Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Investigation of Heat Flux Variability in End Milling: Helix Angle Perspective

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Heat generation in the cutting zone is a significant issue during high-speed milling, primarily due to the higher cutting speeds, which can reduce the quality of the finished surface. Modelling heat generation in milling is more complex than in continuous processes like turning, due to high tool speeds, varying chip thickness, intermittent cutting, and continuous heating-cooling cycles. These factors make evaluating heat flux during milling challenging and necessitate specialized approaches. The impact of milling tool geometry on time-varying heat flux has not been extensively studied. This research investigates the effects of varying the helix angle, an important geometrical parameter, on time-varying heat flux. Experiments were conducted using two materials: one ferrous (EN 8) and one non-ferrous (aluminium alloy Al 7075). The results for both materials were compared to understand the influence of the helix angle on heat flux in different materials. The surface heat flux was determined using the one-dimensional, semi-infinite medium solution for a step change in surface temperature, combined with Duhamel's superposition integral. The recorded surface temperature data was represented as a function of time using polynomial approximation.

Keywords: Heat flux, End Milling, Helix angle, experimental study.

1. Introduction

Sharp-edged cutting tools are used during the machining process to remove undesired portions of the work piece. Primary or cutting motion is the relative motion of the work piece and the tool that causes the material to be cut. Secondary motion, also known as feed motion, is the relative motion used to feed the uncut section of the work piece for cutting. The energy required for the machining operations is transformed into heat, raising the cutting zone's temperature.[1],[2]. The heat generated in the cutting zone is more serious issue during the high-speed machining activities like milling because the use of higher cutting speeds. It might also lead to a reduction in the quality of the surface that is formed. The plastic deformation of the material causes heat to be produced mostly along the shear plane. Normally, this zone is called the primary deformation zone. Friction at the tool-work piece interface causes heat to be produced in the secondary deformation zone. Additionally, heat is produced in the tertiary zone as a result of flank friction. [3]. The impact of elevated cutting temperatures on tool life expectancy, work piece quality, and chip formation emphasizes the paramount significance of heat modelling in these cutting zones [4]. The modelling of heat generated is more complex in milling as compared to continuous machining processes like turning. The complexity mainly arises from high milling tool speeds and varying chip thickness, compounded by the intermittent cutting process and continuous heating-cooling cycles. Solter et al. [5] have developed a thermal model for milling of AISI 4140 steel for finding out heat flux in the work piece and noticed that, the heat flux and heat partition in to the work piece increases with reduction in the undeformed chip thickness. By combining finite element analysis with experimental data, Brandao et al. [6] has accurately predicted the energy entering the work piece and the average convective heat transfer coefficient during ball end milling. Feng et al. [7] employed a similar approach, using a combination of the inverse heat transfer problem and the Particle Swarm Optimization (PSO) algorithm to calculate the heat flux into the work piece. Ming et al. [8] proposed a three-dimensional finite element-based inverse heat transfer model to calculate tool-work interface temperatures and surface heat flux during milling of Al-Cu4-Mg alloy. They observed an increase in heat flux with rising spindle speed and a reduction in the rate of heat flux increase after reaching a critical cutting speed. Wernsing et al. [9], argued that surface heat fluxes could be determined by comparing simulated and measured temperature fields, employing a method similar to that of Solter et al. [5].

A simple method to calculate heat flux during machining using a solution for a step change in surface temperature of a 1D, semi-infinite medium was proposed by Mzad [10]. Using a portable infrared thermometer, temperatures during dry turning and milling were recorded and converted into cubic polynomials. These polynomial coefficients were used to calculate the time-varying heat flux at the work-tool interface. Results showed that milling generated higher heat flux than turning, with milling heat flux being less dependent on cutting speed. Pabst et al. [11], developed a polynomial-based model using regression techniques to calculate surface heat flux during face milling of grey cast iron with coated carbide tools. They varied speed, feed, depth, width of cut, rake angle, and cutting edge radius. The model's heat flux calculations showed an average deviation of 3% from experimental values.

The above discussions lead to the conclusion that evaluating heat flux generated during milling is challenging and requires specialized approaches. Additionally, the effect of milling tool geometry on time-varying heat flux has not yet been studied. Therefore, the current work investigates the effects of varying an important geometrical parameter, the helix angle, on time-varying heat flux. Two work piece materials, one ferrous (EN 8) and one non-ferrous (aluminium alloy: Al 7075), were used for the experimentation, and the results for both materials were compared.

2. Experimental Methodology and Design

The experiments were conducted on a general-purpose, compact, high-precision machining centre (AMS model tool room). This vertical, 3-axis CNC machine has a maximum spindle speed of 6000 rpm and is equipped with a 7.5 kW drive motor (Figure 1). Solid, uncoated tungsten carbide end mill cutters with a 12 mm diameter (Figure 2) were used for the experiments. Eight end mill cutters with five different helix angles, each cut on both ends, were specially designed and manufactured by a leading local tool manufacturer.

Figure 1. AMS machining centre

Figure 2. Cutting tools

The specifications of the end mill cutters used for conducting experiments shown in Table 1.

Table 1 Specifications of the tools

(i)	Number of flutes	4
(ii)	Diameter of cutter	12 mm
(iii)	Flute length	30 mm
(iv)	Rake angle	7°
(v)	Primary and secondary relief angles	9 and 18º
(vi)	Dish angle	2º
(vii)	Helix angle	10°, 20°, 30°, 40°, 50°

In the current work, the strategy adopted by Mzad [10] is used for the determination of the time varying heat flux. The helix angle of the tool was varied for each experiment and the heat flux was calculated for each helix angle. These experiments were carried out for both the materials, Al 7075 and EN 8. During the experimentation, the spindle speed, feed, axial depth of cut, and radial depth of cut were kept constant and the helix angle was varied from 10° to 50° in step of 10°. The other parameters were held constant at the middle values of their respective recommended ranges. In addition, thermal and physical properties of both the materials material such as specific heat capacity, thermal conductivity and density are assumed to be constant [10]. The scheme of the experimentation is shown in Table 2.

Table 2 Scheme of experimentation

Material	Spindle Speed, N rpm	Feed, F mm/min	Radial Depth of cut, Y mm	Axial Depth of cut, X mm	Helix angle, H °
EN 8	2500	250	6	1.5	10 to 50
Al 7075	4000	400	6	1.5	10 to 50

The test specimens were of size 150 mm length and 25 mm x 25 mm cross section. As per the need of the scheme of experimentation, identical specimens were cut to the above dimensions. The work piece was placed in the machining centre using a machine vice and the cutting parameters were set as per the need of experiments.

The temperature rise (T) of the work piece surface was recorded using a non-contact infrared thermometer equipped with a smart sight laser system. This thermometer is designed for measuring the surface temperature of an object. The optical sensor emits, reflects, and transmits energy, which is collected and focused on a detector, then translated into a temperature reading by electronics and displayed on an LCD screen. The laser system was used for targeting. To obtain more accurate results, the laser spot was focused on the object by holding the thermometer as close as possible to the surface. The thermometer can record and transfer data to a personal computer in real-time via USB. Figure 3 Shows the schematic and actual system of the temperature measurement.

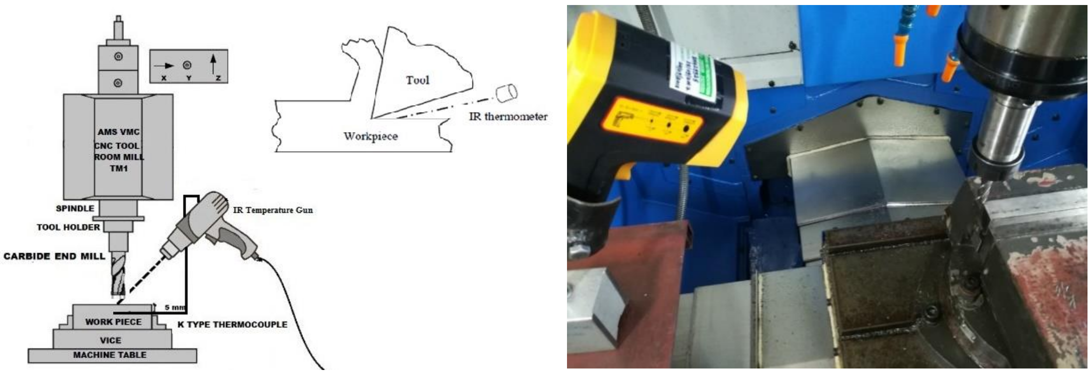


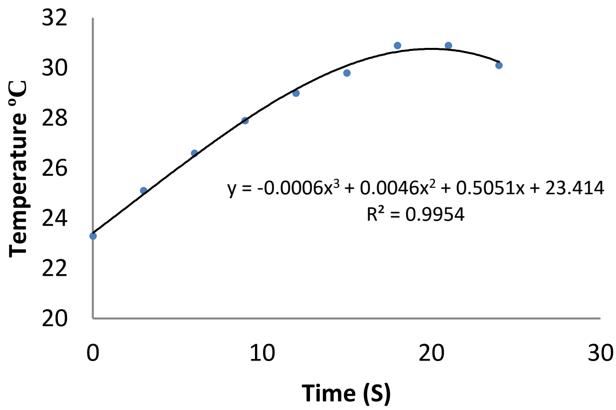
Figure 3 Measurement of temperature

3. Determination of Surface Heat Flux

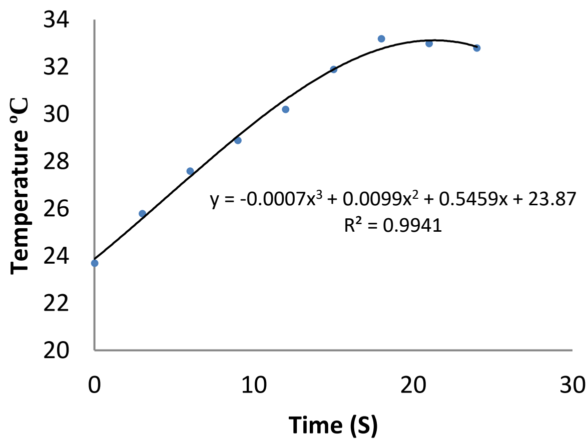
The surface heat flux was obtained by using the one-dimensional, semi-infinite medium solution for a step change in surface temperature and applying Duhamel's superposition integral [12]. The measured surface temperature was expressed as function of time using polynomial approximation. For this, the readings of the temperature variation with respect to time were recorded and were exported into the MS Excel for polynomial interpolation. The instantaneous measured temperature data was converted into cubic spline approximation by ignoring the higher order terms [10]. The polynomial was obtained in the following form as shown in Equation 1.

$$T(t) = A_1 + A_2 t + A_3 t^2 + A_4 t^3 \quad (1)$$

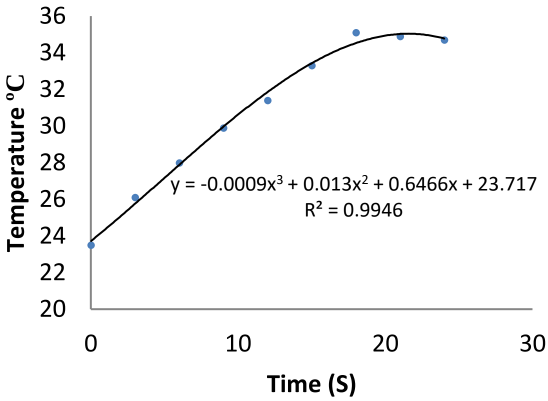
The coefficients of polynomials of the temperature variation curve were obtained from MS Excel for Al 7075 and EN 8 (Figures 4 and 5).



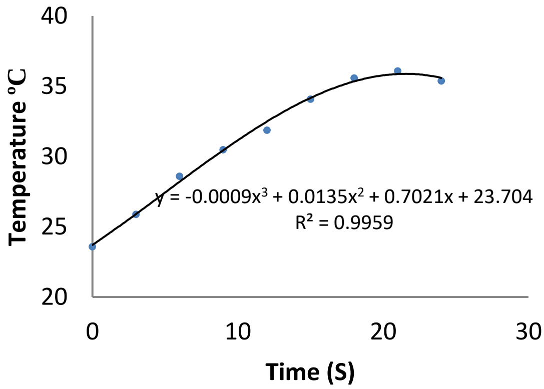
a. Helix angle 10°



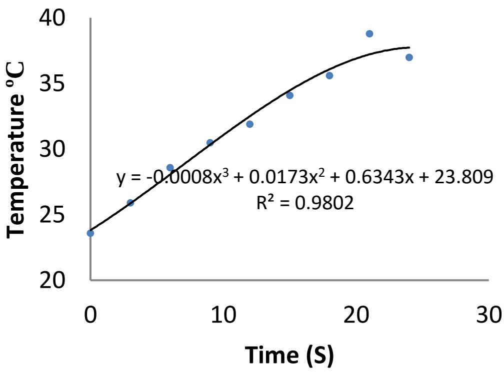
b. Helix angle 20°



c. Helix angle 30°

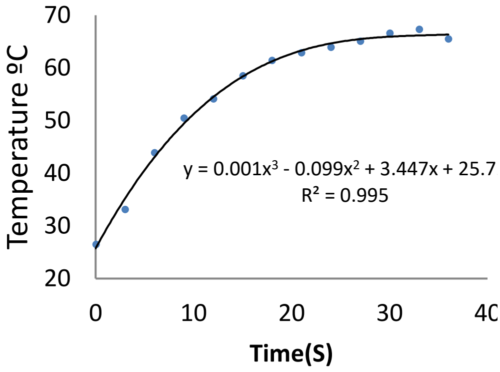


d. Helix angle 40°

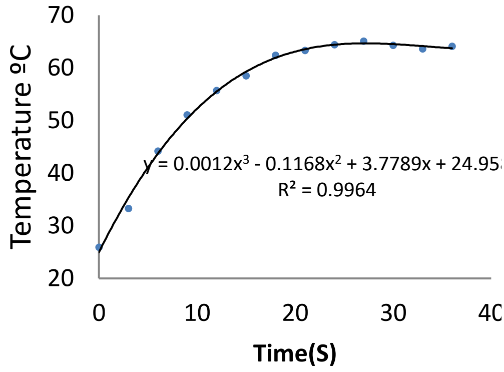


e. Helix angle 50°

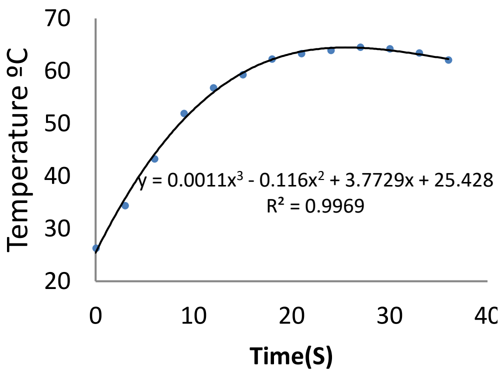
Figure 4 Temperature variations during milling for Al 7075



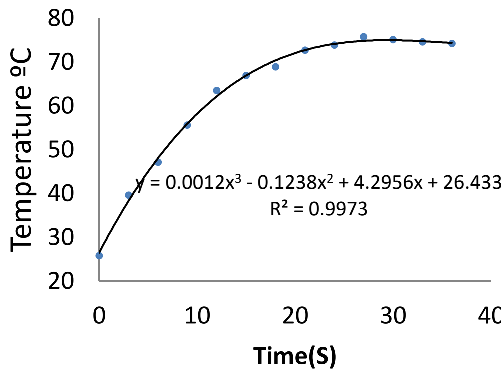
a. Helix angle 10º



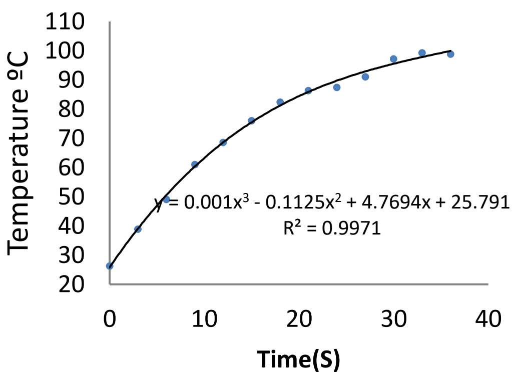
b. Helix angle 20º



c. Helix angle 30º



d. Helix angle 40º



e. Helix angle 50º

Figure 5 Temperature variations during milling of EN 8

Thereafter, the coefficients are substituted into Equation (2), and the resultant algebraic equation is solved to find the time varying heat flux. This equation for work piece heat transfer analysis was based on the theory of one-dimensional heat conduction problem [12].

$$q(t) = 2\sqrt{\frac{kCp}{\pi}}\left(A1\sqrt{t} + \frac{4}{3}A2\sqrt{t^3} + \frac{8}{5}A3\sqrt{t^5} + \frac{64}{35}A4\sqrt{t^7}\right) \tag{2}$$

In the above equation, q(t) was the heat flux to be determined, k is the thermal conductivity of the material in W/m-K, C is specific heat of the material in J/kg K, ρ is density of the material in kg/m3, and t is the time in second. The properties a listed in Table 3.,

Table 3 Properties of the materials

Material	Specific heat C J/kg K	Density ρ kg/m^3	Thermal Conductivity, k W/m- K
Al 7075	960	2810	130
EN 8	500	7850	46

Using these thermo-physical properties of the materials and using the thermal diagnostic results of temperature history represented by Figures 4 and 5; the work piece surface heat flux was computed through Equation 8.2. The instantaneous heat flux graphs for Al 7075 and EN 8 are illustrated in Figures 6 and 7.

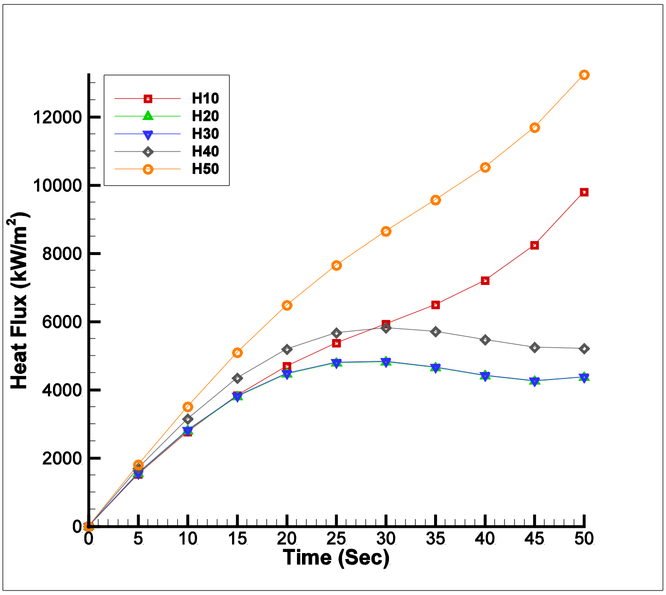


Figure 6 Instantaneous heat flux for Al 7075

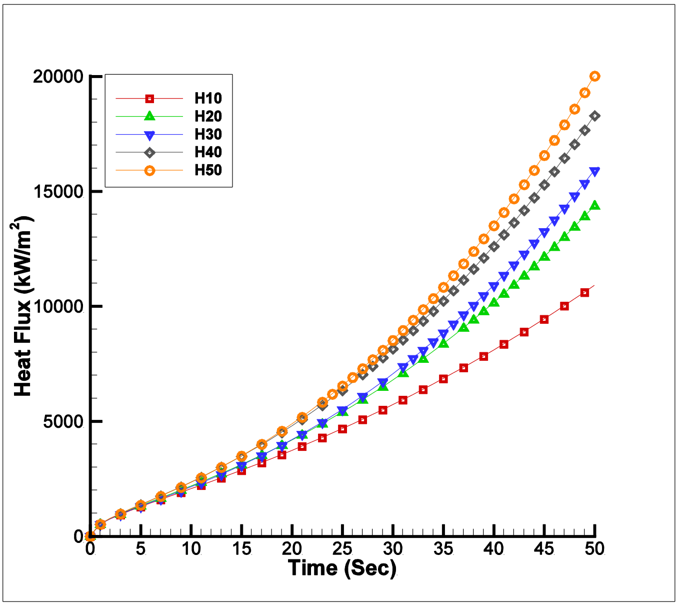


Figure 7 Instantaneous heat flux for EN 8

As shown in the Figures 6 and 7, nature of heat flux variation was comparable for both the materials, Al 7075 and EN 8 for milling operation. The values of heat flux for Al 7075 were found to be increasing with increase in the helix angle. The heat flux after 50 s was of the order of 11 X 106 W/m2, for helix angle of 10º and it was increased up to about 20 X 106 W/m2 for helix angle of 50º which corresponds to a heat increasing of 80 %. The values of heat flux for EN8 were found to be higher for helix angle of 10º then it was reduced with increase in the helix angle up to 30º and again increase for helix angle of 40º and 50º. The variation in the heat flux for the helix angle of 20º and 30º was found to be almost similar in nature.

The heat flux after 50 s was of the order of 4.3 X 106 W/m2, for helix angle of 20º and it was increased up to about 13 X 106 W/m2 for helix angle of 50º which corresponds to a heat increasing of 185 %.

4. Conclusions

The current work, the effects of variation of the helix angle on the transient surface heat flux during end milling process for both the materials were studied using the experimental results.

Based on above work, following conclusions were drawn:

1. The values of heat flux for Al 7075 were found to be increasing with increase in the helix angle. The heat flux was found to be increased by 80 % with the helix angle changing from 10º to 50º.

2. The values of heat flux for EN 8 were found to be higher for helix angle of 10º then it was reduced with increase in the helix angle up to 30º and again increase for helix angle of 40º and 50º. The variation in the heat flux for the helix angle of 20º and 30º was found to be almost

similar in nature. The heat flux after 50 s was of the order of 4.3 X 106 W/m2, for helix angle of 20º and it was increased up to about 13 X 106 W/m2 for helix angle of 50º which corresponds to a heat increasing of 185 %.

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