PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Force calculation using analytical and CAE methods for thin-blade slotting process

Yazdan Kordestany1 and Yongsheng Ma1*

Abstract: A multi-spindle slotting process is taken as the case to analyse the mechanism involved in the cutting process affecting the machining efficiency. The analysis techniques used in this research include force analysis through existing analytical and numerical models and implementing the results to conduct an in-depth analysis of the cutting dynamics. The input parameters considered are blade geometry, cutting speed, and feed rate to investigate their effects on tool life. The study of dynamics of the cutting process was also extended to determine the effect of chatter vibration by determining the stability lobe diagram of the process. Results coupled from these two primary parts of the investigation were used to identify optimal processing conditions. The approaches employed to specify conditions for the stability lobe diagram showed that the method can be applied to analyse different combinations of tool and workpiece materials. Finite element methods along with the obtained force are then applied to simulate the static force distribution for a circular saw blade. The determined blade deformation and a CAD/CAE software are used for the optimization process. Finally, it is possible to compare the resulting deformations for both optimized and original blade geometries.

ABOUT THE AUTHORS

Yazdan Kordestany completed his MSc study under supervision of Prof Ma from University of Alberta in 2017. His research project was characterization and optimization of multi-spindle slotted liner manufacturing process dealing with prevailing setbacks including short tool life due to vibration. He had sound experience conducting comprehensive solid modelling and engineering analysis across a variety of CAD and CAM applications towards optimizing manufacturing processes.

Yongsheng Ma is a full professor with the Faculty of Engineering, University of Alberta. He joined University of Alberta since 2007. Dr Ma is a member of ASEE, SME, and an Alberta registered Professional Engineer. His main research areas include feature-based design and manufacturing modeling, CAD/CAM, and product lifecycle management. Dr Ma received his BEng from Tsinghua University, Beijing (1986), both MSc (1990) and PhD (1994) from UMIST, UK. Dr Ma had been an associate editor of IEEE Transaction of Automation Science and Engineering (2009–2013). Since 2012, he has served as an editor of Advanced Engineering Informatics (Elsevier).

PUBLIC INTEREST STATEMENT

A great number of formed products that are dealt with in engineering undergo machining processes (turning, milling, drilling, sawing) to remove unwanted material from blank using a tool that has a harder material than final products. All manufacturers concern about reducing their cost by justifying economical machining processes. Tool life plays an important role in manufacturing’s cost which is determined by factors such as rotational speed of tools, linear movement of the tool/workpiece, tools’ geometry. Slotted liners are pipes with small openings on their surface used in unconventional oil extraction as a sand control device. This article studies on a thin blade slotting process customized on a multi-spindle machine used to manufacture slotted liners. The main purpose was to identify machine parameters and tool geometry by developing mathematical and numerical model to reduce the machining vibration, tool breakage, and the number of times needed for tool sharpening.
1. Introduction

Close to a third of the crude oil Canada produced from oil sands used Steam assisted gravity drainage (SAGD) (Holly, Mader, Soni, & Toor, 2016) to extract oil from oil sand reserves. Sand control methods such as slotted liner are, therefore, necessary to avoid passing of solids through the open area to flow allowed for oil production. Slotted liners for sand control in SAGD typically include a pipe casing on which rectangular apertures (slots) are made by methods such as cutting with circular saw blades. These slots will provide the required open area to steam injection and oil production while preventing sand particles to enter the pipe. Slotted liners have been extensively used as sand control device in SAGD applications due to their mechanical integrity for long horizontal well completions (Matanovic, Cikes, & Moslavac, 2012).

Circular saw blades can be used as a tool to manufacture slotted liners in slotting machines similar to numeric control (NC) milling machines. There are several industries that apply multi spindle NC machines to produce slotted liners. Since each pipe joint has hundreds of slots, this approach has the advantage of reducing production time and cost by having multi spindles that it allows simultaneous cutting of slots.

The sloting machine considered in this study has been designed and built in-house. Since it was custom made, this research aims at obtaining a comprehensive description of the manufacturing process with respect to interacting performance parameters. The following are the major objectives set for this study as conduct force analysis on the blades to determine the distribution of forces and perform dynamic stability analysis to obtain a stability lobe diagram to determine combinations of feed rate and spindle speed values that are in stable zones. Finally, the geometry of thin blade can be optimized with regard to static force analysis to reduce the tool deflection.

In the slotting process, the mechanics on each tooth on the circular saw blade follows orthogonal cutting theory since the cutting edge of each tooth is parallel to the surface of the workpiece and perpendicular to the cutting orientation (Balihodzic, 2002). The material removal process is also considered to be distributed along the cutting edge. It is thus a two dimensional plane strain problem (Kiliçaslan, 2009).

2. Theory

Direct experimental techniques used to study cutting processes are usually costly and time consuming. Therefore, analytical and numerical approaches may appeal the researcher. It should, however, be noted that the mechanics of machining cannot be fully explained by using only analytical approaches. This is the main reason behind the application of numerical methods such as finite element analysis in conjunction with analytical models.

In the shear plane model from the theory of Ernst and Merchant (1941), shear forms the chip along a single plane inclined at an angle $\phi$. The shear stress along the shear plane is equal to the material flow stress in shear. The chip is assumed a separate body in static equilibrium as shown in Merchant’s circle force diagram given in Figure 1. Merchant derived equations for cutting and thrust forces showing their dependence on the shear angle (angle between shear plane and cutting surface). All forces act at the tool tip. The forces applied to the chip come from two parts: the tooth, and the uncut workpiece. The balance of these forces results in the force equilibrium.

Ernst and Merchant’s theory is based on minimum cutting energy principle to reduce the cutting work to a minimum. Since the main factor is cutting force, two steps should be involved in the
analysis. Establishing the relationship between cutting force and shear angle should be done first followed by identifying the shear angle to keep the cutting force at the minimum. From Figure 1 it can be seen that:

\[
F_s = F_c \cos(\phi + \beta - \alpha) 
\]  

(1)

\[
F_s = \tau_s A_s = \tau_s \frac{w h}{\sin \phi} 
\]  

(2)

where, \(\tau_s\) is the shear stress, \(A_s\) is the shear plane area, \(w\) is the width of cut, and \(h\) is the uncut chip thickness.

From Equations (1) and (2):

\[
F_c = \tau_s \frac{w h}{\sin \phi} \times \frac{1}{\cos(\phi + \beta - \alpha)} 
\]  

(3)

The tangential and feed forces can then be written as:

\[
F_t = F_c \cos(\beta - \alpha) = \tau_s \frac{w h}{\sin \phi} \times \frac{\cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} 
\]  

(4)

\[
F_f = F_c \sin(\beta - \alpha) = \tau_s \frac{w h}{\sin \phi} \times \frac{\sin(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} 
\]  

(5)

The first step in this study is calculation of applied force in the slotting process. Having determined the maximum number of teeth that are in touch with the workpiece during cutting and the corresponding depth of cut, the applied force can be obtained from finite element simulations. The mechanics of machining cannot be fully explained by using only analytical approaches. Therefore, numerical approaches in metal cutting processes have been interesting to researchers using various available explicit and implicit software packages such as ABAQUS, ANSYS, AdvantEdge and etc. For instance, Reiter and Keltie (1976) adapted a rigid-plastic finite element model with an Eulerian formulation to simulate steady-state orthogonal metal cutting. Komvopoulos and Erpenbeck (1991) applied constitutive material behavior models and interfacial friction mechanisms representing real application scenarios for metal cutting simulation of AISI 4340 steel with ceramic-coated tools to investigate the effect of cutting parameters. The effect of tool edge geometry was also studied by Wan, Wang, and Gao (2015) in orthogonal metal cutting by adoption of arbitrary Lagrangian-Eulerian (ALE) approach for simulation in ABAQUS/Explicit and considering P20 as the workpiece material.

The physical separation criteria are based on value of physical properties, such as stress, strain, or strain energy in the elements or nodes immediately ahead of the tool tip. The critical values of the
nodes’ physical quantities are used to estimate the separation and the nodes separate, when the magnitude of the controlled variable in an element is larger than the critical value. Johnson-Cook plasticity and damage model with element deletion technique is gaining popularity to be often applied as separation criteria to finite element simulation of cutting (e.g. Agmell, Ahadi, & Ståhl, 2013; Escamilla, Zapata, Gonzalez, Gamez, & Guerrero, 2010; Liu, Wang, Li, & Deng, 2013; Sawarkar & Boob, 2014; Wang & Liu, 2014; Zhang, Outeiro, & Mabrouki, 2015). It considers the separated effects of strain hardening, strain-rate (viscosity) and thermal softening. It is a relatively simple model and defines the general response of material deformation (Zhang et al., 2015).

3. Methodology
In view of the reviewed relative theories, the methodology of this study can be summarized in Figure 2. After defining the problem as orthogonal cutting process, the cutting parameters along with geometries and material properties of both workpiece and pipe are used as input variables. All input parameters are applied in both numerical and analytical studies. The results from both methods are used for dynamic stability analysis and shape optimization. Finally, the overall results are the optimal values of blade geometries for an improved operation.

The coordinate system should be defined first so that the key time points can be described and each tooth can be positioned at a given time point. Some parameters such as angle per tooth are measured with reference to the centre of the circular saw blade, while others such as the feed rate are measured based on the space transformation of the circular saw blade. Therefore, a single type of coordinate system cannot express all these parameters simultaneously. Two types of coordinate system, namely global coordinate system and local coordinate system are employed in this study.

As shown in Figure 3, the downward direction is set as the positive \( x \)-axis and the rightward direction as the positive \( y \)-axis for the global coordinate system. An important feature to note here is that this coordinate system moves with time, i.e. the absolute physical position of the circular saw blade keeps changing during the slotting process.

Figure 3 shows the starting moment \( t = 0 \) of the slotting process.
When analysing the forces applied to the single tooth, the local coordinate system defined in Figure 3 is used. The $x$-axis is along the cutting direction (tangential direction of the outer circle) and the $y$-axis is the radial direction pointing to the centre of the circular saw blade. Likewise, this coordinate system is also dynamic, i.e. the origin of this local coordinate system keeps changing with time.

Figure 4(a) shows the starting position of the blade with a federate of $v_{f1}$. The first touching time of outer circle can be calculated as:

$$t_0 = \frac{2(H - R)}{v_{f1} + v_{f2}}$$  \hspace{1cm} (6)

Generally, the first touching time of teeth is different from that of the outer circle, i.e. $t_1 \neq t_0$ because there is not always one tooth that touches the workpiece when the outer circle just reaches the workpiece. Only when $t_0 = \frac{2(H - R)}{v_{f1} + v_{f2}} = mT_{tooth}$ (where $m$ is an integer and $T_{tooth}$ is the time in seconds taken by one tooth to travel to the position of its adjacent front tooth), that $t_1 = t_0$ holds. Otherwise, $t_1 > t_0$ i.e., at this condition, the tooth touches the workpiece for the first time at the left hand side (LHS) of the positive $x$-axis. Figure 4(b) shows the locations of the circular saw blade at time $t_0$ and $t_1$, respectively, with Points $O$ and $O'$ as the corresponding centers of the circle. It is obvious that the time period ($t_1 - t_0$) is less than $T_{tooth}$. At time $t_0$, this immediate tooth on the LHS is at $P_1$ and the outer circle of the circular saw blade just touches the workpiece at $P_3$. At time $t_1$, the circular saw blade moves and the immediate LHS tooth travels from $P_1$ to $P_2$. At this time point, this immediate LHS tooth just touches the workpiece at $P_2$. During this time period ($t_1 - t_0$), the center of the circle travels a distance of $v_{f2} (t_1 - t_0)$. Drawing a perpendicular line from $P_2$ to the $x$-axis shows the perpendicular foot to be at $P_3$. The angles $\theta_1$ and $\theta_1'$ define the radial angles of this immediate LHS tooth at time $t_0$ and $t_1$, respectively.

When the circular saw blade cuts through the workpiece, the center of the circular saw blade travels a distance equal to $Th$ (pipe thickness) such that:

$$t_2 = t_1 + \frac{2Th}{v_{f2} + v_{f3}}$$  \hspace{1cm} (7)

when the circular saw blade completes cutting the workpiece, the targeted slot length is met. Therefore,
where $P$ is the plunge distance which is the distance between the deepest point of blade and inner diameter of pipe when the blade reaches its deepest position. 

$$P = R - \sqrt{R^2 - \left(\frac{L}{2}\right)^2}$$

where $L$ is the slot length on the outer surface of the pipe.

The number of teeth involved in the slotting process at a transient time point is defined as the effective teeth which is a function of time shown in Figure 5.

The location of each tooth at a given time point can be denoted by $\theta_{\text{phase}}$ which is the global radial angle of each tooth in reference to the positive x-axis. Its value can be calculated as:

$$\theta_m(n, t) = \frac{2\pi n}{N} + \omega t$$

where $n$ is index of teeth, 
where $t$ is index of time,  

Two components of the resultant force, tangential ($F_t$) in $x'$ direction and feed ($F_f$) forces in $y'$ direction, can be expressed (Altintas, 2012), respectively as:

$$F_t = F_c \cos(\beta - \alpha)$$

$$F_f = F_c \sin(\beta - \alpha)$$

The tangential and feed forces can also be given as:

$$F_t = K_t \frac{2\pi v r(t) \sin(\theta_{\text{phase}}(n, t))}{\omega N}$$

$$F_f = K_f \frac{2\pi v r(t) \sin(\theta_{\text{phase}}(n, t))}{\omega N}$$

where, $K_t$ and $K_f$ are tangential and feed cutting force coefficients, respectively and are equal to (Altintas, 2012):

$$K_t = \frac{\tau_s W \cos(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)}$$

$$K_f = \frac{\tau_s W \sin(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)}$$
Since the slotting machine has eighty spindles, the overall force applied to the machine during the cutting of one slot can be calculated as the sum of the resultant forces applied to all blades. However, there is a phase difference between spindles in reality. Therefore, the summation of forces has to take the phase difference in rotation of all the blades into account of.

To obtain a mathematical solution for the forces as per the above series of discussion, input data that correspond to the specific properties and geometries of the workpiece and tool were used along with the machine parameters in the MATLAB algorithm as shown in the Figure 6. Friction angle, shear angle, and shear stress values are typically obtained from empirical investigations. The literature and small-scale numerical simulations were thus used to determine the values of these three parameters.

**Figure 6. Force calculation algorithm.**
Lagrangian approach was used in ABAQUS/Explicit in 3D model to idealize the chip formation as the mesh nodes are moving with the material movement. The Lagrangian model included the element deletion as the failure criteria to remove chip from the workpiece. The element type used in ABAQUS was eight-node linear brick with reduced integration and hourglass control.

Simulation of cutting processes is complex due to large plastic deformation and material removal at large strain rates and high temperatures (Kershah, 2013). Johnson-Cook material model is one of the commonly used orthogonal cutting models, since it depends on strain rate and temperature. The Johnson-Cook martial model which is used in this study can be represented as:

\[
\sigma = \left( A + B \varepsilon^n \right) \left( 1 + C \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right) \right) \left( 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right)
\]

(17)

where, \( \sigma \) is the equivalent stress, \( A \) is the initial plastic flow stress at zero plastic strain, \( B \) is the strain hardening coefficient, \( n \) is the strain-hardening index, \( C \) is the strain rate index, \( \dot{\varepsilon} \) is the plastic strain rate, \( \varepsilon_0 \) is the reference plastic strain rate, \( T \) is the current temperature, \( T_r \) is the reference temperature, \( T_m \) is the melting temperature, and \( m \) is the thermal softening index. These values are usually obtained from Split Hopkinson Pressure Bar (SHPB) impact testing data (Shih, 1995).

Johnson-Cook damage law was used for chip separation in this study as given by (Agmell et al., 2013):

\[
D = \sum \left( \frac{\Delta \varepsilon}{\varepsilon_f} \right)
\]

(18)

where, \( D \) is the damage parameter, \( \Delta \varepsilon \) is the increment of the equivalent elastic strain which is updated at every load step, and is the equivalent strain at failure and can be expressed as (Agmell et al., 2013):

\[
\varepsilon_f = \left[ D_1 + D_2 \exp D_3 \left( \frac{P}{\sigma} \right) \right] \left[ 1 + D_4 \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right) \right] \left[ 1 + D_5 \left( \frac{T - T_r}{T_m - T_r} \right) \right]
\]

(19)

where, \( P \) is the ratio of hydrostatic pressure to equivalent stress. When \( D \) (damage parameter) of an element reaches 0.1, the failure occurs and the FEM algorithm deletes the element. The L-80 alloy steel pipe is selected for this study as a workpiece which has a similar chemical composition and properties to AISI 4140. The Johnson-Cook plasticity model parameters, damage parameters, and general thermal and mechanical properties of the workpieces obtained from literature having the Young’s modulus and Poisson’s ratio as 219 × 10^9 N/m^2 and 0.29, respectively (Agmell et al., 2013; Johnson & Cook, 1985). Since the elastic modulus of cutting tools are usually higher than those of the workpieces, rigid elastic cutting tool was assumed with the density of 8,160 kgm^{-3}, Young’s modulus 214 × 10^9 N/m^2, and 0.3 Poisson ratio to reduce the computational cost.

Sticking and sliding are two zones that contact interactions between tool and workpiece occur in. Both normal and shear forces are transmitted for the cases where friction contact interaction between bodies exist (Balihodzic, 2002). When there is no contact between the chip and tool, the normal and shear stresses are tend to zero. A constant friction coefficient, \( \mu \), is assumed in the sliding region. In the analytical model, the coefficient of friction was also considered constant based on the assumption that the chip slides with a constant friction coefficient on the tool. This friction coefficient is assumed as 0.15 and related to the friction angle such that (Altintas, 2012):

\[
\mu = \tan \beta = \frac{F_u}{F_v}
\]

(20)
Stresses are maximum at the tool edge which is due to sticking friction. Sticking region was modeled by using Coulomb friction law which is defined by:

\[
\begin{cases}
\tau_f = \mu \sigma_n & \text{when } \mu \sigma_n < \tau_{\text{max}} \\
\tau_f = \tau_{\text{max}} & \text{when } \mu \sigma_n > \tau_{\text{max}}
\end{cases}
\]

where, \(\tau_f\) is the frictional stress, \(\sigma_n\) is the normal stress along the tool-chip interface, \(\tau_{\text{max}}\) is the maximum value of the frictional stress which is assumed to be equal to yield shear stress of the material (\(\tau\)). The friction coefficient used in ABAQUS simulations was 0.15.

### 3.1. Dynamic analysis of slotting process

Regenerative chatter is one of the most common but undesirable phenomena in cutting processes. In real applications where the assumption of having a rigid tool does not hold, the cutting forces from chip cause tool deflection resulting in vibration. The vibration results in wavy surfaces on the workpiece. The material left by a tooth on the surface of the workpiece, has to be removed by the one immediately following it. Therefore, the instantaneous chip thickness varies due to vibration and the time between one tooth to the next (Schmitz & Smith, 2009). The differences in instantaneous chip thickness cause chatter vibration, poor quality of surface, tool wear and instable cutting.

Cutting force direction in milling process is time dependent which makes the analytical solution difficult. Smith and Tlusty (1991) overcomes this difficulty by assuming average force direction during milling process. Therefore, this assumption causes the system to be time invariant. Tlusty then projected the assumed average force to the x and y directions using directional orientation factors. Then the projected results can project onto the surface normal. By obtaining the stability lobe diagram, it is possible to predict the proper values of spindle speed (RPM) and axial depth of cut to machine efficiently while producing higher quality of products.

The force studied in this section for stability lobe is the maximum force applied to the circular saw blade. In this case the stability is investigated at the most vulnerable time of the slotting operation and make the system time invariant and simple. The number of teeth that are in touch with the workpiece is also the highest in this case. Instead of the average cutting force coefficient given in (Schmitz & Smith, 2009), the cutting force coefficients when highest force due to the maximum number of teeth in the process is used.

Defining the oriented Frequency Response Function (FRF) is the first step. Orientation factor can be obtained by knowing the angle between force and corresponding \(x\) or \(y\) directions, and then after projecting in the desire direction, it should be projected onto the surface normal. Thereafter, the following equation can be solved (Smith & Tlusty, 1991):

\[
\varepsilon = 2\pi - 2\tan^{-1}\left(\frac{\text{RE}[\text{FRF}_{\text{orient}}]}{\text{IM}[\text{FRF}_{\text{orient}}]}\right)
\]

The above equation determines the difference between tooth vibrations over the frequency range. Finding depth of cut limit \(b_{\text{lim}}\) for the frequency range from:

\[
b_{\text{lim}} = \frac{-1}{2K_s\text{RE}[\text{FRF}_{\text{orient}}]N_e}
\]

where, \(K_s\) is the applied force coefficient. In the above equation, \(\text{FRF}_{\text{orient}} = \mu_r\text{FRF}_x + \mu_y\text{FRF}_y\) where, \(\mu_r\) and \(\mu_y\) are directional orientation factors. If the direction of the surface normal \(n\) be towards the center of the circular blade, \(F_n = F_y\cos(0) = F_\cos(\beta - \alpha)\cos(0) = F_\cos(\beta - \alpha)\), so the directional orientation factor \(\mu_y\) becomes \(\mu_y = \cos(\beta - \alpha)\). To find the other directional orientation factor, \(F_x\) needs to be projected onto the surface normal, so \(F_n = F_x\cos(90) = F_\sin(\beta - \alpha)\cos(90) = 0\), and \(\mu_x\) becomes zero. Solving the spindle speeds in a frequency range:
where, $f_c$ expressed in Hz, $\Omega$ expressed in revolution/second, and $K$ is the integer value ($K = 0, 1, 2, ...$).

In (23), $\Omega N$ represents tooth passing frequency, and $\frac{f_c}{\Omega N}$ represents the ratio of the chatter frequency to the forcing frequency. $b_{lim}$ vs $\Omega$ should be plotted for several $K$.

4. Results and discussion

To validate the first part of the mathematical model (machine motion configuration) to measure depth of cut, key times obtained from MATLAB are compared with measurements from experiments run by operating the machine with different spindle speed and feed rate as shown in Figure 7.

The parameters selected for this study are given in Table 1. By solving the mathematical model for determining uncut chip thickness for each tooth at time steps, 1,216 unique data points are obtained. It should be noted that the simulation increment is 0.1 s for a blade with 56 teeth. Twenty data points have been selected for simulation and the remaining data points were estimated using linear interpolation to predict results.

Obtaining the uncut chip thickness for each teeth at each time step from MATLAB and the available input data for machine parameters, tooth geometry, and Johnson-Cook model; the finite element simulations are conducted in ABAQUS to find out the values for shear angle and shear stress. The resultant shear angle and shear stress are then used in MATLAB code along with other input parameters to plot the cutting forces and stability lobe diagram.

Modeling the cutting forces is also considered for a blade which has completed cutting several slots. In this case, the blade teeth are not sharp, but have not yet been replaced or re-sharpened. Therefore, the cutting process outputs are compared for two different cases. The first case is for a sharpened blade considered in its first initial cut. Another case is when the blade teeth are not the same shape as their original ones, but still are mounted on the slotting machine to finish cutting slots. The round edge tool for the sharp and dull blade cases are selected as 0 and 0.5 mm, respectively.

In general, as the uncut chip thickness increases, the difference between uncut and deformed chip thickness reduces resulting in an increase in chip compression ratio. Shear angle is also related to chip compression ratio. Therefore, it can be said that by increasing uncut chip thickness, the shear angle is increased.

![Figure 7. Comparison of calculated and measured time.](image-url)
The difference in shear angle for both cases is between 5.4 and 6.7 degrees. Therefore, an angle of 6° is subtracted for all shear angle data points in the sharp case to save the cost of simulations. The shear stress for dull is \(733 \times 10^9\) N/m\(^2\) which was greater than the previous case \(633 \times 10^9\) N/m\(^2\).

The resultant cutting forces in \(x\) and \(y\) directions are shown in Figure 8(a) and (b), respectively. The forces are greater in both directions when the maximum number of teeth is in the workpiece just before time \(t_2\) and before cutting through the workpiece. As the blade passes the time \(t_2\) and is fed downward, the force reduces while the number of teeth that are in touch with the workpiece decreases. It is also shown that a dull blade requires greater force in both directions to cut a slot which shorten the tool life, increase the machining cost, and need to be replaced or re-sharpened.

Although shear power \(P_s = F_s V_s\) at the shear plane for the dull blade is greater than that for a sharp blade, the friction power for both cases is similar referring to Equation (20). This is because the friction coefficient for both cases is the same (0.15), but it is expected that cutting process using a dull tooth will have a greater friction coefficient.

Figure 8(c) shows the stability lobe diagram based on the force calculated for the sharp blade. The blade stiffness is \(2.4e7\) N/m and dimensionless damping ratio is selected as 0.04. The maximum

| Table 1. Input parameters for the whole cutting process |
|---------------------------------|---------|------------------|--------------------|
| Blade diameter (mm) | 77.98  | Pipe thickness (mm) | 9.19  |
| Blade rake and relief angle (degree) | 2, 30 | Pipe diameter (mm) | 177.8 |
| Blade teeth number | 56 | O.D. Slot length (in) | 46.78 |
| Teeth edge radius | 0.01 | Friction coefficient | 0.5 |
| Blade thickness (in) | 0.584 | O.D. Feed rate (mm/min) | 50.8 |
| | | Feed rate (mm/min) | 101.6 |

Although shear power \(P_s = F_s V_s\) at the shear plane for the dull blade is greater than that for a sharp blade, the friction power for both cases is similar referring to Equation (20). This is because the friction coefficient for both cases is the same (0.15), but it is expected that cutting process using a dull tooth will have a greater friction coefficient.

Figure 8(c) shows the stability lobe diagram based on the force calculated for the sharp blade. The blade stiffness is \(2.4e7\) N/m and dimensionless damping ratio is selected as 0.04. The maximum
cutting force coefficient for the time that 12 teeth are engaged is 3.1e10 N/m2. It is possible to determine the stable and unstable regions. These regions are the combination of spindle speed, rpm, and depth of cut. Therefore, it is possible to choose the spindle speed and depth of cut in a stable region to avoid tool chatter. It should be noted that by knowing the maximum value of depth of cut, the value of feed rate can be predicted.

Based on the selection of the rpm value, feed rate, and maximum depth of cut that are selected for the sharp blade in this section, it can be find that the process is stable (255 rpm and maximum 0.01 mm depth of cut) and there is no chatter in a case of having sharp blade.

Figure 8(d) shows the frequency is calculated for the sharp blade using Fast Fourier Transform (FFT). The peaks that are shown in Figure 8(d), are tooth passing frequency due to the spindle speed of 255 rpm. Since the process is stable, no chatter can be seen in the picture.

4.1. Blade geometry optimization

The circular blade is selected to conduct static analysis having the blade fixed at its inner surface due to the machine configuration and applying the resulting force obtained from numerical simulations using CATIA FEA. The aim of this section is to investigate the possibility of changing the blade geometry to reduce the blade teeth displacement due to the applied force. Parametric design is used in CATIA sketch and 3D part for the tool modeling. To design all teeth for the blade, pattern feature uses one tooth to create all teeth along the outer diameter of the blade. Therefore, the teeth number automatically are updated when other dimensions are changed. A local sensor should be placed at the highest applied force to measure the tooth deformation.

There are several constraints that should be included in the problem. The blade has to have enough material to keep its stiffness; it can reach the plunge and cut the workpiece. The upper limit for the outer diameter must be specified such that blades are separated by enough distance. The bore diameter has to be unchanged to mount on the machine arbor. The gullet area has to have enough space to maintain the chips during cutting. The optimization process can thus be represented by Equation (22).

\[
\text{objective: min blade } (\text{deformation})
\]

\[
cstr:\begin{align*}
\text{outer diameter } - \text{bore diameter} & > 1.5\text{in} \\
2\text{in} & < \text{outer diameter} < 4\text{in} \\
\text{bore diameter} & = 1\text{in} \\
2\text{deg} & < \text{rake angle} < 40\text{deg} \\
3\text{deg} & < \text{relief angle} < 30\text{deg} \\
0.06\text{in} & < \text{tooth height} < 0.15\text{in} \\
0.14\text{in} & < \text{tooth pitch} < 0.2\text{in} \\
0.01\text{in} & < \text{gullet radius} < 0.05\text{in}
\end{align*}
\]

Updated design geometries after optimization process for the blade shows decrease in the outer diameter (72.39 mm), number of teeth (50), relief angle (25°), and teeth height (1.62 mm). However, it is observed that increase in rake angle (5°) reduces the blade deformation which improves the tool life. Decrease in the relief angle as rake angle rises is important to maintain blade stability during cutting. The gullet radius (0.66 mm) and teeth pitch (4.54 mm) need to be increased for a better tool life.

Since the blade geometry has changed, the applied force at the time that maximum number of teeth are in contact with the workpiece is to be find. Therefore, the optimized blade geometry should be input in the MATLAB code and FEA simulation to obtain the cutting force that can be used in the
static analysis to measure the blade displacement. Figure 9 shows the highest blade’s teeth deformation of 0.019 mm and 0.017 mm for before and after modification, respectively.

5. Conclusion
In the methodology employed for this research, analysis of forces involved in the cutting process was the major component. An algorithm designed to solve an analytical model specifically developed for a multi-spindle slotting machine that uses thin circular saw blades was used for the force analysis. The model development has accounted for the different time steps caused by the difference in feed rates at progressive stages in the process of the slotting through the pipe. Results from these analyses were later applied to study the chatter frequency during the machining process, and conduct optimization on the geometry of the blade.

Cases where slotting machine included sharp and/or dull blades were investigated by combining analytical models and simulations for the respective scenarios. As expected, dull blades caused significantly higher force requirements and blade displacement. As this condition leads to significant increase in the cost incurred by the operation, monitoring of the blades to keep sharp blades on the machine at all times needs to be implemented. The accuracy of the system that is to be used to monitor shall be given enough emphasis to make sure that dull blades do not reduce the efficiency of the process and/or quality of the product.

The shear angle values that resulted from FE simulations came in good agreement with results from analytical calculation. Therefore, the satisfactory application of the developed analytical model to predict the slotting process’ parameters was strongly indicated. Furthermore, this research demonstrated that the methodologies presented can be applied for any future case to form a basis in the tool selection for a given pipe material.

Optimization was conducted to identify the new blade geometry for improved performance. By making use of the results from the force analysis the optimal blade geometry and dimensions were determined. It was concluded that, if changing the blade geometry for better tool life is considered, the specifications given in Table 1 shall be followed.

Acknowledgement
Special thanks is hereby extended to Mr Michael Leitch (PEng) for his invaluable contributions during the entire course of the research.

Funding
This work was supported by the RGL Reservoir Management Inc; Natural Sciences and Engineering Research Council of Canada [grant number RGPIN 5641].

Author details
Yazdan Kordestany1
E-mail: yazdan@ualberta.ca
ORCID ID: http://orcid.org/0000-0002-6155-0167
1 Mechanical Engineering Department, University of Alberta, P10-225 Donadeo ICE Building, Edmonton, Alberta, T6G 1H9, Canada.

Yongsheng Ma1
E-mail: yongsheng.ma@ualberta.ca
ORCID ID: http://orcid.org/0000-0002-6155-0167
1 Mechanical Engineering Department, University of Alberta, P10-225 Donadeo ICE Building, Edmonton, Alberta, T6G 1H9, Canada.
References

Agnell, M., Ahadi, A., & Stöhl, J. E. (2013). The link between plasticity parameters and process parameters in orthogonal cutting. Procedia CIRP, 8, 224–229. doi:10.1016/j.procir.2013.06.093

Altintas, Y. (2012). Manufacturing automation: Metal cutting mechanics, machine tool vibrations, and CNC design (2nd ed.). Cambridge: Cambridge University Press.

Balihodzic, N. (2002). A numerical investigation of orthogonal machining. Fredericton: University of New Brunswick.

Ernst, H., & Merchant, M. E. (1941). Chip formation, friction and high quality machined surfaces, in surface treatment of metals. American Society of Metals, 29, 299.

Escamilla, I., Zapata, O., Gonzalez, B., Gámez, N., & Guerrero, M. (2010). 3D finite element simulation of the milling process of a Ti-6Al-4V alloy. 2010 SIMULA customer conference (pp. 1–10).

Holly, C., Mader, M., Soni, S., & Toor, S. (2016). Alberta energy. oil sands production profile. 2004–2014. Retrieved from http://www.energy.alberta.ca/oilsands/791.asp

Johnson, G. R., & Cook, W. H. (1985). Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures. Engineering Fracture Mechanics, 21(1), 31–48. https://doi.org/10.1016/0013-7944(85)90052-9

Kershaw, T. K. (2013). Prediction of cutting coefficients during orthogonal metal cutting process using FEA approach. Hamilton: McMaster University.

Kılıçaslan, C. (2009). Modelling and simulation of metal cutting by finite element method. Url: İzmir Institute of Technology.

Konwavoulos, K., & Erpenbeck, S. A. (1991). Finite element modeling of orthogonal metal cutting. Journal of Engineering for Industry, 113(3), 253–267. https://doi.org/10.1115/1.2899695

Liu, X. B., Wang, X. B., Li, C. N., & Deng, S. P. (2013). Finite element simulation of the orthogonal cutting based on abaqus. Advanced Materials Research, 821–822, 1410–1413. Retrieved from http://www.scientific.net/AMR.821-822.1410

Matanovic, D., Cikes, M., & Moslovac, B. (2012). Sand control in well construction and operation. Springer. https://doi.org/10.1007/978-3-642-25614-1

Reiter, W. F., & Kellie, R. F. (1976). On the nature of idling noise of circular saw blades. Journal of Sound and Vibration, 44(4), 531–543. https://doi.org/10.1016/0022-4604(76)90095-X

Sawarkar, N., & Boob, G. (2014). Finite element based simulation of orthogonal cutting process to determine residual stress induced. International Journal of Computer Applications, 33–38.

Schmitz, T. L., & Smith, K. S. (2009). Machining dynamics: Frequency response to improved productivity. New York, NY: Springer. https://doi.org/10.1007/978-0-387-09645-2

Shih, A. J. (1995). Finite element simulation of orthogonal metal cutting. Transactions-American Society of Mechanical Engineers. Journal of Engineering for Industry, 117, 84–84.

Smith, S., & Tlusty, J. (1991). An overview of modeling and simulation of the milling process. Journal of Engineering for Industry, 113(2), 169–175. https://doi.org/10.1115/1.2899674

Wan, L., Wang, D., & Gao, Y. (2015). Investigations on the effects of different tool edge geometries in the finite element simulation of machining. Strojniški vestnik – Journal of Mechanical Engineering, 61(3), 157–166. Retrieved from http://en.sv-jme.eu/data/upload/2015/03/02_2014_2051_Wan_04.pdf https://doi.org/10.5545/sv-jme

Wang, B., & Liu, Z. (2014). Investigations on the chip formation mechanism and shear localization sensitivity of high-speed machining Ti6Al4V. The International Journal of Advanced Manufacturing Technology, 75(5–8), 1065–1076. https://doi.org/10.1007/s00170-014-6191-y

Zhang, Y., Outeiro, J. C., & Mabrouki, T. (2015). On the selection of Johnson-cook constitutive model parameters for Ti-6Al-4V using three types of numerical models of orthogonal cutting. Procedia CIRP, 31, 112–117. doi:10.1016/j.procir.2015.03.052