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## OPPORTUNITIES FOR IMPLEMENTATION THE VIBRATORY SUPERFICIALLY PLASTIC DEFORMATION PROCESS FOR CYLINDRICAL SURFACES USING CNC TURN/MILL CENTERS

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**ABSTRACT:** This article discusses some typical disadvantages of the traditional kinematical scheme for implementing the vibratory superficially plastic deformation process, realized on manually controlled lathe machine tools and the possibilities and some difficulties in implementing that process by using 2 - axis CNC lathes and the more advanced multi-axis CNC Turn/Mill centres. Kinematical parameters of the process having an impact of the toolpath, for forming of regular reliefs from different types through the process are described, and math functions for its calculating are proposed in accordance with the diameter and length of the cylindrical surface, that will be processed. The necessity of using 4-axis turn/mill centres (with rotary C-axis) is examined. The sequence of steps for automated programming of the attributes of the operation, using FeatureCAM software system, for output the required NC code is proposed.

**KEYWORDS:** vibratory superficially plastic deformation process; CNC turn/mill centres; FeatureCAM, Delcam

### INTRODUCTION

Some examples from the technological practice confirms that the nature of the roughness of contact surfaces of various parts, obtained by the most common finish machining methods (e.g. grinding, lapping, polishing, etc.), do not always meet operational requirements for working conditions in the friction pairs, contact with fluids and/or different electromagnetic radiations.

Among finishing methods, the method of processing, known as “Vibratory Superficially Plastic Deformation” (VSPD) is characterized by the best better combination of complex parameters of the quality of treated surfaces [6]. This method is based on plastic deformation (without heating) of the surface layer of the workpiece by pressing the steel ball with high hardness (e.g. from ball roller bearing) with certain force, which moves along complex trajectory regarding it. The VSPD process usually performed on lathes (outfitted with special vibratory rigs) and for cylindrical surfaces of the rotating parts (e.g. plain or drive shafts).

As a result, specific overlays of traces and valleys from the ball-tool are formed onto contact surfaces of parts, which due to its high degree of repeatability are called “regular” micro-reliefs (RMR). On the Fig. 1 (a÷f) are shown the five possible types of the RMRs which can be obtained using the VSPD process. The parameters of their profile of roughness asperities and operational characteristics, which radically differ from those, obtained after implementation of other traditional finishing

methods. Depending on the type of the workpiece’s material (hardness) and process parameters of the VSPD operation (speed, feed, force of pressure and diameter of the ball-tool) roughness asperities with large radii of curvature, ranging from 800 to 8000  $\mu\text{m}$  (at maximum height of roughness asperities from 10 to 35  $\mu\text{m}$ ), small angles of inclination of the roughness asperity profile from  $0^{\circ} 30'$  to  $3^{\circ}$ , and large horizontal distance between the peaks (from 500 to 3500  $\mu\text{m}$ ), the conditions of contact interaction are significantly improved [3,6]. Moreover, this finishing method increases the hardness of the surface layer, which improves resistance to wear of the parts.

Among the known kinematical schemes for processing regular reliefs around cylindrical surfaces by VSPD of the types from Fig. 1 (a ÷ f) with the most wide application has the kinematical scheme, shown in Fig. 2,a. There are some examples for successfully implementation of this scheme for VSPD (by manually operated lathes) and obtained RMRs wrapped around it. These results show, that all types of RMRs from Fig.1, a÷f can be achieved by appropriate combination of values for the regime parameters of the process (depending on the size  $d \times L$  of the cylindrical part), which are follows:

- $d$ , mm - diameter of the cylindrical surface;
- $L$ , mm - length of the cylindrical surface;
- $v_f$ , mm/rev - feed rate;
- $2.e$ , mm - amplitude of the oscillations (which is influenced of the width  $b$ , mm of RMR cells);
- $n_0$ , [ $\text{min}^{-1}$ ]- speed of lathe spindle;

–  $j$ , [osc./rev]- it is so-called "Drive Ratio" in VSPD and determines the number of oscillations of the tool per revolution of the cylindrical workpiece. This parameter basically influences of the size  $a$ ,mm (see Fig. 2,b) and the type (from I to V) of the obtained valleys or cells of RMRs.

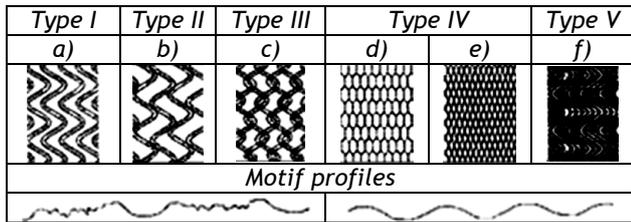


Figure 1. Types and typical motif profiles after implementation the VSPD process: a) system of not tangent ditches b) system of tangent ditches c) system of intersecting ditches d) regular relief with hexagonal cells e) regular relief with rectangular cells; f) regular relief superimposable on each other's ditches.

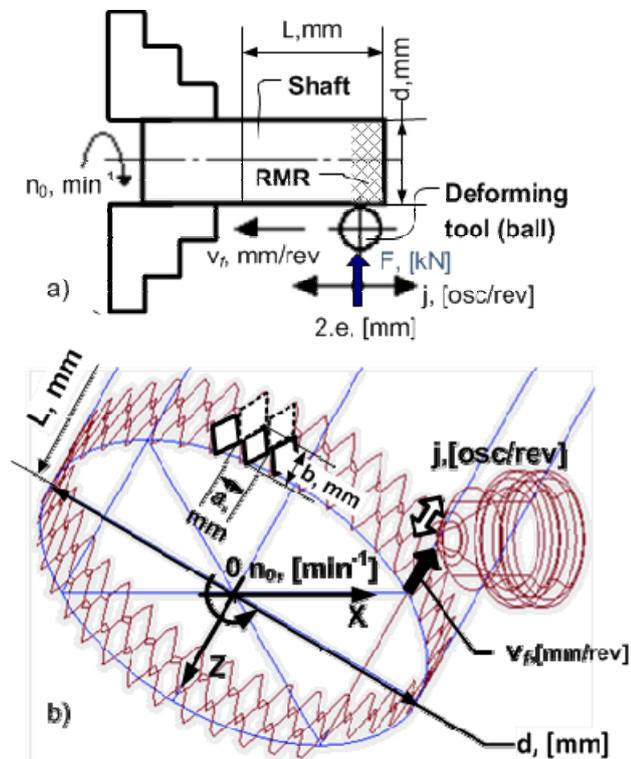


Figure 2. a) Kinematical scheme for VSPD using manually controlled lathes; (b) Toolpath and the way for obtaining the RMR cells from IV-th type, around the cylindrical surface, using VSPD process.

Using these parameters, it is possible to create appropriate mathematical model, based on periodic trigonometric functions for modelling the formation of the valleys (or cells) of RMRs wrapped around to cylindrical surface, as follows:

$$\begin{aligned} x(t) &= 0.5 \cdot d \cdot \cos(n_0 \cdot t) \\ y(t) &= 0.5 \cdot d \cdot \sin(n_0 \cdot t) \\ z(t) &= v_f \cdot t + e \cdot \cos(2\pi \cdot j \cdot t), \end{aligned} \quad (1)$$

where:  $t$ , [sec] is the time needed to processing whole length  $L$ , [mm] of the cylindrical surface. The above system of equations (1) defines the tool path, shown graphically on Figure 2,b.

Equations (1) allows to obtaining preliminary information of the shape and size of valleys or cells of the RMR that will be formed at given combination of regime parameters.

Along with above mentioned operational advantages of RMRs, there are some technological limitations and disadvantages when the process VSPD is performed using manually operated lathes, like follows:

- Constructive embedded kinematics of manually controlled lathes are usually insufficient for realization of the complex trajectory of movement of the spherical indenter in VSPD, making it necessary to design and construct additional equipment devices to provide the necessary oscillations of the tool. This leads to increase the time for preparation and raises the cost of the technological equipment for implementation of this method;
- Spindle rotation speeds and feedrate of manually controlled metalworking machines cannot be changed uninterruptedly, leading to restrictions in the form and dimensions of the achieved cells of RMR;
- The lack of synchronization between spindle rotating and linear feed movements of manually controlled lathe machines often lead to distortion of the shape and no uniformity of the cells of the relief;
- Relatively low speed feeding movements of manually operated lathe machines in comparison with CNC lathes, substantially increases cycle time and thus this method obtains low efficiency for processing of parts with large dimensions.
- The necessity of using lathe machines outfitted with special equipment for implementation the VSPD operations, complicates overall processing of the cylindrical workpieces, due to the need to refixturing from one machine to another the parts, after the execution of the others turning operations. Accordingly, the duration of the cycle increases for the overall processing of the workpiece.

Due to above reasons, the implementation of the regular reliefs, obtained by using VSPD and manually operated lathes still rarely take place in contemporary production technologies, as well as their advantages for improving performances of the contact surfaces of rotary parts are little known in the mechanical engineering industries. So their implementation most often limited to machining a specific machine parts in terms of repair (or restoration) production or in laboratory conditions.

#### PRECONDITIONS FOR IMPLEMENTING THE VSPD PROCESS USING CNC MACHINE TOOLS

The VSPD process productivity and accuracy can be significantly optimized by using opportunities of contemporary CNC machines, instead manually operated lathes, whereby the existing disadvantages and limitations of the method can be minimized or avoided.

Basically this is due to high accuracy, stability, cutting speeds and feeds of modern CNC machines

and ability to perform complex trajectories of movement of tools.

For example, the ability to control from simple 2 Axis (X,Z) turning to highly advanced Mill-Turn and Multi-Tasking centres, eliminates the necessity of using special and expensive additional devices to provide the necessary kinematics for VSPD process. Therefore the use of these machine tools would be particularly suitable for the implementation of the VSPD process in today industrial conditions.

The most basic combination turning or turn/mill machine uses a driven rotary cutter that is mounted in one or more tool pockets on the turning center turret. Linear axis movement of the rotary tool imitates that of the turning tool. Different attachments such as right angle heads allow longitudinal cutting along the X-axis while straight heads do the face work following the Z-axis travel. These tools generally run perpendicular to the workpiece surface being cut. On these machines, any milling off the machine's center curve is not possible because of the 2-axis limit of the CNC turning center. Analysing the kinematical scheme from Fig. 2a is seen that it is entirely possible to implement it on CNC lathes, because the main movements (rotating of the cylindrical workpiece and linear feed movement of the tool) can be performed by all types of CNC lathes.

The main task in this case is the provision of additional reciprocating movement of the tool with an amplitude  $2 \cdot e$ . To avoid the necessity to use additional devices to reciprocating movement of the tool it should be combined with the linear feed movement, provided by the turret of lathe machine. Therefore, the resultant movement of the tool to the linear axis (usually Z-axis for lathes) must be a combination of these two movements. Adding the rotational motion of the cylindrical workpiece (provided by rotary axis C of the spindle of the machine) the necessary tool path for VSPD operation can be obtained (i.e. the spatial sinusoidal curve from Fig. 2.b).

Entire toolpath, however, should be split into a sufficient number of elementary sections, which can be executed by CNC lathe machines (by linear interpolation in appropriate coordinate plan). Therefore it is necessary to calculate in advance the corresponding coordinates of start and end points of all elementary sections (which can be reach several tens of thousands points) of the toolpath to provide the necessary geometric accuracy of the toolpath and hence uniformity of the obtained RMR cells.

**EXPLORING THE OPPORTUNITIES FOR USING CNC LATHES WITHOUT MULTI-AXIS POSITIONING - Defining the toolpath for 2-axis limit CNC lathes**

Because considered workpiece have a cylindrical shape, the diameter  $d$  of the processed surface will be constant for the entire length  $L$  (see Fig. 2b). Therefore X-axis coordinates  $X_i$  of the points from toolpath is the same for the entire length of treatment  $L$ , i.e.  $X_i = d/2 = \text{const.}$  (where  $i \in 0 \dots p-1$ ).

The coordinates of the points  $Z_i$  along the Z-axis are calculated as summation of both feed and reciprocating movement of the tool. The Y-axis is

excluded in the system of equations (2) because the tool doesn't need to interpolate in XY or YZ coordinate plans, i.e.  $Y_i = 0$  (where  $i \in 0 \dots p-1$ ).

For calculation of the toolpath for traditional CNC lathes is used a system of two equations derived from the model equations (1), as follows:

$$X_i = \frac{d}{2}$$

$$Z_i = \frac{i \cdot L}{p} + e \cdot \cos\left(\frac{2 \cdot \pi \cdot i \cdot j \cdot n_0}{p}\right), \quad (2)$$

where:

- $p$  - is the total number of points from the curve of the toolpath ( $5000 \leq p \leq 10\,000$ ),
- $i$  ( $i \in 0 \dots p-1$ ) the index of the coordinates of the current point from the curve.

Figure 3 presents the type of resultant trajectory of movement of the tool, obtained by connecting the points whose coordinates  $X_i, Y_i$  are calculated from the system of equations (2), where curve 1 (in red) shows the evolution of the toolpath in function of time  $t$ , sec., and curve 2 (in blue) shows the arrangement of the points along the axes X and Z in the coordinate system of the CNC lathe.

From Figure 3 can be seen that as much as a larger the number of points that define the curve 2, the more precise description of toolpath will be achieved. On the other hand, the number of points  $p$  will also depend on the full (unfolded) length of the trajectory of the instrument, which itself depends on the dimensions  $d$  and  $L$  of the cylindrical surface of the workpiece. The unfolded length of the toolpath  $L_{uf}$  (see formula 6) itself depends on the dimension  $L$ , amplitude and the frequency of the reciprocating movement of the tool per one revolution of the spindle, i.e. from the parameters  $j$  and  $2 \cdot e$ , from equations (2).

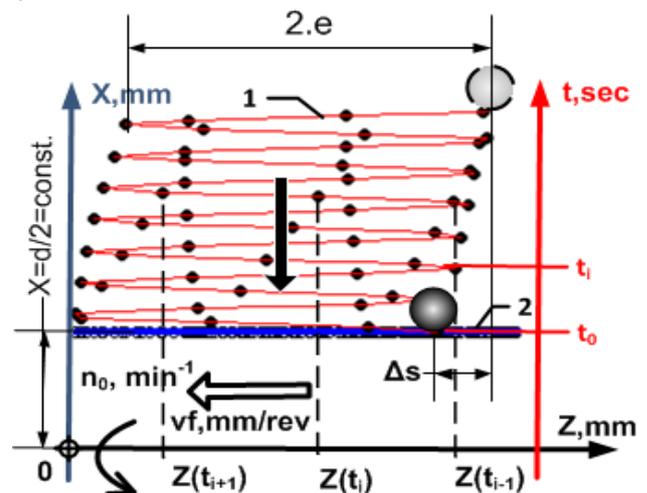


Figure 3. Graphical interpretation of the toolpath, obtained by equations (2)

**Determining of the parameters participating in equations (2)**

In order to obtain RMR cells with the necessary shape and size, the regime parameters must be determined. Some important dependencies that must be taken into consideration when determining the values of the regime parameters in equations (2) are described below.

The frequency  $j$  and amplitude of oscillations  $2.e$  determines the shape and overall dimensions of RMR cells [3]. The frequency (or as also called “Drive Ratio”) by its integer value  $j_{int}$  specifies the number of full reciprocating movements of the tool per revolution of the cylindrical workpiece, and it sets the value of the step  $a$ , [mm] of cells (see Fig. 2b). This parameter can also be determined based on the diameter  $d$ , [mm] and the step  $a$ , [mm] of the RMR cells using the following formula:

$$j \approx \frac{\pi \cdot d}{2 \cdot a} = j_{int} + j_{fract} \quad (3)$$

Typically the parameter  $j_{int}$  assumes values in the range from 50 to 150 and more.

The fractional part  $j_{fract}$  from  $j$ , determines the phase shift of the sinusoidal trajectory after each revolution of the workpiece. By setting values in the range from 0 to 0.5 for  $j_{fract}$  the shape of RMR cells can be amended to achieving fourth and fifth types of reliefs, shown in Fig. 1, d,e.

The length of the cells -  $b$ , [mm] (see Fig. 2,b) in the axial direction can be determined from the displacement  $\Delta s$ , [mm] of the tool per revolution of the workpiece due to the feed  $-v_f$ , [mm/rev] and the amplitude -  $2.e$ , [mm] using the following formula:

$$b = \Delta s + 2 \cdot e, [mm] \quad (4)$$

The necessary number of complete rotations-  $n'$ , for processing the entire length  $L$ , [mm] of the cylindrical surface of the workpiece can be defined as:

$$n' = \frac{L}{\Delta s} \quad (5)$$

where  $\Delta s$ , [mm] is the linear displacement of the tool, along the Z-axis per revolution of the workpiece.

The unfolded length of the toolpath  $L_{uf}$  (i.e. the unfolded length of the curve 2 from Figure 3) can be calculated by summing the lengths of all elementary segments, by the following formula:

$$L_{uf} = \sum_{i=1}^p |Z_i - Z_{i-1}|, [mm], \quad (6)$$

where  $Z_i$  are calculated values of the coordinates of the points in Z-axis from equations (2).

Assuming that the tool feeding speed is constant throughout the unfolded length of the trajectory  $L_{uf}$ , the feed rate  $v_f$  in [mm / rev] can be calculated by the formula:

$$v_f = \frac{L_{uf}}{n'}, [mm / rev] \quad (7)$$

The tool has to travel the entire length -  $L_{uf}$  for the same time that the cylindrical workpiece will be rotated of the required -  $n'$  rotations to completely process the cylindrical surface with length  $L$ .

The actual feed -  $v_{fm}$  in [mm/min] of the turret will be depending proportionally on the actual speed of the spindle and can be determined by known formula:

$$v_{fm} = v_f \cdot n_0 = \frac{L_{uf} \cdot n_0}{n'}, [mm / min] \quad (8)$$

where  $n_0$ , [ $\text{min}^{-1}$ ] is the actual (the lowest possible) speed of the lathe spindle.

### Analysing the results for the regime parameters of the VSPD process

Because the tool actually passes the distance, equal to the length of the unfolded curve -  $L_{uf}$ , [mm] (see the curve - position 2 in Figure 3) for the same time that the spindle will make - $n'$  turns (see equation 5), the actual feed rate must be greater than the feedrate of the traditional turning operation for the cylindrical workpiece with the same diameter  $d$  and length  $L$ . Feedrate  $v_{fm}$ , [mm/min], however, should be limited to the maximum possible feeds of the lathe turret along the Z-axis. For most of CNC lathes, the rapid feed in Z-axis cannot exceeds the upper limit of  $25 \div 35$  m/min.

Under certain combinations of values of the parameters  $L$  and  $\Delta s$  it is possible to be obtained lower values for  $n'$  (for example  $3 \div 25$  rpm) which spindles on two-axis limit CNC lathes cannot execute actually, due to limitations entered by manufacturers in the machine settings that protect them from overheating of driving motors at very low speeds of the spindle [4]. Therefore obtained by formula (5) values for the required numbers of turns of the workpiece - $n'$  will not always match with lowest possible executable speed of the lathe spindle.

Using equations (5) and (6), the resultant feedrates, determined by a formula (8) for six different combinations of sizes  $d$  and  $L$  of cylindrical surfaces, and medium values for the other regime parameters, are shown in the Table 1.

Table 1. Feedrates  $v_{fm}$  obtained from equation (8)

$N_0$	$j_{fract}$	$j_{int}$	$d$ , mm	$L$ , mm	$e$ , mm	$\Delta s$ , mm	$n'$	$n_0$ , rpm	$v_{fm}$ , m/min
1	0.15	50	30	30	1	2	15	25	5.015
2	0.15	50	30	100	4	5	20	30	24.07
3	0.15	150	100	100	4	2	50	25	59.92
4	0.45	50	100	100	1	5	20	25	5.045
5	0.45	150	30	30	4	5	6	25	60.18
6	0.45	150	30	100	1	2	50	30	18.01

As seen from Table 1, even for relatively non large sizes for the cylindrical surface, and medium regime parameters of VSPD, some of the resultant feedrates  $v_{fm}$  in [m/min] exceeds from 1.5 to 1.9x the limits of the rapid feedrates ( $25 \div 35$  m/min), even for the most highly advanced CNC lathe machines.

Moreover, for large values for the drive ratio  $j$ , and even at low frequencies of rotation of the spindle  $n_0$ , the lathe turret should perform a large number of reciprocating movements, with amplitude  $e = 1 \div 4$  mm. For example, if we have  $j = j_{int} + j_{fract} = 150.45$ , [osc./rev] (see Table1) and  $n_0 = 25$  rpm, for the required number of reciprocating movements, which the lathe turret has to be carried out for 1 second along the Z-axis, we get:

$$\frac{n_0 \cdot j}{60} = \frac{25 \cdot 150.45}{60} \approx 63, [osc. / sec] \approx 63, [Hz] \quad (9)$$

The results, from Table 1 and formula (9) clearly show that processing cylindrical parts by using VSPD on only 2-axis limited CNC lathes is practically inapplicable.

### USING MULTI-AXIS TURNING CENTERS FOR IMPLEMENTATION THE VSPD OPERATIONS - Benefits of the multi-axis machining

Multi-axis machining is a manufacturing process, where computer numerically controlled tools that move in 4 or more axes is used to manufacture parts out. Typical CNC tools support translation in 3 axes, but multi-axis machines also support rotation around one or multiple axes.

Multi-axis CNC lathe machines offer several improvements over other CNC lathes at the cost of increased complexity and price of the machine:

- Amount of work is reduced, if the piece would otherwise have to be refixturing manually during the machining.
- Better surface finish can be obtained by moving the tool tangentially about the surface.
- More complex parts can be manufactured, particularly parts with curved grooves, pockets etc.

Number of axes for multi-axis machines usually varies from 4 to 9 [2,4]. Each axis of movement is implemented either by moving the spindle (into which the workpiece is attached), or by moving the tool. The actual configuration of axes varies therefore machines with the same number of axes can differ in the movements that can be performed.

As for the rotary C-axis or spindle, it is generally an orientation-only axis on basic CNC lathe/turn machines. A coupling or other device inhibits rotation while milling, drilling or tapping operations are performed.

The next level of sophistication is to add servo-controlled actuation of the rotary C-axis. This is a common feature available on many turn/mill machine tools. Often a secondary motor is used to drive the spindle for contouring cuts. The main spindle motor would be disconnected in this case. In combination with the live tooling on the turning center turret, the C-axis adds the ability to make spiral-milling cuts, contours or other relatively complex interpolated geometries. The C-axis is widely used for the processing that more than two axes move at the same time, and the speed of rotation around Z-axis may range from 0.06 °/min to 45 rpm. Because of the lower speeds of spindles and possibility for synchronization both linear and rotational movements, would be more appropriate this type of machine tools to be used for the implementation of the process VPPD than the traditional CNC lathes (with only two-axis).

### Defining the VSPD operations using CAM software systems

There are many CAM (computer aided manufacturing) software systems available to support multi-axis machining including software that can automatically convert turning or milling operations into 4-axes toolpaths.

FeatureCAM is a CAD/CAM software suite that automates machining and minimizes programming times for parts on mills, lathes, and wire EDM [1,5]. FeatureCAM generates toolpaths based on the features of the part, and automatically selects appropriate tools, determines roughing and finishing passes, and calculates feeds and speeds, based on the software's built-in machining knowledge.

The module FeatureTURN/MILL as part of FeatureCAM enables both turning and milling features to be created on a single machine in one set-up. It incorporates all the options within FeatureTURN and FeatureMILL2.5D stand-alone modules for traditional turning and 2.5D milling operations, and can be used to program CNC lathes with C-axis milling capabilities. Integrated 3D machine simulation, together with a library of over 350 fully customisable post-processors, enables visualization of exactly how the parts will be machined. During the simulation of the modelled turning and milling operations, FeatureCAM automatically outputs the corresponding NC code for various CNC turn/mill centers.

The main advantages of FeatureCAM, in the context of the present work, are the abilities to easily import (or define) the shape, material parameters and dimensions of the stock and part, quickly programming of turning and milling features on the outside diameter of a part with the FeatureTURN/MILL feature wizard, which in combination with the included "Curve Creation dialog" wizards, greatly facilitates the creation of the required toolpaths and the corresponding operations for processing by VSPD.

The sequence of the steps, required for defining operation for vibratory superficially plastic deformation of the cylindrical surface (using the module FeatureTURN/MILL, v.18 from FeatureCAM 2012, Delcam, UK) of the shaft with length-  $L=80$ , [mm] and diameter -  $d=50$ , [mm], will be discussed below. The required step by step sequence is shown in the flowchart in Figure 4.

#### □ Step 1: Defining the Stock

The Stock wizard of FeatureCAM provides step-by-step dialog boxes for specifying or modifying the general stock shape, specific stock dimensions, part program zero, and the origin of the modelling coordinate system. The stock shape is selected as Round and in the fields Length= 80, mm and OD (outside diameter) = 50, mm are filed in.

#### □ Step 2: Defining the curve of the toolpath

To create the curve that describes the toolpath using the Curve wizard dialog box that provides step-by-step instructions for creating curves using a variety of methods.

Because we already have the mathematical model (see Eq. 1 and Fig. 1), which describes the spatial curve of the toolpath wrapped around the cylindrical surface, using the method Functions from the Other Methods section of the Curve wizard, as follow:

$$x = F(t), y = G(t), z = H(t), \quad (10)$$

where  $F$ ,  $G$ , and  $H$  are fields where the functions  $F(t)$ ,  $G(t)$ , and  $H(t)$  must be entered separately. The

argument in all three functions -  $t$  is the same and varies from Start to End values with step given by the Increment value. When filling the functions in these fields, the other parameters ( $d$ ,  $e$ ,  $v_f$ ,  $n_0$  and  $j$ ) participating in the model (see eq. 1) should be replaced with their numerical values. The three functions are shown below as their parameters are replaced with the appropriate indicative numerical values, for example:

$$\begin{aligned} F: & 25 \cdot \cos(t \cdot 3), & G: & 25 \cdot \sin(t \cdot 3), \\ H: & -t + 2.5 \cdot \cos(2 \cdot \pi \cdot 150.5 \cdot t) \end{aligned} \quad (11)$$

Functions (11) are filled in the fields F, G, and H of the dialog box "Functions" (see Fig.4-Step 2).

which the functions are evaluated. In this box is entered the value 40, which indicates that the curve of the toolpath will end in a point with coordinate  $Z=40$ , mm. The Increment field sets the value added to or subtracted from the previous point evaluated for the functions to determine the next value to be run through the functions. Because the curve in our case is complex for its accurate drawing the increment value should be a smaller (for example 0.005). FeatureCAM generates the curve and apply the generated function to the drawing as geometry (see Step 2 on Fig. 4).

□ Step 3: Defining the toolpath feature and setting up the VSPD operation.

In FeatureCAM, toolpaths are generated from features, not curves; so that the part model is create using features. Features are common shop terms for describing characteristics of a part, for example, holes, pockets, slots, or step bores. These are the objects from which are create and customize toolpaths. Features provide additional information for automating the generation of toolpaths for part. FeatureCAM generates the related operations automatically. The New Feature wizard of FeatureCAM walks through the process of creation of features. This wizard guides the user through following stages:

- Selecting the type and positioning the feature.
- Specifying the manufacturing strategy.
- Reviewing the automatically selected tools, calculated feeds and speeds.
- Overriding the tooling and feed/speed values and changing manufacturing attributes.

A Toolpath feature explicitly represents a single toolpath, which create the moves of a toolpath by the curve defined in Step 2. This allows using the created curve to control the path of the tool precisely. Each Toolpath feature creates a single toolpath operation. Each toolpath operation has a Tools, Feed/Speed, and Toolpaths tabs, where filled out (or selected) the data for the type and the dimensions of the selected tool, feed and speed, and the calculated coordinates of the points of the toolpath.

Basically VPPD process doesn't require the ball-tool to perform rotations during operation, because smooth steel balls without cutting teeth are used instead of cutting tool. Because FeatureCAM not foreseen for modelling the operations such VSPD, the Toolpath operation is actually simulated as a contour milling operation with ball end endmill, that is modified such as hemisphere with a certain diameter. For that reason FeatureCAM calculates and displays in the F/S tab recommended speed of rotation for the tool. The calculated speed can be overridden to the minimum (or recommended) values specified by the manufacturer of the CNC lathe/mill center.

□ Step 4: Simulating the VSPD operation and automatically generating the NC code

FeatureCAM can provide several types of simulation. Step 4 on Fig. 4 shows the 3D Solid Simulation of the part (sometimes called Visicut) and VSPD operation. This style shows a three-dimensional shaded

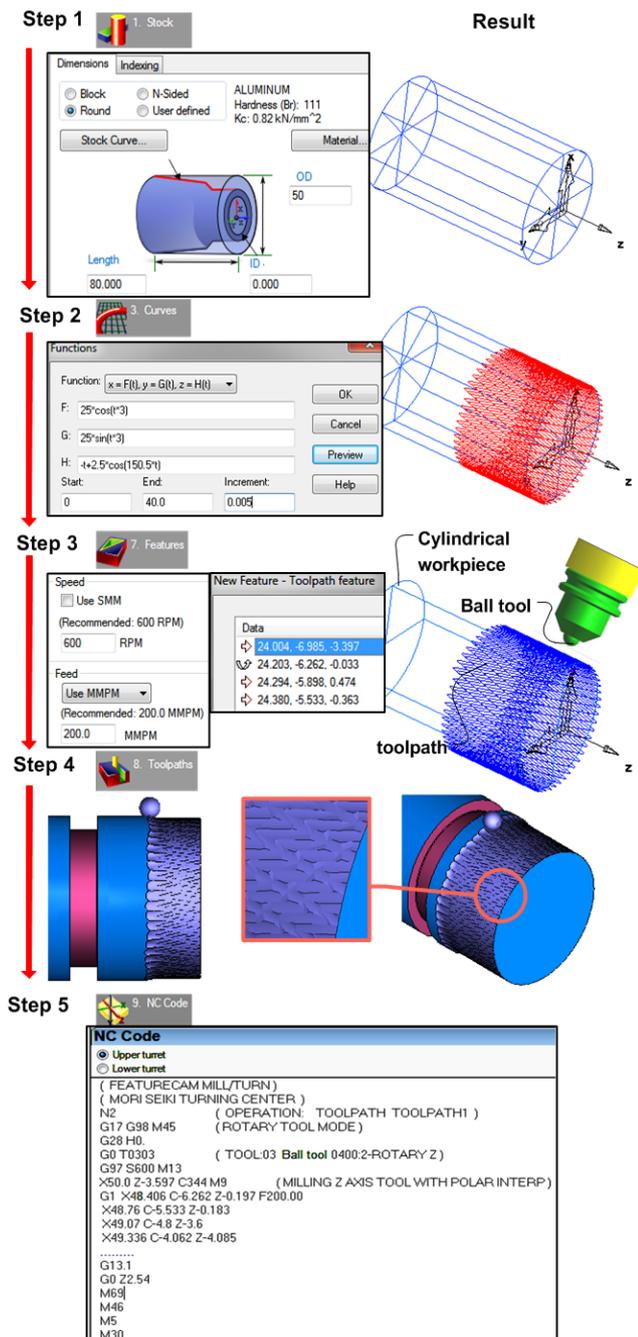


Figure 4. Sequence of steps for modelling the VSPD operation using FeatureCAM software

The Start field sets the starting point for the range over which the functions are evaluated. In this box is entered 0, which indicates that the curve of the toolpath will start from a point with coordinate  $Z=0$ . The End field sets the ending point for the range over

rendering of the initial stock and simulates material removal in 3D. With that simulation method, video-style controls are used to pause, stop, and step through the toolpath, giving a fine control over the process. The Toolpath simulation is an important step in FeatureCAM in order to produce the NC (Numerical Control) code for the part. Prior to start simulation, it is important a suitable postprocessor to be selected, corresponding to the 4-axis CNC Turn/Mill center that will be used to perform the VSPD operation. The selected postprocessor (CNC file) could be either one that comes as standard with FeatureCAM or one that is created/modified with the XBUILD program. Using the different types of simulations that provides FeatureCAM it is possible to trace the toolpath as well as see the characteristics (shape and dimensions) of the cells from regular relief, obtained as a result of the execution of VSPD operation (see Step 4 in Fig. 4). After the simulation of VSPD operation complete the NC Code tab from Results section becomes active.

□ **Step 5: Reviewing and storing the NC code.**

Once the toolpath is simulated, the VSPD operation parameters are translated using a selected postprocessor into machine G-code. The NC Code dialog box of FeatureCAM in which is generated numeric control code is shown in Fig. 4 - Step 5. By clicking the Save NC button in the NC Code dialog generated NC code can be saved as a file.

**CONCLUSIONS**

Considered in this work possibilities for implementing the vibratory superficially plastic deformation process for making the regular reliefs on cylindrical surfaces, using traditional 2-axis lathes and 4-axis turn/mill centers (with rotary C-axis), leads to the following conclusions:

- Despite the fact that 2-axis CNC lathes have the requisite kinematics and seemingly be able to provide the necessary movements both of the workpiece and tool to execute the VSPD operation, in practice the process cannot be implemented to them due to the lack of synchronization between the rotary motion of the workpiece and reciprocation feed movement of the tool. Even at the lowest speed of rotation of the spindle the frequency of reciprocating movement of the lathe turret would be too high (50 to 65 Hz, see eq.9) to actually execute at the lathe machine;
- For practical execution of the VPPD operations, however, can be used appropriate 4-axis turn/mill centers, due to their ability to perform interpolations between the rotation speed of the workpiece (around rotary axes) and linear movements of the ball-tool as well as carrying out the contour milling operations.
- Using the capabilities of FeatureCAM for programming live tooling operations for multi-axis machines, enables the programming of toolpaths and other parameters of the VPPD operations as well as automated generation of the NC code, required for driving the CNC machine tool.

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