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aluminium bronzes, ECAP,
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DEFORMATION OF ALUMINIUM BRONZE BY HPT AND ECAP METHODS

Aluminium bronzes BA1032 having a multiphase microstructure, is low-deformable materials with strength close to that of high-strength steels. The influence of high-pressure torsion (HPT) and equal channel angular pressing (ECAP) on aluminium bronze structure was presented. The HPT method was found to be unsuitable for the processing of the investigated aluminium bronzes. The studies have indicated that it is possible to deform multiphase aluminium bronzes BA1032 in the ECAP process at a temperature of 400-500°C. The deformation of the bronzes at lower temperatures encounters some difficulties – cracks appear which make repeated ECAP impossible.

1. INTRODUCTION

Aluminium bronzes are characterized by good mechanical properties at room temperature and at elevated temperature (Rm ≈ 400-600MPa) and by abrasion resistance and corrosion resistance (high in comparison with that of other copper alloys, owing to passivation and the formation of an Al_2O_3 coating on their surface) [1],[2],[3].

Single-phase aluminium bronzes with an aluminium content of 4-8% can be subjected to both cold and hot plastic working. When multi -phase bronzes containing more than 8% of aluminium are work hardened, they may acquire much better strength properties however they can be only hot deformed [4].

Due to very high strength (comparable with that of high-strength steels) even at elevated temperatures, very resistant to corrosion, abrasion and variable and impact loads they are used for heavily loaded machine and motor parts exposed to abrasion, for control-measuring equipment parts, in the transport industry for shafts and bolts, in hydraulic equipment components, in valve seats and for toothed gears.

Currently there is a great demand for these materials from the industry, but there is a major difficulty relating to low deformability. One can expect that this can be overcome

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by structure refinement. The dimensions of obtained by these methods are very stable at elevated temperature. They are characterized also by very good ductility [5],[6]. The most popular method of obtaining ultrafine grains is ECAP (Equal Chanel Angular Pressing - in this method, a material is cyclically pushed through a die with two intersecting channels and has a simple shear deformation. The amount of plastic strain in one pass depends on the channel angle and dimensions of die) and HPT (the high-pressure torsion is simultaneously subjected to a high pressure and torsion) Fig. 1. HPT has advantages over ECAP because it tends to produce both smaller grain sizes and addition, HPT processing may be used for the consolidation of fine particles (Fig. 1b) [7],[8],[9],[10].

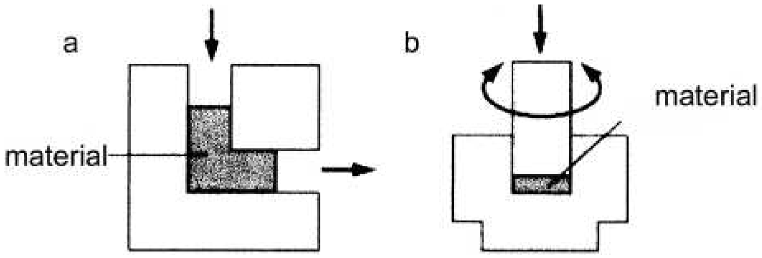

Fig. 1. Scheme of: a) ESCAP and b) HPT

One could expect that using the ECAP process of aluminium bronzes the grain microstructure could be changed. However very high mechanical properties of aluminium bronzes at room temperature and at elevated temperature could make difficulties of the ECAP and HPT deformation. In literature there is information about ECAP and HPT deformation only soft material such as aluminium, copper sometimes the low carbon steel [8],[9].

The aim of the research was to determine the possibility of aluminium bronze BA1032 deformation in HPT and ECAP processes.

2. RESEARCHED MATERIAL

In the research the bronze BA1032 was used with following chemical composition.

Table 1. Chemical composition of aluminium BA1032

No.	sample	%Cu	%Al	%Fe	%Ni	%Mn	%Zn	%Pb
1.	BA1032	84.80	**10.50**	**2.70**	-	**1.90**	0.09	0.002

The aluminium bronzes were gravity cast in the form of cylindrical ingots 205mm in diameter, using the semi-continuous method (Fig. 2). Then they were mechanically cut into 800mm long sections and cut into samples.

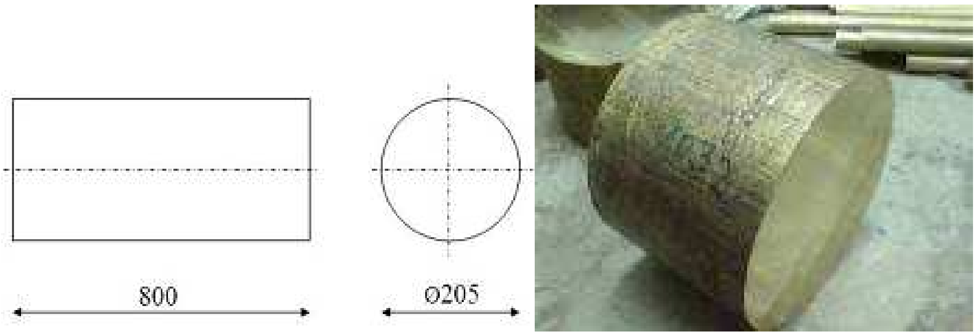

Fig. 2. Scheme showing ingot and its dimensions

The initial structure of researched material is presented in the Fig. 3.

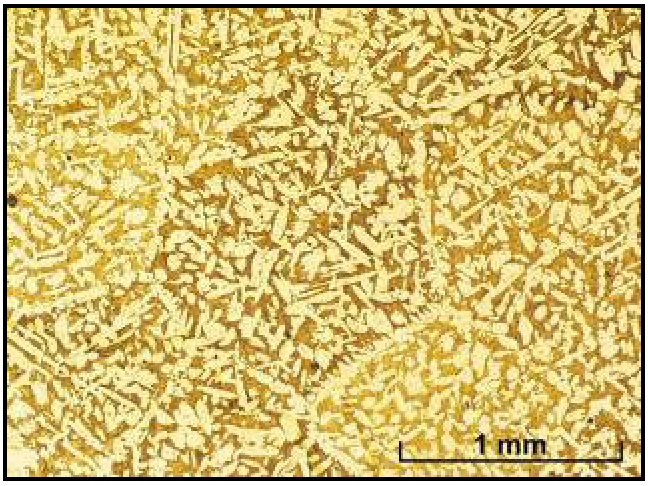

Fig. 3. Initial structure of BA1032

3. HIGH-PRESSURE TORSION (HPT)

The special tools shown in Fig. 4 were made for the HPT process. The tools were mounted on a plastomer modelling complex deformation paths. The diameter of the ram was 5mm and the tools were designed for a pressure of 1-2GPa. Tests were carried out on bronze BA1032 at ambient temperature and at 400°C. Samples have been cyclic torsion at an amplitude of one rotation under a pressure of 1GPa. Ten cycles were carried out for each of the conditions.

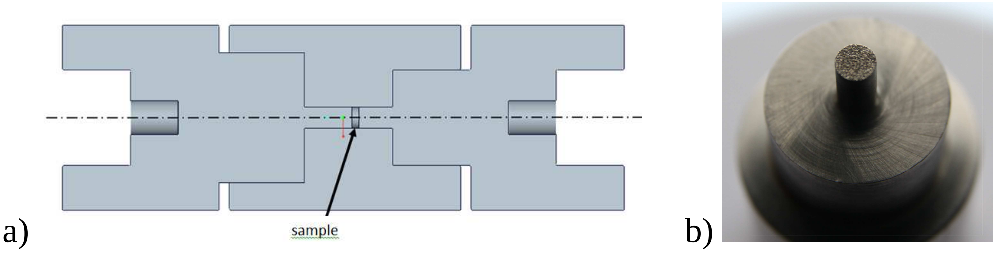

Fig. 4. Tools for HPT process a) sketch b) working surface of tools

In spite of application of special groves on working surface of the tools at ambient temperature the tools would slip on the surface of the samples whereby no material would be deformed. No structural changes relative to the initial material were observed (Fig. 5).

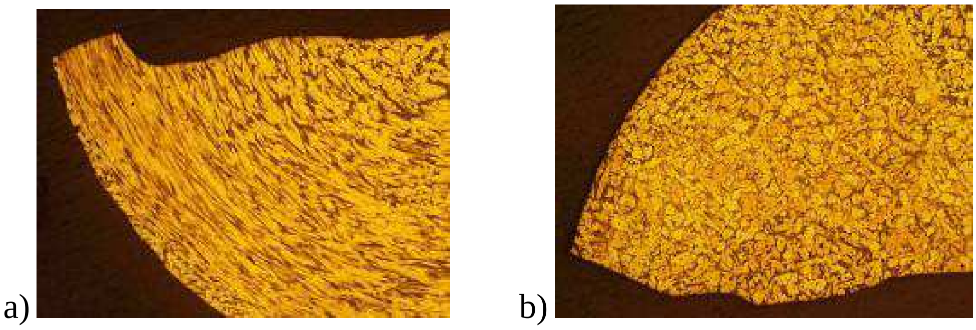

Fig. 5. Microstructure of bronze BA1032 deformed under HPT at ambient temperature: a) cross section, b) top surface of sample

In the samples deformed at 400°C, a deformed microstructure (Fig. 6) was observed close to their surface. In the cross section, strong deformation occurs only in the near-surface layer which is about 0.4mm thick. No signs of structural deformation are visible in the rest of the sample volume. Also the surface of the sample is nonuniformly deformed. The microstructure remains almost undeformed in the axis of the sample and at the contact with the tools.

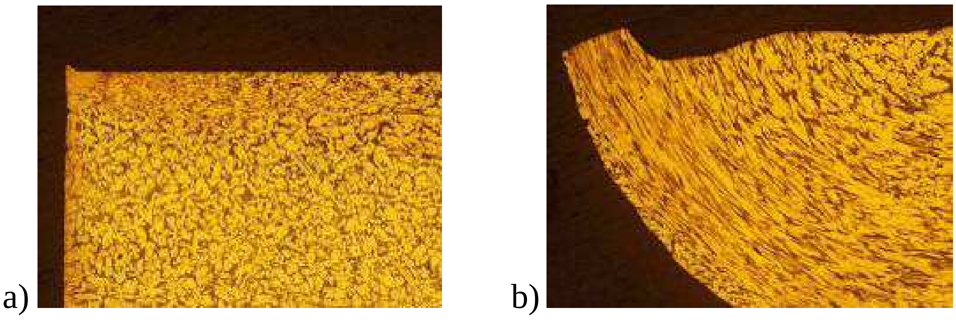

Fig. 6. Microstructure of bronze BA1032 deformed under HPT at 400°C: a) cross section b) top surface of sample

To sum up, the HPT method is limited to small samples with a thickness of about 0.5mm and highly nonuniform deformation occurs in this case. No structure refinement was observed under HPT in the deformed part of the sample even though the latter was subjected to 10 cycles of HPT. The method has been found to be unsuitable for the working of aluminium bronzes.

4. EQUAL CHANEL ANGULAR PRESSING (ECAP)

The test stand consisted of a mechanical press Tiratest 2300 equipped with a computer control system ensuring precise control in a wide range of strain rates, dies for ECAP and a regulated furnace.

The stand which was built enabled the extrusion of 10.5x10.5mm samples. The die consisted of two parts: an outer part and an inner part (Fig. 7). The inner part consisted of two parts forming a truncated cone with a flare angle of 10° ensuring that the extrusion force pressed the two parts of the cone together. An inlet channel and an outlet channel were made in each of the parts in such a way that the two components when put together and placed in the casing (the die’s outer part) formed a channel having the desired dimensions. This design makes it possible to use the ECAP force to press the cone to the casing. A hole was made in the casing to provide a free way out for the material extruded from the cone outlet channel. In addition, the dimensions of the casing outlet hole were such that flare angles Φ between the cone’s inlet channel and outlet channel could be changed from 90 to 135°. The rate of extrusion was 0.2mm/s.

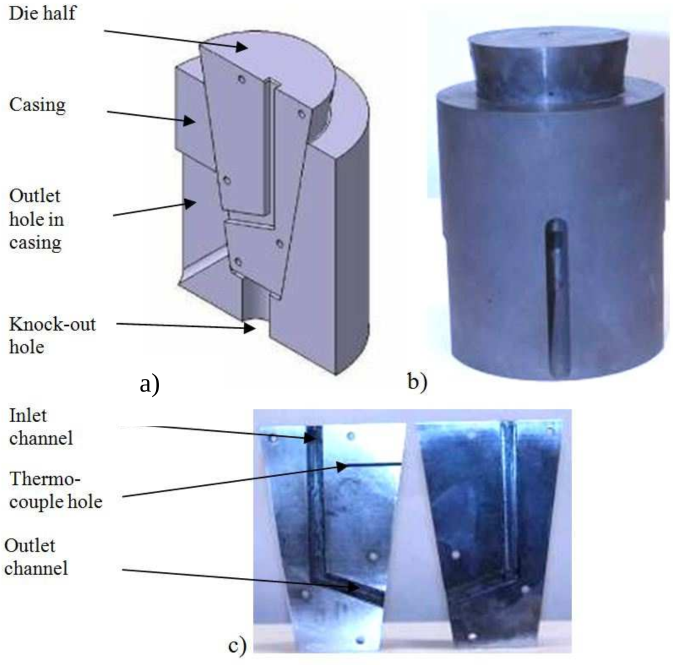

Fig. 7. ECAP die with 10.5x10.5mm angular channel: a) view of ECAP cross section created in CATIA, b) die with casing c) die components forming cone with angular channel Φ =110°

The desired ECAP temperature was produced by a thermoregulator-controlled heater (Fig. 8) in which the whole die set would be placed. The process temperature was controlled by two thermocouples, one measuring the temperature of the tools and the other measuring the temperature of the air between the tools and the heater.

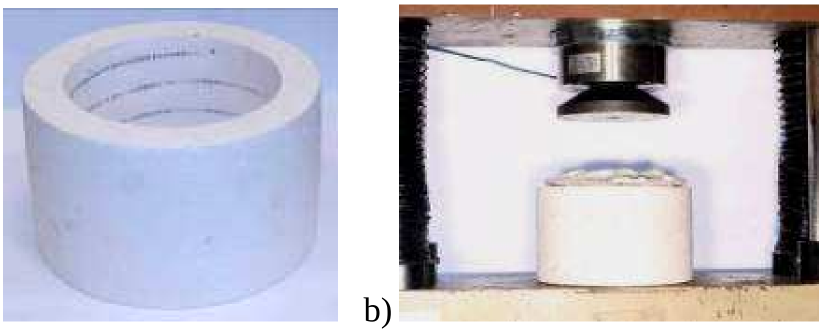
a) b)

Fig. 8. Stand for ECAP tests: a) furnace and b) stand for hot ECAP tests on TiraTest press

Initially aluminium bronze BA1032 in the form of an ingot was extruded at a temperature of 400°C. Figure 9 shows a diagram of the extrusion force. Initially the force increases to 10kN and subsequently temporarily decreases to 5kN as a result of the pressing through (by the stock sample) of the previous ECAP cycle material situated at the intersection of the inlet channel and the outlet channel in the die. Then the extrusion force increases, reaching its peak at about 70kN. In the meantime the stock material is being upset and then its extrusion begins. As the length of the material being in the input channel and its friction against the walls of the ECAP channel decrease, the force also decreases. Unfortunately, in these conditions cracks on the top surface of the sample would appear. Therefore the process temperature was increased to 425°C.

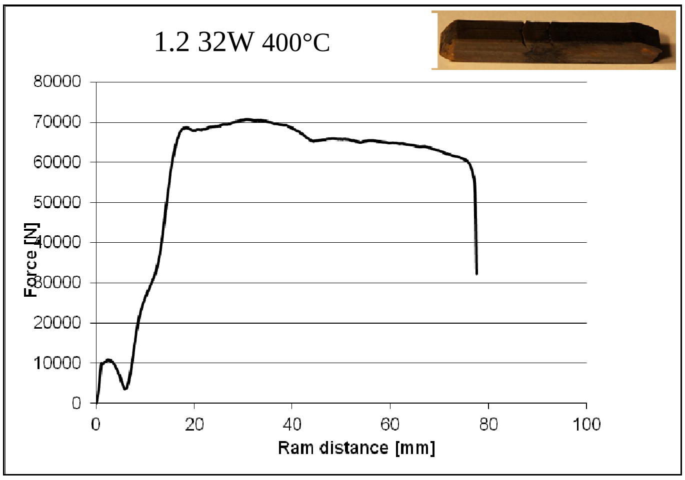

Fig. 9. Diagram of force during ECAP of undeformed aluminium bronze BA1032 (ingot) at temperature of 400°C

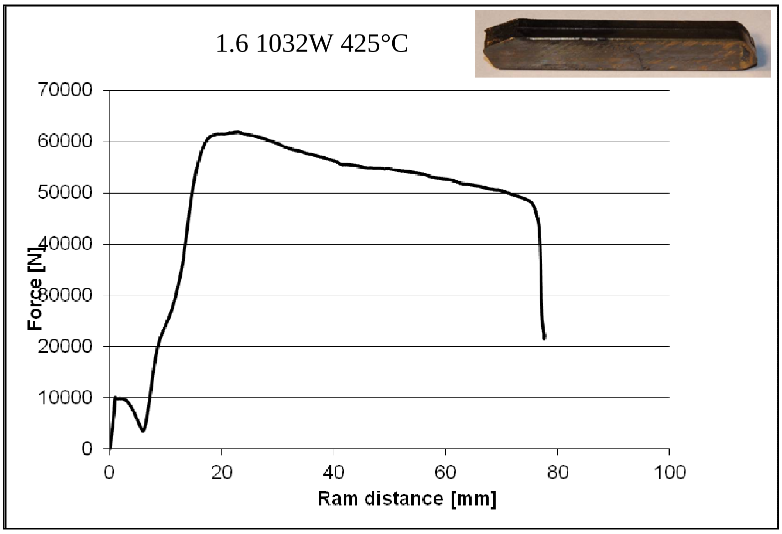

Fig. 10. Diagram of extrusion force during ECAP of undeformed aluminium bronze BA1032 (ingot) at temperature of 425°C

In the first cycle in all the tests carried out at a temperature of 425°C uncracked samples were obtained and the maximum extrusion force decreased to 60kN (Fig. 10). Since in method A the samples are not rotated (the principle of sample extrusion without rotation is illustrated in Fig. 11), they may crack in the next cycles as a result of increased strain hardening. Therefore in the next cycles the extrusion process was conducted at a temperature of 500°C. Quite intensive recovery occurs at this temperature whereby the samples did not crack. When the temperature was raised to 500°C the maximum extrusion force decreased to 35kN (Fig. 12). In the next cycles the maximum force remained at a constant level of 33-36kN.

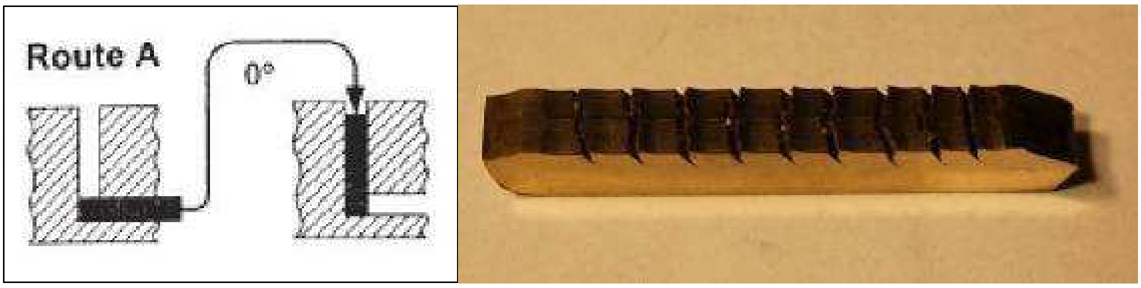

Fig. 11. Schematic diagram of ECAP without sample rotation after each cycle and view of sample with large number of cracks in its upper part (due to too low deformation temperature)

Figure 12 shows the microstructure after the first stage of extrusion. The sample’s upper, middle and lower part is shown in respectively Fig. 13a, 13b and 13c. It is apparent that the upper part and the middle part of the sample are uniformly deformed in the direction in which the material is sheared. The lower part of the sample is much less deformed, which was confirmed by FEM studies.

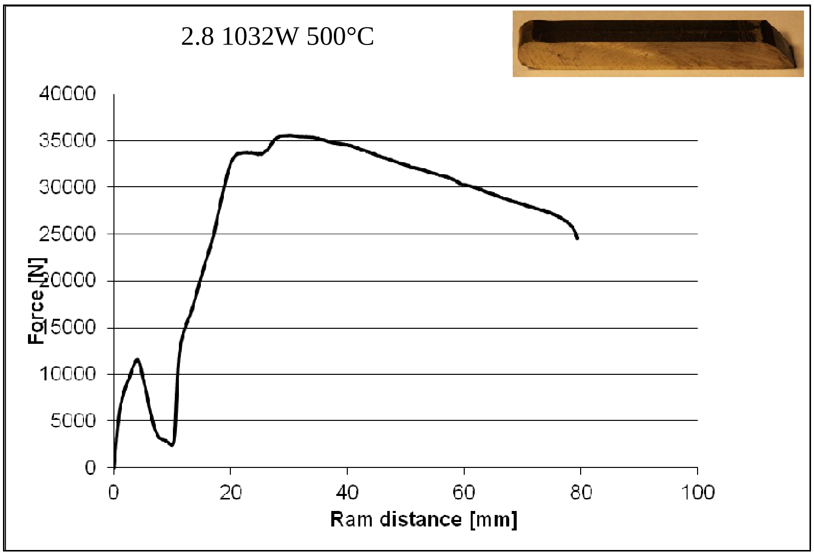

Fig. 12. Diagram of extrusion force in second cycle of ECAP of aluminium bronze 1032 (ingot) at 500°C

Fig. 13. Aluminium bronze BA1032 after first ECAP cycle: a) sample upper part, b) middle part, c) lower part

In the next ECAP cycles (Fig. 14) the segregations of phase α (light) elongate towards the axis of the samples and eutectoid α + γ2 (dark segregations) becomes more refined. In the second stage of ECAP, very large elongation of phase α grains was obtained. The length of the grains reached 0.3-0.4mm and their thickness amounted to 10-30μm (Fig. 14).

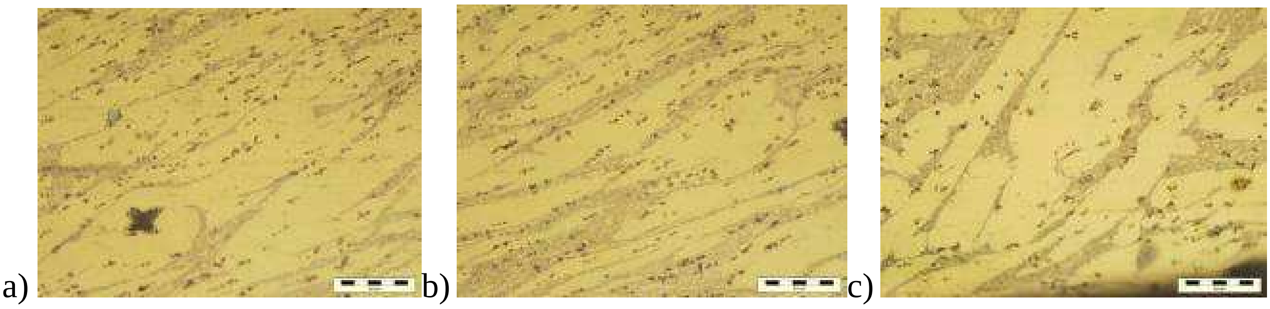

Fig. 14. Aluminium bronze BA1032 after second ECAP cycle: a) sample upper part, b) middle part, c) lower part

Despite the large deformations in the next cycles, the rosette-like segregations rich in iron did not undergo such large deformation as phase α and eutectoid α + γ2 (Fig. 15).

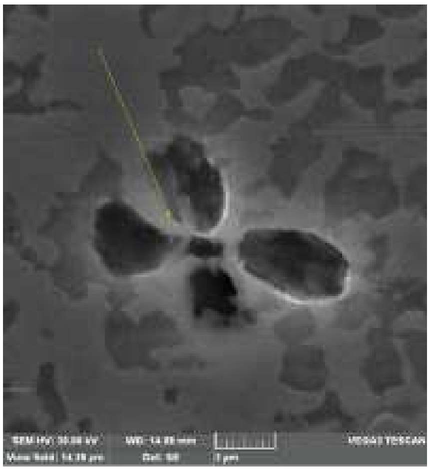

Fig .15. Rosette-like segregation (etched) rich in iron after second ECAP cycle

Figures 13 and14 show photographs of the upper, middle and lower parts of the samples after the next ECAP cycles. In the upper part of the sample the deformation is uniform along a thickness of about 40µm. The previously mentioned segregations rich in iron after the third cycle and after the fifth cycle are shown in respectively Fig. 16a and Fig. 16b. The deformation of phase α and of eutectoid α + γ2, consistent with the shape of the segregations, can be noticed in the vicinity of the latter.

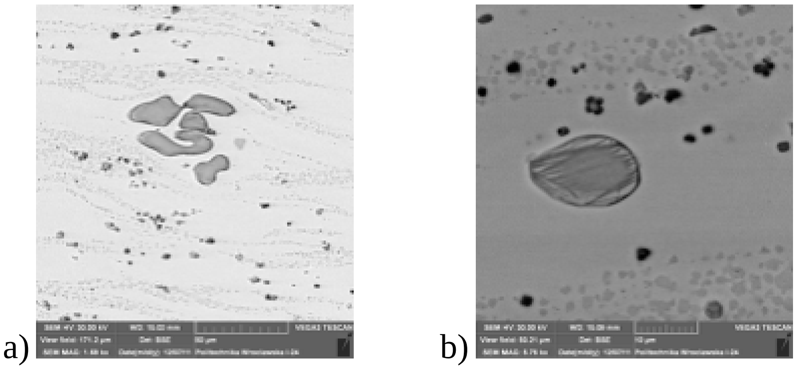

Fig. 16. Segregations rich in iron: a) after third ECAP cycle, b) after fifth ECAP cycle

The tests have shown that the middle of the sample is its most uniformly deformed part. Neither the upper part nor the lower part of the sample undergoes such uniform deformation. Moreover, eutectoid α + γ2 became highly refined already after the second cycle. The rosette-like segregations do not undergo such strong deformation as the matrix. Figure 17 shows the change in the angle of inclination of the segregations in the microstructure of the bronze, as a function of ECAP cycles. It is apparent that the inclination angle sharply changes in the first two ECAP cycles, but from the third cycle onwards its change is smaller. In the sixth cycle the angle amounts to about 5°. Generally speaking, for a larger number of ECAP cycles the angle approaches zero.

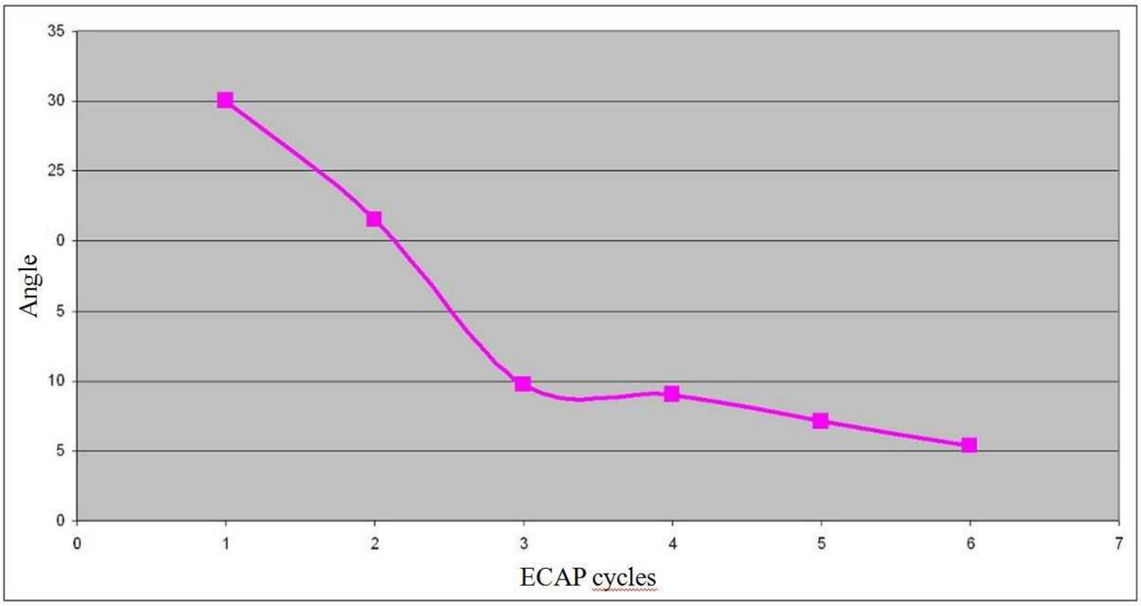

Fig. 17. Change in angle of inclination of segregations in bronze microstructure, as function ECAP cycles

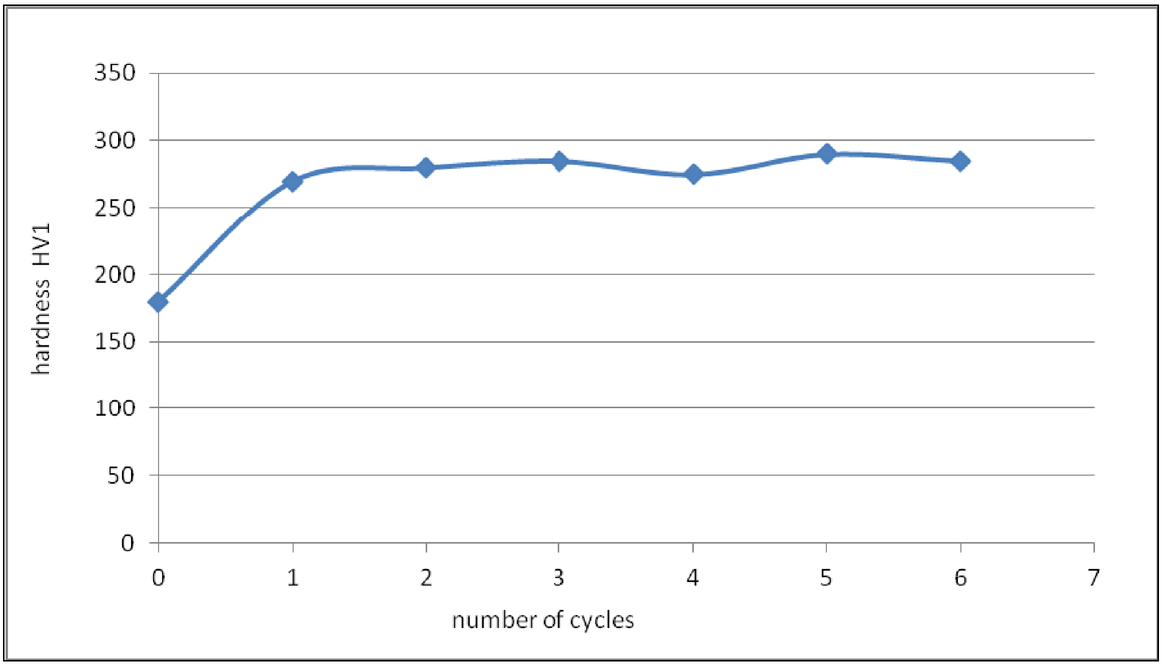

Fig. 18. Sample hardness versus ECAP cycles, (hardness, number of cycles)

The hardness of bronze BA1032 samples was measured after each successive ECAP cycle (Fig. 18). The hardness of the samples increases already after the first cycle. In the next cycles, hardness remains at a level of 265-275 HV1.

5. CONCLUSION

The use of the HPT method is limited to small, about 0.5mm thick, samples, but also here high heterogeneity of strain occurs. In the deformed part of the sample, even though the latter was deformed in 10 cycles, no structure refinement was observed. The method was found to be unsuitable for the processing of the investigated aluminium bronzes.

The studies have indicated that it is possible to deform multiphase aluminium bronzes BA1032 in the ECAP process at a temperature of 400-500°C. The deformation of the bronzes at lower temperatures encounters some difficulties – cracks appear which make repeated ECAP impossible. The cracks appear on the top surface of the samples where it contacts the surface of the outlet channel.

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