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LIMITING PRECISION DISTORTIONS IN SPINDLE UNIT OF HSC MACHINING CENTRE

The paper presents causes of excessive precision distortions, appearing in electrospindles of HSC machining centres. The influence of changing ambient temperature is shown, as well as the precision of its modelling. Phenomena, which appear in the electrospindle unit during large rotational speed changes, have been presented and the functioning of bearing loading sleeve has been shown, which has the task of compensating thermal expansions of a spindle. Conditions of proper functioning of the sleeve have been presented, which should assure minimal displacements of a spindle. Also, possibilities of increasing bearing life span have been pointed out.

1. INTRODUCTION

The production of HSC machine tools requires, in compliance with the increase of rotational speeds of their movements, to overcome number of barriers, constructional, as well as technological. One of these barriers is achieving high precision of functioning, which is vulnerable to distortions, which increase with the value and gradient of speeds, as well as with the increase of translational and rotational accelerations. The behaviour of spindles is then not only influenced by the intensiveness of thermal phenomena, but also by dynamic load of movable elements of spindle units, especially rolling elements.

Thermal loads and loads induced by centrifugal forces, generate deformations, which vary dynamically, causing the elements of electrospindle units not to carry out their function in proper and smooth manner. Often, stroke movements appear, which, corresponding to their intensiveness, cause the raise of errors – for example axial shifts of spindle. This has enormous impact on the dimensional precision of machined parts and is very difficult, or even impossible, to compensate by the CNC unit.

Such behaviour of a machine adds up with the influence of changes in temperature of environment, cutting process, cooling mediums, accumulation of heat in closed spaces and changing with temperature, errors of measurement systems. Possibilities of minimisation of such errors are a topic of further deliberations.

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2. IDENTIFICATION OF ACCURACY DISTORTIONS

Analysed work concerning the identification and improvement of HSC machine tools [1-5], and especially improving their thermal behaviour in operation conditions, indicate the increasing distortions of precision at rotational speeds of spindles above 20.000 rpm. They appear especially during changes of speed. The higher are rotational speeds, the bigger are these distortions and more concern axial displacement of a spindle, directly influencing dimensional precision of machined parts. Such displacements are caused by regular thermal changes of elongation, dependent on variable in time thermal load and spindle axial shift. Such shift is sometimes quite large and often not entirely repeatable in value. It is therefore very hard, or even impossible to compensate precisely. Such adverse effects especially accompany constructions of spindle units equipped with a mechanism to keep a constant value of inner load in spindle bearings.

Independent from the machining process are errors, which are introduced by changes of ambient temperature. In case of precise machining, fluctuations of this temperature are usually limited by temperature regulation in production hall. But even then, axial displacement error of a spindle can reach large, excessive amounts. Fig. 1 shows influence of ambient temperature changes of about 3,5ºC on axial displacement of a spindle in machining centre, used for precise HSC machining. Ambient temperature changes were irregular and accompanied by large displacements of spindle tip, taking place almost with no time offset, because of the symmetry of a construction and the location of headstock in middle position. In other cases such offsets can be large and dictated by thermal inertia of machine bearing structure [1].

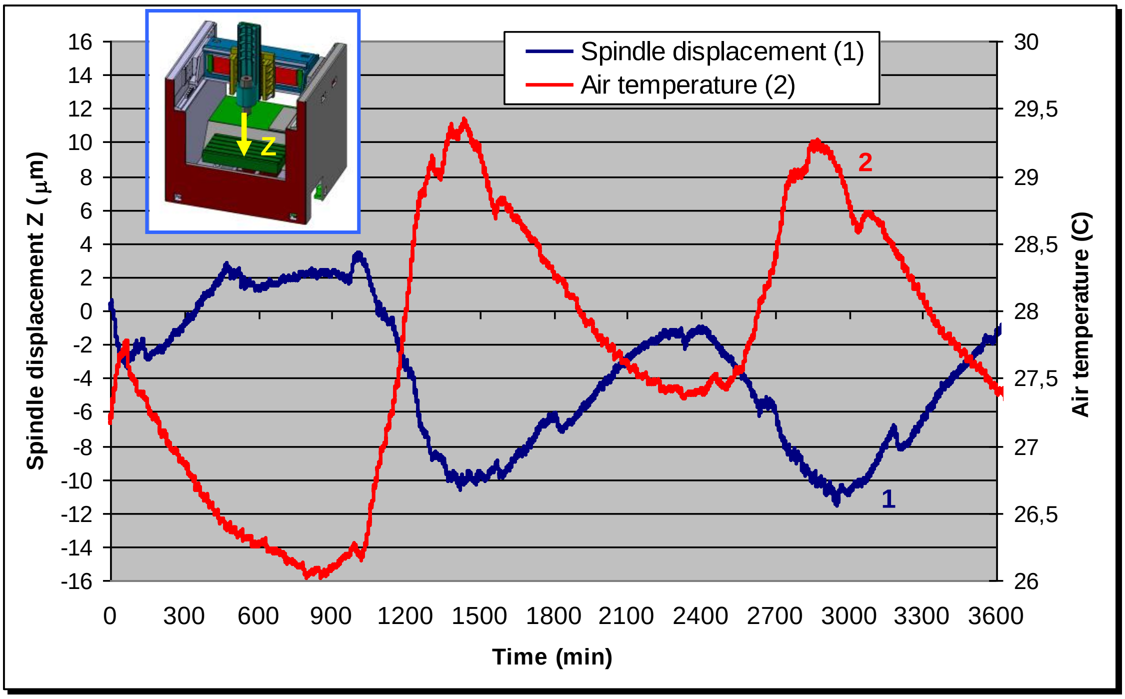


Fig. 1. Changes of ambient temperatures and resulting spindle axial displacements

Modelling of standalone variations in thermal displacement in machine tools, caused by ambient temperature changes, ensures relatively large precision of their representation in a model. Naturally it depends on the complexity of a construction and on the precision of heat exchange model in the machine tool itself, and, what is particularly important – correctness of considering inner and outer spaces of bearing structure (case).

Precision of representation of the order of 2 μm resulting from Fig. 2 can be considered satisfactory, taking into account, that also the temperature and displacement measurement itself was accompanied by an error.

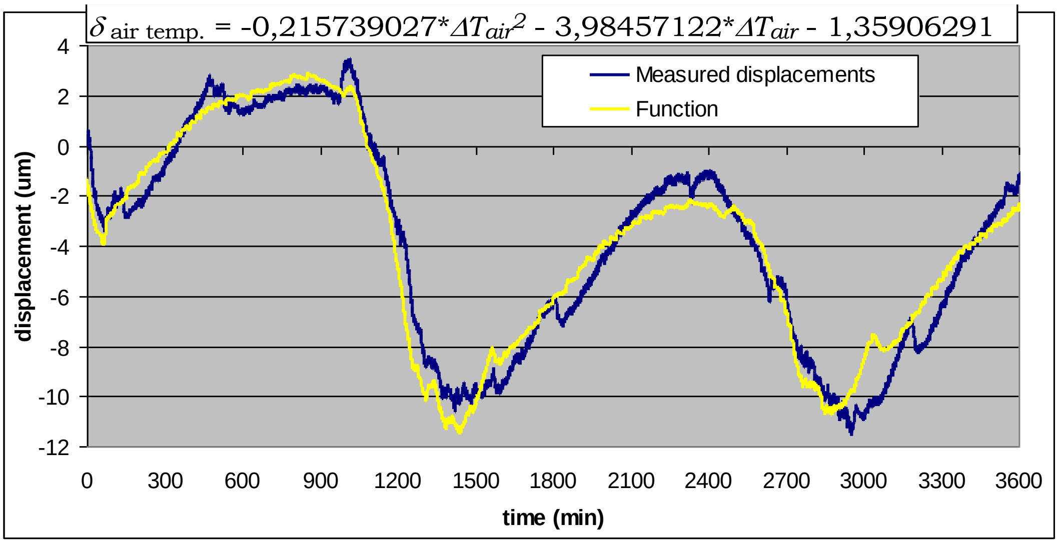


Fig. 2. Measured and estimated from function thermal axial displacements of machining centre spindle

Fig. 3 shows displacement change during compound work cycle, in real thermal conditions present in factory hall. On this figure, a numerically expressed displacement curve is shown, as well as predicted theoretical result of compensation.

In input temperature data (from measurements), distortions appeared after about 300 min, which result from unidentified measurement errors, which naturally result with corresponding distortions in computed displacements. In real-life, temperature cycles are free from distortions and have no influence on spindle displacement, but they show high sensitivity of this very complex computation model. In presented displacement runs, sudden displacement changes and thermal displacement runs are clearly visible. Also, areas are marked, in which it would be very difficult, in numerical method, to achieve high precision of recreating measured displacements.

A very precise analysis of overlapping jumps and thermal displacement of a spindle, has been shown on Fig. 4. Such behaviour is typical for an electrospindle with spring-loaded sleeve, which by definition should counteract to thermal elongations of a spindle, but usually does not fulfil its function in a satisfactory manner. It is clearly seen after enabling of rotational speed of 45000 rpm. It is the cause of the fact, that runs are often unrepeatable and displacement values are very large.

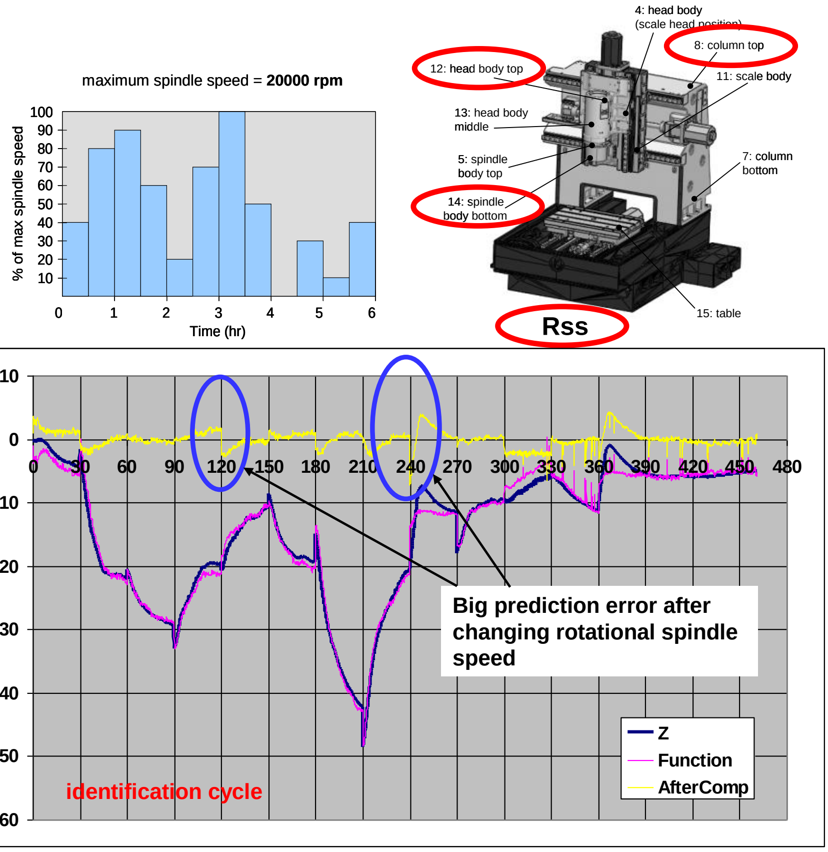


Fig. 3. Experimentally identified and predicted machining centre spindle displacement and theoretical compensation accuracy

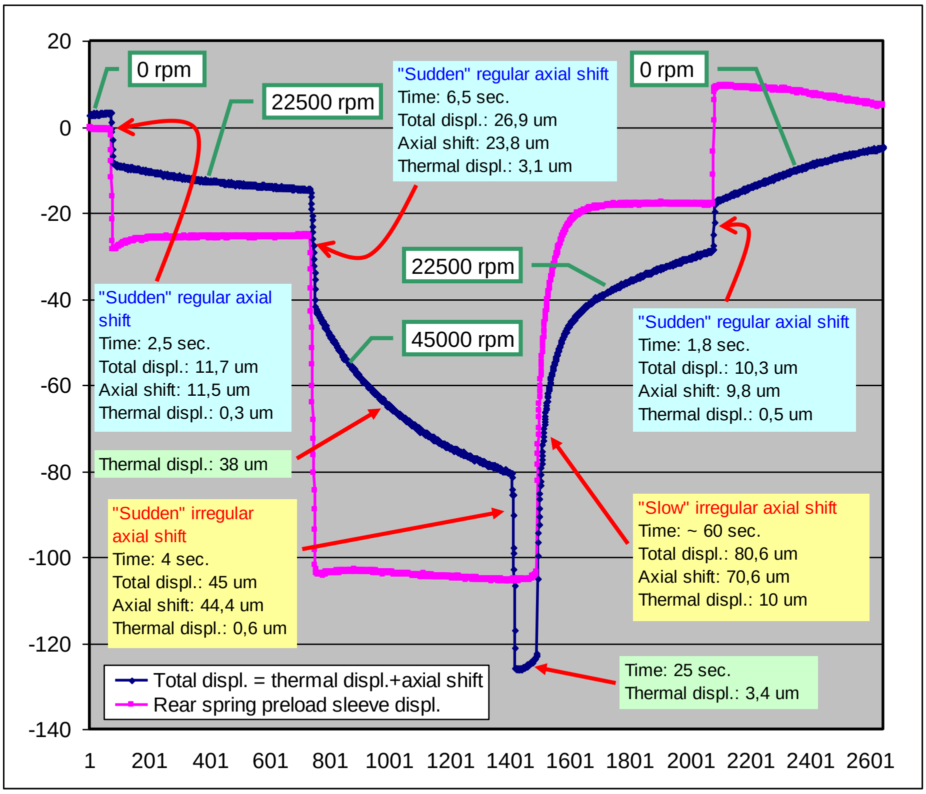


Fig. 4. HS machining centre spindle shift with overlapping thermal elongation, and sleeve movement analysis

3. PERFECTION OF SLEEVE BEHAVIOUR

For proper functioning of moving sleeve as a fastening element of spindle's rear bearing and counteracting of its bevel, it is necessary to eliminate excessive friction forces, occurring mainly due to thermal deformations, between the sleeve and its housing. Practically applied solution by some HSC machine tools manufacturers, is the use of rolling guide of a sleeve. These two constructional solutions of electrospindle unit, without and with rolling guide, are shown on Fig. 5.

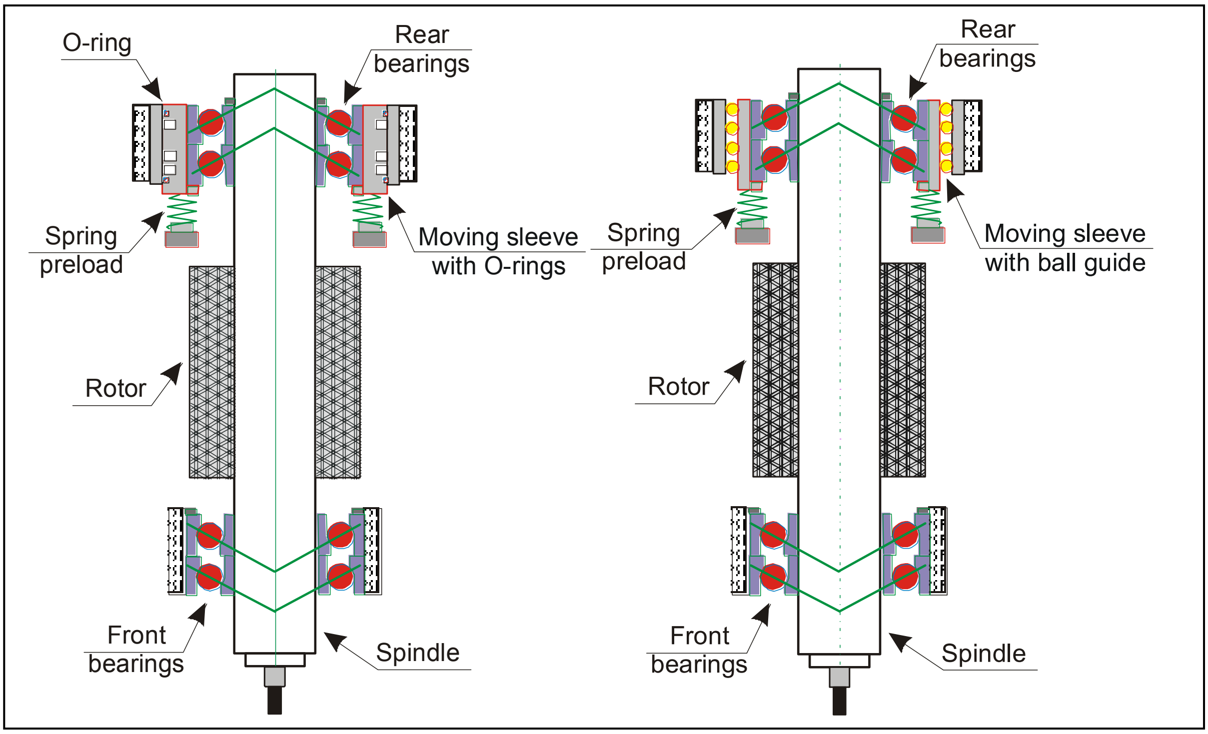
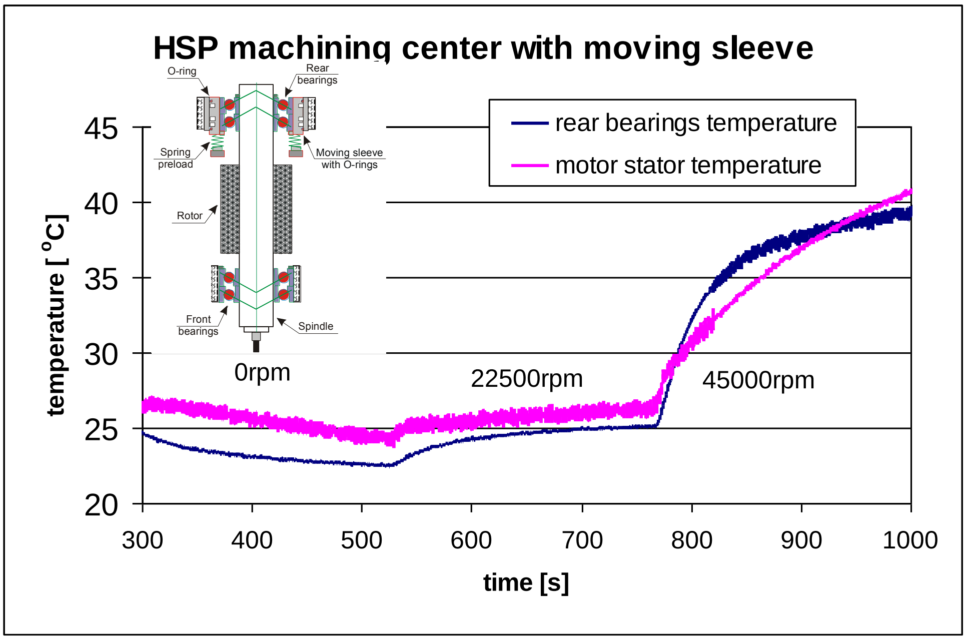


Fig. 5. Electrospindle with moving sleeve

The heating of rear bearing node is very similar to the heating of engine stator (see Fig. 6a), which suggests, that large heat source, such as stator, has dominant impact here on thermal behaviour of bearings. Sudden increase of rear bearings' temperature, observed after enabling rotational speed of 45000 rpm, as well as similar increase of stator's temperature is bound to cause considerable thermal elongations of a spindle. With correctly working moving sleeve, such elongations should cause loading of rolling elements of rear bearings, and spring should displace the sleeve up, causing re-load of bearing system. Thanks to this fact, loading force of a bearing should remain almost constant.

Sleeve movements, recorded during this experiment are shown on Fig. 6b. In time range over 800s, when this spindle suddenly becomes heated and elongates thermally, moving sleeve does not perform any correcting movements. Therefore it does not fulfil its basic function. The consequence of this fact is bound to be releasing of elongations on almost entire spindle length in the direction from front to rear bearings. This results in large values of spindle displacement relative to the housing, also shown on Fig. 6b. Assumed in construction, compensating sleeve movement in upward direction, in such cases, would considerably limit displacement values in downward direction.

a)



b)

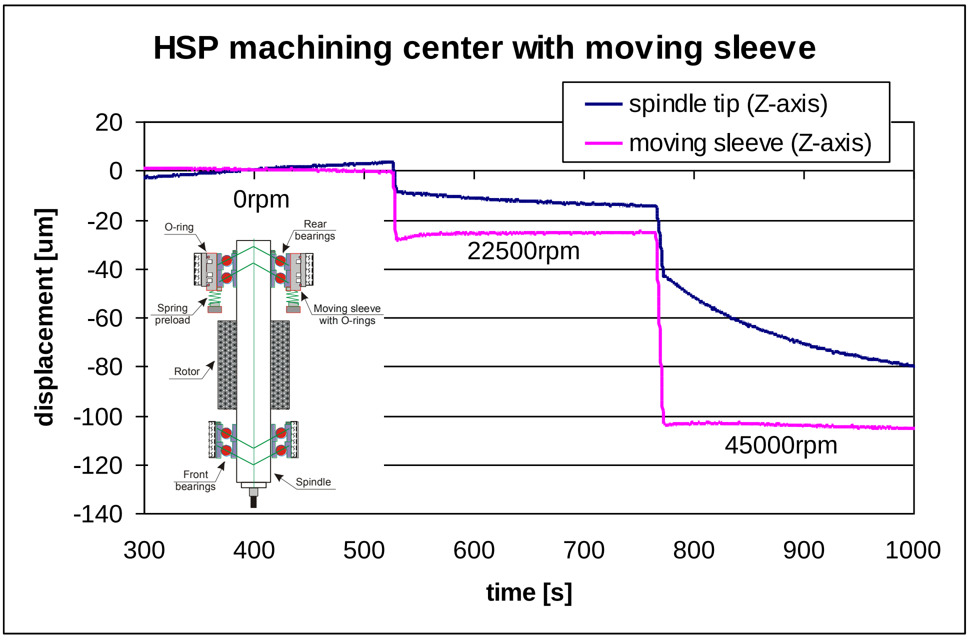


Fig. 6. Influence of clearance NC2 in ball guide clearance NC1
a) heating of bearings and a stator,
b) displacements of a spindle and moving sleeve

The application of constructional solution with moving sleeve, mounted on rolling guide, apart from unquestionable benefits connected mainly with small movement resistances, can also cause additional problems. They are connected with the additional forces deforming the moving sleeve, caused by negative clearance NC2, essential for required stiffness and precision of movement.

An example of modelling of such deformations, corresponding to the change of moving sleeve inner diameter $\mathbf{d_i}$ has been shown on Fig. 7. The diameter $\mathbf{d_i}$ is an important fitting diameter for the rear bearing unit of a spindle.

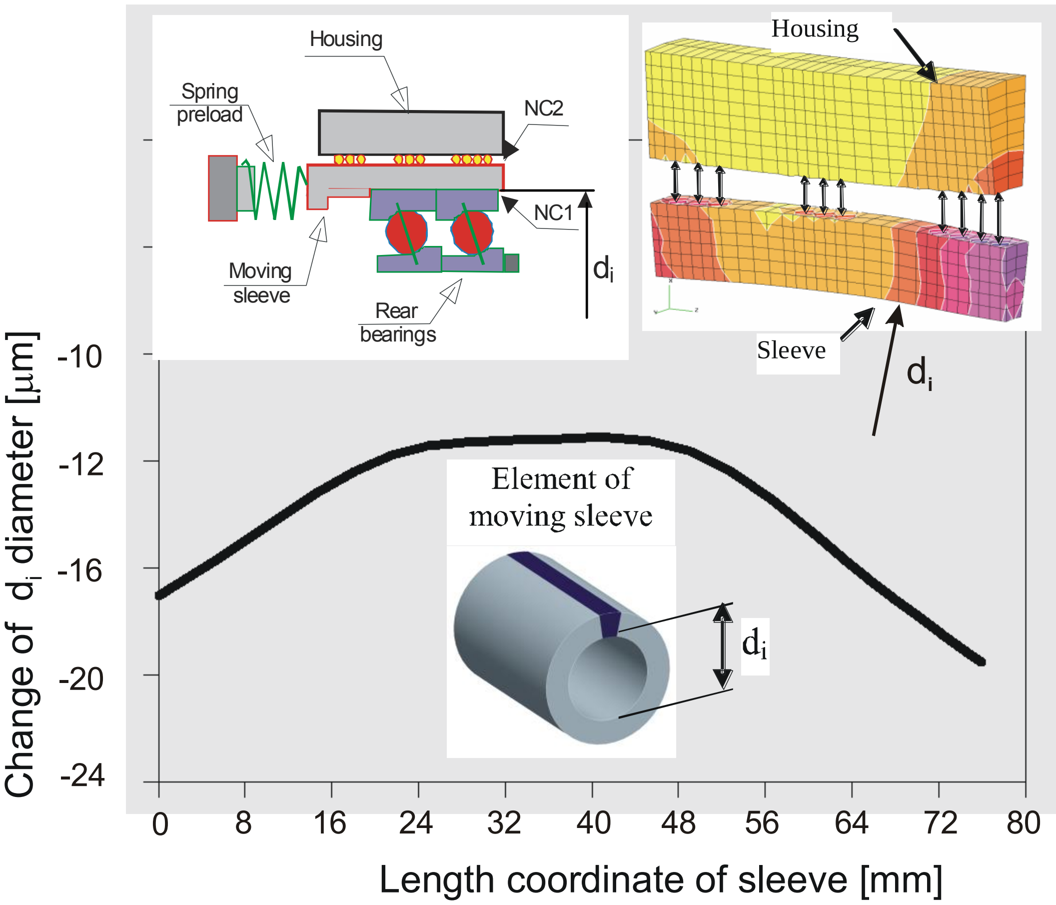


Fig. 7. Modelling of deformations in components of spindle rear support, caused by inner loads in moving sleeve unit with rolling elements

Changes of this diameter, shown on the graph, can cause significant and adverse differentiation of inner loads in the pair of rear bearings. They influence values of clearances or negative clearances NC1 between the sleeve and bearings.

The value of negative clearance in rolling packet of moving sleeve and their distribution along the sleeve during operation, is decided by:

- the value of after-assembly negative clearance NC2,
- thermal changes of diameters of rear spindle support components,
- stiffness of all of these elements.

The dependence of NC1 changes from NC2, independent from causes changing after-assembly value NC2, has been shown on Fig. 8.

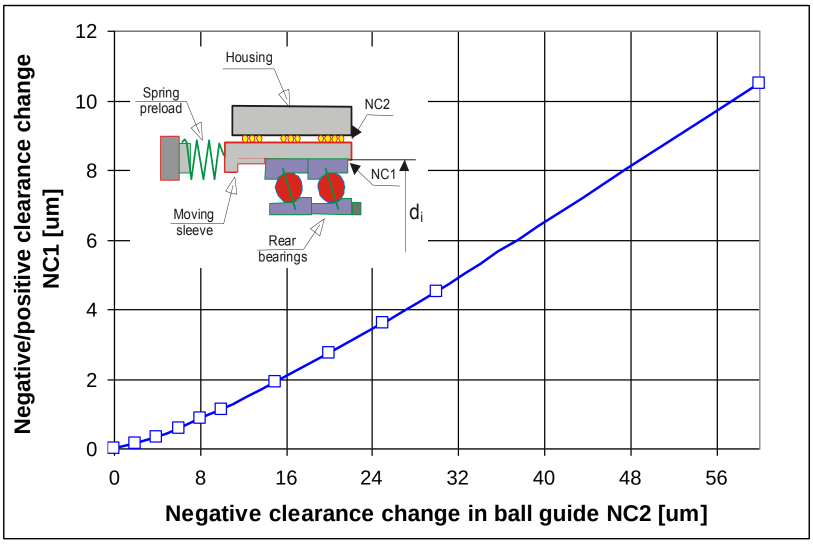


Fig. 8. Influence of clearance NC2 on ball guide clearance NC1

Main condition for proper functioning of moving sleeve is, that in all conditions, the force of a spring should be considerably larger than real sleeve movement resistances. The value of movement resistances, expressed by friction torque in moving sleeve unit, changes during operation, in accordance with thermal, dimensional changes of components in bearing system and centrifugal forces, resulting from rotational frequencies of bearing cages. After-assembly value of NC2 (cold state) has a small impact on such changes during operation, which is indicated by almost parallel run of curves representing cold and heated states (see Fig. 9). Heated state here is the thermal state, which occurs after 2h of electrospindle operation with the rotational speed of 40000 rpm.

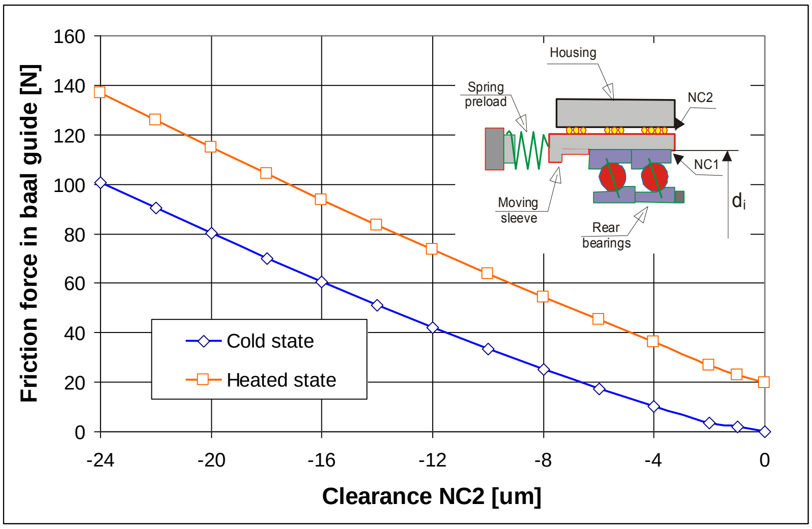


Fig. 9. Relation between friction force and negative clearance in rolling guide, in cold and heated state

Apart from the reduction of displacements in machine tools and their precise compensation, of enormous importance is also the life time of bearings and required precision. The reduction of unnecessarily high loads in bearings by disallowing excessive thermal, dimensional changes and limiting of centrifugal forces acting on balls, work in favour of increasing life time. The introduction of ceramic balls with lower mass and lower friction coefficient, increased the life time of bearing almost twice. Also, the application of new chrome steel, used in space technology, called Chromex®40, for rings of spindle bearings, assured further increase of life time, even up to 2,5 times (see Fig. 10).

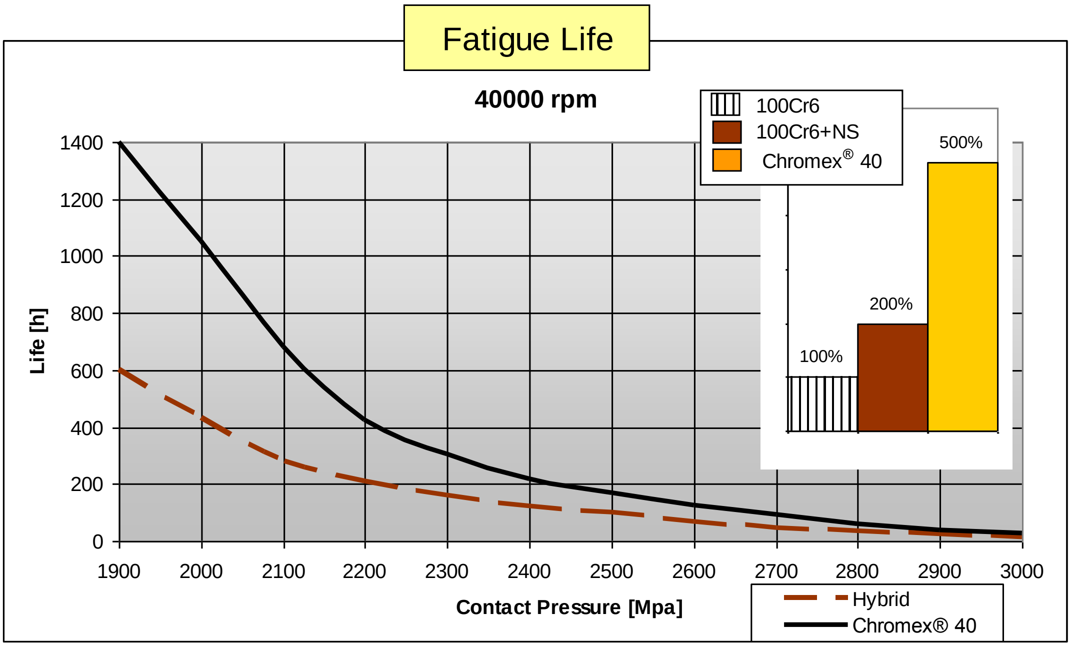


Fig. 10. Bearing life time vs. rings material

Figure 10 also shows the relationship of life time from contact pressure, present in a bearing. However, hybrid bearing with rings made of Chromex®40 steel are always at least 2-2,5 times more resistant that classic hybrid bearing.

4. CONCLUSIONS

The solution for a problem of proper functioning of bearing loading sleeve under the influence of spring force or other actuator, creates the possibility of minimising axial thermal errors, dynamically changing with rotational speed. The influence of the spindle itself on the precision will be then limited to relatively small thermal elongations of only the spindle tip. In such case, axial shift will be proportional to rotational speed and repeatable, therefore easy to compensate. Further work on the influence of centrifugal forces on axial displacement of a spindle will undoubtedly allow their more precise modelling and compensation. Just as with the relation to life time of high speed bearings, the application of a new material for distance rings and cage may also turn out to be beneficial for limiting axial shifts of a spindle, and increasing its life time. Some beneficial effects can be also expected thanks to geometry changes of bearings themselves, for example three or four contact zones bearings [5].

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