Thermal Analysis of Milling Cutter Using Finite Element Analysis Tool

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Abstract- *Milling is a process of producing flat and complex surfaces or shapes by using multi tooth cutting tool, i.e. milling cutter. Milling is an interrupted cutting operation. The teeth of milling cutter enter and exit the work during each revolution. This interrupted cutting action subjects to a cycle of impact forces and thermal shocks on every revolution. In this paper, the thermal analysis of the milling cutter is done. The objective taken into account is to carry out analytical calculations and thermal analysis of milling cutter and to analyze various stress components acting on it. The comparative study of two different materials used for milling cutter i.e. HSS and Cemented Carbide to check stress and deformation. ANSYS software is used for the above purpose.*

Key Words: ANSYS[1], Finite Element Analysis[2], High Speed Steel[3], Cemented Carbide[4]

1. INTRODUCTION

Milling is a process of producing flat and complex shapes with the use of multi-tooth cutting tool, which is called a milling cutter and the cutting edges are called teeth. The axis of rotation of the cutting tool is perpendicular to the direction of feed, either parallel or perpendicular to the machined surface. The machine tool that traditionally performs this operation is a milling machine. Milling is an interrupted cutting operation: the teeth of the milling cutter enter and exit the work during each revolution. This interrupted cutting action subjects the teeth to a cycle of impact force and thermal shock on every rotation.

The gear milling cutter is in fact used only for very small series or individual pieces, for the construction of spare parts or other special productions. Its cost, in terms of time, would be prohibitive for mass production. This system in theory would require a gear milling cutter for each type of gear. Would be necessary to provide a cutter for each module, for each pressure angle and for each number of teeth. In order to limit this vast number of different cutters you give up accuracy using a single type of cutter for each group of gears with the same module and pressure angle whose number of teeth is contained in determined limits. The gear milling cutter are generally an unground profile and are used for cutting wheels at the final size. It is useless to build a milling cutter with ground profile where the cost is higher in order to have greater accuracy when construction errors are inherent in the concept of this work. However this may not be true if you plan to make a milling cutter for a specific gear. In this case the profile of the cutter will be designed based on the characteristics of the teeth to perform and then you can get good accuracy and then it is correct to grind the profile of the tool.

2. TYPES OF MILLING

There are two basic types of milling, are as follows

2.1 Down (climb) milling

It is type of milling in which the cutter rotation is in the same direction as the motion of the work piece being fed. In down milling, the cutting force is directed into the work table, which allows thinner work parts to be machined. Better surface finish is obtained but the stress load on the teeth is abrupt, which may damage the cutter. In conventional milling, friction and rubbing occur as the insert enters into the cut, resulting in chip welding and heat dissipation into the insert and work piece. Resultant forces in conventional milling are against the direction of the feed. Work-hardening is also likely to occur.

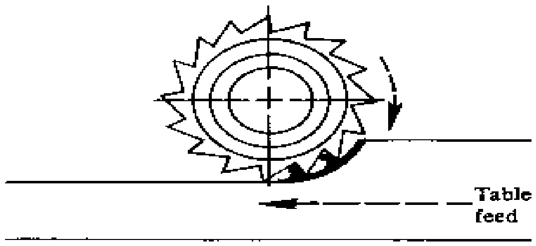


Fig 1: Down (Climb) Milling

2.2 Up (Conventional) Milling

It is the type of milling in which the work piece is moving towards the cutter, opposing the cutter direction of rotation. In up milling, the cutting force tends to lift the work piece. The work conditions for the cutter are more favorable. Because the cutter does not start to cut when it makes contact (cutting at zero cut is impossible), the surface has a natural waviness. The insert enters the work piece material with some chip load and produces a chip that thins as it exits the cut. This reduces the heat by dissipating it into the chip. Work-hardening is minimized. Climb milling is preferred over conventional milling in most situations.

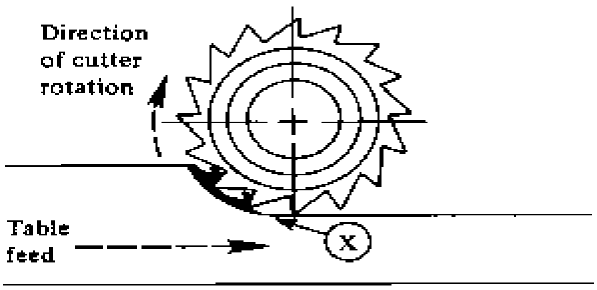


Fig 2: Up (Conventional) Milling

3. MILLING CUTTER NOMENCLATURE

Figure show two views of a common milling cutter with its parts and angles identified. These parts and angles in some form are common to all cutter types.

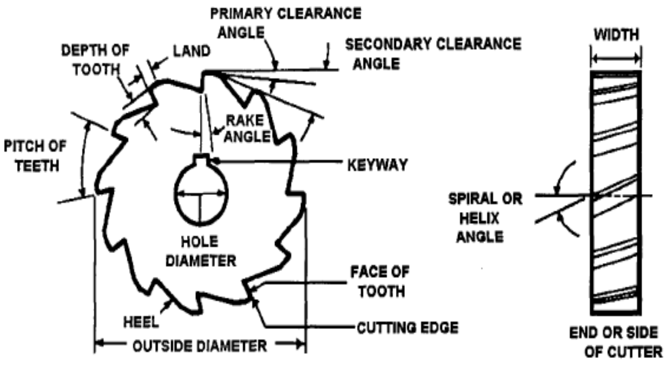


Fig 3: Milling Cutter Nomenclature

- The pitch refers to the angular distance between like or adjacent teeth.
- The pitch is determined by the number of teeth. The tooth face is the forward facing surface of the tooth that forms the cutting edge.
- The cutting edge is the angle on each tooth that performs the cutting.
- The land is the narrow surface behind the cutting edge on each tooth.
- The rake angle is the angle formed between the face of the tooth and the center line of the cutter. The rake angle defines the cutting edge and provides a path for chips that are cut from the work piece.
- The primary clearance angle is the angle of the land of each tooth measured from a line tangent to the center line of the cutter at the cutting edge. This angle prevents each tooth from rubbing against the work piece after it makes its cut.
- This angle defines the land of each tooth and provides additional clearance for passage of cutting oil and chips.
- The whole diameter determines the size of the arbor necessary to mount the milling cutter.
- Plain milling cutters that are more than 3/4 inch in width are usually made with spiral or helical teeth. A plain spiral-tooth milling cutter produces a better and smoother finish and requires less power to operate. A plain helical-tooth milling cutter is especially desirable when milling an uneven surface or one with holes in it.

4. INTRODUCTION TO THERMAL ANALYSIS

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interest are:

1. The temperature distributions
2. The amount of heat lost or gained
3. Thermal gradients
4. Thermal fluxes.

Thermal simulations play an important role in the design of many engineering applications, including internal combustion engines, turbines, heat exchangers, piping systems, and electronic components. In many cases, engineers follow a thermal analysis with a stress analysis to calculate thermal stresses (that is, stresses caused by thermal expansions or contractions).

4.1 TYPES OF THERMAL ANALYSIS

ANSYS supports two types of thermal analysis

1. Steady State Thermal Analysis
2. Transient Thermal Analysis

4.1.1 Steady State Thermal Analysis

It determines the temperature distribution and other thermal quantities under steady-state loading conditions. A steady-state loading condition is a situation where heat storage effects varying over a period of time can be ignored. A steady-state thermal analysis calculates the effects of steady thermal loads on a system or component. Engineer/analysts often perform a steady-state analysis before performing a transient thermal analysis, to help establish initial conditions. A steady-state analysis also can be the last step of a transient thermal analysis, performed after all transient effects have diminished. You can use steady-state thermal analysis to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that are caused by thermal loads that do not vary over time. Such loads include the following:

- Convections
- Radiation
- Heat flow rates
- Heat fluxes (heat flow per unit area)
- Heat generation rates (heat flow per unit volume)
- Constant temperature boundaries

A steady-state thermal analysis may be either linear, with constant material properties; or nonlinear, with material properties that depend on temperature. The thermal properties of most material do vary with temperature, so the analysis usually is nonlinear. Including radiation effects also makes the analysis nonlinear.

4.1.2 Transient Thermal Analysis

It determines the temperature distribution and other thermal quantities under conditions that vary over a period of time. Transient thermal analysis determines temperatures and other thermal quantities that vary over time. Engineers commonly use temperatures that a transient thermal analysis calculates as input to structural analyses for thermal stress evaluations. Many heat transfer applications - heat treatment problems, nozzles, engine blocks, piping systems, pressure vessels, etc. - involve transient thermal analyses. A transient thermal analysis follows basically the same procedures as a steady-state thermal analysis. The main difference is that most applied loads in a transient analysis are functions of time. To specify time-dependent loads, you can either use the Function Tool to define an equation or function describing the curve or then apply the function as a boundary condition, or you can divide the load-versus-time curve into load steps.

5. THERMAL ANLYSIS AND ANALYTICAL CALCULATIONS AND RESULTS

5.1 ANALYTICAL CALCULATION FOR MILLING CUTTER

In order to perform a finite element analysis, it is necessary to determine the forces acting on the cutter. From the given conditions the force acting on the cutter (W) may be calculated as:

Let, H is the power in kW, n is the speed, in rpm, and D is the diameter of the cutter. Here for calculation we take

N = 1000 rpm

H = 1.4914 Kw

D = 68 mm

$$W_t = \frac{60000 \times 1.4914}{\pi \times 68 \times 10^{-3} \times 1000}$$

= 418.48 N

The stress calculation at the tip of the tooth of the cutter is estimated based on the concept of gear tooth stresses. The stress at each speed is determined by

$$\sigma = \frac{6W_1 l}{Ft^2}$$

$$= \frac{6\times 418.48\times 12}{8\times 10\times 10}$$

= 37.66 N/mm2

5.2 ANALYTICAL CALCULATION FOR MILLING CUTTER

There are several analytical approaches used to determine the cutting temperature. These methods are suitable for the analysis of soft materials, in particular low carbon steels containing a high percentage of ferrite. Of these methods, Stephenson found that the most accurate model was Loewen and Shaw's because it accounted for the change in thermal properties of the tool and work piece with temperature.

However, since there is no dynamometer currently available to measure cutting forces, the horizontal force can be closely approximated by the formula proposed by Isakov. Once this quantity has been determined, Loewen and Shaw's approach can be used. Isakov's formula to find the tangential force or the force, in the horizontal orientation, FHO, of a milling cutter is given by,

$$F_{Ho} = \sigma_{UTS}\ n_c\ A\ C_m\ C_w$$

Where,

σ_{UTS} is ultimate tensile strength of the work piece

for AISI 1018 steel, $\sigma_{UTS} = 4.18 \times 10^{10}$ MPa

A is the uncut chip cross sectional area

n_c is the number of teeth engaged in the work piece

Cm is a machinability adjustment factor,

Cw is a tool wear adjustment factor.

For the calculation of feed per tooth we must know the following parameters,

Feed, f = 0.381 m/min = 0.00635 m/s

Spindle speed, N = 1000 rpm,

Number of cutting teeth, n = 12.

The feed per tooth can now be calculated from the following equation,

$$F_t = \frac{f}{N\,n}$$

$$= \frac{0.381}{1000\times 12}$$

$= 3.175 \times 10^{-5}$ m

The rake angle is measured at α = 9^0 and the feed per tooth correction factor, ftc, is given by,

$$F_{tc} = \frac{F_t}{\cos\alpha}$$

$$= \frac{3.175\times 10^{-5}}{\cos 9}$$

$= 3.215 \times 10^{-5}$ m/min

The method being followed is for orthogonal cutting, the case being considered

$$A = F_{tc} * b$$

$$= 3.215 \times 10^{-5} \times 1.27 \times 10^{-3}$$

$$= 4.083 \times 10^{-8} \, m^2$$

No. of teeth engaged is $n_c = 1$

The machinability adjustment factor taken from Isakov's textbook and has a value of unity, and the tool wear adjustment factor is taken as 1.1, also from Isakov. Therefore,

FHO can be calculated.

$$F_{HO} = \sigma_{UTS} \; n_c \; A \; C_m \; C_w$$

$$= 4.2 \times 10^8 \times 4.083 \times 10^{-8} \times 1 \times 1.1$$

$$= 18.86 \text{ N}$$

The chip thickness, tc, was measured to be 1×10^{-4} m, thus, the chip thickness ratio, r, can be calculated from,

$$r = \frac{t_o}{t_c}$$

$$= 0.317$$

This allows the shear plane angle, Φ, to be calculated from,

$$\Phi = tan^{-1}\left(\frac{r \cos \alpha}{1 - r \sin \alpha}\right)$$

$$= 24.55^{\circ}$$

Based on the work of Bowden and Tabor the coefficient of friction between HSS and a low carbon steel during dry rubbing conditions is, μ = 0.78. This allows the calculation of the force in the vertical orientation FVO, which is given by,

$$F_{VO} = \frac{\mu \, F_{OH} - F_{OH} \tan \alpha}{1 + \mu \tan \alpha}$$

$$= 10.43 \text{ N}$$

Hence the force F = 21.55 N

The force along the tool face, F_{AT}, is given by,

$$F_{AT} = F_{HO} \sin \alpha + F_{VO} \cos \alpha$$

$$= 18.86 \sin(9) + 10.43 \cos(9)$$

$$= 13.25 \text{ N}$$

The force normal to the tool face, F_{NT}, can be calculated by,

$$F_{NT} = F_{HO} \cos \alpha - F_{VO} \sin \alpha$$

$$= 18.86 \cos (9) - 10.43 \sin (9)$$

$$= 16.99 \text{ N}$$

Therefore, $F_T = 21.54$ N

The force along the shear plane, FAS, is given by,

$$F_{AS} = F_{HO} \cos \phi - F_{VO} \sin \Phi$$

$$= 18.86 \cos (24.55) - 10.43 \sin (24.55)$$

$$= 12.82 \text{ N}$$

The force normal to the shear plane, F_{NS}, is given by,

$$F_{NS} = F_{VO} \cos \phi + F_{HO} \sin \Phi$$

$$= 10.43 \cos (24.55) + 18.86 \sin (24.55)$$

$$= 21.48 \text{ N}$$

Hence the shear force is given as $F_S = 25.01$ N

We know that,

$$F_S = F_C \cos\phi - F_T \sin \phi$$

$$F_C = 28.73 \text{ N}$$

Cutting velocity is given as,

$$v = r_t \times \omega$$

$$= 0.034 \times \frac{2\pi \times 1000}{60}$$

$$= 3.56 \text{ m/s}$$

Chip velocity,

$$v_c = \frac{v \times \cos\alpha}{\cos(\phi - \alpha)}$$

$$= 1.53 \text{ m/s}$$

Total heat generation is

$W = W_P + W_S$

Where,

W_P = rate of heat generation in primary zone

W_S = rate of heat generation in secondary zone

We have,

$W = F_C \times V$ and $W_S = F \times V_C$

Therefore $W_P = F_C \times V - F_R \times V$

$W_P = 69.30$ W

$W_S = 32.97$ W

When a material particle moves across the primary deformation zone, the temperature rise is given by

$$\theta_p = \frac{(1-\Lambda)w_P}{\rho.c.v.t_1.w}$$

Where,

Λ = Fraction of primary heat which goes to the workpiece

ρ = Density of the material

c = Specific heat of the material

t_1, w = Specific heat of the material

It has been found that Λ is a function of the shear angle and a non-dimensional quantity'

$$\theta = \frac{\rho.c.v.t_1}{k}$$

k = Thermal conductivity of material

therefore, $\theta = 31.83$

For a wide range of work materials and machining conditions,

$$\Lambda = 0.15 \ln\left(\frac{27.5}{\theta \tan\phi}\right)$$

$$= 0.0955$$

Hence $\theta_P = 91.43\ ^0C$

The maximum temperature rise θ_s when the material particle passes through the secondary deformation zone along the rake face of the tool can be approximately expressed as,

$$\theta_s = 1.13\sqrt{\frac{\theta\, t_2}{l}} \times \left(\frac{w_s}{\rho.c.v.w.t_1}\right)$$

$$= 280\ ^0C$$

Where l is the length of contact between the tool and the chip

The final temperature is given as,

$$\theta = \theta_o + \theta_p + \theta_s$$

$$= 25 + 91.43 + 280$$

$$= 396.43\ ^0C$$

Where θ_o initial temperature of work piece

5.3 TEMPERATURE IN MILLING CUTTER USING HSS AS A MATERIAL:

Figure shows the temperature generated in milling cutter using material as a HSS.

From the figure the maximum temperature generated at the tip of milling cutter and it's value is 402.23 ^{0}C. Heat is transferring from the tip of the milling cutter towards fixed support where value of temperature is 223.25 ^{0}C. The maximum temperature generated value is nearer to the analytically calculated temperature and it's value is 396.43 ^{0}C.

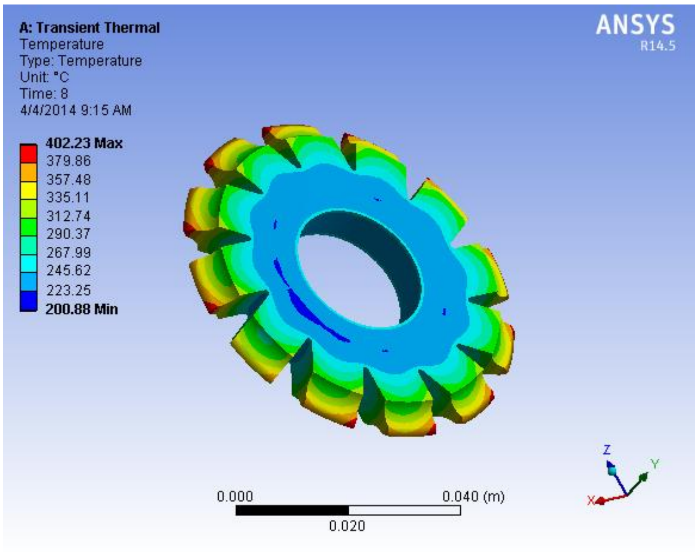


Fig 4: Temperature generated in milling cutter of HSS material for thermal analysis of milling cutter

5.4 TEMPERATURE IN MILLING CUTTER USING CEMENTED CARBIDE AS A MATERIAL:

Figure shows the temperature generated in milling cutter using material as a Cemented Carbide.

From the figure the maximum temperature generated at the tip of milling cutter and it's value is 350.92 ^{0}C. Heat is transferring from the tip of the milling cutter towards fixed support where value of temperature is 266.72 ^{0}C. The maximum temperature generated value is less than the analytically calculated temperature and it's value is 396.43 ^{0}C.

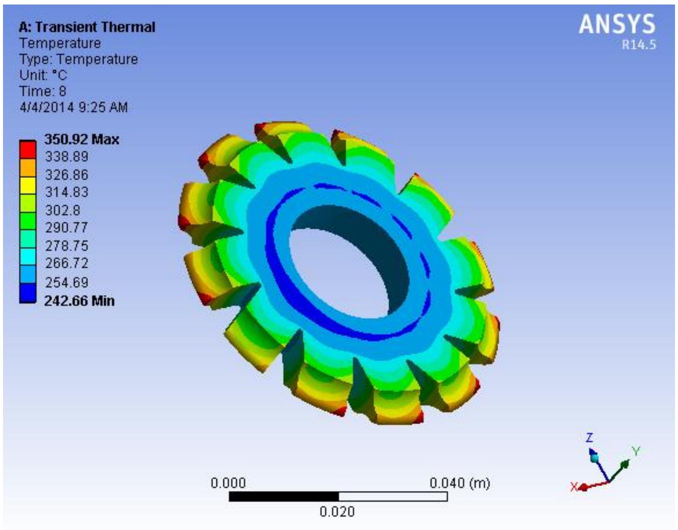
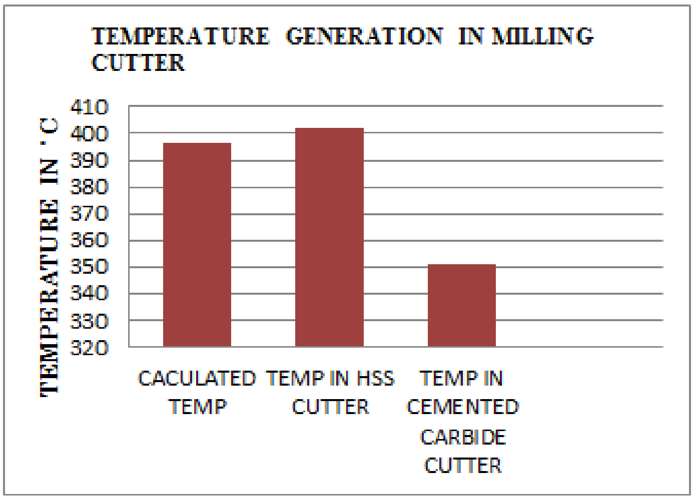


Fig 5: Temperature generated in milling cutter of Cemented Carbide material for thermal analysis of milling cutter

Table 1: Temperature generated in milling cutter of Cemented Carbide and HSS material for thermal analysis of milling cutter

Analytically calculated temperature	Temperature generated in cutter of HSS material	Temperature generated in cutter of cemented carbide material
396.43 ^{0}C	402.33 ^{0}C	350.92 ^{0}C



Graph 1: The temperature generated in milling cutter for thermal analysis of milling cutter

CONCLUSION

In thermal analysis, temperature generated in milling cutter is analytically calculated and it's value is equal to temperature generated in HSS milling cutter in ANSYS workbench 14.5. But in Cemented carbide milling cutter temperature generated is less for same conditions. From this study it is be concluded that the cemented carbide is preferred over HSS for milling cutter.

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