Rapid Design of Carousels for PVD Equipment: Some Considerations

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Abstract. One rapid preparation is often required in industrial Physical Vapor Deposition (PVD) processes for the execution of an order. When the latter is large, it is often necessary to design and manufacture a special carousel collecting enough samples and making the order performance profitable. Some practically justified guidelines for such design are provided here.

Keywords: PVD coatings, carousels, vacuum equipment

1. INTRODUCTION

Nowadays, PVD technologies become more widespread because of their advantages, among which environmental friendliness is very important. The deposited coatings are widely used in industry, medicine, art, etc. (Veprek & Veprek-Heijman, 2008; Zaharieva, 2009; Mishev et al., 2014; Kolaklieva et al., 2017). Some of these coatings are difficult, if not impossible, to be deposited by other known layer making methods (Mrochek et al., 2004; Reshetnyak & Strel'nitskij, 2008; Cselle et al., 2019). At the same time, with the development of the PVD technologies, the variety and quality of deposited coatings constantly increase and the value of the offered services decreases.

An industrial PVD installation is usually equipped with a carousel by default (one or more - replaceable) and various specimen attachments (holders). However, the diversity of customer orders is great and the standard equipment available is not always appropriate. When the batch of specific samples is huge, it is prudent to design a special carousel and/or holders for them. This should be done quickly and, if possible - cheaply. The second is necessary because after processing the batch, these adapts may not be needed soon.

The purpose of the carousel is to move the samples into the chamber, whereby they periodically pass close to the target, thus the coating is gradually formed. The content offered here gives some guidelines for a quick design of cheap carousels for PVD processes (besides, "cheap" often means "fast to build" in practice). The described constructions are applied in cylindrical vacuum chambers with a horizontal base (the most common). Usually, the feedthrough to which the carousels are mounted performs a rotary motion, and there is a great diversity for its implementation (Frolov et al., 1992).

The PVD technologies are relatively complicated for investigation and modeling. With their spread in the industry, practical tasks often have to be solved. Therefore, the shared experience is important, even if it is not theoretically supported. In this paper, an attempt is made to combine theory and practice, showing some of the problems which the author encountered during his work.

2. DESIGN OF THE PARTICULAR COMPONENTS

Different gears are usually used in the carousels. For their fast and cheap production, a laser cutting is suitable. Using a modern Computer Aided Design (CAD) software, one can easily build the gear tooth profile.

The mainly used gearings are involute and cycloidal lantern. The latter allows one easy construction of a wheel with a large diameter, as the role of rods (teeth) play tubular bushings or screw heads (Fig. 1). Often half of the rods are intentionally not placed, which does not obstruct the normal operation of the gearing. It is desirable to round the tops of the teeth. The center distances have to be increased above the calculated ones because of a gradual accumulation of dust and

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flakes in the mechanisms during the exploitation. Respectively, in order to the gearing be capable to work at larger clearances, gears with large teeth are used (with a high modulus).

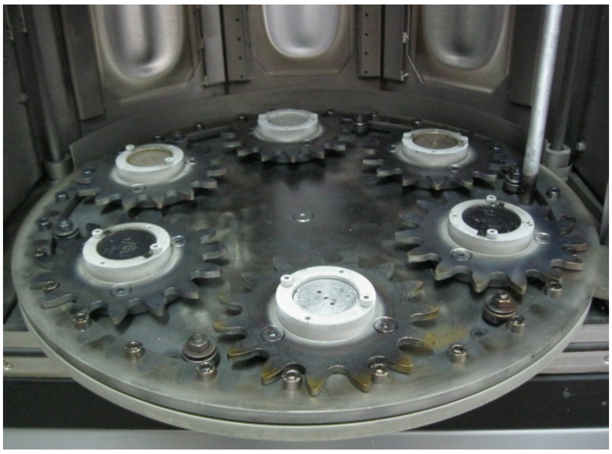

Fig. 1 Cycloidal lantern gearing of a carousel designed for use in equipment HVP100RHD (Milko Angelov Consulting Co.).

The issue of bearing placement in the carousel is of great importance. In general, the weight of the samples loaded into the chamber is not large. The main problem is the high temperature during some PVD processes, as for ordinary bearings the operation above 150 °C is not recommended. Of course, there are bearings which can withstand higher temperatures, but they usually have a ceramic coating or themselves are ceramic. This could be a problem for the conduction of the bias voltage to some elements of the carousel. In addition, such bearings are expensive and more difficult to find.

The experience has shown that the most thermosensitive element of one radial ball bearing is the cage. It is the thinnest and bends easily at higher temperature, blocking the balls and rings (Fig. 2a).

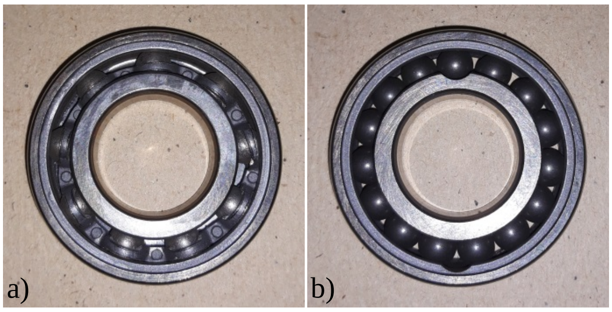

Fig. 2 Radial ball bearing: a) blocked; b) modified (without a cage).

Therefore, at higher temperature (guaranteed up to ca. 300 °C), it is sufficient to use one bearing without a cage. The modification of such a bearing (similar ones are also available for purchase) could be made in the following sequence: the cage is cut, the balls are approached and the rings are disassembled, notches (grooves) are made on them using sinker electrical discharge machining (EDM), the bearing is reassembled. In the last step the balls are inserted through the round hole which is formed by the notches of the inner and outer rings. By reason of the lack of a cage, more balls will be needed than before, so another one bearing has to be broken. A bearing made in this way is shown in Fig. 2b. Such one has to work obligatory horizontally with the notches above to prevent a stall because of the going of balls into the round hole (and possibly falling out).

A problem with the cage could also occur in an angular contact ball bearing. Then one can proceed in the same manner. So, if a bearing with a contact angle of 40° is chosen, then with a precise knock the inner ring is turned out and the bearing is disassembled. The cage is removed (Fig. 3a), balls from another bearing are supplemented and also with a precise knock the inner ring is returned to its original place (Fig. 3b).

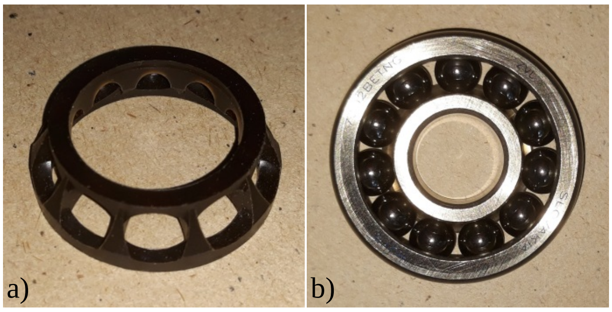

Fig. 3 Angular contact ball bearing: a) cage; b) modified (without a cage).

To remove the cage of a thrust bearing - the procedure is similar to the above mentioned.

It should not be forgotten that all volumes in the structure have to be well related to the chamber's volume - trapped (dead) volumes are not allowed, i.e. - places that retain air (Roth, 1994; Meyer Tool & Mfg., 2010). The latter ones would greatly increase the pumping time, especially to a higher vacuum. Channels have to be made to loose them (Fig. 4).

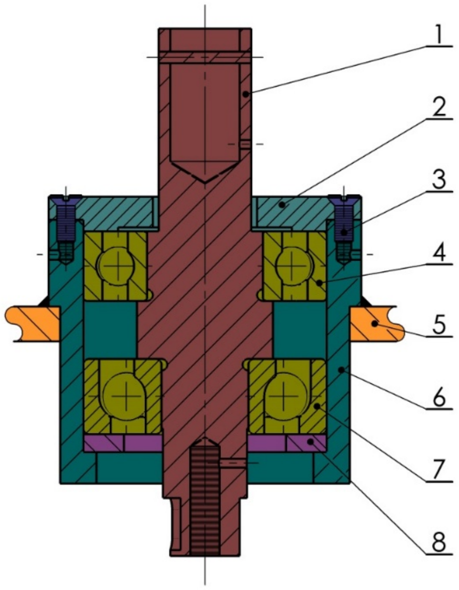

Fig. 4 Section of one fragment of a carousel designed for use in a VAD equipment (CLAP-BAS): 1-support shaft; 2-cap; 3-screw; 4-radial bearing; 5-rotating central plate; 6-nest; 7-angular contact bearing; 8-washer.

Here, such channels are in the support shaft 1 (above for pumping the volume under the inserted rod and below for pumping the internal thread). For a similar reason, there are such ones in the nest 6.

In general, the occurrence of trapped volumes is a normal phenomenon when screwing into blind holes. When making channels to the internal threads is not convenient enough, two solutions have been adopted for preparation of the screws (Fig. 5). The first is somewhat easier for doing, but it affects the thread (Fig. 5a). The second is difficult to apply to threads of small diameter and large length (Fig. 5b).

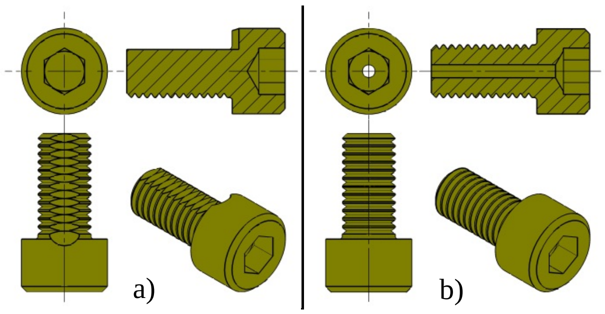

Fig. 5 Screws that prevent the formation of trapped volumes: a) by a lateral duct; b) by a central hole.

It is not recommended that the elements which are involved in the threaded joint, to be of the same material, e.g. stainless steel (one commonly used material in vacuum technology, in particular - for carousels). Then, at high temperature and/or prolonged exploitation, the threaded joint could become self-glued and its disassembling could be very problematic. It is highly desirable to use a suitable lubricant (Dow Corning Corporation, 1998). A deposition of coating on the screws, including silver plating, is also practiced.

3. GEOMETRIC CALCULATIONS

The main consideration when constructing carousels is usually the placement of the maximum number of samples in the vacuum chamber and their processing for one duty cycle, respectively.

This usually requires more axes of rotation, i.e. - creation of planetary 3-axis or even 4-axis carousels (in case of very small samples to place in a very large chamber). Since PVD is essentially a line-of-sight process, increasing the number of axes requires more time for all samples to pass close to the target and to obtain a thick enough layer on them, respectively. But, in general, the small increment of time is paid off by the increased number of samples. One program which calculates the maximum number of samples and gives the geometric dimensions of the carousel is presented in (Pashinski, 2013).

4. REAL MULTI-AXIAL MOTION

Carousels of this type have a constant kinematic connection between the components. The rotation on all axes is performed simultaneously (Fig. 6). Usually these carousels (their chassis) can rotate in the both directions.

Fig. 6 Mixed batch: the upper level performs 2-axis and the lower - 3-axis rotation in equipment π80+ (Platit AG).

Once the carousel geometry has been estimated (par. 3) - pitch circle diameters and numbers of rotation satellites (nests and samples), it is time for the real design. Thus, one interesting moment arises here.

Even assuming that the already mentioned geometrical parameters are known, they themselves do not firmly determine the gear ratios in the mechanism, although they create some range for them. In a nutshell, with a given carousel geometry, it have to be decided exactly what gear ratios to have it.

The gear ratios do not depend on the angular velocity of the carousel, but only on the number of teeth of the gears - in general, these ratios are set in the designed mechanism and they are difficult to adjusting and correction in the future (after the carousel was produced). Therefore, they have to be chosen carefully.

There is lack of direct information about choosing of gear ratios, to the best of author's knowledge. There are publications and manuals which report information on the available gear ratios of the carousel being operated, but not why such values for them were chosen. Several carousel constructions were studied to see if there exists any dependence on the applied gear ratios (it should be emphasized that they depend somewhat on the geometrical parameters mentioned above). Only one of the studied constructions is shown in details here because of the observations of the others confirm the conclusions which were obtained during its investigation.

Fig. 7 depicts the kinematic scheme of a planetary mechanism with 3 axes of rotation (it could also be seen in Fig. 6 - on the left of the lower level). There are shown the positions of the nest (socket) and the sample after one consecutive revolution of the feedthrough (actuator) - of the plate 1, respectively. To determine these positions, the angular velocities of the satellite socket and the sample were initially calculated using the Willis method.

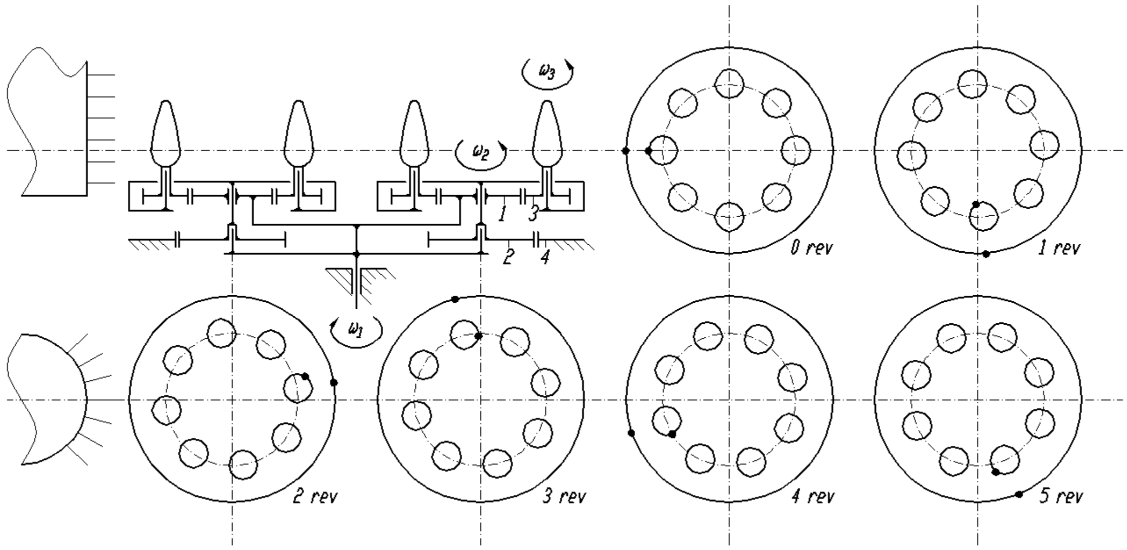

Fig. 7 Kinematic scheme and periodic rotation of a 3-axis carousel used conventionally in equipment π80+ (Platit AG): 1-plate with immobilized sun gears (its revolutions are indicated); 2-satellite socket; 3- sample; 4-casing (vacuum chamber).

For the first stage (rotation of the satellite socket) the link 1 is assumed to be the carrier, i.e.: $\omega_1 = \omega_H$. Hereinafter: ω - angular velocity, z - number of teeth. Then:

$$\frac{\omega_4 - \omega_{1(H)}}{\omega_2 - \omega_{1(H)}} = \frac{z_2}{z_4} \Rightarrow \frac{0 - \omega_1}{\omega_2 - \omega_1} = \frac{z_2}{z_4}$$

$$\therefore \omega_2 = \frac{z_2 - z_4}{z_2}\omega_1 \qquad (1)$$

For the second stage (rotation of the sample) the link 2 is assumed to be the carrier, i.e.: $\omega_2 = \omega_H$. Then, using (1):

$$\frac{\omega_1-\omega_{2(H)}}{\omega_3-\omega_{2(H)}}=-\frac{z_3}{z_1}\Rightarrow\frac{\omega_1-\omega_1\dfrac{z_2-z_4}{z_2}}{\omega_3-\omega_1\dfrac{z_2-z_4}{z_2}}=-\frac{z_3}{z_1}$$

$$\therefore\omega_3=\frac{z_2.z_3-z_1.z_4-z_3.z_4}{z_2.z_3}\omega_1 \qquad (2)$$

The mechanism of Fig. 7 includes wheels with following number of teeth: $z_1=29$, $z_2=19$, $z_3=17$, $z_4=62$ (actually, z_1 is 31, but the gearing is through a tooth – see the beginning of par. 2).

Then, for the angular velocities of the satellite socket and the sample, one can obtain by (1) and (2):

$$\omega_2=\frac{19-62}{19}\omega_1=-2,263\omega_1$$

$$\omega_3=\frac{19.17-29.62-17.62}{19.17}\omega_1=-7,830\omega_1$$

The proportional ratio of the angular velocities is the same as of the revolutions. For example, at 1 revolution of the plate (actuator) 1, the satellite socket 2 will do 2,263 revolutions in the opposite direction. All this is shown in Fig. 7 and it is verified practically.

It is obvious that one clear principle about the gear ratios do not exist. It is only noticeable that the satellite socket and the sample stand in completely different positions after each revolution of the plate. By itself, the last is not an insignificant consideration and guarantees certain equality between the samples as they pass near the target. So, if any rule could be formulated, it is definitely this one and it has been observed in the other studied carousels (a total of four from machines by different manufacturers).

The passage of the samples along the targets is directly related to the properties of more complex coatings (f.e., nanolaminate ones) (Veprek & Veprek-Heijman, 2008). It is significant that when the carousel movement is more chaotic then the finer nanolaminate structure is obtained and the mechanical properties is also improved. (Panjan et al., 2012; Roa et al., 2014; Kroker et al., 2019).

Fig. 8 displays the kinematic scheme of other planetary mechanism with 3 axes of rotation where the samples are hung. Despite the design differences, the kinematic schemes are very close and the dependencies used for the angular velocities are exactly the same.

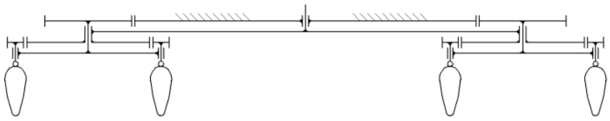

Fig. 8 Kinematic scheme of a 3-axis carousel used conventionally in equipment ВУ-700Д (ОАО "СЗОС").

It is prudent, especially when the processed specimens vary geometrically in some range, to provide a modular construction which allows geometric changes. A modular carousel for hanging of vials is shown in Fig. 9.

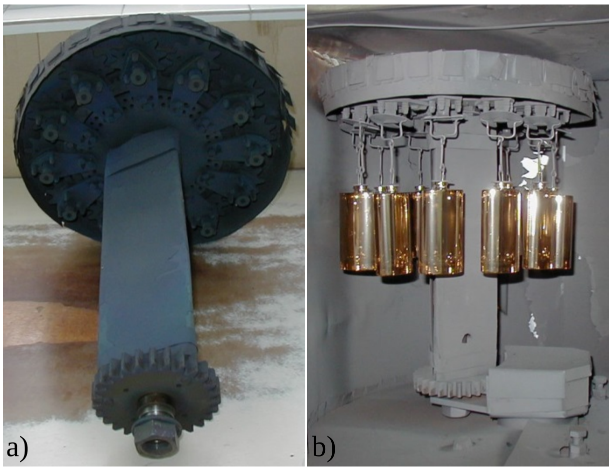

Fig. 9 Modular 2-axis carousel which allows changing of the number of satellite sockets designed for use in equipment ВУ-1БС (ОАО "СЗОС"): a) overall view; b) mounted in the vacuum chamber and loaded with samples.

It can be adjusted according to the vial's geometry so as to collect the maximum amount in the working chamber.

5. PSEUDO MULTI-AXIAL MOTION

Carousels of this type do not have a constant kinematic connection between the components. One simple solution is to use a kicker (with ratchet wheel) to discreetly turn the samples (Fig. 10).

Such mechanisms are easy to implement, the actuator is less loaded (the energy consumption is less resp.), but they have one major drawback - the samples are rotated relatively slowly in the working chamber (in front of the target resp.). In addition, the rotation angle of the samples somewhat depends on the pressure of the kicker upon the ratchet wheel and even on the mass of the samples. Last but not least, there is an intense wear in the area of mechanical contact.

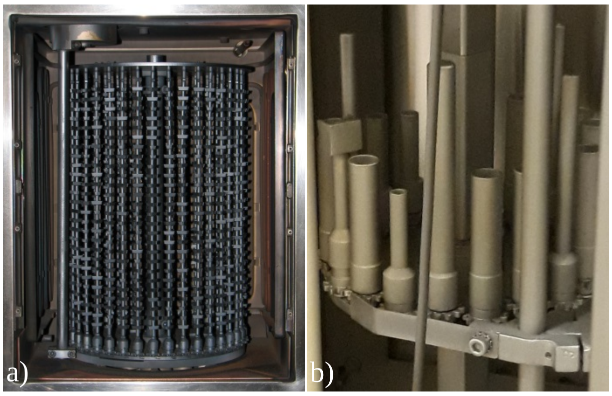

Fig. 10 Carousel with a kicker - designed for use in equipment: a) π80+ (Platit AG) - 2-axis; b) UDP850/4 (Teer Coatings Ltd) - 3-axis (fragment).

6. CONCLUSIONS

The nature of PVD processes has a strong influence on the carousel construction and general engineering knowledge is not always sufficient for a good design. Some basic guidelines were briefly presented which would be useful mostly for specialists who are practically engaged in the coating deposition industry. However, researchers who want to redesign their existing equipment could also appreciate the presented information.

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