Progressive screw shaft manufacturing technology

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Abstract. The progressive screw shaft is one of the very challenging part for machining. It might have a decisive influence on the precision of the parts processed by the machine tool. In this paper is presented a new, innovative technology of its manufacturing. The first goal is to develop a technological process for CNC milling machine. Technological process is fully described and with all parameters given and commented. Technology for progressive screw shaft manufacturing is developed in Autodesk Inventor HSM software. The second goal of the paper is a comparative analysis of the here described process for milling the different profile shapes. In the paper are given the milling examples of rectangular and circular profiles. Paper aims to emphasize the advantages and disadvantages of the proposed method. Some conclusions and directions to next research steps are given at the end of the paper.

1. Introduction

The thread is defined by a profile which is wrapped around of cylinder in the form of helix. The threads can be internal, wrapped into internal cylindrical surface, or external, wrapped onto external cylindrical surface. In the machine practise there are many types of threads such as: metric, trapezoidal, various pipe threads etc. Threads can be used for static components, for assembling purpose, and rotary components. Threads in rotary components turn rotary motion into translation along the thread axis, and torque into axial force. The rotary components with thread are called power screw joints. There are numerous applications for power screw joints such as: car jacks, linear motion applications in tooling machines, usage in processing equipment, lifting applications etc. The described cases of thread usage have the constant thread pitch. In the other thread applications, such as transportation technique, pumps, positioners etc., thread can often have a variable pitch. Shaft with variable thread pitch is called progressive shaft. Progressive shafts can have two, three or more different pitches. Segments having different pitches are joined together to continue each other and form a single thread with variable pitch. Manufacturing technology of progressive shafts is a very demanding one, and it can vary depending on size series in production. The progressive shafts are mostly produced on lathes with special tooling, CNC lathes, CNC machining centres and etc.

The progressive shafts, due to their specific geometry, is a very interesting topic for researchers worldwide from couple different aspects: application, manufacturing technology etc. R F Gillie considered variable pitch screw drive in vehicle stability control [1]. In that case variable pitch screw drives indicates to be very reliable solution. P D Lin and M F Lee did a research about NC data generation in order to produce variable pitch screws with four-axis milling machine [2]. They derived equations which was used for machine NC programming. J Y Liu and H S Yan performed geometry...
design of trapezoidal variable pitch lead screws [3]. Their paper was significant in this research field because it gave complete mathematical model of progressive screw geometry. Senanayake S and Clarke B did a design, manufacturing and testing of food extruder which consists of two meshed progressive screw shafts [4]. Slătineanu L et al. did a manufacturing of threads with variable pitch by using noncircular gears [5]. Their technology is based on turning. Li et al did a program for NC code generation depending of the progressive shaft input dimensions [6]. This research is interesting, but it is performed only for rectangular thread profile. This technology for progressive screw manufacturing is based, as well on turning. The group of authors performed study on the computer numerical control process of variable pitch, groove depth and groove width screw [7]. Gyenge et al. created new manufacturing technology for variable pitch and variable screw profile worms which is based on turning [8]. They were using ProE for doing a CNC machining and developing the technology. Nabeta et al. developed their own algorithm for turning of progressive screw shaft.

Apart from these, in this paper is described a problem with manufacturing progressive screw shaft using three-axis CNC machine. For CNC programming Autodesk Inventor HSM was used. At the end of the paper conclusions are shown and comparison is made with other presented technologies for progressive shaft manufacturing.

2. Manufacturing problem description
The idea of solving the problem with progressive shaft manufacturing on three-axis CNC machining centre, for this particular paper, was developed within an industrial project of the authors. Namely, the authors held CNC machining training course in company which produces packing equipment. One of the training challenging part was introducing the company workers with machining technology of progressive shaft screw. Progressive shaft screw was used as positioner in the bottle filling machine. Examples of progressive shafts are shown in figure 1. Example in figure 1 (b) is done by proposed technology in this paper.

![Figure 1. Installed progressive shaft on the machine.](image)

The progressive shafts, shown in figure 1 were made of Polyamide (PA6). The progressive shafts shown in figure 1 was used for different filling types of bottles. The type of the bottle, bottle geometry dictates the shape of progressive shaft profile. Most commonly used types of bottle are shown in figure 2.
Figure 2. Bottle types: (a) round bottle; (b) square bottle.

On the shaft beginning helix start with smallest pitch, while on the shaft end helix pitch is increased to wanted dimension for bottle distance, position one to another.

The company owns CNC lathes and three-axis CNC milling machine, both shown in figure 3. Both of the machines had the Siemens SINUMERIK 828D controlling unit.

Figure 3. CNC machines:
(a) CNC Lathe and (b) three-axis CNC milling machine.

The problem with machining by using CNC lathe was limited by purchased licenses in the controlling unit and as well with maximum thread pitches which can be achieved. Milling machine was limited because it was three-axis milling machine. The single way to solve this demanding task was introducing the fourth axis into milling machine table which can have the dividing head. The fourth axis was took from company conventional machine. The fourth axis apparatus is shown in figure 4.

Figure 4. The fourth axis introduction to three-axis milling machine table.
In the Siemens SINUMERIK 828D controlling unit the fourth axis is available for usage, but without appropriate equipment it cannot be used. Instead of that progressive shaft manufacturing was performed as 3D milling.

3. Manufacturing technology of progressive screw shafts
For developing of manufacturing technology the Autodesk Inventor HSM software was used. Autodesk Inventor HSM supports a very large amount of post processors for various types of CNC machines, which made it a logical choice for solving this problem. The both helix profiles was used: for square bottles, and for round bottles. The helix profile shapes are given in figure 5.

![Helix profile shapes](image)

**Figure 5.** Helix profile shapes:
(a) for rectangular bottles; (b) for round bottles.

The progressive shaft diameter is 120mm, while pitches are respectively, 90 mm, 120 mm and 150 mm. For both shafts the same diameter and same pitches were used. In figure 6 are sown shaft 3D models.

![Shaft 3D models](image)

**Figure 6.** Shaft 3D models:
(a) for rectangular bottles; (b) for round bottles.

In order to easily do the CNC programming the corrections were done on the progressive shafts models at the joints of two neighbour pitches. Namely, the shaft models were divided into 6 different models states, which represents 6 various separate operations. The example of one model state per one operation is shown in figure 7.
Figure 7. Shaft model state example per operation.

Per each of those operations the roughing and finishing was performed. For roughing it was used bullnose mill with diameter of 10 mm. For finishing it was used ball mill with diameter of 10 mm as well. The machining parameters of cutting tools are given in figure 8. Machining parameters were adopted to be best for machining of PA6.

(a)

(b)

Figure 8. Cutting parameters: (a) bullnose mill; (b) ball mill.

The same parameters were used for machining of both shafts. Roughing phase was done for both shafts by usage of 3D pocket Inventor HSM option. In figure 9 is shown geometry for rouging cutting tool, and finishing cutting tool. These tools have to be set to work with cutting parameters shown in figure 8.
Figure 9. Cutting tools:
(a) bullnose mill-roughing tool;
(b) ball mill-finishing tool [10].

The roughing phase is shown in figure 10.

Figure 10. Roughing phase: (a) for rectangular bottles; (b) for round bottles; (c) path detail.

The finishing phase was performed by Parallel command in Inventor HSM. Doing the parallel command was performed by setting machining angle to be equal with helix angle, except on helix transitions. This action must be performed in order to get helix surface as smoothest as possible. On helix transitions it was used arithmetic mean of helix angles. Finishing phase is shown in figure 11.
Figure 11. Finishing phase: (a) for rectangular bottles; (b) for round bottles; (c) path detail.

The machining time for square bottles progressive shaft per operation is 1 hour and 20 minutes, while for round bottles is around 1 hour and 11 minutes. This difference is caused of the larger section of square profile, so more material to be removed. Total machining time of progressive shaft for round bottles is about 11.25% shorter related to the machining time of progressive shaft for rectangular bottles.

4. Conclusions
In this paper is shown combined usage of old and new technologies in order to get optimal solution for progressive shaft manufacturing constrained with certain circumstances: those given by specific technological equipment endowment of a certain plant. This innovative solution allowed processing complex parts with no supplementary expenses for special technological equipment. The limitation in equipment was overridden by introducing an existing fourth axis to standard 3D CNC milling process. The fourth axis was fictive for the milling process. The progressive shaft manufacturing is bring down to making 3D pockets per certain angles. Advantages of used technology are:

- There were no need for additional special made apparatus;
- The both cases for square and round bottles progressive shat positioners was covered;
- Elix profile by this technology can be very customized;
- There were no need to use the complicated functions with massive NC code output;
- There were no need for customized cutting tools.
- Yet there are some disadvantages, as well:
  - The shaft length is limited by CNC milling machine table; this can be overcome by joining together several parts end to end;
  - Longer machining time related to other technologies;
  - By k axis rotation possible errors on joints might occur;
  - Profiles with negative edges cannot be performed without special cutting tools;
  - Progressive shaft diameter is limited by dividing indexing head.

The presented machining process is very feasible and flexible. However, there is much space for improving the presented process, such as parameterizing the progressive shaft model, parameterizing the machining steps related to the helix profiles, examining various cutting tools to get process better etc. The most challenging one is obtaining a continuous increasing pitch, not one divided into segments with constant pitch. The future direction of the research will be mostly pointed to automate the CNC programming process.

Acknowledgments
This paper is a result of TR33015 project of the Ministry of education, science and technological development, in Serbia. The project is titled "Research and development of a Serbian zero-net energy house". We would like to thank the Ministry of education, science and technological development on their financial support during this research. Authors wishing to acknowledge assistance or
encouragement from colleagues, special work by technical staff or financial support from organizations should do so in an unnumbered.

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