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An Innovative FEA methodology for Minimizing the Heat generation on Tungsten carbide insert by applying Air and Water as Coolants

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Abstract

Air and water cooling is being used as a potential source to the metal cutting industries for a long running job to minimizing the heat generation at the tool tip. Very limited work is available on 3D modeling of cutting zone using CFD. The Present paper will give an innovative approach for sustainable manufacturing operation, The materials used for cutting tool insert and work piece are CNMG Tungsten Carbide insert and Aluminum silicon (Al 6061) alloy respectively. In first phase experimental investigation has been carried out by turning process and the temperature values are recorded and it is followed by the orthogonal cutting operation using a single point cutting tool is modeled using finite element analysis and the temperature gradient at the tool tip is analyzed and compared with experimental results. In the second phase, the temperature obtained in the primary phase was used as input for modeling the temperature at the cutting zone by introducing the coolants. Fluid structure interaction (FSI) model developed to investigate the behavior of thermal stresses using computation fluid dynamics (CFD) approach. Air and water are used as coolants assuming dry and wet machining conditions at the cutting zone. This methodology will give the novel approach for validating the different coolants in metal cutting process.

Keywords: Finite element analysis, Computational fluid dynamics, Fluid thermal interaction.

INTRODUCTION

In metal cutting, lot of heat generated between tool and work piece interface due to the frictional force. Temperature producing during cutting plays an important role in machining efficiency and tool life. Thermal stresses developed by this process directly affect the tool wear and reduce tool life, and indirectly reduced tool life leads to low material removal rate (MRR) in machining. Various lubricants and coolants are used to conquer the effect of thermal stresses produced in cutting tool. Kitagawa et al. [1] conducted the machining operation under turning setup using Inconel 718 and Ti6Al6V2Sn.The study used embedded thermocouple method to estimate the cutting temperature on the cutting tool and study analyzed the influence of cutting temperature on the tool wear. Shu et al. [2] presented an approach of numerical thermal modeling of the cutting temperature with CFD modeling method. This method is 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. Rogerio et al. [3] studied the influence of coating thickness on temperature in the cutting zone and heat flux generation. The cutting inserts used in this study are made ofK10and diamond substrate 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 et al. [4] used finite element modeling approach to predict the temperature distribution for different coated tools. In this study finite element modeling was done using AdvantEdge software package. The study used tool with P20 substrate coated with TiC, TiN and Al2O3. The study pointed out that more accurate data about coatings are required for proper numerical simulations. Yvonnet et al. [5] 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.

Carvalho et al. [6] 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 equations 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. Dhar and Kamruzzaman[7] conducted an experiment on cryogenic cooling and stated that benefits of cryogenic cooling are mainly by substantially reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edge and also shows better surface finish and higher dimensional accuracy as compared to dry and wet machining. MohdHadzley.et.al [9] developed a new FEM model is proposed to simulate machining in conventional and high pressure coolant supply. The effect of the coolant in relation to chip formation, cutting forces and thermal generation will be model using FEM and coupled with FSI algorithm. The effect of the coolant pressure on chip formation, cutting force and temperature generation during the machining of Ti-6Al-4V alloy has been analyzed, compared and visualized in detail. The model enables further understanding of the effect of coolants in the machining zone, such as chip breakage, cutting force and temperature generation. C.Phaneendrakiran.et.al [11] investigated the surface quality of turbine blade steel material which are used for making turbine blades, continues increasing of cutting speed in turning process it will leads to develop the more heat and this will be reduced by maintaining the coolant at room temperature and will result in effective chip quality and fine surface finish. Yousef Shokoohia.et.al[12] introduced a new combined cooling and lubricant .The new lubricant was applied by various lubrication systems on the workpiece and he observed the cooling rate in machine zone and improvement in surface roughness. S. A. Lawal et.al[13] conducted tests to determine the influence of cutting fluids on flank wear during turning of AISI 4340 with coated carbide inserts and he found the influence of cutting fluid on machining performance.

METHODOLOGY

The methodology used in the paper as shown in (Figure 1) is divided into two phases. In the first phase experimentation conducted and followed by machining simulation performed with Arbitrary Eulerian Lagrangian(ALE) approach with coupled temperature displacement analysis using DEFORM Machining 3D, a mechanical simulation package with appropriate material constitutive model, fracture law and friction rule. The temperature in this phase obtained at the cutting zone in between tool and work piece interface is correlated with the experimental results [8].

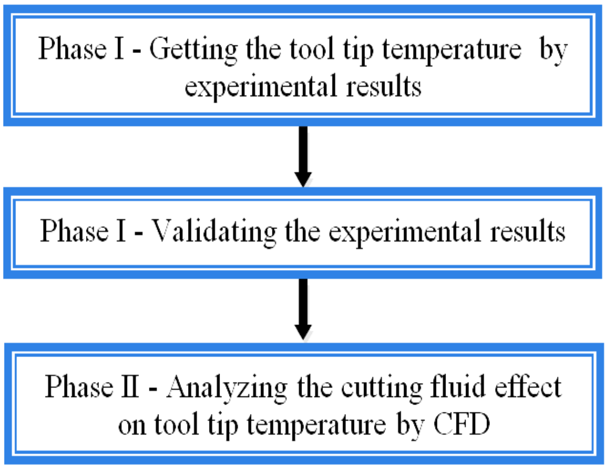

Figure 1: Sequence of Methodology

In the second phase, the recorded maximum temperature is applied on the cutting tool tip, the same cutting tool acts as a solid domain in the CFD environment. ANSYS CFX is used as a CFD package to model the interaction between the cutting tool, which is acting as a heat source and different coolants air and water. The air or water enters the fluid domain through an inlet and leaves through an outlet. The thermal stresses at the cutting zone are simulated for different fluid inlet temperature with constant pressure and flow rate. The environment surrounding the solid domain is assumed to be at 25 deg C.

Phase I- Experimentation and Finite Element Analysis (FEA):

The Phase I starts with the machining experiments and follows with machining simulation for validating the cutting temperature recorded during turning operation.

Experimental Procedure [8]:

A high speed HMT lathe (1450 mm x 800 mm x 5.5 kW) is used. The tested tool tips are set in a standard tool holder. The material of the tool tip is K-20 carbide tool with 94 per cent WC and 6 per cent cobalt. A turning experiment was conducted for the recording of temperature distribution on the cutting insert during machining [8]. Thermocouple is the general equipment used for measure the temperatures at different points on the cutting tool. The thermocouple consisting of a sensor was placed at the chip tool junction and it served as the hot junction. The room temperature 25 deg centigrade was taken as the cold junction. A filter circuit was designed and used to amplify the obtained electromotive force values as these were too small to be detected by the multi meter. The diagram of thermocouple setup is shown in (Figure 2).

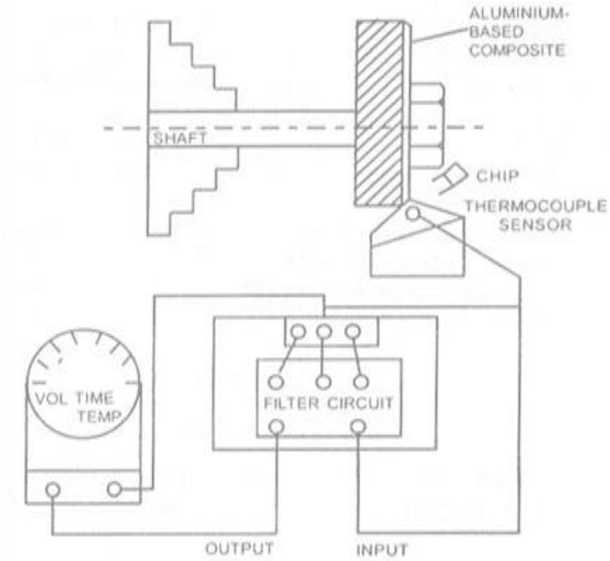

Figure 2: Line diagram of Thermocouple setup [8]

The experimental set up is shown in (Figure 3). The experiments were conducted for cutting speeds of 9.8m/min and 15.7m/min, the depth of cut and feed rate is constant those are 1mm, 0.1 mm/rev and the corresponding temperatures at the tool tip were measured.

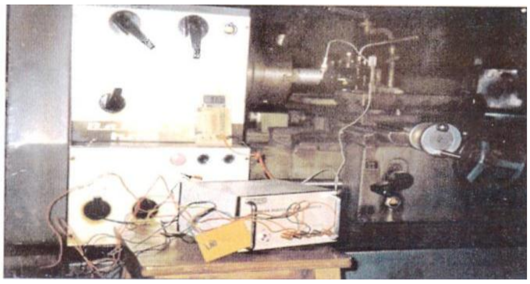

Figure 3: Setup for measurement of temperature [8]

Temperature has been recorded by using thermocouple method. This method is selected because it is an accurate method for measuring temperature by placing thermocouples at tip of the tool. The experiments repeated five times in each case that is at two different cutting speed for reducing errors and getting accurate temperature result [8].

Finite Element Analysis (FEA) of machining simulation:

In the phase I, finite element modeling for machining operation is developed using a commercial software DEFORM-3D. The work piece material is aluminum (Al 6061) and the cutting tool material is Tungsten Carbide (WC) with 94% W and 6% Co.

The general equations for flow stress are taken from Johnson-Cook [10] model and are given in equations (1), (2) and (3)

$$\sigma = (A + B\varepsilon^n)\left(1 + C\ln\left(\frac{\varepsilon}{\varepsilon_0}\right)\right)\left(\frac{\varepsilon}{\varepsilon_0}\right)^{\propto}(D - ET^*) \quad (1)$$

$$T^* = \frac{(T - T_{room})}{(T_{melt} - T_{room})} \quad (2)$$

$$D = D_0 \boldsymbol{exp}\left[k(T - T_b)^{\beta}\right] \quad (3)$$

Where

A=Initial Yield stress (MPa)

B=Hardening Modulus (MPa)

C=Strain rate dependency coefficient

D=Failure parameters determined experimentally

E=Elastic modulus (GPa)

α , β , k = Material parameters.

n = strain exponent

ε0, ε = Reference strain rate, strain rate.

T, T room, T melt = Work piece temperature, Room Temperature, Melt temperature

In this analysis the cutting tool and chip are treated as a single system in which, it is assumed that all the mechanical work is converted into heat. The initial temperature gradient along the width of the tool is assumed to be zero. The governing differential equation (4) for thermal conduction is given by

$$\mathbf{K}\left\{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right\} + \mathbf{q_h} = \mathbf{0} \quad (4)$$

Where $\left\{\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right\}$ are the temperature gradients along the feed and depth of cut respectively. K is thermal conductivity of the tool material and qh is the heat generated (qh)in cutting operation. qh is divided into three zones. The first source due to plastic deformation at the shear zone (qpl), the second source is due to friction between tool and (qf), and the third source of heat generation is due to friction between tool and work piece interface (qt) at flank. The boundary of the machining is assumed to be dry condition. As the chip is nearer to the cutting region, the specified temperature boundary conditions are imposed at the edge of the chip.

The physical parameters given for the FEA model are tabulated in Table 1 and 2.

Table 1. Physical Properties of Aluminum6061 Work Piece [8]

Sl No	Properties	Values
1	Modulus of Elasticity(GPa)	71.9
2	Poison's ratio	0.34
3	Thermal conductivity(W/mK)	180
4	Density (kg/m3)	2700

Table 2. Physical Properties of Tungsten Carbide Tool Insert [8]

Sl No	Properties	Values
1	Modulus of Elasticity(Gpa)	700
2	Poison's ratio	0.22
3	Thermal conductivity(w/mk)	173
4	Density(kg/m3)	19700

The machining operation considered for this analysis is turning and the geometric model considered for the cutting tool and work piece are shown in (Figure 4).

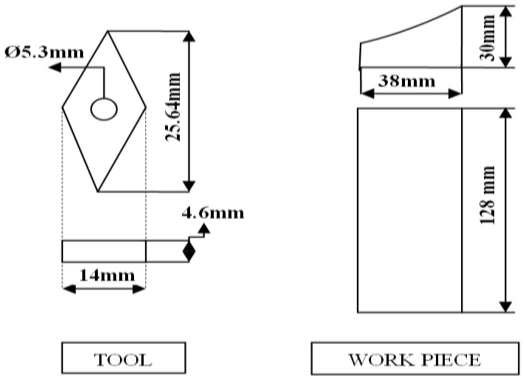

Figure 4: Cutting Tool and Workpiece geometry

In this operation, two cutting speeds are considered while keeping feed and depth of cut as constants and the values are given in Table 3.

Table 3. Machining conditions for FE Analysis

Sl No	Parameter	Unit
1	Depth of cut(mm)	1.2
2	Feed rate(mm/rev)	0.1
3	Cutting speeds(m/min)	9.8 & 15.7

The FEA results obtained are shown in (Figure 5) and (Figure 6). The maximum temperature obtained in both experiment and finite element analysis at the cutting zone with 9.8 m/min cutting velocity is 150 deg C and with 15.7 m/min is 186 deg C.

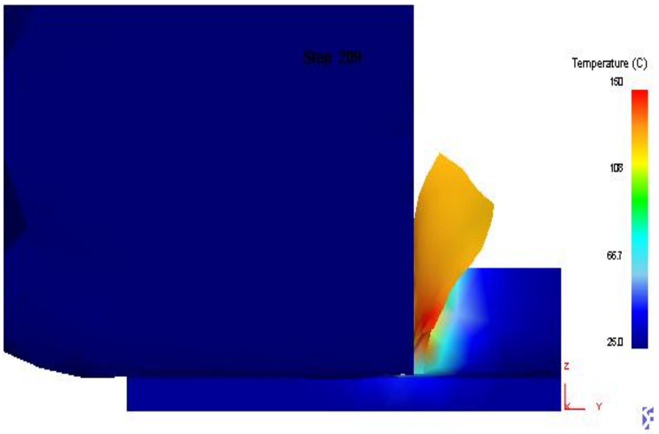

Figure. 5: Temperature Obtained at Cutting Speed 9.8 m/min

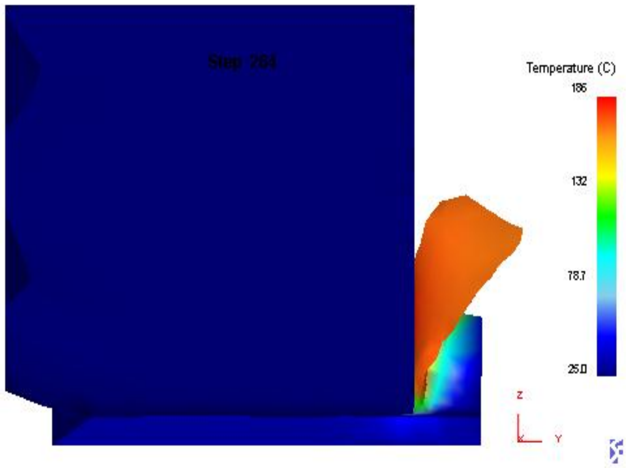

Figure 6: Temperature Obtained at Cutting Speed 15.7 m/min

The results obtained using FEA analyses are verified with the experimental results [8]. The comparative results are shown in Table 4 and (Figure 7) and they are in good agreement with an average experimental error of 6.9%.

Table 4: Generated Temperature at the Cutting zone

Cutting Speed (m/min)	Experiment Temperature (deg C)	FEA Temperature (deg C)	Correlation of Results (%)
9.8	165	150	90.9
15.7	195	186	95.3
Average of Experiment Vs FEA			93.1

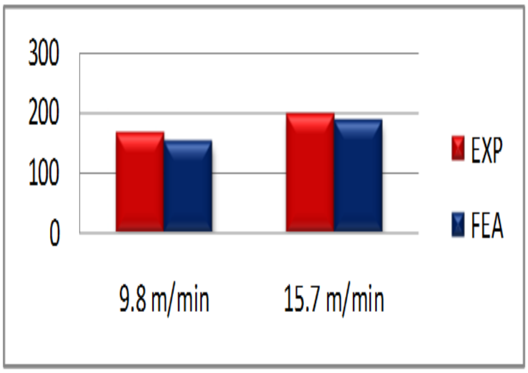

Figure 7: Variation of Temperature Vs Cutting Speed in FEA and Experiment

Phase II- Modeling of Machining zone For Different Coolants Using Computational Fluid Dynamics (CFD):

In the phase II thermal stresses on the cutting tool are investigated for coolants water and air. The coolants are introduced at the cutting zone at a velocity 1 m/sec and the cooling efficiency is obtained at the cutting zone. The maximum temperature at cutting tool and workpiece interface obtained from phase 1 is considered as a heat source at the tool tip. The model considered for fluid flow from the inlet is k-ε turbulence model. A steady state CFD analysis with 1 sec time step with maximum iterations of 10.The heat is transferred from the tip of the tool to entire tool body by conduction heat transfer. The fluid enters from the inlet nozzle with 1m/sec velocity passes over the tool tip and reduces the temperature by the convection heat transfer process. In this analysis, two domains namely fluid domain and solid domain are created to study the flow simulations and thermal stresses is shown in the (Figure 8). The different input conditions for CFD analysis are given in Table 5.

Table 5: Input Condition for CFD Analysis

Sl No	Condition	Unit
1	Inlet velocity of fluid	1 (m/sec)
2	Diameter of Nozzle	50mm
3	Inlet nozzle Angle	45 (deg)
4	Emissivity	0.91
5	Temperature at tool tip	150 C (Experimentation, FEA)
		186 C (Experimentation, FEA)

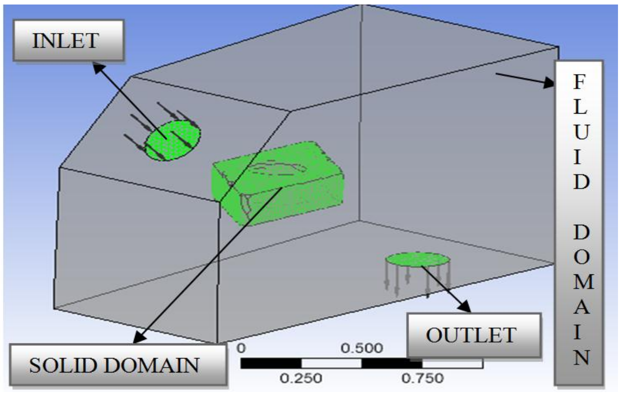

Figure 8: Initialization of Solid and Fluid Domain

The temperature applied at the tool tip at the initial stage is shown in (Figure 9). The results obtained from the analysis are discussed in the chapter 4.

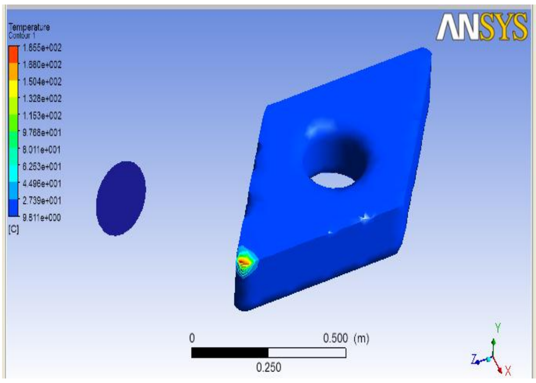

Figure 9: Initializing Temperature at Tool Tip

RESULTS AND DISCUSSION

The reduction in temperature obtained by sending air at 25 deg C is shown in (Figure 10).

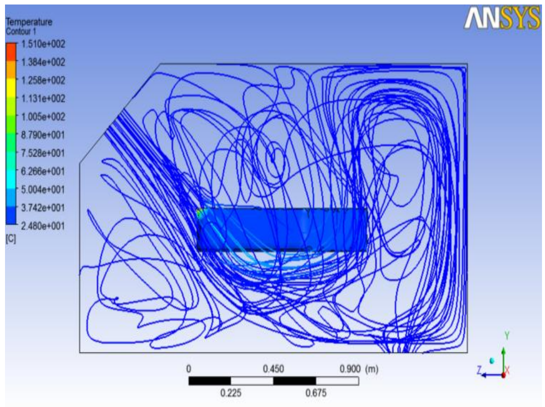

Figure 10: Streamline showing Temperature Profile of Air as coolant passing from Inlet nozzle at cutting speed 9.8m/min.

The streamline velocity profile obtained for the air as coolant at 1m/sec is shown in (Figure 11).

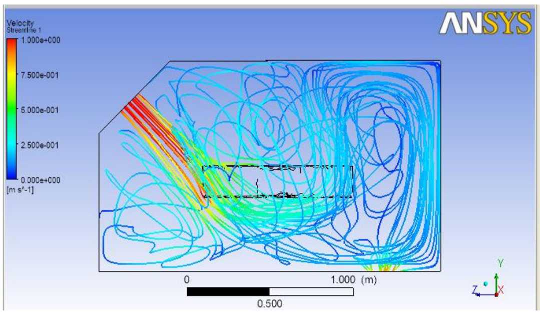

Figure 11: Streamline Velocity Profile of Air as coolant passing from Inlet nozzle at cutting speed 9.8m/min.

At 9.8m/min cutting speed obtained temperature is 150 C; this temperature on tool tip is reduced by the air as fluid passing through the inlet nozzle as shown in (Figure 10) and (Figure 11). obtained results revealing in the form of curves drawn between the temperature and time (1sec) with variable inlet temperature 10, 20 & 25 deg C at cutting speed 9.8m.min is shown in (Figure 12).

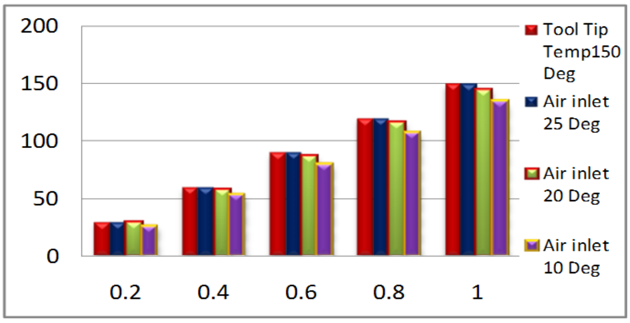

Figure 12: Time Vs Temperature Air as coolant at VC= 9.8m/min.

Similarly at 15.7m/min cutting speed obtained temperature is 186 deg C; and it reduced by the sending air at 10, 20& 25 deg C temperature as shown in the (Figure 13) and (Figure 14).

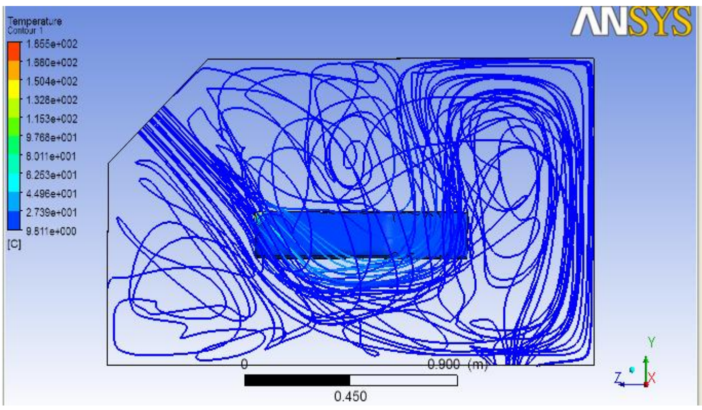

Figure 13: Streamline showing Temperature Profile of Air as coolant passing from Inlet nozzle at cutting speed 15.7m/min.

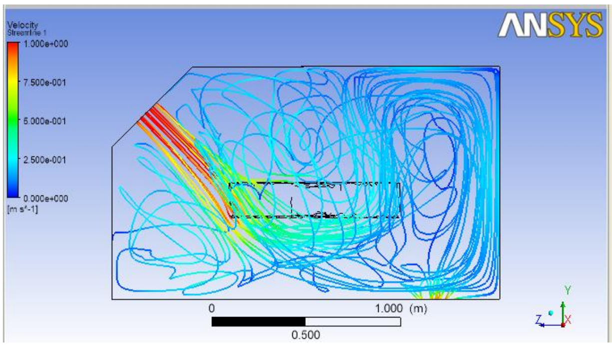

Figure 14: Streamline Velocity Profile of Air as coolant passing from Inlet nozzle at cutting speed 15.7m/min.

Obtained results revealing in the form of curves drawn between the temperature and time (1sec) with variable inlet temperature 10, 20 & 25 deg C at cutting speed 15.7 m/min is shown in (Figure 15).

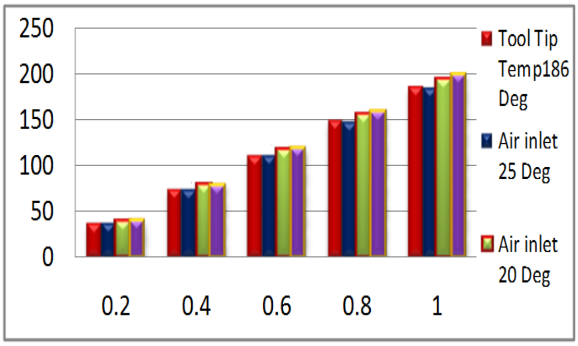

Figure 15: Time Vs Temperature Air as Coolant at VC=15.7m/min.

The (figure16) & (figure 17) showing the graphs drawn between the temperature and constant time(1sec) by sending the water through the inlet nozzle at temperature 10, 20& 25 deg C for decreasing the tool tip temperature 150 deg C and 186 deg C respectively at various cutting speeds.

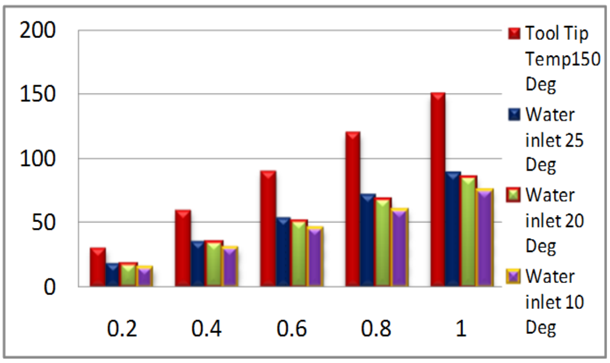

Figure 16: Time Vs Temperature Water as Coolant at VC=9.8 m/min.

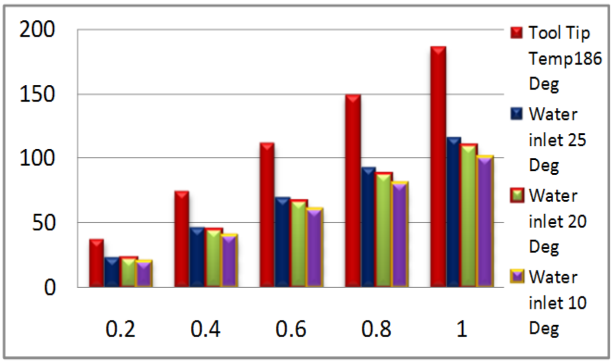

Figure 17: Time Vs Temperature Water as Coolant at VC=15.7 m/min.

The reduction in temperature by using CFD analysis for air and water as coolants given shown better performance and the investigated results are given in the Table 6 and Table 7.

Table 6. Results Obtained through CFD simulation Air as Coolant

Property	Cutting Speed (9.8m/min)			Cutting Speed (15.7m/min)		
Inlet velocity of Air	1m/sec					
Temperature from FEA at Tool tip	150 deg C			186 deg C		
Inlet Air Temp (deg C)	10	20	25	10	20	25
Temperature from CFD at Tool tip (deg C)	135	145	150	185	195	200
Efficiency of temperature reduction (%)	10	6	0	0	-0.5	-0.7

Table 7. Results Obtained through CFD simulation Water as Coolant

Property	Cutting Speed (9.8m/min)			Cutting Speed (15.7m/min)		
Inlet velocity of Water	1m/sec					
Temperature from FEA at Tool tip	150 deg C			186 deg C		
Inlet Water Temp (deg C)	10	20	25	10	20	25
Temperature from CFD at Tool tip (deg C)	75	85	89	100	110	116
Efficiency of temperature reduction (%)	50	47	41	46	41	37

Overall heat reduction efficiency for the present study is given confirmation that the water having effective cooling medium in wet machining compared with the air in dry machining process and it is graphically represented by the (Figure 18).

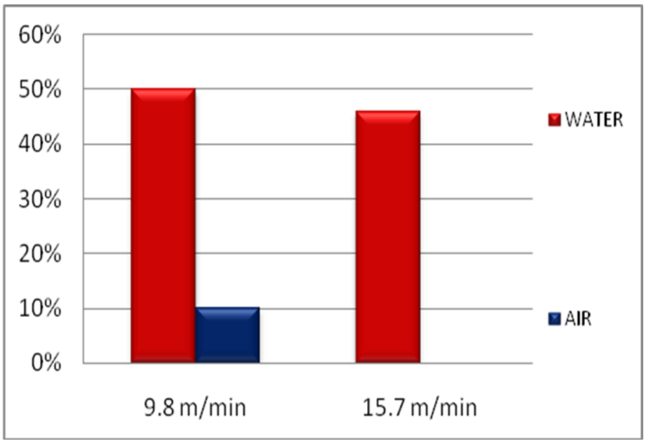

Figure. 18. Efficiency of Heat Reduction Vs Cutting Speed under Air and Water as Coolants.

A variety of methodologies are developed in the previous years on modeling of temperature distribution at the tool tip but in this paper given a new approach for finding the sustainable cutting fluids and their affect on cutting zone.

The following general observations are made based on the results mentioned above

- Water is given satisfactory performance than the air as a cutting fluid.
- Acceptable operating temperature of air is less than 15 deg C.
- Sustainable operating temperature of air is at cutting speed 9.8m/min with 10 deg C of inlet temperature.
- Maximum Temperature reduction efficiency of water acting as cutting fluid observed at the cutting speed 9.8m/min with 10 deg C inlet temperature.
- Minimum Temperature reduction efficiency of water observed at the cutting speed 15.7m/min with 25 deg C inlet temperature.

CONCLUSIONS

From the evaluation process discussed, it is observed that water is more sustainable alternative as compared to air. All the simulations were conducted by keeping flow velocity constant 1m/sec and changing the inlet temperature of fluids. Present paper is a small initiation to model and analyze the cutting zone using different cutting fluid. The developed 3 Dimensional CFD-FEM coupled modeling and analysis gives greater scope to work on effect of variable velocity and pressure on heat transfer rate on machining process.

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