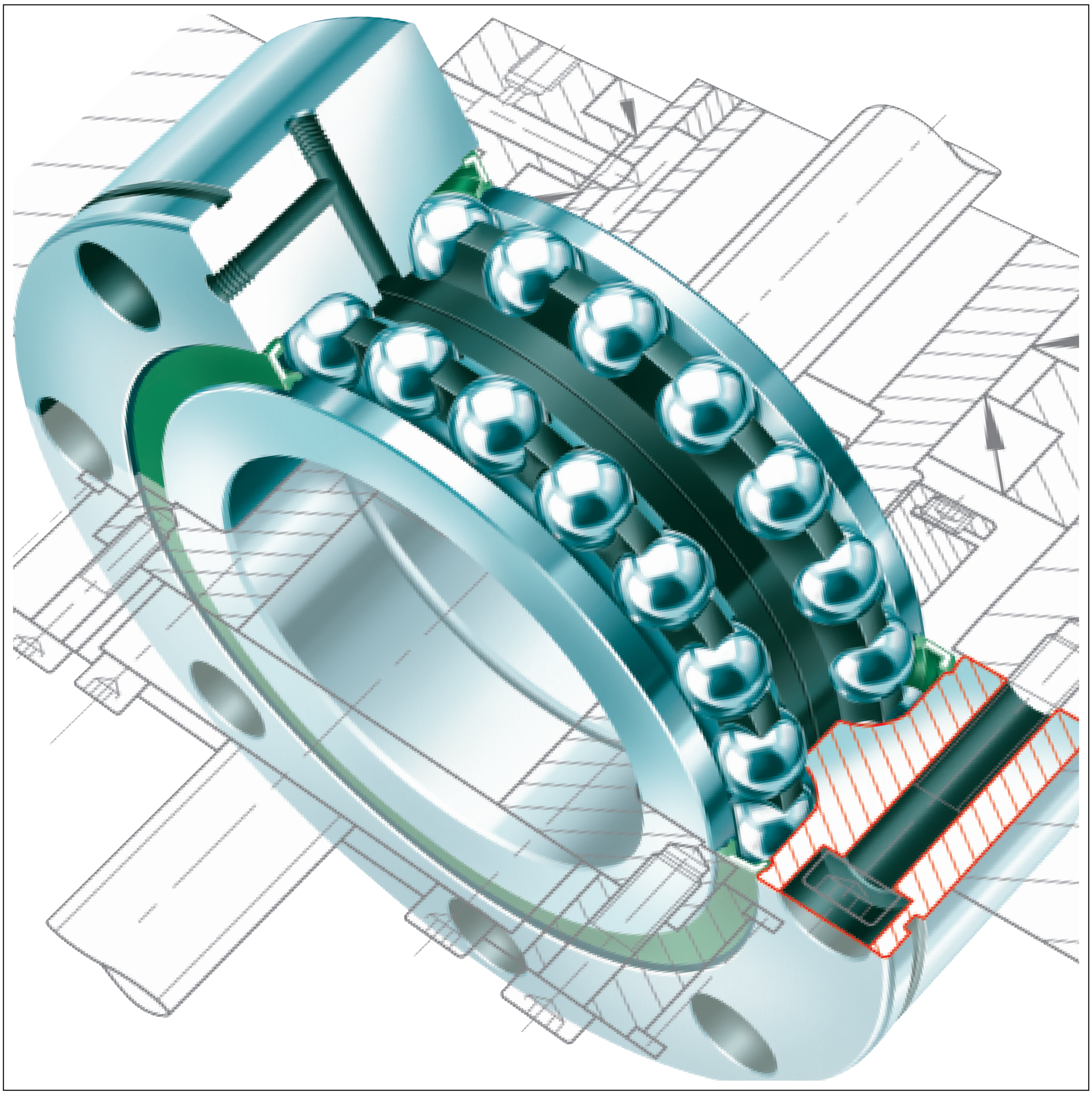

Design of High-speed Ball Screw Drives

Juan José Zulaika, Jokin Lekunberri, José Gorrotxategi

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1 Introduction

The implementation of screw drives in the development of dynamic drive axes is an important aspect of high-speed machining. The performance capacity of these drives is well above the usual operating values, reaching speeds in the neighborhood of 120 m/min and accelerations greater than 1 g, much greater than conventional speeds of 30 m/min and accelerations below 1 g.

The purpose of a high-performance drive is to improve machine productivity by maximizing feed rate and acceleration as well as maintaining feed power. Another aspect is precision, which is essentially determined by the:

- dynamic and static rigidity of the mechanical drive elements and
- thermal endurance.

A guidance system should be selected that can handle the drive's high stresses and support inertial forces while maintaining repeatably consistent precision.

The following discussion, prepared by Fatronik System, S.A., Elgoibar (Guipuzkoa), focuses on various solutions aimed at improving the mechanical design of high-speed drives. Some of these solutions have proven to be effective in testing conducted on a specially designed test rig.

2 Test rig

The test rig was developed in order to evaluate and investigate practical test results and allow hypotheses to be analyzed.

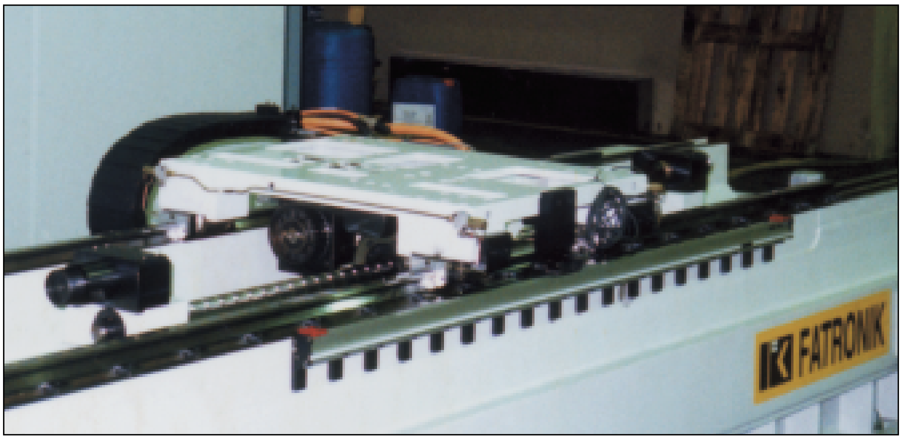
The test rig was designed to be as flexible as possible to ensure that it could be used for a variety of drive concepts with traverse ranges of up to 4 m, i.e., classic drives with rotating spindle or fixed screw drives with driven nut. A large-scale rig was required for this purpose.

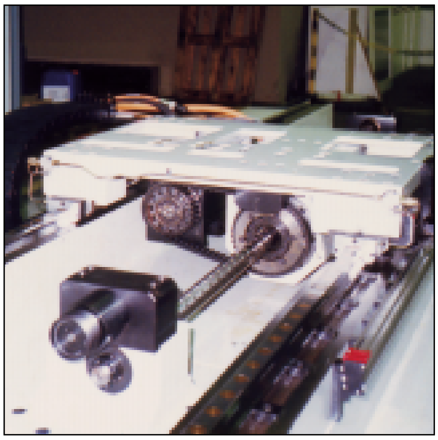
Using this concept, a high-performance drive was designed to the following specifications:

- **max. traverse speed: 120 m/min.**
- **acceleration: ≥ 14 m/s^2**
- **reversed mass: 350 kg**
- **spacing between bearing positions: 2,000 mm.**

The following pre-design tasks were necessary to implement these requirements:

- selection of feed system: rotating spindle or driven spindle nut
- parameter selection: spindle diameter and pitch
- guidance system selection
- selection of motor characteristics
- selection of pulley transmission in the event pulleys are required.





Figs. 1 and 2 The test rig

Other solutions besides the rotating spindle nut with high spindle speed mentioned above should also be evaluated.
For this purpose a calculation program was developed in order to select of the most suitable configuration of preliminary design parameters.

Of the various solutions that met the test requirements, the following values were selected:

type of drive	rotating spindle nut
spindle pitch	40 mm
torque	23 Nm
max. torque	82 Nm
max. traversed mass	350 kg
reduction ratio	1.33

For the set of parameters selected, the following nominal values were obtained and subsequently confirmed:

- acceleration: 17.4 m/s^2
- K_V: 4

After the characteristic values of the drive were determined, it was necessary to define the following design features:

- lubrication system
- spindle nut bearing
- linear guidance system
- spindle end bearing arrangement
- numerical control, regulator, motor and length measuring system.

2.1 Lubrication system

The lubrication system must supply lubricant to three points: the spindle nut bearing, the linear guidance system and the nut itself. The lubrication system to be used was determined by bearing lubrication requirements, particularly those of the nut. As a result, an oil-air-lubrication system was selected for the entire test rig.

It was particularly difficult to ensure the appropriate lubrication for the spindle nut, because of its rotation. A system was designed in which the oil reaches the spindle nut through a series of holes in the nut. Oil supply for the nut was incorporated in an intermediate bushing. The bushing is supplied with oil through a chamber sealed at both ends.

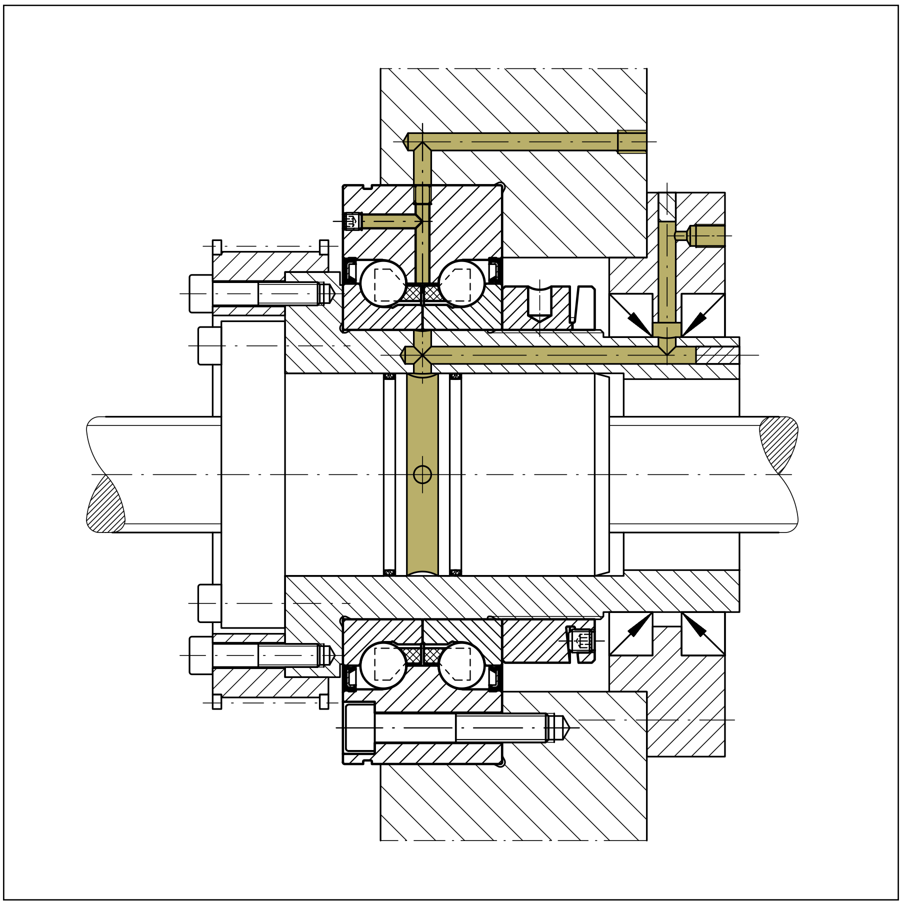


Fig. 3 Lubrication of spindle nut and bearing

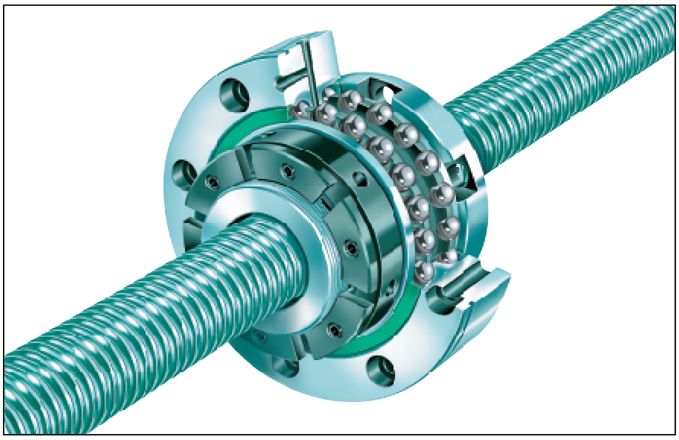


Fig. 4 INA axial angular contact ball bearing series ZKLF

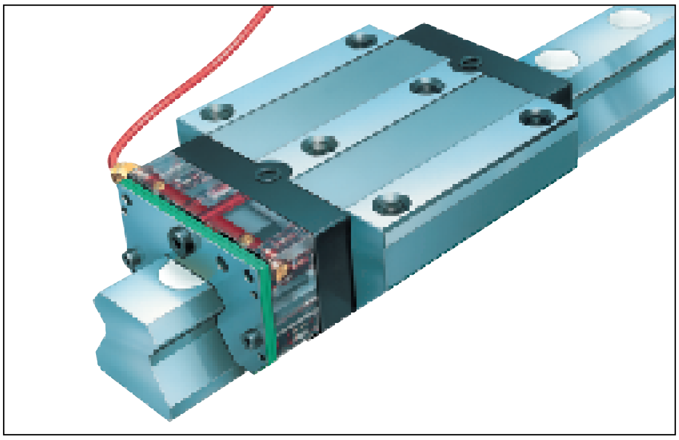


Fig. 5 INA linear recirculating roller bearing and guideway assembly RUE..D with SMDE

2.2 Spindle nut bearing

The spindle nut bearing used is a double-row axial angular-contact ball bearing supplied by INA Wälzlager Schaeffler oHG, series ZKLF 100200.2Z, with a contact angle of 60° (Fig. 4).

The bearing's split inner ring is aligned with both ball and cage assemblies and the outer ring in such a way that the bearing is optimally preloaded when the locknut is tightened with the specified tightening torque, making further adjustments unnecessary.

In the case of grease lubrication the ZKLF 100200.2Z bearing displays a limit speed of 2150 rpm, which was insufficient for the targeted speed value of 120 m/min. To circumvent this limitation, INA specially designed a thrust angular-contact ball bearing with ceramic balls. In conjunction with oil-air-lubrication, the bearing was successfully tested for a long period of time at speeds of 3000 rpm without significant increases in temperature (Fig. 6).

2.3 Linear guidance system

Four-row linear recirculating roller bearing and guideway assemblies, type RUE 45 D OE W2 supplied by INA Lineartechnik oHG, were chosen for table travel (Fig. 5).
In addition, the 2,940 mm long guidance system was equipped with SMDE minimum-lubricant metering units. These standard preloaded roller systems met the stringent rigidity and accuracy requirements.

2.4 Spindle end bearing

Three possible spindle end bearing supports are possible for this kind of drive:

- rigid location at one end of the spindle and non-locating bearing at the other
- rigid location at both ends of the spindle internally cooled to ensure temperature resistance
- rigid location at both ends, with axial tension on the spindle.

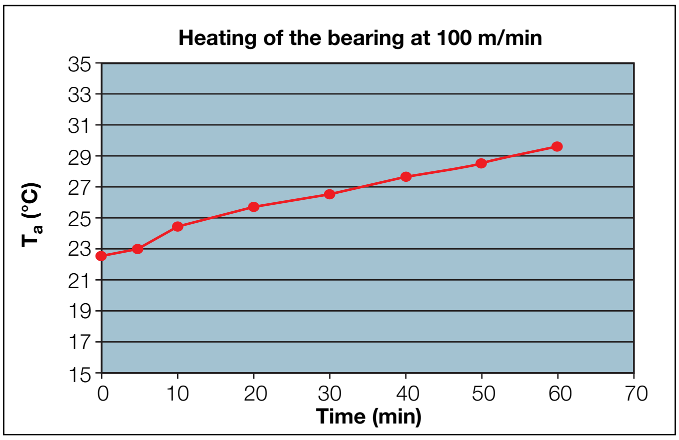


Fig. 6 Heating of bearing tested at 100 m/min

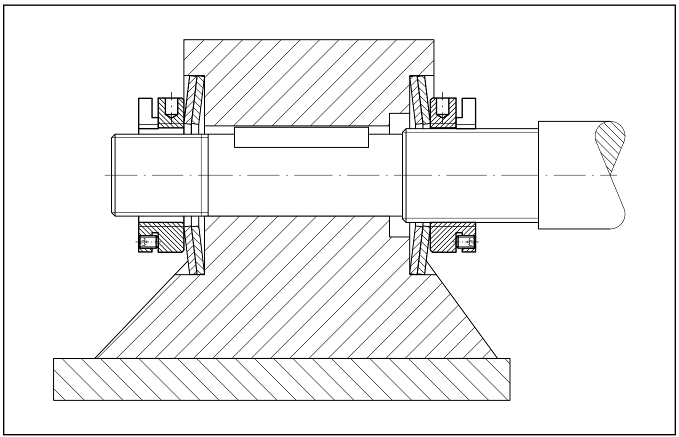


Fig. 7 Non-locating spindle bearing with INA precision locknut AM

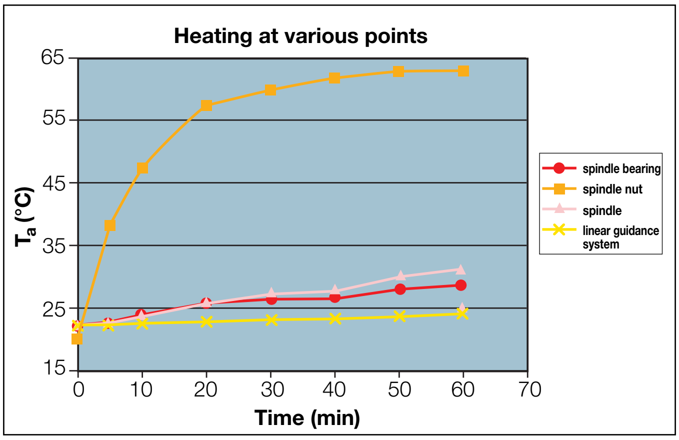


Fig. 8 Test at 100 m/min.

The third alternative is problematic due to the high degree of tension required. The second alternative is practicable and has already proven effective in some machines. The first alternative was chosen, even though it is not the optimum solution. The purpose was to gather data that will be useful for conventional drives.

The spindle was firmly located at one end, and either locating or non-locating bearing supports were used at the other. An adjustable clamping device, capable of supporting the elongation that occurs when the spindle heats up, was used for this purpose.

This arrangement has an effect on the axial rigidity of the spindle. Axial rigidity of the spindle:

$K_{min} = \pi \cdot E \cdot d^2/4 \cdot L$

is minimal when the spindle nut is positioned at the non-locating bearing.

The solution selected called for the spindle to be axially secured in both directions by means of a spring assembly, which compensated for losses in rigidity (Fig. 7).

3 Tests

At the beginning of 1999 testing was not yet complete. Priority was given to those tests that provided data on the thermal behavior of the drive.

The following tests were conducted:

- heat measurements of test rig components
- determination of optimal quantities of lubricant.

Resistance temperature detectors, IR temperature detectors, proximity switches and an A/D converter were used to measure these parameters.

3.1 Heat measurements of test rig components

Temperatures of the following components were measured in order to determine the thermal behavior of the test rig:

- spindle nut
- bearing
- spindle
- linear guidance system

Fig. 8 shows the temperature curves for these components for a period of 60 minutes. Feed rate was 100 m/min.

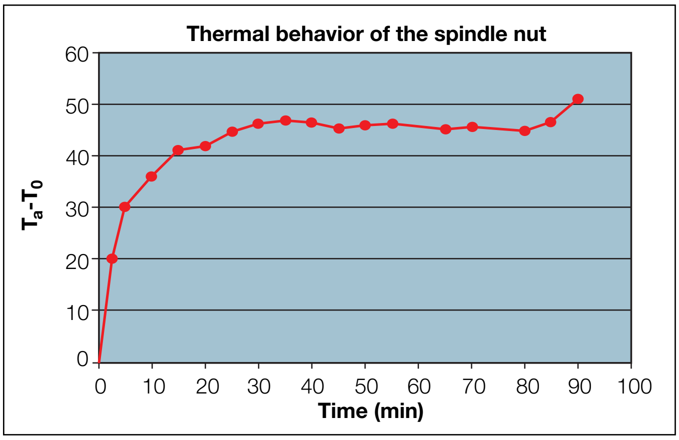


Fig. 9 Temperature curve of spindle nut

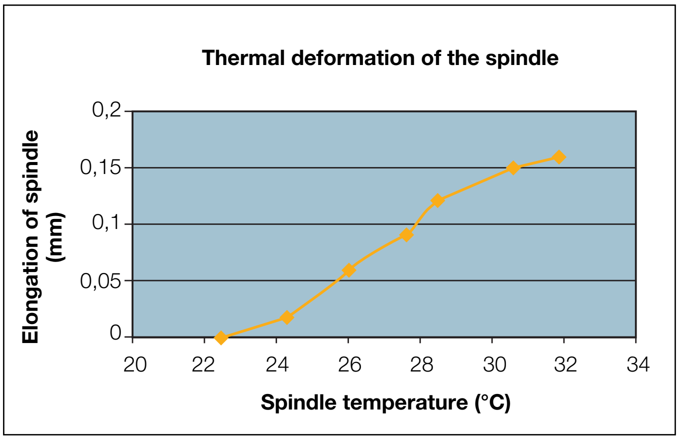


Fig. 10 Elongation of spindle

As expected, the increase in heat was greatest in the spindle nut and insignificant in the other components. Further efforts were thus focused on improving the thermal behavior of the nut.

Fig. 9 shows the curve for the spindle nut. After a quick initial rise, the temperature remains almost uniform, the constant temperature being affected by the addition of a lubricating oil.

Measurements of spindle elongation were also made. The results are shown in Fig. 10.

3.2 Optimizing the lubrication system

Given the rapid heat-up of the spindle nut on the tested drive, it was necessary to optimize the spindle nut lubrication system.

The system chosen was an oil-air-device. The advantages of this type of lubrication, often used for lubricating workspindle or headstock bearings, include higher speeds, lower friction losses and lower oil consumption. One problem with this method of lubrication is that it is difficult to determine the best amount of oil to use. An oil with a viscosity of ISO-VG 68 was chosen in accordance with the recommendations of the lubricant manufacturer.

A separate series of tests was performed to determine the optimum quantity of oil. The results obtained are given below.

Fig. 11 shows the time required for the spindle nut to reach a temperature of 70°C with respect to the quantity of oil added. Feed rate during this test was 100 m/min.

The diagram shows that spindle heat-up is the slowest for an oil rate of approximately 2 mm³/min. Tests carried out for other feed rates yielded quite similar results.

Fig. 12 shows the temperature variation in the spindle nut for differing oil flowrates. The temperature of the spindle nut was recorded after a specific elapsed time in all the tests. The basis for the tests results displayed in Fig. 12 was a period of 20 minutes at a feed rate of 100 m/min.

The optimum oil supply matches the value shown in Fig. 11 (about 2 mm³/min). There are also relative minimum values for greater oil rates. However, these values are above the absolute optimum of 2 mm³/min.

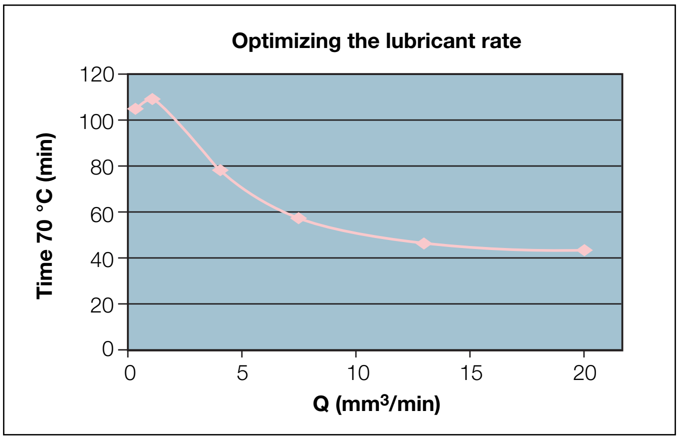


Fig. 11 Time required to reach a temperature of 70 °C for various oil rates

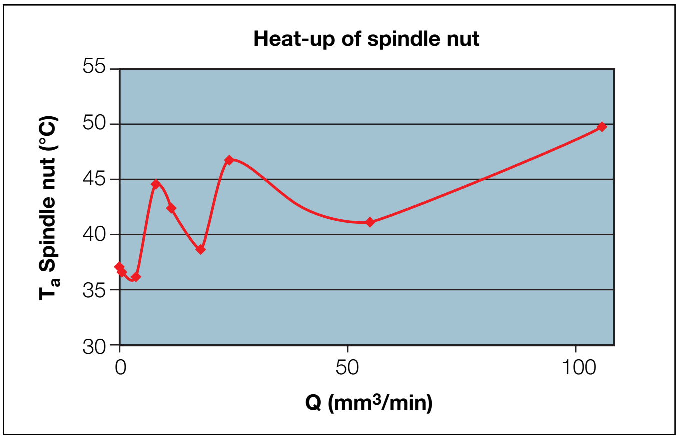


Fig. 12 Heat-up of spindle nut for different oil rates

4 Summary

This article introduces a number of solutions for high-speed drive systems. These are essentially mechanical design improvements in conjunction with an increased dynamic and static rigidity of machine components.

This new approach for screw drive bearing arrangements is highly promising for a wide range of applications including the entire machine tool sector. Existing electromechanical drives may also be retrofitted with this concept.

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