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ORIGINAL ARTICLE

A numerical and experimental study to investigate convective heat transfer and associated cutting temperature distribution in single point turning

Salman Pervaiz [1] · Ibrahim Deiab [2] · Essam Wahba [3] · Amir Rashid [4] · Mihai Nicolescu [4]

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Abstract During the metal cutting operation, heat generation at the cutting interface and the resulting heat distribution among tool, chip, workpiece, and cutting environment has a significant impact on the overall cutting process. Tool life, rate of tool wear, and dimensional accuracy of the machined surface are linked with the heat transfer. In order to develop a precise numerical model for machining, convective heat transfer coefficient is required to simulate the effect of a coolant. Previous literature provides a large operating range of values for the convective heat transfer coefficients, with no clear indication about the selection criterion. In this study, a coupling procedure based on finite element (FE) analysis and computational fluid dynamics (CFD) has been suggested to obtain the optimum value of the convective heat transfer coefficient. In this novel methodology, first the cutting temperature was attained from the FE-based simulation using a logical arbitrary value of convective heat transfer coefficient. The FE-based temperature result was taken as a heat source point on the solid domain of the cutting insert and computational fluid dynamics modeling was executed to examine the convective heat transfer coefficient under similar condition of air interaction. The methodology provided encouraging results by reducing error from 22 to 15% between the values of experimental and simulated cutting temperatures. The methodology revealed encouraging potential to investigate convective heat transfer coefficients under different cutting environments. The incorporation of CFD modeling technique in the area of metal cutting will also benefit other peers working in the similar areas of interest.

Keywords Finite element modeling · Cutting temperature · Computational fluid dynamics · Convective heat transfer coefficient · Machining · Titanium alloys

1 Introduction

Mechanical energy consumed in the form of plastic deformation during a machining operation is generally converted into heat. Major regions of heat appearance are the primary shear plane and at the cutting interface between tool and chip. Generally the heat generated during cutting action flows to the workpiece, cutting tool, and chips. The heat conducted to the cutting tool material can result in a very high value of temperature 1100 °C approximately [1]. The high intensity of temperature at the cutting edge results in accelerated tool wear rates, shorter tool life, and poor surface quality of the machined part [2]. Therefore, temperature distribution at the cutting tool has a prime importance when predicting the tool life and machining performance of the cutting process. But due to the inherent machining difficulties such as chip evacuation and very precise chip–tool contact zone, cutting temperature measurement is still a big issue [3, 4].

This current research work is the continuation of study [5] proposed by authors initially where sequential coupling approach of finite element (FE) model and computational fluid dynamics (CFD) model was proposed. In this study, a

✉ Salman Pervaiz
sxpcad@rit.edu

1 Department of Mechanical and Industrial Engineering, Rochester Institute of Technology – Dubai, Dubai, United Arab Emirates

2 School of Engineering, University of Guelph, Guelph, Ontario, Canada

3 Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt

4 Department of Production Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

modified coupling approach, FE and CFD models couple and execute an iterative process (solving in loops) to reach the optimum value of heat transfer and respective temperature distribution is represented.

2 Literature review

Several researchers have devoted their research work towards the cutting temperature prediction using experimentation. Many researchers [6, 7] agreed that although cutting temperature has a critical influence on the machining performance but its measurement and prediction is not an easy task. Literature reveals several techniques to measure cutting temperature from the cutting interface. Among the other methods, tool-work thermocouple method was considered to be a reasonable approach as reported by Shaw [8] and Stephenson [9]. However, complex calibration with respect to the tool and workpiece material pairs appeared to be the main hurdle for its usage [10]. Kottenstette [11] and Ueda et al. [12] inspected the cutting temperature of the cutting interface experimentally employing two-color pyrometers. The experimental setup provided reasonably good results. Grzesik et al. [13]utilized standard K type thermocouples to investigate the cutting temperature during cutting process by embedding them into the workpiece. The study was conducted using TiC, TiC/TiN, and TiC/Al2O3/TiN coated cutting tools for the machining of different steel grades. The study provided scanned thermal images of tool–chip interface. M'Saoubi et al. [14]utilized charge coupled infrared-based apparatus to capture temperature from the cutting interface. M'Saoubi and Chandrasekaran [15] in another study utilized IR method for the cutting temperature measurement for temperature range of 500–1000 °C. The study revealed that with proper calibration of the system readings with error range of ± 10–15 °C can be captured.

However, due to the difficult nature of experimental setup required to measure cutting temperature, many researchers have focused their attention to develop analytical and numerical solving methods to evaluate cutting temperature. Literature [16] points out that cutting temperature during the steady state machining can be predicted by using finite element method (FEM). Due to the complex nature of cutting process, most of the researchers generally utilize finite element and finite difference methods. However, incorporation of material's constitutive properties during the cutting operation appears to be the biggest challenge for researchers using finite element method for temperature prediction [17]. For finite difference method utilization, the issue of unknown heat flux at the cutting interface has been reported.

To cater the issue of unknown heat flux in the cutting zone, several researchers have utilized inverse heat estimation methodologies. Ohadi and Cheng [18] developed temperature prediction model for abrasive water jet cutting process. The modeling approach adopted in the work was based on the assumption that workpiece is long enough and can be solved using quasi-steady-state conditions. Lima et al. [19] also used conjugated gradient methodology in order to predict cutting temperature. The model was solved numerically using finite volumes approach. Carvalho et al. [3] predicted the

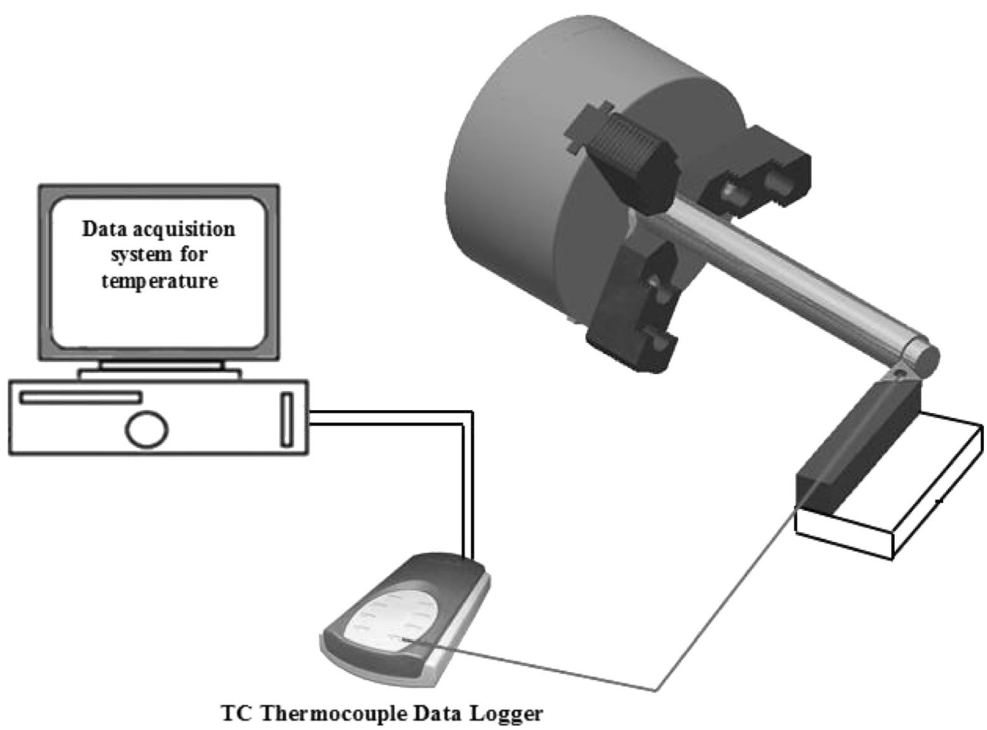


Fig. 1 Schematic illustration of experimental setup

Table 1 Specifications of equipment and machining parameters

Machining parameters	Type/levels
Temperature sensor	K type (nickel–chromium) thermocouple
Cutting speed (m/min)	90, 120
Feed level (mm/rev)	0.1
Depth of cut, DoC (mm)	1
Cutting environment	Dry cutting mode

temperature distribution on the tool holder by employing inverse heat modeling method. The model utilized finite volume method to obtain solution. Yen and Wright [20]utilized inverse thermal model with simplified geometry and boundary conditions by utilizing 1D analytical elliptical thermal modeling approach. The model developed remote sensing methodology useful for predicting temperature at cutting zone. Kwon et al. [21] utilized elliptical thermal modeling technique to predict cutting temperature. However, the simplified model was not able to capture the real heat transfer that occurs in a machining process.

Liang et al. [4] established a 3D inverse heat conduction method to predict temperature at the tool–chip interface under dry machining. The study utilized embedded thermocouple method to acquire temperature of the tool and then it was further used as an objective function of the inverse method. The accuracy of the inverse calculations was disturbed by the grooves produced for the induction of thermocouples. Yvonnet et al. [22]utilized an inverse procedure to estimate heat flux during the cutting operation. The study utilized simple inverse methodology to predict heat flux on the rake face of the cutting tool and heat transfer coefficient between tool and the cutting environment. The study provided a way to couple experimental data with inverse algorithms and finite element-based numerical model. The results showed easier way of getting precise heat flux distribution. Luchesi and Coelho [23]experimentally simulated a heat source on a thin steel plate using electric heating a similar scenario like metal cutting process. The study investigated convective heat transfer coefficient for dry, flood and MQL settings under laminar fluid flow conditions. Vazquez et al. [24] performed computational fluid dynamics (CFD) analysis to study the cooling and lubrication settings for micromilling of Ti6Al4V. The CFD model revealed the disordered flow during the cutting action as flow did not reach the desired location.

Verma et al. [25] performed a study to numerically model the aerosol behavior for internal mixed nozzle. The study focused to predict the performance of aerosol with respect to the grinding operation. The study revealed that increasing pressure can increase wettability and provide better temperature control. Asif et al. [26] in another study developed a heat transfer model when machining titanium alloy (Ti64) using atomization-based cutting fluid (ACF) spray system. The simulated results of thermal field were found in good agreement with the experimental readings. Kundrák et al. [27] evaluated heat transfer under hard turning using computational fluid dynamics (CFD) modeling-based approach. The study provided useful predictions by linking cutting parameters with respect to the heat distribution. Pervaiz et al. [5] previously developed a coupled FE and CFD-based model to get the modeling benefits of both precise temperature distribution and cutting temperature distribution.

This current research work is the extension of the coupled FE and CFD model proposed by the authors earlier [5]. The presented study takes the initial FE and CFD sequential coupling concept from the previous work of the authors and proposes a more refined form of coupling procedure between FE and CFD models. The refined coupled model can be used to conduct an iterative solving procedure to predict optimum value for convective heat transfer coefficient under dry cutting. The FE model-based cutting temperature results were verified experimentally as well.

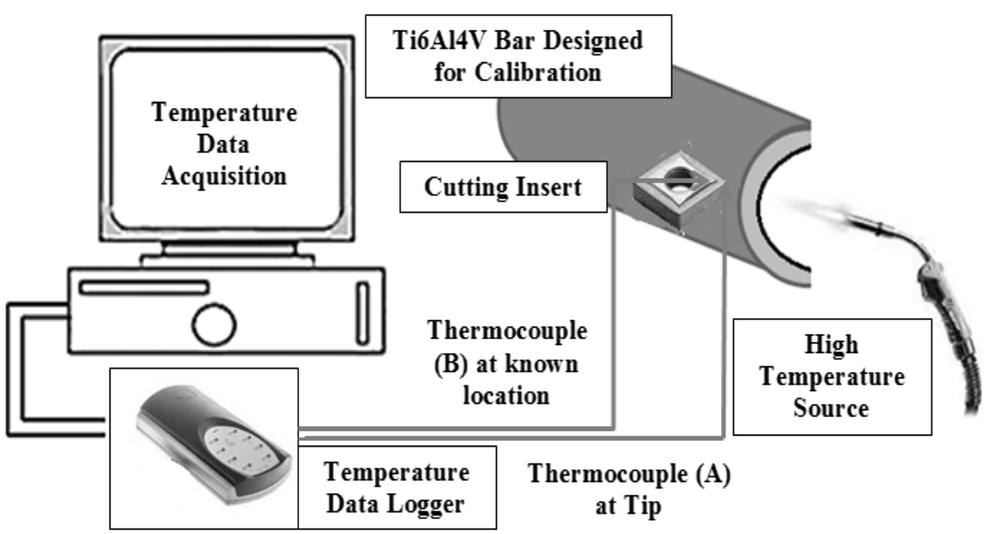


Fig. 2 Schematic illustration of calibration setup for thermocouples

3 Experimental setup

The schematic illustration of the experimental setup has been represented in Fig. 1. In order to get the cutting temperature measurement, cutting parameters were selected from the recommended ranges as available in the handbook. The study was conducted using the cutting parameters as shown in Table 1. In order to measure temperature, K type (nickel–chromium) thermocouples were utilized. Thermocouple is a contact type measuring device that consists of two wires of different materials and the contact point of these dissimilar metals create an open circuit voltage as a function of temperature.

3.1 Workpiece and tool materials

The cutting experimentation was executed using Ti6Al4V as a workpiece material. The study considered Ti6Al4V because approximately 50% of the global titanium consumption is based on the utilization of aeronautic titanium alloy (Ti6Al4V). The cylindrical rods of Ti6Al4V were received as per ASTM B381 standard specifications.

As per the recommendation of cutting tool supplier, H13A grade was selected due to its high wear resistance and good toughness. The study utilized uncoated carbide with ISO specification of TCMT 16 T3 04-KM H13A. The insert has triangular shape with three cutting edges.

3.2 Calibration setup for cutting temperature

Cutting temperature determination using thermocouple-based arrangement has found to be a reliable technique as per the available metal cutting literature. The current study has also utilized K-type thermocouple to investigate the cutting temperature during the study. One of the arrangements has been reported in the literature [28] that was benchmarked for the current study as well. As described in the benchmarked reference [28], oxy-fuel welding torch was used to create flame as heat source. To execute the calibration setup, a specially designed Ti6Al4V workpiece was utilized. In addition, a specially designed fixture was created to mount the welding torch. To perform the desired cutting temperature measurements, two thermocouples (A) and (B) were utilized as shown in the schematic illustration in Fig. 2. Thermocouple (A) was located at the cutting tool tip, whereas thermocouple (B) was planted precisely at known distance and calibration curve was obtained. Soldering was used to fix thermocouple (B) at the described location; however, thermocouple (A) was supported by the contact of workpiece and cutting tool tip.

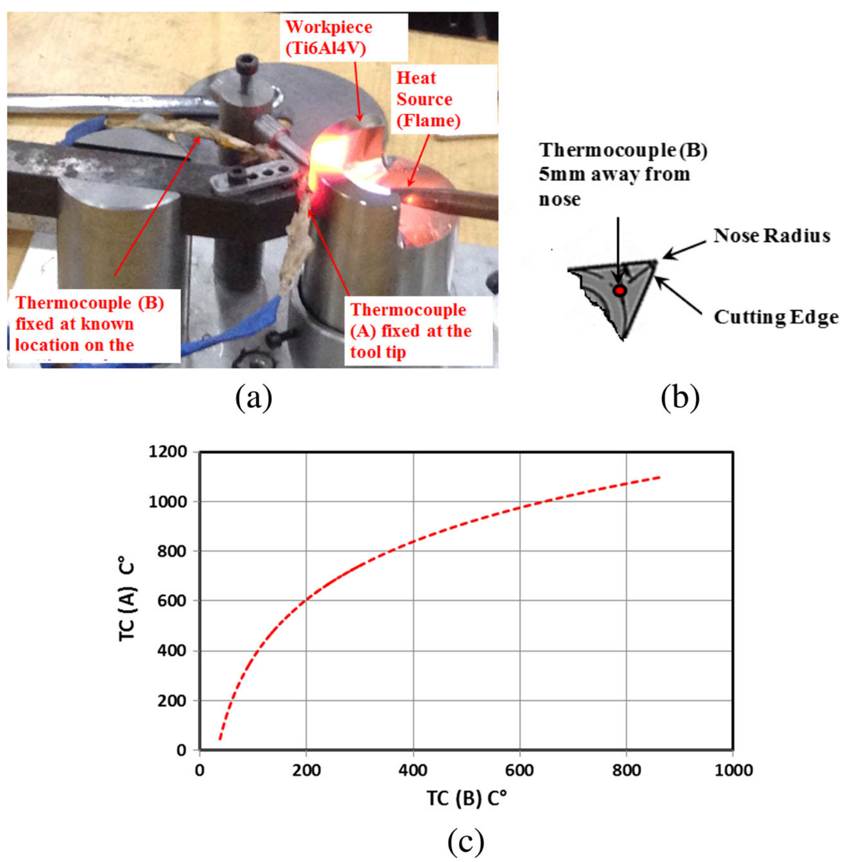


Fig. 3 **a** Experimental setup developed for calibration. **b** Top broken view of the cutting tool. **c** Calibration curve obtained for thermocouple-based setup

The actual experimental arrangement developed in the laboratory has been reported in Fig. 3a [29]. The thermocouple (B) was positioned at the rake face using optical microscope. The hot junction was positioned at the precise distance of 5 mm from the nose of the cutting tool as shown in Fig. 3b. Figure 3c is the calibration obtained by the thermocouple arrangements and the reported curve was used to calculate the cutting temperature in this study.

3.3 Cutting temperature measurement

After the calibration procedure, the thermocouple (B) was kept at the same location as shown in Fig. 3b during the actual machining experiment. Later the temperature reading was reconsidered for the tool tip position by using the calibration curve as shown in Fig. 3c. The cutting temperatures for the considered cutting conditions have been reported in Fig. 4a, b. The average cutting temperatures were then considered for the cutting period only and the value appeared to be 557 and 635 °C for the cutting speeds of 90 and 120 m/min, respectively. The cutting temperature generally stabilizes after some cutting time, it is due to the reason that equilibrium establishes between the heat generation (primary, secondary, and tertiary deformation zones) and heat dissipation (tool-chip-workpiece interface and cutting environment).

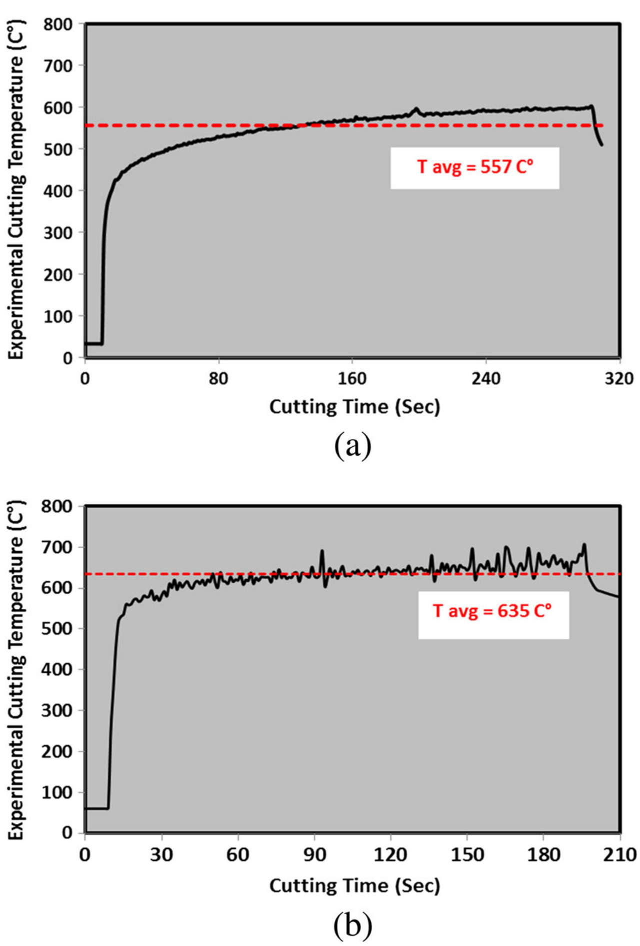


Fig. 4 Experimental cutting temperature when machining Ti6Al4V using uncoated carbide tool (**a**) for cutting speed = 90 m/min, feed = 0.1 mm/rev, depth of cut = 1 mm, and (**b**) for cutting speed = 120 m/min, feed = 0.1 mm/rev, depth of cut = 1 mm [29]

4 FE and CFD modeling considerations

Finite element model was constructed using DEFORM-3D finite element software package. In order to get the precise cutting temperature predictions, precise flow stress for Ti6Al4V has been considered from the available literature [30]. As per the literature [30], modified form of Johnson–Cook model was utilized to model Ti6Al4V. Another important concept is related to the modeling of friction at tool–chip interface. In this current work, the friction was modeled using shear friction law. The reliability of FE-simulated results is also dependent on the fracture mechanisms. Literature [30] suggests to use Cockroft and Latham fracture criterion [31] to facilitate chip formation considering the material as ductile material. Details of this FE model can be attained by going through authors' previous publication on this topic [5, 29]. DEFORM-3D material library data was used to model uncoated carbide as cutting tool material. This modeling procedure has already been discussed by the authors in their previous work [5]. In Deform, the boundary condition for the heat transfer is shown in Fig. 5. The input parameters utilized to control the thermal boundary condition of the FE model are the environment temperature (25 °C) and convective heat transfer coefficient.

The heat transfer in the machining is considered to be under the domain of multiphysics problems because the cutting environment has a controlling influence on the overall heat distribution. It means that principles of fluid dynamics should be utilized here to study the cutting environment interaction with heated solid cutting tool. Fluid flow problems are generally solved using a numerical solver under computational fluid dynamics (CFD) technique. The governing equations such as continuity, Navier–Stokes, and conservation of energy can be found in author's previous work [5]. Here the details of CFD model construction are intentionally not being reported to avoid replication, but the details are available in previous work [5, 29].

The most challenging task in the CFD modeling is the simulation of turbulent behavior. ANSYS® CFX software has many built in turbulence models. This study employed shear stress transport (SST) turbulence model from the ANSYS® CFX software. Literature [32] recommends to use SST model for problems when data near the edge or wall is important. The SST model provides the benefits of both k–ω

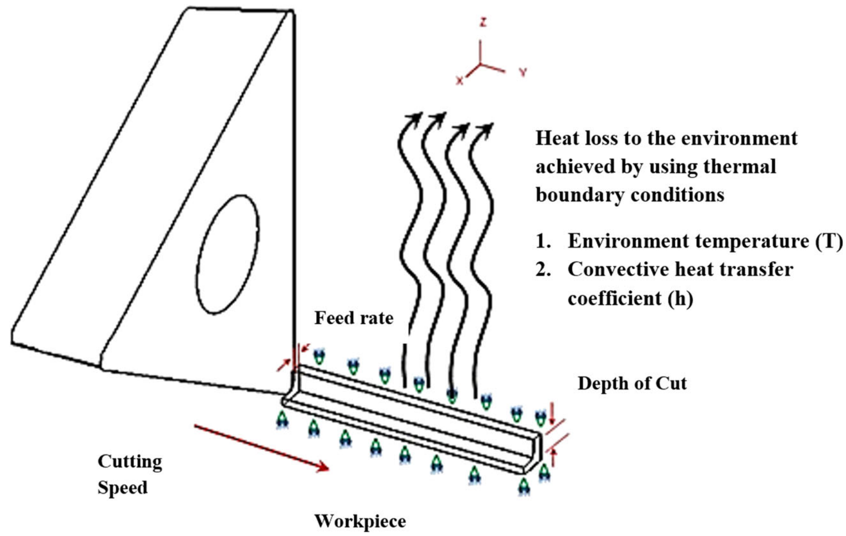


Fig. 5 Finite element model construction with boundary conditions [29]

and k–ε turbulence models. The SST model uses the k–ω model near the walls while the k–ε model away from the walls. The model provides adequate results near the solid boundaries. Figure 6 shows the computational domain using ANSYS® CFX. The details of CFD model construction can be attained from authors' previous publications [5, 29].

The CFD model can be used to calculate the heat transfer coefficient. To compute heat transfer coefficient, basic concepts of conduction and convection heat transfer were utilized. The calculation procedure has been illustrated in Fig. 7. The heat transfer calculation was performed as illustrated in direction (x). The top surface (rake face) of the cutting insert establishes conduction and convection boundary interface. Taking into consideration the boundary condition, the amount of heat conduction and heat convection will be similar. The convection heat transfer is administered by Newton's law of cooling, while the conduction heat transfer is ruled by Fourier's law of heat conduction.

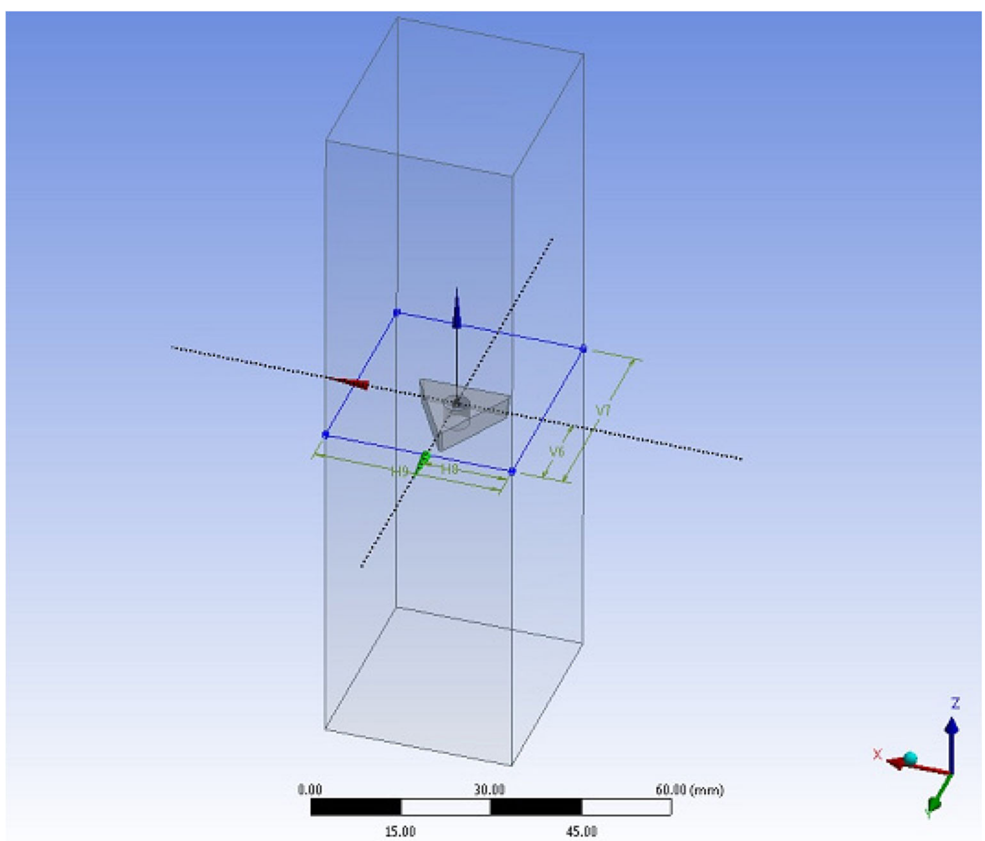


Fig. 6 Geometry of fluid and solid domains

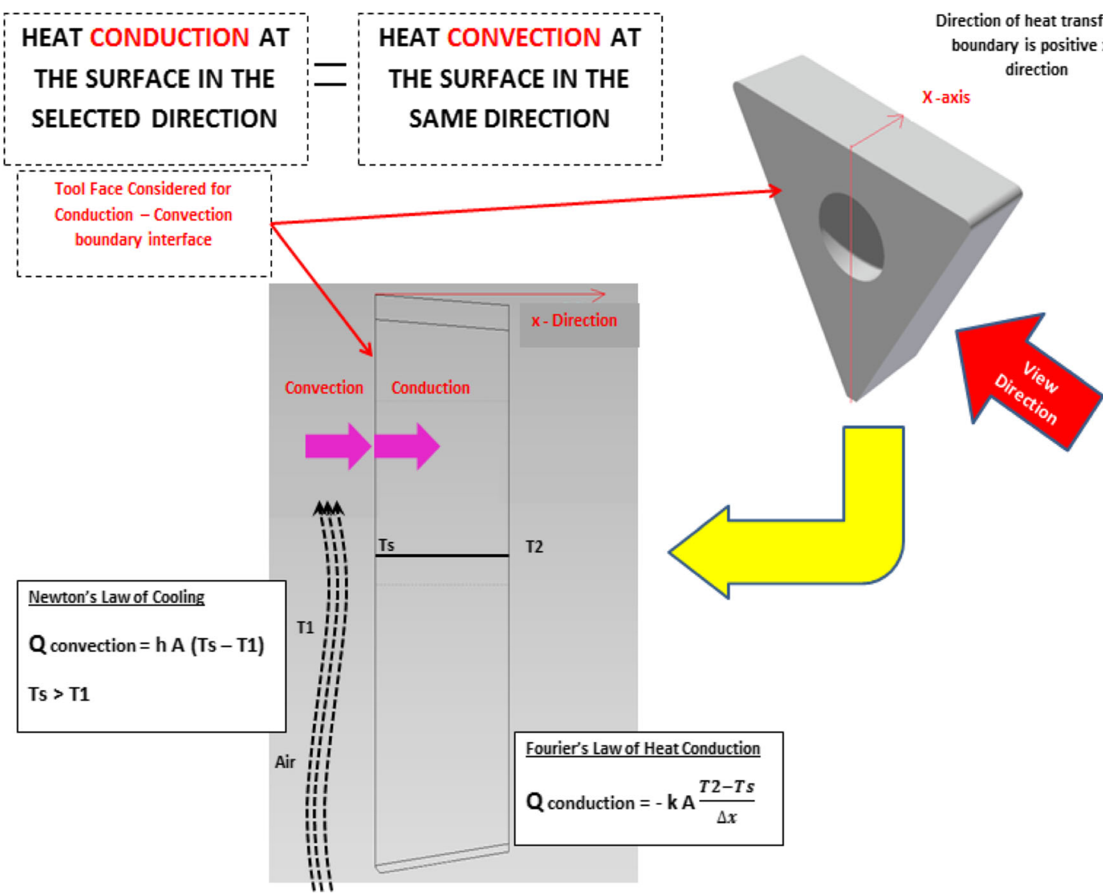


Fig. 7 Concept used for the convective heat transfer using CFD model (adopted from [29])

In a machining operation, heat transfer occurs from the heated cutting zone to the cutting fluid through convection. Convection is achieved by either laminar or turbulent boundary layers resulting from the relative velocities of the heat surfaces in the cutting zone and cutting fluid. The heat transfer rate is generally given by Eq. (1) known as Newton's law of cooling,

$$Q_{convection} = \mathrm{hA}\ [T_s - T_1] \quad (1)$$

Where h is the convective heat transfer coefficient, T_s is the temperature of object, and T_1 is the bulk temperature in the fluid region. Most of the machining simulations utilize finite element-based approach to predict the machining performance of the process. Generally these simulations are conducted using the general values of heat transfer coefficient at the cutting interface as found in literature and reported below in Table 2.

The specific range of values reported in Table 2 above are too wide for practical applications when analyzing the effectiveness of the cutting environment. Generally most of the machining simulations available in literature take the random value of convective heat transfer coefficient based on state (free or forced convection) of the cutting environment and generate cutting temperature. Therefore, the value of convective heat transfer coefficient (h) plays a significant role in an effort to model heat transfer in the metal cutting process.

In this study, a coupling procedure based on finite element analysis and computational fluid dynamics has been proposed to get the optimum value of convective heat transfer coefficient. The flow diagram of the procedure used is shown in Fig. 9. The cutting temperature is acquired from FE-based simulation using a logical arbitrary value of convective heat transfer coefficient from the workable range as available in literature. The FE-based simulated cutting temperature was then used as a heat source on the cutting insert and computational fluid dynamics model was simulated to investigate the convective

Table 2 Convective heat transfer coefficients for different cases of convection [23, 33]

State	Type of fluid	Convective heat transfer coefficient, (W m^{-2} K^{-1})
Free convection	Gases	5–30
	Water	100–900
Forced convection	Gases	10–300
	Water	300–11,500
	Viscous oils	60–300
	Liquid metals	5700–114,000
	Boiling liquids	3000–57,000
Phase change	Condensing vapors	5700–114,000

heat transfer coefficient using air under dry cutting condition. The value of convective heat transfer coefficient was then calculated using the CFD simulation and used again in the finite element model thus running this iterative process. The coupled procedure will provide an optimum value of convective heat transfer coefficient once convergence is achieved using the iterative methodology [29].

5 Results and discussion

It has been observed that literature rarely provides information when it comes to the selection of heat transfer coefficient during the metal cutting operation. Due to the involvement of multiphysics, it is a difficult case for even dry cutting without the application of any external lubricant. The problem of heat transfer coefficient identification becomes more complex when more advanced cooling or lubrication methods are considered. In order to numerically predict the reliable and precise temperature distribution in the cutting zone, it is very important to incorporate the optimum value of heat transfer coefficient. To start the iterative process of FE and CFD coupled approach as described above in Fig. 8, an arbitrary logical value of convective coefficient of 100 (W/m^2 K) was selected by taking recommended value from the literature. For the cutting condition of 90 m/min and the FE simulation phase of the first iteration, average cutting temperature of 642 °C was obtained as reported in Fig. 9c. It was observed that the cutting temperature obtained in the first iteration was having higher deviation from the experimental value of cutting temperature 557 °C as reported in Fig. 9b.

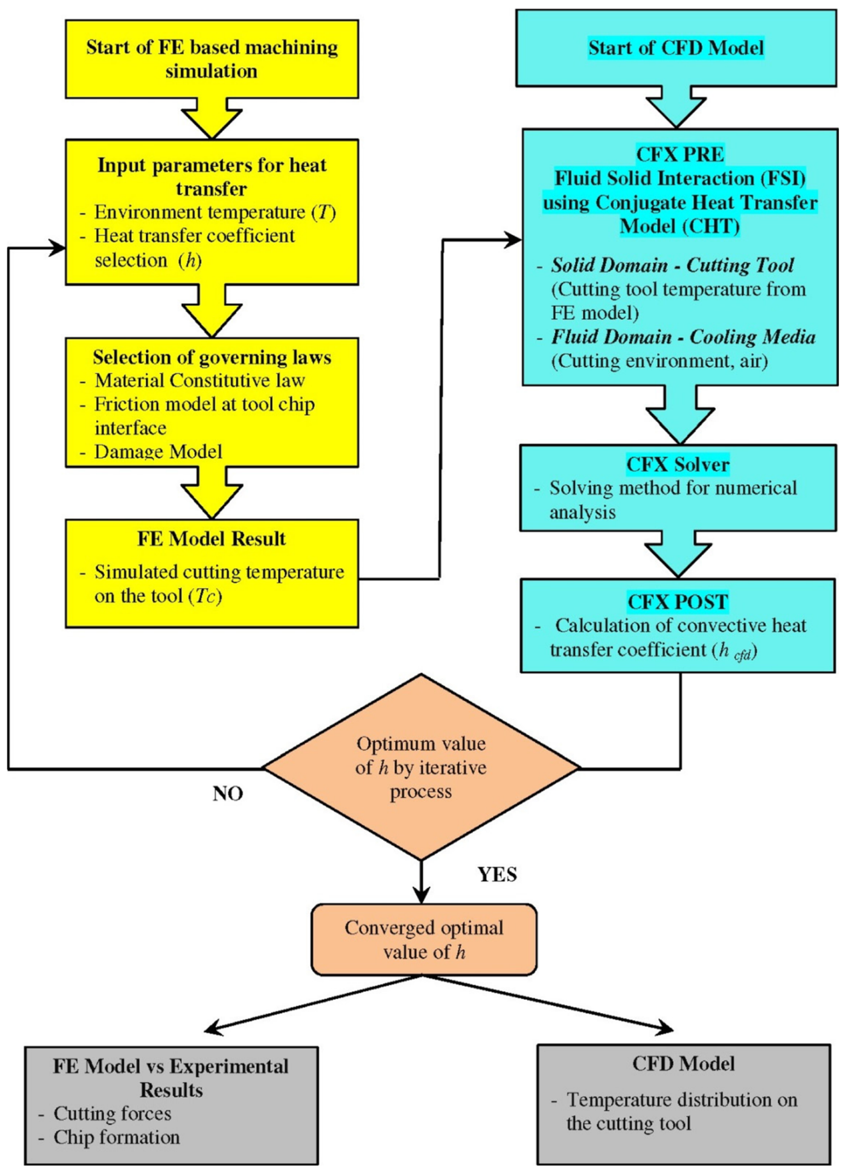


Fig. 8 Modified FE and CFD coupled models to select optimum value of convective heat transfer coefficient (adopted from [29])

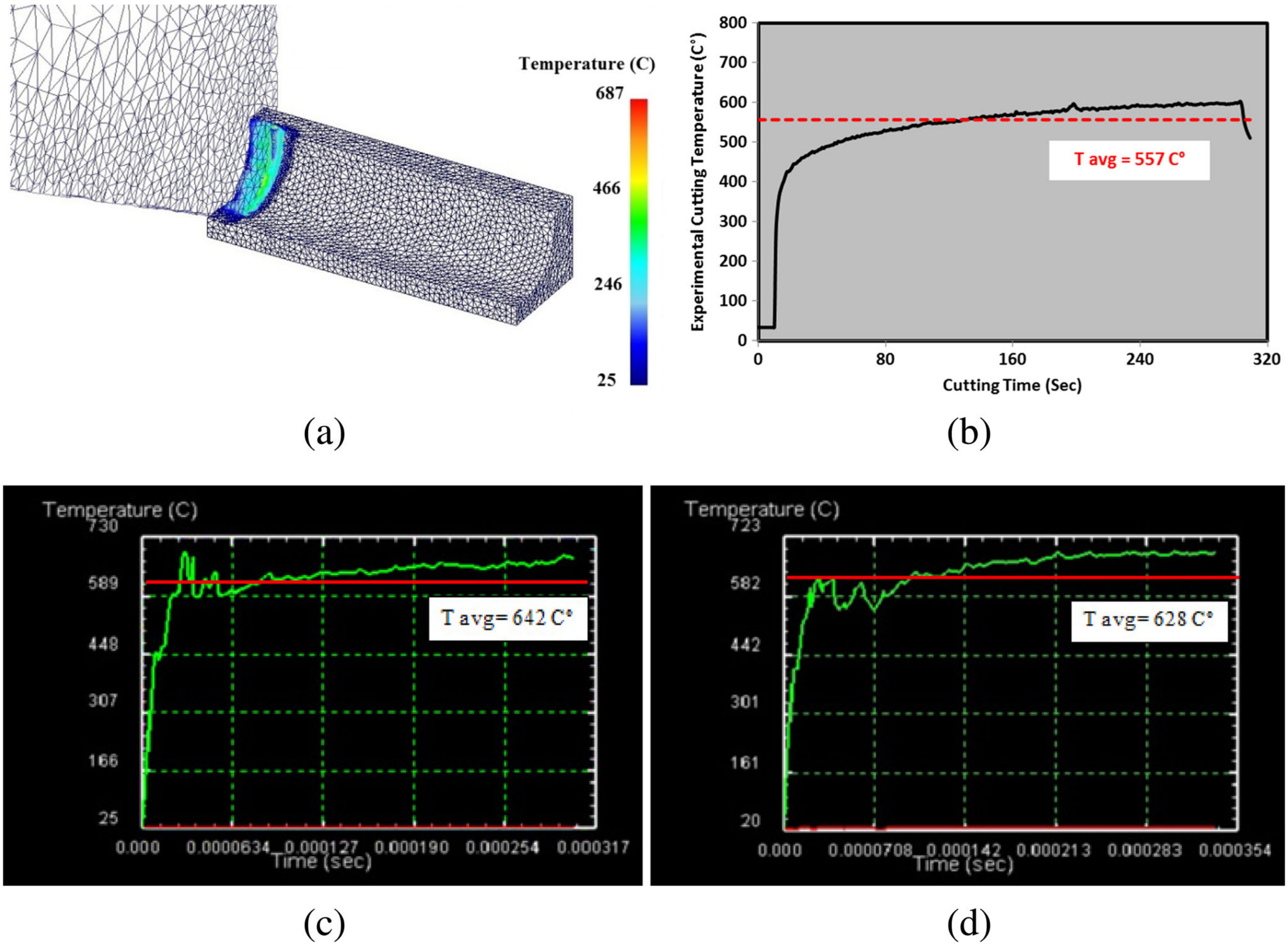


Fig. 9 90 m/min cutting speed. **a** FE cutting model. **b** Experimental value of cutting temperature, 557 °C. **c** FE cutting temperature in the first iteration using h = 100 W/m^2 K. **d** FE cutting temperature in the second iteration using h = 195.96 W/m^2 K [29]

In the second CFD phase of the first iteration, the FE-simulated temperature of 642 °C has been used as a heat source for the cutting tool tip. In the CFD model, the air interaction on the heated cutting tool was established using the appropriate feed rate as reported in Fig. 11a. At the end of the first iteration process, convective heat coefficient adjacent to the tool tip was found to be 195.96 W/m^2 K. The procedure of convective heat transfer coefficient calculation from the CFD model has been represented in Fig. 11b. The 195.96 W/m^2 K heat transfer coefficient was plugged in the FE model to start the second iteration. The FE phase of second iteration provided the average cutting temperature of 628 °C as shown in Fig. 9d. The second CFD phase of second iteration provided the refined value of convective heat transfer coefficient of 195.66 W/m^2 K.

For the cutting condition of 120 m/min and the FE simulation phase of the first iteration, average cutting temperature of 778 °C was obtained as reported in Fig. 10c. It was observed that the cutting temperature obtained in the first iteration was having higher deviation from the experimental value of cutting temperature 635 °C as reported in Fig. 10b.

For 120 m/min cutting speed and the second CFD phase of the first iteration, the FE-simulated temperature of 778 °C has been used as a heat source for the cutting tool tip. In the CFD model, the air interaction on the heated cutting tool was established using the appropriate feed rate as reported in Fig. 11a. At the end of the first iteration process, convective heat coefficient adjacent to the tool tip was found to be 203.95 W/m^2 K. The 203.95 W/m^2 K heat transfer coefficient was plugged in the FE model to start the second iteration. The FE phase of second iteration provided the average cutting temperature of 721 °C as shown in Fig. 10d. The second CFD phase of second iteration provided the refined value of convective heat transfer coefficient of 199.95 W/m^2 K.

Figure 12 represents that iterative process has significantly minimized the error in the cutting temperature from 15 to 12% for 90 m/min, and from 22.5 to 15% for 120 m/min cutting conditions, respectively. The error in terms of heat transfer coefficient was found to be 0.01% at the end of the third iteration that represents that convergence has been attained.

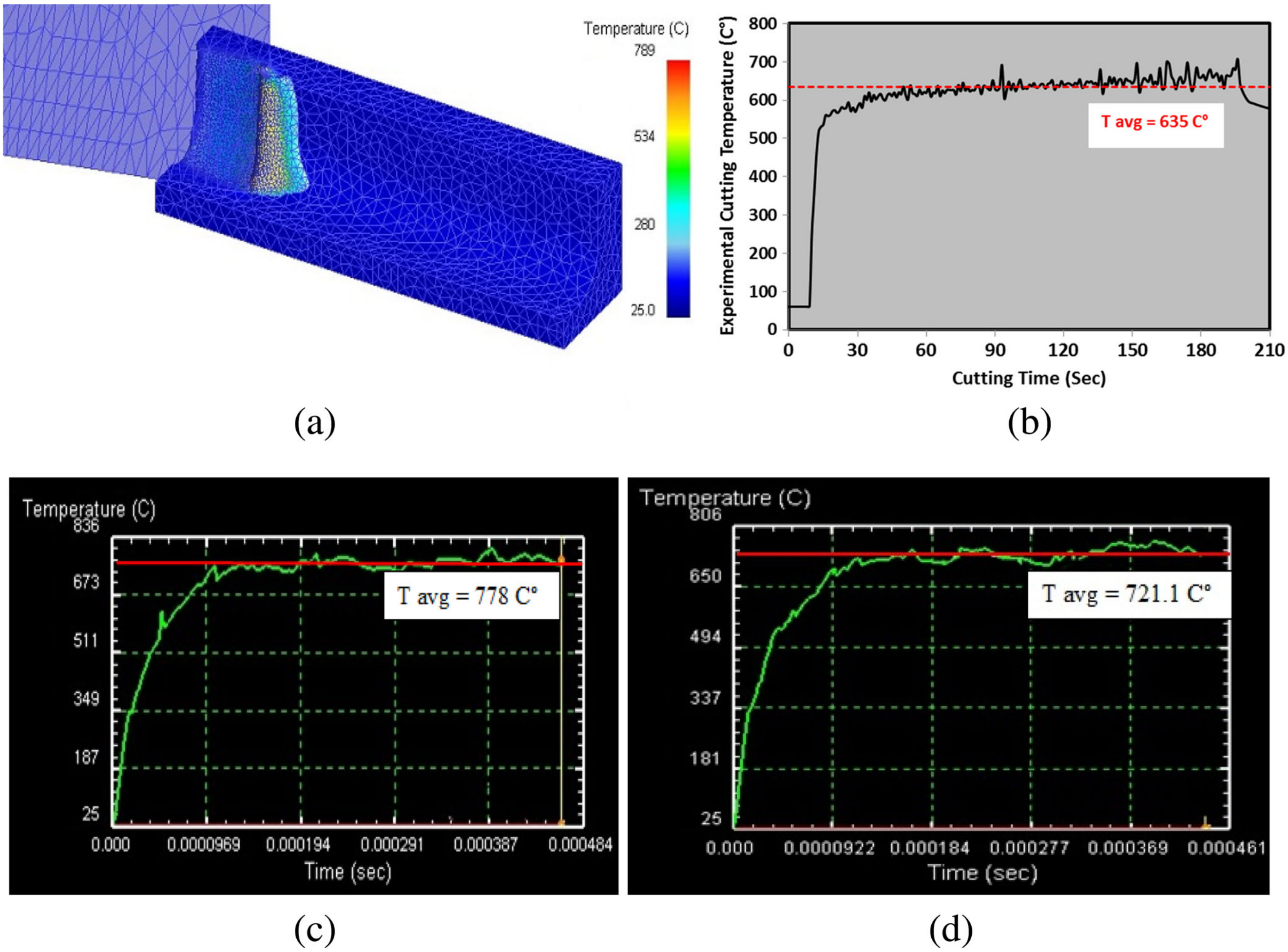


Fig. 10 120 m/min cutting speed. **a** FE cutting model. **b** Experimental value of cutting temperature, 635 °C. **c** FE cutting temperature in the first iteration using h = 100 W/m^2 K. **d** FE cutting temperature in the second iteration using h = 203.95 W/m^2 K

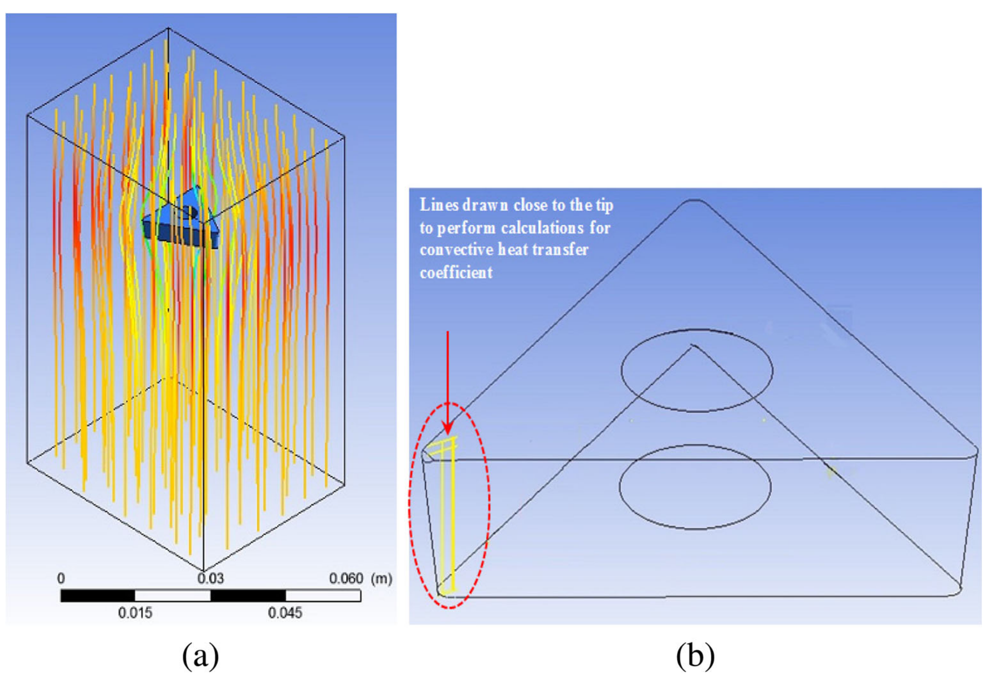
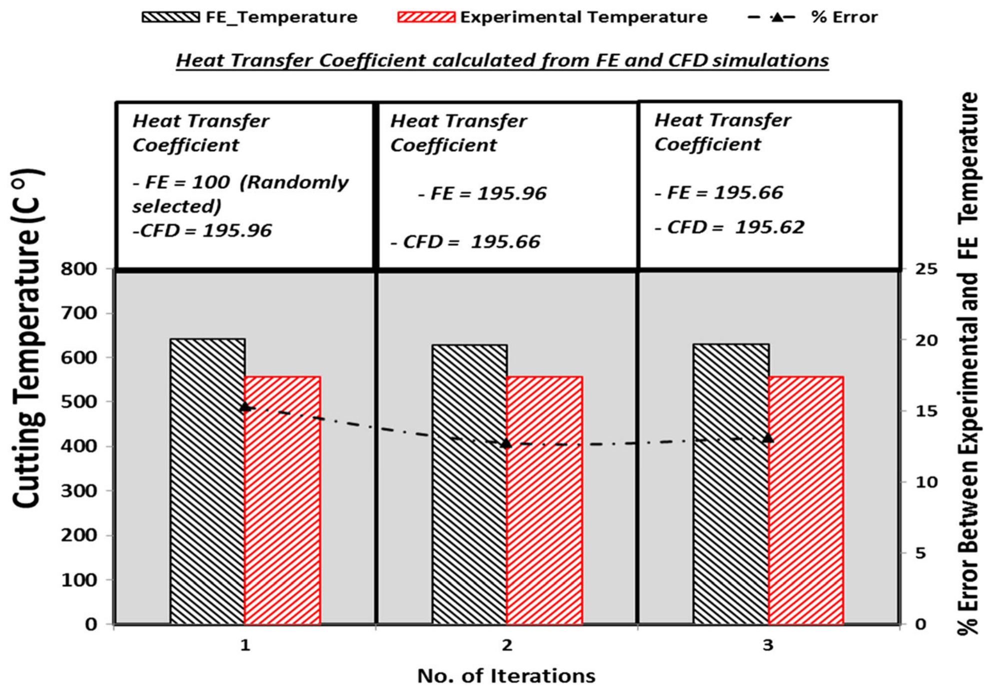
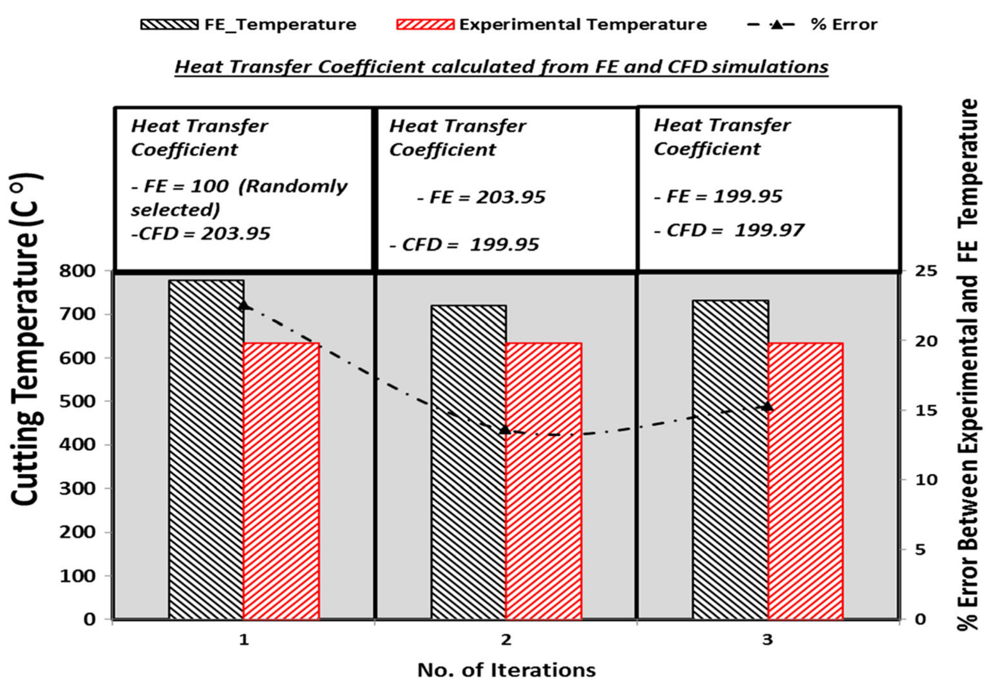


Fig. 11 **a** CFD simulation. **b** Calculation of convective heat transfer coefficient close to tool tip (adopted from [29])

Fig. 12 Error representation in experimental and simulated cutting temperature from iterative process **a** for 90 m/min and **b** for 120 m/min (adopted from [29])



(a)



(b)

Once final cutting temperature has been obtained using the optimized value of heat transfer coefficient, cutting temperature mapping was executed on the cutting insert geometry as shown in Figs. 13a and 14a for 90 and 120 m/min cutting speeds, respectively. To facilitate cutting temperature measurement, a line has been taken on the rake face and Figs. 13b and 14b report the cutting temperature along the direction.

6 Conclusions

The conclusions drawn from the presented experimental and numerical study are presented as under:

- The study demonstrated a functional methodology where FE and CFD models can be coupled to solve complex

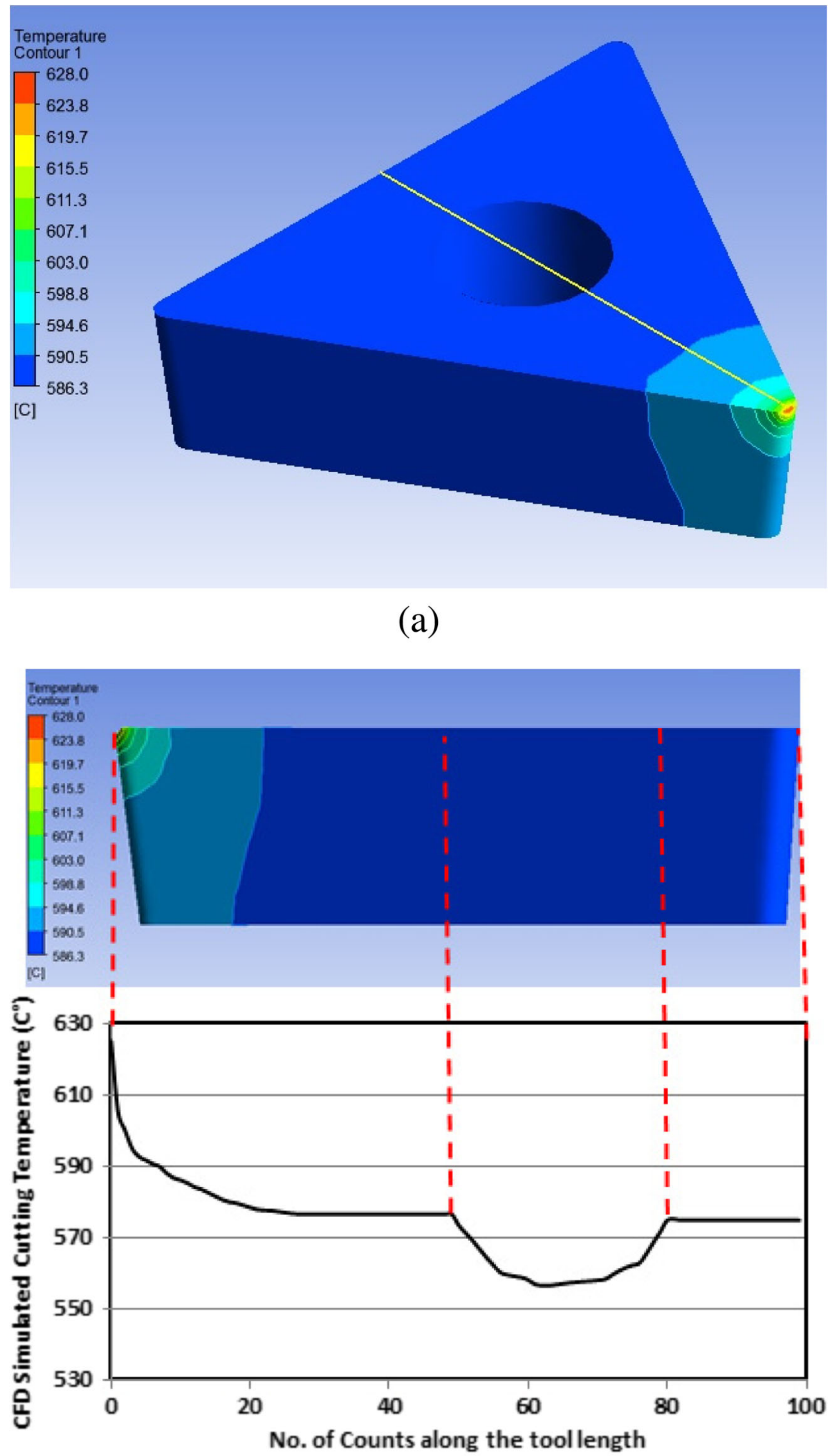
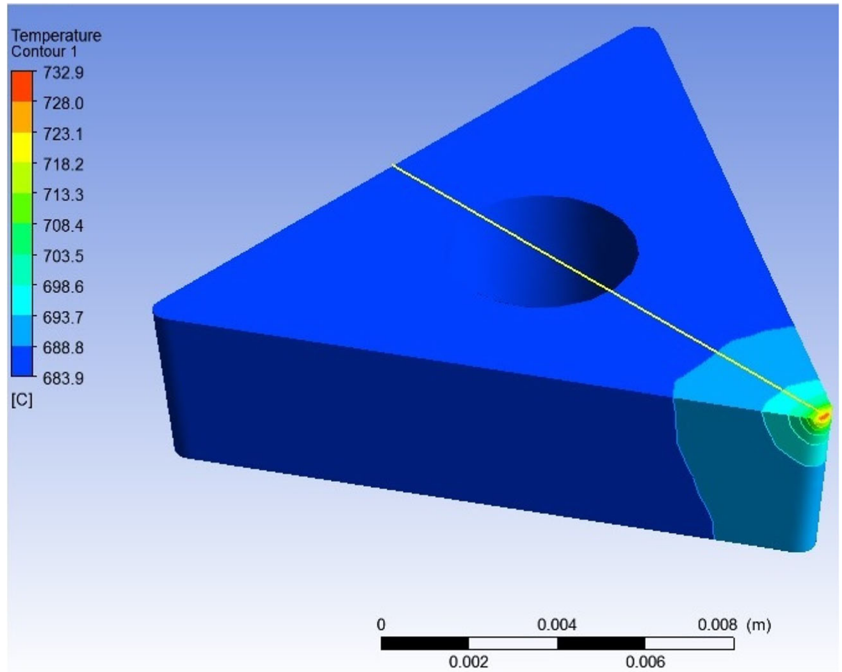


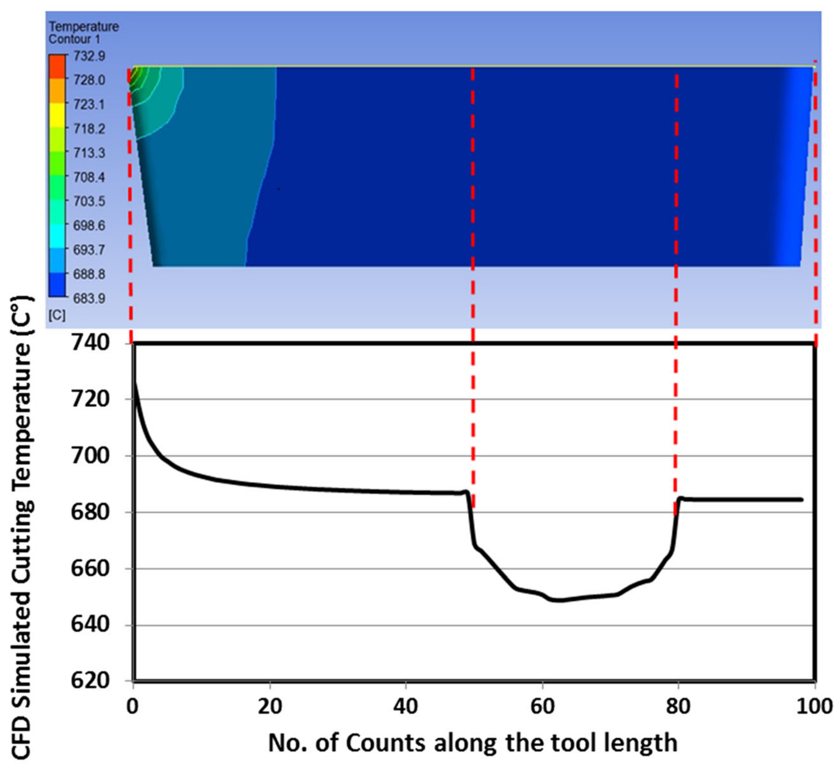
Fig. 13 For 90 m/min cutting speed. **a** Cutting temperature mapping on cutting insert. **b** Measurement of cutting temperature in the direction at line as shown in (**a**)

multiphysics-based machining problems. In this case, user can attain benefits of both FE model such as appropriate constitutive, friction, and damage criteria; however, CFD model can provide appropriate solid–fluid domain interaction.

- The FE and CFD coupled approach is capable to handle all different types of coolants. Similarly different types of parameters such as penetration ability at different flow rates and pressures can also be investigated.



(a)



(b)

Fig. 14 **a** Cutting temperature mapping on cutting insert. **b** Measurement of cutting temperature in the direction at line as shown in (**a**) [29]

- Due to the complexity of minimum quantity lubrication (MQL) and minimum quantity cooling lubrication (MQCL) methods, there is no reliable model available in literature to predict the relevant properties. The current approach can be modeled for two-phase flow to provide a modeling approach for MQL or MQCL machining.
- Multiphase CFD modeling techniques can also be used to develop coupled models for the hybrid cooling methods.

- Using the CFD prediction model, custom made cutting tools with internal coolant delivery channels can be efficiently designed and flow visualization can help the users to develop better understanding. This advantage can be very cost effective because prototyping for such custom made cutting tools is very expensive.

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