Journal of Machine Engineering, Vol. 8, No. 4, 2008

lathe, feed mechanism,
cooling, thermal error,
calculations

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DECREASING OF THERMAL ERRORS IN A LATHE BY FORCED COOLING OF BALL SCREWS AND A HEADSTOCK

The goal of this paper is to present the effective methods of decreasing thermal deformations of a turning centre's structure in order to reduce the thermal error. The design of a machine tool as well as the scope of analyses are described, and calculation methods are specified. The paper also presents the results of computer simulations, concerning studies on the influence of type and parameters of a headstock-cooling liquid on the reduction of spindle displacements. Moreover, the results of feed mechanism’s thermal studies are shown, describing the influence of heat generated during the operation of ball screws and their inner liquid cooling, on tool’s thermal displacements.

1. INTRODUCTION

Efficient and precise machining on turning centres requires the reduction of thermal deformations in their mechanical structure, in order to reduce the magnitude of part machining errors. Thermal errors in a lathe mainly depend on the design of a headstock, feed mechanisms with a tool slide, as well as its bed.

In relation to the headstock assembly, built-in electric motor propelling the spindle generates heat reaching the amount of even several kilowatts. Spindle bearings, not only in high-speed solutions, but also in solutions preferring high stiffness, are heat sources causing many problems.

Thermal expansion phenomena in spindle bearings and in housing often lead to the increase of inner loads during operation, which shortens lifetime of bearings, and in consequence increasing costs. The action of heat sources in a headstock leads to thermal displacements of a housing and a spindle, which then influences machining errors.

In tool feed mechanisms of a lathe, ball screw-nut assemblies are used. Heat generated during feed motion heats both the ball screw and slide body; therefore the thermal expansiveness causes the position of a tool to change during operation.

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To summarise it can be assumed that there are many thermal phenomena in turning centres, which cause the mechanical structure of a machine tool to be unstable, since in the conditions of realising the technological process, changes in dimensions and geometry of the structure often take place. Such thermal displacements of a tool and a spindle significantly influence the part machining error [1 – 5].

The goal of this paper is to show the potential of the effective reduction of thermal deformations in motion systems together with a tool slide, as well as in a headstock of the exemplary turning centre’s structure, by means of liquid cooling.

2. THE OBJECT OF RESEARCH, METHODS AND SCOPE OF ANALYSES

In order to make it possible to assess the effectiveness of methods, which should lead to the decrease of the structure's thermal error, computer modelling and simulation methods were used, aiming at the identification of the intensiveness of heat sources, as well as at the identification of appearing temperature distributions and thermal displacements.

The object of analyses is a separated assembly of a tool slide and a headstock from a turning centre.

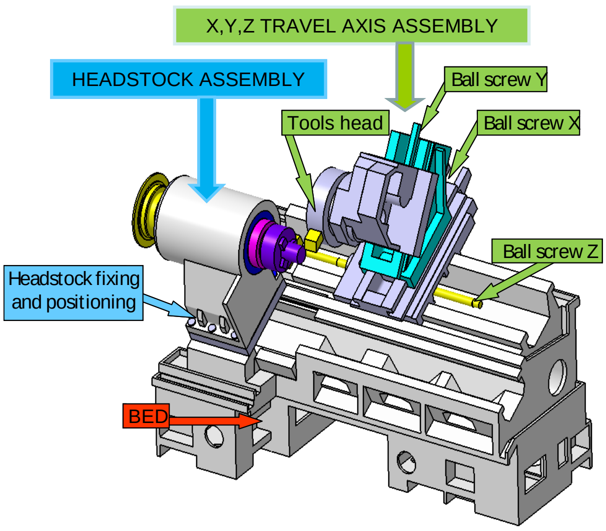

Fig. 1. High-stiffness turning centre and its main components

In the headstock assembly, a built-in electric motor drives the spindle, rigidly supported by roller and ball angular bearings. The body of a headstock, fixed to the bed by means of screws, ensures the possibility of turning elements with a large diameter. Feed mechanism, realized by means of ball screws, ensures the motion of a tool head in three directions.

The starting point for thermal analyses was the definition of power losses generated in bearings and in a spindle motor, as well as in kinematic links of the feed mechanism for directions X and Z. Assuming sparse use of the Y ball screw for regulation purposes, its heat source were not considered.

In the modelling of heat phenomena the following aspects were considered:
- steady-state and transient heat conduction in the material of the structure,
- heat transfer through the connections of parts in assemblies,
- heat exchange with the environment and with cooling liquids [8, 9],
- thermal deformation phenomena in the structure.

Moreover, the representative range of working conditions concerning the speed and load of a spindle and feed mechanisms, as well as parameters of the machine tool's working environment, were taken into considerations.

The calculations were carried out with the use of a proprietary computing system SATO [10], capable of calculating power losses in kinematic links and of determining the temperature and thermal deformations in machine tool assemblies using Finite Element Method, as well as Nastran system. In order to increase the credibility of computer simulations and analyses, the results of the temperature measurements and the thermal displacements of the lathe were used for the verification and improvement of applied computational models.

3. THE ANALYSIS OF RESULTS OF FORCED COOLING IN THE FEED MECHANISM'S BALL SCREWS

As seen from the measurements of the machining error (see Fig. 2) of the turning centre shown on Fig. 1 during operation of the headstock and the feed mechanisms of axes X and Z, the high level of such error justifies the undertaking of the precise analysis aiming for its reduction.

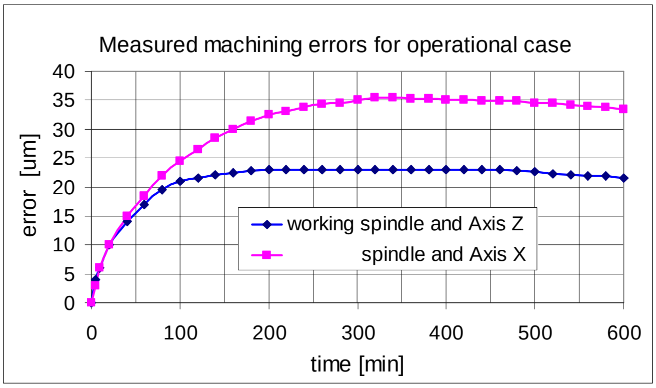

Fig. 2. Measured thermal error of a turning centre caused by the operation of a headstock and a slide

In the investigations, internal cooling of screws was assumed by means of oil with steady intake temperature, in order to decrease the heat stream causing its heating-up, and at the same time decreasing the heat stream passing through the nut to the tool slide body.

Such action should lead to the decrease of the tool displacements caused by thermal deformations of slide body, as well as by thermal elongation of screws.

In the FEM calculation model, shown on Fig. 3 the sources of heat are bearings supporting the X and Z screws, kinematic links ball screw-nut, as well as guides, to a small extent.

Power losses in kinematic links ball screw-nut were defined with the use of relationships published by SKF Company. They mainly depend on the type and dimensions of the screw, its preload, as well as on the axial load, feed velocity (see Fig. 4) and working cycle.

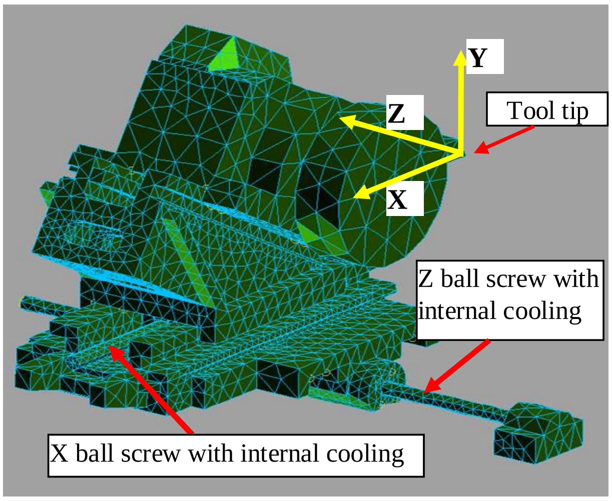

Fig. 3. FEM model of a tool slide with ball screws used for computations of temperatures and thermal displacements

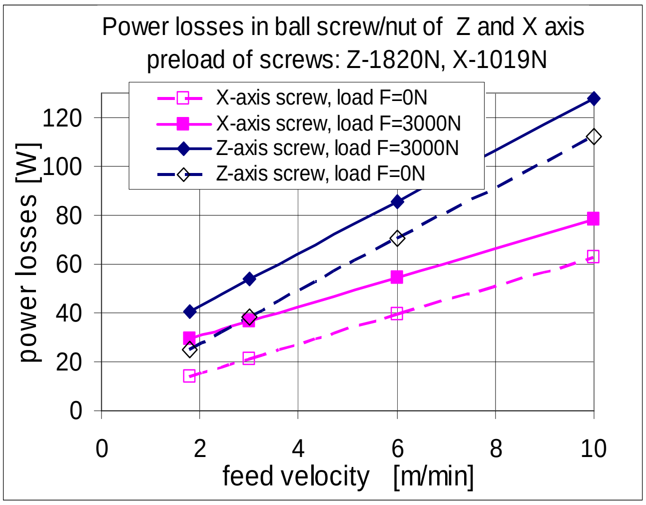

Fig. 4.The relationship between power losses in kinematic links ball screw-nut and feed velocity and axial load

The outcome of the influence of heat sources in a slide assembly is the temperature field, mainly on ball screws and nuts of axes X and Z, and the displacements of a tool (see Fig. 5) caused by the elongations of screws and the deformations of a slide body.

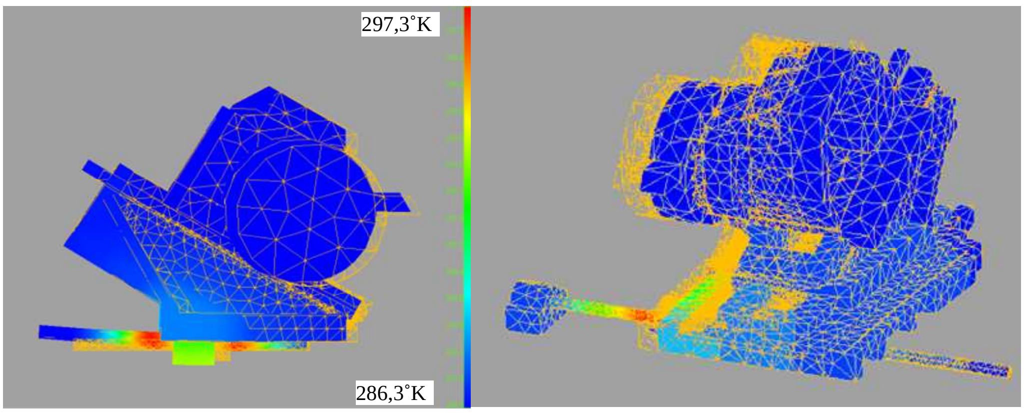

Fig. 5. Temperature distributions and thermal deformations in a tool slide assembly, caused by heat generated in ball screws X and Z

In order to assess the unfavourable influence of heat generated during operation of ball screw assemblies on the position of a tool, a computational simulation for forced cooling of screws with the oil flow rate in range of 0-12 l/min was carried out, assuming that temperature of the oil intake, ambient temperature and starting temperature of the object are equal and constant.

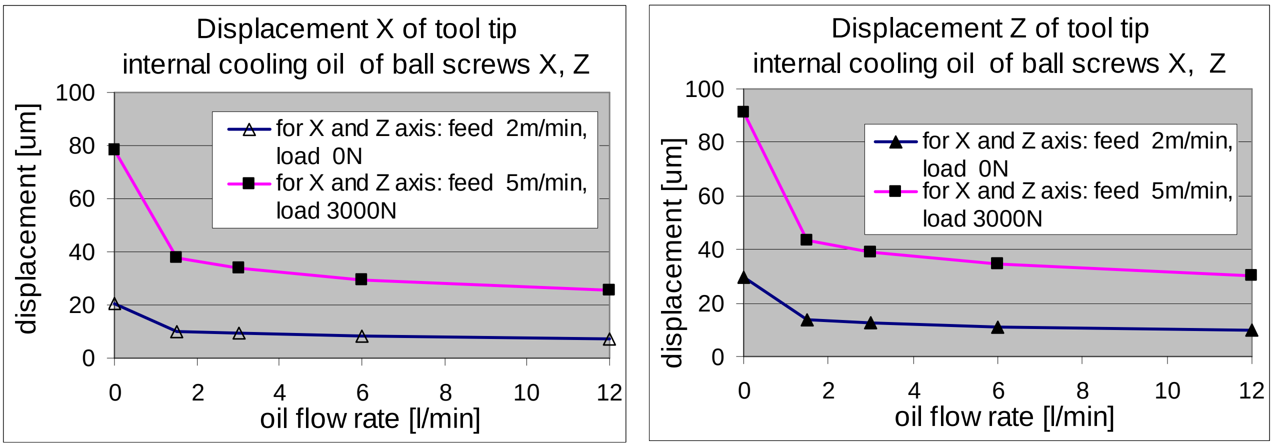

Fig. 6. Thermal displacements of a tool in directions X and Z as a function of the flow of a cooling oil for parallel operation of ball screws under low load=0N and feed=2m/min and high power losses

The results of analyses (see Fig. 6) carried out assuming the parallel operation of X and Z axes point out that even small flow of the cooling oil through the interior of a screw, in the range of 1.5-6l/min, considerably lowers thermal displacements of a tool compared to the case with no cooling. This applies to both operation of screws during idle run with relatively low feed velocity of 2m/min, when small heat is generated (see Fig. 4), and operation with a very high axial load of 3000N and feed of 5m/min causing larger power losses.

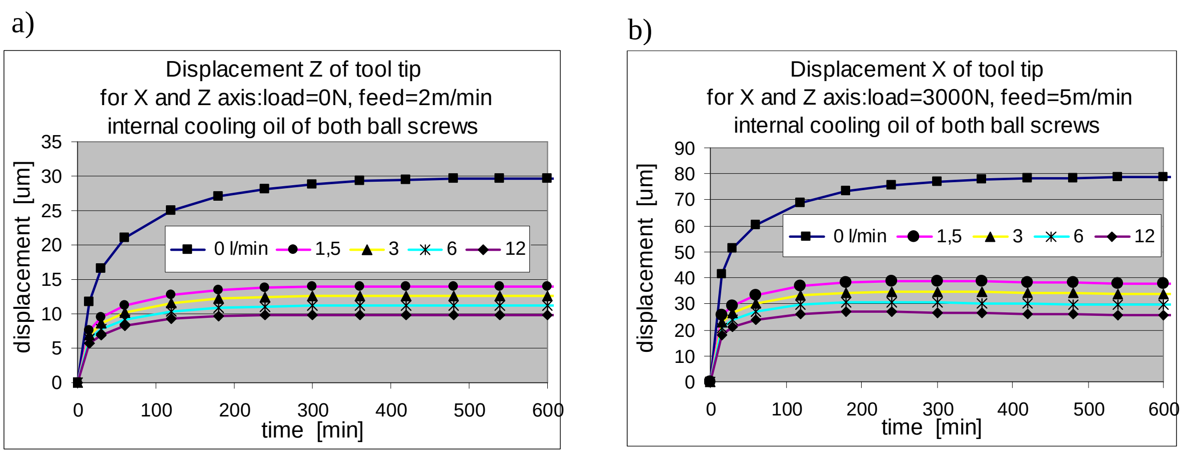

Fig. 7. Transient displacements of a tool in X and Z directions for different cooling oil flow rates in both conditions of low (a) and high (b) power losses in ball screws

The influence of screw cooling on transient tool displacements, shown on Fig. 7, visualises the next positive characteristic of such cooling, namely distinct shortening of time needed to reach stabilised displacements, which increases thermal stability of the assembly.

Besides the thermal effects of parallel operation of both feed screws it is also important to know independent influences of feed mechanisms in both directions Z and X on the displacements of a tool. Fig. 8 shows the results of such calculations, in which identical load and feed of both ball screws was assumed, and the cooling oil flow through both screws was defined to 6l/min, which ensures enough effectiveness.

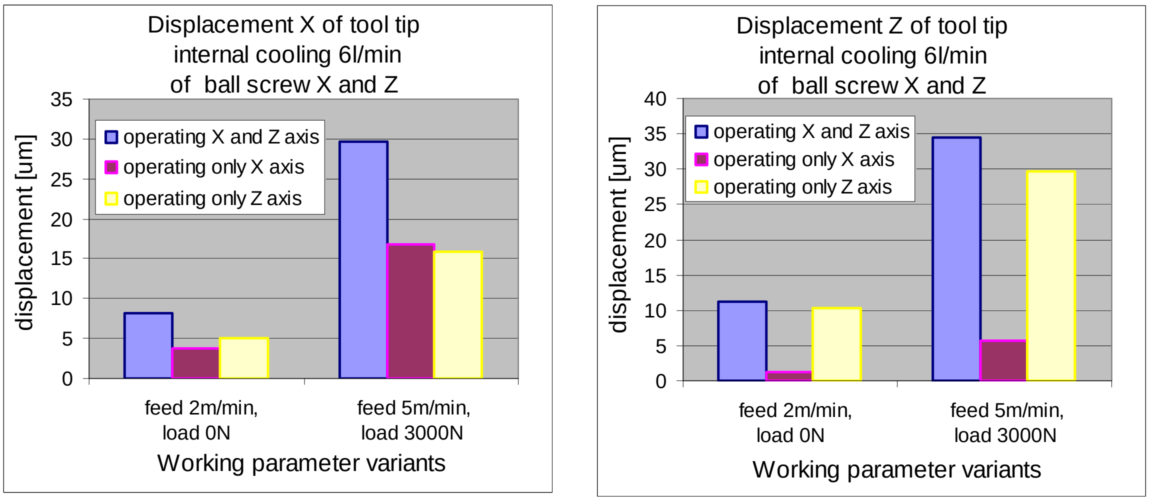

Fig. 8. Influence of operation variants of cooled screws on components X and Z of tool's thermal displacement

As it can be seen, thermal displacement in the Z direction are slightly influenced by operation of the X screw, while heating caused by operation of the Z screw is decisive.

Tool displacement in the X direction is equally influenced by operation of the X screw and the Z screw.

Despite oil cooling, the level of tool displacements, especially with higher feed velocities and ball screw loads, remains unsatisfactory. For further reduction of thermal displacements of a tool slide it is required to introduce liquid cooling in ball nuts. This would prevent the conduction of heat from the nut to the slide body and lower its temperature levels.

4. THE ANALYSYS OF FOCED COOLING IN A HEADSTOCK

The headstock in a turning machining centre (see Fig. 1, 9) is an assembly in which built-in electric motor and high-stiffness bearings generate large heat losses.

In such construction, thermal characteristics and stability are in large measure decided by an efficient liquid cooling of the motor’s stator and bearing housings, and sometimes also of a spindle.

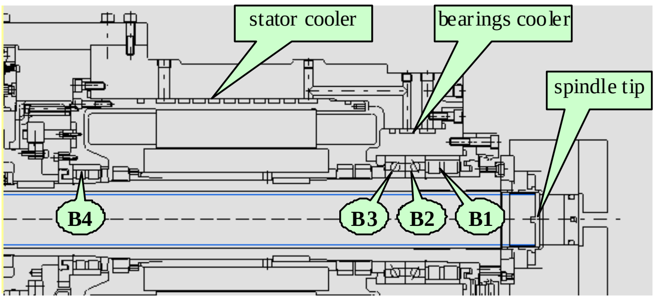

Fig. 9. Construction of a headstock in a high-stiffness turning centre
B1,B2,B3,B4 – bearings of front and rear spindle support

The application of oil as a cooling agent in the cooler of a stator and front bearing housings insufficiently lowers the level of thermal displacements in an assembly (see Fig. 10), despite the use of large flow rates of 30 l/min. Water was applied for further reduction of thermal deformations, as the agent with a larger heat exchange capability than oil.

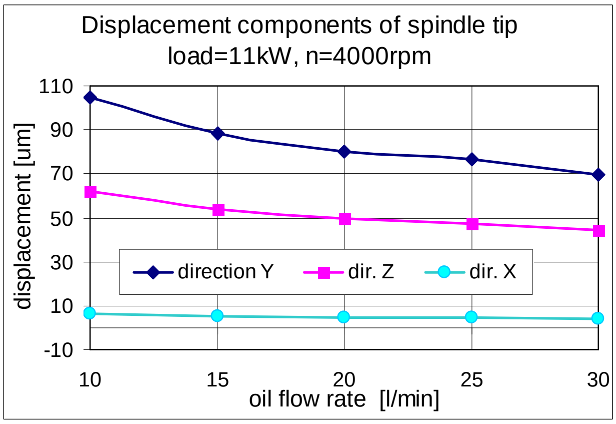

Fig. 10. Influence of the oil flow rate on thermal displacements in a maximally loaded spindle

The results of calculations of the effectiveness of the use of various cooling liquids and the parameters of their flow through the stator cooler and the cooler of front ball roller bearings is shown on the graphs on Fig. 11.

In the conditions of the highest load and spindle speeds the application of water cooling instead of oil cooling radically decreased temperatures. Additionally, the time of reaching the stable temperature also shortened significantly, which makes the construction much more thermally stable than with oil cooling. It is impossible not to notice the fact that water cooling requires significantly lower flow rates, and therefore is more economical.

Water cooling is more beneficial for bearings, because it limits the changes of the negative working clearance (see Fig. 11b), which lowers power losses in bearings nearly twice. Additionally, the decrease of internal loads in bearings leads to the extension of their lifetime.

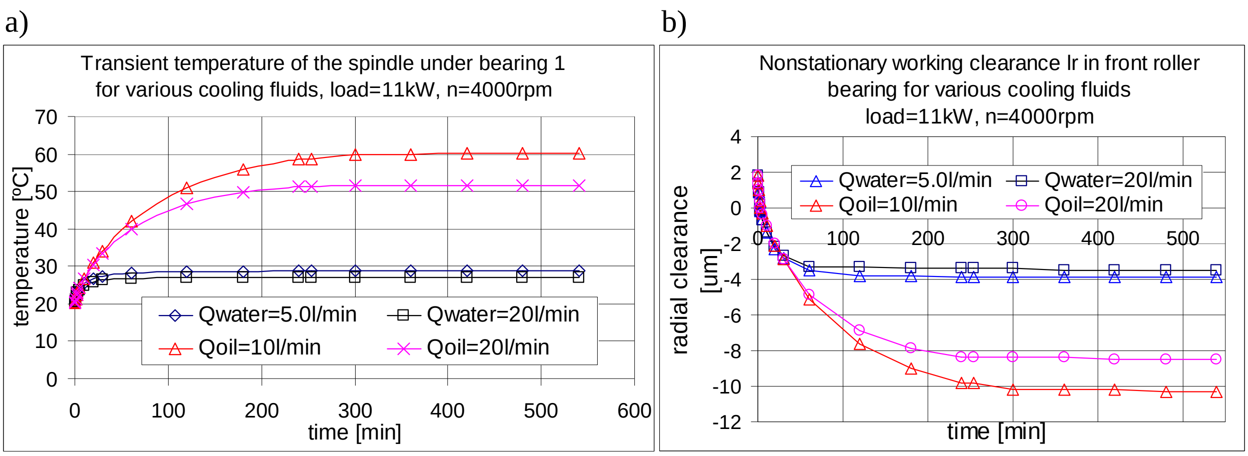

Fig. 11. Influence of the type and liquid flow efficiency on the temperature (a) and working clearance of bearings (b)

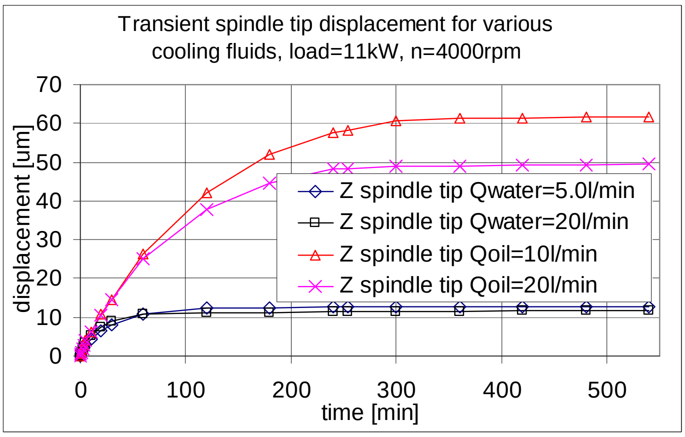

Fig. 12. Influence of the type of cooling liquid and flow parameters on the displacements of a spindle

Water cooling has a highly positive influence on the displacement of a spindle tip (see Fig. 12), because it very distinctly lowers their magnitude; moreover, the time of their stabilisation is significantly lower than in case of the option with oil cooling. Therefore it can be stated that the use of water as a cooling agent will cause the thermal properties of a headstock to be little sensitive to the changes of spindle's rotational speed, its load and other thermal disturbances.

5. CONCLUSION

The conduction of detailed thermal analyses was possible thanks to the use of SATO system, which integrates the calculations of spindle bearings' properties and the heat exchange with the environment and cooling liquids with the calculations of temperatures and thermal displacements, taking place during operation of the electrical headstock.

From the point of view tool of slide it was important to take advantage of the relations describing the forced head exchange inside the ball screw, as well as its power losses, in a FEM model of the assembly.

The conducted analyses of the thermal properties made it possible to formulate the following conclusions:

- the use of the inner liquid cooling of ball screws in feed drives of axes X and Z in a turning centre significantly lowers the level of thermal displacements of a tool and the time of their stabilisation. Additionally, the precision of the screw positioning increases. For further reduction of thermal displacements of a tool slide it is required to introduce liquid cooling in ball nuts.
- the use of water for cooling of a headstock instead of oil clearly decreases the temperatures of a construction even by 50%, the thermal displacements of a spindle tip by 80%, and the time of reaching stable conditions by 60%. Thermal changes of the negative working clearance in ball bearings are limited as well, thereby increasing their lifetime.

The results of thermal analyses point to the fact that through forced cooling of the regarded assemblies of a turning centre it is possible to considerably increase the insensitiveness of the construction to the varying working conditions, which results in the reduction of machining errors.

ANCKNOWLEDGEMENTS

This paper presents the investigation results of turning M.C. done for Doosan Infracore Co., Ltd., Republic of Korea.

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