Using the principles of axiomatic design in the development of bushing manufacturing technology

L Slatineanu¹, O Dodun², G Naţî³, P Duşa⁴, M Coteaţă⁵, A Hriţuc⁶, D Luca⁷, and I Carp⁸

¹, ², ³, ⁴, ⁷Professor, “Gheorghe Asachi” Technical University of Iaşi, RO  
²Lecturer, “Gheorghe Asachi” Technical University of Iaşi, RO  
⁶Ph.D.student, “Gheorghe Asachi” Technical University of Iaşi, RO  
⁸Ph.D. Engineer, “Gheorghe Asachi” Technical University of Iaşi, RO

E-mail: hrituc.adelina3295@yahoo.com

Abstract. There are different types of bushings used in mechanical equipment and they can be used for different purposes. In the case of bronze bushings used to ensure rotation conditions of shaft-type parts, there are some difficulties in addressing the problem of their manufacture. In essence, in order to meet the machining accuracy requirements specific to the outer and inner revolution surfaces, appropriate manufacturing technologies must be established. Some distinct technological paths can be considered for machining and checking the outer and inner cylindrical surfaces of bushings. In solving certain problems specific to the development of bushing manufacturing technologies, the principles of axiomatic design were used. Thus, the axiom of the independence of the functional requirements was used preferentially in establishing the machining operations to be applied to the workpiece to obtain a bushing. The second axiom was applied to identify the best solutions for the machining of the inner revolution surface. In this way, more convenient manufacturing technology for bronze bushings was identified.

1. Introduction

The bushings are mechanical parts that have coaxial inner and outer revolution surfaces. These revolution surfaces could be essential cylindrical and conical, but also there are other types of surfaces (toroidal, spherical, etc.). Various criteria could be used to classify the bushings [1]. Thus, if the outer surface shape is analyzed, there are smooth bushings and step bushings. The steps could have diameters decreasing on one side or decreasing on both sides.

The bushings are used to support the shafts or other parts found in rotational motion (pinions, cams, etc.). Two surfaces of the bushings have an essential role. Thus, an inner revolution surface takes contact with the journals of the part found in rotation motion. The outer revolution surface is used to fix the bearing bush in a housing. The two surfaces mentioned above are generally characterized by a high accuracy and a low roughness. Usually, the outer surface used in fixing the bearing bush in the housing has an accuracy that corresponds to the tolerance classes 7-8 and a surface average roughness $Ra=1.6 \ \mu m$. On the other hand, the inner revolution surfaces used to support the shaft journal must be achieved in the tolerance classes 6-8 and has a surface average roughness $Ra=0.8 \ \mu m$. 
As materials for bearing bushings, the bronzes, cast irons, steels, plastics could be used. In the machine manufacturing, the most used material for bearing bushings seems to be certain types of bronzes that are characterized by low values of the friction coefficient.

An investigation by Morozov et al. showed that the presence of lead in the material of bronze bushings with tin, zinc and lead results in such an arrangement of lead on the movable contact surface that the pressure is reduced (by increasing the contact surface) and the coefficient of friction decreases \[2\]. In the end, this means an increase in the durability of the mobile joint.

The manufacture and modelling of the operating behavior of hybrid aluminum and steel bushings by successive plastic deformation processes were investigated by Behrens et al. [3-5].

An experimental research on the behavior of a zirconium ceramic bushing was performed on a universal friction machine by Alisin [6]. This research allowed the development of a procedure for the evaluation of the reliability and service life of the bushings made of indicated material.

The objective of the research presented in this paper was to find some solutions for particular aspects of the manufacturing of bearing bushings using the axiomatic design principles.

2. Analysis of information provided by the mechanical drawing of the bronze bushing and the technological solutions that can be used to obtain it

An example of mechanical drawing of a bronze bearing bushing can be seen in figure 1. The part had to be made by the students during the practical activities developed in a school workshop that worked in the Faculty of Mechanics from the “Gheorghe Asachi” University of Iaşi – Romania. The part material was an antifriction bronze. As workpieces, tubes achieved by casting were used.

Analyzing the existing information in the mechanical design of the bearing bushing, it was concluded that they were sufficient to proceed to the development of a bushing manufacturing technology, by taking into account the machine tools, jigs, fixtures and tools available, the number of parts to be manufactured, the level of qualification of the operators (students coordinated by foremen) and other conditions specific to the workshop in which these bushings were to be manufactured.

After the analysis of the initial conditions that correspond to the bearing bushing proposed to be manufactured, it also concluded that the main groups of manufacturing phases could be:

1. Machining of the outer surfaces in two distinct phases (roughing and finishing);
2. Machining of the inner surfaces also in two distinct phases, roughing and finishing;
3. Machining of the bushing frontal flat surfaces;
4. Machining of the grease groove.

3. The use of the first axiom to define the technologies for the manufacture of bushings

To apply the first axiom from the axiomatic design, a normal sequence of manufacturing stages has been completed.
If we take into consideration only the process of designing the technology of manufacturing the bearing bushings, as first customer the representatives of an office for organizing the manufacturing process could be considered. These representatives must ensure the providing of the workpieces, jigs, fixtures, and devices, transmit the technological documentation to the manufacturing workshop coordinators etc. As customer need directed to the office of designers of manufacturing processes, it can consider:

*CN*: develop the manufacturing technology to obtain 1000 bearing bushings, in accordance with the information found in the mechanical drawing and the available processing conditions.

In this way, the functional requirement of zero order could be:

*FR0*: design the technological process of manufacturing 1000 bearing bushings following the mechanical drawing and the endowment of the manufacturing workshop.

The functional requirements of first order could have the following shape:

*FR1*: Analyze the mechanical drawing of the bearing bush;

*FR2*: Verify the part manufacturability;

*FR3*: Establish the type of workpiece for manufacturing the bushings;

*FR4*: Establish the technological itinerary (the succession of operations and phases);

*FR5*: Determine the values of the machining allowances and intermediate dimensions;

*FR6*: Establish the values of the operating parameters;

*FR7*: Calculate the operation time;

*FR8*: Evaluate the manufacturing process efficiency;

*FR9*: Complete the technological documentation.

Because the mechanical design was developed in a design office where engineers with extended experience were working and there were inclusively standards referring to the design of bearing bushings [6,7], it has considered that the mechanical drawing is complete and ensures the information necessary to pass to the next stage. On the other hand, similar arguments were considered to evaluate the bush manufacturability. In fact, it has noticed later, some less convenient aspects concerning the bush manufacturability were observed when the problem of establishing the technological itinerary was approached.

As mentioned above, a tubular workpiece obtained by casting was taken into consideration. The selection was evaluated as convenient since the chips obtained during the machining process and eventually wrong parts could be recasted just in a metallurgical workshop existing also in the university.

In this way, the fourth functional requirement was approached.

As functional requirements of second order, it was considered:

*FR4.1*: Establish how to get the revolution and flat surfaces;
FR4.2: Establish how to get the grease groove;
FR4.3: Establish how to control the part from the technical point of view;
FR4.4: Establish how to prepare the machined parts for transport to the beneficiary;
The considered functional requirements of third order could be the following:
  FR4.1.1: Establish how to get the flat surface;
  FR4.1.2: Establish how to get a rough outer cylindrical surface;
  FR4.1.3: Establish how to get a finish outer cylindrical surface;
  FR4.1.4: Establish how to get the conical surfaces of the outer cylindrical surface, at the right end of the tube;
  FR4.1.5: Establish how to get the rough inner cylindrical surface;
  FR4.1.6: Establish how to get the finish inner cylindrical surface;
  FR4.1.7: Establish how to get the conical surface at the inner cylindrical surface, at the right end of the tube;
  FR4.1.8: Establish how to cut the part from the tube type workpiece;
  FR4.1.9: Establish how to get the flat surface at the left end of the detached bushing;
  FR4.1.10: Establish how to get the conical surfaces of the outer cylindrical surface, at the left end of the part;
  FR4.1.11: Establish how to get the conical surfaces of the inner cylindrical surface, at the left end of the part;
  FR4.2: Establish how to get the longitudinal grease groove;
  FR4.3: Establish how to control of the machined part from technical point of view;
  FR4.4: Establish how prepare the machined parts for transport to the beneficiary.

Using the zigzag process, design parameters appropriate to the functional requirements were identified.

Thus, the general design matrix of the bearing bushes manufacturing process is presented in table 1. It can be observed a decoupled design, the result being a diagonal matrix.

Some particular solutions of identifying the design parameters in the case of functional requirement FR4 can be seen in table 2. In the decomposition and zigzagging process, it was observed that turning the flat surface at the right end of the bush and the straight turning of the outer cylindrical surface can be made using the same lathe tool. Also, the same tool can be used both for finishing the outer cylindrical surface and for chamfering the outer cylindrical surface at the right end of the bearing bush. The lathe tool used for boring contributes both to the finishing turning of the inner cylindrical surface and to the chamfering of the inner cylindrical surface at the right end.

After cutting the part from tube type workpiece, the tool used for flat turning also provides conditions for chamfering the outer cylindrical surface at the left end of the bearing bush in the mechanical drawing.

Under the above conditions, it is found that a triangular design matrix is obtained, as some lathe tools are used to meet several functional requirements.

It was necessary to solve some technological difficulties for the realization of grease groove. The initial variants of machining processes considered either did not ensure a sufficiently high productivity (e.g., use of electrical discharge machining) or it was not possible to use them under normal conditions (slotting or broaching). A solution was identified based on the use of an end mill, which does not ensure the realization of flat front surfaces at both ends of the grease groove. However, given the acceptable productivity of the process and with the consent of the beneficiary, it was preferred to end mill processing located, during machining process, in an inclined position relative to the symmetry axis of the bearing bush.
Table 1. General design matrix.

| Line no. | Design parameters | Design parameters |
|----------|-------------------|-------------------|
| 2        | Design parameters of zero order | Design parameters of the second order |
| 3        | DP0: Checks performed and documentation completed | DP1: Verified mechanical drawing |
| 4        | DP2: Verified part manufacturability | DP3: Established technological itinerary |
| 5        | DP4: Determined values of the machining allowances and intermediate dimensions | DP5: Determined values for the operating parameters |
|          | DP6: Calculated operation time | DP7: Evaluated manufacturing process efficiency |
|          | DP8: Evaluated manufacturing process efficiency | DP9: Completed technological documentation |

Functional requirements

| Column no. 1 | Functional requirement of the zero order | Functional requirements of the first level |
|--------------|-----------------------------------------|------------------------------------------|
| 2            | FR1: Analyze the mechanical drawing of the bearing bush | X |
| 3            | FR2: Verify the part manufacturability | X |
| 4            | FR3: Establish the type of workpiece for manufacturing the bushings | X |
| 5            | FR4: Establish the technological itinerary | X |
| 6            | FR5: Determine the values of the machining allowances and intermediate dimensions | X |
| 7            | FR6: Establish the values of the operating parameters | X |
| 8            | FR7: Calculate the operation time | X |
| 9            | FR8: Evaluate the manufacturing process efficiency | X |
| 10           | FR9: Complete the technological documentation | X |
Table 2. Design matrix for the functional requirement FR4.

| Line no. | Design parameters | Functional requirements | Design parameters of second order for the functional requirement FR4 |
|----------|-------------------|-------------------------|---------------------------------------------------------------|
| 2        |                   | DP4.1: Lathe            | DP4. 1.1: Establish how to get the flat surface              |
| 3        |                   | DP4.1.2: Establish how to get a rough outer cylindrical surface |
| 4        |                   | DP4.1.3: Establish how to get a finish outer cylindrical surface |
| 5        |                   | DP4.1.4: Establish how to get the conical surfaces of the outer cylindrical surface, at the right end of the tube |
| 6        |                   | DP4.1.5: Establish how to get the rough inner cylindrical surface |
| 7        |                   | X                       | Design parameter DP that corresponds to each functional requirement |
| 8        |                   | X                       |                                                             |
| 9        |                   | X                       |                                                             |
| 10       |                   | X                       |                                                             |
| 11       |                   | X                       |                                                             |
| 12       |                   | X                       |                                                             |
| 13 | FR4.1.6: Establish how to get the finish inner cylindrical surface | X |
| 14 | FR4.1.7: Establish how to get the conical surface at the inner cylindrical surface, at the right end of the tube | X |
| 15 | FR4.1.8: Establish how to cut the part from the tube type workpiece | X |
| 16 | FR4.1.9: Establish how to get the flat surface at the left end of the detached bushing | X |
| 17 | FR4.1.10: Establish how to get the conical surfaces of the outer cylindrical surface, at the left end of the part | X |
| 18 | FR4.1.11: Establish how to get the conical surfaces of the inner cylindrical surface, at the left end of the part | X |
| 19 | FR4.2: Establish how to get the grease groove | X |
| 20 | FR4.3: Establish how to control the part from the technical point of view | X |
| 21 | FR4.4: Establish how to prepare the | X |
4. Using the second axiom to select the alternative usable for finishing the inner cylindrical surface

According to the information found in the part mechanical drawing, the inner surface must have a diameter $\Phi 40 \ E7 +0.075$ $\pm 0.050$. This means that the maximum size will be 40.075, the minimum 40.050 mm, and the size corresponding to the middle of the tolerance field will be 40.0625 mm.

A grinding operation cannot be used, due to the risk of clogging the abrasive tool with chips detached from the workpiece material (bronze). The following versions of finishing the inner surface of the bearing bush were taken into consideration:

1. Finishing turning in the usual conditions offered by the universal lathe, so without the use of work devices that ensure the increase of the accuracy of adjusting the position of the lathe tool tip to the working dimension. The machining will be performed by the method of test chips, which means a succession of measurements and successive machining sequences, until obtaining a diameter of the processed surface in the tolerance field. The size of the division that can be observed and used by the operator to adjust the radial position of the lathe tool tip when moving the transverse slide is 0.05 mm. The various corrections of the position of the tool tip will be affected also by the subjectivity of the lathe operator in the appreciation of some fractions of the distance between two divisions that correspond to an advancement of the transverse slide by 0.05 mm. Usually, the lathe operator shows a tendency to overlap the adjustment position of the lathe tool tip with the middle of the prescribed tolerance field. It is expected, as such, that the distribution of the diameters of the inner surfaces of parts is carried out in accordance with a Gaussian distribution, but with a fairly large distribution field, due to the use of the scale with the division of 0.05 mm. Such a distribution corresponds, in fact, to tolerance class 9 (class usually appreciated as achievable by finishing turning). Taking into account a dispersion field corresponding to this class ($T = 0.039$ mm) and the value corresponding to the middle of the tolerance field prescribed on the mechanical drawing (valid for tolerance class $E7$), we find that the actual dimensions should be between a minimum value of

$$40.0625 - (1/2) \cdot 0.062 = 40.0625 - 0.031 = 40.0315 \text{ mm}$$

and a maximum value

$$40.0625 + (1/2) \cdot 0.062 = 40.0625 + 0.031 = 40.0935 \text{ mm}.$$ (3.2)

The Gaussian distribution function (which provides information on obtaining a certain dimension between certain values, so on the probability of having a dimension in a predetermined range) is as follows:

$$P = \frac{1}{\sigma \sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{(x-M(x))^2}{2\sigma^2}} dx,$$

where $x$ is the diameter of the processed surface, $\sigma$- the standard deviation, and $M(x)$ - the arithmetic mean of the measured values.

Taking into account the values valid in the analyzed case, we will have:

$$P = \frac{1}{\sigma \sqrt{2\pi}} \int_{40.0315}^{40.0935} e^{-\frac{(x-40.0625)^2}{2\sigma^2}} dx.$$ (3.4)

Determining with the help of statistical calculation tables the proportion of the number of diameters achievable by ordinary finishing turning (i.e., with a tolerance field corresponding to tolerance class 9), but within a dimensional range corresponding to class 7, we find that the probability is 77.2% according to what will be shown later.
2. The second version of finishing turning could consider the use of a device using a dial gauge with a value between two divisions of 0.001 mm to adjust the position of the lathe tool tip at the finishing passes necessary to obtain the inner surface by the trial chip method. This device can be mounted on the guide of the transverse slide of the lathe (figure 2), in order to be able to obtain more precise information regarding the movement of the transverse slide, together with the tip of lathe tool, when adjusting the position of tip of the inner turning lathe tool.

It can be appreciated that the use of the dial gauge with a division of 0.001 mm will result in an increase in machining accuracy, and it is possible to achieve tolerances corresponding to tolerance class 8. If this tolerance class 8 corresponds to a tolerance field $T = 0.039$ mm arranged symmetrically in relation to the mean size to be obtained according to the mechanical drawing ($\phi 40.0625$), it means that the minimum size of the new distribution field could be:

$$40.0625 - (1/2) \cdot 0.039 = 40.0625 - 0.0195 = 40.0430 \text{ mm} \quad (3.5)$$

and the maximum size could be:

$$40.0625 + (1/2) \cdot 0.039) = 40.0625 + 0.0195) = 40.0820 \text{ mm}. \quad (3.6)$$

Determining the probability of having dimensions within the prescribed tolerance field (figure 3) will lead to:

$$P_B = \frac{1}{\sigma \sqrt{2\pi}} \int_{\phi 40.0430}^{\phi 40.0820} e^{\frac{-(x-40.0625)^2}{2\sigma^2}} dx. \quad (3.7)$$

Assuming that we could obtain an accuracy of the dimensions corresponding to class 8 (which means a dispersion field of 0.039 mm, but arranged around the average size $\phi 40.0625$) and using the tables that provide the values of the Laplace function, we arrive at:

$$P_B = 2 \phi \left( \frac{40.082}{\sigma 40.0430} \right) = 2 \cdot 0.472 = 0.944, \quad (3.8)$$

dealing with a value $u = 1.923$, for a standard deviation:

$$\sigma = \frac{0.039}{6} = 0.065. \quad (3.9)$$

This means that there is a 94.4% probability of obtaining machined surface diameters within the prescribed tolerance field or that about 5.6% of the diameters will not fall within the prescribed tolerance field.

In reality, however, even when using the devices to increase the machining accuracy by finish turning on the available universal lathe, it is difficult to obtain a tolerance field corresponding to tolerance class 8 and the actual dispersion is expected to correspond to class 9 (which will correspond to a
tolerance/distribution field of 0.062 mm, i.e., between the dimensions 40.0315 mm and 40.0935 mm). In this way, we will reach:

$$P_9 = 2 \int_0^{u=40.0935} (u) = 2 \cdot 0.386 = 0.772,$$

in the calculation using a value $u = 1.21$, for a standard deviation

$$\sigma = 0.062/6 = 0.0103 \text{ mm}.$$  

(3.10) (3.11)

This means a probability of obtaining diameters within the tolerance field of 77.2% or a risk that 22.8% of the diameters will not fall within the prescribed tolerance range.

3. The third version could involve the use of both the device which includes the dial gauge and a go plug gauge to detect the moment when, by successively removing layers of material from the tubular workpiece, the diameter of the machined surface becomes slightly larger than the prescribed minimum diameter. It is obvious that the new dispersion field will be framed between the minimum size corresponding to the prescription on the mechanical drawing ($\phi 40.050$) and a maximum size that takes into account a tolerance field specific to tolerance class 8 (due to the use of the dial gauge: $40.050 + 0.39 = 40.089$ mm). According to the information in the literature [1], due to the use of plug gauge go and the tendency of the lathe operator to stop machining as soon as it has obtained a size larger than the minimum diameter, there is a probability that the surface diameter will fall in the prescribed tolerance field and we will no longer have a dispersion corresponding to the model constituted by the Gaussian curve. Now, we will have to consider a Maxwell-Boltzmann distribution (figure 4), which is characterized by a certain degree of asymmetry. The mathematical relation corresponding to a distribution function (probability) of the Maxwell-Boltzmann distribution has the form:

$$P = \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{\sqrt{2a}}} e^{-x^2} dx - \frac{2}{\sqrt{\pi}} \cdot \frac{x e^{-x^2}/(2a^2)}{a},$$

(3.12)

where $a = 1$ or $a = 2$.

As can be seen in figure 4, outside the prescribed tolerance field ($40.050$ mm – $40.075$ mm) will remain the parts in which the diameters of the inner surfaces are in the field ($40.075$ mm – $40.089$ mm). Accepting a value $a = 2$, and using a method of graphically approximating the size of the surface between the curve corresponding to the Maxwell-Boltzmann distribution and the abscissa axis, it was found that the interval ($40.075$-$40.089$) will correspond to a percentage of 7.9% of the entire surface located between the curve and the abscissa axis in the field ($40.050$-$40.089$), which means that 7.9% of the parts will have dimensions outside the prescribed tolerance field.

![Figure 4](image)

**Figure 4.** Maxwell-Boltzmann distribution valid when using a smooth plug gauge go.

Summarizing the above considerations, by using the device that includes a dial gauge to increase machining accuracy, we will have a 77.2% probability of obtaining diameters of machined surfaces within the prescribed tolerance range. However, if the device including the dial gauge and the check of machined surfaces with that plug gauge go is used, the probability of obtaining diameters within the prescribed tolerance range reaches 92.1%.
Referring to the second axiom of axiomatic design, it is obvious that for the finishing of the inner surface in the bushing will be preferred the version that provides the use of the device with dial gauge and a plug gauge go to check the acceptability of the bushing if the tolerance field of the hole diameter is taken into account.

5. Conclusions

Bearing bushings are parts used in industrial practice to support rotating shafts. These bushings can be obtained by applying various manufacturing processes. Such a process may be, for example, based in principle on turning pipe-shaped blanks. To establish the sequence of processing operations, axiom I of axiomatic design was used. In this respect, different design parameters were taken into account to meet the functional requirements. On the other hand, it has been found that even for obtaining a certain surface by turning, different processes can be used, if the needs of reaching the machining accuracy established by the indications on the mechanical drawing of a bearing bush are taken into account. To select the most convenient procedure, the second axiom of axiomatic design was used. As such, a machining process has been adopted that offers the highest probability of obtaining hole diameters within the prescribed tolerance field. In this way, the process that is most convenient for machining the surface of the bushing hole was identified, by taking into account the propermachining conditions. The selected procedure is based on the use of a device incorporating a dial gauge to increase the accuracy of adjusting the position of the tool tip to the working size and a plug gauge go for testing the diameter of the machined hole. In the future, it is intended to analyze the possibilities of using the second axiom for selecting machining processes for other bushing surfaces, when several such processes can be used to obtain a certain surface.

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