UDK 669.715:669.3:620.18
Izvirni znanstveni članek

ISSN 1580-2949
MTAEC 9, 36(1-2)49(2002)

# THE EFFECT OF COPPER CONTENTS ON THE MICROSTRUCTURE OF THE ALUMINIUM-COPPER ALLOY

## VPLIV VSEBNOSTI BAKRA NA MIKROSTRUKTURO ZLITIN ALUMINIJ - BAKER

**Biljana Zlatičanin[1], Stevan Đurić[2], Branka Jordović[3], Biljana Stojanović[4], Branislav Radonjić[1]**

[1]University of Montenegro, The Faculty of Metallurgy and Technology, Cetinjski put bb, 81000 Podgorica, Yugoslavia
[2]University of Belgrade, 11000 Belgrade
[3]The Faculty of Technical, Cacak, Yugoslavia
[4]CMS - Belgrade, 11000 Belgrade
biljana@l.cis.cg.ac.yu

*Prejem rokopisa - received: 2001-04-02; sprejem za objavo - accepted for publication: 2001-10-05*

The effect of copper content, in the interval range from 0% to 33%, on the microstructure of aluminium-copper alloys was examined. Using X-ray powder diffraction we established that the tetragonal intermetallic compound $Al_2Cu$ with the lattice parameters: a = 6,076 Å, c = 4,886Å and V = 180,4 $Å^3$, is formed across the whole range of copper additions.

The effect of the copper content on the microstructure was monitored quantitatively. Using automatic image analysis we were able to measure the linear intercept grain size, the secondary dendrite arm spacing (DAS), the size of eutectic cells (Le), as well as the size distribution and volume fractions of the α-solid solution and the eutectic. In alloys containing more copper the average value of the DAS was found to decrease.

Key words: copper-aluminium alloy, intermetallic compound, $Al_2Cu$, lattice parameters, solidification structure

Raziskan je bil vpliv bakra v razponu od 0 % do 33 % na mikrostrukturo zlitin aluminij-baker. Z uklonom rentgenskih žarkov je bilo potrjeno, da v vsem razponu vsebnosti bakra nastaja intermetalna faza $Al_2Cu$ s parametri kristalne mreže a = 0,6076 nm, c = 0,4886 nm in V = 18,04 $nm^3$. Vpliv bakra na mikrostrukturo je bil določen s kvantitativnimi meritvami. Z avtomatsko analizo slike so bile določene linearne intercepcijske dolžine, širina sekundarnih dendritnih vej (DAS) in velikost evtektskih celic (Le). Določeni so bili tudi velikostna porazdelitev in delež trdne α-raztopine in evtektika; širina sekundarnih dendritnih mej se zmanjšuje pri naraščanju vsebnosti bakra.

Ključne besede: zlitine aluminij-baker, intermetalna spojina $Al_2Cu$, parametri kristalne mreže, strjevalna struktura

## 1 INTRODUCTION

Standard industrial aluminium-copper alloys solidify with the formation of a dendritic structure, however, a tendency to form with a globular structure at higher copper contents was reported[1,2] and confirmed in our earlier unpublished work. We have examined the solidification structure in the aluminium-copper system over a wide range of copper content. The experimental work consisted of melting and casting alloys with different compositions representing the range of copper contents in standard aluminium alloys, as well as alloys with higher copper contents for an investigation of alloys with X-ray powder diffraction and quantitative microstructure analysis. The hardness and compression strength of the alloys were also determined. The solidification structure was modified by the addition of the AlTi5B1 alloy in the range of 0.02 to 0.25 % Ti.

## 2 EXPERIMENTAL

The X-ray diffraction analysis was performed on pure aluminium and pure copper, as well as on the aluminium-copper alloys: AlCu5, AlCu8, AlCu15, AlCu15Mg3, AlCu23, AlCu33, using a wide range of angles (2θ) from 5 to 100° with a step of 0,02° and a holding time of 0,4 s. A diffractometer with a graphite monochromator and a constant divergence slit (D) of 1mm was used. The current and the voltage of the X-ray tube during the analysis were 32mA and 40kV, respectively. The width of the receiving slit (R) was 0,1mm, corresponding to fine focussed X-ray tubes. The radiation was the Cu $K\alpha_1/\alpha_2$, doublet ($\lambda\alpha_1$= 1,54051 Å and $\lambda\alpha_2$ = 1,54433 Å).

Special attention was given to an assessment of the different structural parameters by quantitative microstructure analysis, which was considered as more reliable, accurate and faster than conventional manual methods of microstructure analysis.

## 3 RESULTS AND DISCUSSION

### *3.1 Results of the X-ray analysis*

From the X-ray diffractograms the microstructural parameters have been calculated: the average sub-grain size (**Table 1**), the microvoltage (**Table 2**) and the dislocation density (**Table 3**).

**Table 1:** Average crystallite size in the crystallographic direction [110] for different copper contents in aluminium-copper alloys

**Tabela 1:** Povprečna velikost kristalitov v kristalni smeri [110] pri različni vsebnosti bakra v zlitinah aluminij-baker

| Type of sample | Average crystalite size, Å |
|---|---|
| AlCu5 (0,08% Ti) | 641 |
| AlCu8 (0,08% Ti) | 561 |
| AlCu15 (0% Ti) | 748 |
| AlCu15Mg3 (0,08% Ti) | 374 |
| AlCu23 (0,08% Ti) | 897 |
| AlCu33 (0,08% Ti) | 748 |

**Table 2:** The microvoltage in the crystallographic direction [110] for different copper contents in aluminium-copper alloy

**Tabela 2:** Mikronapetosti v kristalni smeri [110] pri različni vsebnosti bakra v zlitinah aluminij-baker

| Type of sample | Microvoltage (mV) |
|---|---|
| AlCu5 (0,08% Ti) | 0,1920 |
| AlCu8 (0,08% Ti) | 0,2194 |
| AlCu15 (0% Ti) | 0,1644 |
| AlCu15Mg3 (0,08% Ti) | 0,3305 |
| AlCu23 (0,08% Ti) | 0,1371 |
| AlCu33 (0,08% Ti) | 0,1644 |

**Table 3:** Dislocation density in the direction [110] for different copper contents in aluminium-copper alloys

**Tabela 3:** Gostota dislokacij v kristalni smeri [110] pri različni vsebnosti bakra v zlitinah aluminij-baker

| Type of sample | Dislocation density, $cm^{-2}$ |
|---|---|
| AlCu5 (0,08% Ti) | $7,3 \times 10^{10}$ |
| AlCu8 (0,08% Ti) | $9,5 \times 10^{10}$ |
| AlCu15 (0% Ti) | $5,4 \times 10^{10}$ |
| AlCu15Mg3 (0,08% Ti) | $21,4 \times 10^{10}$ |
| AlCu23 (0,08% Ti) | $3,7 \times 10^{10}$ |
| AlCu33 (0,08% Ti) | $5,4 \times 10^{10}$ |

**Table 4:** Grain size for different copper contents in aluminium-copper alloys

**Tabela 4:** Velikost zrn pri različi vsebnosti bakra v zlitinah aluminij-baker

| Type of sample | average, µm | min, µm | max, µm | RSE, % |
|---|---|---|---|---|
| Al (0%Ti) | 537,69559 | 78,94737 | 2210,52632 | 6,53767 |
| Al (0,08%Ti) | 101,31646 | 18,98734 | 303,79747 | 3,45954 |
| AlCu5 (0,08%Ti) | 85,72152 | 18,98734 | 215,18987 | 2,59978 |
| AlCu8 (0,08%Ti) | 74,49620 | 12,65823 | 189,87342 | 2,81358 |
| AlCu15 (0%Ti) | 810,48387 | 193,54839 | 2709,67742 | 5,06863 |
| AlCu15 (0,02%Ti) | 230,63492 | 47,61905 | 777,77778 | 3,78064 |
| AlCu15 (0,08%Ti) | 53,00000 | 9,37500 | 162,50000 | 2,94158 |
| AlCu15 (0,15%Ti) | 49,71717 | 15,15152 | 121,21212 | 2,99332 |
| AlCu15 (0,25%Ti) | 48,39966 | 10,10101 | 126,26263 | 2,76879 |
| AlCu15Mg3 (0,08%Ti) | 87,31313 | 30,30303 | 212,12121 | 2,42991 |
| AlCu23 (0,08%Ti) | 57,71717 | 20,20202 | 151,51515 | 2,91693 |
| AlCu33 (0,08%Ti) | 366,78722 | 113,92405 | 721,51899 | 9,03907 |

The sub-grain is the range of the lattice of the crystal grain from which the X-rays are coherently diffracted. The sub-grains are separated by dislocation walls and have a space orientation which is different by several angle minutes. Using X-ray diffraction of polycrystals, the sub-grain is defined as a range of quantitative values, starting from the average length in a definite crystallographic direction, through the average volume, to their dimensional distributions.

Microvoltages are the most-often used parameter of crystal-lattice deficiency and represent the deviations in the distance d between two crystal planes having identical {hkl} indices in a determined crystallographic direction. This kind of a crystal-lattice deficiency is the result of the distribution of dislocations or the difference in the chemical composition of the alloy. The dislocation density is also a parameter of the lattice defectiveness. It is most often defined as the minimum density of dislocation-free areas compared to the number of dislocations on the crystallite edges.

The X-ray examination of the different aluminium-copper alloys showed very high microvoltage values (**Table 2**), which were expected because of the way the alloys were manufactured and the method used to investigate them.

### *3.2 Quantitative microstructure analysis*

The grain size (minimum, maximum and average values), the relative standard measuring errors (RSEs) (see **Table 4**), the dendrite arm spacing[3] (DAS) (see **Table 5**), the eutectic cell length (Le) (see **Table 6**), as well as the size distribution and the volume share of the α-solid solution and eutectic were measured.

**Table 5:** Dendrite arm spacing (DAS) for different copper contents in aluminium-copper alloys

**Tabela 5:** Širina sekudarnih dendritnih vej pri različni vsebnosti bakra v zlitinah aluminij-baker

| Type of sample | average, µm | min, µm | max, µm | RSE, % | Vv,αh.s. % |
|---|---|---|---|---|---|
| AlCu5 (0,08%Ti) | 30,19837 | 1,63 | 134,69 | 2,9381 | 84,75599 |
| AlCu8 (0,08%Ti) | 26,88980 | 1,63 | 102,04 | 2,3774 | 83,48839 |
| AlCu15 (0%Ti) | 20,22536 | 1,63 | 123,27 | 2,1228 | 75,14505 |
| AlCu15 (0,02%Ti) | 23,13044 | 1,63 | 112,65 | 2,2226 | 76,67941 |
| AlCu15 (0,08%Ti) | 23,30254 | 1,22 | 90,61 | 2,3228 | 74,38530 |
| AlCu15 (0,15%Ti) | 20,66491 | 1,22 | 102,86 | 2,1645 | 74,28727 |
| AlCu15 (0,25%Ti) | 18,98537 | 1,63 | 92,24 | 2,0971 | 71,12862 |
| AlCu15Mg3 (0,08%Ti) | 19,65894 | 1,63 | 102,86 | 2,0845 | 76,84319 |
| AlCu23 (0,08%Ti) | 17,37533 | 1,63 | 79,18 | 2,0074 | 54,49193 |

The copper content in the standard aluminium alloys was up to about 5%, slightly below the value of 5,65% that represents the maximum solid solubility of copper in aluminium at the eutectic temperature of 548 °C. Since alloys with as much as 33% copper were tested, a considerable amount of eutectic is found in the microstructure. With standard alloys the primary phase of the α-solid solution solidifies in a dendritic form. With higher copper contents the eutectic appears in the inter-dendritic space.

The grain size and the distribution of dendrites and eutectic depend on the casting parameters[4], the melt

**Table 6:** The linear intercept size of eutectic cells (Le) for different copper contents in aluminium-copper alloys
**Tabela 6:** Linearna intercepcijska dolžina evtektičnih celic (Le) pri različni vsebnosti bakra v zlitinah aluminij-baker

| Type of sample | min, μm | max, μm | average, μm | RSE, % | Vv,e.% |
|---|---|---|---|---|---|
| AlCu5 (0,08%Ti) | 1,63 | 44,90 | 5,65236 | 3,35377 | 14,59140 |
| AlCu8 (0,08%Ti) | 1,63 | 34,29 | 5,55443 | 3,00760 | 16,34898 |
| AlCu15 (0%Ti) | 1,63 | 46,53 | 7,05516 | 2,74649 | 24,58736 |
| AlCu15 (0,02%Ti) | 1,63 | 51,43 | 7,38373 | 3,24170 | 22,81881 |
| AlCu15 (0,08%Ti) | 1,63 | 63,67 | 8,34064 | 3,50108 | 25,01952 |
| AlCu15 (0,15%Ti) | 1,22 | 42,86 | 6,67921 | 3,04908 | 23,15246 |
| AlCu15 (0,25%Ti) | 1,22 | 55,10 | 7,30999 | 2,93505 | 26,14938 |
| AlCu15Mg3 (0,08%Ti) | 1,63 | 48,98 | 6,20416 | 2,80237 | 23,07952 |
| AlCu23 (0,08%Ti) | 1,63 | 165,71 | 14,56085 | 3,91495 | 44,43566 |

**Table 7:** Hardness and compression strength of aluminium-copper alloys with different amounts of copper
**Tabela 7:** Trdota in tlačna trdnost zlitin AlCu z različno vsebnostjo bakra

| Type of sample | HBaverage | $\sigma_{0,2p}$ ($N/mm^2$) | $\sigma_{mp}$ ($N/mm^2$) |
|---|---|---|---|
| Al (0%Ti) | 25,025 | 38,22 | 119,74 |
| Al (0,08%Ti) | 27,000 | 49,94 | 141,66 |
| AlCu5 (0,08%Ti) | 64,350 | 101,92 | 471,34 |
| AlCu8 (0,08%Ti) | 76,725 | 147,77 | 478,98 |
| AlCu15 (0%Ti) | 90,000 | 214,01 | 491,72 |
| AlCu15 (0,02%Ti) | 91,250 | 221,66 | 491,72 |
| AlCu15 (0,08%Ti) | 96,625 | 229,30 | 557,96 |
| AlCu15 (0,15%Ti) | 102,400 | 230,83 | 558,98 |
| AlCu15 (0,25%Ti) | 103,375 | 239,49 | 558,98 |
| AlCu15Mg3 (0,08%Ti) | 142,500 | 371,97 | 675,16 |
| AlCu23 (0,08%Ti) | 110,000 | 292,99 | 563,45 |
| AlCu33 (0,08%Ti) | 197,500 | 501,91 | 672,61 |

temperature and the solidification rate, which also affect the properties of the alloys. The microstructure can be influenced by controlling the casting parameters and by the addition of titanium and boron in form of the alloy AlTi5B1 to produce particles of $TiB_2$ in the melt. These particles are then the nuclei for the $TiAl_3$ phase that affects the solidification. Titanium and aluminium produce a peritectic reaction with the $TiAl_3$ and the solid peritectic acts as a solidification nucleus for pure aluminium and its solid solutions.

### *3.3 Mechanical properties*

The Brinell hardness and the compression strength are shown in **Table 7**. The changes in chemical composition of the alloy cause changes in the structure that are reflected in the Brinell hardness and the compression strength. The hardness of the modified alloy is higher than the hardness of the alloy without any modification treatment. By increasing the content of copper and titanium the hardness and compression strength also increase.

## 4 CONCLUSIONS

Based on our findings we can draw the following conclusions about the effect of the content of copper on aluminium-copper alloys:

– With increased amounts of copper in the alloy[5] the average value of the DAS is decreased (see **Table 5**).
– With the same chemical composition but increased titanium content, the average value of the grain size is decreased (see **Table 4**). With the addition of AlTi5B1 a modification to the solidification structure and smaller solidification grains are obtained. We confirmed that titanium is a very effective grain refiner. The resulting dispersion of insoluble components as well as a smaller porosity and fewer non-metal inclusions improved the mechanical properties.
– Compression strength and hardness increase with the content of copper and titanium (**Table 7**). The compression strength and hardness of the magnesium alloy are also greater; compared to the copper alloy it has a smaller grain size for the same content of titanium.

Across the whole range of copper content tested the lattice parameters of the tetragonal intermetallic compound remained constant.

## 5 REFERENCES


[1] L. F. Mondolfo, *Aluminium Alloys: Structure and Properties*, Butterworth and Co (Publishers) Ltd, London 1976, 253

[2] X. Yang, J. D. Hunt and D. V. Edmonds, *A quantitative study of grain structures in twin-roll cast aluminium alloys*, part II: AA 3004, Aluminium, 69 (**1993**) 2, 158-162

[3] AM. Samuel, FH. Samuel, Effect of Alloying Elements and Dendrite Arm Spacing on the Microstructure and Hardness of an Al-Si-Cu-Mg-Fe-Mn (380), Journal of Materials Science, 7 (**1995**) 4, 1698-1708

[4] B. Radonjic, *Directionality of Cast Aluminium Structure*, Aluminium, 58 (**1982**) 11, 646-649

[5] WQ. Jie, W. Reif, Effect of Cu Content on Grain - Refinement of an Al-Cu Alloy with AlTi6 and AlTi5B1 Refiners, Zeitschrift fur Metallkunde, 84 (**1993**) 7, 445-450