DETERMINATION OF CUTTING PARAMETERS FOR PERIPHERAL END MILLING USING DISCRETE HANDBOOK DATA

Abdullahil Azeem
Department of Industrial and Production Engineering
Bangladesh University of Engineering and Technology
Dhaka – 1000, Bangladesh

Abstract: *Cutting speed and feed rate are the two main factors in determining cutting conditions in computer aided process planning, which are directly related to the tool life, machining cost and surface quality. There are experimental data available in the Handbook as the recommendations for academic study and practical applications. But the trends to characterize the data within the entire range and the determination of the intermediate data lying between the known data points are usually not clearly presented in such resources. This research focuses on building a "Composite Constrained Fitting Model" to determine the trends of the experimental cutting speed and feed data and thereby to obtain the intermediate data points. The model fits a composite curve through all the different curve segments, maintaining their boundary conditions and constraints on the coefficients to make its trend have valid physical interpretations.*

Keywords: *Cutting speed, Feed rate, Fitting model*

INTRODUCTION

Today, Computer Numerical Control (CNC) machines are found almost everywhere, from small workshops in rural communities to big companies in urban areas. The CNC machines have radically changed the machining operations, especially those having high variety and moderate batch sizes. Selection of different input cutting parameters for machining process includes cutting speed (v), feed rate (f_r), radial depth of cut (d_r) and axial depth of cut (d_a). Once suitable machining operations and their sequence are selected, the cutting tools and the parameters for each of the operations have to be determined. The tooling and the cutting parameters will have a significant influence on the cycle time, the tool life and the material removal rate as well as on the quality of the surface finish and dimensional accuracy.

For the past years, researchers have developed process models to determine the input cutting parameters and then to achieve the accuracy as well as economic objectives of a machining operation. Three main techniques are used for selecting the cutting parameters for computer aided machining that were mentioned by Hatna *et al.*[1] in their studies. They are Data retrieval methods, Optimization mathematical method and Empirical equation methods. Wong and Hamouda[2] brought up a combination of a retrieval method and empirical equations used for developing an expert system for the automatic selection of cutting conditions for common machining operations. Jerard *et al.*[3] discusses a number of models used for optimizing cutting parameters during NC machining. A technology was presented by Ko *et al.*[4] to automatically determine optimum feed rates for 2.5D axis CNC machining, in which the expertise of a machinist or the information contained in a machining data handbook is not required. The feed rate adjusted in Tarng and Shyur's[5] research is based on the formulation: $f=f_r\,A_r/A$, where f_r is the reference feed rate corresponding to the radial depth of cut equals to tool diameter and A_r is the area of chip cut according with f_r. A similar study[6] in feed rate adjustment is $f=f_r\,F_r/F$, here F_r represents the reference average cutting force and F is the estimated average cutting force. Jerard *et al.*[7] developed a method to determine the cutting conditions in order to compare the cutting times and forces for an NC program prepared using the traditional methods

with an optimized program. Although the studies insist in dealing with the determination of cutting parameters based on cutting force models, it is still very difficult to experimentally measure the cutting parameters during a machining process, as it varies with the cutting conditions. Cus and Balic[8] proposed an optimization technique based on a genetic algorithm for the determination of the cutting parameters in a machining operation in order to minimize the machining costs without violating any imposed cutting constraints. The same objective has been addressed in Tansel *et al.*[9], in which minimizing the production cost is achieved by employing the genetically optimized neural network system for the selection of cutting conditions from experiment data when analytical or empirical models are not available. Vidal *et al.*[10] focused on designing a system to help select the parameters in the cutting process in milling operations.

There are experimental data available in the Handbook[11] as the recommendations for academic study and practical applications. But the trends to characterize the data within the entire range and the determination of the intermediate data lying between the known data points are usually not clearly presented in such resources. The trends of the experimental cutting speed and feed data can be determined by curve fitting and thereby to obtain the intermediate data points. The non-linear curve fitting technique has been widely adopted in modal analysis application. Chalko *et al.*[12] discussed deficiencies in existing modal analysis algorithms and introduced a new algorithm, which is capable of significantly increasing the accuracy of the eigenvalues and eigenvectors reconstructed from experimental measurements on real structures and minimizes the non-linear function of weighted global least square error for all available data. Brown[13] introduced a simple, easy method to carry out non-linear regression analysis based on user input function using an easily understood and reliable program. Either linear or non-linear technique is crucial in least square curve fitting. Kumar and Sivanesan[14] worked on the comparison analysis of linear least square and non-linear least square methods for estimating parameters in three models. Although the studies are inclined to adopt non-linear method in least square techniques, the researchers have to face the complex properties of high computational burden and the difficulties of seeking the proper fitting models. When performing
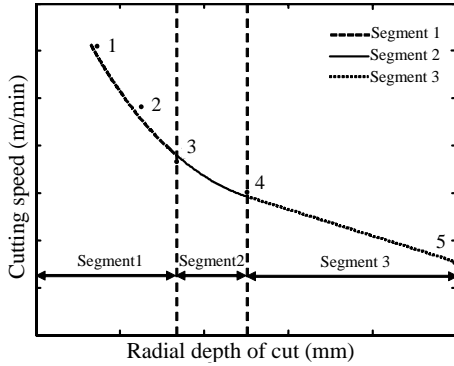
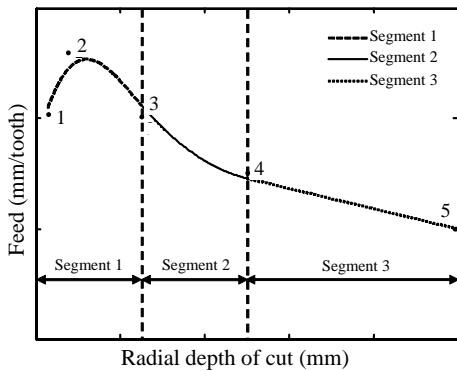Figure 1: Segmentation of composite curves: cutting speed

Figure 2: Segmentation of composite curves: feed

non-linear fitting, it is crucial to take into consideration, all the information that is provided and to check if the fit is really a good one that makes physical sense, especially in engineering applications.

In this paper, a fitting model is built with mathematical objective equations, which fit curves to characterize the discrete machining data. Thus, the tedious cutting force models are avoided and this model could be adopted in varied manufacturing environments.

MODEL FORMULATION

The first component of the fitting procedure is to divide the entire data range into three adjacent intervals and then individual curve segments are fitted within their intervals. A composite curve is generalized with continuity considerations at the connecting points to combine the three curve segments such that the resulting continuous curve could follow a specific trend. It is proposed to compare the data corresponding to the radial depth of cut, cutting speed or feed data in peripheral milling as well as slotting into one fitting curve such that, the range of radial depth of cut is from the recommended minimum value *0.5mm* to the maximum, i.e. the width of slot cut. Therefore there are five known data points to be fitted for both cutting speed and feed. The common way is to find an overall trend with a single curve, which is almost a requirement when beginning to study variability of the observed values. Nevertheless, when dealing with the cutting parameter data, one polynomial equation can hardly interpret a valid physical interpretation for the entire data range.

This work proposes a new method to obtain the overall trend of the fitted curve, simultaneously, computing a set of cutter diameter dependent parameters. Figures 1 and 2 show that the whole data range is divided into three intervals by two connection points, which are corresponding to the radial depth of cut of quarter diameter (*Dia./4*) and half diameter (*Dia./2*) of the cutter and named as Segment 1, Segment 2 and Segment 3 from left to right. Three different polynomial fitting equations are used within each interval, as the individual trends are significantly different. Accordingly the five data points are numbered from left to right as 1, 2, 3, 4 and 5. The three curve segments will compose an objective fitting curve that represents the properties of the whole trend over the data range.

The second component of curve fitting procedure is to determine the fitting equations for each individual interval. Since the data in each interval have a significantly different trend than the adjacent intervals, separate fitting equations are proposed for each of them, as shown below:

Segment 1 (Cubic):

$$f_1(x_i) = y_i = a_3 x_i^3 + a_2 x_i^2 + a_1 x_i + a_0 \qquad (1a)$$
$$\text{where } i = 1,2,3;$$

Segment 2 (Quadratic):

$$f_2(x_j) = y_j = b_2 x_j^2 + b_1 x_j + b_0 \qquad (1b)$$
$$\text{where } j = 3,4;$$

Segment 3 (Linear):

$$f_3(x_k) = y_k = c_1 x_k + c_0 \qquad (1c)$$
$$\text{where } k = 4,5.$$

Because the first curve segment has the most complex trend, the polynomial with third degree is adopted to fit it whereas the following two segments are less complex in their information content, so that the quadratic and linear polynomials are proposed. As the fitting technique is based on linear least square method, these three fitting equations have the same structure as $Y = X\beta + \varepsilon$, but the coefficients have different physical meanings. Here Y is an *7-by-1* vector of cutting parameter (cutting speed or feed data), β is a *9-by-1* vector of coefficients dependent on cutter diameter, X is the *7-by-9* design matrix for the model of the radial depth cut dependent variable, ε is an *7-by-1* vector of errors, *9* is the number of unknown coefficients and *7* is the number of data points to be fitted. The matrix structure is expressed as,

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_3 \\ y_4 \\ y_4 \\ y_5 \end{bmatrix} = \begin{bmatrix} x_1^3 & x_1^2 & x_1 & 1 & 0 & 0 & 0 & 0 & 0 \\ x_2^3 & x_2^2 & x_2 & 1 & 0 & 0 & 0 & 0 & 0 \\ x_3^3 & x_3^2 & x_3 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & x_3^2 & x_3 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & x_4^2 & x_4 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_4 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & x_5 & 1 \end{bmatrix} \times \begin{bmatrix} a_3 \\ a_2 \\ a_1 \\ a_0 \\ b_2 \\ b_1 \\ b_0 \\ c_1 \\ c_0 \end{bmatrix}$$

$$(2)$$

Thus, the following information can be stated about the above system of equations,

- Number of unknowns: 9, a_i ($i = 0$ to 3), b_j ($j = 0$ to 2), c_k ($k = 0$ to 1);
- Number of equations: 7;

The third component of the curve fitting procedure is to apply the boundary conditions to the connection of two adjacent curve segments, which is one of the two types of constraints applied in this model. The number of unknowns (9) is greater than the number of equations (7). Such a condition in mathematics for a system of linear equations is termed as underdetermined. In order to solve this problem and obtain a continuous and smooth composite curve, some constraints must be applied to the connection points, which are termed as Boundary Conditions.

A C^k function is a function with k degrees that is differentiable for all degrees. All *k-degree* polynomials are C^k functions, as they have k continuous derivatives. A function with k continuous derivatives is called C^k continuous function as both the functions and their derivatives have no discontinuities. In this study, the highest possible continuous derivative is taken as constraint to the connection points during the fitting process. C^0, C^1 and C^2 continuities are referred to position, slope and curvature respectively.

At connection point 3 given in Fig 1 and 2, the objective of the composite curve fitting technique is to obtain a continuous and smooth connection between curve Segment 1 and Segment 2, which are cubic and quadratic respectively. Thus, the highest possible continuity is that of the second degree. Then the following continuity conditions must be satisfied at point 3,

i. Zero-degree continuity (C^0): $C_1^0(x_3) = C_2^0(x_3)$;

$$f_1(x_3) = f_2(x_3): \quad a_3 x_3^3 + a_2 x_3^2 + a_1 x_3 + a_0 = b_2 x_3^2 + b_1 x_3 + b_0 \quad (3a)$$

ii. First-degree continuity (C^1): $C_1^1(x_3) = C_1^1(x_3)$;

$$f_1'(x_3) = f_2'(x_3): \quad 3a_3 x_3^2 + 2a_2 x_3 + a_1 = 2b_2 x_3 + b_1 \quad (3b)$$

iii. Second-degree continuity (C^2): $C_1^2(x_3) = C_1^2(x_3)$;

$$f_1''(x_3) = f_2''(x_3): \quad 6a_3 x_3 + 2a_2 = 2b_2 \quad (3c)$$

Similarly, point 4 connects Segment 2 and Segment 3, which are quadratic and linear respectively. Thus, the highest possible continuity is that of the first degree. Then the following continuity conditions must be satisfied for Point 4,

i. Zero-degree continuity (C^0): $C_1^0(x_4) = C_2^0(x_4)$;

$$f_2(x_4) = f_3(x_4): \quad b_2 x_4^2 + b_1 x_4 + b_0 = c_1 x_4 + c_0 \quad (4a)$$

ii. First-degree continuity (C^1): $C_1^1(x_4) = C_1^1(x_4)$;

$$f_2'(x_4) = f_3'(x_4): \quad 2b_2 x_4 + b_1 = c_1 \quad (4b)$$

where in function C_j^k, k is the degree of continuity, $k = 0, 1$ and 2 and $j = 1, 2$ and 3 corresponding to the fitting equations of Segment 1, 2 and 3 separately.

Based on above mentioned boundary conditions, the number of unknowns could be reduced by the Elimination Method. Substituting Eq. (3) and (4) into (2), a new set of linear equations is obtained in the matrix form as following,

$$
\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_3 \\ y_4 \\ y_4 \\ y_5 \end{bmatrix} =
\begin{bmatrix}
x_1^3 + 3x_3^2 x_1 - x_3^3 - 6x_3 x_4 x_1 + 3x_3 x_4^2 & (x_1 - x_4)^2 & x_1 & 1 \\
x_2^3 + 3x_3^2 x_2 - x_3^3 - 6x_3 x_4 x_2 + 3x_3 x_4^2 & (x_2 - x_4)^2 & x_2 & 1 \\
x_3^3 + 3x_3^2 x_3 - x_3^3 - 6x_3 x_4 x_3 + 3x_3 x_4^2 & (x_3 - x_4)^2 & x_3 & 1 \\
3x_3(x_3 - x_4)^2 & (x_3 - x_4)^2 & x_3 & 1 \\
3x_3(x_4 - x_4)^2 & (x_4 - x_4)^2 & x_4 & 1 \\
0 & 0 & x_4 & 1 \\
0 & 0 & x_5 & 1
\end{bmatrix}
\begin{bmatrix} a_3 \\ a_2 \\ c_1 \\ c_0 \end{bmatrix}
$$

$$(5)$$

Now the number of unknown coefficients is reduced to *4*. The number of the linear equations is still *7*. The new fitting model with boundary constraints in this form could be used to solve a system of simultaneous linear equations for estimating unknown coefficients. The other type of constraint is the constraint on coefficients of fitting equation, which will be discussed in the later chapters. Based on the proposed Composite Constrained Fitting Model, some computational algorithms are used to availably determine the coefficients of the fitting equations.

DETERMINATION OF CUTTING SPEED

Accurate fitting of the cutting speed based on Composite Constrained Fitting Model largely depends on the reliability of estimation of the coefficients of the fitting equation. As stated in the previous chapter, a new composite curve fitting technique is developed by combining the three individual curve segments along the Arc Length Ratio (r_{arc}) axis.

The Arc Length Ratio (r_{arc}) is the independent variable used for fitting a curve to the cutting speed data. It is the length of the arc on the circumference of a cutter measured from the point where a cutting edge starts entering the work piece to the point where the same cutting edge exits the work piece in the cutting process. θ is measured from the cutter centre according to the arc length and the formulation of l_{arc} is given by,

$$\theta = arccos\left(\frac{r - d_r}{r}\right) \quad (6a)$$

$$l_{arc} = r\theta = r\,arccos\left(\frac{r - d_r}{r}\right) \quad (6b)$$

where r is the radius of cutter.

In the Handbook, the range of cutter diameter is selected from *10mm* to *18mm*. At each radial depth of cut, the arc length of the slot cut for a particular cutter is taken as the Reference Arc Length of Cut (l_{arc_ref}), which equals to $r\pi$, and then Arc Length Ratio is defined for the particular cutter diameter and radial depth of cut as given below,

$$r_{arc} = \frac{l_{arc}}{l_{arc\_ref}} \quad (7)$$

Substituting l_{arc} from Eq. (6b) and putting $l_{arc\_ref} = r\pi$ into Eq. (7), we get

$$r_{arc} = \frac{arccos(1 - d_r / r)}{\pi} \quad (8)$$

The possible values of r_{arc} lie within the range of 0 and 1, which corresponds to no cut and slot cut respectively, thus, it covers the entire cutting data range.

Since there exists a similar trend in the fitted curves for different cutters within a particular interval, it is proposed that the fitting equation for a particular curve segment has the same structure and their coefficients are dependent on the cutter diameters. For instance, representing the cubic structure of the equation for the Segment 1 as,

$$y_{sp}(r_{arc}) = a_3 r_{arc}^3 + a_2 r_{arc}^2 + a_1 r_{arc} + a_0 \quad (9)$$

where y_{sp} is the cutting speed. A second order polynomial is selected to estimate the coefficients of fitting equations using cutter diameter. As the coefficients are dimensionless, the cutter diameters are also made
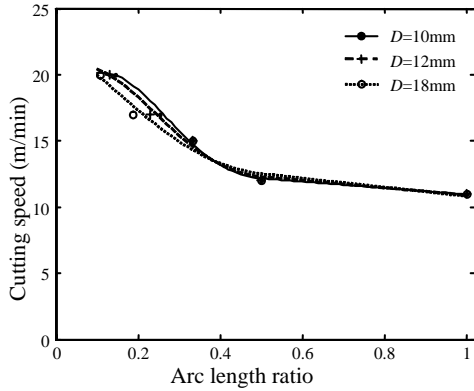
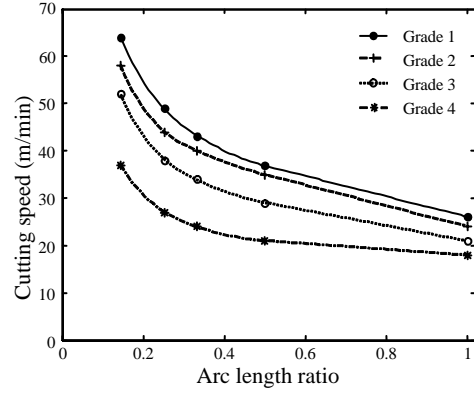Figure 3: Fitted curves for cutting speed data: before coefficient adjustment

Figure 5: Fitted curves for cutting speed data to different grades
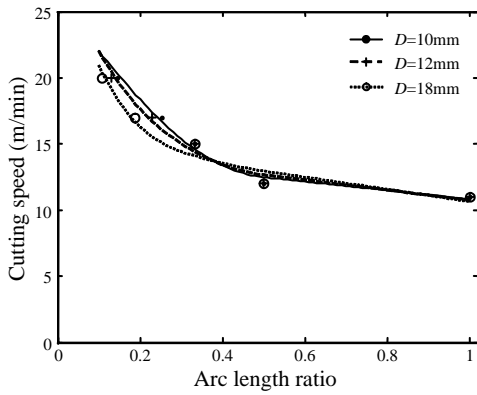
Fittings are implemented to fit curves to the cutting speed data in the same grade referred to different cutters, *D=10, 12* and *18mm*. In the fitting to the material of Alloy Steels, Wrought Medium Carbon with the hardness of 325 to 375 BHN, Fig. 3 is the fitting before coefficient adjustment. It is clear to see that at least one of the three curves on Segment 1 is indicating the convex trend after initial fitting; the estimated values of three a_2's are -355.7309, -195.1754 and -27.6262, i.e. the curve in Segment 1 has a negative curvature and is convex. To maintain the constraints on the coefficients, these a_2's must be adjusted. Figure 4 gives the final fitting.

The fitting to different grades in one material group referred to one cutter is presented in this section. In one material group, a grade is defined by the hardness. In The Handbook, it is observed that with the increasing of hardness, the general trend of cutting speed is monotonously decreasing. One of the cases selected as example is proposed in Fig. 5. The material is *Carbon Steel, Wrought, Low Carbon* and the cutter diameter is *10mm*. There are four grades in this group referred to the hardness of 85 to 125, 125 to 175, 175 to 225, and 225 to 275 BHN. The four composite curves have the similar trends, which are all decreasing along with the increasing of Arc Length Ratio. Thus, the figure shows a reasonable effect of hardness on the fitting curve to cutting speed data, as the curves for individual grades do not overlap.

Figure 4: Fitted curves for cutting speed data: after coefficient adjustment

dimensionless by dividing each diameter term by a reference diameter of *18mm*, such that, the range of the independent variable is from zero to one.

Considering a cubic, quadratic and linear individual fitting equations for each curve segment using r_{arc} for Segment 1, 2 and 3 respectively, the composite fitting equation for the cutting speed data for the entire data range could be written as,

Segment 1:

$$y_{sp1} = \left\{ e_2\left(\frac{D}{18}\right)^2 + e_1\left(\frac{D}{18}\right) + e_0 \right\} r_{arc}{}^3 + \left\{ j_2\left(\frac{D}{18}\right)^2 + j_1\left(\frac{D}{18}\right) + j_0 \right\} r_{arc}{}^2 + \left\{ k_2\left(\frac{D}{18}\right)^2 + k_1\left(\frac{D}{18}\right) + k_0 \right\} r_{arc} + \left\{ l_2\left(\frac{D}{18}\right)^2 + l_1\left(\frac{D}{18}\right) + l_0 \right\}$$

(10a)

Segment 2:

$$y_{sp2} = \left\{ m_2\left(\frac{D}{18}\right)^2 + m_1\left(\frac{D}{18}\right) + m_0 \right\} r_{arc}{}^2 + \left\{ p_2\left(\frac{D}{18}\right)^2 + p_1\left(\frac{D}{18}\right) + p_0 \right\} r_{arc} + \left\{ q_2\left(\frac{D}{18}\right)^2 + q_1\left(\frac{D}{18}\right) + q_0 \right\}$$

(10b)

Segment 3:

$$y_{sp3} = \left\{ t_2\left(\frac{D}{18}\right)^2 + t_1\left(\frac{D}{18}\right) + t_0 \right\} r_{arc} + \left\{ u_2\left(\frac{D}{18}\right)^2 + u_1\left(\frac{D}{18}\right) + u_0 \right\}$$

(10c)

where y_{sp1}, y_{sp2} and y_{sp3} are the cutting speed data within the range of Segment 1, Segment 2 and Segment 3; $e's, j's, k's, l's, m's, p's, q's, t's$ and $u's$ are the cutter diameter dependent coefficients.

DETERMINATION OF FEED

Like the feed rate, accurate fitting of the cutting speed also depend on the reliability of estimation of the coefficients of the fitting equation. As stated in the
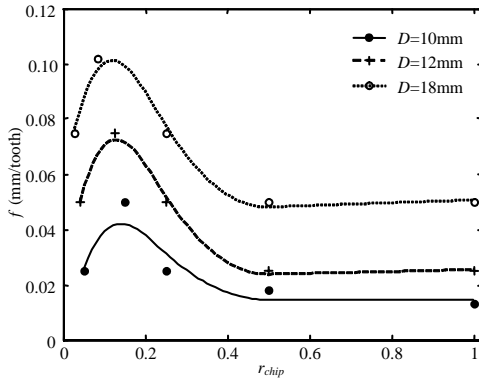
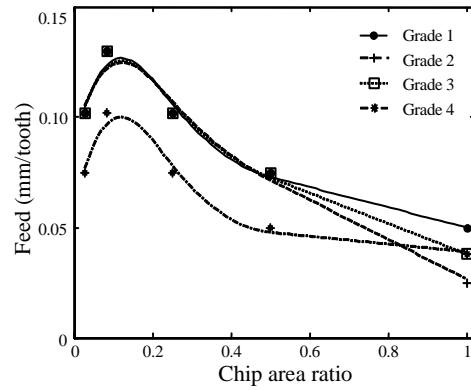Figure 6: Fitted curves for feed data: before coefficient adjustment

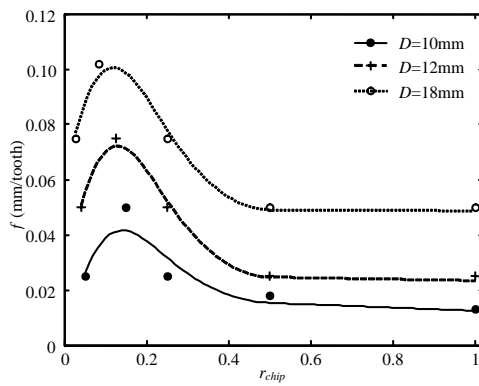Figure 8: Fitted curves for feed data to different grades

Figure 7: Fitted curves for feed data: after coefficient adjustment
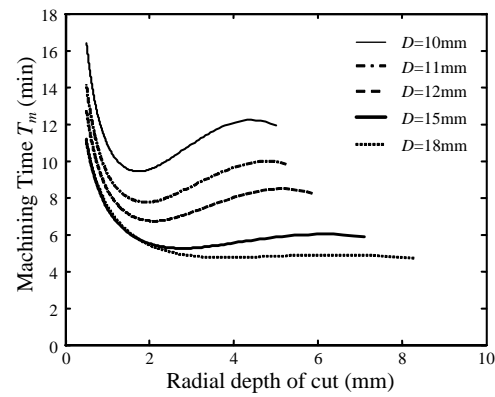

Figure 9: Machining time for cutters of different diameter

previous section, a new composite curve fitting technique is developed by combining the three individual curve segments along the Arc Length Ratio (r_{arc}) axis. Instead of arc length ratio, chip area ratio is considered in developing the equations.

Chip Area and Radius Swept Area constitute the Total Area (A_t), which is surrounding by the boundary of Chip Area and the cutter radius. The Total Area is calculated as given below,

$$A_t = \int_0^\theta \frac{(r + t(\theta))^2}{2} d\theta \qquad (11)$$

Substituting the value of chip thickness $t(\theta) = f \sin\theta$ in Eq. 11, we can write

$$A_t = \int_0^\theta \frac{(r + f \sin\theta)^2}{2} d\theta \qquad (12)$$

After integrating Eq. (12), we get

$$A_t = \frac{r^2\theta}{2} + rf(1 - cos\theta) + \frac{f^2}{4}(\theta - sin\theta cos\theta) \qquad (13)$$

Because $f^2(\theta - sin\theta cos\theta)/4 << r^2\theta/2$ and

$rf(1 - cos\theta)$, Eq. (13) could be written as

$$A_t = \frac{r^2\theta}{2} + rf(1 - cos\theta) \qquad (14)$$

And A_r is simply defined as,

$$A_r = r^2\theta/2 \qquad (15)$$

Therefore, the formulation to calculate Chip Area is,

$$A_{chip} = A_t - A_r = \frac{r^2\theta}{2} + rf(1 - cos(\theta)) - \frac{r^2\theta}{2} = rf(1 - cos\theta) \qquad (16)$$

Similar to Arc Length Ratio discussed in the previous chapter, to fit a curve to the feed data, Chip Area Ratio (r_{chip}) is proposed as the independent variable in the fitting procedure. The value of Chip Area at $\theta=\pi$ is $2rf$ and taken as Reference Chip Area (A_{chip_ref}) for a certain cutter. Therefore, Chip Area Ratio is a relative magnitude defined as,

$$r_{chip} = A_{chip} / A_{chip\_ref} \qquad (17a)$$

Substituting Eq. (6a), (16) and the value of A_{chip_ref} into Eq. (17a), we get,

$$r_{chip} = \frac{rf(1 - cos\theta)}{2rf} = \frac{1 - cos\theta}{2} = \frac{d_r}{2r} \qquad (17b)$$

The fitting equations for the three curve segments can be defined as

$$y_f(r_{chip}) = a_3 r_{chip}^3 + a_2 r_{chip}^2 + a_1 r_{chip} + a_0 \qquad (18)$$

The general fitting equations of the three curve segments in the fitting to feed data can be represented in term of r_{chip} and the cutter diameter dependent coefficients as given below,

Segment 1:

$$f_{sp1} = \left\{ e_2 \left(\frac{D}{18} \right)^2 + e_1 \left(\frac{D}{18} \right) + e_0 \right\} r_{chip}{}^3 + \left\{ j_2 \left(\frac{D}{18} \right)^2 + j_1 \left(\frac{D}{18} \right) + j_0 \right\} r_{chip}{}^2 +$$

$$\left\{ k_2 \left(\frac{D}{18} \right)^2 + k_1 \left(\frac{D}{18} \right) + k_0 \right\} r_{chip} + \left\{ l_2 \left(\frac{D}{18} \right)^2 + l_1 \left(\frac{D}{18} \right) + l_0 \right\}$$

(19a)

Segment 2:

$$f_{sp2} = \left\{ m_2 \left(\frac{D}{18} \right)^2 + m_1 \left(\frac{D}{18} \right) + m_0 \right\} r_{chip}{}^2 + \left\{ p_2 \left(\frac{D}{18} \right)^2 + p_1 \left(\frac{D}{18} \right) + p_0 \right\} r_{chip} +$$

$$\left\{ q_2 \left(\frac{D}{18} \right)^2 + q_1 \left(\frac{D}{18} \right) + q_0 \right\}$$

(19b)

Segment 3:

$$f_{sp3} = \left\{ t_2 \left(\frac{D}{18} \right)^2 + t_1 \left(\frac{D}{18} \right) + t_0 \right\} r_{chip} + \left\{ u_2 \left(\frac{D}{18} \right)^2 + u_1 \left(\frac{D}{18} \right) + u_0 \right\}$$

(19c)

where y_{f1}, y_{f2} and y_{f3} are the feed data within the range of Segment 1, Segment 2 and Segment 3; $e's, j's, k's, l's, m's, p's, q's, t's$ and $u's$ are the cutter dependent coefficients.

The fitting of Carbon Steels, Wrought, Low Carbon with hardness of 175 to 225 BHN indicates the adjustment happened to c_1. In the initial fitting of Fig. 6, in Segment 3 the three values of c_1 corresponding to cutters of *10mm*, *12mm* and *18mm* are *0.0001, 0.0033* and *0.0052* respectively. These three positive values imply that the trend of the feed data is monotonously increasing rather than decreasing within Segment 3. This is not practically possible when tool life and surface requirements are considered. After adjustment and refitting, Fig. 7 gives the final plot, in which the above-mentioned three c_1's are *-0.0058, -0.0026* and *-0.0007* respectively.

Fitting data of different grades gives another view to study the properties of the fitted feed. An interesting characteristic would be observed that, the same feed data are repeated in different grades in one material group, which are not observed in the cutting speed data. Fig. 8 shows the fitting to feed data for a particular cutter of *D=18mm*. It can be observed that the data of peripheral cut in Grade 1, 2 and 3 have the same values but their slot cut data is different. This can again be accounted for the fact that hardness of the above group does not have much effect on the fitting of feed data.

APPLICATION OF THE PROPOSED MODEL

The previous chapters have discussed the method to determine the trends of the discrete experimental data of cutting speed and feed obtained in the Handbook. So far, not only the data suggested in the Handbook is easy to use, but also the intermediate data lying between the known data points could be estimated and then worked on in the normal way. The following work is to show the practical applications, based on the presented Composite Constrained Fitting Model. A rectangle pocket with planar bottom and vertical walls is considered as the sample part to be machined by using end mills. There are two main tool path patterns for pocket machining: Direction-parallel and Contour-parallel patterns. In direction parallel pattern, the tool paths are all parallel to each other, whereas in Contour-parallel tool path pattern, the tool path spiral-type. Briefly, the cutter follows in a spiral-like motion, the tool path is generalized by offsetting the inner boundary of pocket or outer boundary of the island, and they reduce

Table 1 Calculated minimum machining time for different cutters

Cutter Dia. (mm)	Radial Depth of Cut (mm)	Min. Total Machining Time (min.)
10	1.7431	9.4222
12	2.0889	6.7295
18	8.667	4.6161

inward for the outer contour and increase outward for the islands. The theoretical machining time is obtained by summing up the values from the division of each length of tool path segment by the feed rate applied on that. Different tool path pattern gives different tool path length. For the given pocket, direction parallel milling method is selected as the tool path for machining the assigned pocket.

For the selected material Aluminum Alloys, Cast Sand and Permanent Mould with hardness of 40 to 100 BHN, Fig. 9 shows five curves of total machining time corresponding to five cutters, from the top to the bottom, the diameter of the cutters are *10mm, 11mm, 12mm, 15mm* and *18mm*. Among them, the data of cutter *D=11mm* and *15mm* are the intermediate data not listed in the Handbook, but determined by the Composite Constrained Fitting Model.

The minimum machining time could be taken as a quantitative tool for the machining efficiency. The marker X's in Fig. 10 indicate the minimum total machining time calculated for different cutters. The working material is Aluminium Alloys, Wrought with the hardness from 30 to 80 BHN. In Table 1, the recommended radial depth of cut
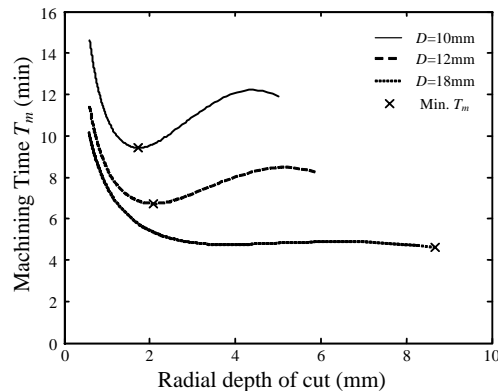
Figure 10: Minimum machining time for different cutters

for each cutter is listed with their minimum total machining time.

CONCLUSIONS

The need for fitting curves arises principally from the fact that many physical phenomena and experimental results are in nature continuous, although their measured data is discrete. Based on such discrete data, mathematical tools are often used to reconstruct their continuity in order to have the knowledge of the entire characteristics of the data.

The proposed Composite Constrained Fitting Model in this research generates continuous plot of cutting data using discrete data available in the Handbook. The model is uniform and consistent in nature as it characterizes both cutting speed and feed data for all the selected data, with acceptable accuracy. It is based on new techniques developed to improve the traditional linear least square fitting models.

Since the Composite Constrained Fitting Model could characterize the entire range of cutting speed and feed data available in the Handbook, for a given radial depth of cut, the user can determine the cutting data corresponding to any cutter diameter. Thus, it extends the scope of using the discrete data in the Handbook, which can provide a more accurate prediction of the intermediate data, consistent for all the selected cutting speed and feed data.

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