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INFLUENCE OF THE VARIABLE CONTENT OF Al, Ni AND Fe ON THE MECHANICAL PROPERTIES AND SUSCEPTIBILITY TO COLD WORKING OF ALUMINIUM BRONZE

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In this study, the influence of the variable content of Al, Ni, Fe on the grain refining and the change of mechanical properties of aluminium bronze cast into iron ingot mould was investigated. The ingots were tested for susceptibility to cold plastic working in the rolling process. It was shown that a small amount of iron (0,8 wt. %) influenced a significant level of grain refining and improvement of mechanical properties. For alloys with an increased content of Al, Fe and Ni, the maximum value of the true strain of 0,36 was achieved in the cold rolling process. The possibility of achieving similar mechanical properties for alloy with reduced content of alloying elements was demonstrated after applying the true strain of 0,61.

Keywords: aluminium bronze, plastic deformation, mechanical properties, microstructure, X-ray research

INTRODUCTION

Aluminium bronzes are copper alloys with high strength and resistance to variable loads and corrosive conditions. The main alloying component is aluminium, which increases the strength and hardness properties. In addition to aluminium, iron, manganese and nickel are important additives. Iron has a modifying effect, ensuring fine-grained microstructure, which positively affects the increase in strength, hardness and resistance to abrasion. The addition of manganese improves the mechanical properties and also increases the corrosion resistance. By increasing strength of the alloy, nickel also increases thermal and electrical conductivity and operating temperature. Aluminium bronzes with a content of up to 9 % by weight of aluminium exhibit a single-phase α microstructure under equilibrium conditions. Under non-equilibrium cooling conditions, they undergo a martensitic β transformation at high temperatures. The β phase undergoes eutectoid decomposition at lower temperatures to $\alpha + \gamma2$. The formation of $\gamma2$ is undesirable because it lowers the toughness of the alloy and increases the susceptibility to corrosion. The formation of undesirable $\gamma2$ is suppressed by the addition of nickel and iron, which increase the solubility limit of aluminium to 11 % and affect the precipitation of the more desirable κ phases. This phenomenon is used for the thermal improvement of aluminium bronze in order to increase the strength properties [1 - 3]. In many research works the influence of annealing, hot plastic working and cooling speed on the microstructure and mechanical properties of nickel-aluminium bronzes was analysed [4 - 5]. Comparative research was conducted on the mechanical properties and changes in the microstructure of aluminium bronze produced with the Wire Arc Additive Manufacturing (WAAM) technology in relation to the casting technology. It was shown that WAAM samples that are deposited with low heat input showed a much finer and smaller volume of the second intermetallic phases, and no κ_I phases compared to the casting samples. As a result, WAAM samples showed much higher tensile strength and ductility than cast samples [6 - 7]. Aluminium bronzes usually undergo hot working due the limited cold workability, low ductility and quick hardening. This article presents the results of research on the influence of the variable content of Al, Fe and Ni on the degree of refinement of the microstructure and the effect of the content of these elements on the mechanical properties of aluminium bronze cast and the susceptibility to cold working in the rolling process.

EXPERIMENTAL PROCEDURE

Material

The research material consisted of samples taken from ingots of aluminium bronze with a variable content of Al, Fe, Ni and a constant content of Mn. Electrolytic copper Cu-ETP, metallic nickel, aluminium wire rod, CuMn30 and CuFe20 pre-alloy were used for the production of alloys. Ingots with a diameter of 50 mm were produced by melting in an open induction furnace and static casting into a cast iron ingot mould. A liquid metallic bath was prepared in a graphite crucible and the surface was protected with dried charcoal. The cast

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iron ingot mould was heated to a temperature of about 150 °C. Casting was carried out with a temperature in the range of 1 150 – 1 200 °C. The chemical composition of the materials tested is presented in Table 1.

Table 1 **Chemical composition of samples / wt.%**

Alloy	Al	Fe	Ni	Mn	Cu
1	8,60	1,63	1,50	1,58	rest
2	9,03	4,31	3,95	1,50	
3	8,95	3,45	4,00	1,55	

Microstructure analysis

The microstructure of the alloys was tested after casting in the middle area of the bottom of the ingot. The samples were ground on sandpaper, and then polished on a 3 µm diamond suspension and 1 µm aluminium oxide. A water solution of FeCl3 was used for the etching. Observations of the microstructure were performed using a Keyence-VHX 7100 digital microscope (LM) and a Zeiss Gemini 1525 scanning electron microscope (SEM). The grain size was analysed using the microscope software. 70 measurements were made for randomly selected α phase dendrites in the tested area of the sample. The mean dendrite size, standard deviation, minimum and maximum values were calculated.

Tensile test

The static tensile test was carried out on the Instron 100 kN universal testing machine. Three samples of each material at a speed of 2 mm / min were stretched. The tensile strength R_m and the yield strength $R_{p0,2}$ were determined. The $A50$ elongation was calculated on the basis of the dimensional changes of the applied datum on the samples.

Cold-rolling process

Cold forming properties of the manufactured materials were tested in the rolling process. Rectangular samples with dimensions of 10 x 10 x 50 mm were cut from the longitudinal section of the ingot. Cold rolling was carried out on a Small Rolling Machine Z-10 Yoshida Kinen. The applied rolling reduction was about 20 %. The rolling speed was 0,5 m / s. The samples were rolled to the maximum state of hardening and cracking of the material.

Hardness test

Hardness measurements were made for samples as cast and for samples after cold rolling. Hardness was measured by the Vickers method with the universal Wolpert 2Rc hardness tester. A load of 10 kg of the indenter was applied for 15 seconds. After casting, 7 measurements were made on the samples, and 4 measurements after rolling. Based on the measured values, the mean value was calculated.

RESULTS AND DISCUSSION

Microstructure analysis

The microstructure of tested alloys as cast is shown in Figures 1 - 3. The results of the dendrite size measurements (α phase) are shown in Figure 4. The SEM microstructure images are presented in Figures 5 - 7. The highest degree of refining was observed for alloy 2 with the highest Fe content, which is consistent with the information in the literature.

The mean size of the α-phase dendrites was about 50 µm. The largest size dendrites were observed for alloy 1. The average size of the dendrites was approximately 256 µm. In alloy 3, containing about 0,8 wt. % less iron, the mean size of the dendrites was 89 µm. A high level of microstructure heterogeneity was found for each of the alloys, which is indicated by high values of standard de-

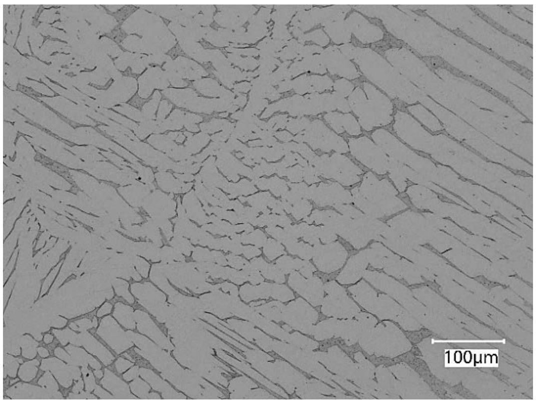


Figure 1 Microstructure (LM) of alloy 1

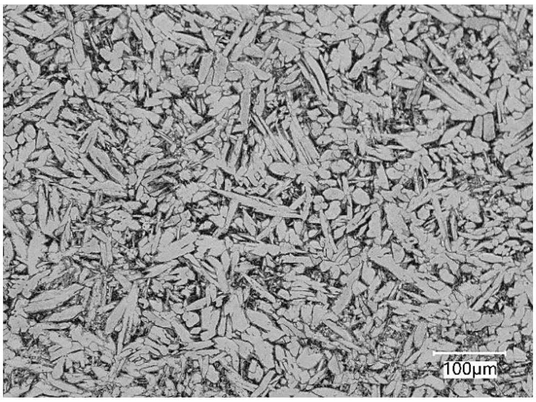


Figure 2 Microstructure (LM) of alloy 2

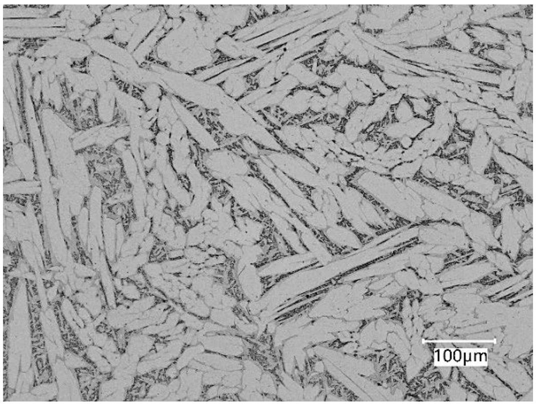
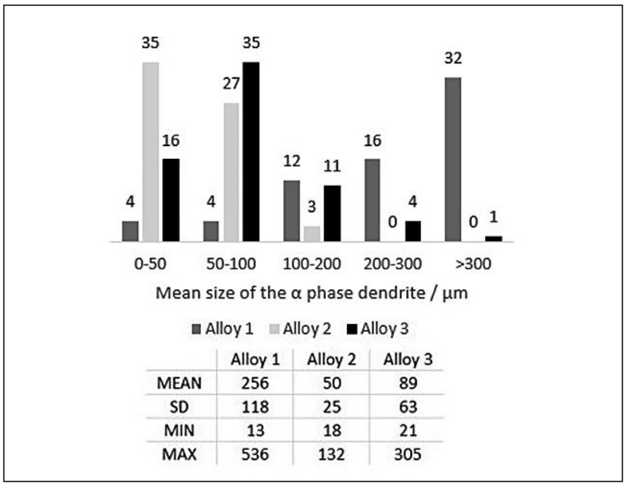


Figure 3 Microstructure (LM) of alloy 3



	Alloy 1	Alloy 2	Alloy 3
MEAN	256	50	89
SD	118	25	63
MIN	13	18	21
MAX	536	132	305

Figure 4 Measurement results of the mean size of α phase dendrites

viations from the mean dendrite size. In the SEM microstructure of the studied alloys, dendrites of the α phase were observed, in the inter-dendritic spaces the α + κ phase and the lamellar α + κ_{III} phase, as well as numerous precipitations in the form of the κ_I rosette, the fine spherical κ_{II} phase at the α phase boundaries, the κ_{IV} fine phase on the surface of the dendrites. The highest proportion of κ phases in various forms was observed for alloy 2. The microstructure analysis was based on the results obtained for nickel-aluminium bronze as cast in the works [2, 3, 7].

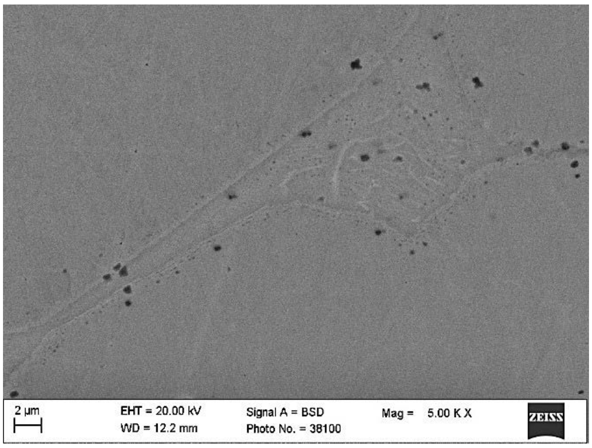


Figure 5 SEM microstructure of alloy 1

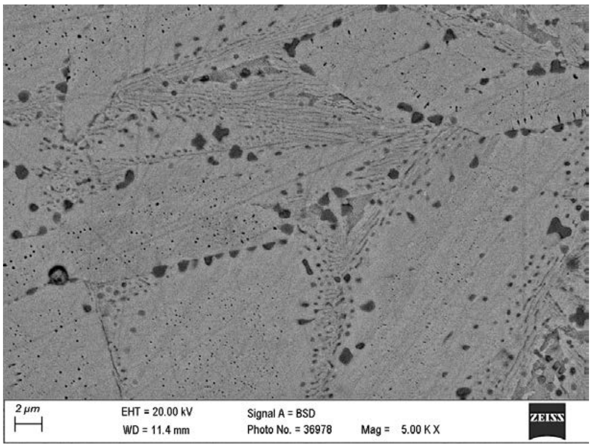


Figure 6 SEM microstructure of alloy 2

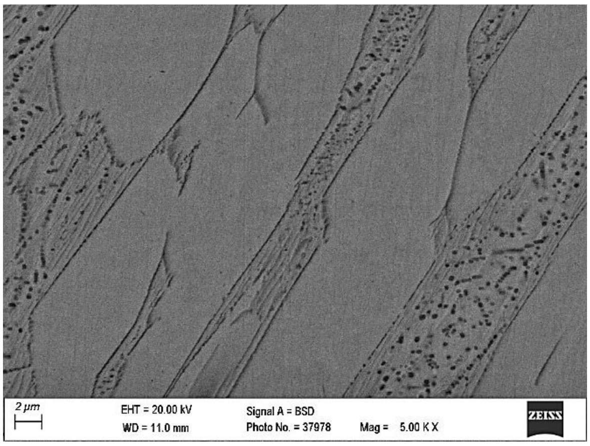


Figure 7 SEM microstructure of alloy 3

Table 2 **Results of tensile test**

Alloy	R_m / MPa	$R_{p0,2}$ / MPa	*A*50 / %	
1	504	177	40,0	Mean
	3	1	0,7	SD
2	676	281	23,2	Mean
	8	4	1,9	SD
3	580	261	19,2	Mean
	6	2	0,5	SD

Tensile test analysis

The course of the tensile curves for selected samples of the tested materials are shown in Figure 8. Table 2 summarizes the determined values of R_m, $R_{p0,2}$ and *A*50.

Increase of iron at the level 0,8 wt. % in alloy 2 compared to alloy 3, it increased the tensile strength from about 580 MPa to 676 MPa (15 %) and increased elongation by about 4 %. Comparing the samples from alloys 1 and 2, the increase in the content of Fe, Al and Ni resulted in an increase in tensile strength by 34 % and a reduction in elongation by about 17 %.

Hardness test and rolling process analysis

The results of the hardness measurements of the samples as cast are presented in Table 3, and after the rolling process in Table 4 and in Figure 9.

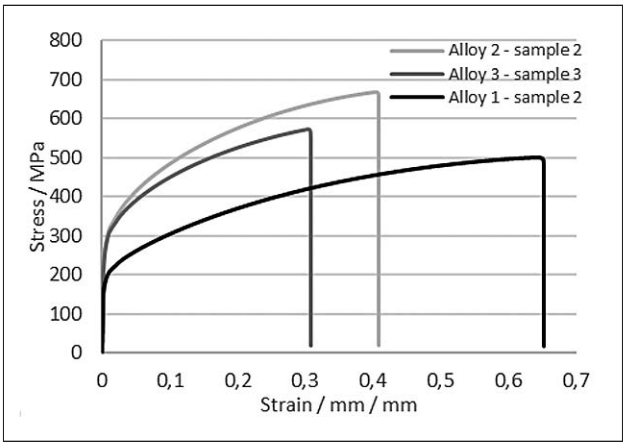


Figure 8 Stress-strain curve for selected samples

Table 3 **Vickers hardness measurement results for samples after casting**

Alloy	Indentation / HV10							Mean	SD
	1	2	3	4	5	6	7		
1	104	109	112	111	110	109	111	109	2
2	161	172	171	169	166	177	169	169	3
3	151	150	151	150	159	151	152	152	2

Table 4 **Vickers hardness measurement results for samples after cold-rolling**

Alloy	True strain level	Indentation / HV10				Mean	SD
		1	2	3	4		
1	0,23	187	180	170	208	186	16
	0,61	244	253	247	248	248	4
2	0,23	243	231	257	236	242	11
	0,36	252	270	267	263	263	8
3	0,23	239	231	237	235	235	3
	0,36	268	258	265	262	263	4

As with the tensile strength, alloy 2 (169 HV10) achieved the highest hardness value in the as-cast condition. The value obtained is 11 % higher than the value obtained for alloy 3 and by 36 % than the value obtained for alloy 1.

The higher value of hardness is due to the greater degree of refining of the microstructure and the participation of a greater number of separated κ phases. After the cold rolling process, a similar tendency of material strengthening was observed. After applying a true strain of 0,23 for alloy 1, the hardness increased by 42 %, for alloy 2 by 30 %, and for alloy 3 by 36 %. After the deformation of 0,36, the alloys 2 and 3 reached the limit deformability. The samples cracked and further deformation at the given rolling parameters was not possible. At this level of deformation, the hardness for both materials was approximately 263 HV10. For the sample from alloy 1, a similar hardness level (248 HV10) was achieved after the true strain was set at the level of 0,61. This alloy showed better cold-rolling susceptibility

CONCLUSIONS

After conducting microstructure studies and mechanical properties for aluminium bronzes with variable content of Al, Fe and Ni in the state after casting and cold rolling, the following conclusions were drawn:

Increasing the content of Al by 0,43 % wt., Fe by 2,68 % wt., and Ni by 2,45 % wt. decreased the average grain size of the aluminium bronze casting from about 256 µm to 50 µm, and also increased the tensile strength by 34 % and hardness by 36 %.

Introduction of an additional amount of iron at the level of 0,8 wt. %. for aluminium bronze with a constant and similar content of Al, Ni, Mn influenced grain refinement from about 89 µm to 50 µm, increased tensile strength by about 17 % and hardness by 11 %.

For the applied parameters of the rolling process (percentage reduction of about 20 %), alloys with a higher Fe content reached the limit deformability after exceeding the true strain of 0,36.

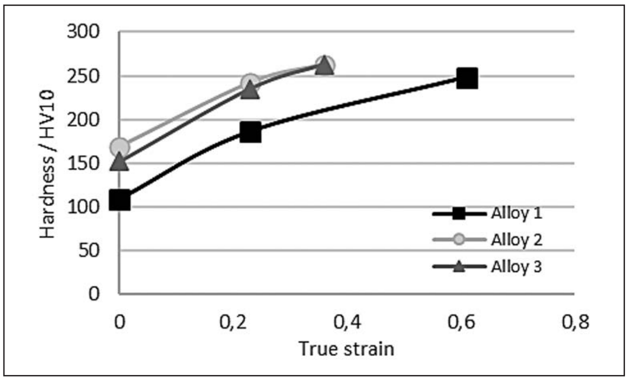


Figure 9 Hardness - true strain curve for samples after cold rolling

An alloy with a lower content of Al, Fe and Ni is characterized by better susceptibility to plastic processing. Similar mechanical properties were obtained after applying the true strain at the level of 0,61.

Acknowledgments

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Note: The translator responsible for English language: Małgorzata Krystowska, Gliwice, Poland