Technology development and future challenge of machine tool spindle

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Abstract

In this paper, the history for this 40 years of spindle speeding up and future technological challenge are described, at the same time, the latest spindle technology is introduced.

Keywords: Machine tool spindle, Oil-air lubrication, 5-axis machine, Grease replenishing lubrication, Intelligent spindle

1 INTRODUCTION

The machine tool spindles have been developed with a focus on high-speed technology as the reason behind that they aimed the improvement of cutting efficiency by the development of machining center on 1975 or later, in accordance with the demand of speeding up was increased rapidly.

After that the wide range of needs such as higher accuracy, higher stiffness, and improvement of reliability etc. is come out. In addition, the needs in response to environment, saving energy, 5-axis machine, multitasking machine and intelligent machine are come out. In this article, the history of spindle speeding up and future technological challenge are described, at the same time, the latest spindle technology is introduced.

2 SPEEDING UP OF SPINDLE

2.1 History of spindle speeding up

Figure 1 shows the history of spindle speeding up. The $d_m n$ value of spindle bearing has been increased spectacularly in response with the cutting needs with the times. As the key technologies making progress of speeding up, the improvement of lubrication method such as grease lubrication, oil-air lubrication, and jet lubrication, the application of new material to bearings (rolling elements , inner and outer rings and cage) such as ceramic balls, and the advancement of design approach and technique of analysis are mentioned.

Figure 2 shows the investigation results of high-speed spindle (10000min^{-1} over) displayed in Japan International Machine Tool Fair (JIMTOF) since 1982. In JIMTOF2010, the progress of speeding up is standstill in recent years, and the maximum rotating speeds are focused on around 12000min^{-1} and 20000min^{-1}. As the features of whole machines, speaking of machining center, the exhibits of 5-axis machining center which has the turning mechanism of spindle(tool side) and table(work side) are increased, and in the case that they are used as processing machine of aircraft components or dies, in order to attain high-efficiency process, high-speed spindle is equipped. In case of multitasking lathe, the trend toward speeding up

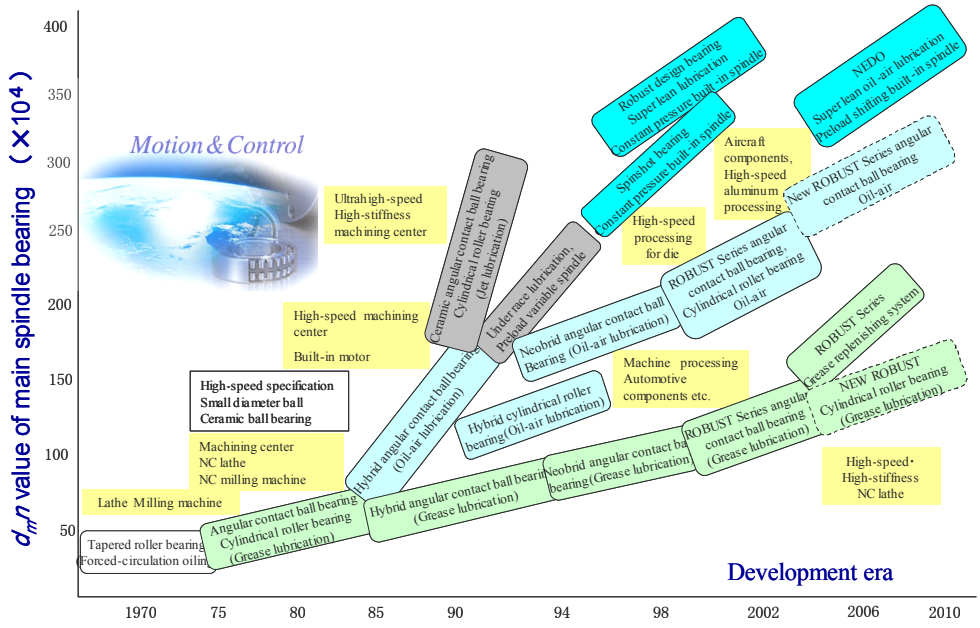

Figure 1: Transition of speeding up of machine tool spindles

of milling spindle is remarkable.

The so-called built-in motor spindle which the driving motor is integrated inside the spindle is become regular use as it is indispensable technology for high-speed spindle, for the attainment of ultrahigh-speed rotation, further speeding up, high output, and downsizing of the rotor and stator are expected. Recently in response to environment and saving energy, additional speeding up and improvement of reliability of grease lubrication begin to be required.

2.2 High-speed bearing technology

As for the high-speed spindle of recent machine tool, in order to make the inertia of rotating parts, the adoption of built-in motor spindle which integrates compact and high output rotor is increasing. However, in case of such spindle structure, at the transition period of rapid rotational fluctuation, ambient environmental variation (heat generation change of motor and outer cylinder cooling) becomes significant, and the bearing of spindle is exposed under the harsh thermal fluctuation condition. For the spindle bearing, it is the most important to have the characteristics of seizure resistance under such environmental condition, and it is necessary to have temperature robust performance (against thermal load fluctuation, the bearing itself shows small fluctuation of heat generation value, more specifically, against the thermal disturbance, the bearing has a characteristic of thermal insensitivity). For these high-speed spindles, to respond the demands described above, the ultrahigh-speed bearings “ROBUST Series”, which bearing internal design was optimized as described below are adopted[1]. (Refer to Figure 3)

Under the processing conditions with various cutting conditions and rotational fluctuation, the temperature change inside the spindle is significant and the temperature difference between inner and outer rings involved, it causes the decrease of bearing internal clearance, the contact angles between balls and raceway groove of inner and outer rings change rapidly, and the internal preload of bearing increases, the PV value (P: Contact surface pressure, V: Sliding speed) of rolling contact area between the raceway groove of inner and outer rings and balls increases. The internal specification of ROBUST Series bearings is that the change of PV value is minimized under the conditions described above on the basis of analytical results by the computer as the affectors such as ball diameter, raceway groove curvature of inner and outer rings, and contact angle etc. are considered the parameters. And the application of special carbonitrided steel (SHX steel) and the adoption of high-strength plastic cage of special configuration that has

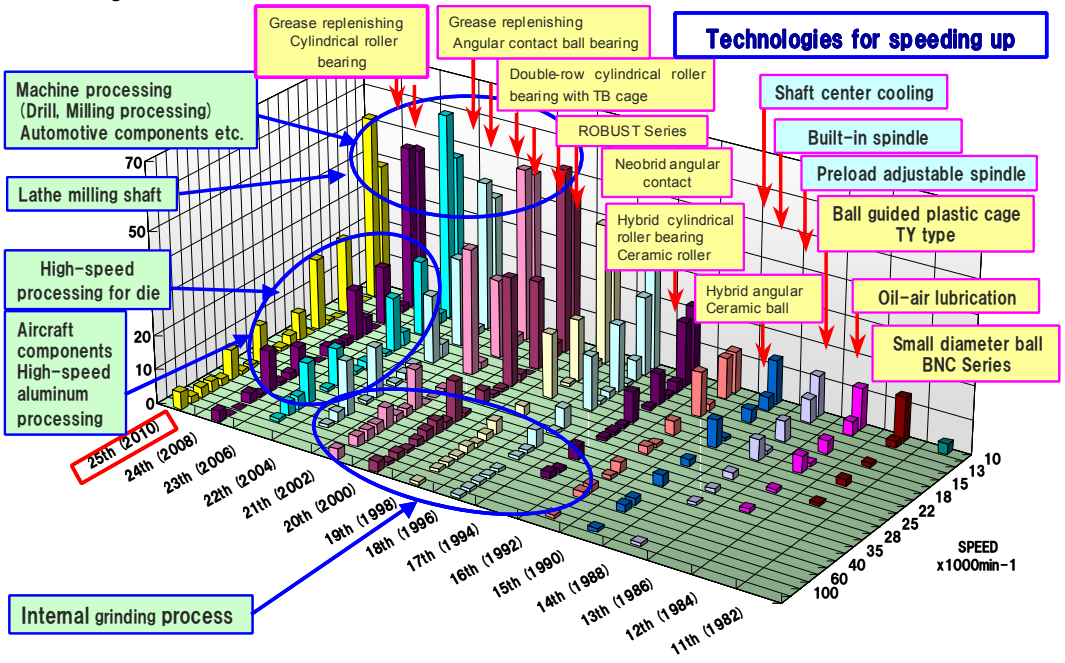

Figure 2: JIMTOF High-speed spindle display situation (10000min^{-1} over)Investigated by NSK

Ultrahigh-speed angular contact ball bearing Spinshot II bearing Ultrahigh-speed single-row cylindrical roller bearing

Figure 3 : Examples of various ROBUST Series

excellent heat resistance and wear resistance improve seizure resistance additionally. Also, the Spinshot bearings that the lubricating oil is replenished effectively under the condition of high-speed operation by optimizing the bearing configuration are developed.

3 TECHNICAL CHALLENGE OF SPINDLE

Figure 4 shows the technologies required from the machine tools in Japan in the future. To begin with, the technologies required from the machine tools, secondly the technologies required from the spindle and the bearings were summarized. Until recently the development of high speed, high accuracy, and high stiffness was focused but recently the durability and the improvement of reliability are required, especially in the past several years, the environmental responsiveness, saving energy, and advanced grease lubrication for maintenance-free operation are required. And the requirement of Intelligent and Smart by applying the sensor is increasing.

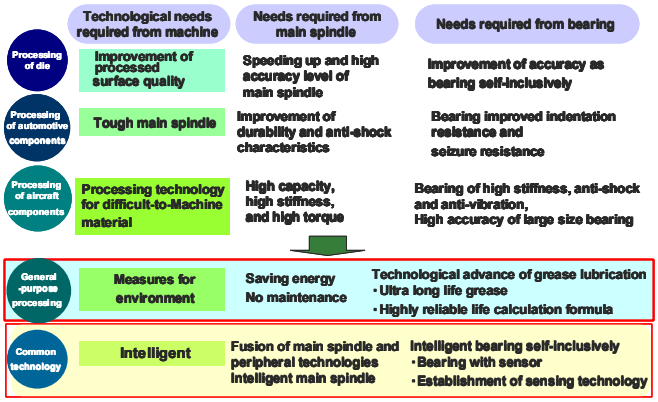

Figure4: Technologies required from Japanese machine tools in the future

3.1 Measures for high speed and high accuracy

As the lubrication method used generally for spindle of machine tool, grease lubrication,oil-air lubrication and oil mist lubrication etc. are quoted. Depending on the method of supplying or retaining the lubrication oil or the difference of quantity, their features are different respectively. For the spindle of machine tools, from the aspect of the improvement of machining accuracy, as the basic characteristics, low heat generation and low temperature rise are required.

3.1.1 Oil-air lubrication

The oil-air lubrication was developed and put to practical use as the suitable lubrication method for ultrahigh-speed rotation by adopting advantages of grease lubrication and oil mist lubrication and by eliminating disadvantages respectively. As shown in Figure 5, the oil-air lubrication system is that high-pressure air and tiny oil droplet are fed from bearing side face to bearing inside with the use of oil feeding nozzle. In this system, the air curtain which is generated by high-speed rotation (the air curtain in this case means the wall of circumferential high-speed air stream generated by the friction between the air and high-speed rotating outside surface of inner ring.) blocks the oil flow from the nozzle. As the result, the lubrication oil was not fed into the bearing inside certainly, it was likely the cause of seizure. There was the lack of stability in the range where the $d_m n$ value exceeding (200-250)x10^4 .

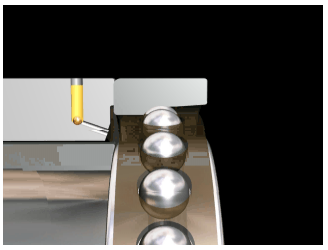

Figure 5: Conventional oil-air system

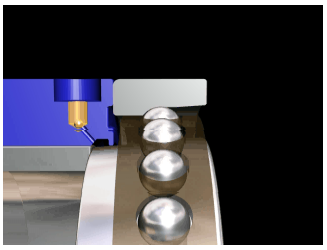

Figure 6: Spinshot system

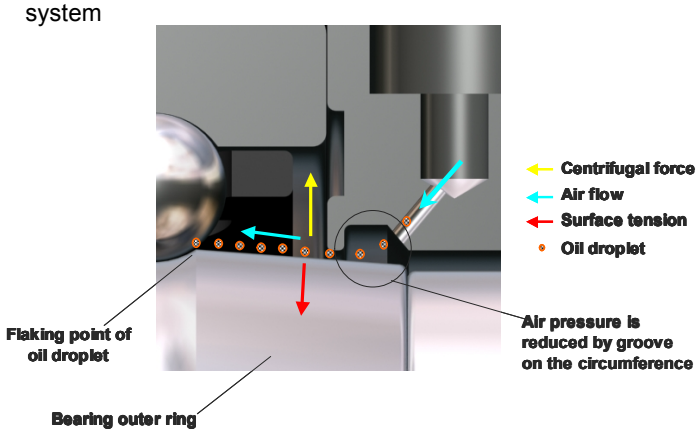

Figure 7: Lubrication principle of Spinshot II

3.1.2 Spinshot bearing

New bearing “Spinshot II”[2] as shown in Figure 6, was developed to solve the problem described above, and it has the design specification of improved temperature robust performance described in the section 2.2 and special bearing structure additionally that the width of inner ring is wider than that of outer ring and the outside surface of inner ring is tapered configuration. By this configuration, the lubrication oil assisted with air, is sprayed from the outer ring spacer to the tapered surface of outside surface of inner ring, as shown in Figure 7, the lubrication oil is moved on the tapered surface by centrifugal force of rotation and guided to the inside of bearing and fed to the rolling elements certainly. And since the structure is that the air is not blown to the inside of bearing directly, it is able to control harsh air noise of high frequency due to the air generated by high-speed rotation. In addition, as it is free from the blocking of oil by the air curtain, it is not necessary to speed up the flow rate of air and it was possible to reduce the air pressure. For the amount of air and oil, it is 10L/min(Normal) per one nozzle, in comparison to conventional oil-air lubrication, about 60% reduction in air consumption was attained. And in case that the lubrication oil is fed externally, to realize the stable rotation at ultrahigh-speed rotation, it is important to attach the sensor, which is monitoring whether the lubrication oil is fed from lubrication equipment to spindle side certainly or not.

3.1.3 Development of super lean oil-air lubrication

In order to make further speeding up of oil-air lubrication, as the lubrication method feeding much less quantity of lubrication oil, the super lean oil-air lubrication was developed. The super lean oil-air lubrication is the system feeding lubrication oil by use of air as well as oil-air lubrication, but it is possible to control the discharge rate of 0.001cc or less for one shot. As the spindle adopted the super lean oil-air lubrication, the spindle of

Table 1: 50000min^{-1} Spindle specification

Spindle end taper	HSK-E50
Maximum rotating Speed (d_mn value)	50000min^{-1}(d_mn380x10^4)
Bearing bore diameter	Front side Φ60mm, Rear side Φ50mm
Lubrication	Super lean oil-air lubrication
Preload type	Constant pressure preload (DT+DT arrangement)
Preload shifting	3 steps preload shifting

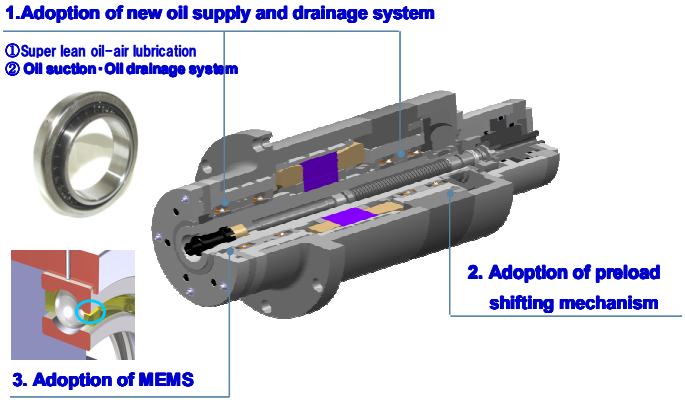

Figure 8: Features of 50000min^{-1} Spindle

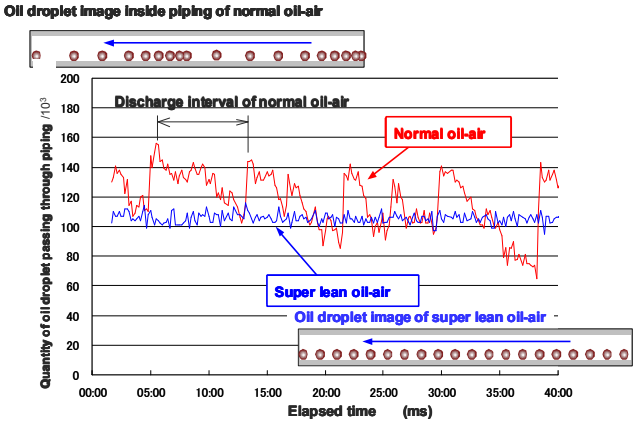

Figure 9: Comparison result of oil droplet quantity passing through piping

the highest speed in the world was developed. The specification is that the taper of spindle end is HSK-E50, spindle diameter is 60mm, the maximum rotating speed is 50000min^{-1} (d_mn 380x10^4).

In Table 1, the specification is listed and the features of this spindle are shown in Figure 8[3]. As the first feature, new oil supply and drainage system was adopted. For the oil supply side, by using the super lean oil-air lubrication described above, as shown in Figure 9, in comparison with the oil-air lubrication, the flow of oil droplet inside piping is able to be stabilized and it is possible to control the heat generation of bearing and the change of temperature rise. Also, for the drainage side, newly oil suction and oil drainage system was adopted. By this mechanism, even if the spindle goes up and down or turns, the lubrication oil does not stay inside the bearing and to be drained easily the change of heat generation inside spindle is controlled and it is possible to stabilize

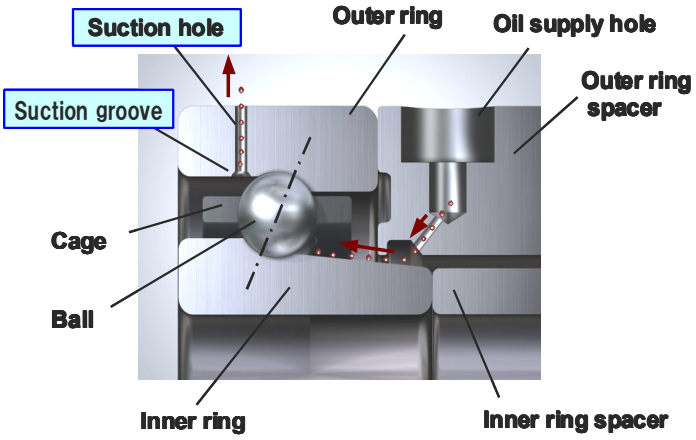

Figure 10: Flow of lubrication oil inside bearing

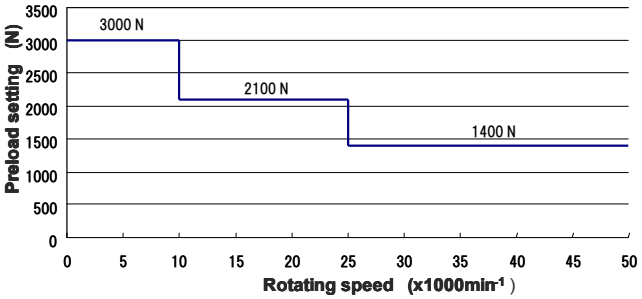

Figure 11: Constant pressure 3 steps preload shifting

the temperature rise. Figure 10 shows the flow pattern of lubrication oil supply and drainage inside the bearing.

As the second feature, by using tandem duplex bearings (DT+DT) with constant pressure preload, the preload shifting mechanism (Figure 11) that can control the preload such as heavy preload at low speed, medium preload at medium to high speed, and light preload at high to ultra-high speed, was adopted. By this preload shifting system, it can bring about the realization of heavy cutting at low speed to ultrahigh-speed cutting. As the third feature, by attaching MEMS (Micro electro mechanical System) temperature sensor inside of the bearing, the temperature around heat source of bearing was measured. By adopting MEMS temperature sensors, it was able to improve the responsiveness of temperature measurement. And for the needs of speeding up and high rigidity of spindle, the higher speed spindle, the more technologically advanced measures are required such as multi balance control at high-speed rotation and high accuracy of bearing etc. In addition, in the case of built-in motor, when the channel of stator cooling oil is not line symmetry channel to the shaft center of spindle, the thermal displacement in radial direction occurs easily, and the shaft elongation affects heavily the quality of finished surface, so that it is looking forward to the arrival of high-speed bearing and motor with excellent heat generation properties, and material of low linear expansion coefficient.

3.2 Measures for high rigidity

Meantime, for the aluminum processing profiler as represented by aircraft components, since the aluminum material has a good machinability, high-speed (high feed)

Table 2: Required characteristics from turning spindle and problem area

(1) Shortening of overall length	(2) Reliability of bearing lubrication structure
●Selection of number of bearing row	●Smooth drainage of lubrication oil
●Downsizing of bearing system	●User friendliness of piping
●Downsizing of built-in motor	●Control of grease drop out
●Shortening of tool clamping mechanism	●Prevention of ingress of coolant

processing is mainstream, and for the spindle, in addition to the speeding up, the high rigidity that is conflicting performance is required. In addition, for this type of machine, the work tends to increase in size, and the turning spindle type is general. In this case, in order to attain fine profile processing of complex and small circular arc, the downsizing of spindle is more advantageous, but to ensure the compatibility with high rigidity, higher technology level is required.

3.3 Measures for 5-axis machine and multitasking machine

3.3.1 Required function in case of tool side turning

For the machine tools of tool side turning, the required characteristics from spindle,as shown in Table 2, are classified by two such as (1) How to shorten the overall spindle length. (2) Reliability of bearing lubrication structure that is able to respond to the position change. The shortening needs of item (1) was come from that by shortening the spindle, the oscillation space of turning is reduced, the effect on the linear motion shaft is controlled, and to avoid useless overgrown of the machine, and by downsizing the spindle, the capacity of turning motor is decreased. For the position change of item (2), is it designed that the reliability of bearing lubrication is not damaged by the position change?

3.3.2 Shortening of overall spindle length

To increase the load capacity of spindle, by increasing the number of bearing row and reducing the load per a bearing row is common practice, but the spindle is lengthened and it is difficult to use for 5-axis machine of turning spindle type. As far as the angular contact ball bearing, the matched back-to-back arrangement (DB) is shorter than the four-row back-to-back arrangement (DBB), and for the cylindrical roller bearing, the single-row is shorter than the double-row, but the load capacity is smaller in each case. Especially in case of multitasking lathe in comparison to 5-axis machining center, the case that it is forced to make compromise this point is found here and there. In case of the machining center, if 2-axis turning are equipped at work side, this point does not become something of a problem. And though the machine adopting turning spindle system in such composition, since the machine itself is large mostly, the problem is hard to become obvious. However, when it is considered that the deployment and expansibility of 5-axis machine to various processes in the future, it is necessary to take measures to shorten the overall length as much as possible by composing compact bearing system including lubrication mechanism and by optimizing bearing arrangement inside the spindle.

And recently since the built-in motor is used in the spindle, and the spindle itself becomes compact, for turning spindle system 5-axis machine, the built-in motor spindle is optimum. In such case, since the motor is the factor determining the overall length of spindle in many cases, the commercialization of smaller size and higher output motor is desired.

3.3.3 Measures for position change

For the oil-air lubrication which is now perfectly established as the lubrication system of high-speed spindle, the smooth drainage of lubrication oil which is fed continuously is an important point to realize the stability in the aspect of lubrication. In case of the composition of turning spindle, it is necessary to pay full attention for the design of drain channel in response to the turning angle.

Also, for the units performing turning motion, it should be free from wiring and piping as much as possible. If possible, to adopt grease lubrication is the one of solutions. However, in such case, there is a concern about the deterioration of life due to dropping out of grease in comparison with the spindle without position change. In addition, as the big challenge which the spindle has, there is the problem that how to prevent the ingress of coolant inside the spindle. In this point, the risk of ingress increases from the vertical type, the horizontal type, and the turning type in order.

3.4 Measures for grease lubrication

3.4.1 Sealed angular contact ball bearing

For the machine tool spindle bearing, the environment friendly clean technology attracts a lot of attention, as the bearing in response to such requirement, the precision sealed angular contact ball bearing (refer to Figure 12) is come into use. In this bearing, compact non-contact seals are adopted, while it is holding the interchangeability with conventional bearing, and the workability improvement by prelubricated grease, splash prevention of grease, and improvement of high-speed rotation are striven. Also, by using this bearing, it is not only the extension of grease life is able to be striven but also it is

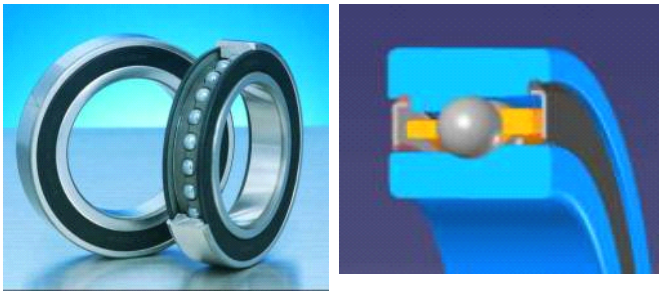

Figure 12: Sealed angular contact ball bearing

possible to prevent the drop of grease in case of the vertical type spindle.

3.4.2 Grease replenishing lubrication bearing

Since the grease lubrication can be used for a long time only to be filled the specified amount of grease when the bearing is mounted, it is very easy and it is widely used as the most common lubrication method. However, in case of the built-in motor spindle, the continuous running at high speed with urgent acceleration and deceleration is increasing, though it is possible to rotate for a short time with conventional grease lubrication, the failure case that the grease is deteriorated or depleted by high-speed continuous running and it causes the occurrence of seizure begins to increase.

Consequently, when the grease life is considered, for existing grease lubrication the maximum rotating speed is limited. As well as the oil lubrication, the grease replenishing lubrication is that by supplying the lubricant externally, the grease life was improved spectacularly, and it attained the maximum rotating speed 20000min^{-1} though it is grease lubrication.

Figure 13 illustrates the structure of new grease replenishing lubrication system developed by NSK Ltd. For the application except the area of machine tool spindle, until recently, there were the methods to grease into bearings with use of grease replenishing piping or grease nipple etc. However, in this new system, there are the biggest features such as the quantity of supplied lubricant is extremely small amount, in addition the grease is fed directly into the bearing which is rotating athigh speed. In case of the oil-air lubrication, as the oiling quantity, the lubrication oil of about 1-3cm^3 is

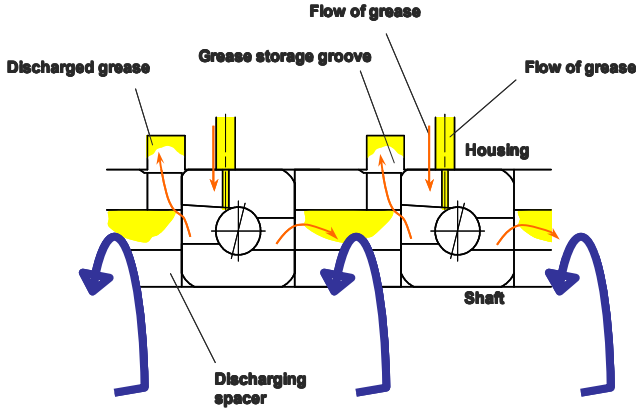

Figure 13: Grease replenishing lubrication system

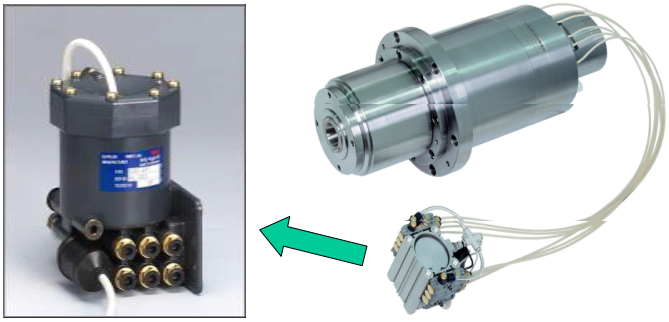

Figure 14: Grease replenishing unit Fine-Lub II

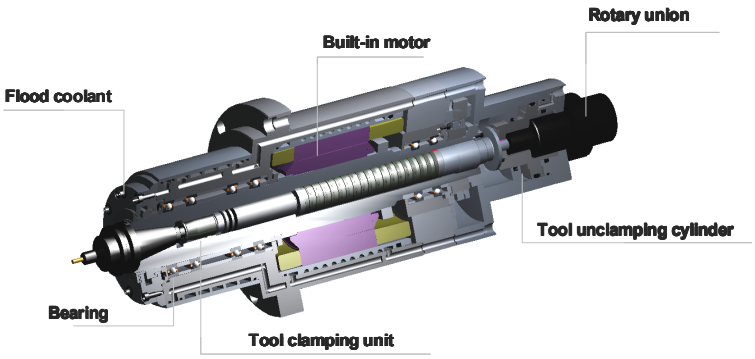

Figure15 : High-speed built-in motor spindle

Table 3: B1 Spindle specification (L type)

Spindle end taper	NT40/HSK-A63(Op)
Maximum rotating speed	20000min^{-1}
Maximum output	22/18.5kW(15Minutes/Continuous)
Maximum torque	118N･m(25%ED)
Bearing bore diameter	Φ70mm
Preload type	Position preload (DBB arrangement)

consumed by single row of bearing for 24 hours. In the meantime, the grease quantity of grease replenishing lubrication is extremely small such as less than 0.1cm^3, and it is not necessary to drain the lubricant to outside.

In addition, since the consumption of air to supply the lubrication oil is not necessary; as a result, it is free from splashing the oil to atmosphere, as ecological point of view, the grease replenishing lubrication is superior to the oil-air lubrication or the oil mist lubrication. Figure 14 shows the grease replenishing unit “Fine-Lub II” used for the grease replenishing lubrication system.

NSK Ltd. Has developed “High-speed built-in motor spindle”[4] as the standard spindle of NT40 Class adopted grease replenishing lubrication (Refer to Figure 15). This spindle adopted the world’s first new lubrication system saying that grease replenishing lubrication, it attained the maximum rotating speed 20000min^{-1} though it is grease lubrication. The main specifications of this spindle are listed in Table 3[4].

3.5 Measures for intelligent spindle

As the direction of machine tool spindle in the future, the demand of intelligent spindle is increasing, but there is not yet the intelligent spindle which comes into practical use in the market. NSK Ltd. has developed the spindle[5] in which the load displacement sensor and the encoder were integrated to detect the axial displacement during cutting process in addition to MEMS sensor described above. The rotation of this spindle was demonstrated in JIMTOF2010.

The purposes of development of this spindle were the control of tool life by detecting the load change at cutting process, the automatic process shutoff by detecting abnormal load, the review of process conditions, and the preventive measures of bearing failure by detecting the preload of bearing etc. Figure 16 illustrates the image of

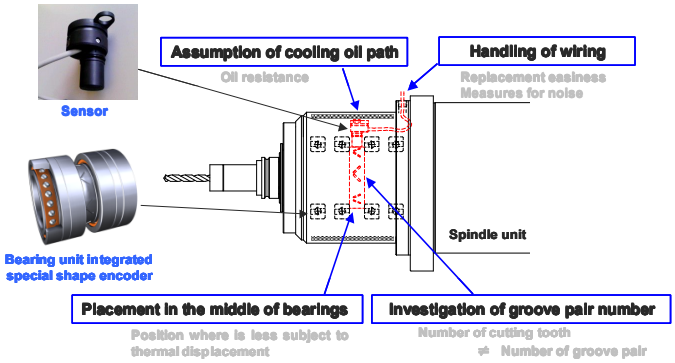

Figure 16: Image of cutting load

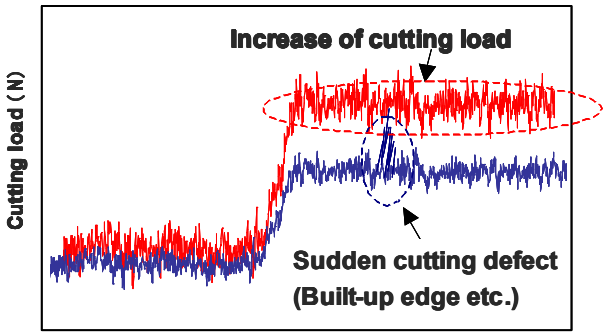

Figure 17: Spindle integrated load displacement sensor

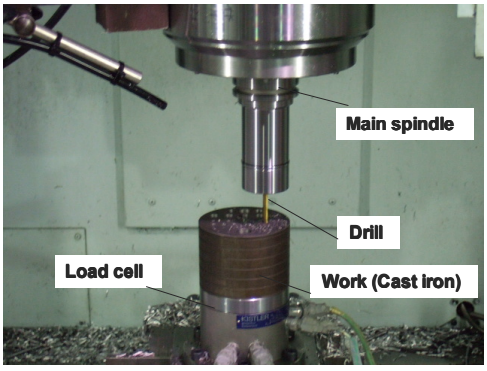

Figure 18: Cutting process test by actual machine

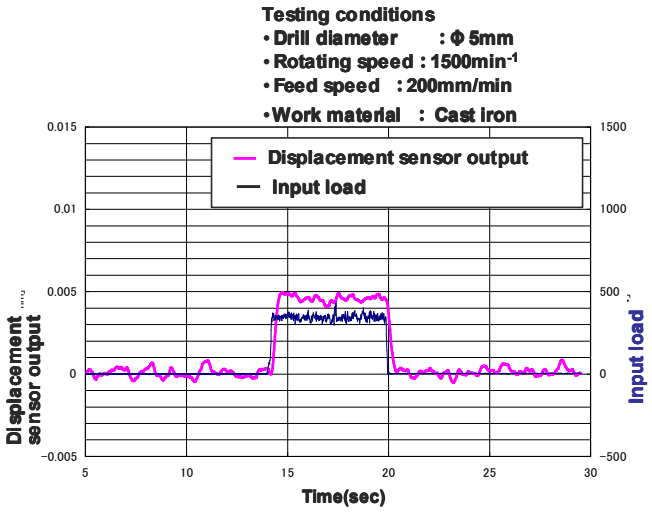

Figure 19: Comparison of cutting process test results

load change at cutting process. It is possible to detect the increase of cutting load or emergent cutting defect. Figure 17 shows the mounting arrangement of the load displacement sensor in the spindle. The shape of sensor is like nozzle top of oil-air lubrication, and the encoder is the inner ring spacer of bearing.

This spindle was mounted on the actual machining center; a work (cast iron) was put on the Kistler dynamometer, and when the drilling process was operated as shown in Figure18, the cutting process test was conducted by comparing the output of displacement sensor and the input load. The comparison result of the test is shown in Figure 19. Including other end mill cutting etc., the almost same values are obtained between the input load and the output of displacement sensor.

4 CONCLUSIONS

With a focus on the speeding up of machine tool spindle, the technology development of spindle for about 35 years was explained but the speeding up is standstill in recent years, the market requirement is changing from high speed and high accuracy to high stiffness and improvement of reliability, and nowadays environmental responsiveness, saving energy, and intelligent spindle. In this year, JIMTOF2012 is scheduled to be held, it is considered that Japanese machine tool industry aims saving energy and ecology-conscious directivity in the future, and the high value-added machine tools are increasing by adopting new material such as CFRP and by performing curved surface processing of 3 dimension. Above all, it is considered that the technology aiming further speeding up of spindle along with the life enhancing and improvement of reliability of grease lubrication will be revived newly. Continuously I will lead the world from the aspect of spindle technology and intend to advance new research and development aiming the improvement of unique machine tool technology of Japan.

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