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EVALUATION OF INFEED STRATEGIES FOR TURNING OF LARGE THREAD PROFILES

Abstract: *Several infeed strategies for multipass threading operations on CNC lathes are well known and they are implemented in form of apropriate canned cycles in system software of CNCs. These strategies are especially suitable for triangular profiles of thread. Paper presents method developed for analysing of infeed strategy in threading operations for arbitrary geometry of thread profile and geometry of tool profile, including trapezoidal threads and worm wheels. Proposed method uses two criteria for evaluation of specific infeed strategy in multipass turning of threads. The first one is the measure of balance of uncut chip area in subsequent passes (implemented application in Matlab is described). Calculation of chip area is based on numerical integration The second criterion is referred to predicion of cutting forces and their distibution in subsequent passes.. Cutting force estimation is based on specific cutting forces and engaged chip area acting on discretized lenghts of cutting edges.*

Key words: *CNC lathe, threading, infeed strategy, turning operations*

1. INTRODUCTION

CNC lathes enable very efficient machining of the helix surfaces on rotating parts. It is possible, in mode of strong kinematic connection (G32 function) between main spindle an X and Z servo axis, to machine of various internal and external threads, lead screws, worm wheels and spiral slots on face of the workpiece. In cases of small thread profile (small pitch and depth) programming of machining of thread is very simple, and it is reduced on one or two program blocks, with call of specific canned cycle, and with specification of input parameters (thread geometry, thread profile and technology parameters) of this cycle. In such case (small profile) critical element of whole system is the cutting tool and its vulnerable nose.

In some cases, especially in machining of larger thread profiles, these cycles may exhibit some limitations. In these situations tool design is more complex, larger length of cutting edges are engaged, power consumption and required spindle torque are not negligible. There is also higher tendency to vibrations especially in machining of thin-walled parts.

Comparing to other machining methods, turning of threads is treated in very small number of scientific papers [1, 2]. This paper presents results of research aimed to develop procedures for better insight in this process, with focus on prediction of cutting forces.

2. TYPICAL INFEED STRATEGIES IN CANNED CYCLES FOR THREAD TURNING

Different infeed strategies [5] implemented in canned cycles for thread turning assume infeed with constant radial increment, or with constant cross section of uncut chip for subsequent machining passes (strategy with decreasing increment). Also (Fig.1a) infeed can be performed in radial direction (R), along flank (F) of profile or with alternating infeed (incremental infeed- I).

One of the most popular formula for calculation of radial infeed amount for particular pass is derived, according to Fig.1b, assuming zero radius of tool nose (H_r denotes profile depth reduced for finishing allowance, p-number of passes):

$$dA_{c,1} = u_1^2 tg(\frac{\alpha}{2}),\ dA_{c,\mathrm{i}} = tg(\alpha/2)(u_i^2 - u_{i-1}^2)$$

$$(u_i^2 - u_{i-1}^2) = K,\ \ Ap = H_r^2 tg(\alpha/2)$$

$$Ap = \sum_1^p dAc(i) = pK,\ \ K = H_r/\sqrt{p}$$

$$u_1 = H_r/\sqrt{p},\ \ u_i = \sqrt{(H_r^2/p)+u_{i-1}^2}\ . \qquad (1)$$

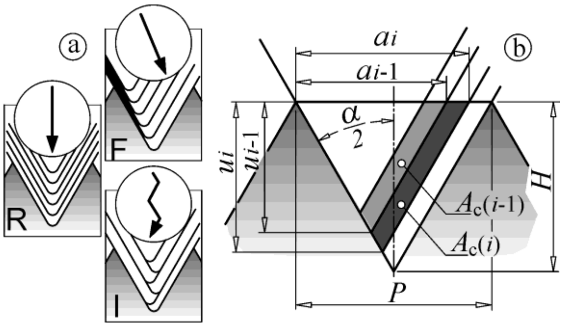

Fig1. Different infeed strategies (a) and model for infeed strategy with constant chip area (b)

This strategy, simple but effective, is implemented in many CNCs of lathes. Another, empirical, formula is recommended from [3]:

$$u_i = H_r\sqrt{\frac{\varphi_i}{p-1}},\ \varphi_1 = 0.3,\ \varphi_2 = 1,\ \varphi_i = p-1 \qquad (2)$$

$$\varphi_i = i-1\ \text{, for}\ i = 3,\dots,p\,.$$

Finally, recommended number of passes and quantity of infeeds, for particular standard thread and its nominal pitch can be found in form of tables [3].

3. EVALUATION OF INFEED STRATEGIES FOR TURNING OF THREADS

Among the other criteria, evaluation of quality of infeed strategy for turning of particular thread can be performed through analysis in two levels in order to achieve:

1. Limited and balanced cross sections of uncut chip area in subsequent passes.

This criterion is based on premise that cutting forces, among other factors, are strongly influenced with area of engaged uncut chip section. This dependence is not quiet linear, but without some other criteria, balanced chip area in all passes are indicator for well planned process. Exception is the last pass, with intentionally small chip area, needed for finishing of thread flanks and root.

2. Limited and balanced cutting force components in subsequent passes.

Prediction of cutting forces is one of the most reliable tool for evaluating of planned machining process. As a rule this approach assumes more complex input data structure, as well as more complex procedures implemented in computer programs.

In chapter 3 of this paper, procedure and implemented Matlab application for prediction of chip area during passes of thread turning, is presented. In chapter 4, mechanistic approach of cutting force predicting is discussed and one procedure for identification of chip thickness, for arbitrary element of discretized cutting edge, is presented.

4. ESTIMATION OF UNCUT CHIP AREA

Calculation of chip cross section in particular passes of thread turning process, based on specific cutting tool geometry and infeed strategy, has not trivial solution. Some authors [2] developed algorithms of analytical obtaining of this area, but only for few kinds of standard thread profile (API-Buttress). Different approach, using discretization of workpiece longitudinal section, and specific description of cutting tool geometry, in our research was applied. Calculation of chip cross section area is based on numerical integration, and it is found that this approach is more flexible and sufficiently accurate.

Developed Matlab application requires three input data files: *ThreadProfile*, *ToolProfile* and *InfeedStrat*. The last one is two column matrix with subsequent infeeds, for all passes, in Z and X (radius) direction. *ThreadProfile* matrix has rows with attributes of linear segments and arcs of thread profile in form of:

$[1, Z_{start}, X_{start}, Z_{end}, X_{end}, 0, 0, 0, 0, 0]$

for linear segments, and:

$[2(3), Z_{start}, X_{start}, Z_{end}, X_{end}, R, X_c, Z_c, A_{start}, A_{end}]$,

for arcs on cutting edge (constant 2 or 3 indicates if arc is convex or concave, view from $X+$). Matrix *ToolProfile* has *ToolSeg* rows with almost the same structure as rows of *ThreadProfile*. Additional attribute in description of tool segment is indicator that shows if the particular line or arc is part of cutting edge or noncutting geometry of the tool. This noncuting segments are useful in checking of possible collision during machining of thread.

Additional two input variables are radial allowance (*TopStockR*) for full profile machining, as well as resolution (R_f) of rays (fringes) parallel to Xaxis, needed for discretization of the workpiece. In area of worpiece with length of one thread pitch *N*ray fringes parallel to Xaxis will be generated, according to *FrgRes*, from raw material axis to its diameter. This is the way for discretization of longitudinal cross section of the workpiece. Default value for R_f is $P/100$, for achieving of high accuracy of numerical integration of particular areas. For certain threading pass (i=1:np) several steps will be performed:

Step 1. Translation of each segment (j=1:$tseg$) of the tool profile according to infeed parameters (*InfStrat(i,:)*).

Step 2. For fringe (k=1:nf) check if Zf(k) is between Z limits of particular j translated segment of the cutting edge (Case1).

If the Case1 is satisfied, find intersection of fringe k with *ToolSeg*(j). In case of Xf(k) > Xt,T(Zf) of intersection, Calculate $dAc(i)=X_f-X_{int}$, as the contribution of this fringe to the total chip area. Update local radius of the workpiece $X_f(k)= X_f(k)-dA_c(i)$. Proceed to next fringe (k=k+1)

If the Case 1 is not satisfied proceed with checking of next segment of the tool edge (j=j+1)

Step 3. Go back to step 2

Step 4. Calculate chip area for current pass

$A_c(i)=dA_c * R_f$.

Step 5. Return to step 1.

Results of this developed Matlab application in (ThreadSimArea.m) are supported with diagrams of workpiece/tool engagement for each threading pass and with diagram of change of chip area for each pass. One illustrative example of these results, for turning of ISO Tr6 thread in extremely low number of passes (6 passes are practically impossible) are shown in Fig.2.

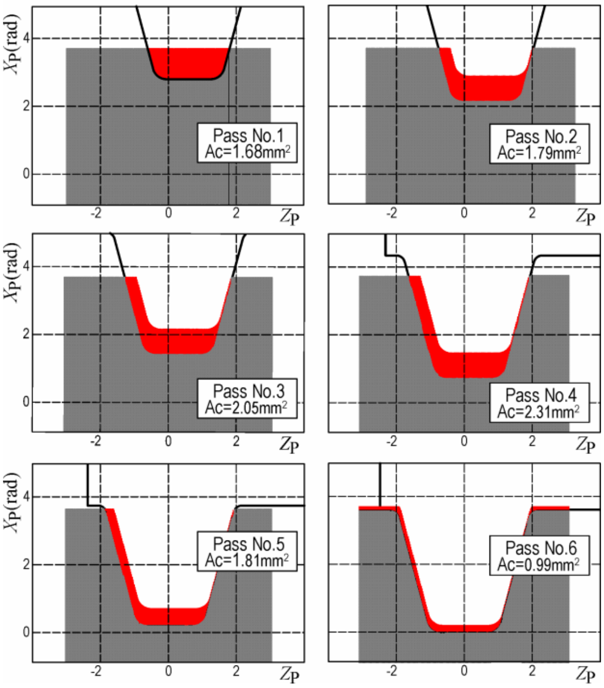

Fig 2 One example of calculation of uncut chip area in subsequent passes of thread turning

Accuracy of calculated chip areas were checked through CAD program in number of examples, and it was found that with error was not greater than 0.5% with chosen resolution $R_f=P/100$.

Fig.3 shows comparison of calculated uncut chip area for the same example, and another example with 16 passes according with recommendations [3]. Uncut chip area is the same for the last pass in both cases (both with same finish allowance).

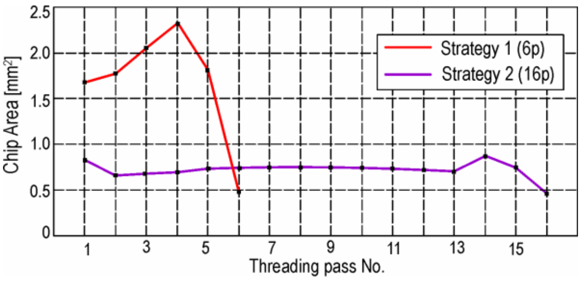

Fig 3 Comparison of two infeed strategies for ISO Tr6

One of practical problem in using of this Matlab application is generation of required data for tool profile description in proposed format. From this reason, one program module is developed to complete matrix *ToolProfile*, using generic geometry of several thread profiles and data from tables in standards for various threads (ISO-MM, ISO-Tr, DIN-Tr, Worms 20°). Creating of *ToolProfile* matrix, need just few additional parameters (in dialog) for specification details of cutting edge responsible for generating the top of the profile (full profile machining).

5. PREDICTION OF CUTTING FORCES IN TURNING OF THREADS

During recent decades, very good results in modeling of cutting forces using mechanistic models, were achieved, for different machining methods. Basic idea is very simple. It assumes discretization of cutting edge(s) in small increment of length dL. Three cutting force components ($dF_t(l)$, $dF_r(l)$ and $dF_a(l)$), acting on particular increment of cutting edge are functions of: area of uncut chip corresponding to this increment, orientation of incremental edge to cutting speed and feed vectors and of specific cutting forces (K_v, K_f) obtained from tests with orthogonal cutting. After completion of calculation of $dF_t(l)$, $dF_r(l)$ and $dF_a(l)$, for all $l=1:ne$, they should be integrated and project onto three orthogonal directions (y,z and x) for obtaining three corresponding principal cutting force components (F_1, F_2 and F_3) [2]:

$$\begin{bmatrix} dF_t(l) \\ dF_r(l) \\ dF_a(l) \end{bmatrix} = \begin{bmatrix} K_{tc}(l) \\ K_{rc}(l) \\ K_{ac}(l) \end{bmatrix} dL(l)h(l) \tag{3}$$

With $h(l)$ the local uncut chip thickness is denoted. Specific cutting forces in oblique cutting can be obtained from orthogonal cutting data and angles of orientation of cutting edge $dL(l)$:

$$\begin{bmatrix} K_{tc}(l) \\ K_{rc}(l) \\ K_{ac}(l) \end{bmatrix} = \boldsymbol{T}_{ob}(l) \begin{bmatrix} K_v(l) \\ K_f(l) \end{bmatrix} \tag{4}$$

Supposing that chip flow angle $\eta(l)$ is equal to the local inclination angle $\lambda(l)$, elements of $\boldsymbol{T}_{ob}$ can be calculated from sine and cosine functions of $\lambda(l)$ and local rake angle $\chi(l)$ [2].

In order to build program application for predicting of cutting force components in particular pass of thread turning it is obvious that functions for calculation of local chip depth are required. Further text of this paper deals with this issue.

5.1 Uncut chip area on finite length of cutting edge

It should be noted that previous application (ThreadSimArea.m) creates Matlab workspace with all of its input matrices, and results in form of vectors of x coordinates of all updated fringes for all machining passes. Procedure for calculating of chip area corresponding to particular finite length of cutting edge starts with discretization of its length. Increment for discretzation (ΔL on fig.4) need not to be too small, as (R_f) for procedure for estimating chip area for entire tool.

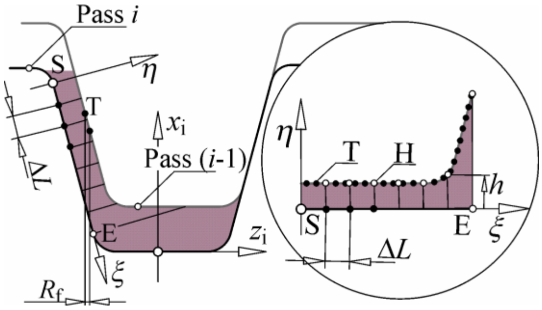

Fig4.

Points of discretized edge can be found from description of tool geometry (*ToolProfile* matrix), and from offsets of tool coordinate system, according to elements of *InfeedStrat* for current machining pass. Establishing of local coordinate system $S\xi\eta$ for particular segment of cutting edge is required. For all points on profile of previous pass (T points) their ξ and η coordinate need to be calculated (only points with $|\xi_T| < \xi_E$). All pairs (ξ_T, η_T) of one segment of cutting edge can be used for interpolation in calculating of η_H (local depth h of the chip) for particular ξ_H (obtain through discretization of edge segment). Local chip area can be obtained as $\xi_H \Delta L$.

This approach has two problems, illustrated on Fig.5. The first one is the fact that, in general case, particular points on contour, made in previous pass, have their orthogonal projections (E', E'', on Fig.5) on more than one segment of cutting edge. As a consequence, a part of chip area (A_i) contributes to chip load corresponding to more than one edge segment, and this situation should be avoided. Another problem is obtaining the part (A_R) of uncut chip area corresponding to arc segments of the cutting edge

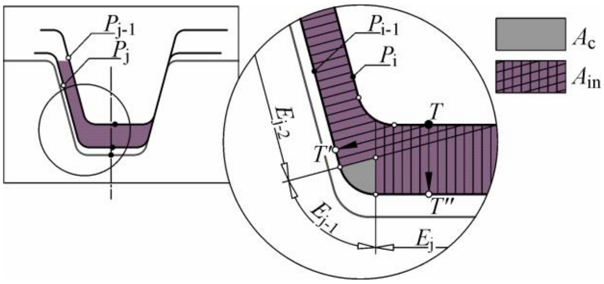

Fig.5 Initial solution for chip thickness for finite length of edge

In order to overcome these problems specific algorithm was presented in [2]. It uses rediscretization of workpiece contours in previous and current pass. This rediscretization assumes that both contours for analyzing have the same number of points, with limitation of angles between connecting lines of corresponding points and edge segment in previous and current pass.

In this paper an alternative approach is presented. Procedure of correction of η_H-coordinates (chip thickness, *h*, Fig.5) corresponding to finite length of the cutting edge assumes following steps:

For current <u>linear segment</u> of cutting edge (Fig. 6):

1. Find η_H coordinates of all *T* points from contour P_{i-1} in local coordinate $\xi\eta$ system of current linear segment E_j.
2. Find angle between actual E_j and first previous linear segment E_{pr}.
3. If this angle is greater than 180° keep η_H coordinates obtained through the step1. If this angle is less than 180 ° reduce η_H until to intersection with symmetry line of E_j and E_{pr}.
4. Find angle between current E_j and first next linear edge segment E_{nx}.
5. If this angle is greater than 180° keep η_H coordinates obtained through the step 1. If this angle is less than 180 ° reduce η_H until to intersection with symmetry line of E_j and E_{nx}.

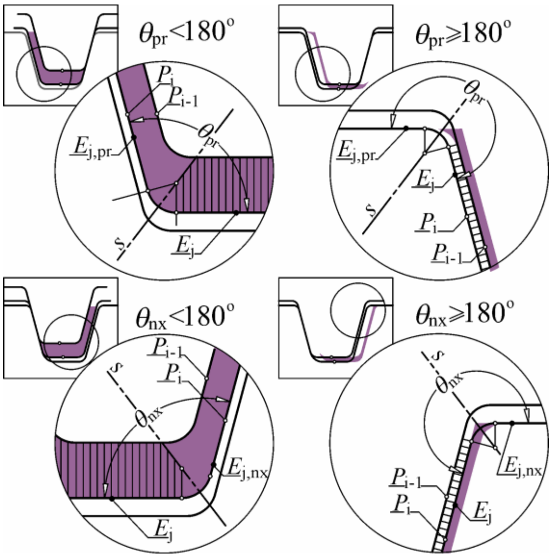

Fig.6 Examples of corrections of chip thickness on finite length of discretized cutting edge

For current <u>arc segment</u> of cutting edge points for discretization are obtained keeping the same increment of discretization as for linear segments. Obtaining of local chip thickness, ρ(*l*), and area, on finite length of such edge segment is performing through scanning of contour of previous pass with lines, each of them connecting point on arc edge and its center:

$$d\theta = d_L / R_n,\quad \bar{\rho}(l) = 0.5(\rho(l-1)+\rho(l)) \qquad (5)$$

$$dA_c(l) = \frac{dL + (R_n - \bar{\rho}(l))d\theta}{2}\bar{\rho}(l)\cos(\frac{d\theta}{2}) \qquad (6)$$

6. CONCLUSION

Two procedures for evaluating of process of thread turning are discussed in this paper. The first one is based on calculation of engaged chip area in subsequent machining passes, according to specified infeed strategy. Developed Matlab application performs these calculations, using very limited set of input data. It is flexible and it can be use for arbitrary tool geometry and infeed strategy. The second procedure for evaluating of the process is based on mechanistic approach in modeling of cutting forces. That model requires relatively small experimental base and more complex algorithm. In that sense, this paper presents algorithm for computing of chip area on arbitrary finite lengths of discretized cutting edge. Further work on this problem assumes Matlab implementation of this algorithm and its experimental verification.

7. REFERENCES

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