A coupled FE and CFD approach to predict the cutting tool temperature profile in machining

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Abstract

The paper presents an innovative methodology of coupling the conventional finite element machining simulations with computational fluid dynamic (CFD) model to analyse the temperature distribution at the cutting tool. The conventional finite element machining simulations were conducted using DEFORM 2D to predict the heat generation and tool tip temperature during the cutting action. Machining simulations were conducted using Ti6Al4V and uncoated carbide as a workpiece and tool material respectively. Modified version of Johnson-Cook constitutive model was incorporated in the conventional finite element based machining simulations to predict the behavior of flow stresses for Ti6Al4V titanium alloy. Computational fluid dynamics (CFD) simulations were performed using ANSYS® CFX. CFD model has incorporated air as a cooling media to simulate the dry cutting and temperature distribution at the tool surface was obtained. The coupled numerical modeling methodology showed encouraging potential of predicting precise temperature distribution on the cutting tool. The approach can be further evaluated to predict temperature distribution under flood cooling and minimum quantity lubrication (MQL).

Keywords: Titanium alloy; Finite element modeling; Computational fluid dynamics (CFD); Johnson-Cook model

1. Introduction

Cutting temperature generated during the machining phase plays very critical role towards the overall machining performance. Elevated cutting temperature during the machining process introduces rapid tool wear rate, built-up-edge (BUE) formation, thermal flanking and plastic deformation at the cutting edge resulting in very short tool life. Ultimately it also affects the dimensional accuracy and surface integrity of the component. Due to these problems cutting temperature provides limitation for increasing material removal rate (MMR). Different types of lubricants/ coolants are employed in the metal cutting sector to dissipate the generated heat efficiently.

Several researchers have conducted research to explore the possibilities for machinability improvement using different cooling strategies using both experimental data and numerical models. Finite element simulations have shown enormous success for modeling the orthogonal machining setup. Finite element modeling is generally preferred over analytical modeling as there is a lesser amount of complex assumptions required as compared to analytical modeling [1]. Stephenson and Ali [2] performed machining test using 2023 aluminum and grey cast iron with carbide tools. For interrupted and continuous cutting arrangements cutting speed up to the level of 18 m/s was utilized. They measured cutting temperatures using infrared and tool-work thermocouple technique. The
study revealed that cutting temperature increases with increasing cutting cycle time and approach steady state value for very lengthy cutting cycles.

Kitagawa et al. [3] also conducted the machining operation under turning setup using Inconel 718 and Ti6Al6V25n. The study used embedded thermocouple method to estimate the cutting temperature on the cutting tool and study analysed the influence of cutting temperature on the tool wear. Shu et al. [4] presented an approach of numerical thermal modeling of the cutting temperature with CFD modeling method. They modeling method was based on the working of smart tool with internal cooling arrangement. The study compared the numerical finding with theoretical data that was found in good agreement with each other. The study revealed that temperature distribution on the cutting tool has strong dependency on the inlet velocity of cooling media. Rogério et al. [5] performed another study to study the influence of coating thickness in temperature on the cutting zone and heat flux generation. The study was conducted using the cutting inserts with substrate K10 and diamond with TiN and Al2O3 coatings. The numerical modeling was performed using AdvantEdge for machining simulations and CFD modeling was performed using ANSYS CFX. The study revealed that heat flux generation was slightly lower for the coating thickness of 10 μm.

Grzesik [6] performed study using different coated cemented carbide tool to investigate the influence of coating on tool-chip contact area and average temperature of the tool-workpiece. Grzesik et al. [7] in another study utilized finite element modeling approach to predict the temperature distribution for different coated tools. The study was performed for continuous cutting and finite element modeling was achieved using Advantage software package. The study used tool with P20 substrate with TiC, TiN and Al2O3 thin coating. The study pointed out that more accurate data about coatings are required for proper numerical simulations. Yvonnet et al. [8] provided an innovative approach to predict the heat flux on the cutting tool in orthogonal cutting setup. The approach was based on the coupling of finite element numerical modeling, inverse approach algorithms and experimental data. The study provided encouraging results and much simpler way to identify heat flux distribution.

Luchesi and Coelho [9] experimentally estimated the convective heat transfer of cutting media under laminar flow conditions. The study was beneficial for machining especially when modeling minimum quantity lubrication (MQL) techniques. Carvalho et al. [10] in another study proposed an inverse thermal modeling technique to predict cutting temperature at the tool-chip interface. The study developed a three-dimensional inverse algorithm for heat flux and cutting temperature predictions under transient state. The thermal modeling was based on the solution of transient three-dimensional heat diffusion equation that accounts for the whole tool assembly. The study also considered the effects of tool holder and the shim. The approach was verified experimentally as well and found in good agreement with the experimental data and literature.

Finite element modeling of machining problems need a lot of attention towards material constitutive law for flow stresses, friction model at tool-chip interface and fracture law to facilitate fracture. Several studies have been conducted to predict the machining performance of Ti6Al4V accurately by using different tooling materials. Arrazola and Özçel [11] found that precision of the simulated results was extremely dependent on the constitutive model for workpiece material’s flow stress, heat transfer conditions and frictional rule at tool-chip interface. Özçel et al. [12] also examined the machinability of Ti6Al4V using uncoated and coated carbide inserts. They established a modified version of constitutive model for accurate chip formation. Simulated cutting forces and tool wear were found in good compromise with experimental data. Özçel and Sima [13] examined various form of Johnson-Cook constitutive equation in the finite element models to estimate the machinability of Ti6Al4V. Modified material models were capable to incorporate the influences of flow softening, strain hardening and thermal softening effects. The study showed that cutting temperature, heat generation and cutting forces are highly dependent on the flow stresses. Umbrello [14] also performed a study to investigate the machining performance of high speed machining of Ti6Al4V using finite element modeling. The study compared the forces and chip morphology with experimental data and found in good agreement with each other.

In the present study an innovative approach of coupling the conventional finite element machining simulation using Deform-2D and CFD model using ANSYS CFX was implemented to investigate the temperature distribution on the cutting insert under the cooling of dry air at room temperature. The approach showed encouraging potential for thermal modeling of complex machining scenarios such as minimum quantity lubrication (MQL) and cutting tool with internal cooling options.

2. Proposed Methodology

The methodology, implemented in this study, consist of two separately conducted finite element based simulations. In the first phase, conventional finite element machining simulation was conducted using appropriate material constitutive model, friction rule and fracture law. This modeling phase was executed using Deform 2D software package. Cutting temperatures generated in the cutting zone, shear plane and tool tip were obtained during this first part of simulation phase.

In the second phase the highest temperature value obtained at the tool tip was used as heat source and placed at the nose of the cutting tool geometry. ANSYS CFX was employed in the second phase where thermal interaction of cutting tool with heat source and air as a cooling media was simulated. The simulated results show encouraging results.
3. Finite element machining simulation (First phase)

Finite element machining model was developed using DEFORM – 2D software package considering Ti6Al4V as workpiece material and uncoated carbide as a cutting tool material. Flow stress behavior of titanium alloy (Ti6Al4V) was modeled using modified Johnson-Cook constitutive model as advised in literature [12-13, 15-16]. Eq. 1 represents the modified version of Johnson-Cook equation used in the current study. The equation consists of additional parameter tanh that provides better flow softening behavior at higher strains. Other parameters such as p, r, S and D depend on the workpiece material being used [16].

\[
\sigma = \left[ A + B\varepsilon^n \left( \frac{1}{\exp(\varepsilon^m)} \right) \right] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \\
\left[ 1 - \left( \frac{T-T_m}{T_m-T} \right)^m \right] \left[ D + (1-D) \tanh \left( \frac{1}{(\varepsilon + p)r} \right) \right] S
\]  

Table 1. Johnson-Cook parameters [12]

| A  | 782.7 MPa | S  | 0.05 |
|----|-----------|----|------|
| B  | 498.4 MPa | r  | 2    |
| C  | 0.028     | d  | 5    |
| n  | 0.28      | b  | 1    |
| m  | 1.0       | a  | 2    |

Where D=1-(T/Tm)^d and p=(T/Tm)^b

Where \( \varepsilon \) is flow stress, \( \varepsilon \) is true plastic strain, \( \dot{\varepsilon} \) is strain rate, \( \dot{\varepsilon}_0 \) is reference strain rate, T is workpiece temperature, Tm is melting point and T° is ambient temperature. The study used Johnson-Cook parameter as available in literature [12]. These parameters are stated in Table 1. Table 2 shows thermal and mechanical properties of Ti6Al4V with respect to temperature.

Table 2. Temperature dependent mechanical and thermal properties of Ti6Al4V [12]

| E(T) (MPa) | v(T) (1/°C) | λ(T) (W/m°C) | Cp(T) (J/kg°C) |
|-----------|-------------|--------------|---------------|
| 57.7T+111.62 | 3.10^{-9}T+7.10^{-6} | 0.015T+7.7 | 2.7e0.0002T |

The finite element machining simulation used the shear friction model to illustrate the friction present at tool-chip interface. Shear friction law as shown in Eq. 2, is mostly utilized in machining simulations to describe environment with severe contact [17]. Where m represents frictional factor, \( t \) is frictional shear stress and k is shear flow stress of work material. The model incorporated friction factor (m) as 0.6 for uncoated carbide tools.

\[
m = \frac{t}{k}
\]

Fig. 1. Finite element simulated cutting temperature at Cutting speed (Vc) of 150 m/ min and feed of 0.2 mm/ rev

To facilitate the fracture mechanism in finite element model Cockroft and Latham fracture criterion [18] was also used. Cockroft and Latham model states that fracture starts when integral of maximum principal stress component over a strain path becomes equal to the critical damage value. Eq. 3 denotes the Cockroft and Latham damage model. The current study utilized the commonly used critical damage value as 0.6.

\[
\int_0^{\varepsilon_f} \sigma_1 \, d\varepsilon = D
\]

Where \( \varepsilon_f \) denotes effective strain, \( \sigma_1 \) is maximum principal stress and D is critical damage value based of the material.
4. CFD model (Second Phase)

In order to investigate the thermal interaction between the cutting tool with a heat source and air as a cooling media, ANSYS CFX software was employed in the current study. ANSYS CFX is CFD software that solves Navier-Stokes equations for the conservation of mass, momentum and energy [19].

The standard shear-stress-transport (SST) $k - \omega$ turbulence model was used in the current study. The cutting tool tip temperature was obtained from the machining simulation using DEFORM, and then maximum tool tip temperature of 663°C (936 K) was employed on the tool as a heat source to study the effect of dry air cooling and respective temperature distribution on the cutting tool. The CAD model of the cutting tool was created in Autodesk inventor and imported to ANSYS CFX as IGES model. The geometry of the cutting tool was used as solid domain and a rectangular geometry was created that acts as fluid domain as shown in Fig. 2. The simulation parameters are mentioned in Table 3.

![Fig. 2. Cutting tool material as solid domain and rectangular geometry as fluid domain](image)

Table 3. CFD simulation parameters [11]

| Parameter                                | Value   |
|------------------------------------------|---------|
| Density of insert [Kg/m^3]               | 15000   |
| Thermal conductivity of the insert [W/mK] | 46      |
| Specific heat of the insert [J/Kg/K]     | 203     |
| Air temperature [K]                      | 298     |
| Inlet velocity of air [m/sec]            | 0.2     |

The thermal and physical properties of air at 298K were incorporated by the material library available in ANSYS CFX. In order to define the CFD model properly it is very important to define the inlet and outlet for the considered problem. Fig. 3 shows the velocity inlet taken for the CFD model used in the current study. Similarly it is important to define the proper outlet of the fluid and solid domain. Pressure outlet condition is shown in Fig. 4.

![Fig. 3. Inlet condition for the fluid solid interface](image)

![Fig. 4. Outlet condition for the fluid solid interface](image)

After defining the inlet and outlet conditions for the solid fluid model, air has been introduced through inlet. The thermal interaction between air and cutting insert with a tool tip temperature as a heat source has been analyzed as shown in Fig. 5. It can be observed in Fig. 6 that the temperature distribution in a cutting tool using dry air shows very slow cooling as the tip shows maximum temperature of 936K and minimum temperature of 778K on the remaining portion of insert. It clearly indicates that the dry cooling cannot reduce temperature significantly. This strengthens the finding of researchers working in the field of metal cutting that dry cutting is not capable to dissipate heat properly especially when difficult to cut material such as titanium or nickel alloys are being machined.
5. Conclusion

Previously several studies have shown very good potential of predicting temperature distribution in the cutting zone but incorporating the influence of cooling strategy is very difficult. This work provides an easier approach to estimate the temperature distribution of the cutting tool by considering the solid fluid interface approach executed using ANSYS CFX software package. The coupled approach for conventional machining FE model and CFD model can be used to study the tool temperature distribution for minimum quantity lubrication (MQL) techniques. The presented approach shows good potential to study the influence of air inlet velocity. By increasing the velocity of air, force convection can be achieved and simulated to study the tool temperature distribution. In the metal cutting process to design a CFD model, conduction and convection are treated as major heat transfer modes. However, there is a need to explore the role of radiation heat transfer mode in the metal cutting CFD simulations.

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