

Article

Development of a Dezincification-Free Alloy System for the Manufacturing of Brass Instruments

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Abstract: Conventionally used brass alloy CuZn30 shows problems with corrosion resistance in the form of dezincification when used in brass instruments. Therefore, within the scope of this investigation, a new brass alloy CuZn30 is developed in the microalloy range with corrosion-free or corrosion-inhibiting properties. First, the influence of microalloying elements on the phase composition is investigated by simulation using Thermo-Calc. On the basis of this, suitable alloying elements and contents are selected and a modified CuZn30X alloy with 0.1% phosphorus, tin, and nickel in mass fractions, respectively, is produced. The modified alloy is then investigated with regard to its mechanical and microstructural composition and its corrosion properties. The corrosion properties were examined using stress corrosion cracking tests, dezincification tests, and the recording of polarization curves. The modified alloy exhibited good cold and hot rolling properties as well as good corrosion resistance. The dezincification test confirmed the improved corrosion resistance of the modified CuZn30X alloy, which is attributed to the formation of a protective top layer due to the alloying elements.

Keywords: brass alloys; dezincification; corrosion resistance; thermodynamic calculations; mechanical properties



Citation: Berndorf, S.; Markelov, A.; Guk, S.; Mandel, M.; Krüger, L.; Prahll, U. Development of a Dezincification-Free Alloy System for the Manufacturing of Brass Instruments. *Metals* **2024**, *14*, 800. <https://doi.org/10.3390/met14070800>

Academic Editor: Antoni Roca

Received: 24 May 2024

Revised: 1 July 2024

Accepted: 4 July 2024

Published: 9 July 2024



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1. Introduction

Brass is used in brass instrument manufacturing because of its shiny golden color, special acoustics, and last but not least, good formability. The most common brass alloys have a zinc content of 5% to 45%. In the brass instrument industry, CuZn30 is preferred. The phase diagram [1] shows the α -solid solution region, up to a zinc content of 37.5 wt.% at 454 °C, where zinc dissolves completely in copper. At higher zinc content (approximately 37 to 46 at. % Zn), an additional bcc β -phase occurs. The addition of various alloying elements can favor or inhibit the formation of the β -phase [2,3]. Due to the bcc crystal structure, the β -phase shows poorer formability in contrast to single-phase α -solid solution alloys. Brass color is also determined by the alloy content of zinc from reddish gold (CuZn5) to golden yellow (CuZn15) and a rich yellow tone (CuZn37) [4]. Even the addition of small amounts of other alloying elements can significantly change the color. However, in a traditional industry, such as instrument making, this is usually not welcome.

Brass instrument manufacturers have noticed increasing signs of dezincification in the CuZn30 alloy, which is the most widely used brass material today (Figure 1). Dezincification is one of the most common selective corrosive phenomena in brass alloys. The cause of dezincification is generally attributed to the attack of an active medium. There are two hypotheses regarding the exact process of dezincification [5–10]. One hypothesis describes dezincification as the dissolution of brass by a medium and the subsequent reduction in copper on the material surface [4,11]. Another hypothesis considers the process of dezincification as the selective dissolution of zinc [12]. There is also the possibility that

both mechanisms occur simultaneously [5–8,13–15]. Another corrosion sign in copper alloys is stress corrosion cracking. The prerequisite for its occurrence is the sensitivity of the alloy to stress corrosion cracking and the occurrence of internal or external tensile stresses in conjunction with an active medium. If all three criteria occur simultaneously, an intergranular or transgranular fracture occurs without a previously detectable corrosion attack [4,16]. Brass with a higher zinc content is more sensitive to stress corrosion cracking than brass with a lower zinc content [17,18]. Brass components strengthened by forming have an increased risk of the formation of residual stresses, requiring special consideration for stress corrosion cracking. Brass instruments are exposed to various potential media that can lead to corrosion. The main ones are human hand perspiration and the high humidity inside the instruments combined with saliva.



Figure 1. Dezincification of brass instruments.

Human hand perspiration contains fatty acids, urea, uric acid, cholesterol, protein, and table salt, among others, and varies in its composition depending on the diet, for example [4]. Stress corrosion cracking is caused by the effect of ammonia, which acts on the material through perspiration [19]. Furthermore, the high humidity inside, in combination with saliva residues, is responsible for corrosion phenomena. After just a few minutes of playing, the relative humidity in the instruments is already greater than 90%, and it takes 2–3 days of non-playing to reduce the humidity to 50% [20,21]. The composition of saliva also depends on the diet of the musicians. The increased consumption of salty or sugary food leads to the formation of chlorine-containing solutions or to an acidic pH value [22,23]. In combination, this creates an acidic chloride-containing active medium within the instruments. It should also be noted that dezincification is strongly dependent on the concentration of Cl^- anions and pH value [24].

Another reason for the increased susceptibility of the instruments to dezincification could be the alloy composition. Historical brass instruments contain a variety of impurities, including lead, tin, zinc, iron, nickel, arsenic, antimony, and silver [25–28]. In contrast to today's brass alloys of the highest purity, these historic brass alloys rarely show signs of dezincification. Among the impurities in historical instruments, the elements arsenic, antimony, silver, and nickel are known to inhibit dezincification [29,30]. In addition, auxiliary devices that simplify the forming process are being increasingly used in the traditional craft of making brass instruments. For example, the use of a bending machine speeds up the shaping process while bending a tuning slide, but the risk of microcracks forming in the material occurs. Microcracks in the material can serve as preferred points of attack for corrosion [31]. Furthermore, the phase composition has a significant influence on corrosion resistance. The β -phase of the brass shows significantly lower corrosion resistance compared to the α -phase [29,32]. The α -brass has a higher noble potential with -0.38 V than the β -brass with -0.56 V [33], which is why corrosion in inhomogeneous alloys occurs preferentially in the β -phase. This is due to the high solubility of zinc, which is finally attacked in the β -phase [33,34].

Elements known from the literature to reduce dezincification are phosphorus, tin, nickel, aluminum, gold, silicon, arsenic, and antimony [13,16,29,30,35–37]. For environmental and health protection reasons, no further consideration was given to the elements As and Sb. Studies in the sanitary sector [36] show that adding phosphorus to an alloy of 62.6 Cu, 2.8 Pb, 0.1 Fe, and 0.07 Ni, with the remainder being Zn, improves corrosion resistance. Phosphorus additions of 0.00016, 0.057, and 0.137 wt.% reduced corrosion susceptibility in single-phase brass pipes for drinking water. The alloy with the highest phosphorus content had the lowest corrosion rate of 10.8 μm per year.

This is attributed to the inhibited dissolution of Zn from the α -brass due to the formation of a P-containing covering layer [36,38]. The growth of the oxide-containing top layer on CuZn21Si3P alloys increases the potential above the value for the redeposition of copper, which stops the dezincification [39]. Phosphorus, like arsenic, prevents the redeposition of copper and thus effectively inhibits dezincification [30]. The corrosion inhibitory effect of tin is due to the formation of a passivation layer [16,29]. The SnO_2 layer on the surface of the material prevents zinc from being dissolved by the corrosive medium. The tin concentration at the interface between the surface and the base metal is higher than inside [16,29]. The literature also refers to the formation of protective cover layers consisting of corrosion products containing copper and zinc, such as Cu_2O , ZnO , or CuCl_2 [40–43]. The addition of nickel in small quantities (<1 wt.%) only leads to a slight improvement in corrosion resistance in brass. In contrast, investigations [16,29] on the binary 60Cu-40Zn alloy showed good results through a combination with tin. The pure 60Cu-40Zn alloy showed a corrosion depth between 1500 and 2000 μm and the addition of tin reduced the corrosion depth to 650 μm . The best results were achieved with a content of 0.7% tin and 0.5% nickel with a corrosion depth of 350 μm . It is important to note that the effects influence each other [16,29].

The dezincification of the brass components of brass instruments is currently a major problem for brass instrument manufacturers. In addition to considerable economic damage due to warranty claims, the damage to the image, particularly in the brass instrument manufacturing industry, should not be neglected. Dezincification, however, is not merely an aesthetic issue; it can also lead to more severe structural problems, such as the formation of holes or cracks in the material [44,45]. Despite a large number of hypotheses, there have been no scientifically proven investigations into the causes of dezincification in brass instrument manufacturing. Therefore, the objective of this study is to develop a dezincification-resistant alloy for use in brass instrument manufacturing. The acceptance of new alloys among brass instrument manufacturers and musicians is limited due to expected changes in acoustic properties, coloration, and workability. For this reason, the CuZn30 alloy currently used can only be modified in the micro-alloy range.

2. Materials and Methods

First, the possible modifications of the CuZn30 alloy were simulated. Subsequently, a promising phase composition was selected. This modified CuZn30X alloy was cast, rolled, and examined with regard to its mechanical properties and susceptibility to corrosion.

2.1. Simulations

The phase composition was simulated using the “Thermo-Calc 2019b” program [46]. This simulation tool allows the thermodynamic modeling of multicomponent alloys, such as the composition and microstructure fractions of phases and precipitates. The calculation method is based on experimental and theoretical characteristic values, which are used in the calculations of the “CALPHAD method” (Calculation of Phase Diagrams). The calculation principle of mathematical models is based on the efforts to achieve phase equilibrium (the minimization of Gibbs free energy) [46]. The aim was to simulate potential alloys with additional alloying elements for the tendency to form the β -phase of brass. The starting point for the CuZn30 simulations is the brass alloy. For the simulation of the phase compositions after the addition of various elements in the microalloy range and in the

low-alloy range (X to 3.6 wt.%), the zinc content was kept constant at 30 wt.%, while the amount of the alloying element added was subtracted from the copper content:

$$(70 - X)\text{Cu} + 30\text{Zn} + X\text{ Alloying element}$$

Phase composition was simulated in steps of 0.01 wt.% for the microalloy range ($X \leq 0.1$ wt.%) and 0.1 wt.% were used for higher alloy contents ($X > 0.1$ wt.%). Phase composition was determined in a temperature range of 1227 to 127 °C. All simulations were carried out using the “Python” (<https://www.python.org/>) access to the “Thermo-Calc” copper database.

2.2. Alloy Production

The CuZn30X alloy was cast using the gravity die casting process with a VC400 casting machine (Indutherm Blue Power Casting Systems, Walzbachtal, Germany) with a casting weight of approximately 500 g. The raw material used was CuOFE and the master alloys CuZn36, CuP15, CuNi9Sn6, and tin as the pure element. The casting was carried out under vacuum in a rectangular graphite mold with a length of 200 mm, a width of 50 mm, and a thickness of 5 mm. The alloy composition was determined using an optical emission spark spectrometer (OES, Spectrotest, SPECTRO Analytical Instruments GmbH, Kleve, Germany) and is shown in Table 1.

Table 1. Chemical composition of the as-cast samples in wt.%.

Element	Cu	Zn	Ni	Sn	P
Average	66.97	32.63	0.15	0.09	0.17

The cast samples were cold rolled and hot rolled. Cold rolling was carried out in 10 passes to 0.97 mm ($\varphi = 1.64$). For hot rolling, the as-cast material was first annealed at 700 °C and then rolled to 1.04 mm ($\varphi = 1.57$) in 5 passes without intermediate heating. Samples of a CuZn30 alloy from the “Jürgen Voigt Meisterwerkstatt für Metallblasinstrumente” with a thickness of 0.53 mm, hereinafter referred to as the standard material, were available as a comparison for the corrosion tests.

2.3. Investigation

The phase composition of the CuZn30X alloy after cold and hot rolling, as well as the reference alloy CuZn30, was measured by XRD analysis using Co radiation ($\lambda = 1.78897$ Å). The diffraction patterns were recorded in the 2θ range of 20 to 150° with a step size of 0.01°. Furthermore, the scanning electron microscope (GeminiSEM 450, Zeiss, Oberkochen, Germany) equipped with an EDS detector (Ultim Max 100, Oxford Instruments, Abingdon, UK) was used for the analysis of dezincification. For the imaging, secondary electron (SE) (Zeiss, Oberkochen, Germany) contrast was used. Hardness was determined using the Vickers method as the mean value of five measurements. Before measurement, the oxide layer on the samples was removed using 1200 SiC paper (Struers, Willich, Germany).

2.4. Corrosion Analysis

To investigate the corrosion properties, the dezincification test was carried out according to DIN EN ISO 6509 [47] and the stress corrosion cracking test with ammonia according to DIN 50916 [48]. Furthermore, the polarization curves were recorded according to DIN 50918 [49]. The tests were carried out on the CuZn30X alloy after cold and hot rolling, as well as on the reference alloy CuZn30.

The stress corrosion according to DIN 50916 (Part 1) [48] was carried out with ammonia, as it detects the lowest residual stresses in the material [50]. The test samples consisted of three pieces each of cold and hot rolled CuZn30X as well as tube components from the brass instrument manufacturer. The modified alloy was taken from the rolled pieces and not further processed to check the susceptibility to stress corrosion cracking after the

basic forming steps. The samples were suspended in the ammonia vapor phase without touching each other and the test was carried out at a constant room temperature of 20 °C in a fume hood for 24 h. The main objective was to verify the minimum requirements for the modified alloy CuZn30X and the maximum requirements for the standard alloy CuZn30 using components for brass instruments. After the test, the samples were pickled in 10% sulfuric acid for 1 min exposure time at room temperature, as a black corrosion layer formed during the experiment, which can be identified as a Cu₂O-containing layer according to the literature [51].

The focus of the investigation with regard to corrosion resistance was on the dezincification test according to DIN EN ISO 6509 [47]. The samples were exposed to a 1% aqueous copper(II) chloride solution at 75 ± 5 °C for 24 h. The samples were then cleaned with water and ethanol and dried in hot air. To evaluate the dezincification, the samples were separated perpendicularly to the exposed test surface and embedded and prepared for further metallographic examination. Grinding was carried out using the tegrapol system (Struers, Willich, Germany) with SiC paper with grain sizes of 800, 1200, and 4000, followed by polishing with DiaPro Mol and OPS. Dezincification was metallographically examined in the polished state using optical microscopy (VHX 6000, Keyence Deutschland GmbH, Neu-Isenburg, Germany).

DIN 50918 [49] specifies the conditions for recording polarization curves, which are used to quantify the rate of metal dissolution or passivation based on the measured current density as a function of the applied voltage. Measurements were carried out at 37 °C in a 1 wt.% NaCl solution using a conventional three-electrode cell configuration with the sample as the working electrode, a platinum mesh as the counter electrode, a saturated Ag/AgCl as reference, and a potentiostat (PSV, Biologic Science, Seyssinet-Pariset, France). Tests performed at different scan rates indicate no significant changes in polarization characteristics, and the potential was ultimately increased with a scan rate of 1.5 mV/s. Reaching a current density of 1 mA/cm² was defined as the termination criterion. To ensure reproducibility, the polarization tests were repeated three times.

3. Results and Discussion

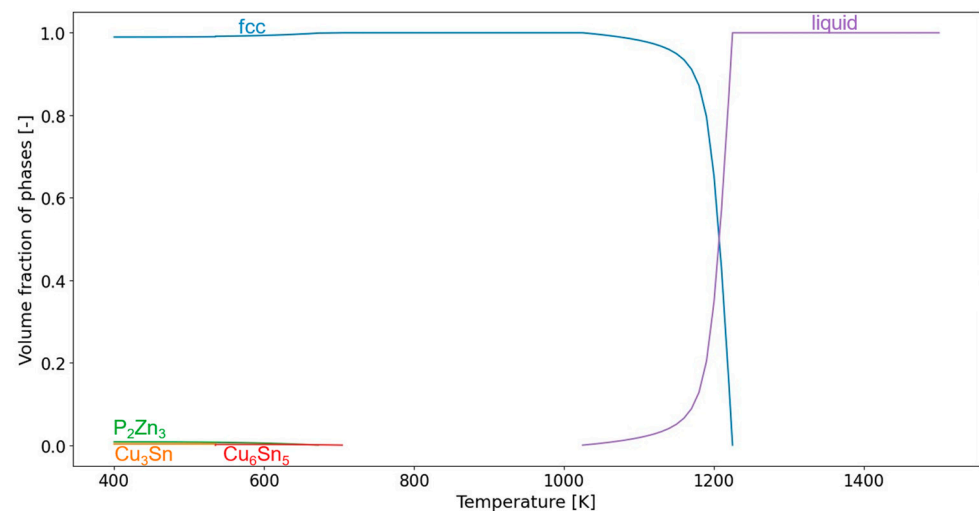
3.1. Simulations Using Thermo-Calc

The phase compositions determined using Thermo-Calc as a function of the additional alloying elements and their respective content are summarized in Table 2. The table shows the content of the elements in which the β -phase occurs, while the α -phase is the primary component in all simulated CuZn30X variants. To maintain clarity, the α -phase content is not included in the table. The appearance of the β -phase causes an increase in the tendency for corrosion on the one hand and an increase in strength with reduced cold formability on the other. The latter results in higher forming forces and the associated risk of microcracks during forming. Furthermore, additionally occurring phases and their element contents are indicated. It can be seen that there are only a few elements that form a consistently pure α -structure. These include only gold and platinum. These were not considered further as a result of the high metal price. Other elements, such as aluminum, have a negative effect on the solderability or coloration of the alloy [4].

Based on thermodynamic simulations and literature studies [16,29,35–37] the elements phosphorus, nickel, and tin were selected as alloying elements. The effectiveness of phosphorus in the microalloying range has been confirmed in the literature [35]. On the contrary, nickel and tin are added in the literature in higher contents compared to the microalloying range [29]. As a synergistic effect of both alloying elements is shown in the literature, resulting in better corrosion resistance [34], an addition of 0.1% each is investigated in the present work. The composition of the alloy was determined to be 69.7Cu-30Zn-0.1P-0.1Ni-0.1Sn (wt.%). The Thermo-Calc simulation of phase formation (Figure 2) shows that no β -phase occurs. Ni dissolves completely in the α -brass and small amounts of P₂Zn₃ (0.0076 vol.%) and Cu₃Sn (0.0024 vol.%) precipitate.

Table 2. Phase compositions of alloys containing $(70 - X)\text{Cu} + 30\text{Zn} + X\text{-Element}$, $T = 127\text{ }^{\circ}\text{C}$.

Element	β -Brass X in wt. %	Other Phases X in wt. %	Other Phases Name
Ag	2.2	-	-
Al	1.0	0.4	γ -phase
As	2.2	0.7	Cu_3As
Au	-	-	-
B	0.01	0.2	B
Be	0.01	-	-
Bi	-	0.2	Bi
C	0.01	0.2	Gr.
Ca	0.8	0.01	CaCu_5
Cd	-	0.06	Cd_8Cu_5
Co	-	0.02	γ -phase
Cr	0.01	-	-
Fe	0.01	-	-
Mg	1.2	0.02	Cu_2Mg
Mn	-	0.2	CuMnZn
Mo	0.01	.	.
Nb	0.01	.	.
Ni	-	0.2	NiZn
O	0.8	0.01	Cu_2O
P	-	0.01	P_2Zn_3
Pb	-	2.5	Cu_3P
Pt	-	0.01	Pb
Pt	-	-	-
Se	2.7	0.01	Cu_2Se
Si	0.6	0.8	Si
Sn	2.7	0.02	Cu_3Sn
Ti	3.1	0.01	CuTi
Zr	2.2	0.01	$\text{Cu}_{51}\text{Zr}_{14}$

**Figure 2.** Phase composition of micro-alloyed special brass CuZn30X .

3.2. Properties of the Alloy in Cold and Hot Rolled Conditions

The phase composition measured by XRD of the standard alloy and the modified alloys in cold rolled and hot rolled conditions is shown in Figure 3. All three samples show a single-phase composition of the α -phase of the brass. Therefore, the presence of the β -brass cannot be considered as a possible cause in the event that corrosion occurs.

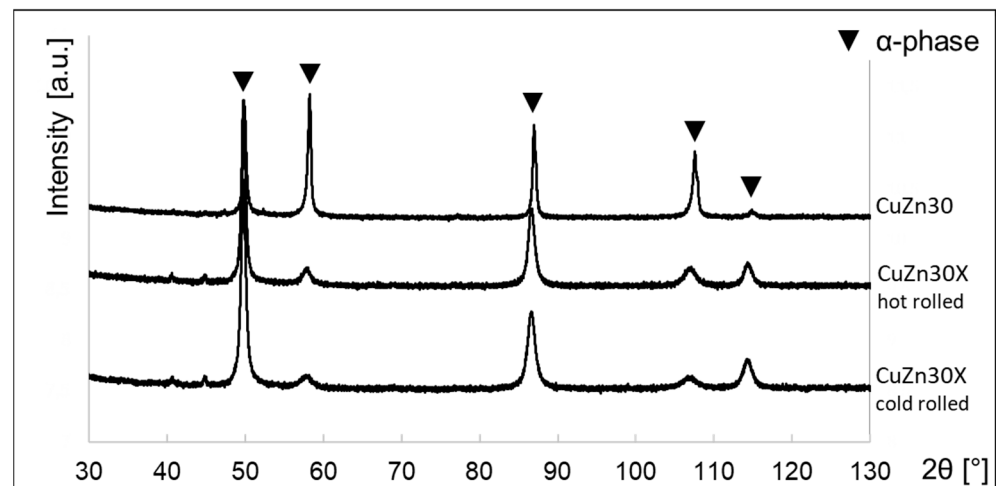


Figure 3. Phase composition determined by XRD analysis of the CuZn30X alloy in cold and hot rolled conditions compared to the standard CuZn30 alloy.

The mechanical properties of the modified alloy CuZn30X under cold and hot rolled conditions are shown in Table 3 in comparison to the standard material CuZn30 from the data from the literature [52]. The 0.2 yield strength $R_{p0.2}$, the tensile strength R_m , and the elongation at break A were measured for the modified alloy CuZn30X under cold and hot rolled states. The mechanical properties of the cold-rolled modified alloy show higher values for the 0.2 yield strength and tensile strength compared to the hot rolled condition, while the elongation at break is lower. The values for the 0.2 yield strength and elongation at break of the cold-rolled CuZn30 alloy from the data from the literature agree well with the values for the cold-rolled modified alloy. Therefore, the addition of the alloying elements nickel, tin, and phosphorus has no influence on the mechanical properties of the modified alloy. The elongation at break A of the modified alloy is too low for further processing of the sheets in the field of brass instrument manufacturing, and therefore it is necessary to perform solution annealing of the material before further use.

Table 3. Mechanical properties of the tested alloys.

Alloy	φ	Hardness [HV1]	$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]
CuZn30X (cold rolled)	1.64	229 ± 5	683 ± 9	736 ± 9	1.5 ± 0.3
CuZn30X (hot rolled)	1.53	233 ± 5	604 ± 7	647 ± 11	2.9 ± 0.4
CuZn30 (cold rolled) [52]	1.61		680		2.5

Using an EDX measurement of copper and zinc in the scanning electron microscope, it was checked whether the modified alloy CuZn30X and the standard alloy CuZn30 showed signs of dezincification on the surface in cold and hot rolled conditions prior to corrosive exposure. Figure 4 shows the element content for copper and zinc at the surface of the cold rolled and hot rolled samples. There are no signs of dezincification in any of the three samples.

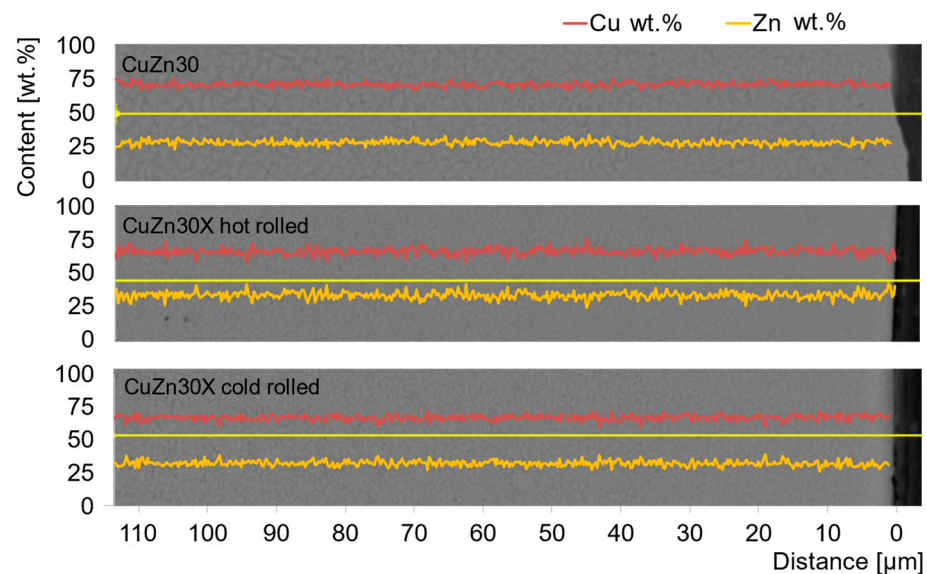


Figure 4. The element content of copper and zinc near the surface of the standard alloy CuZn30 in rolled and annealed and of the modified alloy CuZn30X in the hot- and cold-rolled condition (longitudinal to the rolling direction) shown above the SEM image in SE contrast. The yellow line marks the position of the line on which the EDS measurement was carried out as a line scan.

3.3. Corrosion Properties

3.3.1. Stress Corrosion Cracking Test

As a result, no critical cracks were found in any of the samples, either in the modified alloy CuZn30X or in the standard alloy CuZn30. Even a careful visual inspection with a magnifying glass did not reveal cracks or damage (Figure 5). These results are particularly important because testing in ammonia vapor is an extremely aggressive environment. Although this medium leads to cracking at residual stresses of around 10 MPa [51], all samples were found to be free of critical residual stresses.

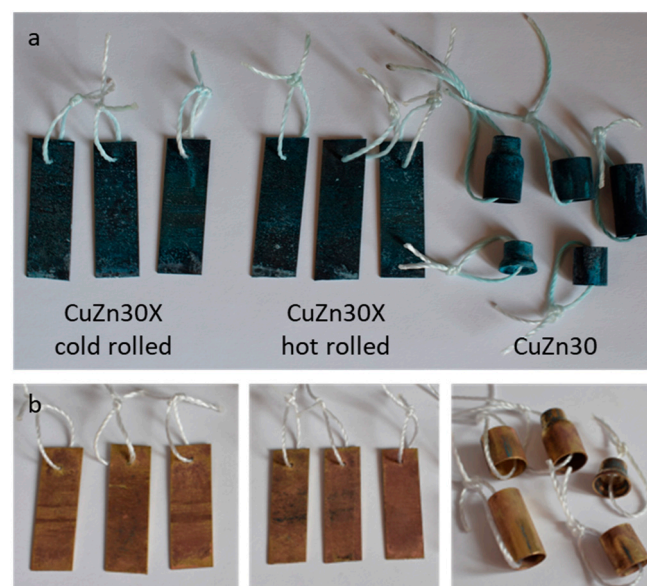


Figure 5. Stress-corrosion cracking test—samples before (a) and after (b) pickling.

It can be summarized that the tested materials did not exhibit sensitivity for stress corrosion cracking under the given conditions. However, for the further investigation of the

modified alloy, the stress corrosion cracking test should also be carried out on components for brass instruments made from the modified alloy CuZn30X.

3.3.2. Dezincification Test

The effects of the dezincification test on the surface of the hot rolled and cold rolled alloy CuZn30X compared to the standard alloy CuZn30 are shown in Figure 6. The standard alloy CuZn30 is clearly copper red in color. This is due to the uniform dezincification of the standard alloy. The modified alloy CuZn30X showed dark colored layers on the surface immediately after the test in both cold rolled and hot rolled conditions, indicating a protective top layer. According to DIN EN 125022 [53], these coating corrosion products can be identified as $\text{Cu}_2\text{O}/\text{CuO}$.

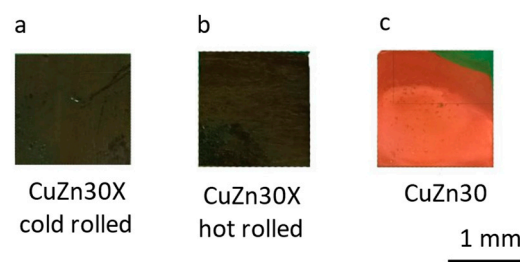


Figure 6. Comparison of the test samples before and after the dezincification test of the CuZn30X alloy in cold rolled (a) and hot rolled (b) conditions, as well as the standard alloy CuZn30 (c).

The depth of dezincification was qualitatively assessed in the longitudinal section using an optical microscope. In particular, the corrosion-free appearance of the samples of the modified alloy CuZn30X should be emphasized. No abnormalities were found, while the standard alloy showed the characteristic appearance of dezincification (Figure 7). A maximum dezincification depth of $359\ \mu\text{m}$ was measured. This value must be considered extremely critical regarding the total thickness of the sample of $0.53\ \text{mm}$.

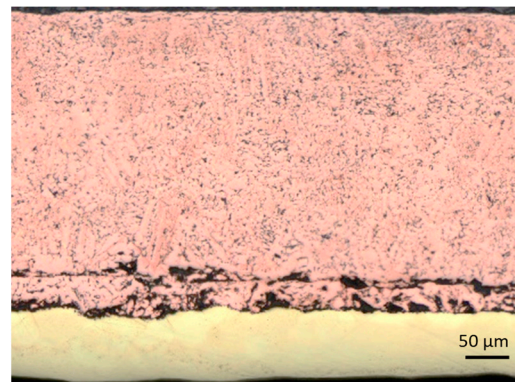


Figure 7. Standard alloy CuZn30 after the dezincification test. The dezincified area is reddish due to the high copper content, the non-dezincified brass is yellowish.

However, the scanning electron microscope (Figure 8) shows the formation of a thin surface layer of approximately $20\text{--}30\ \mu\text{m}$ in the cold-rolled state and approx. $2\ \mu\text{m}$ in the hot rolled state. The element contents of copper and zinc at the surface are shown in the EDS line scan.

Using OES, a copper content of 66.97 wt.% and a zinc content of 32.63 wt.% were determined (see Table 1). Similar values can be seen in the EDS line scan up to directly below the surface layer and show that no dezincification occurs below the layer. The element contents under the surface layers under both cold and hot rolled conditions initially show an increase in the Zn content at the interface between the brass and the surface layer, followed by an increase in the copper content with a simultaneously lower Zn content

to this in the alloy bulk. In the hot rolled condition of the modified alloy CuZn30X, the surface layer is significantly less pronounced than in the cold rolled condition (Figure 8). The layer thickness here is less than 2 μm . This is due to the increased dezincification rate in cold rolled alloys, as reported by [19,54]. However, the alloy appears to be resistant to corrosion attack.

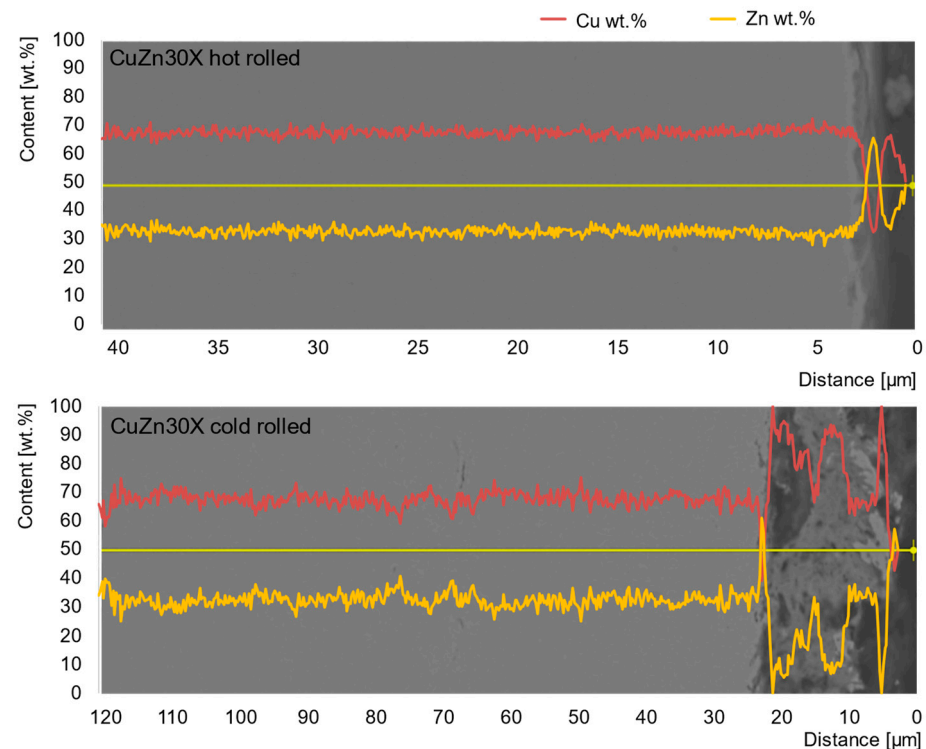


Figure 8. Investigation of element content by means of an EDS line scan at the surface of the modified alloy CuZn30X in cold and hot rolled conditions longitudinal to the rolling direction shown above the SEM image in SE contrast. The yellow line marks the position of the line on which the EDS measurement was carried out as a line scan.

The morphology and the element composition of the surface layers was analyzed using SEM and EDS, respectively. Figure 9 shows an example of the layer of the standard alloy CuZn30 (a) compared to the modified alloy CuZn30X in the cold-rolled condition. It can be seen that both samples have an irregular surface. The standard sample has a porous surface (a) while the cold-rolled modified alloy has an uneven surface (b). The modified hot rolled alloy exhibits the same appearance of the surface layer as the modified cold-rolled alloy in Figure 9b.

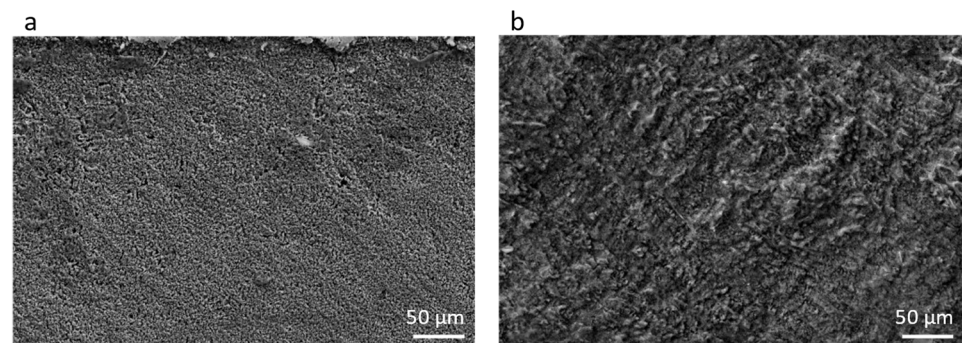


Figure 9. SEM image in SE contrast of the surface layers of the standard alloy CuZn30 (a) compared to the modified alloy CuZn30X in the cold-rolled state (b).

The entire area, as shown in Figure 9a,b, was examined using EDS measurements with respect to the chemical composition (Table 4). The modified alloy CuZn30X had low tin and phosphorus (<1 wt.%) as well as high zinc values (up to 20 wt.%) with a copper content below 68 wt.%. The detected presence of tin and phosphorus in the layer indicates the formation of protective cover layers containing Cu_2O [36,42,55] or the reaction products of the alloying elements [29]. The presence of Cl in the layer is attributed to the retention of electrolytes within the porous structure. Based on these limited experiments, it can be concluded that a protective top layer forms on the modified alloy, both in the cold rolled and hot rolled conditions, due to the addition of the alloying elements, which prevents the redeposition of copper and thus successfully inhibits dezincification.

Table 4. The element composition of the layer determined using EDS.

Element	Cu	Zn	Ni	Sn	P	O	Cl
CuZn30	85.4	3.1	-	-	-	6.6	4.9
CuZn30X cold rolled	63.9	15.4	-	0.6	0.4	8.0	11.7
CuZn30X hot rolled	66.8	19.6	-	0.7	0.5	8.1	4.9

However, the absence of these elements obviously leads to a strong corrosive attack. An indication of this is the standard alloy CuZn30. Consistently high copper values (<90 wt.%) and very low zinc contents (<6 wt.%) correspond exactly to the brass dezincification theory. This theory [6,7,9] assumes that the zinc is dissolved from the alloy and the copper is redeposited, leaving behind a porous layer. This permeable layer could also be captured with the scanning electron microscope (Figure 9a).

3.3.3. Polarization Curves

The results shown in Figure 10 indicate, in general, no significant change in polarization behavior for the modified and standard alloys. However, the cold-rolled alloy shows a marginal shift towards negative potentials, suggesting a slightly higher susceptibility to corrosion in the test solution. For low anodic polarization, the sharp increase in current density indicates an almost uninhibited metal dissolution process. Only a minor distinction was noted for the cold-rolled new alloy, as indicated by the circled area in the diagram. The cold-rolled material exhibits a slight kink in the polarization curve, suggesting a weak passivation effect. As the potential is increased further, a local maximum is reached, and the slope of the polarization curves decrease significantly. It is assumed that the local maximum corresponds to a passivation potential and that the subsequent flat rise of the curves indicates the weak passivation effect of the surfaces.

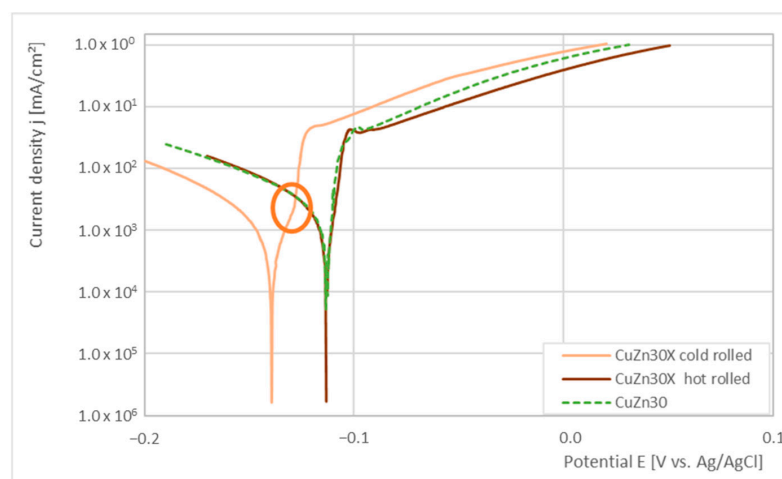


Figure 10. Potentiodynamic polarization curves of the tested alloys in 1% NaCl solution at 37 °C. The circled area marks the slight kink in the polarization curve, suggesting a weak passivation effect.

In sum, the trends of the polarization curves reveal no significant differences, indicating no change in corrosion characteristics for the used test conditions.

4. Conclusions

The aim of this study was to find an alloy with improved corrosion resistance for use in brass instruments. The selection of elements for alloy enhancement (microalloying) was severely limited by environmental compatibility, price, and, above all, the effects on the processing properties. The modified CuZn30X alloy with 69.7 wt.% copper; 30 wt.% zinc; and 0.1 wt.% of phosphorus, tin, and nickel each was created, taking these aspects into account. The phase composition was determined with the aid of thermodynamic simulations. The modified alloy is single phase and does not contain any of the corrosion-prone β -phase of brass. Furthermore, it was proven that neither the standard alloy CuZn30 nor the modified alloy CuZn30X suffered the dezincification of the surface due to the rolling process.

The corrosion properties of the modified alloy CuZn30X compared to the standard alloy CuZn30 were determined by means of the dezincification test according to DIN 6509, the stress corrosion cracking test with ammonia according to DIN 50916, and the recording of polarization curves in 1% NaCl solution. The dezincification test confirmed the improved corrosion resistance of the modified CuZn30X alloy. On the other hand, it also showed susceptibility to the corrosion of the standard alloy CuZn30, in which uniform dezincification with corrosion holes was observed down to the depth of the center of the sample. The stress corrosion cracking test showed no signs of critical tensile stress for the modified alloy CuZn30X or the standard alloy CuZn30. For the standard alloy, components of the brass instruments were tested. These had slight cracks after the test, but due to the aggressive test medium, no major significance can be attributed to these. The recording of polarization curves did not show any significant improvements in the new alloy compared to the conventional one. As a result of the aggravated conditions that affect the material through accelerated ion exchange in the course of the voltage being applied, no direct reference to the application can be made. The modified alloy CuZn30X shows good conditions for cold and hot rolling. The dezincification tests also delivered positive results.

The selected corrosion tests are standardized assessments evaluating the alloys' corrosion resistance under specified standard conditions; however, they only reflect the application to a limited extent. Under these conditions, the modified alloy CuZn30X shows no major changes in terms of stress corrosion cracking resistance and the recording of polarization curves. However, due to the promising results in the dezincification test, the next step planned is to carry out complex tests to map artificial sweat. Furthermore, the next step planned is to manufacture components for a brass instrument from this alloy and test them in use. For this purpose, not only should the optical and processing properties be tested during the manufacture of the instrument but also the acoustic properties.

Author Contributions: Conceptualization, S.B.; methodology, S.B.; software, A.M.; formal analysis, S.G. and M.M.; investigation, S.B. and A.M.; resources, S.G., U.P., M.M. and L.K.; data curation, S.B.; writing—original draft preparation, S.B. and A.M.; writing—review and editing, S.G. and M.M.; visualization, S.B.; supervision, S.G. and M.M.; project administration, S.G., U.P., M.M. and L.K.; funding acquisition, S.G., U.P., M.M. and L.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Federal Ministry of Education and Research (BMBF) as part of the project "Avoidance of zinc corrosion in brass instrument manufacturing" as part of a WIR! alliance initiative of the musical instrument manufacturing industry (www.imatech-musik.de, (accessed on 24 May 2024)) and managed by Project Management Jülich (PTJ). The authors would like to thank the funding organizations for their support.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank J. Dölling and A. Zilly, DHBW Stuttgart, for the casting of the alloy CuZn30X on a VC400-casting machine (Indutherm Blue Power Casting Systems, Walzbachtal, Germany) and OES-Spectroscopy (Spectrotest, SPECTRO Analytical Instruments GmbH, Kleve, Germany), C. Schimpf, IWW (TU Freiberg) for XRD analysis, and K. Voigt, Instrumentenbau Jürgen Voigt GmbH & Co. KG, for the provision of components from brass instruments.

Conflicts of Interest: The authors declare no conflicts of interest.

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