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BEARING AREA – WHAT IT MEANS AND HOW TO HANDLE IT

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Abstract: *The fast integration of the young engineers in the machine tool design activity is, for a long time, a manufacturers' desire, very seldom achieved. For, at least, two de-cades the problem was raised, and the Universities are trying to solve that problem. The paper presents the author's considerations and experience regarding one of the fundamentals in machine tool design: the bearing area.*

Key words: *machine tool, designing, education, bearing area, shape error tolerancing.*

"All of us are originating in "something" not so much from "genes", as from what it is given to us"
Tatiana SLAMA-CAZACU

1. INTRODUCTION

Often and for a long time the machine building industry representatives have expressed their dissatisfaction on the incapacity of the young engineers to assume the designing tasks short time after getting their diploma. The industry needs young engineers with good knowledge in designing, which are able to harmonize within the company activity with a minimum training [4]. It is necessary that those young specialists to have the possibility to cultivate the skills and aptitudes for solving the specific problems [5].

Probably that in a very few schools for engineers, both professors and future specialized engineers in machine tools are aware that a machine tool engineer has to be a system engineer.

That means that excepting the basic knowledge, the design engineers are "assembling technologies". The success depends also, on knowing the

- customer's / market needs;
- possibilities vs. requirements;
- way to "assembly technologies".

The list of the knowledge and aptitudes a designing engineer must have is long and diverse.

Additionally, the technical innovations are asking higher and higher requirements for designing engineers, who must be creative and able to work in a team [5].

One of the reasons for which in the designing science in machine building it has not been done progress as in other disciplines lays in the fact that in the education process there is no agreement concerning the basic elements, fundamentals of the mechanical designing [1 and 2]. The fundamentals in this field could be built by identifying the principles on which the best products in the field have been achieved and by using the research work results.

This implies other two aspects:

- the specialists – elder or younger, more or less experienced – must exchange knowledge; the wider knowledge is exchanged (questions, answers, opinions, design solutions etc.), the richer is the knowledge of all partners;
- way to transfer the knowledge, experience (know-how), from the elder towards the new generations, the way to avoid failures, negative experiences etc.

The EU put that problem and is asking ideas, proposals to turn to the best account the experience of the mature and retired specialists.

Further on we want to bring in front a problem considered to be one of the fundamentals, which any mechanical engineer (and by extension, any specialist implied in mechanical systems) have to to know: *the bearing area*. Do not mix up with the *contact surface*, which takes into account the micro and macro-geometry of the surfaces into contact.

The problem was presented in [3], including the way the bearing area has to be considered into manufacturing documentation, by supplementary constrains – the agreed direction of the deviation, not only its value.

The simplest illustration, the image of the bearing area, is the footprint on the soil (Fig. 1) [3]. Almost all people including specialists were asked which is the bearing area, and answered that it includes both the footprint contact area and the surface between them. Also all asked people (specialists or not) answered that the more stable position of the human body is that providing the maximum bearing area.

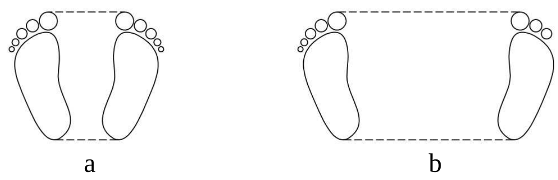

Fig. 1. Bearing area – the footprint on the soil: *a* – closed feet; *b* – spread feet.

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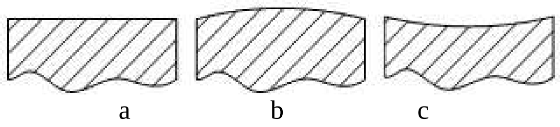

Fig. 2. Types of surfaces: *a* – plane (perfect, very rare); *b* – convex; *c* – concave.

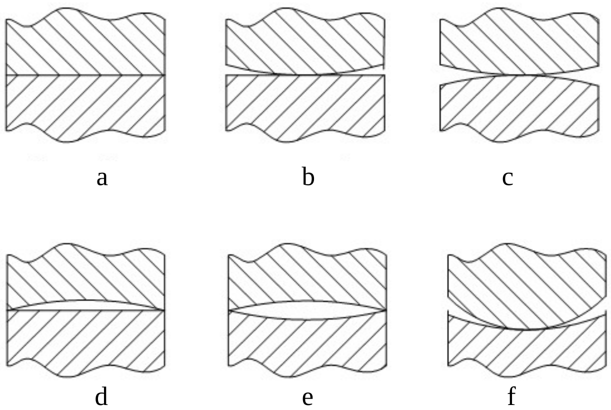

Fig. 3. Contact of two assembled surfaces: *a* – plane-plane; *b* – convex-plane; *c* – convex-convex; *d* – concave-plane; *e* – concave-concave; *f* – convex-concave.

Let's suppose two technical situations:

a. The contact of two plane surfaces. Theoretically, any plane surface could be:

- perfect flat (zero flatness deviation, which, in technique, does not exist);
- convex;
- concave (Fig. 2) [3].

It is possible to "assembly" them as in Fig. 3 [3]. Even for a less familiar person to the technique it is obvious that stable are the variants flat-flat (extremely, if not impossible to be met, except block-gauges), flat-concave and concave-concave.

One of the situations in which that problem is met is the machine tool table (fixed, moving or rotating): by the geometrical accuracy testing standards (without any exception) it is required that the work-piece holding table surface to be flat, the only accepted deviation direction being the concavity.

b. The contact of two bodies one of which has a step on which the second is propped, pushed by a certain force towards the prop step (Fig. 4). The contact between the two bodies had to be, theoretically, done on a surface square to the locating surface. As in the previous situation, due to the squareness error, the square surface will make an acute ($\alpha \leq 90^\circ$) or an obtuse ($\alpha \geq 90^\circ$) angle with the locating surface. From Fig. 5, it follows that according to the bearing area principle, the suitable version is that in which the angle α is acute. It implies that in the manufacturing documentation to stipulate both the squareness condition (and its value), and its direction (orientation): $\alpha \leq 90^\circ$ (Fig. 6).

In the followings, we present some examples of errors which could appear when carrying out the bearing area and what consequences those errors could have.

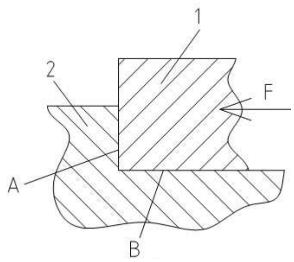

Fig. 4. Contact of two bodies on two perpendicular surfaces by means of a certain force.

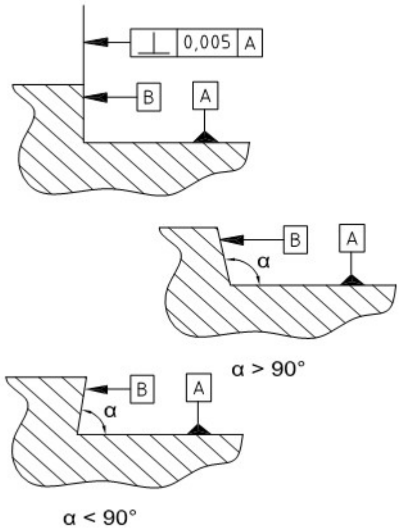

Fig. 5. Suitable version in which the angle α is less than 90º.

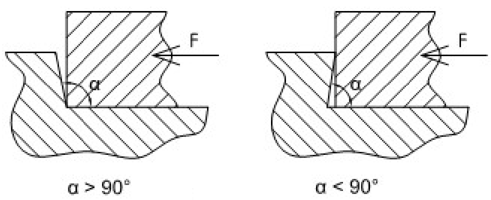

Fig. 6. Squareness conditions (value, orientation) as documentation parameters.

2. THE CONTACT OF TWO CONICAL SURFACES

Among the most frequently met conical joints there are:

- cutting tool fastening into the main spindle or the main spindle taper bore;
- assembling the radial bearings with two roller rows and inner ring with taper bore (the series NN…K).

One of the most frequent cases of the real joints is shown in Fig. 7 [7]. In the manufacturing documentation of the mating parts – taper bore of the main spindle or the main spindle journal – it is specified both the rake (taper), and its permitted error. Sometimes it is requested that the contact area between the two conical surfaces to cover at least 75–85% of the theoretical contact area.

Usually, from our experience, in the great majority of cases, the contact is done in the part of the small diameter of the cone. The checking of the contact area is

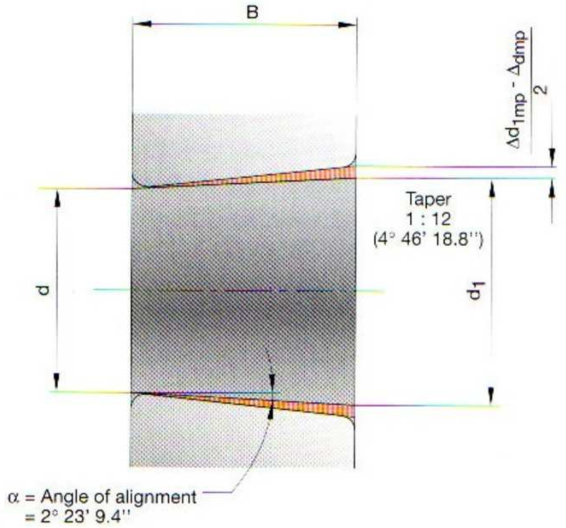

Fig. 7. Frequent case of contact surfaces.

another problem which depends on the knowledge, experience of the technical staff (workers, engineers), but also on their conscience and technical discipline.

The position of the contact area in the small diameter zone is leading to the unsteadiness of the joint, or in other words, at a low static and dynamic stiffness. Accordingly, the cutting tool preset at a certain dimension will cut another one, and it could vibrate in the cutting process with all consequences.

To increase the bearing area there are several solutions:

- repeated trials to machine the mating part (the taper hole of the main spindle or the taper spindle journal) in correspondence with the mating part (tool shank or bearing inner ring), but this means additional time and money;
- mating part machining so that the minimum accepted contact area to be placed towards the big diameter of the taper joint (the most used method, but requiring technological discipline);
- accomplishing a recess on the taper tool shank, between the minimum and maximum tool cone diameters; some tool producers are using that solution only.

To avoid some problems in operation – static and dynamic stiffness – when assembling the bearings from series NN, …, K, one of the manufacturing companies [9] offers to the users a procedure for adjusting the bearing play/preload assembling, which takes into account the reel situation of the "male" and "female" cones.

3. BEARING AREA OF THE CYLINDRICAL ROLLERS OF THE RADIAL BEARINGS

In operation, between the rollers and the rolling track could appear variations of the contact pressure:

- due to rolling track shape (cylindrical or concave);
- due to deformations produced by loading, Fig. 8 [12].

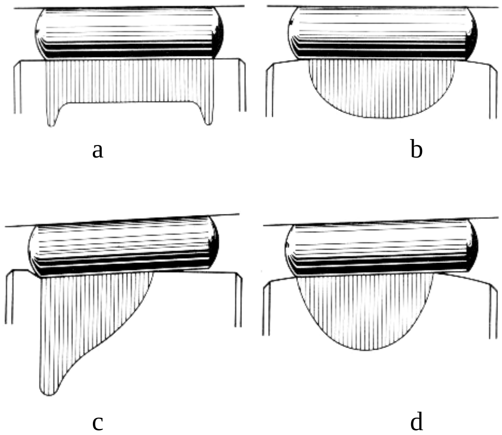

Fig. 8. Deformations produced by loading.

To keep the bearing area, and consequently the contact pressure within acceptable limits, the rollers and the rolling tracks are machined with curves providing the largest bearing areas, within the whole variation field of the operating conditions (speeds, loading, deformations etc.). The corresponding curves were defined after years of experience and trials [9 and 12].

4. MAIN SPINDLE BEARINGS LAY-OUT

From economical (costs), technological (components machining capabilities, their assembling and adjusting), operating (lubrication), maintenance, operating and machining accuracy etc. point of views, when designing a main spindle bearing system, we take into account:

- the distance between the bearings (supporting points), which represents the main spindle bearing area (it is recommended to consider the distance between the middle of the bearing widths as 2.5–3 times the value of spindle nose diameter [13], or 3–3.5 times the inner ring diameter of the front bearing [9]; the recommended distance value assures an optimum stiffness value and a thermal balance of the whole assembly;
- the way to place the radial-axial bearings (angular contact ball bearings, taper roller bearings).

Depending on the direction of taking over the thrust forces, the bearing could be placed

a- back-to-back (DB code), or
b- face-to-face (DF code), Fig. 9 [6].

It results from figure that the bearing area of the back-to-back version is bigger than of the other one.

That property provides to the back-to-back lay-out the following advantages:

- higher stiffness, also with the possibility of taking over bending moments;
- small influence of the temperature increase on the whole spindle thermal extension.

The back-to-back lay-out is unfavorable if the housing manufacturing accuracy is not suitable and if the main spindle journals are out of the accepted co-axiality error limits.

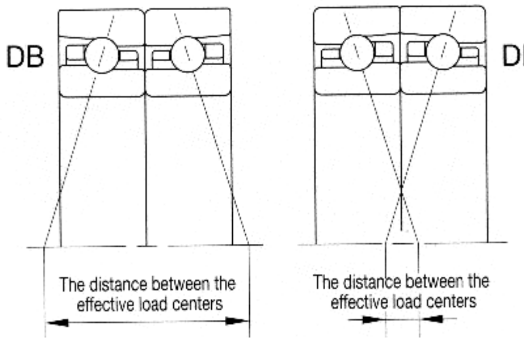

Fig. 9. Face-to-face assembling type of bearings.

5. BEARING AREA VARIATION IN ASSEMBLED ROLLING BEARINGS

5.1. Inside the rolling bearing

Depending on the bearing preloading, the raceway loaded zone could show a large variation of related life, according to Fig. 10 [11].

In the main, the ideal operating adjustment of the angular contact ball bearing or of the taper roller bearing must be set at zero endplay, considering the fatigue life (Fig. 11) [11], vibrations, wear, etc.

The zero endplay or preloading could be assured, depending on the manufacturer's experience, either when assembling, or in operation (because of heating).

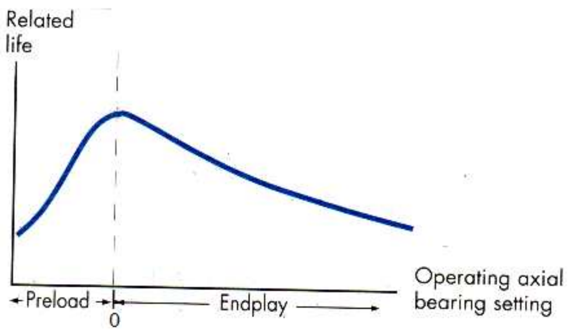

Fig. 10. Large variation of the related life depending on preloading.

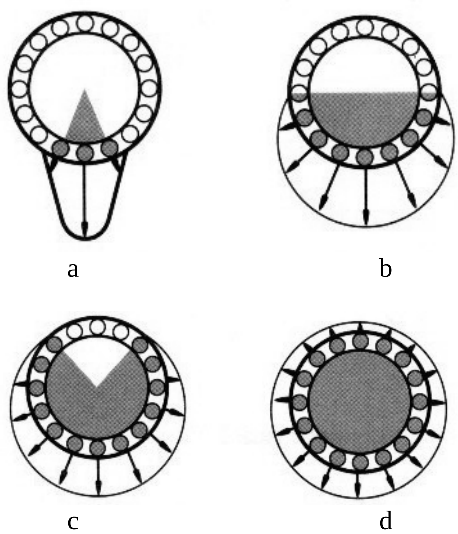

Fig. 11. Operating adjustment of the angular contact ball bearing: *a* –internal clearance; *b* – 180º load zone, zero clearance; *c* – small preload; *d* – 360º load zone, heavy preload.

5.2. In the joints of the bearing rings with the mating surfaces

To get an optimum rolling bearing behavior, it is necessary that the fits of its rings with the spindle journal and the housing bore to be properly done. If between those surface couples there is no tight, the ring could rotate as against the mating surface – creeping [8]. That movement could lead to:

- excessive bearing wear;
- spindle journal/housing bore damage;
- vibration and excessive heating occurrence;
- penetration of foreign bodies (chips, small particles resulting from other components wear) into the bearing, which accelerates the bearing wear.

For avoiding such phenomenon, the following measures are taken:

- the inner ring is assembled on the shaft journal by an interference fit and the external ring is assembled, as a rule, into the bore by a clearance fit

NOTE: The values of those fits depend on the designer's, manufacturer's (in assembly shop) experience, on operating conditions (stiffness, machining accuracy, allowed temperature variation etc.).

As in operation the inner ring has a higher temperature than the external ring, the clearance of the later will be cancelled by dilatation in operation. All those depend on the builder's experience.

Within certain limits, the bearing rings fits with the mating surfaces could be adjusted when assembling by using the spacers (rings, bushes). That generates additional problems, which will be discussed later.

The variation of different bearing operating parameters as a function of clearance/interference (preloading) fit could be seen in Figs. 12–14 [6].

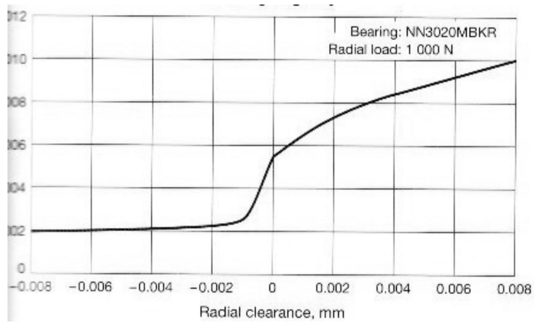

Fig. 12. Bearing rigidity as function of radial clearance.

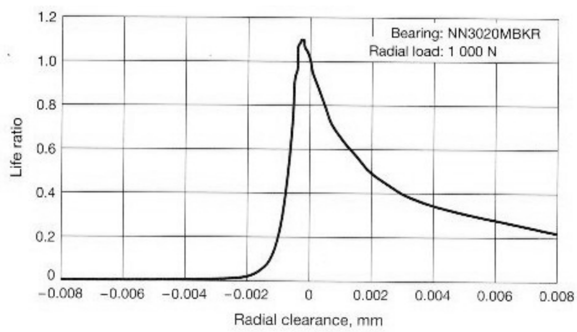

Fig. 13. Life ratio depending on radial clearance.

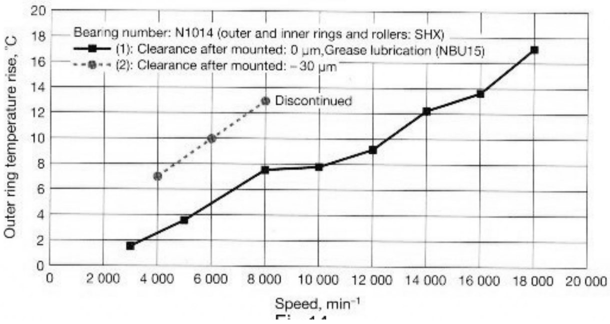

Fig. 14. Outer ring temperature as function of speed.

A first conclusion which could be drawn is that for a proper rolling bearings operation (stiffness, high speed with minimum developed heat, vibration free) it is necessary that between surfaces in contact (bearing rings and the mating surfaces, rolling elements and raceways) there must not be clearance.

5.3. Methods for carrying out the clearance-free fits for rolling bearings

In the rolling bearings catalogues there are indications on the method for selection of the tolerance fields for spindles and bores. In [8] it is shown a computing procedure of the fit variation as function of several parameters (bearing loading, temperature variation, roughness etc.). In [9], for the first time it is presented in a bearing catalogue another philosophy. The starting point is that the bearing has materialized the two systems

- the inner ring bore is in basic bore system;
- external diameter of the external ring is in standard shaft system.

For the mating surfaces – spindle journal and housing bore – there are stipulated tolerance fields as function of the actual dimensions of the bearing (inner ring bore and external ring external diameter). They could be found starting from the two nominal diameters, corrected by the actual deviations values (in µm), and marked on each ring (they are considered rolling bearings in P4 accuracy class or better).

It could happen that after machining the bearing mating surfaces, the specified tolerances are not achieved. Because a machine tool main spindle or a housing are expensive components with a long manufacturing time, the problem of producing new components is not taken in consideration, coming up the question about how to compensate the machining errors.

In [11] it is shown a procedure, a method for correction of the machining errors, beyond the allowed tolerance field.

From our experience, using data from [9] and [11] and introducing other additional corrections, together with the team, we obtained peripheral speeds for main spindles even over 20 m/s, with a stabilized temperature of 10–15 ºC over the environmental one. The lubrication is another extremely important aspect (not subject of this paper).

The co-operation with foreign companies – heavy machine tools manufacturers/users – offered us an interesting experience: the values of the actual deviations must be within the first third of the tolerance field and do not be over the half of it. This is a method offering a high certitude level that in operation no problem will appear.

5.4. Shape and relative position deviations of the bearing mating surfaces and their roughness

The machine tools are requested to cut at higher and higher speeds. One of the methods to increase the cutting speed is to grow the rotation speed of the workpiece/tool. The requirement is fulfilled by providing a bearing system allowing the rotation at high speeds (described either by the raceway peripheral speed [11], or by the speed indices $n\ d_m$ that is rotation speed times bearing mean diameter), at high accuracy and at smallest possible heat generation (by lubrication methods, heat removing etc.).

Among the required conditions to the bearing systems there are also those referring to the mating surfaces shape and relative position deviations, and roughness.

If comparing the asked conditions in [9] and [10] – shape and relative position deviations in accuracy classes IT1 and IT0 – with the same parameters in other catalogues, one can see much difficult conditions to get a high speed rotation.

In Fig. 8 above one can see an effect of the relative position deviation on the bearing area of the roller and consequently on the contact pressure distribution.

The bearing rings are elastic components, easily distorted. They are taken the shape of the mating surfaces they assembled on/in. Therefore, the geometrical proper (accurate) rotation of the spindle supported on rolling bearing depends in a very great measure on of the geometrical errors – shape and relative position – of the mating surfaces.

In Fig. 15 [9] the circularity errors are shown. They are found on the machined surfaces owing to the bearing ring mating surface (spindle or bore, or both) own shape errors.

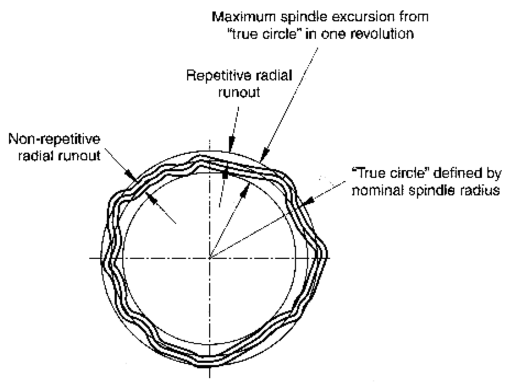

Fig. 15. Circularity errors.

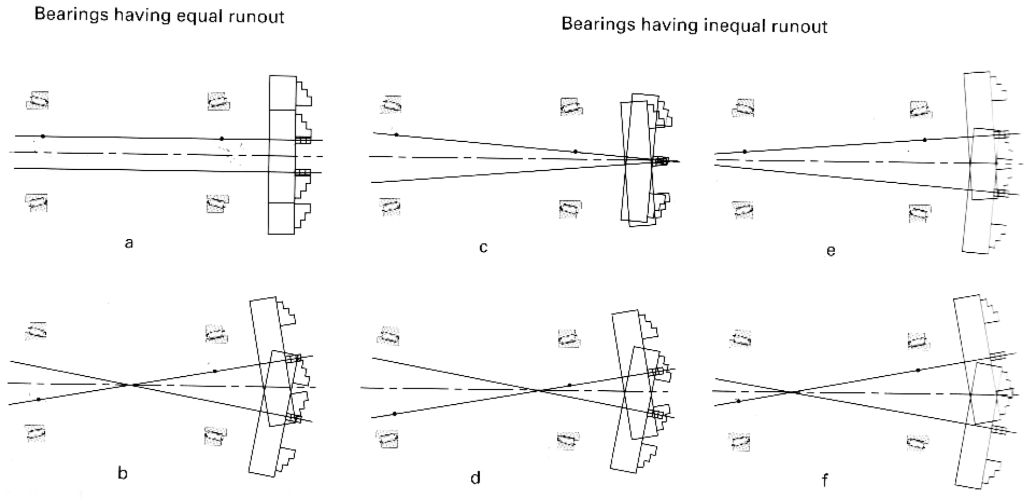

Fig. 16. Spindle geometrical errors and their maximum position.

Even if

- the bearing ring mating surfaces – spindle and bore – are machined within the accuracy specifications (dimensions, shape and relative position deviation, roughness),
- bearing are of a high accuracy class, the bearings assembling on the spindle could lead to getting positive results (variants *a*, *c*), or negative (variants *b*, *d*, *e*, *f*) concerning the radial run-out of the main spindle. The proper assembly, according to Fig.16 [13] of the inner ring supposes to know exactly (with the suitable marking) of the spindle geometrical errors and their maximum position (high points).

5.5. Bearing shoulders

The rolling bearing manufacturers are offering in their catalogues enough data to the designers for a proper supporting of the bearing rings on the shoulders, that is referring to:

- shoulder height for providing a proper bearing area;
- the value of the shoulder radius or shape and dimensions of the recess, for providing a stable rest.

6. DISTANCE RING/BUSHES (SPACERS)

For technological and in-operation behavior reasons, for a proper adjustment/correction of the rolling bearing preloading, the distance rings/bushes are used. Also, their role is to guaranty a right bearing preloading: not too small, not too big, limiting the stroke of the lock nuts. In other words, the bearing preloading is not let at the assembly staff latitude (experience, technological discipline, force, etc.).

In ideal manufacturing conditions (dimensions) the spacer's lengths both for inner and external rings are equal. Otherwise, the difference between the lengths of those spacers is calculated taking into account the actual dimensions of the spindle journal and housing bore.

An essential condition for those spacers is the parallelism between their front faces. It is required that the error to be about 0.003 mm [6].

7. BEARING LOCK NUTS

At least two problems are generated by those components in connection with the bearing area:

- accomplishment of the front "active" surface square to the spindle center line,
- parallel motion (keeping the same position of the front "active" surface) of the nut during the tightening operation.

The conditions mentioned above are fulfilled by:

- grinding the screw and nut as a clearance free joint,
- grinding the front "active" surface of the nut, assembled on the screw, in the theoretical tightening zone.

Non-observance of those rules lead at the shaft bending (main spindle, ball screw) and appearance of the radial run-out, with all implied consequences.

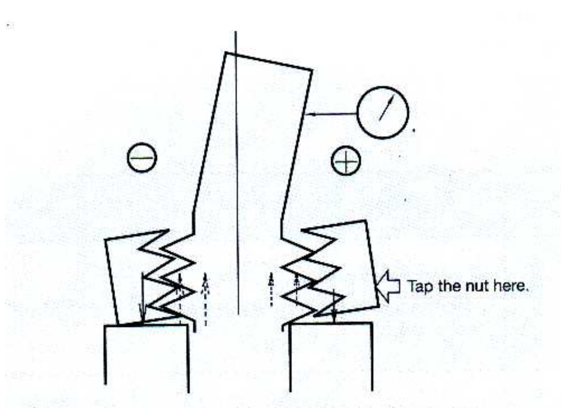

Fig. 17. Effects of screw nut clearance and squareness.

In Fig. 17 [6] it is shown amplified what happens:

- if into the screw-nut joint a clearance appears;
- if the front "active" surface of the nut is out of squareness to the shaft central line.

In our professional experience, we have met several times machine tools having main spindles or ball screws with large radial run-out, with components and assembling apparently in proper accuracy conditions. The source of the problems represented the nuts.

The same problems are generated by the fastening/locking flanges of the rolling bearings.

8. BALL SCREW NUTS

At the execution of the ball screw nuts, tens or over hundred balls are used depending on the circuit number. Depending on the ball screw accuracy class, sorted out balls in certain accuracy classes are used (the ball diameter could vary within specified limits). If within the same accuracy class (with the limits of 5 µm, e.g.) an additional sorting out is done, and for the nut external circuits (placed at the nut ends) the balls with the maximum diameters (but the same for a circuit) are used, obtaining a similar situation as in Fig. 1. The nut is more stable in operation (position, efforts variation etc.) and in time its behavior is improved. Applying this method, we achieved positive results.

9. CONCLUSIONS

Keeping a series of rules (the bearing rings fits with the mating surfaces, accuracy specifications of the mating surfaces, assembling conditions of the inner rings, specifications for the spacers, locking nuts machining, squareness error and its orientation etc.), together with the teams we worked with we obtained:

- high rotation speeds (peripheral speed over 20 m/s);
- bearing heating with 10–15 ºC over the environment temperature;
- very good rotation accuracy of the main spindle (radial run-out of 1–2 µm, axial run-out 0–1 µm);
- very small straightness errors and backlash (under 1 µm) etc.

A very close co-operation, a permanent dialog among designing-manufacturing-assembling-purchase and keeping the technological discipline are leading to good results comparable to those in the top in the world.

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