State of the Art Ball Screw Trends for Machine Tool Applications

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Abstract

This paper reviews the latest technical trends in precision ball screws, which are especially used in the machine tool industry. At the JIMTOF (the Japanese International Machine Tool Fair) 2012, an obvious juxtaposition of demands, high axial speed and high positioning accuracy, were observed in the latest machine tools. NSK has suggested some new solutions to improve machine performance in these areas. The NSK HSS (high speed SS) series ball screws, equipped with the SRC (Smooth Return Coupling) return components, contribute to exceeding 60 m/min feed rates with a d・n value (d : diameter of a ball screw shaft, n : 1 / minute) of over 160,000. A hybrid lead table unit is another solution, overcoming a physical speed limitation of ball screws. Meanwhile, nut cooling ball screws have also been developed in order to reduce a temperature increase on overall feed components. The effective heat dissipation of this design leads to high positioning accuracy, less distortion of the machine structure and also excellent machining integrity.

Keywords : Ball Screw, Machine Tool, High Feed rate, High Accuracy, Heat Transfer, Nut Cooling

1 INTRODUCTION

The first generation of ball screws was developed in the late 1930's, as steering gear devices for the United States automotive industry.

Precision ball screws were subsequently developed for the manufacturing industry. The first NC (Numerical Control) machining center was commercialized in 1961, and this historical achievement was possible, due to both precision ball screw and NC system development.

Since then, precision ball screw adoption has expanded in the machine tool industry, and in the 1970's, also to the semiconductor and electronics manufacturing industry, in which much higher feed rates and short stroke motions were vital for achieving competitive productivity. This led to the expansion of design specification ranges of ball screws, and to quality improvement and increased production quantity.

Ongoing product development of ball screws requires careful investigation of the market's needs and an astute vision for suggesting useful improvements.

Figure 1 shows the historical trend of the maximum feed rate of each machining center, investigated by NSK in every JIMTOF (the Japanese International Machine Tool Fair) continuously over 16 years. Figure 2 summarizes this chart into the number ratio of machines to overview a trend of feed rate distributions at each exhibition. These charts show an increasing trend in machining centers with the feed rate ranges of 50 to 60 m/min, while there is another trend in the feed rates up to 40 m/min.

The 50 to 60 m/min feed rate area represents rapid machining processes, such as milling and drilling of automotive and aeronautic components. The feed rates up to 40 m/min are for those applications requiring accurate trajectory control of the tool pass for machining geometries precisely. A typical industrial area can be found in machining of the mold and die units for the plastic injection molding and pressing industries.

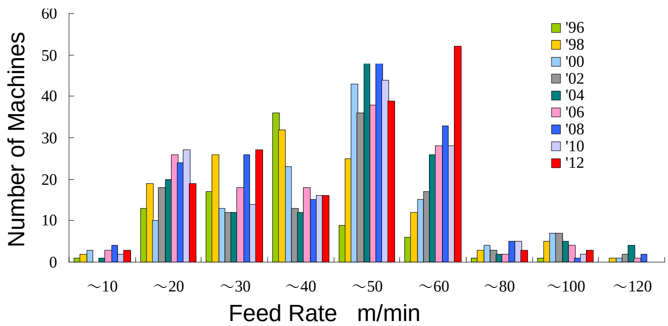

Figure 1: Number of Machining Centers vs. Feed Rate.

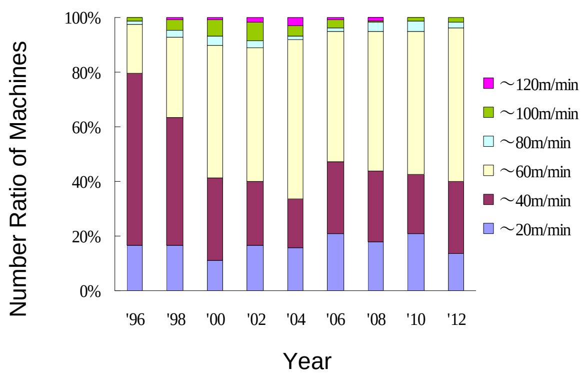

Figure 2: Number Ratio of Machining Centers vs. Feed Rate in 1996 ～ 2012.

2 BALL SCREW SOLUTIONS FOR HIGH SPEED MACHINING APPLICATIONS

High lead ball screws used to be regarded as a typical solution for high speed applications. However, this specification needs a high power motor and high axial stiffness on the feed system. Meanwhile, around the time when linear motor drive systems appeared commercially in the machine tool industry in the 1990's, NSK developed a new design to increase speed capability. This idea focuses on the advantage of a high d・n value (d : diameter of a ball screw shaft, n : 1 / minute) to increase the revolution speed and the feed rate in axial direction. Although the d・n value had been limited due to the physical damage caused at the tip end of return components such as tubes, deflectors and end-caps by the continuous ball impact force, NSK has overcome this limit with new type deflectors. In the new design, the balls are picked up smoothly by the tongue of each deflector along the tangential direction of a thread line. This results in a smooth and continuous motion through the ball recirculation sequence.

The latest version of this new type deflector is introduced below. In addition, a hybrid lead table unit, capable of achieving an extremely high lead of over 100 mm per revolution, is also described as one of future visions for ball screw applications.

2.1 NSK HSS (High Speed SS) Series Ball Screw

NSK installed new type deflectors onto the NSK HMD series precision ball screw in 2008 [1]. This series had been released specifically for machine tools, and thus adopted a double nut type preload configuration and a relatively high lead of 16 ～ 30 mm suitable for high speed machining. These ball screws have been chosen for achieving a feed rate of 50 m/min in the ball screw shaft diameter of 40 ～ 50 mm, and have contributed to high productivity in the machine tool industry.

Meanwhile, precision machining applications, which require high accuracy in the sub-micron range, tend to use a relatively fine lead of 8 ～ 12 mm. This design specification is preferable for achieving accurate positioning control and high axial stiffness. In this fine-lead design, axial stiffness can be increased by adding either tubes or conventional deflectors. The tube type design tends to be selected for this purpose in the Japanese market to meet the cost requirements, while the conventional deflector type design is popular in the European market to reduce the nut outer diameter and lower the nut inertia force.

In order to achieve a high feed rate of over 50 m/min with this fine lead design, it is necessary to increase the revolution speed, and thus the limitation of the d・n value has to be overcome. NSK has developed the next generation of return tube components, the SRC (Smooth Return Coupling) return components, for this purpose.

Figure 3 shows the general view of a typical SRC component on a nut. Although its structural arrangement is close to that of a tube type ball screw, each ball is guided into the SRC return component continuously along the tangential direction of a thread line. This reduces ball impact contacts against the return components. Since the SRC return component is a plastic part, the return circuit also contributes to lower noise and smooth motions of the balls, resulting in less vibration on the axial feed system.

The diameter of each SRC circuit type nut is completely compatible with that of a tube type ball screw nut. If it is necessary to increase the load capacity, additional SRC return components can be used. This flexible design modification capability is another major advantage of the SRC circuit type ball screws.

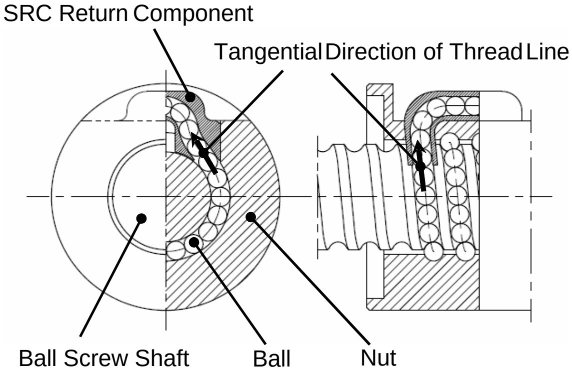

Figure 3: SRC Circuit Type Component.

The combination of these characteristics has enhanced the performance of precision ball screws dramatically. The d・n value has increased to 160,000. The reduction of noise has been evaluated as an acoustic pressure level of 6 dB (A), and the vibrating acceleration has become less than a half.

NSK has adopted the concept and advantages of the SRC return components into the NSK HMS series ball screws. The HMS ball screws have been highly accepted in the precision machining field, which intends to accommodate recent demands for higher speed production.

NSK's newest ball screw development is the NSK HSS (High Speed SS) series ball screws, released in 2012. Figure 4 shows an overview of the series and an optional support bearing unit. This series is a standard variation of the HMD and HMS series ball screws, in other words, an expansion of the SRC family.

Figure 4: Variation of HSS Series Ball Screws with Support Bearing Unit.

The HSS series ball screw is intended for use in the high end designs of industrial applications. The maximum d・n value is 160,000, compared to 70,000 for conventional standard series ball screws, and the highest lead of 20 mm results in a top feed rate of over 60 m/min.

All HSS series ball screws can be supplied with unfinished shaft ends. This allows machine builders to complete their unique shaft end finishing processes per their short delivery time requirements. A series of support bearing units has been designed to reduce the temperature increase even at preloaded conditions. This minimizes the axial expansion of the ball screw shaft, and improves the positioning accuracy.

2.2 Hybrid Lead Table Unit

As one of new visions, NSK has developed a new high speed axial feed system, the Hybrid Lead Table Unit, and exhibited in the JIMTOF 2012.

Figure 5 shows a general concept of this mechanism. Since both right hand and left hand ball screw threads are fabricated onto a single ball screw shaft, relative linear motions between Nut 1 and Nut 2 can be generated interactively on this mechanism. If the Nut 1 is fixed on a base, the Nut 2 attached on a table can be fed in the lead of “ Lead A + Lead B ” per one revolution of a motor. Although there used to be a certain geometric limitation to increase the lead on ball screw components, the suggested hybrid table can overcome the disadvantage, and provides an extremely high lead design specification. The hybrid lead table unit has the capability to increase productivity in the next generation of high speed machine tools.

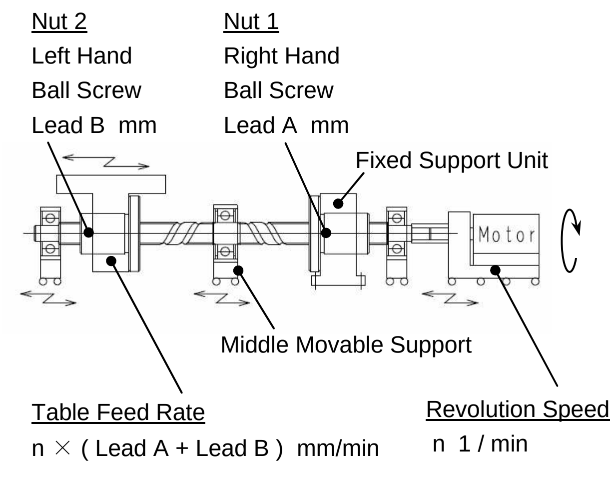

Figure 5: Hybrid Lead Table Unit.

The presented hybrid lead table unit has a 32 mm shaft diameter ball screw, and a 128 mm (64 mm × 2) lead. This table unit has achieved the extremely high feed rate of over 350 m/min, well beyond the limit of conventional ball screw feed units.

Although an extremely high speed is applied, the critical speed condition is not a limiting factor. This is because a bearing support unit arranged at the middle of the ball screw shaft moves together with the ball screw shaft, maintaining a consistent support span in either right hand or left hand side of the ball screw shaft. This design arrangement helps to improve the dynamic performance of the axial feed system.

If both threads on the ball screw shaft are specified in the same thread-winding direction, either right hand or left hand, the mechanism becomes distinct from the hybrid table unit, and can be called the Differential Lead Table Unit with an axial feed speed of “ n × (Lead B - Lead A) ” mm/min.

The advantage of this system is that a fine lead resolution is achieved with less lack of uniformity of rotary motions in a motor, and without microscopic damages of ball contact interfaces due to fretting corrosion. NSK has presented a fundamental concept of this differential mechanism at the JIMTOF 2012, with Lead A of 64 mm and Lead B of 54 mm, and a 32 mm shaft diameter of a double right hand thread type ball screw shaft. Since the revolution speed of the ball screw shaft is relatively slow compared to the hybrid lead table unit, the above mentioned movable bearing support unit, located in the middle of the ball screw shaft, is not required on the differential lead table unit. This mechanism is appropriate for highly precise machining processes, such as various types of precision hard milling and grinding, in which high resolution of the feed motion is vital to achieving fine and consistent depth of cut.

These new ball screw solutions for achieving high speeds and fine resolutions meet the latest demands of the machine tool industry, not only with internal design improvement of ball screws but also with concept innovation of the feed system.

3 BALL SCREW SOLUTIONS FOR HIGHLY ACCURATE MACHINING APPLICATIONS

Selection of a fine lead ball screw has been the conventional wisdom for precision machining applications, which require an accurate relative positioning between the processing tool and the work piece.

Since highly specified machine tools have to ensure comprehensive finished integrity, such as geometric accuracy, surface roughness and textural consistency based on the utilization of a semi-closed or closed positioning control system, the axial feed resolution and motion accuracy of ball screws is expected to be so high that the ball screws themselves can be regarded as a kind of precision linear scale unit.

During operation of the machine tool, relative motion between the nut and ball screw shaft induces heat generation at the ball grooves due to rolling and slipping of balls, and this leads to a dimensional growth of other components including the ball screw shaft length. This thermal influence deteriorates quality of positioning behaviors, and subsequently causes trajectory control error between the processing tool and work piece, owing to thermal deformation of the machine structure.

In order to minimize this error, shaft cooling ball screws have been utilized [2].

Figure 6 shows a typical arrangement of a shaft cooling ball screw installed onto an axial feed system. A continuous cooling oil supply is fed into the hollow shaft, reducing excessive heat generation. This consequently ensures a minimum shaft-temperature increase so that lead accuracy deterioration can be minimized.

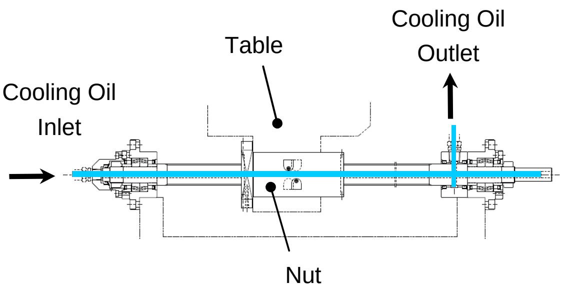

Figure 6: Shaft Cooling Ball Screw.

While shaft cooling enhances positioning accuracy, there are some essential issues. For example, a long hollow ball screw shaft can be difficult to manufacture accurately. Additionally, seal units and hydraulic circuit connectors must be installed at both ends of the ball screw shaft. Although the ball screw shaft is cooled, any excessive nut temperature rise will be transferred to other components from the table unit.

3.1 Nut Cooling Ball Screw

To further enhance cooling performance and simplify the system installation, nut cooling ball screws have been developed. Figure 7 shows a diagram of the nut cooling circuit. The first generation of nut cooling ball screws is an offset lead single nut type. This ball screw has been mainly utilized for precision milling of mold and die units for the plastic injection molding and pressing industries.

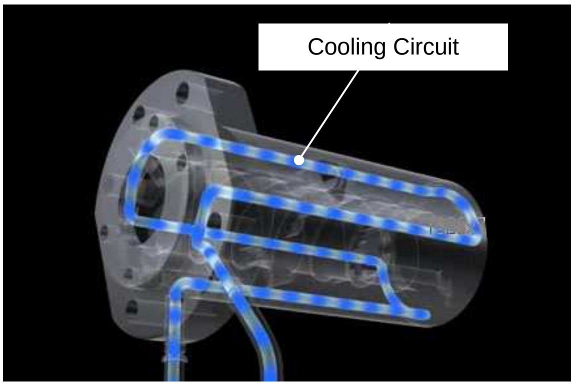

Figure 7: Cooling Circuit inside Single Nut.

Subsequently, the same demands, i.e. easy installation with high accuracy and productivity, appeared among heavy duty milling applications, especially in the aeronautic and shipbuilding industries, and also in various types of power supply and environmental equipment fields.

In order to simultaneously achieve higher geometric accuracy, finer surface finishing, a higher material removal rate, and higher productivity in these applications, NSK has developed double nut ball screws equipped with nut cooling circuits. Figure 8 shows the preload condition of these ball screws, and Figure 9 shows the internal cooling circuits. The ball screw itself is preloaded in an offset lead style with a spacer, and the individual nuts contain separate cooling circuits. This type of ball screw has been already installed on various precision machining centers for the heavy industrial markets, and has enhanced production quality.

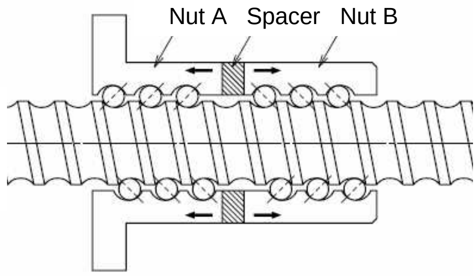

Figure 8: Preload Condition of Double Nut Ball Screw.

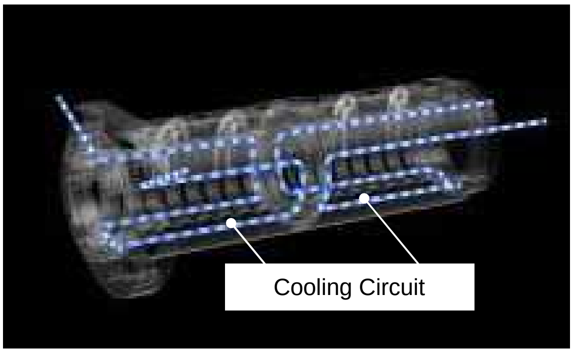

Figure 9: Cooling Circuits inside Double Nuts.

In regards to ball screw preload methods, the issues are similar to that of the spindle bearing units.

In general, direct cooling of the bearing outer ring in a high speed spindle unit should be avoided, as it could cause bearing seizure due to ring contraction and severe increase of ball contact point stress.

In order to prevent this issue on ball screw nuts, the interaction between a preload condition and the cooling performance of double nut cooling ball screws has been carefully investigated and verified for precision machine tool applications. In case of the preload design verification, since there is certain width of ball contact points in the axial direction, a continuous ball contact stress analysis is vital to predict the influence of nut cooling in a preloaded ball screw.

Figure 10 represents the schematic stress condition of an offset lead single nut with cooling circuits. As shown in the equation, the microscopic nut contraction and expansion in both the radial and axial directions affects the internal preload condition.

According to this ball contact stress analysis in nut cooling condition, less preload stress variation can be expected on the ball screw preloaded in tensile direction, while the ball contact stress is integrated to a high level in the alternate compressive preload type. Therefore, NSK has adopted the tensile preloaded concept in the latest model of nut cooling ball screws.

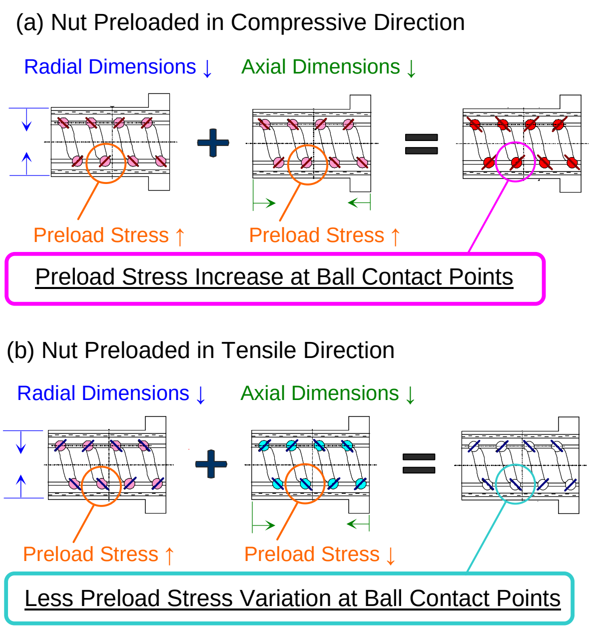

Figure 10: Stress Condition in Offset Lead Cooling Nut.

Throughout the nut cooling design process, NSK has developed numerical cooling models, and predicted and optimized actual cooling performance.

In accordance with the theory of internal heat transfer in a tube, the convective heat transfer coefficient is proportional to the 4/5 power of Reynolds number. This implies that, when a smaller tube diameter is selected, the flow speed inside the tube increases inducing a much higher heat transfer effect.

Since the heat transfer performance is also proportional to the flow contact area, the number of cooling tubes should be increased as much as possible. As a result, the cooling circuits as shown in Figure 7 and Figure 9 effectively dissipate heat from the ball screw components.

Heat dissipation models for shaft cooling and nut cooling are shown in Figure 11 and Figure 12 respectively. The convective heat transfer functions are described in both figures, whereas ΔQ : the heat radiation extent, α : the heat transfer coefficient, L : the effective length where a heated component and cooling liquid are in contact, and $\Delta\theta$: the temperature difference between a heated component and cooling liquid. The subscripts " s " and " n " indicate a shaft and a nut respectively.

Although these equations seem to be similar, there is a significant difference in their heat transfer abilities.

The effective length for a heat transfer corresponds to " the axial operating distance ", i.e. Ls, for the shaft cooling ball screw in Figure 11, and " the nut axial length × cooling tube numbers ", i.e. $Ln \times n$, for the nut cooling ball screw in Figure 12.

If a shaft cooling ball screw is used in a short-stroke application, the total heat radiation extent ΔQs becomes relatively small. Meanwhile, in a nut cooling ball screw, the contact surface area between axial cooling tubes and cooling liquid is constant, even if the nut stroke is reduced. As a result, the heat radiation extent ΔQn is not affected by the axial operating distance.

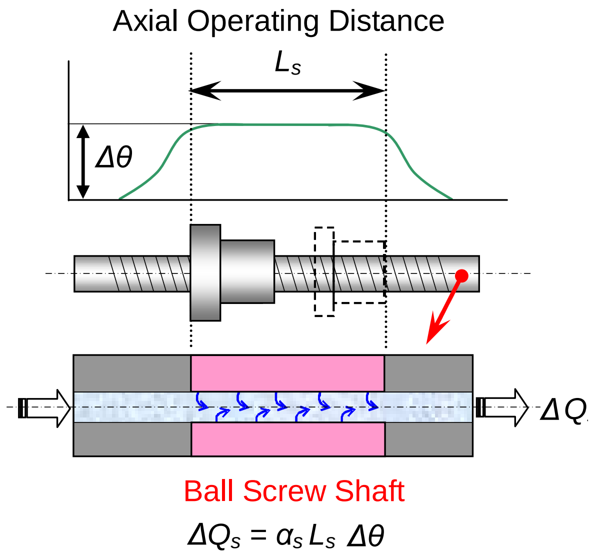

Figure 11: Heat Transfer Model for Shaft Cooling Circuit.

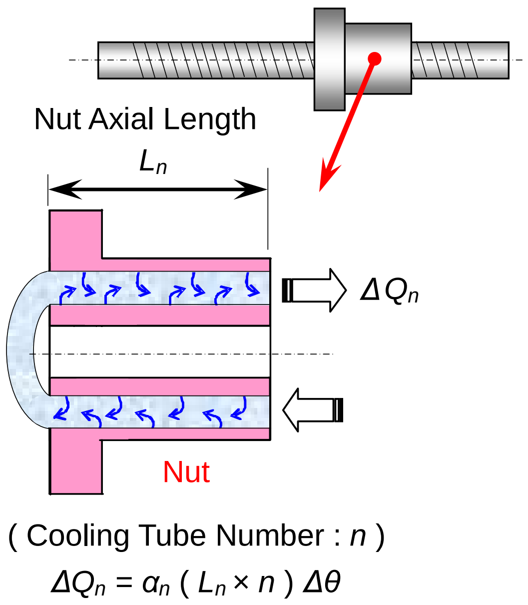

Figure 12: Heat Transfer Model for Nut Cooling Circuit.

Figure 13 and Figure 14 show experimental results of ball screw shaft-temperature increases with a nut stroke of 750 mm and 200 mm respectively. Additional operating conditions are : ball screw diameter × lead : 50 mm × 25 mm, ball screw revolution speed : 241 rpm, cooling liquid : oil, kinematic viscosity : 1.58 cSt, cooling liquid flow rate : 3 ℓ / min, temperature control for cooling liquid : entrainment towards room temperature.

Since a nut cooling ball screw has been designed to have equal heat transfer performance with a shaft cooling ball screw at the 750 mm nut stroke, Figure 13 shows the actual test result that a shaft-temperature increase of the nut cooling ball screw was quite similar to that of the shaft cooling ball screw.

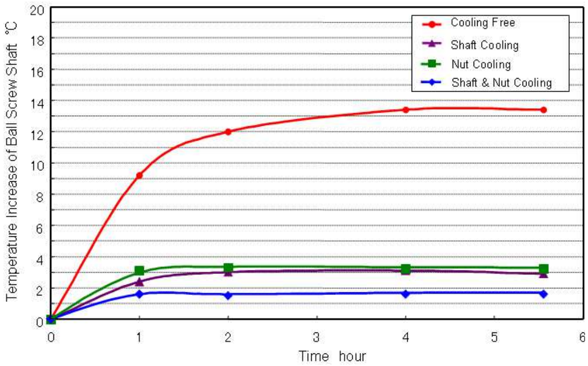

Figure 13: Temperature Increase of Ball Screw Shaft at 750 mm Nut Stroke.

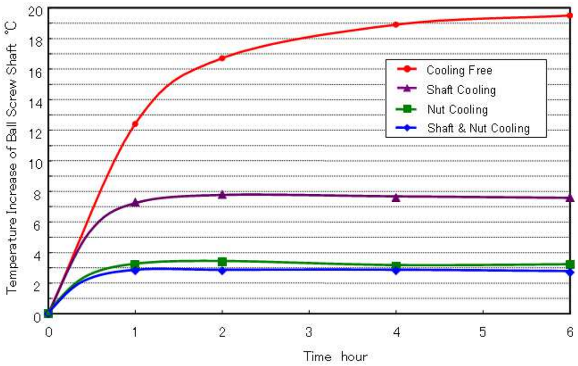

Figure 14: Temperature Increase of Ball Screw Shaft at 200 mm Nut Stroke.

Meanwhile, when the nut stroke was reduced to 200 mm, the shaft-temperature increase of the shaft cooling ball screw was much more than that of the nut cooling ball screw. This is a result of the difference in the heat radiation extent *ΔQs*, which was reduced from the 750 mm nut stroke test.

With respect to the best heat dissipation performance, the most effective cooling is achieved by combining both shaft cooling and nut cooling in the same ball screw in Figure 13 and Figure 14. This hybrid cooling ball screw can be a preferable solution to enhance a heat transfer effect more significantly, in case that a relatively long axial operating distance is selected for milling or grinding process.

Figure 15 shows comprehensive temperature distribution of the axial feed table during the 750 mm nut stroke evaluation. The temperature distribution was continuously monitored with a thermo-graphic scope. While a cooling free ball screw shows approximately 20 degrees C of a temperature increase along the length of the axial feed table, a nut or shaft cooling ball screw reveals a temperature increase of less than 4 degrees C everywhere. This means trajectory control accuracy can be highly ensured in whole length of the axial feed table with the appropriate cooling method.

With regard to the table surface temperature increase, the nut cooling ball screw exhibits less temperature increases of 3 degrees C compared to the shaft cooling ball screw, as shown in Figure 15 with oval marks. The result implies that the nut cooling ball screw can minimize possible thermal distortion not only in the axial feed table components but also in the machine tool structure. This contributes to significant structural satiability and highly sophisticated machining integrity.

These results show that the suggested nut cooling ball screw design is effective, and can accommodate real-world operating conditions on precision machine tools.

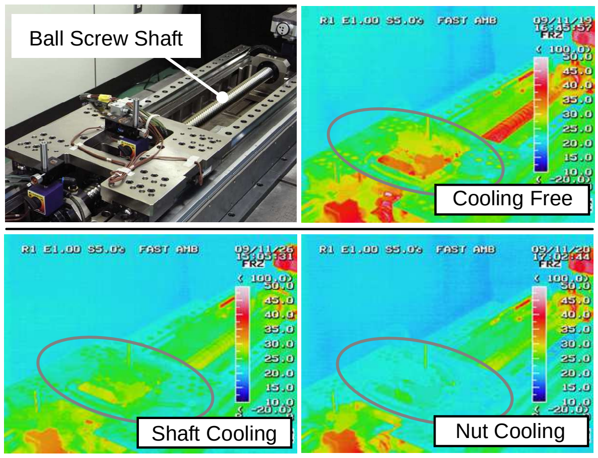

Figure 15: Temperature Distribution of Axial Feed Table.

Other advantages of the nut cooling ball screw include nut external diameter similarity with conventional nuts, if the cooling circuit tubes are properly designed without any interference, and a reduced cost since the cooling tubes are much shorter as compared to a shaft cooling ball screw.

4 CONCLUSIONS

This paper outlined the latest technical trends of ball screws especially utilized in the machine tool industry. The NSK HSS series ball screw is one of the latest models for enhancing feed rates, because of the SRC return components capable of applying a higher d・n value. A hybrid lead table unit is another solution, overcoming a physical speed limitation of ball screws. A nut cooling ball screw has been developed for highly precise machining processes, and this achieves a higher cooling capability than a shaft cooling ball screw. The lower temperature increase of the nut cooling ball screw leads to higher positioning accuracy, and furthermore contributes to less distortion of the machine structure and more excellent machining integrity.

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