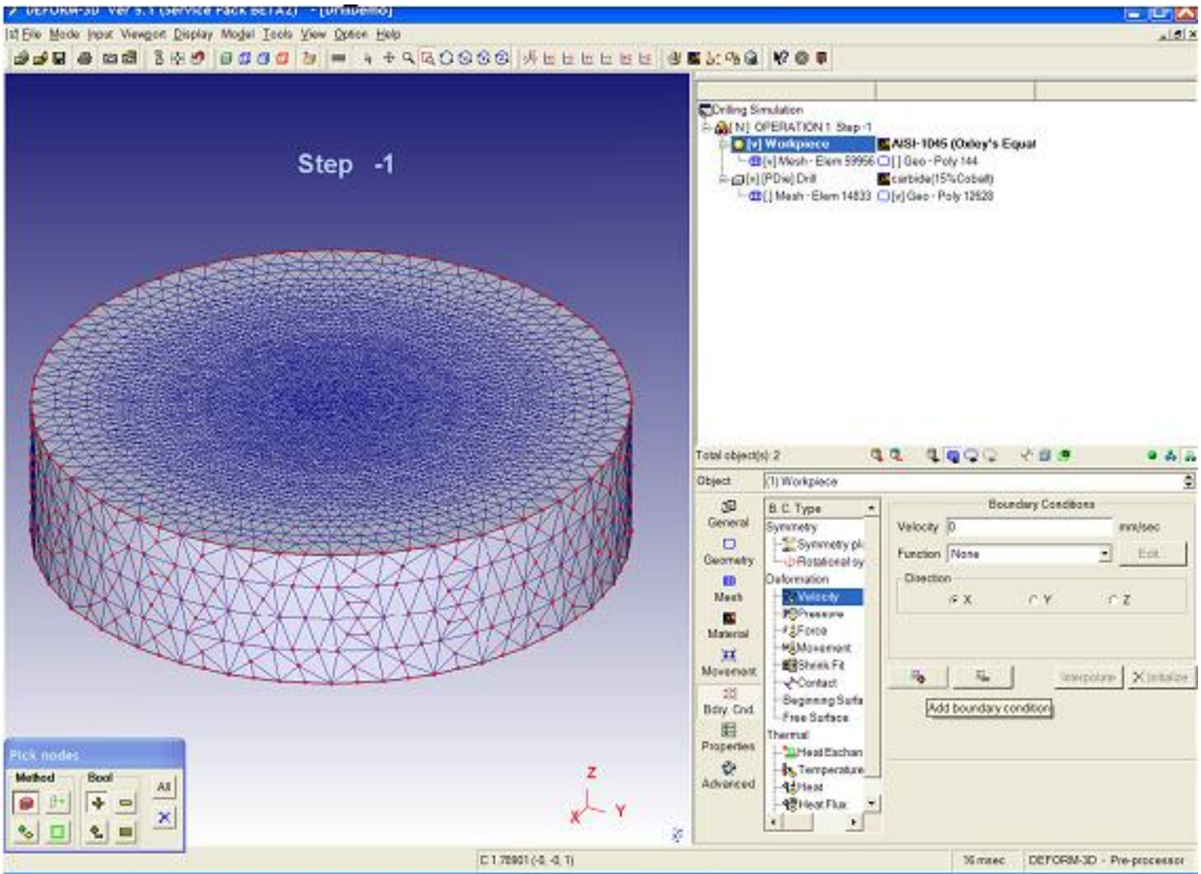

Figure 5. Deformable workpiece

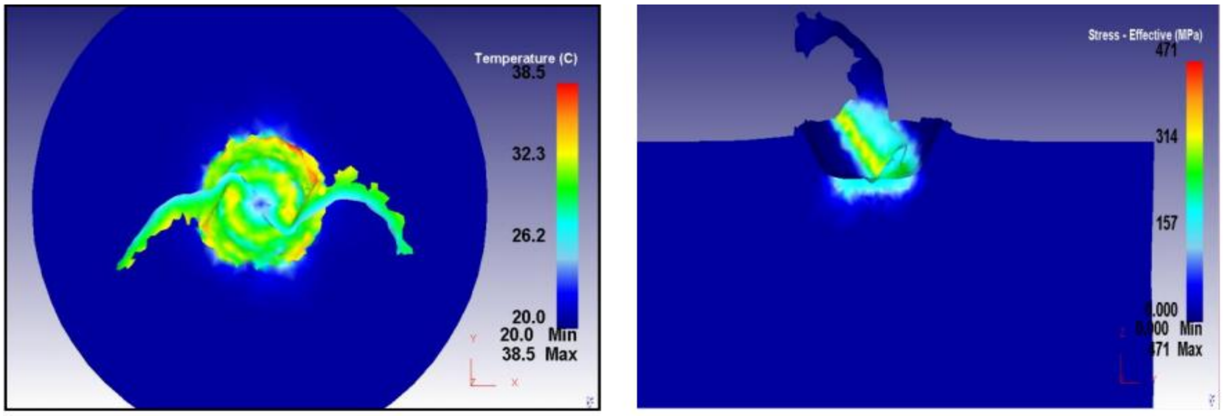

Figure 6. The chips formation because of remeshing technique

Due to the number of revolutions of a drill necessary to establish characteristic behavior, drilling simulations in DEFORM are time consuming. Therefore, to optimize problem size considerations include keeping the workpiece as small as possible while capturing geometry (both in diameter and thickness), using the largest element which can adequately capture chip geometry, and possibly pre-shaping the workpiece to eliminate the necessity to simulate the transient point penetration before the drill reaches full depth.

The drill-bit had a diameter of 3,2 mm, a helix angle of 30^o, a point angle of 118^o and a web thickness of 0.9 mm was used in analysis. The ambient temperature was selected as 21^{o}C for the drilling tool and workpiece.

In metal cutting, a process of chip separation from the workpiece involves excessive plastic deformation in the process zone and of the chip; hence, the elements near the cutting lip of a drill bit distort significantly. Therefore, chip separation from the deformable workpiece was achieved by using global-remeshing techniques to replace such distorted elements with geometrically consistent ones [13]. The chips formation as result of successful implementation of remeshing technique is shown in Fig. 2.

Various constitutive material laws are available to associate the shear strength of a material to strain, strain rate and temperature [15-16]. However, in this work, a piecewise-linear material model was used to incorporate the material behaviour of Ti6Al4V for strain, strain rate and temperature (Figure. 7).

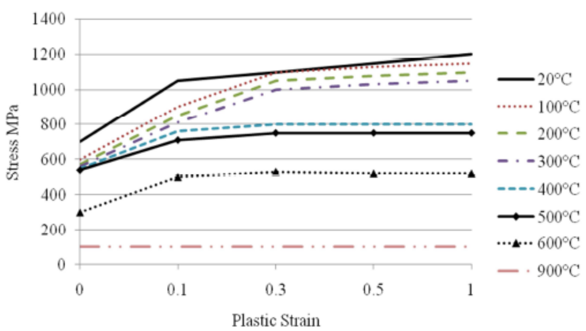

Figure 7. Material model for Ti6Al4V [15]

The material properties of Ti6Al4V are v=0.3, ρ=4430 kg/m^3, where v and ρ are the Poisson's ratio and density of the material, respectively. Similarly, a temperature-dependent modulus of elasticity (E), coefficient of thermal expansion (α), thermal conductivity (K) and specific heat (C_p) of Ti6Al4V were incorporated in the FE simulation.

RESULTS AND DISCUSSION

In this work, FE analysis of drilling processes with different cutting conditions were carried out. Varying cutting speeds (rpm) and feed rates (mm/rev) are used in the FE simulation of drilling process. The results obtained from the FE simulations are presented and discussed below. Maximum temperature values and their distribution along the workpiece were calculated and compared for 0.2, 0.3 and 0.4 mm/rev feed rates at 2000 and 3000 rpm rotational cutting speeds.

In Figure 8, maximum temperature can be obtained as 213^{0}C and in stroke of 0.305 mm by using 0.4 mm/rev feed rate and 2000 rpm cutting speed.

In Figure 9, maximum temperature can be obtained as 159^{0}C and in stroke of 0.116 mm by using 0.2 mm/rev feed rate and 2000 rpm cutting speed.

During drilling, heat is generated mainly from the cutting process (shear deformations) and the friction between the rake face of the drill bit and the chips; secondary heating effects are driven by friction between the chips, drill bit body, and the WP. A large portion of the energy used for shear deformations and the friction on the rake face is transformed into heat, which is the main heat source during drilling.

From these simulations, it is clear to understand that the effect of feed rate and cutting speed on temperature distribution is important. From FE simulations of the drilling process, it is observed that the temperature increases with the increase of feed rate and cutting speed as shown in Figure 10.

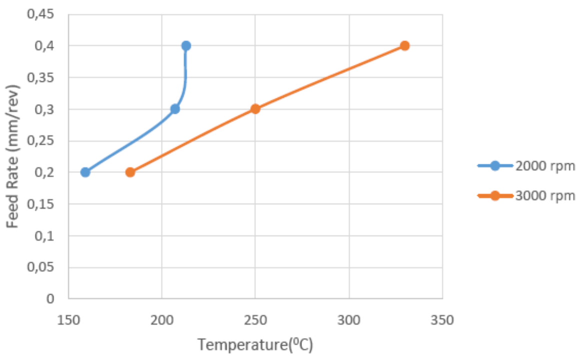

Figure 10. Change of temperature with respect to cutting conditions

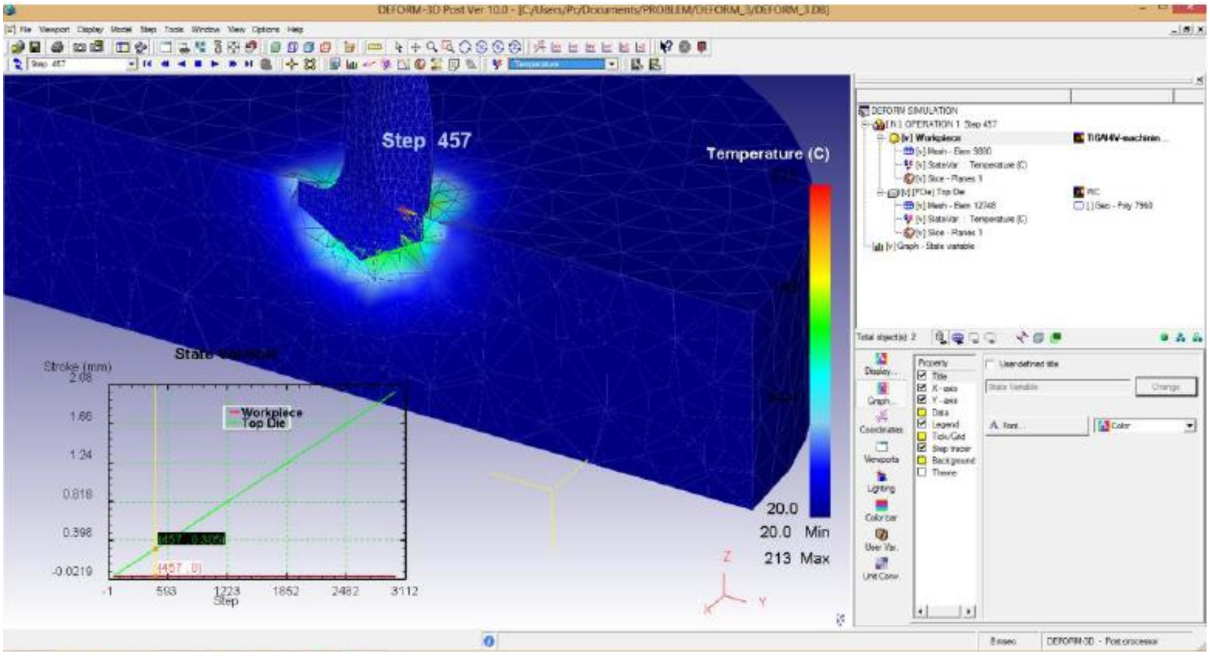

Figure 8. Temperature distribution in stroke of 0.305 mm by using 0.4 mm/rev and 2000 rpm.

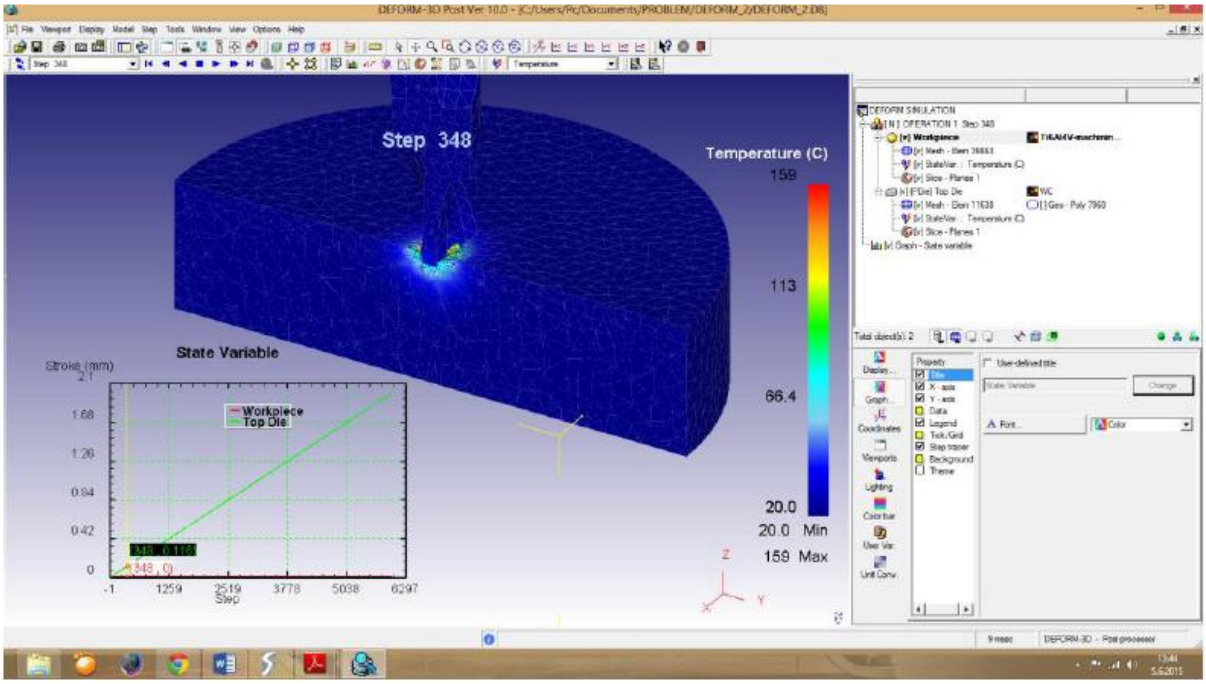

Figure 9. Temperature distribution in stroke of 0.116 mm by using 0.2 mm/rev and 2000 rpm.

A numerical study of the process of drilling is carried out to analyze the effect of various cutting conditions on the temperature generated. A comparison of feed rate shows that a 50% increase in feed rate causes approximately 30% increase in temperature. The effect of cutting speed on temperature generated during drilling process is also studied. A 50% increase in cutting speed causes approximately 18% increase in temperature.

CONCLUSION

The experimental approach to study machining processes is expensive and time consuming, especially when a wide range of parameters is included: tool geometry, materials, cutting conditions, etc. The alternative approaches are mathematical simulations where numerical methods are applied. Determination of temperatures in drilling operations is easier today by development of computing machines and implementation of FEM. To study machining is a quite complicated task where complex disciplines such as metallurgy, elasticity, plasticity, heat transfer, contact problems, fracture mechanics, and lubrication are involved. The goal of FEA is to derive a computational model predicting the deformations, stresses and strains in the workpiece, as well as the loads on the tool working under specific cutting parameters

In this work; a 3D FE model of drilling is presented which includes fully adaptive unstructured meshing, tight thermo-mechanical coupling, deformable tool-chip-workpiece contact, interfacial heat transfer across the tool-chip boundary, and constitutive model appropriate for high strain-rate, large strain and high temperature deformation.

Heat generation during drilling processes is inherent problem due to cutting deformation and friction between workpiece and the drilling tool. In this study, thermo-mechanical analysis models are developed by using FEA software in order to determine heat distributions and to minimize temperature rise. Maximum temperature values and their distribution along the workpiece were calculated and compared for 0.2, 0.3 and 0.4 mm/rev feed rates at 2000 and 3000 rpm rotational speeds.

Acknowledgements

Author would like to thank for the support given by Cukurova University under the contract of BEK 2015 922

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