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Design and test rig experiments of a high speed tapered roller bearing for main spindle applications

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Abstract

A new design of tapered roller bearings (TRB) for main spindles for high-performance cutting (HPC) or heavy roughing applications is presented. The bearing's key features to increase the speed rating are an outer ring rib, additional means of lubrication and ceramic rollers. First results of test rig experiments show that its speed rating is considerably higher than that of standard TRBs while calculations indicate that its stiffness and load rating are superior to conventional spindle bearings (SPB). Measured runout values of the new TRB and a reference SPB indicate that regarding accuracy the new TRB concept can be applicable for main spindles.

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Keywords: Bearing; spindle; milling

1. Introduction

In HPC or heavy roughing applications the spindle speeds are considerably lower than in high-speed cutting (HSC) applications whereas the cutting forces and thus the bearing loads are higher. Additionally, there is a growing demand for multi-purpose spindles that can be operated at low speeds and high loads as well as at lower loads and medium speeds.

Today, high speed / high accuracy SPBs (angular contact ball bearings) are the most common type of rolling element bearings used in main spindles for milling. Designed with a contact angle of 15°…25° and adapted internal geometries (e. g. osculation) they are suitable for high speeds and enabled to carry combined radial and axial loads. However, the point contacts between the balls and the raceways limit the load carrying capacity and the stiffness of these bearings. In addition to that, their stiffness decreases considerably with increasing speed due to the relatively large contact angle. [1, 2]

Regarding the load rating and the stiffness, TRBs are superior to spindle bearings. However, their speed rating is in most cases not sufficient for the main spindle applications described above. In addition to that, so far most TRB developments focused on the load rating, the service life and the bearing friction. Although there are some documented concepts of TRBs for high speed applications they are either not suitable for main spindle applications or their performance has not been thoroughly investigated yet.

Parker et al. [3] describe a 120.65 mm bore TRB that was successfully operated up to 20,000 rpm ($n \times d_m = 2.4 \cdot 10^6$ mm/min). However, the fact that this bearing has to be lubricated and cooled with an oil flow through the bearing of up to 15 l/min (4 gal./min) makes it unsuitable for main spindle applications. A TRB design for main spindle applications by Timken features a direct lubrication of the roller-rib contact [4]. However, spraying oil on the shaft were it is centrifuged to a collecting disk directing it to the rib makes this bearing difficult to implement in main spindles. The same applies to another high speed TRB that features a hydrostatically preloaded outer ring rib [4]. The hydraulic system makes the application of this bearing complicated and expensive. Another high-speed TRB tested up to $n \times d_m = 1.25 \cdot 10^6$ mm/min is presented by Mori / Kobayashi [5]. It features an outer ring rib, ceramic rollers, an outer ring guided resin cage as well as oil nozzles in the rib for the direct lubri-

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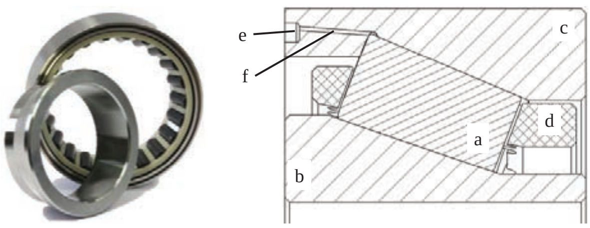
cation of the roller-rib contact. The cone (i. e. the raceway) and the rib of the outer ring are manufactured as two separate components. The two-part design of the outer ring is assumed to lead to manufacturing difficulties regarding the position accuracy of the raceway relatively to the rib.

This article describes a new type of TRB that is designed to feature a considerably higher speed rating than standard TRBs while its design allows for a simple implementation in main spindles. The milled polyether ether ketone (PEEK) cage and the hard turned rings allow for simple variations of the bearing design for future investigations Additionally it is designed to overcome the described manufacturing difficulties. The results of first test rig experiments with the new TRB and calculations for an extended load and speed range presented here suggest that this bearing is a promising concept for TRBs for main spindle applications.

2. Design of the new high speed tapered roller bearing

Among others Houpert [6] and Zhou / Heoprich [7] emphasize the vital importance of the roller-rib contact and the tribological conditions within it for the overall friction characteristics of TRBs. Consequently Parker / Signer [8] suggest direct lubrication of this contact as one promising way to improve the speed rating of TRBs. Further improvements of the tribological conditions can be achieved by using ceramic rollers [1, 9]. Due to the lower mass of ceramics compared to steel, this measure also reduces mass and speed induced phenomena like centrifugal forces or gyroscopic moments.



a: roller, b: inner ring, c: outer ring, d: cage,
e: circumferential notch, f: lubrication bore

Fig. 1: Design and key features of the new hybrid TRB

The TRB shown in Fig. 1 was designed and manufactured in cooperation with Cerobear GmbH, Herzogenrath, as part of the activities of the industry funded research workgroup "Arbeitskreis Spindel-Lager-Systeme" at WZL. With an inner / outer diameter of 70 mm / 110 mm it is designed for spindles with a HSK-A63 tool inferface. The rollers have approximately the same diameter and length as rollers for standard 32014X TRBs according to DIN 720 [10].

The contact angle is larger than that of standard TRBs to provide a larger axial stiffness. The other key features of the bearing aim at increasing its speed rating. First, as described above, the ceramic rollers reduce the speed induced mass forces and improve the tribological behavior. Second, by means of 0,5 mm bores in the rib lubricant can be fed to the roller-rib contact from a circumferential notch. Conventional oil-air lubrication systems as they are standard for main spindle applications can be used to feed lubricant to this notch. Third, the location of the rib at the outer ring allows a considerably better heat dissipation.

The outer ring guided cage is machined from PEEK. The rings are made from high-nitrogen steel by hard turning without additional finishing. In contrast to the bearing introduced by Mori / Kobayashi [5] described in paragraph 1, the raceway and the rib of the outer ring form one part to ensure a high position accuracy between both outer ring surfaces (i. e. raceway, rib) being in contact with the rollers. Table 1 sums up the key properties of the new bearing and the spindle bearings used as a reference for the further investigation and comparison of the operating behavior.

Table 1: Properties of the investigated bearings

Property	New hybrid TRB	Reference SPB
Number of rollers	22	18
Contact angle	21°	25° (calculations) 15° (runout meas.)
Inner / outer diameter	70 mm, 110 mm	70 mm, 110 mm
Width	31 mm	20 mm
Roller length / mean diameter / angle	17 mm , 9.19 mm, 4°	n/a, 12.7 mm, n/a
Ring / roller / cage material	X 30 CrMoN 15 1 / Si_3N_4 / PEEK	100 Cr 6 / 100 Cr 6 / fiber reinforced phenol formaldehyde resin
Accuracy class	P4	better than P4

3. Experimental setup and calculation methods

For a first assessment of the applicability of the new hybrid TRB for HPC spindles two types of test rig experiments were carried out: To determine the high speed capability eight speed step-runs were performed with the same bearing (see Table 2 for test conditions). Each test run ended at a higher speed than the one before. Thus, these tests do not only show the operating behavior of the bearing but also its repeatability. To determine the accuracy of the new TRB the radial runout was measured and compared to that of a reference SPB.

The test rig (see Fig. 2) described earlier by Rossaint [11] allows the measurement of the inner and outer ring temperature and the bearing friction. It was used to carry out both, the speed step-runs as well as the runout measurements.

For the radial runout measurements the rotor of the telemetry system was replaced by a tool holder allowing the application of the Spindle Error Analyzer (SEA) by Lion Precision [12]. The measured runout includes shares from the support bearing and other parts of the test rig. Thus, the results can only give a relative comparison between the test bearings. The absolute values are of minor interest.

Besides the measureable bearing characteristics, several of the bearing's internal conditions like the contact stresses in the rolling contacts or the stiffness are vital to assess its suitability for certain operating conditions. Since some of these characteristics cannot be measured with the test rig used here, a simulation model developed within a DFG funded project (see Acknowledgements) was used for a first assessment of the bearing's operating stiffness and contact stresses.

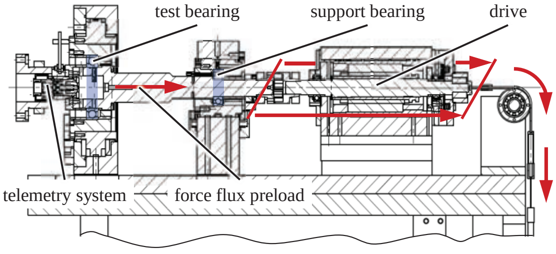


Fig. 2: Spindle bearing test rig according to [11]

For the runout tests and the comparison of the calculated operating behavior two standard spindle bearing with large steel balls and a contact angle of 25° (operating behavior) and 15° (runout) were taken as a reference (see Table 1). Compared to other SPBs they feature a high load rating and stiffness at a lower speed rating making them the SPBs to be possibly replaced by the new TRB in certain applications.

The spindle bearing calculations were carried out with the software WinLager, developed at WZL Aachen, based on the work of Tüllmann [13].

Table 2: Test run conditions

Condition	Speed step-run	Runout measurements
Speed	0…15,000 rpm	500…9,500 rpm
Axial load	1,250 N	2,000 N (preload class "high" for ref. SPB)
No. of test runs	8 (with increasing max. speed)	3 at each speed (Fig. 4 shows the mean value for each speed)
Measured variables	inner ring temp. (T_{IR}) outer ring temp. (T_{OR}) friction moment (M)	total runout (split into synchronous and asynchronous by SEA proprietary software)

4. Experimental results

Fig. 3 shows the speed dependent operating behavior of the newly developed TRB and a standard 32014X TRB. The good compliance between the different test runs of the new TRB shows that there is no significant running-in that is common for standard TRBs. Up to a speed of 14,000 rpm stable friction and temperatures are reached at the end of each speed step indicating that the bearing can safely be operated at this speeds. The friction exaggeration in the lower half of the speed range is a phenomena known from spindle bearings, too [11]. Although it is not fully understood yet, one main reason is thought to be excess lubrication. The very steep friction peak at the speed of 15,000 rpm indicates a sudden bearing failure due to a failure of the lubrication system (i. e. insufficient lubrication film thickness in one of the contacts). For the given conditions the tribological speed limit of the bearing was reached. However, for the standard 32014X TRB the speed limit is already reached at a speed of 10,000 rpm, indicated by the facts that no stable temperature conditions are reached there and that the bearing temperature as well as the friction (not shown) increase suddenly and very steeply.

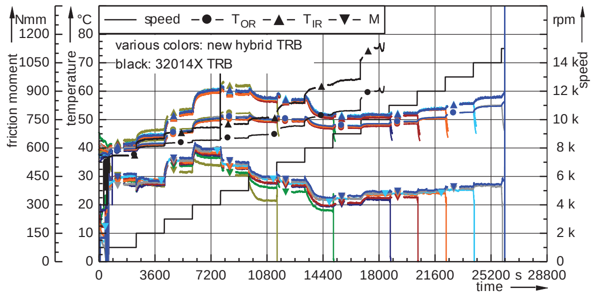


Fig. 3: Operating behavior at 1,250 N axial load and various speeds

Fig. 4 shows the results of the SEA runout measurements for both the new TRB and the standard SPB. As expected for rolling element bearings, the asynchronous runout dominates the synchronous runout [14]. Whereas both bearings show a tendency of larger asynchronous runout with increasing speed the tests show that the new TRB features approximately the same runout as a standard SPB with an accuracy class better than P4.

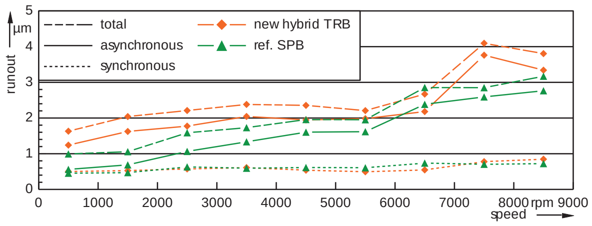


Fig. 4: Radial runout of the new hybrid TRB and the reference SPB

5. Calculation results

Due to the rolling element-raceway contact geometry (profiled line contact in TRB, point contact in SPB) the contact pressures in the rolling contacts of the TRB are considerably lower than in the spindle bearing (see Fig. 5). At low to medium loads, the speed induced mass forces and the resulting shift in the contact angles lead to increasing outer ring contact pressures and a considerable decrease of stiffness with increasing speed in the spindle bearing. This effect diminishes with increasing loads as they tend to dominate the load regime inside the bearing. As expected the TRB shows no speed dependent effects on the stiffness or the rolling element-raceway contact stresses since there a no speed induced changes in the contact angles.

In contrast to the roller-raceway contacts the roller-rib contact shows a considerable dependency between the contact stress and the rotating speed in the lower load range (see Fig. 6). For example at an axial load of 1,000 N the contact stress in the roller-rib contact increases by about 65 % between

0 and 15,000 rpm. Although this effect is almost negligible at high loads, this is another indicator that the roller-rib contact is crucial for the high speed applicability of TRBs.

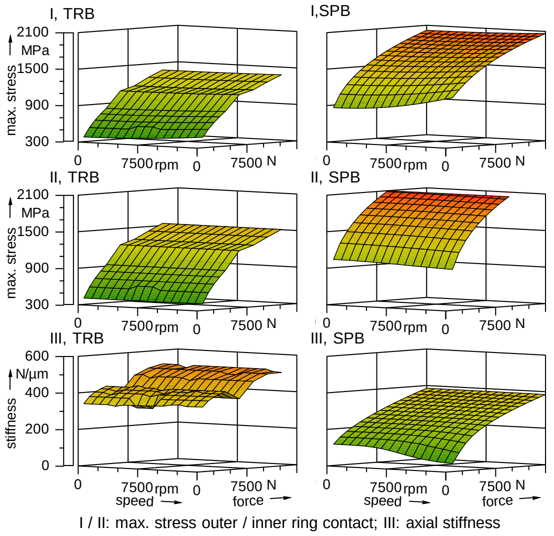


Fig. 5: Comparison of contact stresses and stiffnesses (calculated)

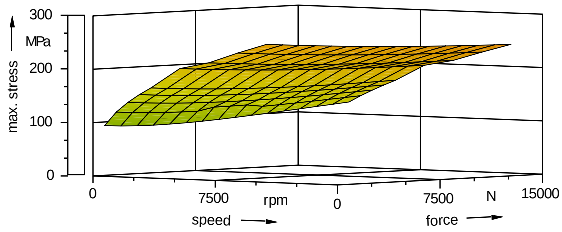


Fig. 6: Roller-rib contact pressure in the new hybrid TRB (calculated)

6. Summary and outlook

Due to their limited stiffness and load rating spindle bearings are of limited applicability for HPC or heavy roughing applications. While TRBs perform considerably better regarding these criteria their speed rating is too low for most main spindle applications. However, TRBs with a higher speed rating could be a substitute for spindle bearings in some of the above mentioned applications. Consequently, several designs for high speed TRBs were presented in the past. However, most of them show shortcomings regarding the applicability for main spindle applications or the degree to which they have been investigated independently.

Consequently, the TRB presented here is designed to feature both, a high stiffness and load rating as well as a high speed rating. Test rig measurements of the bearing temperature and friction at various speeds proof the bearing's high-speed capabilities up to 14,000 rpm. The measured values for synchronous and asynchronous runout are in the range of those of a spindle bearing of accuracy class better than P4. Thus, the first experimental results indicate that this bearing is a promising concept for future main spindle applications.

Calculations of the bearing stiffness and internal stresses show that up to 15,000 N of axial load the bearing shows considerable higher stiffness values than the reference spindle bearing while the internal stresses remain below 1,500 MPa.

However, the sudden failure of the new TRB at 15,000 rpm and the considerable increase of contact stresses at the roller-rib contact with increasing speed at low loads indicate that this contact is crucial for the speed rating of the bearing.

Thus, this contact has to be one of the main focuses of future research. Additionally, the calculated values for bearing stiffness at high loads and speeds have to be verified experimentally. To do so, the test rig used here has to be redesigned for higher axial loads within the DFG funded project (see acknowledgements).

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