A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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HIGH STRENGTH SILICON BRONZE (C65500) OBTAINED BY HYDROSTATIC EXTRUSION

WYSOKO WYTRZYMAŁY BRĄZ KRZEMOWY (C65500) UZYSKANY METODĄ WYCISKANIA HYDROSTATYCZNEGO

C65500 is a high strength engineering alloy that has excellent resistance to a wide range of corrosive environments. Combination of corrosion resistance, strength, and formability place it among the most widely used copper alloys. In the present study, a C65500 alloy was subjected to severe plastic deformation by hydrostatic extrusion at room temperature with goal to increase its strength by grain refinement without modification of the chemical composition. Cumulative hydrostatic extrusion was applied with a total true strain of 4.1. The microstructure of SPD samples was evaluated by transmission electron microscopy. The size of grains was quantitatively described. The resulting mechanical properties were determined in tensile tests and via microhardness measurements. The results show that the applied cumulative HE route, leads to a substantial grain size refinement accompanied by high increase in strength. In comparison to commercial alloy after conventional plastic treatment, ultimate tensile strength and yield strength were higher by 45% and 130% respectively.

Keywords: severe plastic deformation, hydrostatic extrusion, grain refinement, copper alloys

Stop C65500 jest wysoko wytrzymałym stopem inżynierskim charakteryzującym się bardzo dobrą odpornością korozyjną w wielu agresywnych środowiskach. Połączenie odporności korozyjnej, wysokiej wytrzymałości i podatności do przeróbki plastycznej sprawia że jest powszechnie stosowanym stopem miedzi. W pracy stop C65500 został poddany dużym odkształceniom plastycznym metodą wyciskania hydrostatycznego na zimno. Celem przeprowadzonej obróbki było podniesienie wytrzymałości na drodze rozdrobnienia mikrostruktury, bez modyfikacji składu chemicznego stopu. Zastosowano kumulacyjny proces wyciskania hydrostatycznego z łącznym odkształceniem rzeczywistym 4.1. Mikrostrukturę odkształconych próbek obserwowano techniką transmisyjnej mikroskopii elektronowej (TEM). Określono ilościowo średnie wielkości ziaren. Własności mechaniczne były zmierzone w testach rozciągania oraz za pomocą pomiarów mikrotwardości. Uzyskane wyniki wskazują, że zastosowanie kumulacyjnego wyciskania hydrostatycznego prowadzi do wyraźnego rozdrobnienia wielkości ziarna czemu towarzyszy znaczny wzrost wytrzymałości. W porównaniu ze stopem komercyjnym przerabianym na zimno metodami konwencjonalnymi uzyskano wzrost wytrzymałości na zrywanie oraz granicy plastyczności odpowiednio 45% i 130%.

1. Introduction

Severe Plastic deformation (SPD) applied to metals and alloys yields solid materials with a nanocrystalline (NC) or ultrafine grained (UFG) structure [1]. Formation of such structures results in a considerable improvement of the mechanical properties of materials. A very high mechanical strength is usually accompanied by a reserve of plasticity on a level unachievable with classical techniques employing conventional hardening methods [2, 3]. Among the most popular SPD techniques there are high-pressure torsion HPT and equal channel angular pressing ECAP and multiply forging MP [1, 3-6]. In the case of hard-to-deform materials, all these methods are usually performed at elevated temperature.

Hydrostatic extrusion (HE) conducted at room temperature is an efficient and promising method for fabrication of NC and UFG structures in titanium, Al-alloys, Cu-alloys, Mg-alloys, iron, 316LVM steel and nickel [2, 7-13].

In the present study, we report the possibility of structure modification (refinement) and mechanical properties improvement for a silicon bronze (Cu-3%Si-1%Mn-0.4%Zn-0.2%Fe) processed by hydrostatic extrusion. C65500 is a high strength engineering alloy that has excellent resistance to a wide range of corrosive environments, including fresh and salt water, most acids, alkalies, salts and organic chemicals. It has a combination of corrosion resistance, strength, and forma-

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bility that places it among the most widely used copper alloys. Typical rod-shape applications of silicon bronze alloy include electrical conduits, valve stems, tie rods, fasteners, marine and pole-line hardware, nuts, bolts, screws, rivets, nails, and wire.

2. Experimental procedure

Commercial C65500 alloy 40 mm rods have been hydrostatically extruded in 5 steps at room temperature with a total true strain of 4.1. Before HE samples were solution heat treated at 900°C for 2 hour and water quenched. HE process was carried out in a cumulative manner with one pass strains 1.28, 0.7, 0.67, 0.6, 0.45, 0.40 until the final diameter was reduced to 5 mm. Pressure characteristics p=f(lnR),where R is the reduction ratio, of HE process for C65500 alloy is show in Fig. 1. At the die exit, the samples have been water quenched to reduce undesirable recovery and recrystallisation phenomena. The starting microstructures were analyzed by light microscopy LM whereas after deformation by transmission electron microscopy TEM. The grain size was determined by measuring equivalent diameter (d2) defined as a diameter of circle with a surface area equal to a given grain. The mechanical properties were evaluated by static tensile tests conducted at room temperature. Microhardness (HV0.2) of the material was also measured at the transverse cross section of the rods.

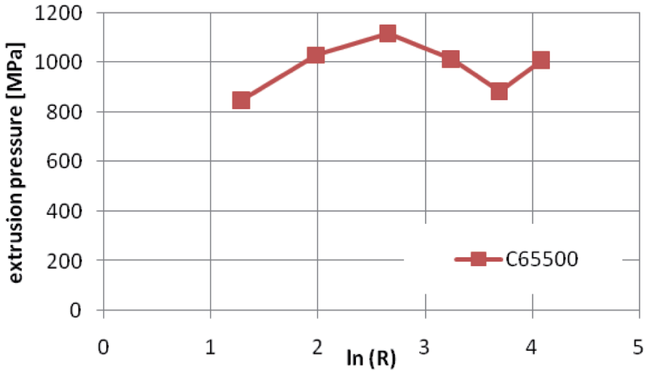

Fig. 1. Pressure characteristics p=f(lnR) of cumulative HE process of C65500 alloy

3. Results and discussion

Material after quenching exhibits coarse grain microstructure with the average equivalent grain diameter $E_{(d2)}$~200 μm. The annealing twins within microstructure are observed, Fig.2a. After HE, the observed microstructure is highly refined, Fig. 2b. The average grain size was $E_{(d2)}$ = 60 nm with grain size variation coefficient $CV_{(d2)}$ = 0.53. It is over three order of magnitude grain refinement in compare to initial state. Grains size distribution is typical for homogeneous fine structure, Fig. 3.

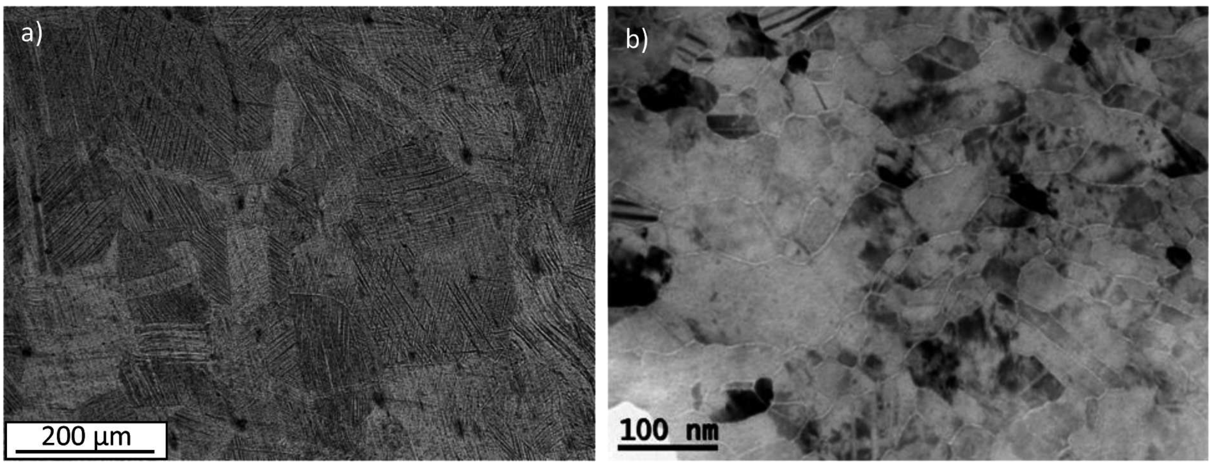

Fig. 2. C65500 microstructures: a) after solution heat treatment SST, b) after hydrostatic extrusion HE

TABLE 1

Mechanical properties of C65500 alloy after HE in comparison to commercial cold worked C65500 alloy and austenitic stainless steel

Material	C65500 after HE	C65500 – Herculoy ®	BioDur ®316LS Cold Worked
UTS [MPa]	1250	860	1034
YS [MPa]	1035	450	848
Elongation [%]	8	5	16

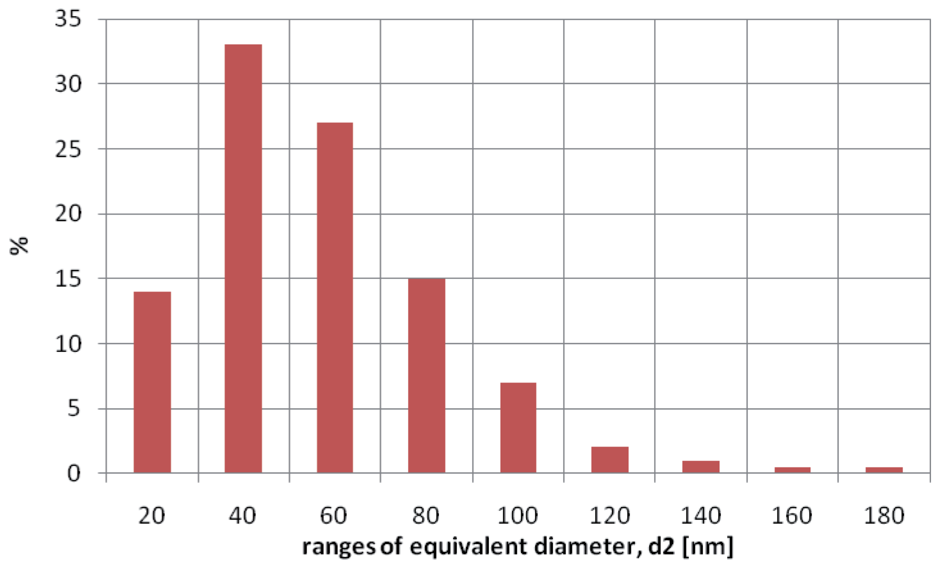

Fig. 3. Grains sizes distribution for C65500 alloy after hydrostatic extrusion with total (cumulative) of 4.1 true strain

Such a grain size refinement results in an enormous increase in mechanical strength (UTS=1250 MPa, YS=1035 MPa) and moderate ductility (8% elongation). For comparison, the commercial high-silicon bronze Herculoy®in the hard state after conventional deformation process has UTS=860 MPa and YS=450 MPa with 5% of elongation [14], Tab.1. This excellent combination of exceptionally high strength and reasonable ductility can be attributed to a very small grain size (60 nm) which implies grain boundary strengthening according to the well known Hall-Petch relationship and the presence of nanotwins inside the small grains, which are known to enhance ductility of NC materials [15].

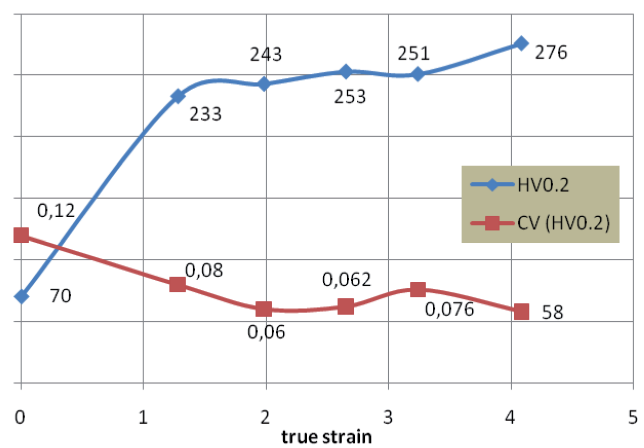

Fig. 4. Changes of microhardness HV0.2 and coefficient of variation $CV_{(HV0.2)}$ as a function of true strain during HE

Fig. 4 shows changes in microhardness (HV0.2) and coefficient of variation $CV_{HV0.2}$ as a function of cumulative true strain. A maximum hardness of 276 HV0.2 has been obtained after the last HE step. However, the plateau in HV0.2 is obtained starting for true strain ~2. Decrease of coefficient of variation with increasing true strain indicates more homogeneous microhardness distribution. This fact proves the better microstructure homogenization after HE.

4. Conclusions

HE process with cumulative true strain 4.1 applied to C65500 alloy led to significant increase of the strength properties. In comparison to commercial alloy after conventional plastic deformation process, the ultimate tensile strength and yield strength were higher by 45% and 130% respectively remaining elongation at the acceptable level. Such high mechanical properties were related with enormous refinement of microstructure during HE. Homogeneous microstructure with mean grain size E(d2)~ 60nm was observed. The fabricated material – high strength silicon bronze C65500 alloy can be attractive for various application where the operation under high load in corrosive environments is necessary.

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REFERENCES

[1] R. Valiev, Nanostructuring of metals by severe plastic deformation for advanced properties, Nature **3**, 511-516 (2004).

[2] M. Kulczyk, W. Pachla, A. Mazur, M. Sus-Ryszkowska, N. Krasilnikov, K.J.

K u r z y d ł o w s k i, Producing bulk nanocrystalline materials by combined hydrostatic extrusion and equal channel angular pressing, Materials Science Poland, **25 No 4**, 991-999 (2007).

[3] V.M. S e g a l, Materials processing by simple shear, Materials Science and Engineering A **197**, 157-164 (1995).

[4] R.Z. V a l i e v, R.K. I s l a m g a l i e v, I.V. A l e x a n d r o v, Bulk nanostructured materials from severe plastic deformation, Progress in Materials Science **45**, 103-189 (2000).

[5] A.P. Z h i l y a e v, B.-K. K i m, J.A. S z p u n a r, M.D. B a r o, T.G. L a n g d o n, The microstructural characteristics of ultrafine-grained nickel, Materials Science and Engineering A **391**, 377-389 (2005).

[6] E. S c h a f l e r, R. P i p p a n, Effect of thermal treatment on microstructure in high pressure torsion (HPT) deformed nickel, Materials Science and Engineering A **387-389**, 799-804 (2004).

[7] W. P a c h l a, M. K u c z y k, M. S u s - R y s z k o w s k a, A. M a z u r, K.J. K u r z y - d ł o w s k i, Nanocrystalline titanium produced by hydrostatic extrusion, Journal of Materials Processing Technology **205,** 173-182 (2008).

[8] W. P a c h l a, M. K u l c z y k, A. M a z u r, M. S u s - R y s z k o w s k a, UFG and nanocrystalline microstructures produced by hydrostatic extrusion of multifilament wires, International Journal of Materials Research (formerly Z. Metallkd.) **100**, 984-990 (07/2009).

[9] J. B u d n i a k, M. L e w a n d o w s k a, W. P a c h l a, M. K u l c z y k, K.J. K u r z y d ł o w s k i, The influence of hydrostatic extrusion on the properties of an austenitic stainless steel, Solid State Phenomena **114**, 57-62 (2006).

[10] W. P a c h l a, A. M a z u r, J. S k i b a, M. K u l - c z y k, S. P r z y b y s z, Wrought Magnesium Alloys ZM21, ZW3 AND WE43 processed by hydrostatic extrusion with back pressure, Archives of Metallurgy and Material **57**, 2, 485-493 (2012).

[11] W. P a c h l a, M. K u l c z y k, A. S w i d e r s - k a - S r o d a, M. L e w a n d o w s k a, H. G a r b a c z, A. M a z u r, K.J. K u r z y d ł o w s k i, Nanostructuring of metals by hydrostatic extrusion, Proceedings of 9th International Conference on Metal Forming ESAFORM 2006, Eds. N. Juster, A. Rosochowski, Publ. House Akapit, 535-538 (2006).

[12] M. L e w a n d o w s k a, Stability of second phase particles during processing by hydrostatic extrusion, Archives of Metallurgy and Materials **51**, 569-574 (2006).

[13] B. Z y s k, M. K u l c z y k, M. L e w a n d o w s k a, K.J. K u r z y d ł o w s k i, Effect of heat treatment and hydrostatic extrusion on mechanical properties of a CuCrZr alloy, Archives of Metallurgy and Materials **55**, 143-149 (2010).

[14] www.matweb.com

[15] K. L u, Novel properties of nanostructured metals, Materials Science Forum **475-479**, 21-30 (2005).

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