

Chapter 2

Analysis of Contact Between Chip and Tool Using Nanostructured Coated Cutting Tools

2.1 Introduction

The stages of contact between a metal chip of AISI 1018 steel and a coated cutting tool creates significant opportunities for manufacturers of machined products to understand how dry machining and minimum quantity lubrication affects the economics of manufacturing. The present work not only compares various computational approaches to the solution of shear plane and tool face temperatures during dry machining with nanostructured coated milling tools, but also explains why there is a large discrepancy when calculating temperature generated during machining when using Loewen and Shaw's method for calculating shear plane and tool face temperatures. There has been a great deal of activity in understanding metal cutting mechanics. Traditional metal cutting theories are being challenged as a result of advances in computational mechanics. Astakhov and co-workers [1–4] are particularly critical of using theories developed in the 1940s that describe the mechanics of metal cutting. In response to Astakhov's [1–4] assertions that the previous theories do not readily apply to current machining practices, the authors have conducted a series of computational analyses of machining AISI 1018 steel in order to understand if the Loewen and Shaw's method can be applied to calculating shear plane and tool face temperatures by comparing with finite element models that were constructed using a commercial software package known as Third Wave SystemsTM. The following analysis allows one to test if Astakhov's statements apply to the primary stages of chip formation and the subsequent stages of chip formation where a secondary shear zone is established that is caused by the formation of a built-up edge [5–14].

2.2 Computational Analysis of Machining Conditions

2.2.1 Loewen and Shaw's Method to Calculating Cutting Temperatures

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 [13] found that the most accurate model was Loewen and Shaw's because it accounted for the change in thermal properties of the tool and workpiece with temperature. Therefore, Loewen and Shaw's approach is used as demonstrated by Shaw [12] in order to explain the use of such formulae for the current experimental work. 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 [8]. 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, F_{HO} , of a milling cutter is given by,

$$F_{HO} = \sigma_{UTS} A_n C_m C_w \quad (2.1)$$

where, σ_{UTS} , is the ultimate tensile strength (UTS) of the workpiece (for AISI 1018 steel, $\sigma = 4.18 \times 10^{10}$ MPa), A , is the uncut chip cross sectional area, n_c , is the number of teeth engaged in the workpiece, C_m , is a machinability adjustment factor, and C_w , is a tool wear adjustment factor. The feed per tooth, f_t , must be calculated, to do this the following quantities must be known, the feed, $f = 0.381$ m/min $= 0.00635$ m/s, the spindle speed, $N = 2500$ rpm, or in radians the angular velocity, $\omega = 261.8$ rad/s, the number of cutting teeth, $n = 4$. The feed per tooth can now be calculated from the following equation,

$$f_t = \frac{f}{Nn} \quad (2.2)$$

$$f_t = \frac{0.381(\text{m/min})}{2500(\text{rpm}) \times 4} \quad (2.3)$$

$$f_t = 3.81 \times 10^{-5} \text{m}$$

The rake angle is measured at $\alpha = 9^\circ$, and the feed per tooth correction factor, f_{tc} , is given by,

$$f_{tc} = \frac{f_t}{\cos \alpha} \quad (2.4)$$

$$f_{tc} = \frac{3.81 \times 10^{-5}(\text{m/min})}{\cos 9^\circ} \quad (2.5)$$

$$f_{tc} = 3.86 \times 10^{-5} \text{m/min}$$

The method being followed is for orthogonal cutting, the case being considered is milling. Therefore, the orthogonal width of cut is replaced by the milling axial depth of cut, b , which is 1.27×10^{-3} m and the uncut chip cross sectional, A , is given by,

$$A = f_{tc}b \quad (2.6)$$

$$A = 3.86 \times 10^{-5}(\text{m}) \times 1.27 \times 10^{-3}(\text{m}) \quad (2.7)$$

$$A = 4.9 \times 10^{-8} \text{ m}^2$$

The tool diameter, $d = 1.27 \times 10^{-2}$ m, and the width of cut, W , is 0.635×10^{-2} m. The number of teeth engaged in the cut, n_c , can now be calculated by,

$$n_c = \frac{n(90 + \sin^{-1}((2W - d)/d))}{360} \quad (2.8)$$

$$n_c = \frac{4(90 + \sin^{-1}((2 \times 0.00635(\text{m}) - 0.0127(\text{m}))/0.0127(\text{m})))}{360} \quad (2.9)$$

$$n_c = 1$$

The machinability adjustment factor taken from Isakov's [8] textbook and has a value of unity, and the tool wear adjustment factor is taken as 1.1, also from Isakov [8]. Therefore, F_{HO} can be calculated.

$$F_{HO} = \sigma A n_c C_m C_w \quad (2.10)$$

$$F_{HO} = 4.2 \times 10^8 \times 4.9 \times 10^{-8} \times 1 \times 1 \times 1.1 \quad (2.11)$$

$$F_{HO} = 22.63 \text{ N}$$

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

$$r = \frac{t_o}{t_c} \quad (2.12)$$

$$r = \frac{3.81 \times 10^{-5}(\text{m})}{1 \times 10^{-4}(\text{m})} \quad (2.13)$$

$$r = 0.381$$

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

$$\Phi = \tan^{-1} \left(\frac{r \cos \alpha}{1 - r \sin \alpha} \right) \quad (2.14)$$

$$\Phi = \tan^{-1} \left(\frac{0.381 \cos 9^\circ}{1 - 0.381 \sin 9^\circ} \right) \quad (2.15)$$

$$\Phi = 21.81^\circ$$

Based on the work of Bowden and Tabor [7] the coefficient of friction between tungsten carbide and a low carbon steel (in this case AISI 1018 steel) during dry rubbing conditions is, $\mu = 0.78$. This allows the calculation of the force in the vertical orientation F_{VO} , which is given by,

$$F_{VO} = \frac{\mu F_{HO} - F_{HO} \tan \alpha}{1 + \mu \tan \alpha} \quad (2.16)$$

$$F_{VO} = \frac{0.78 \times 22.63(\text{N}) - 22.63(\text{N}) \tan 9^\circ}{1 + 0.78 \tan 9^\circ} \quad (2.17)$$

$$F_{VO} = 12.52 \text{ N}$$

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

$$F_{AT} = F_{HO} \sin \alpha + F_{VO} \cos \alpha \quad (2.18)$$

$$F_{AT} = 22.63(\text{N}) \sin 9^\circ + 12.52(\text{N}) \cos 9^\circ \quad (2.19)$$

$$F_{AT} = 15.91 \text{ N}$$

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

$$F_{NT} = F_{HO} \cos \alpha - F_{VO} \sin \alpha \quad (2.20)$$

$$F_{NT} = 22.63(\text{N}) \cos 9^\circ - 12.52(\text{N}) \sin 9^\circ \quad (2.21)$$

$$F_{NT} = 20.4 \text{ N}$$

The force along the shear plane, F_{AS} , is given by,

$$F_{AS} = F_{HO} \cos \Phi - F_{VO} \sin \Phi \quad (2.22)$$

$$F_{AS} = 22.63(\text{N}) \cos 21.81^\circ - 12.52(\text{N}) \sin 21.81^\circ \quad (2.23)$$

$$F_{AS} = 16.36 \text{ N}$$

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

$$F_{NS} = F_{VO} \cos \Phi + F_{HO} \sin \Phi \quad (2.24)$$

$$F_{NS} = 12.52(\text{N}) \cos 21.81^\circ + 22.63(\text{N}) \sin 21.81^\circ \quad (2.25)$$

$$F_{NS} = 20.03 \text{ N}$$

Since the milling process is being approximated by an orthogonal cutting operation, the milling axial depth of cut is equal to the orthogonal chip width, b . The maximum uncut chip thickness is equal to the feed per tooth t_o . The area of the shear plane A_s is given by,

$$A_s = \frac{bt_O}{\sin \Phi} \quad (2.26)$$

$$A_s = \frac{(1.27 \times 10^{-3}(\text{m}))(3.81 \times 10^{-5}(\text{m}))}{\sin 21.81^\circ} \quad (2.27)$$

$$A_s = 1.3 \times 10^{-7} \text{ m}^2$$

The shear stress, τ , is given by,

$$\tau = \frac{F_{AS}}{A_s} \quad (2.28)$$

$$\tau = 16.36(\text{N})/1.3 \times 10^{-7}(\text{m}^2) \quad (2.29)$$

$$\tau = 125.62 \times 10^6 \text{ N/m}^2$$

Similarly the normal stress, σ , is given by,

$$\sigma = \frac{F_{NS}}{A_s} \quad (2.30)$$

$$\sigma = 20.03(\text{N})/1.3 \times 10^{-7}(\text{m}^2) \quad (2.31)$$

$$\sigma = 153.82 \times 10^6 \text{ N/m}^2$$

The shear strain, γ , is given by,

$$\gamma = \frac{\cos \alpha}{\sin \Phi \cos(\Phi - \alpha)} \quad (2.32)$$

$$\gamma = \frac{\cos 9^\circ}{\sin 21.81^\circ \cos(21.81^\circ - 9^\circ)} \quad (2.33)$$

$$\gamma = 2.73$$

The cutting velocity, V , at the tool tip is given by,

$$V = r_t \omega$$

where, r_t , is the tool radius and the units of, ω , are radians/s.

$$V = 0.00635(\text{m}) \left(\frac{2\pi}{60(\text{s})} \times 2500(\text{rpm}) \right) \quad (2.34)$$

$$V = 1.66 \text{ m/s}$$

The chip velocity, V_C , is given by,

$$V_C = \frac{V \sin \Phi}{\cos(\Phi - \alpha)} \quad (2.35)$$

$$V_C = \frac{1.66(\text{m/s})\sin 21.81^\circ}{\cos(21.81^\circ - 9^\circ)} \quad (2.36)$$

$$V_C = 0.632 \text{ m/s}$$

Similarly the shear velocity, V_s , is given by,

$$V_s = \frac{V \cos \alpha}{\cos(\Phi - \alpha)} \quad (2.37)$$

$$V_s = \frac{1.66(\text{m/s})\cos 9^\circ}{\cos(21.81^\circ - 9^\circ)} \quad (2.38)$$

$$V_s = 1.68 \text{ m/s}$$

In order to determine the strain rate, $\dot{\gamma}$, the shear plane spacing, Δy , must be determined from chip images, in this case $\Delta y = 10 \mu\text{m}$.

$$\dot{\gamma} = \frac{V \cos \alpha}{\Delta y \cos(\Phi - \alpha)} \quad (2.39)$$

$$\dot{\gamma} = \frac{1.66(\text{m/s})\cos 9^\circ}{(1 \times 10^{-5}(\text{m}))\cos(21.81^\circ - 9^\circ)} \quad (2.40)$$

$$\dot{\gamma} = 168.39 \times 10^3 \text{ s}^{-1}$$

The theoretical scallop height, h , which reflects the surface roughness of the machined surface in an end milling operation is given by,

$$h = \frac{f_t^2}{4d} \quad (2.41)$$

$$h = \frac{(3.81 \times 10^{-5}(\text{m}))^2}{4(0.0127(\text{m}))} \quad (2.42)$$

$$h = 2.86 \times 10^{-8} \text{ m}$$

The energy per unit time, U , is given by,

$$U = F_{HO} V$$

$$U = 22.63(\text{N}) \times 1.66(\text{m/s})$$

$$U = 37.63 \text{ Nm s}^{-1}, \text{ or } 37.63 \text{ J s}^{-1}$$

The energy per unit volume, u , is given by,

$$u = \frac{F_{HO}}{bt_0} \quad (2.43)$$

$$u = \frac{22.63(\text{N})}{(1.27 \times 10^{-3}(\text{m}))(3.81 \times 10^{-5}(\text{m}))} \quad (2.44)$$

$$u = 467.76 \times 10^6 \text{ Nm/m}^3 \text{ or } 467.76 \times 10^6 \text{ J/m}^3$$

The shear energy per unit volume, u_s , is given by,

$$u_s = \tau\gamma \quad (2.45)$$

$$u_s = 125622347(\text{N/m}^2) \times 2.73(\text{m/m}) \quad (2.46)$$

$$u_s = 342.49 \times 10^6 \text{ Nm/m}^3 \text{ or } 342.49 \times 10^6 \text{ J/m}^3$$

The friction energy per unit volume, u_f , is given by,

$$u_f = \frac{F_{AT}r}{bt_0} \quad (2.47)$$

$$u_f = \frac{(15.91(\text{N}))(0.381)}{(1.27 \times 10^{-3}(\text{m}))(3.81 \times 10^{-6}(\text{m}))} \quad (2.48)$$

$$u_f = 125.27 \times 10^6 \text{ Nm/m}^3 \text{ or } 125.27 \times 10^6 \text{ J/m}^3$$

To determine the shear plane temperature, the method of Loewen and Shaw taken from Shaw [12] is used. The process involves several iterations, the final iteration is shown. The initial step is to estimate the shear plane temperature, $\theta_s = 70^\circ\text{C}$, and the ambient temperature is $\theta_o = 25^\circ\text{C}$, then calculate the mean of these two temperatures, θ_{AV} .

$$\theta_{AV} = \frac{\theta_s + \theta_o}{2} \quad (2.49)$$

$$\theta_{AV} = \frac{70^\circ\text{C} + 25^\circ\text{C}}{2} \quad (2.50)$$

$$\theta_{AV} = 47.5^\circ\text{C}$$

The thermal properties of the workpiece must be determined; in this case a low carbon steel. Shaw [12] displays these properties. At 47.5°C , the thermal diffusivity, $K_1 = 1.58 \times 10^{-5} \text{ m}^2/\text{s}$, and the volumetric specific heat is, $\rho_1 C_1 = 3.72 \times 10^6 \text{ J/m}^3 \text{ }^\circ\text{C}$. Calculate the quantity R_1 from,

$$R_1 = \frac{1}{1 + 1.328 \left(\frac{K_1 \gamma}{V_{t_0}} \right)^{1/2}} \quad (2.51)$$

$$R_1 = \frac{1}{1 + 1.328 \left(\frac{1.58 \times 10^{-5}(\text{m}^2/\text{s}) \times 2.73}{1.66(\text{m/s}) \times 3.81 \times 10^{-5}(\text{m})} \right)^{1/2}} \quad (2.52)$$

$$R_1 = 0.48$$

Calculate the quantity $\theta_s - \theta_o$ from,

$$\theta_s - \theta_o = \frac{R_1 u_s}{J \rho_1 C_1} \quad (2.53)$$

Where J is the mechanical equivalent of heat, the value used by Shaw [12] of 9340 lbin/BTUs² for low carbon steel, or 0.99 Nm/J s², will be used here,

$$\theta_s - \theta_o = \frac{0.48(342.49 \times 10^6 \text{ (J/m}^3\text{)})}{(0.99 \text{ (Nm/Js}^2\text{)}) (371.88 \times 10^4 \text{ (J/m}^3 \text{ }^\circ\text{C)})} \quad (2.54)$$

$$\theta_s - \theta_o = 43.99 \text{ }^\circ\text{C}$$

Therefore,

$$\theta_s = 68.99 \text{ }^\circ\text{C}$$

Shaw states the process is repeated until the initial estimate produces a shear plane temperature within 3.88 °C of the initial estimate. Therefore, in this case the accepted shear plane temperature is 68.99 °C.

To calculate the tool face temperature estimate the tool face temperature $\theta_T = 89.25 \text{ }^\circ\text{C}$. Then determine the thermal properties of the workpiece at this temperature, in this case a low carbon steel, they are taken from Shaw [12]. At 89.25 °C, $K_1 = 1.49 \times 10^{-5} \text{ m}^2/\text{s}$, $\rho_1 C_1 = 3.91 \times 10^6 \text{ J/m}^3 \text{ }^\circ\text{C}$. The chip contact length, a , is approximated as half the uncut chip length l , which is given by,

$$l = (dt_o)^{0.5} + \frac{f}{2nN} \quad (2.55)$$

$$l = (0.0127 \text{ (m)} \times 3.81 \times 10^{-3} \text{ (m)})^{0.5} + \frac{0.381 \text{ (m)}}{2 \times 4 \times 2500 \text{ (rpm)}} \quad (2.56)$$

$$l = 7.15 \times 10^{-4} \text{ m}$$

Thus,

$$a = l/2 \quad (2.57)$$

$$a = 7.15 \times 10^{-4} \text{ (m)} / 2 \quad (2.58)$$

$$a = 3.57 \times 10^{-4} \text{ m}$$

$$\frac{m}{l} = \frac{b}{2a} \quad (2.59)$$

$$\frac{m}{l} = \frac{1.27 \times 10^{-3} \text{ (m)}}{2(3.57 \times 10^{-4} \text{ (m)})} \quad (2.60)$$

$$\frac{m}{l} = 8.89$$

Using Shaw's textbook [12] to find $\bar{A} = 2.1$, determine the thermal conductivity of the workpiece, k_s , at the previously calculated shear plane temperature of 68.99°C , in this case, $k_T = 6.12 \times 10^{-3} \text{ J/m}^2 \text{ s } ^\circ\text{C}$. This allows C' to be calculated from,

$$C' = \frac{u_f V t_0 \bar{A}}{J k_T} \quad (2.61)$$

$$C' = \frac{(125.27 \times 10^6 (\text{J/m}^3)) (1.66 (\text{m/s})) (3.81 \times 10^{-5} (\text{m})) \times 2.1}{(0.99 (\text{Nm/Js}^2)) (6.12 \times 10^{-3} (\text{J/m}^2 \text{s}^\circ\text{C}))} \quad (2.62)$$

$$C' = 27.24 \times 10^5$$

Calculate B' from,

$$B' = \left(\frac{0.754 u_f}{J p_s C_s} \right) \left(\frac{V t_0^2}{a r K_s} \right)^{1/2} \quad (2.63)$$

where the subscript S denotes the thermal properties determined at the previously calculated shear plane temperature, $\rho_s c_s = 3.91 \times 10^6 \text{ J/m}^3 ^\circ\text{C}$ and $K_s = 1.49 \times 10^{-5} \text{ m}^2/\text{s}$.

$$B' = \left(\frac{0.754 (125.2 \times 10^6 (\text{J/m}^3))}{(0.99 (\text{Nm/Js}^2)) (3.91 \times 10^6 (\text{J/m}^3 ^\circ\text{C}))} \right) \times \left(\frac{(1.66 (\text{m/s})) (3.81 \times 10^{-5} (\text{m}))^2}{(3.57 \times 10^{-4} (\text{m})) \times 0.381 \times (1.49 \times 10^{-5} (\text{m}^2/\text{s}))} \right)^{1/2} \quad (2.64)$$

$$B' = 18.87$$

Calculate the quantity R_2 from,

$$R_2 = \frac{C' - \theta_s + \theta_o}{C' + B'} \quad (2.65)$$

$$R_2 = \frac{(2.72 \times 10^6) - (68.99(^\circ\text{C})) + (25(^\circ\text{C}))}{(2.72 \times 10^6(^\circ\text{C})) + 18.87} \quad (2.66)$$

$$R_2 = 0.99 ^\circ\text{C}$$

Calculate the temperature rise in the chip surface due to friction, $\Delta\theta_F$, from,

$$\Delta\theta_F = R_2 B' \quad (2.67)$$

$$\Delta\theta_F = 0.99(^\circ\text{C}) \times 18.87 \quad (2.68)$$

$$\Delta\theta_F = 18.67 ^\circ\text{C}$$

Table 2.1 Table of computational parameters used for machining simulations

Cutting speed—V (m/s)	1.662426113
Undeformed chip thickness— t_0 (m)	0.0000381
Width of cut—b (m)	0.00635
Cutting force— F_p (N)	22.63344932
Feed force— F_q (N)	12.52230092
Chip thick ratio—r	0.381
Shear strain— γ	2.726369114
Shear energy/unit volume— u_s (mN/m ³)	342492886.91
Friction energy/unit volume— u_f (mN/m ³)	125266001.2
Mechanical equivalent of heat—J (Nm/Js ²)	0.998996696
Tool diameter—d (m)	0.0127
Cutting speed—V (m/min)	99.74556675
Number of cutting teeth—n	4
Cutting speed—w (rpm)	2500

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Finally the tool face temperature, θ_T , can be calculated from,

$$\theta_T = \theta_s + \Delta\theta_F \quad (2.69)$$

$$\theta_T = 68.99(^{\circ}\text{C}) + 18.67(^{\circ}\text{C}) \quad (2.70)$$

$$\theta_T = 87.66^{\circ}\text{C}.$$

Shaw [12] states that the procedure for calculating the tool face temperature should be repeated until the initial estimate and the final calculated temperature are in agreement. In this case the difference of 1.59 °C cannot be doubted since the material properties are determined from interpretation of line diagrams. Therefore, 89.25 °C is the accepted tool face temperature. Tables 2.1, 2.2 and 2.3 show the experimental parameters and equations that were used to calculate the shear plane and tool face temperatures. The tables include sample calculations to demonstrate the use of the equations and parameters shown above. Table 2.4 shows the shear

Table 2.2 Calculation of shear plane temperature

To calculate shear plane temperature—°C		
Step 1		
Estimate initial shear plane temperature θ_s		70.00 °C
Ambient temperature θ_0		25.00 °C
Average temperature		47.50 °C
Find material properties from fig 12.25 at		47.50 °C
	K_1 —thermal diffusivity	$1.5812E-05 \text{ m}^2/\text{s}$
	$C_1\rho_1$ —volume specific heat	$3718849.84 \text{ J/m}^3 \text{ °C}$
Calculate R_1	$R_1 = 1/(1 + 1.328(K_1\gamma/Vt_0)^{1/2})$	
	$R_1 =$	0.477191655
Step 2	$\theta_s - \theta_0 = R_1 u_s / JC_1\rho_1$	
	$\theta_s - \theta_0 =$	43.99179692 °C
Since $\theta_0 =$		25.00 °C
$\theta_s =$		68.99 °C
Step 3		
If initial guess is within 3.88 °C use that temperature, if not repeat		
		−1.01 °C
	Feed rate—f	
	(m/min)	0.381
	Chip contact length—l	
	(m)	$7.15E-04$
	Chip contact length—a (m)	0.000357329
	(m)	

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plane approximation and calculation temperatures. It also includes the tool face approximations and calculations of the temperatures. The last column shows the percentage error between estimated and calculated temperatures. The coefficient of friction of 0.78 has been taken from Robinson [11] in order to compare with the calculations shown above. It is intended to be factual information based on the experimental work performed by Robinson [11]. The shear plane temperature and the tool face temperature have been calculated using different values of coefficient of friction in order to provide a parametric analysis and to compare with the values for the different coatings. This ranges from 0.1 to 1.0 with 0.1 increments. This has then been compared to the approximate amounts of shear plane and tool face temperatures. The percentage error is then calculated for a comparison between the approximation and the calculation. The percentage of error is less than 3.5 % for all calculations. From Figs. 2.1 and 2.2, it can be seen that increasing the coefficient of friction lowers the shear plane temperature, but conversely the tool face temperature tends to increase.

Table 2.3 Calculation of tool face temperature

To calculate tool face temperature—°C		
Step 4	Estimate initial shear plane temperature θ_T	89.25 °C
	Ambient temperature θ'_0	25 °C
Material properties from fig 12.25 [12] at estimated tool temperature of		89.25 °C
	K_2 —thermal conductivity	1.49E−05 m ² /s
	$C_2\rho_2$ —volume specific heat	3912751.678 J/m ³ °C
Calculate the ratio		$m/l = b/2a$
	$m/l =$	8.89
Use figure 12.17 [12] to find A		2.1
Find k_3 from fig 12.25 at calculated shear plane temperature of		68.99
	k_3	6.12E−03 J/ms °C
Step 5	Calculate the quantity	$C' = u_f V t_0 A / J k_3$
	$C' =$	2724338.49 °C
Step 6	Calculate the quantity B'	
	$B' = (0.754 u_f / J \rho_3 C_3) (V t_0^2 / a r K_2)^{1/2}$	18.66628618 °C
Step 7	Determine R_2	$R_2 = (C' - \theta_s + \theta'_0) / (C' + B')$
	$R_2 =$	0.999977001
Step 8	Temp rise in chip due to friction, $\Delta\theta_F$	$\Delta\theta_F = R_2 B'$
	$\Delta\theta_F =$	18.66585687 °C
Step 9	Calculate θ_T from	$\theta_T = \theta_s + \Delta\theta_F$
	$\theta_T =$	87.66 °C
Repeat analysis until calculated value and estimate match		
	Diff =	1.59

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2.3 Finite Element Studies of Machining Conditions

A metal cutting finite element software was chosen to simulate the metal cutting operation. The choice of the software is important because the output results may vary from software to software and with the input parameters also. Therefore, AdvantEdge™ (provided by Third Wave Systems) was used in this study. The software uses adaptive meshing to improve the quality and precision of the output results and it also includes a wide range of workpiece material library. The simulations are replicas of what was done experimentally and the cutting parameters used were the same in both processes. Third Wave AdvantEdge™ allows improving and optimizing of machining processes. To model the thermal-visco plastic behavior of the materials, the software employs a constitutive equation, the Johnson–Cook law, which can be represented by the following formula:

$$\sigma_{eq} = (A + B\varepsilon^n) \left(1 + C \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) \left(1 - \left(\frac{T - T_{room}}{T_m - T_{room}} \right)^m \right) \quad (2.71)$$

Table 2.4 Approximate and calculated tool face temperatures and shear plane temperatures

CoF	Shear plane approximate (°C)	Shear plane calculated (°C)	Error (°C)	Tool face approximate (°C)	Tool face calculated (°C)	Error (°C)
0.1	80	82.03	−2.03	85	87.4	−2.4
0.2	80	79.85	0.15	87	85.06	1.94
0.3	79	78	1	85	85.51	−0.51
0.4	76	75.45	0.55	84	85.32	−1.32
0.5	75	74.14	0.86	86	86.6	−0.6
0.6	74	72.71	1.29	87	87.44	−0.44
0.7	72	70.41	1.59	88	87.2	0.8
0.78	70	68.99	1.01	89.25	87.66	1.59
0.9	68	67.1	0.9	91	88.28	2.72
1	65	65.42	−0.42	92	88.58	3.42

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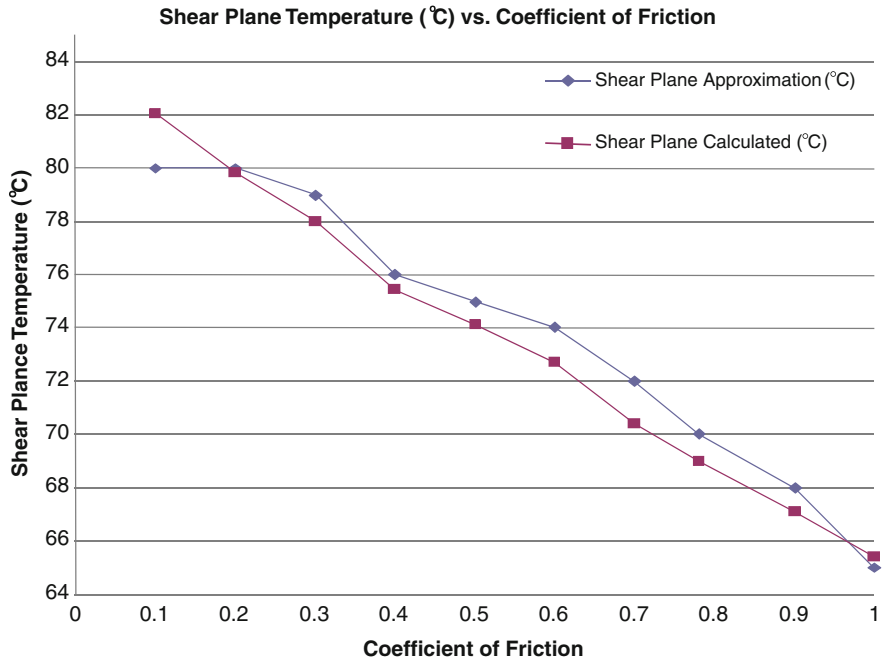


Fig. 2.1 Shear plane temperature versus coefficient of friction. Re-produced from ‘Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

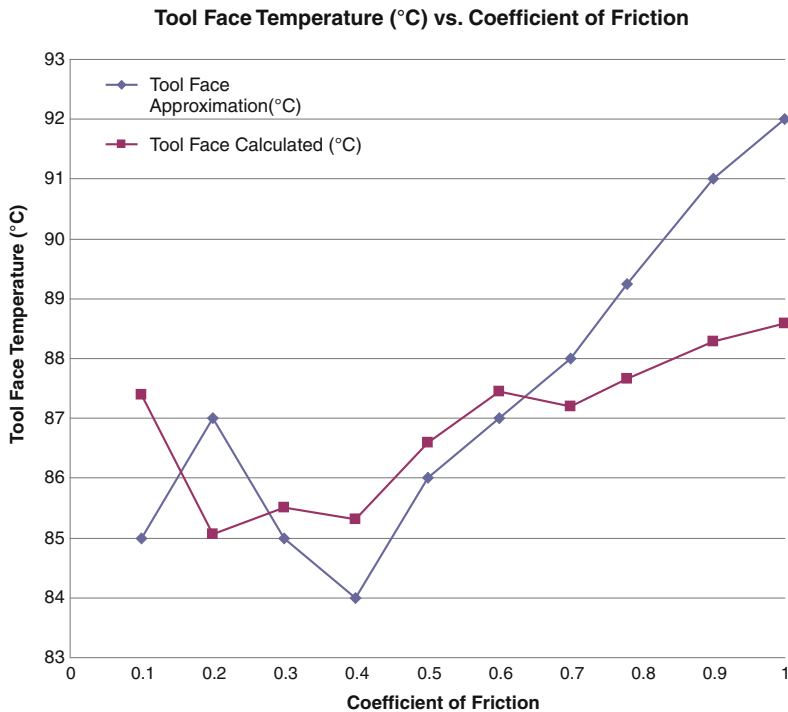


Fig. 2.2 Tool face temperature versus coefficient of friction. Re-produced from 'Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

where, ϵ , is the plastic strain, $\dot{\epsilon}$, is the plastic strain rate (s^{-1}), $\dot{\epsilon}_0$ is the reference plastic strain rate (s^{-1}), T , is the temperature of the workpiece material ($^{\circ}C$), T_m , is the melting temperature of the workpiece material ($^{\circ}C$), and, T_{room} , is the room temperature ($^{\circ}C$). Coefficient, A , is the yield strength (MPa), B , is the hardening modulus (MPa), and, C , is the strain rate sensitivity coefficient, n , is the hardening coefficient and, m , the thermal softening coefficient. The friction coefficient was obtained using the Coulomb model and was calculated with the following formula:

$$u = \frac{F_f + F_c \times \tan \gamma}{F_c - F_f \times \tan \gamma} \quad (2.72)$$

where, F_f , the feed force, F_c , the cutting force, and, γ , is the rake angle.

The experiments were conducted using the following conditions: Cutting speed used was 300 m/min; the feed rate was kept constant at 0.15 mm per revolution; depth of cut was constant at 1 mm; length of cut was constant at 6 mm; the length of the work piece was 5 mm; the experimental specimen was 1018 steel; initial temperature was 20 $^{\circ}C$, and the coating thickness was constant at 4 μ' thickness. The coefficient of friction was varied between 0.1 and 1 in steps of 0.1 in order to compare results generated using Loewen and Shaw's method.

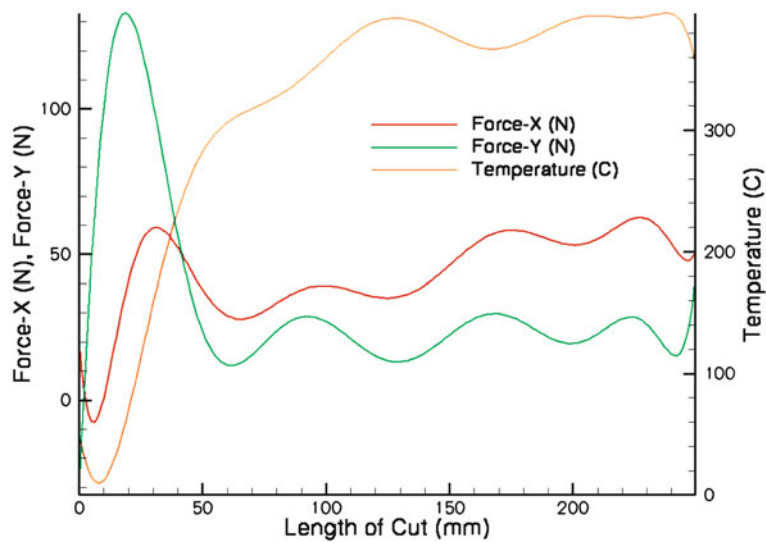


Fig. 2.3 Peak tool temperature as a function of the length of cut for a coefficient of friction of 0.1 between tool and chip. Re-produced from ‘Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

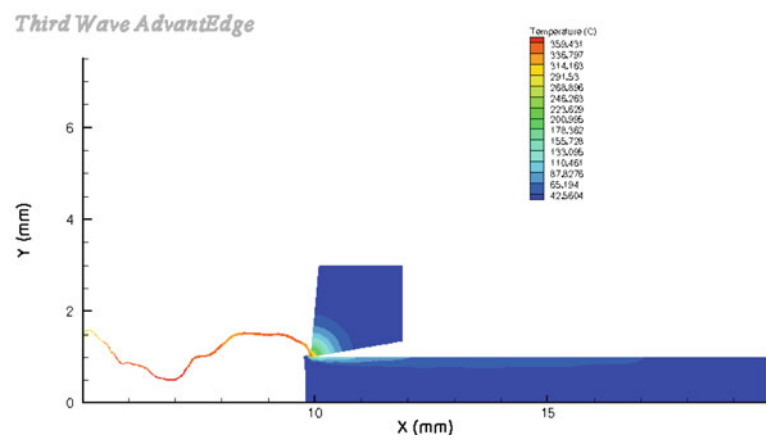


Fig. 2.4 Temperature profile between chip and tool for a coefficient of friction of 0.1 between chip and tool. Re-produced from ‘Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

The finite element generated results (Figs. 2.3–2.8) show the machining variables peak tool temperature and machining temperatures as a function of the coefficient of friction. In order to minimize computational effort, calculations for coefficient of friction of 0.1, 0.5, and 1.0 are shown in this paper. Figures 2.9 and 2.10 shows the

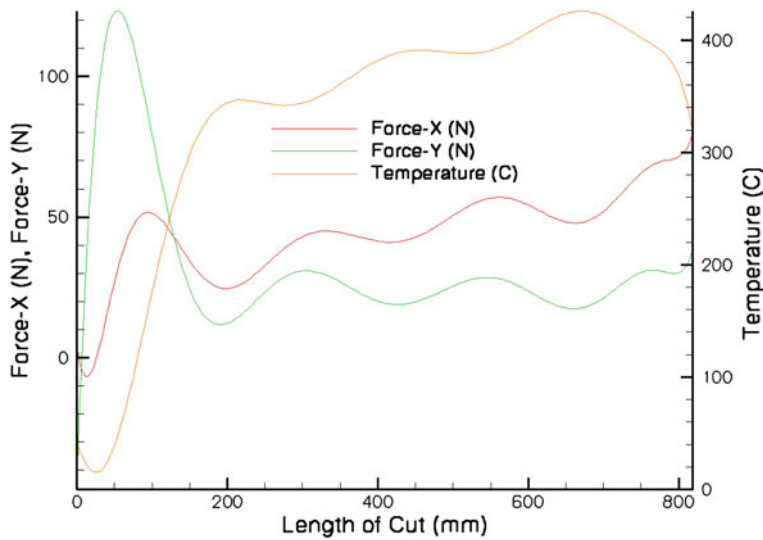


Fig. 2.5 Peak tool temperature as a function of the length of cut for a coefficient of friction of 0.5 between tool and chip. Re-produced from ‘Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

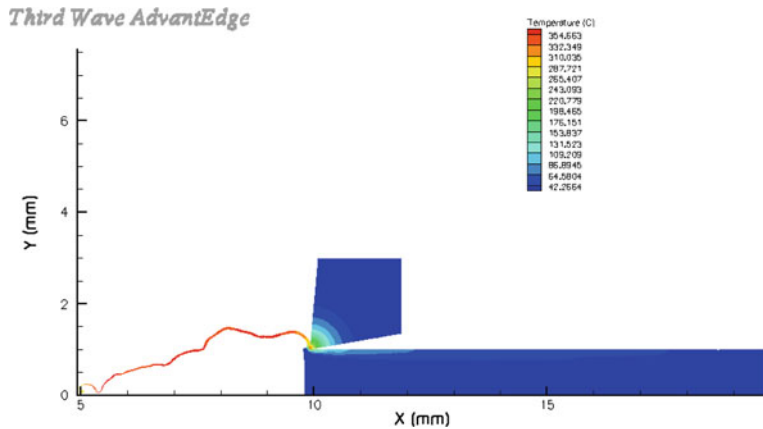


Fig. 2.6 Temperature profile between chip and tool for a coefficient of friction of 0.5 between chip and tool. Re-produced from ‘Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

comparison between calculated, approximate, and finite element generated shear plane and tool face temperatures. It is shown that as machining develops, shear plane and tool face temperatures increase rapidly after the initial frictional interactions between workpiece and cutting tool. Here, the method of Loewen and Shaw does not

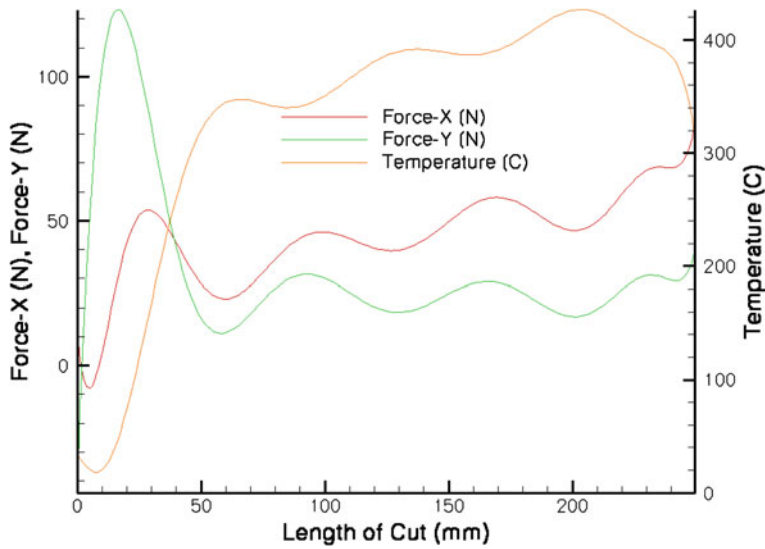


Fig. 2.7 Peak tool temperature as a function of the length of cut for a coefficient of friction of 1.0 between tool and chip. Re-produced from ‘Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

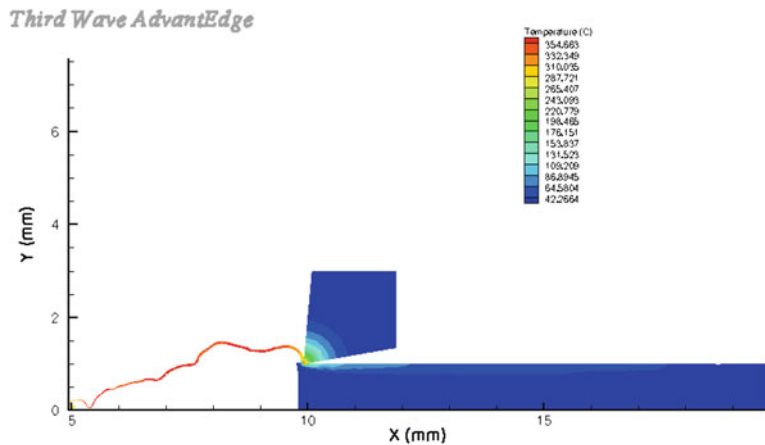


Fig. 2.8 Temperature profile between chip and tool for a coefficient of friction of 1.0 between chip and cutting tool. Re-produced from ‘Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

compare well. However, at the beginning of the cut, i.e., after the first 25 mm is machined, it can be seen that Loewen and Shaw’s method produces a very accurate estimate of shear plane and tool face temperature. This implies that their method is

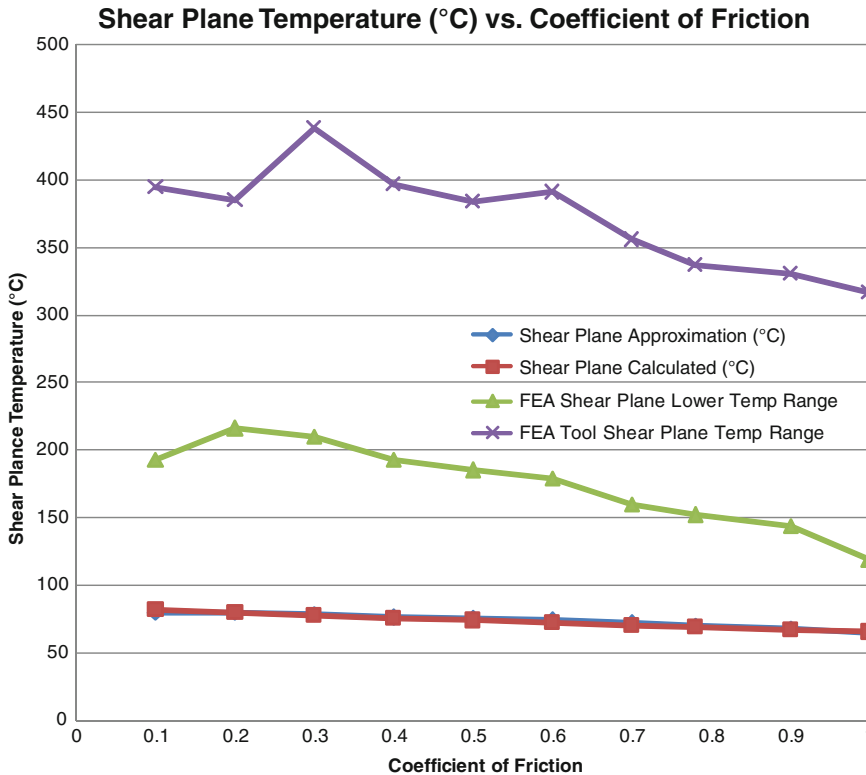


Fig. 2.9 Comparison of approximate and calculated shear plane temperatures with finite element generated temperatures at the end of the machining pass (800 mm machined). Re-produced from 'Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

applicable at the first stages of intimate contact between chip and tool. Clearly, it is noted that a secondary shear zone between chip and tool is not created at first contact. This implies that the secondary shear zone is somewhat responsible for frictional heating. This effect should be studied further using transparent sapphire tools in terms of understanding this effect on the generation of heat. The computational analysis leads us believe that intermittent contact caused by interrupted cuts and/or oscillating the cutting tool during machining is not only beneficial, but is well described by Loewen and Shaw's method.

2.4 Discussion

When one inspects the results of finite element modeling (Figs. 2.3–2.8), it is observed that the change in the coefficient of friction tends to lower the shear plane temperature and increase the tool face temperature as it increases in value. In order to make the removal of the chip easier, it is advisable to focus the generation of

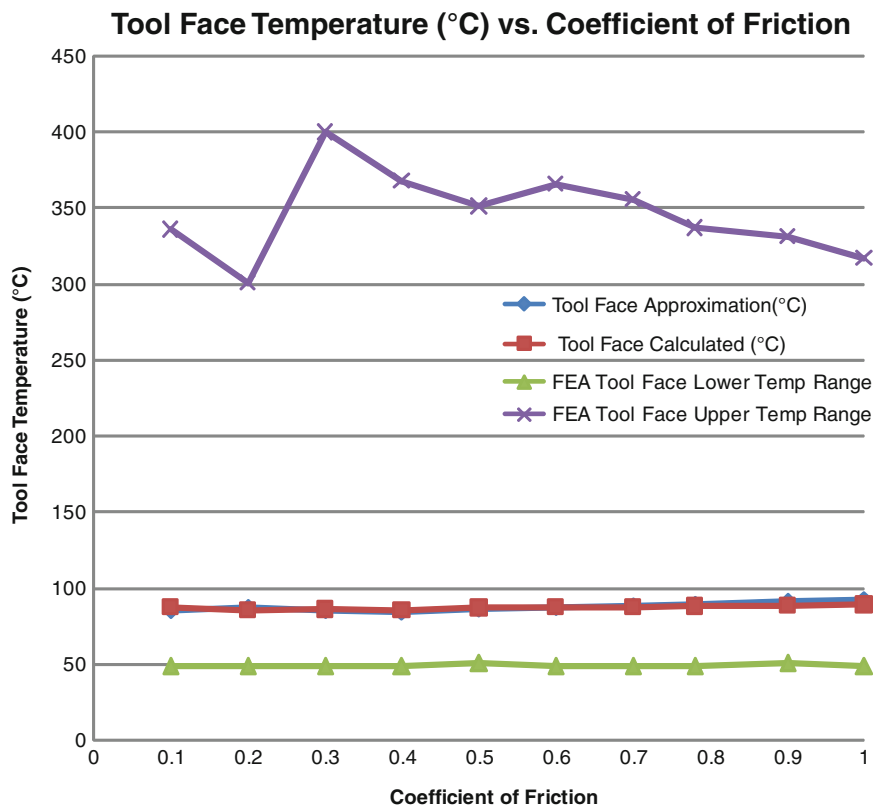


Fig. 2.10 Comparison of approximate and calculated tool face temperatures with finite element generated temperatures at the end of the machining pass (800 mm machined). Re-produced from ‘Machining with Nanomaterials, Edited by M. J. Jackson and J. S. Morrell, with kind permission from Springer Science+Business Media B.V. (Permission Received February 22, 2012)

heat towards the shear plane rather than toward the cutting tool. Therefore, during dry machining operations it is necessary to lower the coefficient of friction between chip and tool by providing a thin film coating to the tool in order to lower the coefficient of friction. It is also observed that the tool face temperature and the shear plane temperature increases rapidly as a large chip is cut. The initial stages of chip formation are usually confined to the point at which the chip does not stick to the tool, i.e. perfect sliding takes place between chip and tool. This appears to generate lower temperatures on the tool face. However, once the chip sticks to the tool a secondary shear zone is established and quickly heats up the tool face. It appears that the discrepancy between Loewen and Shaw’s calculations and the finite element calculations occurs when adhesion of the chip to the tool takes place, i.e., after the first ten millimeters, or so, of chip formation depending on the coefficient of friction. The calculated peak tool temperature of the initial stage of chip formation is remarkably accurate to the finite element calculations, but not so

when the secondary shear zone is established, i.e., when the chip sticks to the tool face.

Figures 2.9 and 2.10 show the difference in values very well at the end of the machining stroke when 300 mm of chip has been cut. When one inspects Figs. 2.3, 2.5, and 2.7, it is clear that Loewen and Shaw's method provides very good accuracy at the primary stages of chip formation. This statement implies that Astakhov's statements concerned with using the early forms of machining mechanics are both valid and invalid depending on how one describes the machining conditions, i.e., primary stages of chip formation where the secondary shear is non-existent, or steady-state machining conditions when the secondary shear zone is fully established.

2.5 Conclusions

The calculations of the change in coefficient of friction have shown that increasing the coefficient of friction will lower the shear plane temperature. Conversely, the tool face temperature will increase with the increase in coefficient of friction.

Loewen and Shaw's method of calculating shear plane and tool face temperature appears to be applicable at the first stages of intimate contact between chip and tool when the secondary shear zone is non-existent.

Loewen and Shaw's method of calculating shear plane and tool face temperature does not appear to be applicable under steady-state conditions when the secondary shear zone is firmly established.

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