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CONCEPTIONAL CUTTING TOOL DESIGN FOR INTERNAL THREAD TURNING

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Abstract: This article describes the different machining methods of the ball nut thread. One of the disadvantages of machining high pitch ball nuts by grinding process is to produce a modified tool profile to avoid collisions between the tool holder and the workpiece. However, by using profiled lathe inserts, it is possible to produce the thread profile of the ball nut using turning technology. The applicability of the technology is verified by tooling and experimental machining based on conceptual designs, the results of which are described at the end of the article.

Keywords: *turning, tool, ball nut*

1. MACHINING METHODS OF BALL NUTS

In recent decades, very narrow machining technology has become suitable for machining ball nuts, depending on the heat treatment condition of the workpiece [1], [2]. When cutting in the softened state, turning *(Figure 1)* and milling *(Figure 2)* technologies are applied, in hardened and case-hardened state grinding technology is used for finishing of ball nuts.

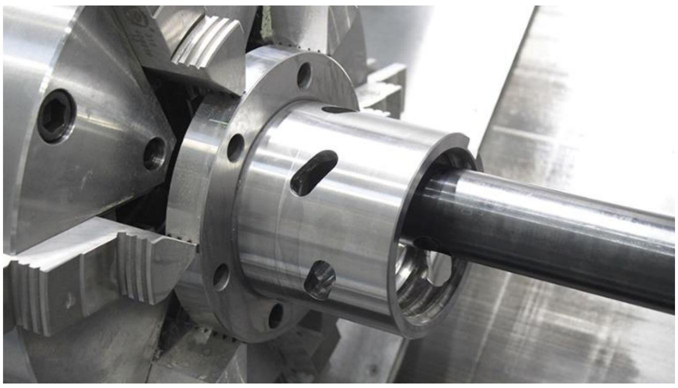

Figure 1
Internal threading of a ball nut [3]

Considering the lifespan of the ball nut, the martensitic tissue structure is widespread. The advantage of the martensitic fabric structure is the high hardness and wear resistance; however, this makes cutting difficult. For this reason, profile grinding is used as a finishing machining in conventional manufacturing operations, which can be used very well within certain technological constraints (nut inner diameter, thread length). The aim of this study is to investigate the possibility of hard turning for machining gothic-arc profile nuts in hardened or case-hardened condition.

Figure 2
Internal thread milling of a ball nut [4]

For ball nuts with high pitch, a tool with a modified profile due to the pitch angle must be designed. To avoid profile distortion, turning and milling tools also solve this problem with back angle compensation. The size of the applied (working) back angle is obtained as the sum of the minimum back angle required for cutting the material quality and the angle of inclination calculated for the smallest diameter of the ball nut.

For this reason, milling technology cannot be applied to machining in a hardened state without effective tilting of the tool, as the result of large back angles adversely affects the edge environment of the tool. A further disadvantage is that only one-edge milling cutter can be considered without tilting, as the additional milling edges would chip the unmachined surfaces in the feed direction. If the milling tool can be tilted without collision during machining, a multi-edged tool is also suitable for cutting. One of its advantages is that more edges mean higher productivity, but the profiles of the edges cannot be precisely synchronized, thus it is not suitable for producing high-precision threads. This method can only be used productively for roughing, because when smoothing a profile, the contact ratio is less than 1, therefore only one edge can cut at a time.

The technological limitation of grinding is the internal diameter of the ball nut, the diameter of the grinding wheel and the thread length of the ball nut, since the grinding tool must be tilted in the axial direction according to the pitch angle [5]–[7]. In contrast to low- and medium-pitch nut versions, hardened profile grinding is not feasible in case of high thread lengths, for two main reasons. The pitch angle resulting from the long thread length and the large thread pitch results in a collision of the tool holder on the core hole diameter. The other main problem stems from the pitch angle, the greater the degree to which a profile tool must be tilted, the greater the degree of profile distortion. The value of the wheel tilt angle is also affected by the diameter of the grinding wheel, which affects the speed of the tool. The disadvantage of the smaller grinding disc diameter is that it can operate technologically well at high speeds and reduces the disc tilt angle. *Table 1* lists specific technologies for ball screws production in the *20–80 mm* range. In the table, it can be clearly seen that the preforms made by rolling are most prevalent in the left and lower table regions of the table. The main reason for this may be the force required for plastic forming, as the depth of the ball raceways also increases with increasing diameter. The technological limitations of grinding are limited by the pitch and the associated pitch angle, as the grinding wheel must be tilted according to the pitch angle.

For ball nuts which have at most *6°* lead angle parameter, turning, milling and grinding technologies are also suitable for machining due to the negative effects of the previously mentioned geometrical and technological parameters.

Based on the experience gained in the industry, the upper limit of turning in the production of a ball nut is approximately $P/D \approx 0.63$ (where P is pitch, D is nominal diameter of ball nut). This ratio of *0.63* resulted in a high feed demand. In the case under study, this proportion is approximately *0.48*, but in contrast to previous experience, cutting must be performed at a much greater depth of cut.

Table 1

Applied technologies on ballscrew depending on its sizes

		Nominal diameter (D) [mm]						
		20	*25*	*32*	*40*	*50*	*63*	*80*
Nominal pitch (P) [mm]	*5*	●○	●○	●○	●○			
	10	○	●○	●○	●○	●○	●○	●○
	15			○	○		○	
	20	●	●	●	●○	●○■	●○■	○■
	25					■	○■	○■
	30							○
	32			●				
	40			●	●			
	50	●	●					

●Rolled ○ Ground/Whirled ■ Heavy Duty Ground/Whirled

The individual technological limitations can be linked not only to the need for strength and power of the machining, but also to the manufacturability of the tool. The tiltability of the cutting inserts is not a particular problem, as such inserts are not produced in a tool body belonging to its position in cutting, but in a tool body with a so-called tiltability of $\gamma_{radial} = 0°$ or $\gamma_{axial} = 0°$, so the tool inserts are made with a distorted profile. The grinding limit for the primary back angle is approximately *30°*, but can be higher with electrical discharge machining *(EDM)* and a suitable device. The manufacturing technology limitation is also limited by the tilting angle γ_{axial} of the insert, as the useful profile width of the insert decreases with tilting, which limits the manufacturability of the required profile.

The literature differs in the definition of hard cutting technology, but it can be stated that steels with hardness *55–64HRC* can be considered hard cutting. Inherent in the technology is that due to the high hardness, the shear plane does not form and the chip elements tear off the surface of the workpiece at the onset of a crack, while significant forces are exerted compared to the machining in the softened state.

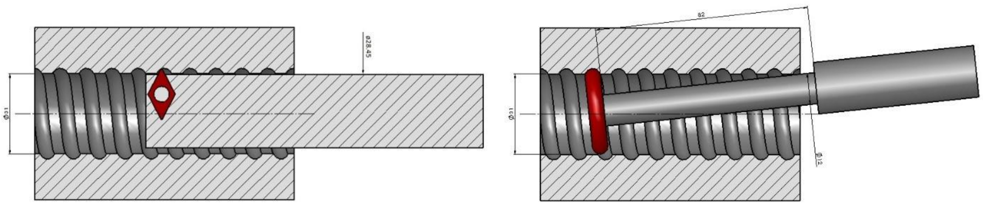

Figure 3
Hard turning (left) and profile grinding (right) of a ball nut [8]

Figure 3 shows the machining process of a ball nut in case of hard turning and grinding process. The different machining parameters and the achievable accuracies are listed in *Table 2* (according to thread turning and thread grinding processes).

Table 2
The differences between hard turning and grinding

	Thread turning	*Thread grinding*
Metal rate removal	150–1,500 mm³/min	10–60 mm³/min
Possible tool rigidity	15–100 N/µm	0.1–8 N/µm
Pitch errors	0.5–2 µm	0.5 µm*
Roughness Ra	0.2–0.5 µm	0.1–0.4 µm*
Accuracy class	IT 1–2	IT 1–5

**According to the bibliographical references*

Grinding was used for finishing in the early stages of hard turning. One of the environmental disadvantages of using grinding is that during grinding a so-called “grinding mud” is formed from the workpiece material and the components of the grinding wheel. Therefore, the material quality of *CBN/PCBN* has been purposefully developed, which, when applied with WIPER geometry, results in surface and microtopographic characteristics characteristic of the ground surface in hard turning. *CBN* technology also has limitations, such as hardness, i.e. it is not economical to use *CBN* below *48HRC*. The *CBN* tool material is recommended for large series above *60HRC* where the chance of payback is higher. To produce the ball nut, *CBN* technology causes several technological problems. In the case of the tested part, the profile of the ball nut is too wide, so due to the large temperature difference during soldering of the *CBN* insert, the carbide bed can crush the *CBN* insert, so it would be expedient to use *CBN* coating layers, if any. However, there are boron-containing coatings which also show high hardness e.g. Ti_2B_2 or *TiBN* [9].

Another problem that arises from the threading technology itself is that *CBN* inserts can be used at high cutting speeds as opposed to threading technology. Thus, thread cutting cycles are not possible due to low cutting speeds and high feeds. Another solution could be the type of coating with the fancy name *OERLIKON BALZERS ALDURA*, which is specifically recommended for machining high-hardness material grades. Ceramic insert tools can be included in the field of hard turning. The use of two known ceramics is widespread in industrial practice. Silicon nitride (Si_3N_4) is one of the known ceramics which is very advantageous for intermittent cutting, as its breaking strength is even higher than that of *CBN*. Silicon nitride also has a high oxidation resistance and is economical to use at higher cutting speeds. Ferrous metals are especially suitable for roughing strategies and are more economical to use at high cutting speeds and medium volume production. The proposed workpiece hardness limit is *50–55HRC*, located in terms of cost between carbide inserts and *CBN* insert inserts.

Alumina (Al_2O_3) ceramics are used for cutting continuous surfaces (smoothing technologies) and should be used in an even higher cutting speed range than silicon nitride. Similar to silicon nitride ceramics, alumina also has high oxidation resistance. Both ceramics are only recommended for dry cutting, as the tool material snaps upon cooling. With its high oxidation resistance compared to other tool materials, it is specifically used in higher temperature ranges.

Conventional carbide insert grades can also be used for hard cutting, but at low cutting speeds and up to *55HRC* hardness. It is worth applying when talking about low-volume production, as the service life of carbide is significantly reduced during hard cutting.

2. DESIGN OF CUTTING TOOL FOR BALL NUT THREAD TURNING PROCESS

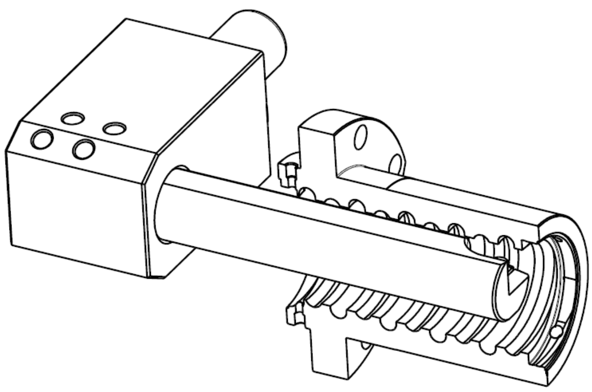

Figure 4
Conceptional design of cutting tool for ball nut thread

The conceptional design of the shank and the insert was performed for a ball nut with dimensions *D = 50 mm* nominal diameter and *P = 25 mm* nominal pitch. *CATIA V5R19* software was used for conceptual design. The schematic diagram of the developed conceptual tool is illustrated in the *Figure 4*.

For the test cutting, it was necessary to manufacture the previously designed cutting insert and tool shank *(Figure 5)*.

Figure 5
The manufactured cutting insert (left) and shank (right)

Test conditions for experimental machining of the thread surface:

- machine tool: *DMG CTX Alpha 500* (controller: *SINUMERIK 840D*),
- coolant lubricant was applied,
- spindle speed: $n = 180\ min^{-1}$ (cutting speed: $v_c \approx 30\ min^{-1}$),
- feed rate: *f = 25 mm.*

The self-excitation phenomenon of the elements involved in the cutting be a function of the distance from the end plate, which also requires further tests as a function of the depth of cut.

Figure 6
Result of an experimental machining of the ball nut thread

In the initial stage of cutting, when even the insert is not working in the full cross-section of the profile, the vibrations are not significant. With the full operation of the profile section (moving towards the workpiece gripper), the vibrations are amplified, and the phenomenon of self-excitation can be sensed from the fact that the grooves gradually deepen on the workpiece surface along the thread length. In the left part of the *Figure 6*, both the beginning and the end of the run can be observed for comparison. The thread surface is smooth at the beginning of machined surface; however, the surface roughness becomes rougher with increasing thread length. This type of self-excitation can also be a defect on the tool carriage.

3. SUMMARY

The article provides a brief summary of the manufacturing technology options for machining the inner thread surface of ball nuts. Based on the literature and previous experience, soft turning and thread milling are primarily suitable for rough cutting of ball raceways. Suitable tooling was designed for experimental machining to make the thread surface of a ball nut of a given size, where the evaluation of machining results shows that conventional thread grinding and hard turning should be chosen to achieve adequate dimensional accuracy and surface roughness if a machine tool with stiffness and stability is available.

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