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INCREASING THE ACCURACY OF VARIABLE-PITCH CONE WORMS

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Abstract: *Variable-pitch cone worms are cut on special numerically controlled machine tools. The article provides the basics of machining of these worms on a universal multi-purpose CNC machine tool. The developed machining program is universal in character and makes it possible to increase the efficiency and accuracy of worm machining. For the programming of worm and cutter relative motion, the G01linear interpolation function was employed. The trials were carried out on a MAZAK INTEGREX IV 200ST CNC machine tool.*

Keywords: *cone worm, programming, variable pitch, multi-purpose machine tool.*

1. INTRODUCTION

Variable-pitch cone worms are used in extruding presses for processing plastics. The accuracy of worm execution determines the efficiency of the extruding press and the degree of material mixing in the extruder's plasticizing system. A plasticizing system is ideally composed of two variable-pitch cone worms that mesh together non-tightly [1, 4].

Such worms are cut on special numerically controlled machine tools. As the geometry of variable-pitch cone worms is variable along the worm length, the verification and technology of these worms are very difficult. Worms are cut with a finger-type conical milling cutter, positioned perpendicularly to the worm cut bottom. At the same time, the distance of the cutter axis from the worm axis should be variable as the tool moves along the worm axis during machining (Fig. 1), which is not possible to achieve on any machine tool. Special machine tools are very expensive, and their productivity is generally low. The machining of a warm takes up to several dozens hours (worms are up to 6 m in length). Below, a change to this technology is proposed, based on modern multi-purpose CNC machine tools; for this purpose, an appropriate program has been developed to control the Mazak INTEGREX universal machine tool.

2. THE MACHINING PROGRAM

Many CAD/CAM programs offer capabilities to create the design of the geometry of a part to be machined, after which the code of machining of this part on the CNC machine tool is automatically generated. In the case of the variable-pitch cone worm, this has not been possible due to its specific geometry.
In the EIA/ISO code for programming worm machining, the *G*33 function can be utilized, which, however, does not allow the variable warm pitch to be programmed.

As the helical motion is a composition of rotary motion and rectilinear motion, the possibility of separate programming of these two motions was used. Thus, the programming of variable-pitch cone worm machining was based on the use of the function *G*01 of linear interpolation. A cylindrical finger-type milling cutter was employed for machining, whereby the cutter had different angles of inclination for the left-hand and the right-hand side of the worm convolutions.

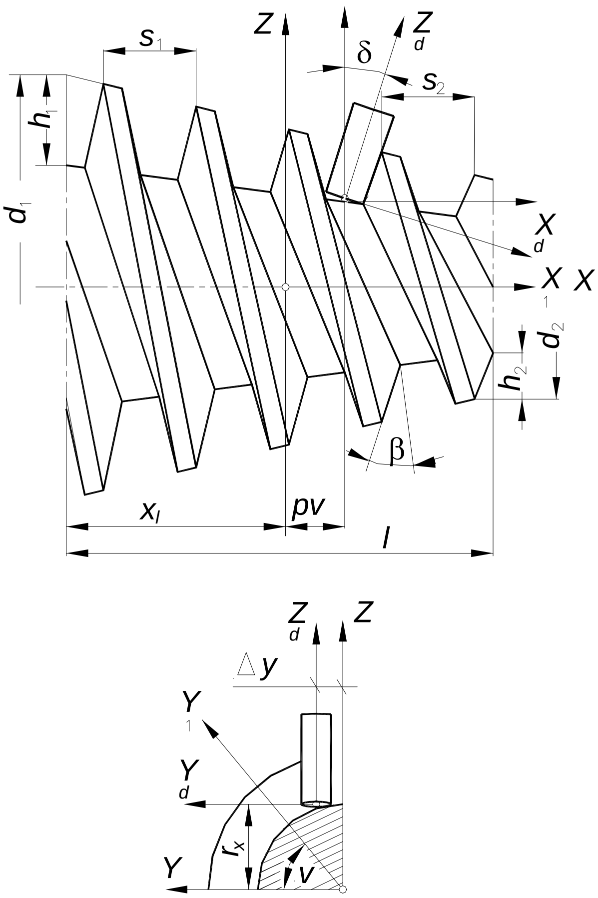

Fig. 1. Warm and cutter positioning: indexes 1 and 2 mean start and end of the zone (worm), *l* - zone length, *S* – pitch, *h* – profile height, β - axial section profile angle, Δy - offset (distance between the tool axis and the worm axis), *p* – parameter of the relative helical motion of the worm and tool, *d* - outer diameter, δ - inclination of the tool, x_l – the cross section distance along the axis of the worm, r_x – the radial distance of the tool from axis of the worm.

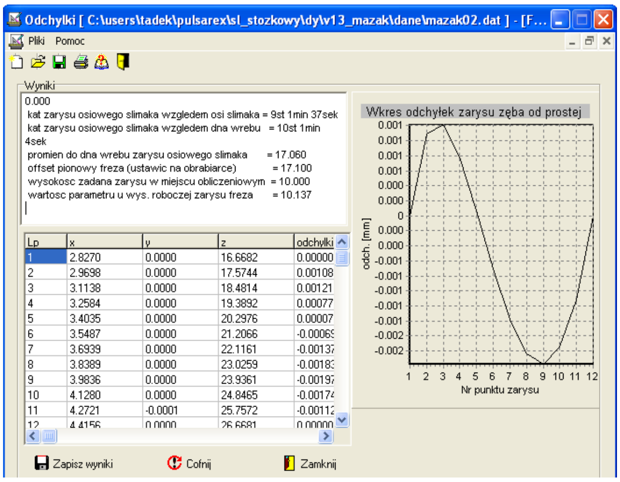

Fig. 2. Deviations of the worm axial profile from the straight line in the computational section.

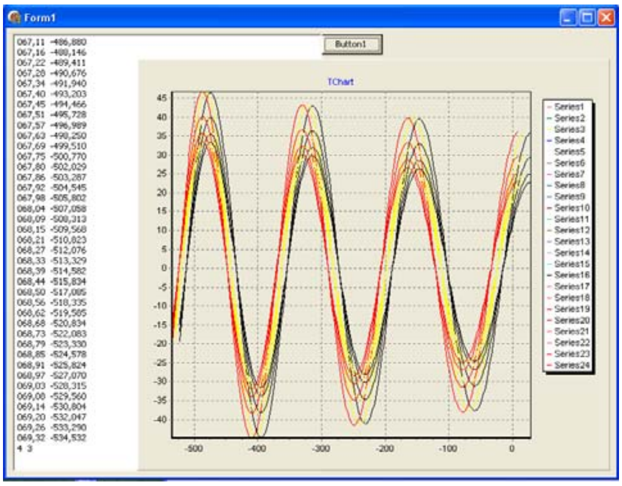

Fig. 4. Simulation of successive tool passes during cone worm machining.

In such a case, the warm cut bottom and the warm convolution flanks are machined separately. The worm profile in the axial section should be rectilinear. In order to obtain the adequate accuracy of the worm axial profile, the value of the distance between the cutter axis and the worm axis, Δy (Fig. 1) should be determined at the beginning and at the end of the worm. For the optimal value of this parameter, the deviations of the axial worm profile from the straight line are symmetrical (Fig. 2).

The program has been developed for the Mazak INTEGREX IV 200ST CNC machine tool with the MAZATROL MATRIX CAM control system[6], which has a stepwise regulation of spindle rotation about the $C1$ axis with a step of 0.0001° (the machine tool has also another spindle with the axis of rotation C_2 and the axial displacement W) and a stepwise regulation of tool slide displacement with a step of 0.0001 mm. Due to the high profile height, the worm is machined in several passes. The upper tool slide (with the controlled axes X, Y, Z and B) can make use of up to 20 tools from the tool store (the machine tool has also a lower tool slide with the axes X_2 and Z_2), which enhances the engineering capabilities of the machine tool.

The machine tool has a capability to perform the control of tool motion trajectory simulation on the control panel screen (Fig. 3), also during machine tool operation and machining of another part. Simulation can be carried out in the real time of machining, which enables the selection of appropriate parameters in terms of efficiency and machining accuracy (in the main program of worm machining control, the simulation time was regulated with the parameter #104; simulation may also be discontinued at any time).

Mazak machine tools can operate in the Ethernet network and can also be remotely programmed. The MAZATROL MATRIX CAM control system runs in the MS Windows environment and, just like a PC, has a 20 GB hard disk for archiving of programs, and a USB port. In the process of geometrical analysis [1, 2, 3, 4] and determination of engineering worm parameters, simulation was also carried out on a computer (Fig. 4).

The program is written in the EIA/ISO code, and due to the fact that the worm is normally multi-convolution, the modular program structure and the universal procedures in-cycle call are used. Parametric programming is utilized, owing to which the program is universal in character and, after changing the input parameters, it can serve for controlling a machine tool during machining of cone or cylindrical worms (Fig. 5) with either a variable or constant pitch. The worm pitch has different values at the end and at the beginning, but can also be different for the left-hand or right-hand side of the worm.

Not only should the worm axial profile be rectilinear, but also the worm profile angle should be constant. The INTEGREX IV machine tool enables an infinitely variable change of the tool around the axis B during worm machining, which should make it possible to reduce any errors in the worm axial profile angle. Special machine

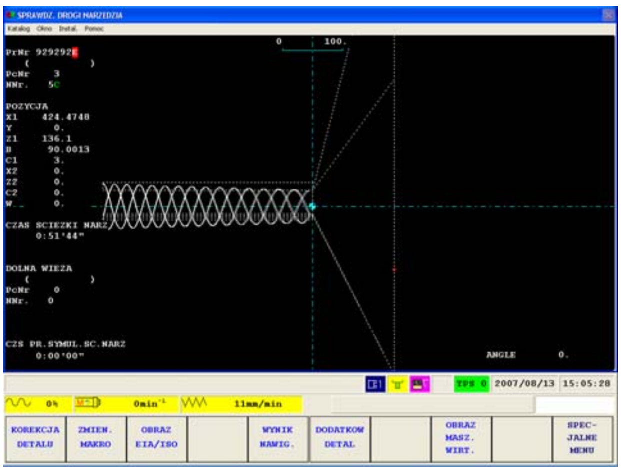

Fig. 3. Simulation of the tool motion trajectory.

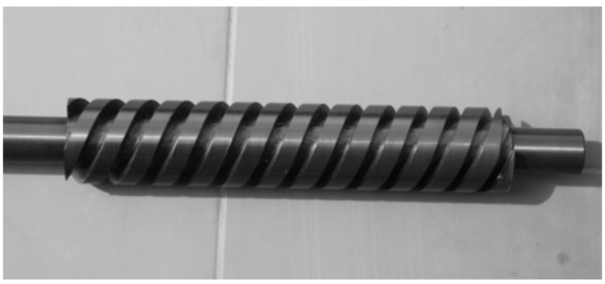

Fig. 5. A variable-pitch cylindrical worm.

tools designed for the machining of cone worms intended for extruding presses generally have no such a capability.

The whole program is divided into three parts. The main module controls the program's operation and the sequence of calling up individual subroutines. The input data module contains values input by the user. Some of those values describe directly the worm geometry (for example, #117=3 defines the number of worm convolutions), and the others result of the geometric worm analysis (for example, #126=6 describes the offset on the right-hand convolution side at the worm beginning) and are computed in a special program.

```
<1000>    (INPUT DATA SUBROUTINE)
#100=12      (DF SR. FR.)
#101=347.7626 (CUTTER VERTEX ROT. RADIUS)
#102=120     (PERIMETER DIVISION)
#104=1000    (ACCEL.)
#105=360/#102   (UNIT ANGLE)
#115=180     (S1ZONE START PITCH)
#116=144     (S2ZONE END PITCH)
#117=3       (Z  NO. OF CONVOLUTIONS)
#118=675     (L  ZONE LENGTH)
#119=90.5    (D1    ZONE START O. DIAM.)
#120=115.408 (D2    ZONE START O. DIAM.)
#121=22      (H1    ZONE START PROFILE HEIGHT)
#122=24.299 (H2    ZONE END PROFILE HEIGHT)
#123=35.22   (B1    ZONE START CUT  O. WIDTH)
#124=29.7    (B2    ZONE END CUT O. WIDTH)
#125=10      (ALFA        PROFILE ANGLE)
#126=-6      (DY1PO RIGHT START OFFSET)
#127=6       (DY1L    LEFT START OFFSET)
#128=-4.35   (DY2PO RIGHT END OFFSET)
#129=4.35    (DY2L LEFT END OFFSET)
#130=23.25   (X1P  RIGHT X RAD. DEV. AT ZONE START)
#131=23.25   (X1L  LEFT X RAD. DEV. AT ZONE START)
#132=33.405 (X2P  RIGHT X RAD. DEV. AT ZONE END)
#133=33.405 (X2L  LEFT X RAD. DEV. AT ZONE END)
#134=10.08   (DW   CUT BREAK-UP)
#136=8       (DALFAP1 CORR. OF RIGHT START. MILL POS. ANGLE)
#137=8       (DALFAL1 CORR. OF LEFT START. MILL POS. ANGLE)
#138=8       (DALFAP2 CORR. OF RIGHT END MILL POS. ANGLE)
#139=8       (DALFAL2 CORR. OF LEFT END MILL POS. ANGLE)
```

Further on in this module, additional auxiliary data are calculated, which are used in the machine tool control program.

The universal module includes procedures that do not require any intervention by the program's user. Using parameters in this part of the program makes the code difficult to understand without an additional description.

```
<2000>(2000 – RIGHT-HAND SIDE SUBROUTINE)
G98110000M203
#500=#500+1
#912=#911+#105*#500
#580=#115+#160/[#106-1]*#500
#582=#582+#580/#102
#584=-#176+#582
#590=#175+2*#166*#500
#592=#126+#168*#500
G1Z-#584X#590Y#592F#104*#580C#912
M99

<3000>(3000 - LEFT-HAND SIDE SUBROUTINE)
G98S10000M203
#500=#500+1
#912=#911+#105*#500
#581=#115+#161/[#106-1]*#500
#583=#583+#581/#102
#585=-#176+#583
#593=#175+2*#167*#500
#594=#127+#169*#500
G1Z-#585X#593Y#594F#104*#581C#912
M99
```

The two last subroutines (shown above) related to the machining of the left-hand and right-hand side of the worm, respectively, and, as indicated by the rows starting from the instructions *G*1, four axes are controlled. This version of the program has not taken advantage of the possibility of changing the inclination angle of the axis B of the machine-tool tool spindle yet, though such a possibility does exist, which is indicated by the fragment of the main program's module shown below. Due to the use of the finger-type cylindrical cutter for the machining of two convolution sides, changes in the cutter positioning angle are foreseen. This is on condition, however, that this angle is changed between the respective machining cycles. In the program fragment quoted above, the *SIN* and *COS* trigonometric functions are used. The MAZATROL MATRIX CAM control program enables the building of very complex control programs employing elements characteristic of languages used for programming computation on PCs.

```
G0X#170Z#172            (P. A)
B[90-#151-#136]
#570=#170-2*#101*[COS[#151]-COS[#151+#136]]
#571=#172+#101*[SIN[#151+#136]-SIN[#151]]
G0X#570Z#571            (P. A)
#911=0
G0C#911
G0X#175Z#176            (P. 1)
#600=0
#566=#175
#567=#176
#586=#175
#587=#176
G65P4200L4
B[90-#151+#137]
#570=#170-2*#101*[COS[#151]-COS[#151-#137]]
#571=#172-#101*[SIN[#151-#137]+SIN[#151]]
G0X#570Z#571            (P. A)
#911=0
G0C#911
G0X#175Z#176            (P. 1)
#600=0
```

```
#566=#175
#567=#176
#586=#175
#587=#176
G65P4300L4
```

Obviously, an infinitely variable change of this angle (rotation around the axis *B*), by analogy to the change of the main machine tool spindle rotation angle (around the axis C_1), is possible. This requires, however, and additional geometrical analysis of the worm machining process and the calculation of the limiting values of this angle (the parameter Δy has a vital effect on the accuracy of the worm axial profile).

Considering the engineering capabilities of the INTEGREX machine tool and the increasingly high demands on the accuracy of execution of machine parts, investigation in this matter has also been undertaken. Whereas, the modification of the control program will already be simple.

On special machine tools, worms are machined with solid finger-type conical cutters of a frontal diameter of 14 mm and an axial profile angle of 9°, irrespective of the worm size [1]. The machining efficiency and accuracy is small. The surface roughness is much higher than the worm profile accuracy obtainable theoretically [1, 4]. After milling, the worms are ground with grinding belts on a turning lathe. The use of finger-type cutters with a diameter matched to the worm cut width should enhance the efficiency and accuracy of machining. In some instances, it will be possible to use composite cutters, with the reservation that, when machining with a finger-type cutter, an undercutting of the other cut side will occur, if the cutter diameter is too large. The INTEGREX universal machine tool has high rigidity and allows a high efficiency to be achieved with a high machining accuracy. The development of this technology requires further studies, which are, however, difficult to accomplish due to the costs of the worms themselves. Nevertheless, this development will certainly pay off. This is all the more that, on a principle similar to that for variable-pitch cone worms, also globoid worms with a rectilinear axial-section profile could be cut on an INTEGREX- type machine tool.

The geometric analysis program enables the simulation of the mating of a system composed of two worms, and the examination of clearances between worm convolutions [1, 4, 5]. In practice, the distribution of clearances is determined after the worms have been executed, and it happens that the worms do not mesh together, or the clearances are not correct. This is due to the fact that, in principle, there is no suitable method of worm measurement in the process of worm machining. The measurement of the clearance between the convolutions of mating worms, on the other hand, is actually very inaccurate. A very efficient method of examining the mating of worms at the stage of their design has now been developed, whereby worm engineering parameters are determined, which are taken into account in the machine tool control program.

3. CONCLUSIONS

Modern multi-purpose CNC machine tools enable the machining of variable-pitch cone worms that have been machined so far on specialized machine tools. The engineering capabilities of a universal machine tool are much higher, and the machining process can be easily optimized by writing an appropriate computation program. As a result, not only an increased machining efficiency, but also an enhanced machining accuracy can be achieved. The developed program is universal in character and can be used for cutting of cone or cylindrical worms with either a constant or variable pitch. Making use of the results of geometrical cone worm analysis and simulation of the operation of the two-cone worm system in the machine tool control program enables the elimination of rejects and a reduction of production costs. The systems of programming modern CNC machine tools make it possible to build programs executing complex computational algorithms, and the operation of the machine tool's control panel is analogous to working on a PC.

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