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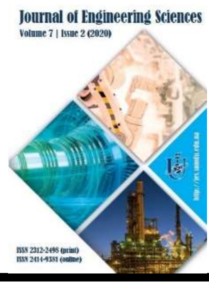

Contact of Working Surfaces for Spherical Washers and Recommendations for Determining the Gap in the Joint

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Abstract. In article analyzes the technical requirements for spherical washers used in threaded connections of pumps, which made it possible to highlight contradictions in paragraphs of the current standards for pump fasteners. They regarding recommendations for manufacturing technology and control of the working surfaces of washers. Publication analysis in the spherical surfaces lapping showed the absence of research in the spherical surfaces contact after lapping and the dependence of contact parameters by the technological parameters for this operation. The presence of a gap in conjunction with spherical washers after the lapping process was proved geometrically. Its location was determined, and a mathematical dependence was obtained to determine the maximum gap value in conjunction. It was found that the gap depends on the design parameters of the washers' conjunction and the abrasive material grain size used for lapping. Recommendations for selecting the abrasive material grain size for the lapping operation for the most common values of the roughness parameters for the working surfaces of spherical washers have been formed. In the article was proposed to introduce into the technical requirements for the spherical washers drawings changes concerning the gap size allowable in the conjunction, and as well as tolerances value changes of the radii of the working surfaces of the washers, thus increasing their manufacturability without conflicting with the requirements of the current standards.

Keywords: lapping, turning, tolerance, contact square, manufacturability.

1 Introduction

The development of the world's technological progress requires more energy for production and human life activity. By 2050, energy consumption is projected to increase by more than two times compared to 2020. In this case, the central part will be directed to production [1]. Almost any production requires the transportation of water, various liquids, and mechanical mixtures with solids, liquefied gases, which is possible using pumps. This makes their design and production relevant now and for several decades in the future [2]. Therefore, to succeed in Ukraine enterprise's competition and foreign pumping enterprises, it is necessary to improve the manufacturing quality. This is expressed in the declared uptime, terms of warranty service, duration of overhaul periods, and service manufacturability of the post-warranty period [3–5]. Also, for the initial attraction of the client's interest, the initial price for pumping products must be less than that of concurrent.

2 Literature Review

The pumps' scope covers all life spheres, where it is necessary to create the energy of the fluid flow. Nuclear energy occupies a special place in human life activity. The pumps used in this area have special requirements for machining quality and acceptance.

Some of the regulatory documents regulate requirements for pumps operating directly in the thermal circuit of nuclear stations. They differ significantly from the requirements for pumps for general industrial purposes and ensure demand structural changes for pumps by nuclear stations.

One of these requirements is used lapping operation in the final processing of spherical washers' contact working surfaces.

Spherical washers are used in threaded connections for seals in the cover-case conjunction in pumps. Washers intended to the non-parallelism compensated of the cover planes and support plane of the nut when tightened. The advantage of these washers compared with flat washers is the possibility of self-alignment of the convex washer relative to the concave one [6]. This property is eliminates bending stresses on the pump stud, which favorably affects the overall stud performance.

But the machining technology of spherical washers, compared to the flat washers, is different, leading to additional costs in their production. According to GOST 23304-78 “Bolts, studs, nuts, and washers for flange connections of nuclear power plants. Technical requirements. Acceptance. Test methods. Labeling, packaging, transportation, and storage”, the final machining for the contact working surfaces of spherical washers for nuclear pumps should be carried out by lapping them.

The lapping is a time-consuming and costly process since it is a thin final treatment of the surface layers for parts working in pairs. Lapping allows ensuring the best contact of the mating working surfaces and the tightness of the conjunction between parts.

Research of the lapping process is considered in [7], which shows the effect of grain size and the direction of the tool movement for the spherical surface shape error with a variable radius. A. A. Fiocchi’s work [8] is devoted to studies of the flat surface shape deviations on the finishing operations for processing parts made of ceramic materials. J. Yuan [9] established the dependence of the roughness on high-precision spherical surfaces when changing the lapping speed during the planetary tool movement of the relative by part. M. N. Durakbasa in [10] identified the factors that significantly impact the measurement of flat and spherical surface roughness on the finishing grinding and lapping operations. Researchers J. Chenac and T. Sun proposed a new agglomerated diamond abrasive with excellent micro-cutting and self-sharpening capabilities for lapping with a bonded abrasive [11]. Simultaneously, the cutting conditions were determined to achieve the minimum possible roughness, which could be obtained with new material. S. Huang, in paper [12], determined dependence of workability indicators during lapping with a bonded abrasive using water-based suspension with nanoparticles of silicon dioxide.

Research in the field of cutting diamond processing of spherical surfaces is shown in [13]. The finite element analysis obtained dependence of the roughness of surface machined by diamond turning with the development of a program for controlling the movement of a diamond cutter. The factors that have the greatest influence on roughness are also identified.

A literature review source follows that research of the lapping processes and spherical surfaces machining is an actual task. However, these studies did not address questions related to spherical surfaces' contact area analysis after lapping.

Thus, the research purpose is to analyze the contact area of the working surfaces of spherical washers after lapping and the dependence of the gap in conjunction with the washers' geometric parameters and the size of grain abrasive material.

3 Research Methodology

3.1 The analysis of technical requirements for spherical washers by nuclear pumps

The regulatory documents defining the rules for the manufacturing and acceptance control of nuclear pumps considered in [14] are as follows:

- “Rules for design and safe operation of equipment and pipelines of nuclear power plants” PNAE G-7-008-89 [15];
- “Fasteners for detachable conjunctions of nuclear power plants. Technical conditions” GOST R 54786-2011 [16];
- “Bolts, studs, nuts and washers for flange conjunctions of nuclear power plants. Technical requirements. Acceptance. Test methods. Labeling, packaging, transportation and storage”. GOST 23304-78 ambiguously interpret the requirements concerning the working surfaces of spherical washers.

The complexity of spherical washers designing compared with flat washers consists of absent information about their design parameters. Therefore, the designer should be based on his own experience determining their design and dimensions because the current standards for spherical washers give him only general guidelines.

These instructions are given in most detail in the standard, which regulates the requirements for fasteners by nuclear equipment. In par. 1.17 of this standard verbatim states that “Conjunction convex and concave washers should be lapped on spherical surfaces. The contact area must be at least 80 %. The lapped washers must be marked with the same serial number”.

This means that the conjunction of spherical washers is non-interchangeable, and the main requirement that must be met upon obtaining is the contact area of the working surfaces of washers. Also, the authors of the standard, apparently from the designers' area, most likely do not suspect that this requirement is indefinite in terms of control, namely:

- par. 2.8 indicates that: “Spherical washers should be subjected to a complete control of the coincide of the conjugating surfaces”;
- par. 3.17 indicates that "The coincide of the mating surfaces of spherical washers (par 1.17) should be controlled "for paint"".

Simultaneously, the thickness of the paint layer is not regulated, that when using a layer thickness greater than the maximum gap in the conjunction of the working surfaces of washers, 100 % contact will always be ensured. In this case, the location of the gap will not be determined visually.

Requirements are set forth regarding the control of spherical washers, which were mentioned in [15], namely [16]:

- par. 5.5.5 indicates that: "Spherical washers should be subjected to complete visual coincide control for conjunction surfaces "for paint". Requirements for quality coincide of the conjunction surfaces must be ensured by the technology approved at the manufacturer";
- par 5.5.6 reads as follows: "Conjucnting convex and concave washers should be lapped by spherical surfaces. The contact area must be at least 80 %. The lapped washers must be marked with the same serial number".

Analyzing [16], one can notice a contradiction in the specified paragraphs concerning control of spherical washers, namely par. 5.5.5 and par. 5.5.6 [15] for working surfaces on spherical washers, processing should be used with the technology approved at the manufacturer and in par. 5.5.6 [15] says that the conjunction spherical surfaces should be obtained by lapping.

The contradiction lies in the fact that the fit of spherical washers can be ensured in any way according to technology approved by the manufacturer. But in par. 5.5.6, the alternative manufacturing technology excluded and introduces a mandatory requirement to obtain conjunction spherical surfaces only by lapping.

The analysis of technical requirements for spherical washers also made it possible to establish that these requirements outlined in [15] are a revision of the requirements from GOST 23304-78.

3.2 The analysis of geometric parameters in the conjunction of the working surfaces of spherical washers

In a detailed analysis, from the point of view of elementary geometry, the conjunction in a set of spherical washers must be considered until the axial force application occurs when the nut is tightened. In this case, it is conjunction with a gap. As a rule, the designer establishes tolerances according to the classical scheme, depending on the surface is covering or covered. In this case, if the concave washer has a positive tolerance, and the convex washer has a negative tolerance. The contact occurs along the smaller diameter, and the gap will be accordingly located on the larger diameter (Figure 1 a). In the case when the tolerances are set as opposed to the above, then the contact is formed over a larger diameter (Figure 1 b).

For the operability ensured of the conjunction of spherical washers in the process of performing their service purpose, it is necessary to obtain a metal contact on the entire surface of the spheres. In this case, if the contact occurs according to the scheme (Figure 1 a), then after the axial load application, the upper convex washer receives bending deformation, and the gap in the conjunction closes, and metal contact formed on the entire surface of the spheres. If the first contact occurred to the scheme (Figure 1 b) assumes that after the axial load application, the washers in the diameter of about *Dmax* to close the gap receive a crushing deformation. This is not preferable from the washers' point of view during subsequent tightening of the threaded conjunction. In addition, the variant in Figure 1a is always the result of lapping spherical washers against each other. This is more widely practiced when meeting the requirements of par. 1.17 of GOST 23304-78 and par. 5.5.6 [16].

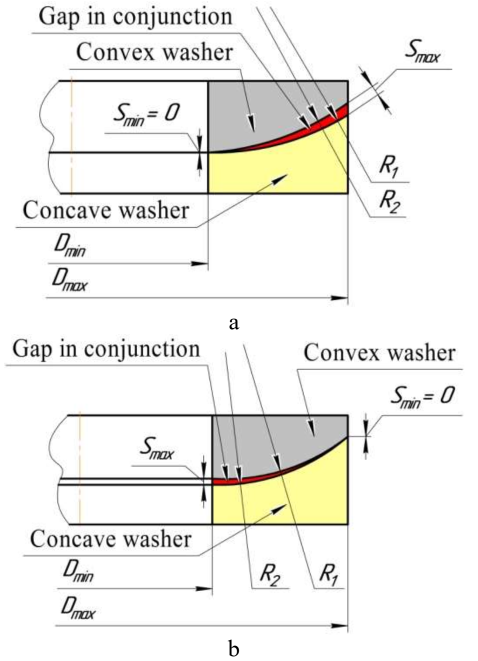

Figure 1 – Possible variants of the gap in the conjunction of spherical washers:a – on a larger diameter; b – on a smaller diameter.

Consider the conjunction of spherical washers from the point of view of their geometric contact at the conjugate place of spherical surfaces (Figure 2).

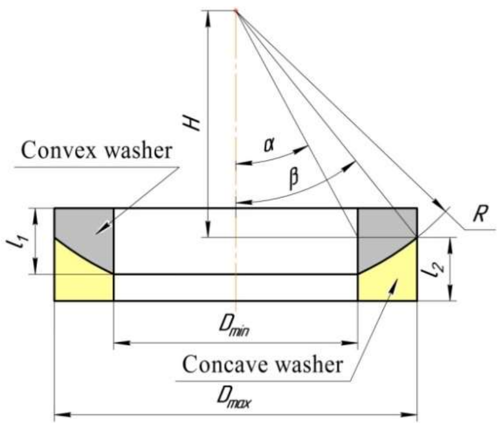

Figure 2 – General view of the spherical washers conjugation

The based information that can be obtained from the drawing of any pair of washers is:

- *Dmin* – hole diameter in the washer, which defines the theoretical starting point of the spherical washer surface;
- *Dmax* – outer diameter of the washer, which represents the theoretical endpoint of the spherical washer surface;

- l_1 – thickness of the convex washer;
- l_2 – thickness of the concave washer;
- R – radius of the washers spherical surfaces.

Also, in the drawing of spherical washers in *the Dmin convex washer diameter, there is a bluntness of a sharp edge as a rul*e. This is done to avoid damage to the working sphere surface of the concave washer. Correspondingly, the concave washer has a blunt edge at the diameter Dmax. In the process of washers contact analysis, the bluntness dimensions are not taken into attention due to their small size. To further explain the contact process and inference determine the correlation between a maximum gap in conjunction, we will introduce parameters that are not indicated in the drawing for manufacturing but exist geometrically and will participate in further calculations:

- α – angle defining the theoretical interference point of the upper plane and the internal concave washer diameter relatively to her axis;
- β – angle defining the theoretical endpoint of the spherical washer surface relatively to her axis;
- H – height center of the surface of spherical washer relative to the upper plane of the concave washer.

Let us consider in more detail the place of contact between washers during the lapping process with the abrasive material presence (Figure 3 a) and after lapping with complete abrasive material removal (Figure 3 b).

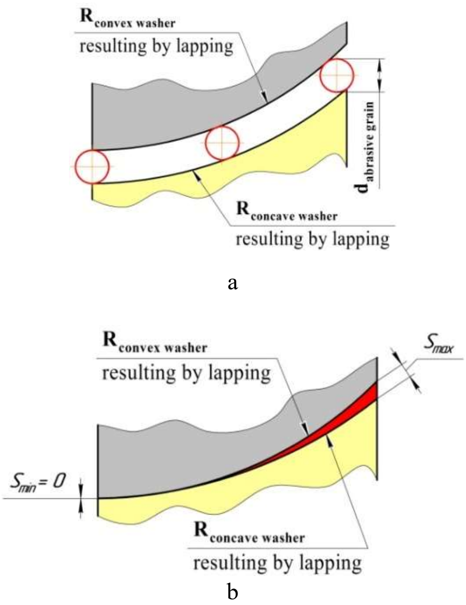

Figure 3 – Place of spherical washers contact:
a – with abrasive grains; b – without abrasive grains.

From Figure 3 a, if the abrasive material is present between the washers' spherical surfaces, the convex washer radius after lapping is less than the concave washer radius by an amount equal to the abrasive grain diameter. As a result, after the abrasive layer removing from the spherical contact surfaces and in conjunction with them, contact occurs along the smaller washers' diameter (Figure 3 b). In this case, on the larger diameter in the spherical surfaces, conjugation is formed the maximum gap – *Smax*. The gap character of them, along with on conjugated spheres arcs, is variable and resembles a sickle. Thus, it is a conjunction with a circular sickle gap (Figure 3 b). Consequently, lapping allows a gap to be provided exclusively over the larger diameter, which is the preferred option, as said above.

Therefore, in the design process, designers must be disturbing the question of what gap size can be allowed in the washer conjunction. After applying for the required axial force in the threaded conjunction, the gap between the spherical surfaces on the large washers' diameter must be closed. Since that there is no information on the gap size, the designer, as a rule, assigns rather “tight” tolerances to the radius of the spherical surface of the washers within 0.05 mm for washers with a sphere radius from 80 to 150 mm. This is also done to reduce the required time for lapping washer’s conjunction surfaces. After turning, it only remains to bring the necessary parameters in terms of the contact area and surface roughness. As a result, it is not required to make cutting a lot of material during the lapping operation. These tolerances are complicated to achieve with turning, but it is even more difficult for small tolerances controlled, especially short-length spherical surfaces.

4 Results

Therefore, to explain and determine the gap size in spherical washers’ conjunction, consider the conjunction in the maximum gap place in more detail and enlarged (Figure 4). This place is characterized by the end of convex and concave washers’ surfaces, where abrasive grains fall out of the contact zone of the washers working surfaces during lapping.

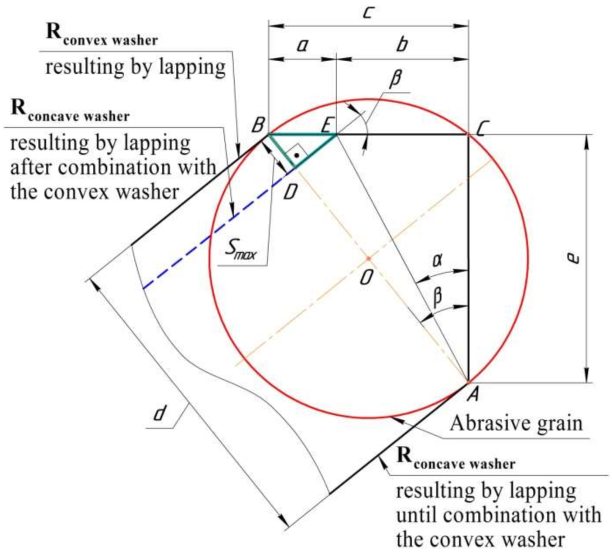

Figure 4 – Conjunction of spherical washers
in the maximum gap place

Using the basic trigonometric constructions, we obtain ΔABC, for which the angle BAC = β, and the side

AB = d (abrasive grain diameter), and ΔAEC for which the angle EAC = α. From a right triangle ΔABC we find:

$$c = d \cdot \sin(\beta) \quad (1)$$

$$e = d \cdot cos(\beta) \quad (2)$$

From a right triangle ΔAEC we determine the line segment b:

$$b = e \cdot tg(\alpha) \quad (3)$$

From Figure 2, we express the trigonometric functions necessary for substitution into equations (1), (2), (3), namely, sin(β), cos(β), tg(α):

$$\sin(\beta) = \frac{\mathrm{Dmax}}{2\mathrm{R}} \quad (4)$$

$$\cos(\beta) = \frac{\mathrm{H}}{\mathrm{R}} \quad (5)$$

$$\mathrm{tg}(\alpha) = \frac{\mathrm{Dmin}}{2\mathrm{H}} \quad (6)$$

Substituting the expressions of trigonometric functions (4), (5), (6) into equations (1), (2), (3), respectively, we obtain:

$$\mathrm{c} = \frac{\mathrm{d \cdot Dmax}}{2\mathrm{R}} \quad (7)$$

$$\mathrm{e} = \frac{d \cdot H}{\mathrm{R}} \quad (8)$$

Substituting formula (8) and (6) into formula (3), we obtain:

$$b = \frac{\mathrm{d \cdot Dmin}}{2\mathrm{R}} \quad (9)$$

From the dimensional chain a, b, c, we determine the size, substituting formulas 3 and 7 into the equation:

$$a = \mathrm{c} - \mathrm{b} = \frac{\mathrm{d \cdot (Dmax - Dmin)}}{2\mathrm{R}} \quad (10)$$

From a right triangle ΔBED with BED = β and side BD = Smax, we obtain:

$$Smax = a \cdot \sin(\beta) \quad (11)$$

After substituting the parameters a and sin (β) into formula (11), as well as performing mathematical transformations to reduce the formula, we obtain:

$$Smax = \frac{\mathrm{d \cdot Dmax \cdot (Dmax - Dmin)}}{4R^2} \quad (12)$$

For example, let us calculate a particular case with specific washers' dimensions (Figure 5) and the abrasive grain diameter value, equal to 1 mm. We will also perform a check by comparison calculation results and results from the geometric model.

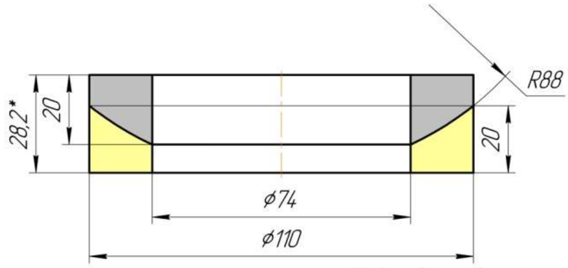

Figure 5 – The conjunction of spherical washers

According to Figure 5:

$$Smax = \frac{1 \cdot 110 \cdot (110 - 74)}{4 \cdot 88^2} = 0.1278\ (mm).$$

Constructing the corresponding arcs of the conjunction washers surfaces in the CAD-system, measured with an accuracy of 0.0001 mm. The maximum gap in the place of the larger washer's diameter Smax geom. = 0.1296 mm.

The error between the calculated and measured values of the maximum gap in the conjunction of spherical washers is no more than 1.4 %. Therefore, we can speak of the obtained correctness dependence of the maximum gap in spherical conjunction on the abrasive grain size and geometric parameters of the spherical washers.

Thus, using the obtained dependence, we determine the value of the maximum gap in spherical washers conjunction when using grain abrasive material with various sizes. The size of grain abrasive material, which is used for lapping, depends required on the contact surfaces spherical washers roughness parameter.

The analysis of the washers working drawings used in nuclear pumps made it possible to establish that the most common values on the contact surface roughness of spherical washers according to the Ra criterion from 0.8 to 2.5 µm.

Based on [17, 18] and GOST R 52381-2005, the grain abrasive material size values were selected, providing the above values of the contact surfaces roughness of spherical washers. The maximum gap calculating for Figure 5 and roughness parameters Ra 2.5, Ra 1.6, Ra 0.8 with the specified dimensions of the abrasive material are given in Table 1. Besides, Table 1 shows the error results of the calculated maximum gap value with the value obtained geometrically.

Table 1 - Values of the maximum gap in the contact area of the spherical washers working surfaces, depending on the required roughness parameter

The parameter of contact surfaces spherical washers roughness Ra, µm	Abrasive material designation according to GOST R 52381-2005	The medium grain size of the abrasive material d, mm	The value of the maximum gap in washers conjunction of the spherical surfaces		Relative error, %
			Calculation Smax calc., mm	Geometrically Smax geom., mm	
2.5	F30	0.5	0.0639	0.0631	1.3
1.6	F54	0.3	0.0384	0.0378	1.4
0.8	F70	0.18	0.0230	0.0229	0.5

5 Discussion

The practical results obtained by spherical washers machining at PJSC "Nasosenergomash" showed that modern CNC lathes' technical characteristics allow providing the necessary roughness of spherical surfaces constancy of spheres radius. This ensures the required coincide of them to each other without using the lapping operation by par. 1.17 of GOST 23304-78. The lapping requirement creates some problems with the presentation of ready washers' kits for verification, especially for nuclear pumps, because strict compliance to standards in this industry is the basis for the safe nuclear stations' exploitation.

This problem arose since, during the development period, CNC lathes had not yet become widespread. And their precision capabilities did not satisfy standard requirements for the contact area of the working spherical washers surfaces. Therefore, the authors of the standard for designers have provided, in fact, the technological requirement of lapping spherical surfaces during the manufacturing [14]. Simultaneously, the standard does not contain information on the permitted gap, which would allow technologists, during manufacturing and controllers during verification, to calculate the thickness of the paint layer when measuring the contact area in spherical conjunction.

Therefore, a rational solution to the contradiction between the standards' requirements and the new technological capabilities of CNC lathes is to introduce changes into GOST 23304-78. These changes would make it possible to obtain the necessary contact of the spherical washers working surfaces by any processing.

But since the changing process in standards applicable to nuclear power is reasonably conservative, it can take a long time. Therefore, for the transitional period, before making changes in the standard, the following recommendations are proposed:

- to include in the technical requirements on the spherical washers' drawings a clause regulating the permissible gap with indicating the required contact area of 80 %, and at the same time allowing lapping used if necessary;
- the tolerances for the spherical washer's surface radius should be at least 0.5 mm, which can be controlled using a template.

Thus, the lapping required is not excluded, but it is not obligatory if the required roughness of the working surfaces of spherical washers, and the required area of their contact, will be achieved differently. In this case, the control of the washers' radius becomes a reality.

6 Conclusions

By analyzing the technical requirements of the design documentation for spherical washers for threaded conjunctions of pumps, it was found that:

- the technological capabilities of the equipment dictate the need lapping by the contact surfaces of the spherical washers under GOST 23304-78 at the time when the standard has been created;
- in the standards GOST 23304-78 and GOST R 54786-2011, there is no method for calculating the paint layer thickness, which necessary for required contact area verification;
- the clauses of the standard GOST 23304-78 contain a contradiction in that one of them allows ensuring the coincide of the spherical washers surfaces with the technology adopted at the manufacturer. The other clause includes an indication of the need to ensure the spherical surfaces coincide exclusively by lapping.

By analyzing the geometric parameters in the conjunction of the spherical washers working surfaces before and after lapping, a universal analytical dependence of the maximum gap in the conjunction by design parameters of the washers and the grain abrasive material size was obtained.

The reliability of the obtained dependence is established, for example, of specific conjunction, by comparison, calculation gap values and the gap measured in connection on the drawing, which was made in the CAD program.

For the most frequently encountered roughness of the working surfaces of spherical washers in design documentation (Ra 2.5, Ra 1.6, Ra 0.8 μm) is tabulated with the recommended values of the grain abrasive material size for lapping.

In order to improve the manufacturability making of spherical washers by using the technical capabilities of modern CNC equipment, without conflicting with the requirements of current standards, it is proposed:

- on the drawings of spherical washers, indicate the sphere's radius with tolerance at least 0.5 mm, which makes it possible to radius control at the workplaces;
- to include in the technical requirements of the drawings of spherical washers an indication for ensuring 80 % of the contact area with the conducting surface with the maximum permissible gap, while allowing lapping spheres surfaces over each other if this necessary.

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