

Original Research

EFFECT OF Ni AND Si ADDITIONS ON
FUNCTIONAL PROPERTIES OF Cu-30Zn BRASS

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Ljubiša T. Balanović^{1,a*}, Uroš S. Stamenković^{1,b}, Ivana I. Marković^{1,c},
Kristina N. Božinović^{1,d}, Milan D. Gorgievski^{1,e}, Vesna J. Grekulović^{1,f},
Teodora S. Jogrić^{1,g}

¹ University of Belgrade, Technical Faculty in Bor, Vojske Jugoslavije 12, 19210 Bor, SERBIA

^a <https://orcid.org/0000-0002-3551-6731> ^b <https://orcid.org/0000-0002-7579-2159>

^c <https://orcid.org/0000-0003-4431-9921> ^d <https://orcid.org/0000-0002-9834-448X>

^e <https://orcid.org/0000-0002-9899-719X> ^f <https://orcid.org/0000-0001-6871-4016>

^g <https://orcid.org/0009-0009-6582-8160>

Abstract

The present work investigates the effect of Ni and Si additions on functional properties of Cu-30Zn brass. One base alloy without Ni and Si additions and one alloy with Ni and Si additions were prepared by conventional casting from high-purity Cu, Zn, Ni and Si, followed by solution annealing at 900 °C for 2 h and water quenching, cold pressing, and subsequent ageing at 300 °C for 8 h. Building on earlier studies of Ni₂Si-strengthened Cu–Zn and Cu–Ni–Si alloys, this processing route was selected to promote the formation of fine Ni–Si-rich precipitates within an α -brass matrix and to combine solid-solution and precipitation strengthening with acceptable electrical and thermal conductivities. The heat-treated alloys were characterized by measurements of electrical conductivity, Vickers microhardness (HV0.15), Leeb hardness (HLD) and thermal conductivity. Increasing Ni and Si contents is expected to raise hardness through solid-solution and Ni₂Si-type precipitation strengthening, while moderately reducing conductivity due to enhanced electron scattering by solute atoms and nanoscale particles. The results of this study provide composition–property guidelines for designing lead-free, precipitation-strengthened brasses based on the Cu-30Zn system.

Keywords: Cu-30Zn brass, precipitation, microhardness, conductivity.

INTRODUCTION

Brass alloys are widely used in electrical and mechanical engineering due to their combination of good corrosion resistance, satisfactory strength and relatively high electrical and thermal conductivity [1,2]. Recent work on next-generation lead-free $\alpha + \beta$ brasses has further highlighted the need to maintain these properties while eliminating lead, especially for free-cutting and plumbing applications where human exposure and environmental release are critical concerns [3]. Systematic reviews of lead-free brass development for machining applications highlight the dual challenge of meeting increasingly strict environmental

* ljbalanovic@tfbor.bg.ac.rs

regulations while achieving machinability and performance comparable to conventional leaded brasses [4].

In recent years, special attention has been paid to Ni–Si-modified brasses, in which fine Ni_2Si precipitates provide significant precipitation strengthening while maintaining acceptable conductivity [1,2,5,6].

Chen *et al.* showed that the addition of 1.5–3 wt.% Ni and 0.34–0.68 wt.% Si to Cu–20Zn brass, followed by appropriate thermo-mechanical treatment, can almost double the tensile strength compared to conventional Cu–Zn alloys due to combined solid-solution and Ni_2Si precipitation strengthening [1], building on their earlier work on Ni–Si-modified Cu–10Zn and Cu–20Zn alloys [5]. In that previous study, the same authors examined Cu–10Zn and Cu–20Zn alloys with small Ni and Si additions in order to obtain high-strength brasses without a serious loss of ductility. They related the large increase in strength mainly to solid-solution and Ni_2Si -type precipitation strengthening and to the corresponding microstructural changes in the Cu–Zn matrix [5].

Systematic studies on Cu–Ni–Si alloys have demonstrated that an optimized Ni/Si mass ratio of about 4–5 leads to a dense distribution of nanoscale Ni_2Si precipitates and a favourable balance between hardness, strength and electrical conductivity [2].

Shan *et al.* used CALPHAD-aided design to develop complex Cu–Zn–Ni–Si brasses and to clarify how $\delta\text{-Ni}_2\text{Si}$ precipitates form and evolve as the main reinforcing phase in these alloys. By combining thermodynamic calculations with experimental verification, they optimised the alloy composition and heat-treatment parameters to promote a high volume fraction of finely dispersed $\delta\text{-Ni}_2\text{Si}$ particles, which provide strong precipitation strengthening while retaining acceptable toughness and castability [6].

Zhou and Su reported a novel Cu–Ni–Zn–Al alloy in which high strength is achieved primarily through a controlled precipitation-hardening treatment. In their study, they showed that suitable aging conditions lead to the formation of a fine, homogeneous distribution of strengthening precipitates in the Cu–Ni–Zn matrix, resulting in a marked increase in yield and tensile strength while maintaining reasonable ductility [7].

Rojas-Rodríguez *et al.* investigated how different precipitation-heat-treatment temperatures affect the microstructure, thermal properties and microhardness of an α -brass, showing a clear link between ageing conditions and property changes [8].

At the same time, there is growing interest in replacing traditional leaded brasses with environmentally friendly, precipitation-strengthened alloys that offer similar machinability and strength without toxic elements and with reduced environmental and health impacts of alloy production and recycling [1–3]. In this context, Ni–Si-strengthened Cu-based alloys are considered promising candidates for lead-free components in electrical and mechanical applications where a combination of high strength, good conductivity and improved environmental compatibility is required [1,2].

Previous work on Cu–30Zn brass has mainly focused on the effect of cold work and annealing on twin formation and anneal hardening, while systematic data on the influence of small Ni and Si additions on functional properties of Cu–30Zn-based alloys are still limited [1,9].

Therefore, the present study focuses on Cu-30Zn-based alloys with a small amount of Ni and Si, in order to clarify how these additions, in combination with solution treatment and ageing, influence conductivity and hardness.

MATERIALS AND METHODS

Experimental Procedures

Alloy preparation

Two Cu-30Zn- x Ni- y Si alloys (L1–L2) were prepared from high-purity cathode copper, zinc, nickel and silicon. The charge for each composition was melted in an electric resistance furnace using a graphite crucible and a protective flux. After complete melting and initial homogenization, the alloy was remelted several times, with the crucible periodically inverted to enhance chemical homogeneity. In designing the alloy with additions, the Ni and Si contents were selected to maintain a Ni:Si mass ratio of 4.4:1, following previous CALPHAD-assisted studies on Ni-Si reinforced brass alloys [6], and experimental investigations of Ni₂Si-strengthened Cu-Zn brasses [1]. The nominal chemical compositions of the alloys are listed in Table 1.

Table 1 Chemical composition of the alloys

Sample	Ni (wt.%)	Si (wt.%)	Cu (wt.%)	Zn (wt.%)	Total (wt.%)
L1	0	0.00	70.00	30.00	100
L2	0.5	0.11	69.57	29.82	100

Solution treatment and ageing

The cast alloys were machined to remove surface defects. All samples were solution annealed at 900 °C for 2 h in air, followed by immediate quenching in water to obtain a supersaturated α -brass matrix. The heat-treatment schedule and deformation route were adopted from previous studies on Ni₂Si-strengthened Cu-Zn brasses [1], where specimens were hot-rolled by 80% and subsequently cold-rolled by 80%. In the present work, after solution annealing and quenching, the specimens were cold pressed in a hydraulic press under a load of 15 t in order to introduce a comparable level of plastic deformation prior to ageing. Ageing was carried out at 300 °C for 8 h in a resistance furnace, followed by air cooling to room temperature. All property measurements and investigations were performed on samples in this aged condition.

Property characterization

Electrical conductivity was measured at room temperature using a Sigmatess 2.063 eddy-current device on flat, ground specimens; for each alloy, at least five readings were taken and averaged. Microhardness was determined by the Vickers method (HV0.15) with a 0.15 kgf load and 10 s dwell time, and a minimum of five indents per condition were performed on polished cross-sections. Macroscopic hardness was evaluated using a portable Leeb hardness tester Time 5350, and the results are reported in HLD units. Thermal conductivity was determined indirectly from the measured thermal diffusivity and the specific

heat capacity of each alloy, using the approach originally proposed by Parker et al. [10,11], for homogeneous materials. Thermal diffusivity was measured by the light-flash method using a Discovery Xenon Flash (DXF 500 - TA Instruments) apparatus on disc-shaped samples with both faces finely polished, at 25, 50, 100, 200, 300, and 400 °C, and the thermal conductivity was then calculated for each composition and temperature using equation 1. In this method, once the thermal diffusivity and the specific heat capacity are known, the thermal conductivity can be calculated as the product of density, specific heat capacity and thermal diffusivity:

$$\lambda = \alpha \cdot \rho \cdot C_p \quad (1)$$

where: λ is the thermal conductivity (W/mK), α is the thermal diffusivity (m²/s), ρ is the density (kg/m³) and C_p is the specific heat capacity (J/kgK).

The specific heat capacity of the investigated alloys was obtained by comparing the temperature rise of the sample with the temperature of a reference material of known specific heat under identical differential measurement conditions.

RESULTS AND DISCUSSION

Table 2 summarizes the basic geometrical characteristics and densities of the investigated samples L1 and L2, which were prepared as disc-shaped cylinders with a diameter of 12.7 mm.

Table 2 Geometrical characteristics and densities of samples L1 and L2

Sample	Mass (g)	Height (mm)	Height (cm)	Diameter (mm)	Diameter (cm)	Base area (cm ²)	Volume (cm ³)	Density (g/cm ³)	Density (kg/m ³)
L1	4.17	3.86	0.386	12.81	1.281	1.2882	0.4972	8.3865	8387
L2	4.02	3.72	0.372	12.82	1.282	1.2902	0.4799	8.3760	8376

Electrical conductivity measurements

Results of the electrical conductivity measurements are presented in Table 3, which lists the mean value of five measurements taken on each side of the sample and the corresponding overall average value for each alloy, while Table 4 compares these results with literature data for Cu–Zn brasses.

Table 3 Electrical conductivity of Cu-30Zn–Ni–Si alloys

Sample	Side I (MS/m)	Side II (MS/m)	Average (MS/m)
L1	12.9	14.3	13.6
L2	12.1	12.5	12.3

The base Cu–30Zn alloy from this work exhibits an electrical conductivity of 13.6 MS/m (23.45%IACS), which is lower than the nominal industrial value of about 16 MS/m (≈28%IACS). This reduction can be attributed to differences in thermomechanical processing

and cold pressing, as well as to microstructural defects and residual stresses associated with the specific melting and heat-treatment route used in this study.

Table 4 Comparison of electrical conductivity of Cu–Zn brasses in this work and literature

Sample	Electrical conductivity (MS/m)	Electrical conductivity (%IACS)	References
(L1)	13.6	23.45	This work
(L2)	12.3	21.21	This work
Cu–20Zn–1.5Ni–0.34Si	12.9	22.3	[1]
Cu–20Zn–3Ni–0.68Si	12.5	21.6	[1]
Cu–20Zn–15Ni	4.06	7	[12]
Cu–20Zn–10Ni–1.2Al	6.38	11	[7]

The addition of 0.5 wt.% Ni and 0.11 wt.% Si in Cu–30Zn leads to a moderate decrease in conductivity to 12.3 MS/m (21.21%IACS), consistent with the expected reduction due to solid-solution and precipitation strengthening. In contrast, alloys containing higher Ni contents, such as Cu–20Zn–15Ni [12] and Cu–20Zn–10Ni–1.2Al [7], show significantly lower conductivities (down to about 7%IACS, and 11%IACS), illustrating the strong detrimental effect of high Ni additions on electrical transport.

Vickers microhardness measurements (HV_{0.15})

Results of the Vickers microhardness measurements (HV_{0.15}) for samples L1 and L2 are presented in Table 5, showing individual indentations on both sides of each sample and the corresponding mean values.

Table 5 Vickers microhardness (HV_{0.15}) of samples L1 and L2

Sample	Side I			Mean (Side I)	Side II			Mean (Side II)
	I	II	III		I	II	III	
L1	131.48	124.57	122.92	126.30	121.31	109.48	115.17	115.30
L2	124.57	133.30	127.95	128.60	126.24	109.48	124.57	120.10

The measured microhardness values (about 115–129 HV_{0.15}) fall within the range typically reported for thermomechanically treated Cu–30Zn brasses [1,5,9,13], with hardness values around 110–130 HV depending on the degree of cold work and alloying additions. The slightly higher mean hardness of L2 compared to L1 is consistent with reports in the literature that Ni and Ni₂Si-type precipitates contribute to additional strengthening of Cu–Zn brasses through solid-solution and precipitation hardening mechanisms [1,2,5,14].

Leeb hardness measurements (HLD)

Results of the Leeb hardness measurements (HLD) for samples L1 and L2 are presented in Table 6, showing individual impacts on both sides of each sample and the corresponding

mean values. The measured Leeb hardness values (about 350–422 HLD) correspond, according to standard hardness conversion charts [15], to Vickers hardness levels on the order of 110–130 HV, which is consistent with the microhardness results obtained for these alloys. Such hardness levels are in line with reported values for cold-worked or precipitation-strengthened CuZn30-based brasses [1,5], confirming that the applied thermomechanical treatment and Ni–Si additions provide a noticeable increase in hardness compared with annealed CuZn30 products described in datasheet literature [16].

Table 6 Leeb hardness (HLD) of samples L1 and L2

Sample	Side I			Mean (Side I)	Side II			Mean (Side II)
	I	II	III		I	II	III	
L1	343	247	461	350	376	379	338	364
L2	439	355	472	422	380	400	374	385

Thermal conductivity measurements

Thermal diffusivity, thermal conductivity and specific heat capacity were measured three times for each condition, and the values reported in Table 7 represent the corresponding mean values for samples L1 and L2.

Table 7 Thermal diffusivity, thermal conductivity and specific heat capacity of samples L1 and L2

Temperature (°C)	Thermal diffusivity (mm ² /s)		Thermal conductivity (W/mK)		Specific heat capacity (J/kgK)	
	L1	L2	L1	L2	L1	L2
25	35.42	30.90	131.49	112.02	421.25	411.53
50	36.30	32.52	135.09	114.43	432.10	420.12
100	38.73	34.65	138.13	124.77	425.35	422.23
200	41.37	37.42	152.06	137.29	438.25	438.05
300	43.22	39.41	161.59	147.00	445.78	445.37
400	44.71	41.79	172.83	162.89	460.87	465.37

The thermal diffusivity of L1 increased from 35.42 mm²/s at 25 °C to 44.71 mm²/s at 400 °C, whereas L2 increased from 30.90 mm²/s to 41.79 mm²/s over the same temperature range. In all cases, L1 exhibited higher diffusivity than L2, suggesting more efficient heat transport in the base alloy. The increase with temperature is typical for this type of material and can be related to changes in the thermal response of the matrix, as well as the temperature dependence of heat-carrier scattering.

The thermal conductivity of L1 rose from about 131.5 W/mK at 25 °C to 172.8 W/mK at 400 °C, while L2 increased from 112.0 W/mK to 162.9 W/mK. Again, L1 showed consistently higher values than L2 at all temperatures, which indicates that the Ni–Si additions reduced thermal transport in the alloy. This behaviour may be explained by increased scattering of heat carriers by solute atoms and possible second-phase particles,

together with the general temperature dependence of thermal properties in copper-based alloys.

The specific heat capacity of L1 was about 421 J/kgK at 25 °C and increased to around 461 J/kgK at 400 °C, while L2 changed from approximately 411 J/kgK to 465 J/kgK. Both alloys showed a gradual increase in C_p with temperature, which is expected because more vibrational modes become active as temperature rises. Small differences between L1 and L2 most likely reflect compositional differences and the effect of microstructure on heat storage.

Overall, the base Cu–30Zn alloy (L1) showed higher thermal diffusivity and thermal conductivity than the Ni–Si-containing alloy (L2) across the whole temperature range, indicating that the additions reduced thermal transport, while the effect on specific heat capacity was comparatively small.

Figures 1 show the temperature dependence of thermal diffusivity (a), specific heat capacity (b) and thermal conductivity (c) for alloys L1 and L2, together with literature data from [17], which reports our previously published results for a Cu–30Zn brass produced in the Sevojno Copper Rolling Mill.

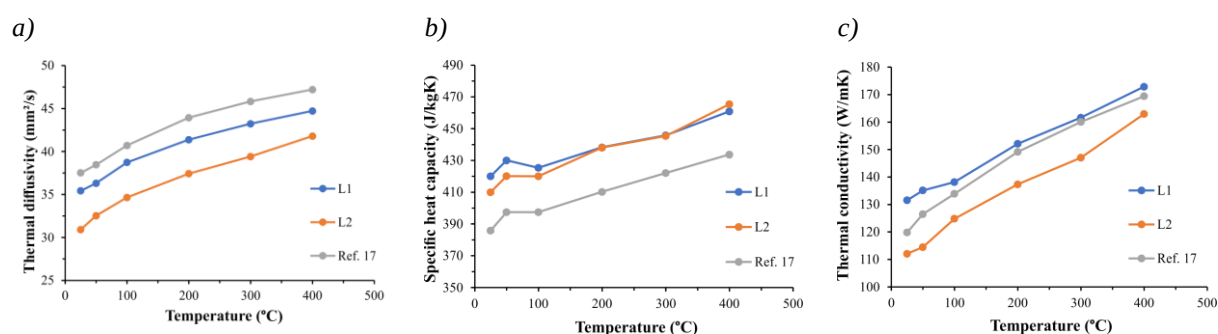


Figure 1 Temperature dependence of (a) thermal diffusivity, (b) specific heat capacity and (c) thermal conductivity of investigated alloys L1 and L2, compared with literature data for Cu–30Zn brass [17]

In our previous work [17], the examined sample was annealed at 540 °C for 4 h, had a composition of 70.1 wt.% Cu (balance Zn) with small amounts of impurities (0.001 wt.% Pb and 0.017 wt.% F), and was in a fully soft condition with an average grain size of about 0.035 mm. In this reference state, the material represents a well-annealed α -brass with relatively coarse grains, whereas in the present study, L1 and especially L2 were subjected to a different thermomechanical route (solution treatment, quenching, and cold pressing) and, in the case of L2, modified by Ni–Si additions. As a consequence, L1 generally exhibits slightly higher thermal transport properties than the annealed Cu–30Zn from [17], while L2 remains below both L1 and the reference curve, which is consistent with the combined influence of Ni–Si microalloying and the altered processing on thermal conductivity, thermal diffusivity and specific heat capacity.

CONCLUSION

The present study examined the effect of small Ni and Si additions on functional properties of Cu–30Zn brass processed by solution annealing, water quenching, cold pressing and

ageing. The results show that the Ni–Si-modified alloy L2 (0.5 wt.% Ni, 0.11 wt.% Si) achieves higher Vickers microhardness and Leeb hardness than the base Cu–30Zn alloy L1, confirming that the applied thermo-mechanical treatment promotes combined solid-solution and precipitation strengthening, most likely associated with the formation of fine Ni–Si-containing phases within the α -brass matrix.

At the same time, both electrical and thermal conductivities of L2 are moderately reduced compared with L1, but remain within the range reported for technologically relevant Cu–Zn brasses and previously studied Ni₂Si-strengthened alloys, thus preserving acceptable functional performance. Thermal diffusivity, thermal conductivity and specific heat capacity of both alloys increase with temperature, in agreement with literature data for α -brasses and Cu-based alloys, while L1 consistently exhibits higher thermal transport than L2 over the entire temperature range, reflecting the influence of Ni–Si additions and processing on heat-carrier scattering. The present results indicate that minor Ni–Si additions to Cu–30Zn brass, combined with an appropriate heat-treatment route, offer a viable strategy for designing lead-free, precipitation-strengthened brasses that achieve an improved strength–conductivity balance suitable for applications requiring both mechanical robustness and good thermal and electrical conductivity.

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