Effect of heat treatment of beryllium bronzes on the quality of critical engineering parts

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Abstract. The paper considers the peculiarities of thermal hardening of beryllium bronzes (Cu + 2% Be) and the feasibility of stepwise aging on BrB2 alloy parts with different requirements for their geometry. The factors determining the occurrence of stresses in beryllium bronzes parts are described. Attention is drawn to the fact that stepwise aging does not help to straighten the details as it happens during aging in special devices. Studies have shown that for cylindrical parts, when controlling deviations in straightness, stepwise aging minimizes warpage even during heat treatment without special devices. For flat parts with stringent geometry requirements, the processing of which is carried out in devices, dispersion hardening in a free state is not acceptable. For parts made of BrB2 alloy, heat treatment of which is not economically feasible in devices, but the geometry is significant, it is recommended to introduce an operation to “relieve stress” at a temperature of 210±5°C for one hour (step aging) before the operation "dispersion hardening", that will minimize distortion during heat treatment without the use of special devices. It is shown that in each particular case, analysis is necessary on the feasibility of using staged aging, since in some cases its use can lead to a more expensive process without a significant effect in terms of reducing warpage of parts.

1. Introduction
Copper-based alloys are widely used as functional and structural materials [1]. At the same time, Cu-Be alloys are characterized by an attractive combination of performance properties, such as corrosion resistance, fatigue endurance, electric conductivity, etc. [2]. In addition, these alloys are characterized by a wide range of achievable level of mechanical properties, which can be controlled by selecting optimal conditions and conditions of thermal and thermomechanical processing [3-6]. As is known, a characteristic feature of beryllium bronzes is the variable beryllium in copper, which decreases with decreasing temperature, i.e. they are dispersion hardened alloys; therefore, their thermal hardening is possible [7-11].

During the heat treatment of elastic elements from beryllium bronzes, significant stresses arise, which causes deformation (warping) during the heat treatment itself and cause instability of the size and shape of the products during operation. This complicates the heat treatment technology, since the problem is solved by the use of devices during aging after hardening, in which parts are usually manually fixed [12, 13]. Stress relaxation during aging ensures the stability of the product configuration [14, 15].
One of the factors determining the occurrence of stresses is the difference in the intensity of volumetric changes in the surface and middle layers of the part already during the heat treatment [16-19]. This heterogeneity also affects the decomposition of the solid solution during aging, which is accompanied by a significant volumetric effect, even if the part has a small thickness. In the middle layers of the section of parts in which no structural changes occurred during hardening, the decay process will develop with some delay and with less intensity.

In [20], the effect on the level of residual stresses of the surface state is noted. The authors present data that aging of BrB2 beryllium bronze in vacuum at 340 °C for 20 h leads to the appearance of residual tensile stresses in the surface layers of $a = 32$ N/mm$^2$. And under conditions of strong oxidation during aging in a furnace without a protective atmosphere, the magnitude and sign of the residual stresses change. Residual compressive stresses (rather than tensile ones) arise in the surface layers. The authors explain this by the difference in the beryllium content in the surface layer and in the middle of the part.

As a solution to the problem of deformation of parts, the following options are proposed:
- plating on parts before dispersion hardening;
- carrying out low-temperature stress relief (210 °C for 1 hour until dispersion hardening at 320 °C for 3 hours).

Since most of the BrB2 alloy parts are coated in their final form, the protective layer applied before aging can significantly reduce the surface quality of the finished parts, a decision was made to test the stepwise aging mode.

The purpose of the research was to determine the feasibility of stepwise aging on BrB2 alloy parts with different requirements for their geometry.

2. Methods
The object of the study was the BrB2 alloy parts according to the nomenclature of the V.A. Degtyarev Plant: "Piston", "Terminal" and "Ring". A piston is a cylindrical type part, made of a bar $\Phi$10 mm. Maximum dimensions of the part: diameter 8 mm, length 34.6 mm. The terminal is a flat part, the section of which has an angle of inclination. The maximum dimensions of this part are $14.6 \times 8 \times 0.2$ mm. The ring is made by deformation along a given contour of the tape with a thickness of 0.5 mm, the maximum size is 23.5 mm. The above details were subjected to heat treatment in vacuum electric resistance furnace according to the accepted factory technology (Table 1) and proposed technology.

| Material  | Heat treatment       | Purpose of heat treatment                  | Mode of heat treatment |
|-----------|----------------------|--------------------------------------------|------------------------|
| BrB2 (Cu + 2% Be) | Dispersion hardening | Obtaining the necessary strength characteristics during the decay of the $\alpha$-solution | 300-350 °C for 2 hours |

Hardness measurement was carried out on universal hardness testers according to the Vickers method. Visual control and monitoring was carried out using special calibres.

3. Results and Discussion
The "Piston" type part is made of a bar $\Phi$10 mm. When the aging operation was performed according to the standard mode (see Table 1), visual control observed a deviation from straightness. The specified heat treatment process did not involve the use of devices. Bad parts are being corrected or rejected. Table 2 shows the piece withdrawal of parts according to the specified geometric parameter when performing the aging operation immediately after machining and when performing stepwise aging.
Table 2. Results of measurements of the geometry of the "Piston" type parts

| Pre-treatment | Amount of parts | Total amount of parts in batch | Hardness, HV |
|---------------|-----------------|-------------------------------|--------------|
|               | Accepted        | Refused                       |              |
| With preliminary heat treatment | 197            | 3                             | 200          | 395          |
| Without preliminary heat treatment | 136           | 64                            | 200          | 420          |

The hardness of parts after a standard aging operation and after step aging is measured on witness samples and satisfies the requirements of the design documentation in both cases (HV > 330). Studies have shown that for cylindrical parts, when controlling deviations in straightness, stepwise aging minimizes warpage even during heat treatment without special devices.

The “Terminal” type part is made of 0.2 mm tape. The design of this part has rather stringent requirements for geometry, in particular for the angle of inclination of the “antennae” of the terminal. The standard mode of heat treatment of these parts provides for the operation “aging” in devices. After heat treatment, control is provided for the angle of the calibres. The pilot batches carried out input control. Heat treatment was carried out according to a regular technological process in devices and without devices with step aging. The measurement results are summarized in Table 3 and 4.

Table 3. Results of measurements of the geometry of the “Terminal” type parts after dispersion hardening in devices

| Dispersion hardening in devices | Total |
|--------------------------------|-------|
| Accepted                       |       |
| Refused                        |       |
| Measurement of parts before heat treatment | 227  | 73  | 300  |
| Measurement of parts after heat treatment | 296  | 4   | 300  |

Table 4. Results of measurements of the geometry of the “Terminal” type parts after dispersion hardening in a free state

| Dispersion hardening in a free state using preliminary heat treatment | Total |
|-----------------------------------------------------------------------|-------|
| Accepted                                                             |       |
| Refused                                                              |       |
| Measurement of parts before heat treatment                           | 248   | 52   | 300  |
| Measurement of parts after heat treatment                            | 172   | 128  | 300  |

It can be seen that stepwise aging did not bring the expected results, which was most likely because the devices during the heat treatment straighten the parts, while stepwise aging stabilizes the dimensions obtained by machining. The hardness of the parts was measured on witness samples and in both cases corresponds to the design documentation (HV > 330). Therefore, for flat parts with stringent geometry
requirements, the processing of which is carried out in devices, dispersion hardening in a free state is not acceptable.

A part of the "Ring" type is made of 0.5 mm tape. The design of the part provides for control of the non-flatness of the part. The regular technological process of aging is carried out without the use of devices. Non-flatness control is carried out on a plate using calibres. The data on the measurements of the geometry of the parts heat-treated according to the standard manufacturing process and the step-by-step aging technology are given in Table 5. The hardness of the parts complies with the design documentation and is measured on witness samples (HV> 330).

| Table 5. Results of measurements of the geometry of the "Ring" type parts |
|---------------------------------------------------------------|
| Amount of parts | Total amount of parts in the batch |
|-----------------|----------------------------------|
| With preliminary heat treatment |                        |
| Accepted        | 293                              |
| Refused         | 7                                |
| Total           | 300                              |
| Without preliminary heat treatment |                      |
| Accepted        | 285                              |
| Refused         | 15                               |
| Total           | 300                              |

It can be seen that in both cases, the waste of parts is a small percentage, which gives an idea of the inefficiency of step aging in relation to parts of this type.

On the basis of literature analysis and experimental studies for parts made of BrB2 alloy, heat treatment of which is not economically feasible in devices, but the geometry is significant, an operation should be introduced to “relieve stress” at a temperature of 210±5°C for one hour (step aging) before the operation "dispersion hardening". The recommended mode of heat treatment of bronze will minimize distortion during heat treatment without the use of special devices.

4. Conclusions
Thus, the analysis of the results showed that the use of stepwise aging reduces internal stresses, and also positively affects the behaviour of the part in the process of dispersion hardening, reducing its warpage. It should be noted that stepwise aging does not help to straighten parts as it happens during aging in devices.

Experimental studies have shown that for thin parts made of sheets, the use of stepwise aging was less effective, since there is no possibility of correcting the geometry defects that were obtained at earlier stages of production.

Based on the foregoing, we can conclude that in each particular case, analysis is necessary on the feasibility of using staged aging, since in some cases its use can lead to a more expensive process without a significant effect in terms of reducing warpage of parts.

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