Increased Performance of High Speed Spindle Bearings

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ABSTRACT. Most machine tool spindles, including high speed cutting, are fitted with rolling element bearings. In the last few years, the high speed cutting process has brought a whole new set of requirements to bearings. Reduced manufacturing time, longer operating life, minimal lubrication, and better work piece quality are among some of the requirements being sought by customers everyday. Basic research work in bearing material, lubricants, lubrication systems, and analytical methods have improved the design of high performance bearing systems. Operating conditions and the design of spindle components directly influence the bearing geometry and its performance. Bearings high performance capabilities are maximized only when there is an optimum match between the application requirements and bearings. This paper covers in-depth the bearing characteristics, recent technology advances, and their benefits in spindle applications.

KEYWORDS: Rolling element bearings, High speed machine tool spindle, Bearing life

Introduction

In the last few years, the demands from the aircraft, automotive, and electronic industries for machines with increased capability and productivity have placed a significant amount of pressure on the machine tool manufacturers to improve their existing technologies. Areas of improvement include production rate increases, increased capabilities for machining of smaller components, tighter tolerances, better workpiece overall quality, and extended tool life. The implementation of these improvements affects the entire production system: machines, tools, production engineering, working sequences, etc. HIGH SPEED CUTTING/MACHINING is a major step towards accomplishing most of these goals.

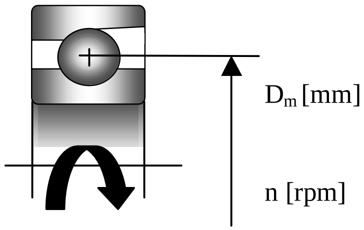
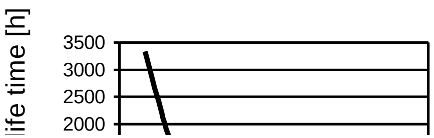


Figure 1. *Speed Factor n.D_m*

High Speed Cutting requires high power and a constant high speed, or a wide speed range. The rolling element bearing speed capability is best described by the speed factor n.D_m mm/min (Fig.1), with high speeds starting at values over 1 million n.D_m. Typical speeds in machining centers are 1.5 million n.D_m, and top speeds in HSC applications can go over 3 million n.D_m. High speeds have been reached before in aircraft turbines, and on test stands. Machine tool spindles are also capable of operating at high speeds, but, additionally, they must also meet other criteria for good performance:

- acceleration
- dynamic stiffness
- accuracy
- good vibration behaviour
- reliability
- efficiency

The classical bearing useful life is limited by the fatigue of the material, and is dependent on load and speed. Fatigue life when computed for high speed conditions results in a significantly low number (Fig. 2), which at first appears to suggest that rolling element bearings are not suitable for high speeds.



Basic research shows that rolling element bearings have a similar stress cycle behaviour as other machine components. The stress in a rolling element bearing is defined by the Hertzian pressure in the contact zone. If contact stresses do not exceed the threshold level, the bearing is considered fail safe, i.e. infinite material life [1,2]. Many field experiences have confirmed this concept. Additionally, evaluations of failed machine tool bearings have demonstrated that classic material fatigue with the failure starting at the subsurface level doesn’t occur. For these reasons, it’s more significant to focus in the case of machine tool spindles on the stress that happens at the surface level. This stress is induced mostly by friction, and its causes and methods for reduction are best addressed by considering the bearing kinematics.

The single row angular contact ball bearing is the type most used in high speed machine tool spindles. Fig.3.

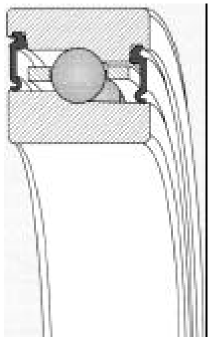


Figure 3. *Angular contact ball bearing in a sealed version for high speed application*

1. Bearing: A Tribological System

Very high stresses (Hertzian pressure) develop between the ring raceways and the rolling elements. . Infinite fatigue life is achieved when stress values up to and including 2000 MPa occur in the elliptical contact zone (ball-to-race) using standard bearing materials. Material, lubricant, and contact area geometry play an important role in a damage free operation, and must all be analysed together. How well they

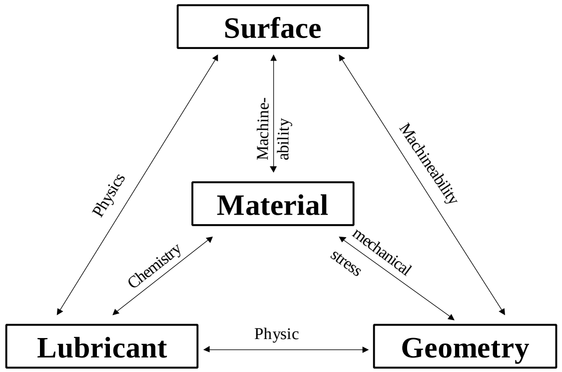


Figure 4. *Tribology system components and their interactions.*

The bearing material, functional surface geometry, and surface finish parameters influence the bearing performance in the following way:

	Material	Lubricant	Geometry	Surface
Stiffness	X		X	
Friction	X	X	X	X
Kinematics	X		X	
Service Life	X	X	X	X
Temperature	X	X		
Acceleration	X		X	

Figure 5. *Effect of influencing parameters on system performance*

2. Material

In the past, ball bearing designs were mostly based on the fatigue life that was heavily dependent on the material type and quality. However, it has been common knowledge amongst bearing producers and customers for at least twenty years that the bearings will last indefinitely if they operate with a full EHD film and the contact stresses don't exceed 2000MPa. The cutting forces in high speed machining are inherently low which results in high load ratios (C/P). These high C/P ratios, 8 or higher, will result in infinite life conditions.

The combination of steel and ceramic offers:

- increased dynamic stiffness - higher resonance frequency
- reduction of lubricant stress - longer grease life
- lower preload changes - less temperature dependent
- extended bearing life - system cost savings
- lower surface wear rates - lower noise
- better kinematics - improved spindle capabilities

Work done to date has shown that only balls made of silicon nitride can offer this combination of performance characteristics. The ring material commonly used in hybrid bearings is 52100 steel. This steel has been manufactured to very high quality standards for years and no other bearing steel, including M50 used in Aircraft engines, can match the 52100 performance obtained in machine tool spindles.

2.1. CRONIDUR 30

The requirements for higher corrosion resistant bearings in aircraft applications have led FAG into the development of Cronidur 30 for other bearing applications.
This alloyed material belongs to the group of high nitrogen alloyed steel (HNS), and it can be heat treated in a martensitic way, or case hardened. Main composition differences between 52100 and Cronidur 30 are in carbon, nitrogen, and chromium contents.

	C	N	Si	Cr	Mo
52100	1.00	-	0.25	1.45	-
Cronidur 30	0.31	0.38	0.55	15.2	1.02
440C	1.08	-	0.40	17.0	0.52

Figure 6. *Bearing steels chemical composition W %*

The special composition allows for higher operating temperatures, increases in the bending strength, and fracture toughness.

	52100	Cronidur 30
Hardness	> 58 HRC	> 58 HRC

The carbon content of Cronidur 30 is lower, but the final hardness is within the same range of the values obtained in a typical carbon steel. The hardness in Cronidur 30 is obtained by the combination of carbon and nitrogen. Compared with the other commonly used bearing materials, Cronidur 30 shows a homogeneous microstructure with small carbonitrides. Excellent bearing performance characteristics are generated with Cronidur 30 due to the positive residual stress conditions and a special grain formation. Basic tests have shown higher life under several different lubrication conditions (Fig.8 and 9), and results with a full EHD condition showed that the Hertzian stress limit for infinite material fatigue life was increased by 25%.

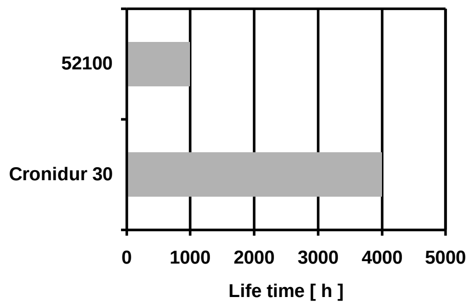
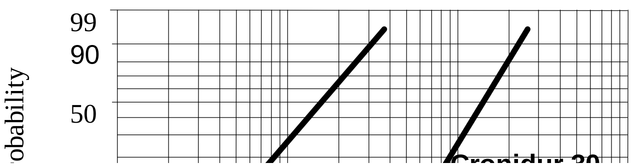


Figure 8. *Bearing material fatigue.* p_0 *=2800 MPa , full EHD condition; test with Cronidur 30 bearings was stopped before failure*

Mixed friction can occur at low speeds when the full film thickness is not established. This phenomenon occurs during the start–stop phases very common in high speed machining. Under mixed friction conditions, Cronidur 30 clearly shows fatigue life gains.



When tested with mixed lubrication conditions along with the 52100 bearings, the Cronidur 30 bearings achieved at least 10 x higher service life. Additionally, Cronidur 30 has shown x100 times better corrosion resistance than 440C, the bearing steel most commonly used in applications with corrosion resistance requirements. High corrosion resistance and better wear behaviour can be expected to result in a much higher service life in machine tool applications. Spindle tests performed in real life applications with Cronidur 30 showed a substantial reduction in temperature for the same running speeds. The low operating temperatures were achieved after the standard running-in procedure.

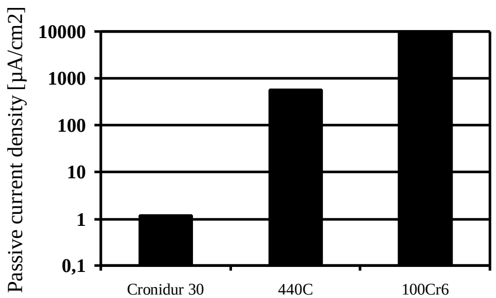
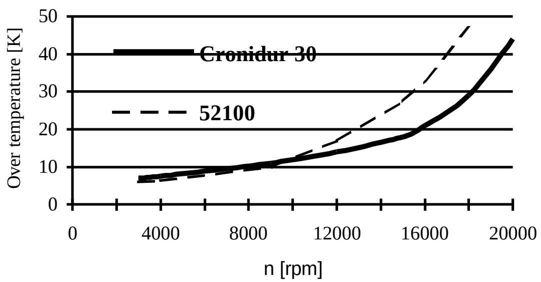


Figure 10. *Passive current density: lower values equate to better corrosion resistance behaviour.*



reduction associated with the elimination of complex lubrication systems. Additionally, Cronidur 30 has also better wear behaviour and microstructure stability. Grease life is enhanced by the better wear characteristics of this material. Wear particles are generated at a very reduced rate, and contrary to what happens with 52100, the Cronidur 30 particles once mixed with the grease don't accelerate its deterioration.

3. Lubrication

The lubricant is still an essential element for the good performance of a bearing in a machine tool spindle. With the available bearing/spindle technology it is still not possible to run a bearing at high speeds and without any lubrication for any significant amount of time. However, some environmental groups push for safer, cleaner working places have the machine manufacturers currently focusing some of their research work into developing "dry machines" that will operate free of oil spills and grease leaks. Most bearing systems are being designed to operate with minimum amounts of grease or oil, and this work is being done not only for environmental reasons but also to generate cost savings. The lubrication system still represents a large percentage of the total bearing system cost.

3.1 *Grease lubrication*

A large percentage of machine tool spindles are grease lubricated. In the last few years great advances in bearing speed vs. lubrication performance have been achieved. Only ten years ago a bearing system to operate with speeds of 1 million $n.D_m$ needed oil lubrication for satisfactory operation. Today the same speed values can easily be reached and exceed with grease lubrication.

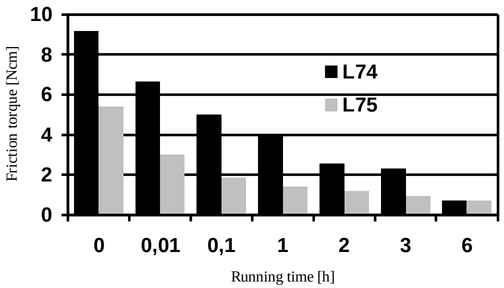
The first big achievement towards higher speeds was the use of ceramic balls. On one hand the ceramic balls raised the speed limit to 1.5 million $n.D_m$, while applications using hybrid bearings and grease lubrication showed gains of at least 3x longer lubricant life. These improvements with the ceramic balls have made the use of hybrid bearings a standard in spindles lubricated with grease, even in applications with no high speed requirements.
A high speed grease must meet the following requirements:

- low friction

	FAG ARCANOL L74	FAG ARCANOL L75
Thickener	Barium complex	Polyurea
Base Oil	Ester/ Mineral oil	PAO / Ester
Viscosity (cSt) @40°C	23	22
Consistency class (NLGI)	2	3

Figure 12. *Technical data for high speed greases*

ARCANOL L75 contains a smaller amount of thickener than L74, and has no toxic constituents. The thickener, Polyurea has a higher thermal stability than the barium complex soap (L74). The base oil features roughly the same viscosity at 40 °C but it is a fully synthetic oil with a less steep VT curve. The new grease is stiffer with lower worked penetration limits (NLGI consistency number is one point higher). This characteristic is beneficial in high speed applications and sealed bearings where leakage is a particular concern. Other specifications are similar to grease L74. All fundamental tests performed with this grease were in accordance with FAG



standard procedures of lubricant testing and verification.

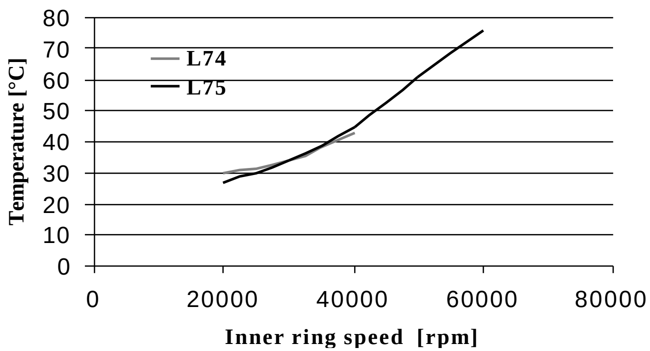
Figure 13. *Running-in behaviour of two high speed greases*

Without a proper running-in procedure, bearing and grease can be damaged in the beginning resulting in short bearing service life. A good running-in procedure for the grease is extremely important. In this respect L75 offers a clear advantage over

Maximum temperatures of 82 °C were reached with L74 in the same tests. Finally, in-house tests also showed that after the grease distribution run the L75 grease achieved a significantly higher degree of operational reliability.

The standardised FE8 tests yielded very good results, and in some cases no wear was observed on any functional surfaces. In one qualification test the greases were subjected to high speed conditions. The standard L74 grease reached speeds up to 42000 rpm with low temperatures, but when the speed was increased the bearings failed quickly. The new L75 is capable of much higher speeds. In the same speed test, speed factors of 2.5 million n.D_m were reached while maintaining low and stable values of temperature. A decisive contributing factor to this performance was the thermal stability of the thickener. In the high temperature test FE9, the L75 operated with temperatures up to 120°C with no consequences on its long term life. L75 wide temperature ranges and excellent speed performance are ideal characteristics for applications such as motorized spindles where operating temperatures can reach high limits. Because of its wide operating temperature range, L75 has a longer service life.

For long grease life it is important to keep the lubricant near the ball-to-race contact zones. FAG shielded spindle bearings (Fig.3) are now available to provide excellent grease containment and contamination protection. Bearings are filled with the right amount of grease. Every grease lot is inspected and verified before release to production.



3.2 Oil lubrication

Presently, grease is used in applications with speeds of 1.5 million $n.D_m$ or lower. Recent developments have demonstrated excellent running behaviour at 2.0 million $n.D_m$. Above these speeds oil lubrication is the preferred option. The initial oil jet lubrication design with high oil flow rates for lubrication and cooling is no longer used. The modern oil lubrication methods supply only small amounts of oil to the bearings and are called minimal oil quantity systems. A typical oil flow rate for a bearing with 70 mm bore size is 110 mm^3/hour. Small oil quantities prevent the high hydraulic losses that can result in high temperatures and poor efficiency of the bearing system.

Most common method is OIL-AIR lubrication. In this method, there is no mix of oil and air. Both fluids travel through the pipes separated from each other. The standard supply procedure is to feed the oil axially from the side into the bearing. For high reliability and optimum quantity the minimum oil flow has to be adjusted for each individual spindle system. Turbulence and airflow will influence the supply of oil inside the bearings, and drainage must also be carefully considered.

Higher reliability is achieved when the oil is fed directly into the bearing. The FAG Direct Lube bearings have integrated oil supply holes in the outer ring (Fig.15). Oil leakage is prevented by the O-rings installed on each side of the oil distribution groove. For installation, the oil distribution groove has no special requirements for angular location in the housing. For ease of mounting and better accuracy, the O-rings grooves should be integrated in the outer ring rather than the housing.

Tests performed at the University of Aachen showed that low viscosity oils, often used in high speed spindles, do not provide an optimum lubrication film. In minimum oil quantity systems, oil viscosity of 68 cSt/40°C is recommended. Calculation methods for the required oil film thickness would show values that are lot lower than the recommended 68 cSt. The high viscosity oils are suggested because they have better surface wettability properties and travel to the critical ball-to-race contact areas in a more predictable and reliable way. Standard hydraulic oils (HLP) with wear additives, and some EP additives are good candidates for high speeds. Oils from the CLP group are not as good as the HLP oils. Also not suitable are the oils used in sliding feeds.

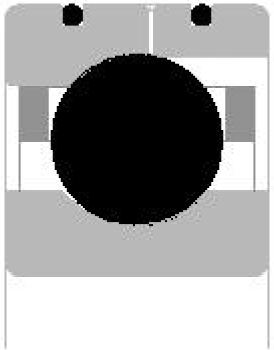


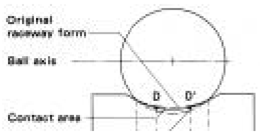
Figure 15. *FAG Direct Lube bearing with integrated oil holes, grooves and O-rings to avoid leakage in the housing fit.*

4. Bearing calculation

As mentioned before, the traditional bearing calculation based on material fatigue no longer applies for high speed applications. In these applications, the bearing kinematics, and spindle dynamic behaviour need to be considered.

4.1 *Bearing kinematics*

Bearing kinematics consider the motions between the rings and the rolling elements. In operation, microslip occurs in the contact zone between the balls and the race, and depends significantly on the raceway curvature radius (Fig. 16). In addition, tighter curvatures with their larger ball-to-race contact areas generate higher friction.



Sliding motion is affected also by the contact angle. Ball spinning motions occur for any contact angles greater than 0° (Fig. 17).

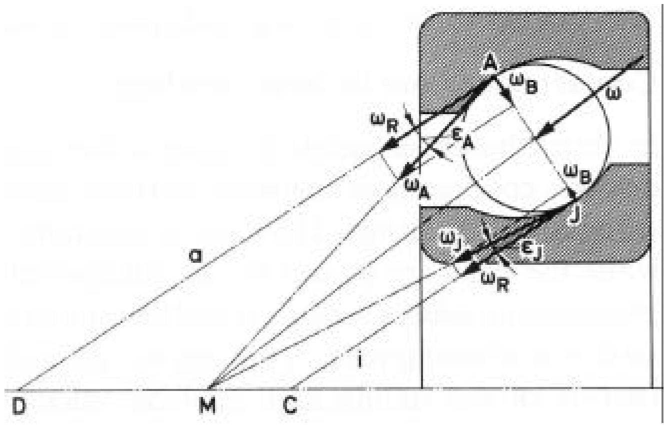


Figure 17. *The speed vectors in an angular contact ball bearing [3]*

On both ball contact locations on the inner and outer rings the vector ω_B represents the spin motion, and the vector ω_R the rolling motion. For proper bearing performance the ω_B / ω_R a spin–roll ratio of 0.5 should not be exceeded. High spin -roll ratios cause excessive ball-to-race sliding motions which result in most cases in accelerated surface wear, increased temperature, grease deterioration, and ultimately premature failure.

The centrifugal forces acting on the rolling elements and inner ring are significant in high speed applications. As the speed increases the centrifugal forces push the balls towards the bottom of the outer race causing a change of the initial contact angle between the balls, inner and outer races. The contact angle between ball-to-outer race is reduced while between ball-to-inner race increases. This contact angle difference has a direct influence on the spin-roll ratio, and, therefore, on the amount of sliding motion or friction between balls and races. Internal design parameters such as the raceway curvature radius can be adjusted to reduce the amount of sliding friction and ball-to-race contact stresses. Centrifugal loads are influenced by the ball diameter and material. The centrifugal effects are reduced significantly with the use

Preload and stiffness are also affected by the centrifugal loads. Preload can be adjusted at bearing installation to account for the centrifugal effects.

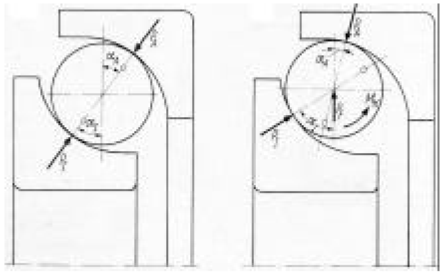


Figure 18. *Contact forces a: n=0 ; b: n > 0; the centrifugal ball loads generate different contact angles on inner and outer races [4]*

Fig.19 shows preload and stiffness for a solid clamped system of two bearings in a back-to-back arrangement.

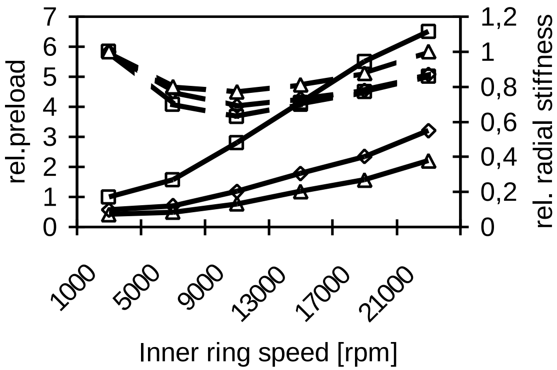


Figure 19. *Centrifugal forces influence on preload and radial stiffness .*
- - - *stiffness* —— *preload* ÿ *large steel balls* à *small steel balls* ? *small ceramic balls [5]*

Graph shows the stiffness decrease with speed, but an increase again at the higher

Small contact angles result in lower ball spinning motions and reduced sliding friction. Bearings must not operate with a delta contact angle value that would result in high spin/roll ratios >0.5 (Fig.21).

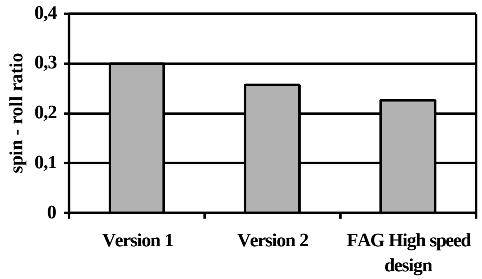


Figure 20. *Spin-roll ratios for different internal bearing design parameters.*

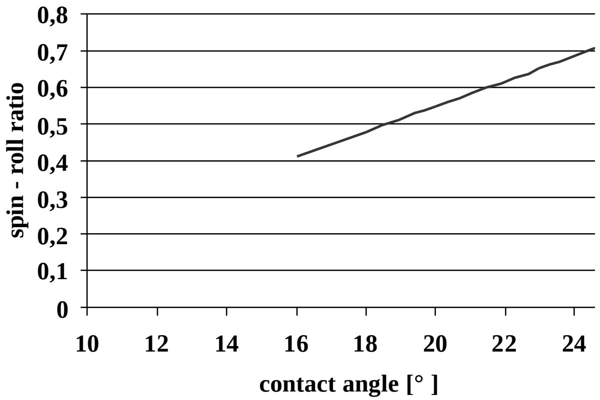


Figure 21. *Spin-roll ratio vs. contact angle*

For bearings subjected to pure thrust loads, the balls operate with the same contact angles and have the same spin/roll ratios. However, in cases of combined radial and thrust loads, the contact angles vary, and the spin-roll ratios increase with the radial

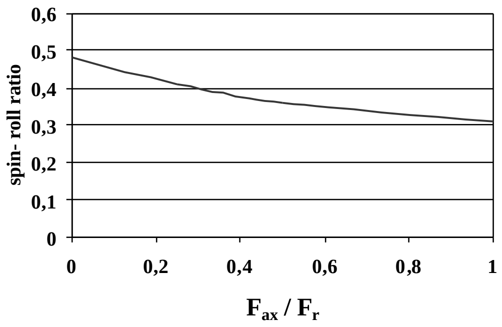


Figure 22. *Spin-roll ratio vs. load*

High radial loads can cause unloading of the balls. When this happens, the unloaded balls basically slide during the short travel through the load free zone(opposite to radial load location). However, because the balls are travelling at high speeds and with very low loads the cage is not damaged by the excessive ball excursion. (Fig.22).

To optimize the bearing designs and obtain the best performance, all bearing parameters and application conditions need to be evaluated together during the spindle design. A computer program SPICAS (Spindle bearing Calculation System) was developed to calculate the bearing kinematics, hertzian contact pressure, and the stiffness for every bearing in the spindle. Field tests have demonstrated excellent correlation between the computer results and the data obtained from applications.

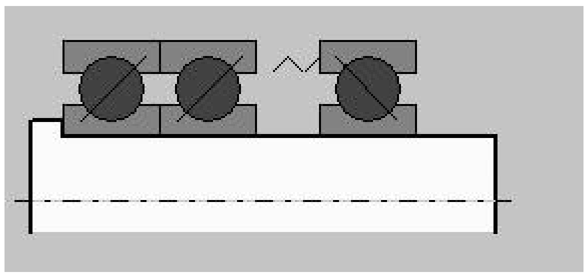


Figure 23. *Bearing arrangement in a high speed milling spindle. The bearings are*

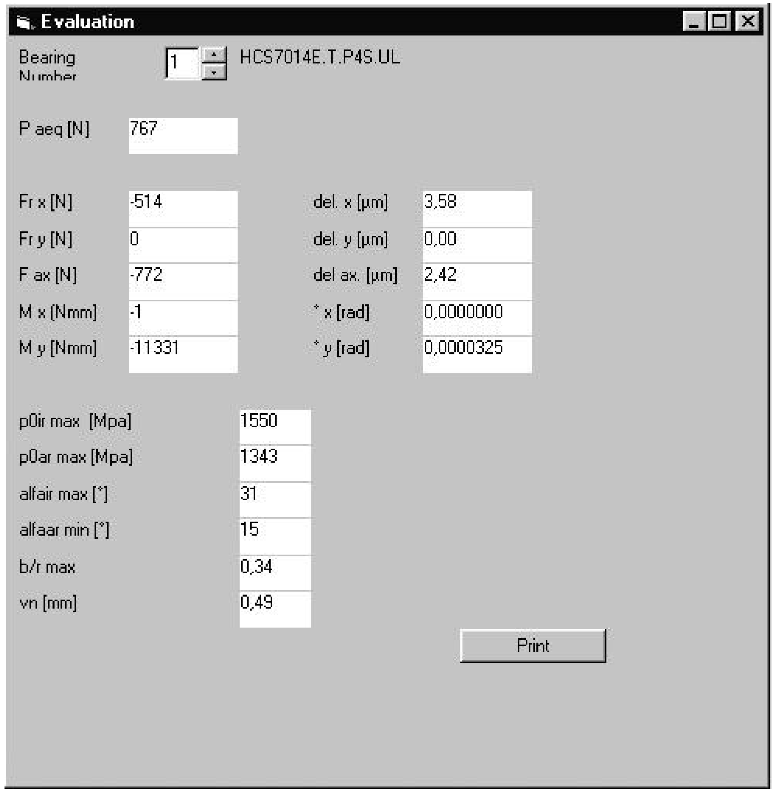


Figure 24. *Calculation results for the first bearing of the bearing system, fig.23. The contact pressure is lower than the limit for infinite life time (2000 MPa) The kinematic factors b/r(spin-roll ratio) and vn(ball excursion) are in the permissible range.*

Summary

The present demands placed on the high speed machining spindles for faster cutting rates, better reliability, higher efficiency, and improved capability are being met by new bearing materials, higher speed greases, and sophisticated analytical software.

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