IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X
PP. 28-34
www.iosrjournals.org

Conjugate Heat Transfer Studies of Milling Cutter Inserts

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Abstract: *Milling cutter inserts during cutting operation are subjected to high stresses and high temperatures. The power consumed during cutting operation is transformed into heat at insert tips. Part of the heat flows inside the inserts rising high temperature spots. Due to high temperatures prevailed over a long period affects the life of the inserts. Therefore it is necessary to estimate the temperature distribution inside the metal region of the insert. In some cases it is necessary to provide cooling for the cutter tips. In such cases combined mode of convective and conductive heat transfer takes place. For such application CFD techniques are very useful in predicting the temperature distribution pattern on the insert. In this project the insert geometry with its material property is considered for heat transfer analysis. The amount of power required incutting is measured experimentally. Part of which is applied as a heat source in a smaller region near the insert tip. The surrounding zone about the insert is modeled for air flow purpose. With different air flow velocity the CFD analysis is performed for conjugate heat transfer (combined heat transfer for conduction and convection). The trend of temperature distribution with air velocity is obtained. From this study effectiveness of cooling is found out. Temperature distribution plot, flow path lines are obtained in all the cases studied. The present work emphasizes the need for CFD analysis to get optimum utilization of cooling.*

I. Introduction

Heat is released during the transformation of workpiece into chips in any machining and it is the most important factor that affects the process.Ng et al [1] stated that most of the heat is generated in the primary shear zone and secondary deformation zone when machining is being done. The shear stress in the primary shear zone may be reduced because of high temperatures which lead to reduction in cutting forces, even though majority of heat generated is removed in the chip. Hence disservice of tool wear occurs.

Wet machining using different kinds of cutting fluids is a most widely used technique to maintain the cutting temperature below some specified optimal cutting temperatures [3]. However, the excessive use of cutting fluids becomes a major problem owing to some associated economic, environmental and health concerns [4]. Dry machining can be considered as a feasible approach to eliminate the use of cutting fluids because of low processing cost and soft ecological hazard [5]. Temperature has an impact on tool wear.Thus temperature is an important consideration for the cutting process.

Generation Of Heat At Various Zones

i) Primary shear zone where the major part of the energy is converted into heat.
ii) Secondary deformation zone at the chip – tool interface where further heat is generated due to rubbing or shear.
iii) At the flanks, due to rubbing between the tool and finished surface.

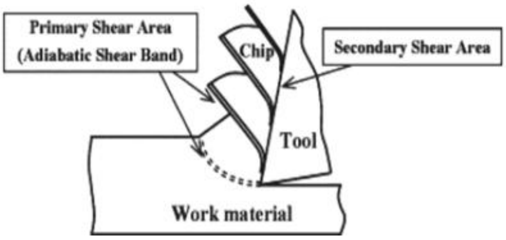


Fig 1: Illustration of segmented chip formation

Carvalho et al. [6] proposed the estimation of the temperature and the heat flux at the chip–tool interface using the inverse heat conduction problem technique.

Effects Due To Heat Generation

a. On work piece
  i) Dimensional accuracy of the job may be disturbed due to the thermal distortion and expansioncontraction during and after machining process.
  ii) Surface of the work piece may be damaged by oxidation, rapid corrosion etc.
  iii) Induction of tensile residual stresses and micro cracks at the surface and sub surface

b. On tool
  i) The tool life may be reduced due to rapid tool wear.
  ii) Plastic deformation may take place.
  iii) Development of thermal shocks may cause thermal fractures.
  iv) Built Up Edge (BUE) formation.

Heat is mostly dissipated by,
1) The discarded chip carries away about 60~80% of the total heat (q1)
2) The work piece acts as a heat sink drawing away 10~20% heat (q2)
3) The cutting tool will also draw away ~10% heat (q3).

As the cutting action proceeds and the heat has been generated. Most of the heat is dissipated in the following manners (chip, work piece, cutting tool and cutting fluid). Brandao[7] compared theoretical and experimental results of end milling process in hardened steel at high speeds. They evaluated heat transfer to the work piece and average convection coefficient. All the modes of heat transfer i.e. conduction, convection and radiation will exist in any machining operation. However radiation studies are rarely done when compared to other two modes.

In the present study, the investigation of temperature is made on the cutting inserts during milling operation on hardened steel under dry cutting conditions i.e. at room temperature. The hardened steel is difficult to machine due to its high strength (850-1000Mpa), Toughness and Hardness (28-36 HRC). Such steels are used extensively in aerospace and automobile industries. Due to high work hardening capacities, low thermal conductivity and lowspecific heat high cutting temperatures are generated.

As a result, both cutting forces and temperature in the cutting zone are extremely high. Therefore, machining rates and tool life values are very low. It is felt that the study on the cutting tool temperature during machining needs to be done so that production rates and tool life values might be increased.

Thus, combined study of heat transfer analysis using FEM and CFD is done. Computational Fluid Dynamics (CFD) provides a qualitative (and sometimes even quantitative) prediction of fluid flows by means of

- mathematical modeling (partial differential equations)
- numerical methods (discretization and solution techniques)
- software tools (solvers, pre- and post processing utilities)

CFD enables scientists and engineers to perform ‘numerical experiments’ (i.e. computer simulations) in a ‘virtual flow laboratory’. Brandao et al. [7] presents an experimental and theoretical study on heat flow when end milling hardened steels at high speed. The temperatures on the work piece have been measured. The heat transferred to the work piece and the average convection coefficient for the cooling system have been evaluated in order to minimize the error between theoretical and experimental results

II. Proposed Methodology

The methodology involved finite element simulation study in the first phase, where cutting temperature generated in the cutting zone and tool tip were obtained.

In the second phase, heat transfer between cutting tool (Insert) and the air at room temperature during machining is analyzed using ANSYS FLUENT.

Finite Element Machining Analysis (PHASE I)

Finite element machining model was developed by considering the following conditions
Work piece – Hardened Steel
Cutting tool – Tungsten Carbide
Coating on cutting tool – TiAlN layers

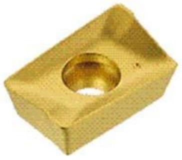


Fig 2: HM90 APKT 1003 PDR-IC 908

Tables 1 and 2 give chemical composition and mechanical properties of hardened steel.

Table 1: Chemical composition of Hardened Steel

Elements	C	Mn	Si	Cr	Ni	Mo	V	Co	Cu
Weight%	0.39	1.4	1.7	0.69	0.35	0.3	0.828	0.04	Remaining

Table 2: Mechanical and thermal properties for Hardened Steel

Property	**Symbol**	**Value**
Density	ρ	785 kg/m^3
Specific heat	C_p	460 j/kg-k
Thermal conductivity	K	45 W/m-k

The following conditions were considered in finding the cutting tool temperature during machining.

Speed 4775 rpm

Feed 150 m/min

Depth 1.5 mm

CFD MODEL (SECOND PHASE)

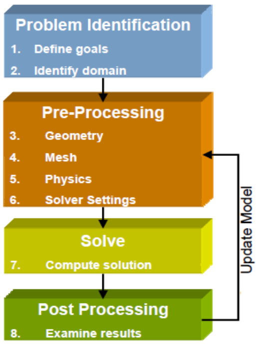


Fig 3: CFD Modeling steps [11]

Methodology adopted in CFD analysis is shown in Fig. 3. In the study of conjugate heat transfer (CFD)analysis ANSYS ICEM CFD, FLUENT were employed for Preprocessing, solving and Post processing. Using ANSYS ICEM CFD, advanced geometry creation, mesh generation and mesh optimization can be made which satisfies today's sophisticated analysis. Most of the Engineering analysis like Computational Fluid Dynamics, Structural, and Thermal analysiscan be done easily.

The design geometryof the Insert was taken from IC 908 manufacturers and was imported into ICEM CFD as IGES model for further modeling. In modeling, the insert was considered as a solid domain and the rectangular geometry which was created over the insert is considered as fluid domain Inlet and outlet for the air flow has been defined as shown in Fig. 4 and 5.

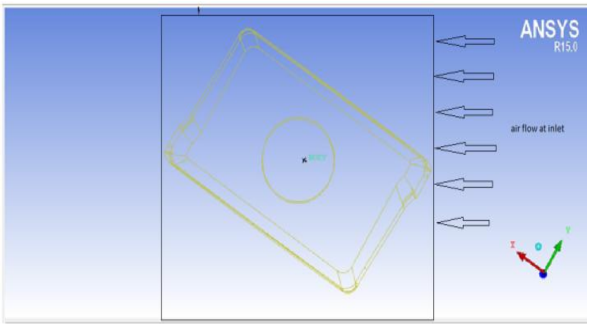


Fig 4: Cutting tool as solid and rectangular geometry as fluid domain

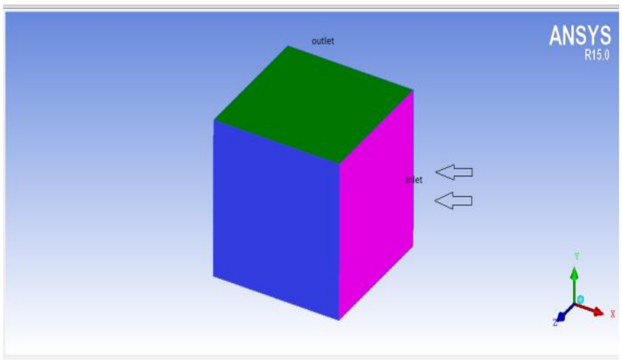


Fig 5: Fluid domain showing the inlet and the outlet

In the mesh generation, unstructured Tetrahedral and Prism meshes have been created. The volume is filled with tetrahedral elements i.e..; it generates a tetra mesh on the objects surface. In the boundary layers of the object the prism mesh has been employed as it provides better resolution by creating more elements perpendicular to the surface which could not be achieved with a very fine tetra mesh.
A sphere of radius 0.005m (Fig. 6)is assumed at the tip of the insert which selects the specific cells of the insert zone whose centroid lies withinthesphere. The tip of the insert cutting edge is assumed to be at point which is the centre of the sphere.

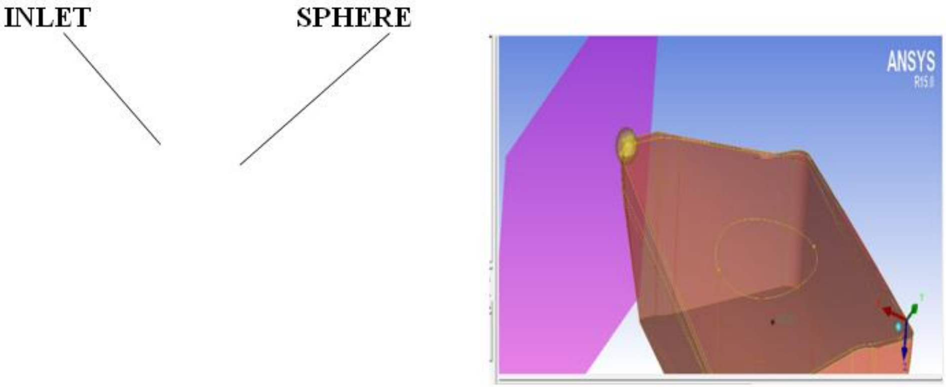


Fig. 6: A small spherical zone at Insert tip

3 functions (UDF) have been created using Define MACROS.

i) Select volume: The total volume occupied by the cells, lying within the sphere is identified. The total heat of 5W is considered as the heat added to the tip inside the sphere zone.

ii) Heat source: This is the function to give input to the solver (Fluent); the amount of heat rate (Q) to be introduced is a source term in energy equation.

iii) Heat rate: This function is only used to check whether the actual amount of heat is added or not.

Properties of air used are given in Table 3. Air is treated as ideal incompressible gas. A turbulence K-ε model is used, where K is the turbulence kinetic energy which is defined as the variance of the fluctuations in velocity and ε is the turbulence eddy dissipation.

Table 3: Mechanical and thermal properties of air (fluid)

Property	Symbol	Value
Density	ρ	1.225 kg/m^3
Specific heat	C_p	1006.43 j/kg-k
viscosity	ν	1.7894*10^{-5} kg/m sec
Thermal conductivity	K	0.0242 W/m-k

Different approaches were carried out to predict quantitatively the temperature level and heat flux at the interface with cutting speed, feed rate, rake angle, tool geometry, tool material and work piece materials [10].In this model, speed, feed, depth of cut are taken as the generating heat considerations(Ptotal in W).
P_{total} = Ks x DOC x Feed rate x Cutting Speed(1)

The Specific Cutting Force Ks, primarily depends on the work material and the feedrate. The value of Ks was obtained from the tool manufacturer's data handbook [8]. The Specific Cutting Force, Ks, for the above condition is approximately 3645 N/mm2

Equation 1 was applied to calculate the heat inputs, using the machining parameters. It was taken that 3.3% of the total calculated heat entered ~~into~~ the tool tip insert as Fleisher et al. [9] he concluded that in general 92.7% of the heat is conducted away by the chips, 4% of the heat goes into the work piece, and 3.3% of the heat enters into the tool tip. As per this reference 3.3% of total heat enters tool tip. So,we can consider heat rate inside the insert as 15*0.033 W i.e. 5W. The maximum temperature, average temperature of the inserts and at the outlet is obtained at various velocities in FLUENT flux reports ranging from 0.05m/s to 0.2m/s.

III. Results And Discussions

CFD and conjugate heat transfer analysis is performed for various cases. Velocity of air flow is varied from 0.05 m/s to .2 m/s in steps.

For Case 1: following results are obtained-

Case 1:

Velocity=0.05m/s: Power=5W

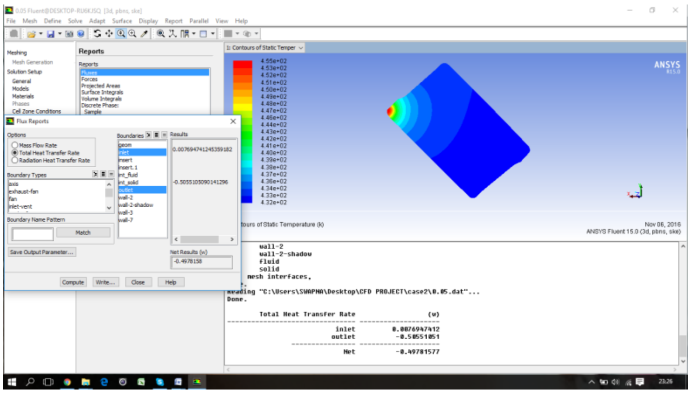
Heat transfer rate: net flow=-4.9995W

Maximum temperature of insert: 454.5896K

Minimum temperature of insert:432.1375K

Average Temperature of insert: 433.55048K

Average Temperature of outlet: 375.93466K



Flux Reports

Options: ○ Mass Flow Rate ● Total Heat Transfer Rate ○ Radiation Heat Transfer Rate

Boundary Types: axis, exhaust-fan, fan, inlet-vent

Boundaries: geom, inlet, insert, insert.1, int_fluid, int_solid, outlet, wall-2, wall-2-shadow, wall-3, wall-7

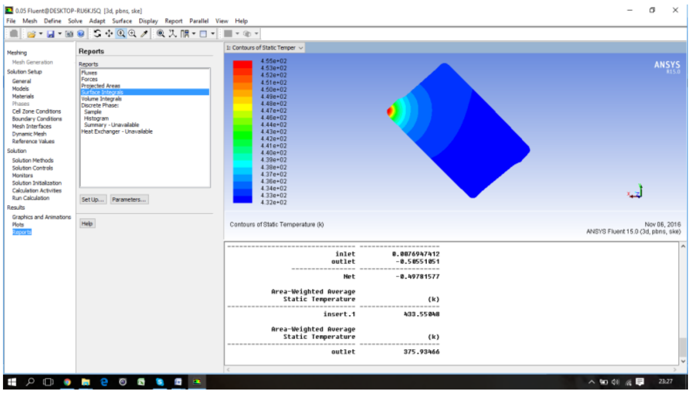
Results:
0.00769474124535 9182
-0.5055105090141296

Net Results (w): -0.4978158

```
        wall-2
        wall-2-shadow
        fluid
        solid
     mesh interfaces,
  e.
Reading "C:\Users\SWAPNA\Desktop\CFD PROJECT\case2\0.05.dat"...
Done.

        Total Heat Transfer Rate                    (w)
-------------------------------- --------------------
                           inlet         0.0076947412
                          outlet          -0.50551051
                ---------------- --------------------
                             Net          -0.49781577
```

Fig. 7: Temperature contour at insert- Heat Rate

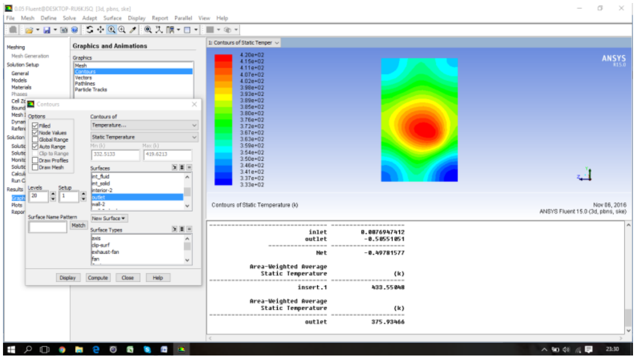


```
-------------------------------- --------------------
                           inlet         0.0076947412
                          outlet          -0.50551051
                ---------------- --------------------
                             Net          -0.49781577

          Area-Weighted Average
             Static Temperature                   (k)
-------------------------------- --------------------
                        insert.1            433.55048

          Area-Weighted Average
             Static Temperature                   (k)
-------------------------------- --------------------
                          outlet            375.93466
```

Fig.8: Temperature contour at insert- Average temperaure



```
------------------------------ --------------------
                         inlet         0.0076947412
                        outlet          -0.50551051
                ---------------- --------------------
                           Net          -0.49781577

        Area-Weighted Average
           Static Temperature                   (k)
------------------------------ --------------------
                      insert.1            433.55048

        Area-Weighted Average
           Static Temperature                   (k)
------------------------------ --------------------
                        outlet            375.93466
```

Fig.9 Temperature contour at outlet- Average temperaure

Temperature distribution in insert is shown as contour plot in Fig.7 and 8.Temperature distribution at outlet is shown in Fig.9. It is seen that the flow is heated up in the central zone due to removal of heat from insert. It shows heat conduction process. The values for other cases are tabulated as follows where the temperature values are noted in Celsius:

For the remaining cases results are tabulated (Table 4) and shown in the graphical form (Fig. 10)

Table 4: Resultant temperature values

Case no	**Velocity (m/s)**	**Max Temperature(c) T_{max}**	**Average Temperature of insert(c) T_{avg}**	**Average Temperature of outlet (c) T_{outlet}**
1	0.05	183	162	104
2	0.1	148	127	66
3	0.15	133	112	54
4	0.2	124	103	48

The reduction of temperature with increase in velocities can be clearly seen in the graph.

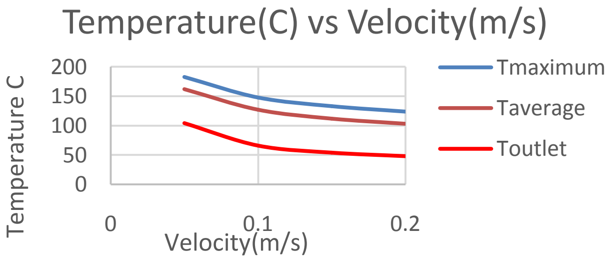


Fig. 10 Trend of temperatures reduction with air velocity

IV. Conclusion

CFD analysis provide a technique of determining maximum temperature in the insert. It also predicts the reduction in hot spot temperature with increase in air velocity. This information can be used to determine optimum air flow velocity

For future work the role of heat trasfer due to radiation can be investigated.

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