

ORIGINAL PAPER

Influence of Heat Treatment Temperature on Dezincification of Duplex Brass

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Abstract. This study investigates the influence of thermal processing on the microstructural evolution and dezincification resistance of duplex brass, an alloy characterized by a dual-phase microstructure comprising a copper-rich α -phase and a zinc-rich β -phase. Specimens were heat-treated between 300°C and 600°C, followed by water quenching, to evaluate temperature-induced phase transformations. Corrosion susceptibility was quantified via potentiodynamic polarization, while pre- and post-corrosion morphologies were characterized using confocal microscopy, optical microscopy, and SEM-EDS. Results reveal that the microstructure remains stable up to 400°C but undergoes pronounced phase coarsening and segregation at 600°C. Critically, electrochemical analyses demonstrate that the topology of the zinc-rich β -phase dictates the overall corrosion behavior. The 300°C treatment induced maximum dezincification susceptibility, driven by a continuous, interconnected β -phase network that facilitates rapid anodic dissolution. Ultimately, this research establishes that the physical interconnectivity of the susceptible β -phase—rather than the overall phase-area fraction—serves as the primary determinant of dezincification propagation in duplex brass.

Keywords: Duplex Brass, Dezincification, Potentiodynamic Polarization, Heat Treatment

1. Introduction

Duplex brasses are a critical class of engineering alloys, widely utilized for their exceptional balance of strength, formability, and cost-effectiveness (Atsumi et al., 2011; Jennane et al., 2019). These alloys consist of a dual microstructure containing the ductile, copper-rich alpha (α) phase and the harder, zinc-rich beta (β) phase. Heat treatment plays a critical role in designing mechanical properties for specific applications, such as marine hardware, plumbing, and fittings

(Toulfatzis et al., 2016; Toulfatzis, 2018). However, the presence of the β -phase introduces a significant weakness in terms of corrosion resistance. Duplex brass with a zinc content of approximately 38–42%, the β -phase is significantly richer in zinc than the α -phase (Al-Fadhalah et al., 2021). This compositional variation results in distinct electrochemical behavior; the β -phase exhibits a more negative corrosion potential, thereby functioning as the anodic site in galvanic coupling (Choucri et al., 2019; Moriarty et al., 2021). Consequently, duplex brasses are highly susceptible to dezincification, a selective dealloying phenomenon where zinc is preferentially dissolved from the matrix (Selvaraj et al., 2003). This galvanic interaction triggers corrosion of the anodic β -phase, resulting in a porous, copper-rich structure with significantly reduced mechanical strength (Michel et al., 2017; Sarver et al., 2011). Corrosion susceptibility depends on microstructural features such as size, morphology, and phase distribution, making β -phase control essential for improving dezincification resistance (Moriarty et al., 2021).

Heat treatment offers a powerful metallurgical tool for modifying these microstructural characteristics (Loto & Loto, 2018; Özhan Doğan & Ekici, 2020; Liu et al., 2012). However, despite extensive research into brass corrosion, significant gaps remain regarding the quantitative relationships between specific heat treatment parameters, the resulting microstructural evolution, and the electrochemical

behavior of duplex brass. Most studies have focused on limited heat treatment conditions or single-phase brasses, with relatively few systematic investigations comparing multiple heat treatment schedules on duplex alloys using standardized electrochemical protocols (Loto & Loto, 2018; Özhan Doğan & Ekici, 2020; Liu et al., 2012; Haubner et al., 2020; Hoshi et al., 2023). Furthermore, the mechanistic links between specific microstructural parameters (such as β -phase area fraction, grain size, and phase connectivity) and polarization curve characteristics remain incompletely understood.

To address this, the present study aims to systematically investigate the influence of heat treatment temperature on the microstructural evolution of duplex brass. Furthermore, it seeks to correlate these microstructural changes with electrochemical behavior and the resulting dezincification morphology, providing a comprehensive understanding of how thermal processing affects corrosion resistance.

2. Methodology

2.1 Materials

The base material used in this study was commercial-grade duplex brass. The chemical composition of the as-received alloy was determined using wavelength-dispersive X-ray fluorescence (WD-XRF) and is presented in Table 1. Specimens were cut to dimensions of 10 mm x 20 mm x 2 mm for heat treatment and subsequent corrosion testing. To evaluate the effect of heat treatment temperature on the microstructure and dezincification resistance, the specimens were subjected to thermal treatment at three individual temperatures: 300°C, 400°C, and 600°C. Each heat treatment was maintained for a duration of 30 minutes, immediately followed by water quenching to freeze the microstructure. To establish a baseline, a non-heat-treated specimen was retained in its as-received (AR) condition.

2.2 Microstructure, Phase Area Fractions, and Dezincification Area of Duplex Brass

Surface preparation for both heat-treated and non-heat-treated samples followed standard metallographic protocols. Specimens were mechanically ground using silicon carbide (SiC) abrasive papers (320 to 2000 grit) and polished with 3 μ m and 1 μ m diamond suspensions to a mirror finish. These as-polished samples were utilized directly for potentiodynamic polarization testing. For microstructural characterization, a polished specimen was chemically etched (10 g FeCl₃ and 30 mL HCl in 100 mL distilled water) and examined via confocal microscopy. After polarization testing, the samples were rinsed with deionized water and ethanol, air-dried, and subsequently examined via optical microscopy to assess surface dezincification. To analyze the penetration depth and cross-sectional morphology of the dezincification layer, the samples were sectioned, mounted, and subjected to the identical grinding and polishing protocol before confocal microscopic evaluation. Quantitative microstructural analysis was performed using ImageJ software. To ensure statistical reliability, all optical evaluations were conducted at 50X magnification. Phase area fractions of α and β were averaged from five micrographs per sample, while the extent of dezincification was quantified using five surface and five cross-sectional confocal micrographs per specimen. Finally, Scanning Electron Microscopy equipped with Energy Dispersive Spectroscopy (SEM-EDS) was employed to characterize surface phase morphology and local elemental composition across the unaffected parent matrix and the dezincified zones.

2.3 Electrochemical Measurements

Potentiodynamic polarization measurements were performed using a potentiostat/galvanostat in a conventional three-electrode electrochemical cell. The prepared duplex brass sample was used as the working electrode (WE). A Saturated Calomel Electrode (SCE) served as the reference electrode (RE), and a graphite rod was used as the counter electrode (CE).

All experiments were conducted in 3.5 wt% NaCl at room temperature. Before each measurement, the working electrode was immersed in the electrolyte, and the open-circuit potential (OCP) was monitored until a stable value was achieved, with a stabilization period of 600 seconds. Subsequently, the potentiodynamic polarization scan was initiated from a potential of -0.50 V relative to

the OCP and scanned in the anodic direction to a final potential of +0.55 V relative to the OCP. A constant scan rate of 1 mV/s was used for all experiments. The acquired polarization data, specifically the corrosion potential (E_{corr}) and corrosion current density (i_{corr}) were subsequently analyzed using a non-Tafel extrapolation method (Rivera-Grau et al., 2013) as shown in Figure 1.

Table 1. Elemental composition of as-received duplex brass

Element composition (wt%)			
Cu	Zn	Pb	Fe
Bal.	38.300	1.730	0.132

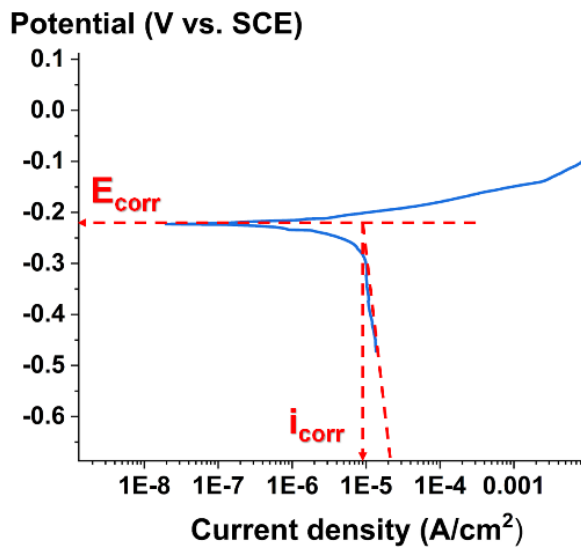


Figure 1. Evaluation of the corrosion potential (E_{corr}) and corrosion current density (i_{corr}) of duplex brass via the non-Tafel extrapolation method.

2.4 Microhardness Testing

Vickers microhardness was evaluated on the original surface (before testing) and on the dezincified regions after potentiodynamic polarization. Each test applied a 200 gf load for 15 s at three randomly selected points.

3. Results and Discussion

3.1 Microstructure of Duplex Brass

The microstructural evolution of the duplex brass as a function of heat-treated temperature is presented in Figure 2. The as-received alloy (Figure 2a) displays a β -dominated duplex microstructure (phase area fraction 58% β , 42% α), comprised of a bright yellow, copper-rich α -phase and a dark brown, zinc-rich β -phase. Heat treatment at 300°C (Figure 2b) produced a dense, interconnected morphology with a minor phase shift (phase area fraction 55% β , 45% α). However, treatment at 400°C (Figure 2c) increased the bright α -phase area fraction to 54%. The increased continuity of the α -phase at 400°C effectively severed the interconnected β -phase network. Further heating to 600°C (Figure 2d) triggered significant phase coarsening and segregation. At 600°C, the β -phase reached a maximum area fraction of 65%, forming large, isolated islands (white arrows) dispersed among coarse α grains, thereby eliminating the fine network observed at lower temperatures. This transition is driven by the minimization of total interfacial energy and grain boundary area (Porter et al., 2021). Overall, the microstructural evolution of this duplex brass is strictly dictated by heat treatment temperature, controlled through thermal activation and diffusion (Mapelli & Venturini, 2006; Moriarty et al., 2021).

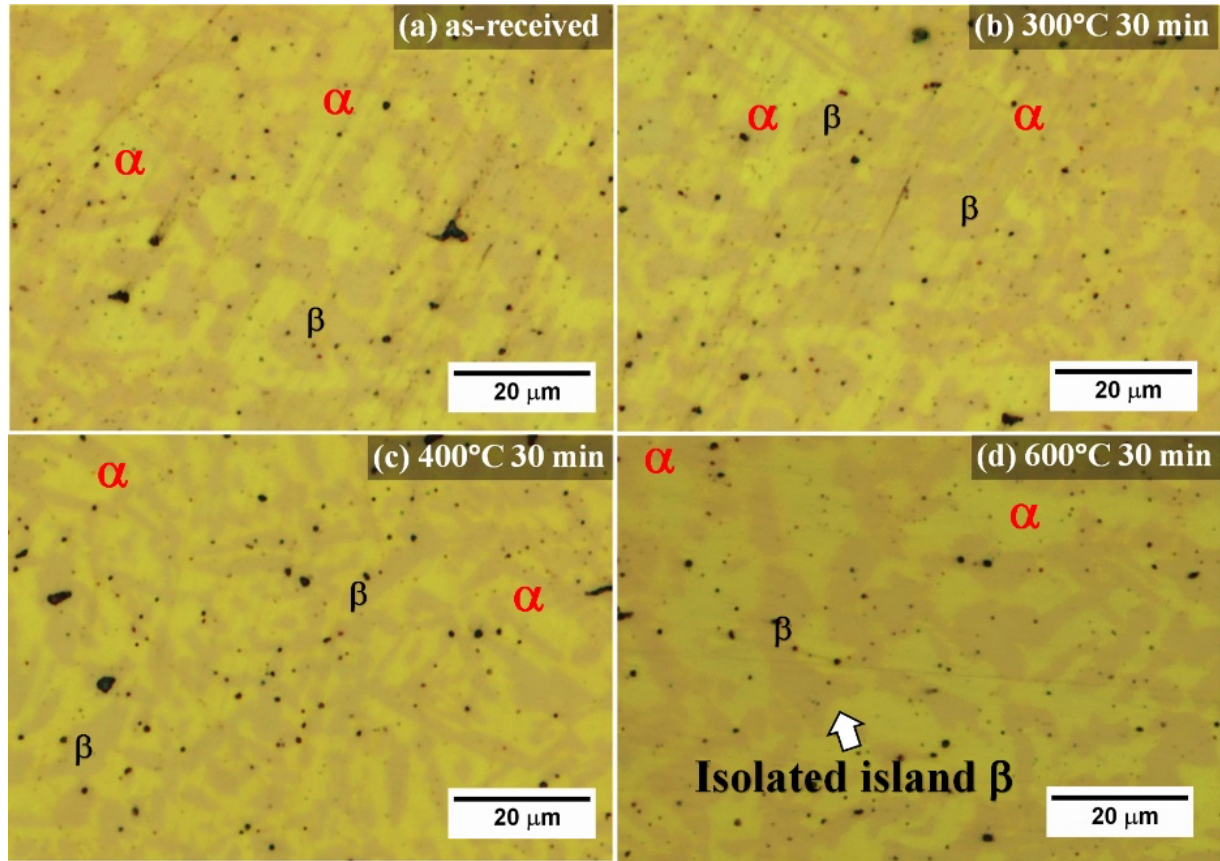


Figure 2. Confocal Micrographs of duplex brass of (a) as-received, and heat-treated at (b) 300°C, (c) 400°C, (d) 600°C

3.2 Electrochemical Behavior

Figure 3a presents the potentiodynamic polarization curves for the as-received and heat-treated duplex brass specimens tested in a 3.5% NaCl solution. All specimens exhibited corrosion potential (E_{corr}) clustered in a range between -0.22 V and -0.24 V vs. SCE. Additionally, the cathodic branches exhibited similar features, indicating that the heat treatment process does not significantly alter the cathodic kinetics of the alloy as shown in Figure 3b. In the anodic region (Figure 3c), the decrease in current density observed for all samples at a potential of approximately $+0.04$ V (blue arrow) is attributed to the formation of corrosion products resulting from dezincification (Zhou et al., 2021).

Table 2 indicates that thermodynamic nobility improves with increasing heat treatment temperature, as reflected by the open-circuit potential (E_{ocp}). The 300°C specimen was the most active (-504 ± 4.00 mV), while the as-

received sample, 400°C, and 600°C specimens shifted positively to -499 ± 3.00 mV, -492 ± 2.00 mV, and -491 ± 3.00 mV, respectively. These trends align with corrosion potential (E_{corr}) values, where a positive shift reflects reduced corrosion susceptibility, establishing the stability order as $400^\circ\text{C} \approx 600^\circ\text{C} > \text{as-received} > 300^\circ\text{C}$. The corrosion current density (i_{corr}) further confirms this behavior. The 300°C specimen exhibited the highest i_{corr} (9.68 ± 0.41 $\mu\text{A}/\text{cm}^2$), indicating rapid zinc dissolution from the β -phase. This electrochemical response reflects severe dezincification (surface $\sim 77\%$, cross-section $\sim 45\%$) as shown in Table 4, consistent with a continuous β -phase network that promotes anodic current flow and accelerates zinc dissolution. Conversely, the 400°C specimen exhibited the lowest i_{corr} (8.08 ± 0.27 $\mu\text{A}/\text{cm}^2$), indicating better corrosion resistance compared to the 300°C condition. This improvement is attributed to the barrier effect of the copper-rich α -phase. At this temperature, the microstructure contains a higher fraction of coarse α -phase (Figure 2c),

which is more noble than the β -phase and acts as cathodes in the local galvanic couple (Langenegger & Robinson, 1969). The arrangement of the α grains physically interrupts the continuity of the susceptible β network. This morphological obstruction restricts the effective surface area available for the anodic. The 600°C specimen exhibited intermediate electrochemical performance (i_{corr} : $8.21 \pm 0.38 \mu\text{A}/\text{cm}^2$). Despite its high-area fraction of the anodic β -phase, corrosion resistance was moderated by the phase's segregated topology. At this temperature, the β phase segregates into isolated islands (Figure 2d). This isolation prevents the formation of a continuous path for the anodic current, thereby limiting the extent of dezincification despite the high-area fraction of the susceptible phase.

3.3 Correlation between Phase Fraction and Dezincification Susceptibility

As shown in Figure 4, the surface contrast after dezincification reveals a clear distinction between the two phases, with the α phase remaining bright. In contrast, the β phase appears as dark, porous regions due to severe corrosion. Figure 5 illustrates the cross-sectional view of the dezincification layer for each sample. The selective attack is clearly distinguished by color contrast, where the reddish dezincification β phase stands out against the yellow background of the non-attacked α phase. For both the as-received sample (Figure 4a) and the specimen heated to 400°C (Figure 4c), corrosion occurred in some non-interconnected β -phase regions, consistent with the microstructures shown in Figures 2a and 2c. Additionally, cross-sectional analysis (Figures 5a and 5c) corroborates this observation, confirming the morphology of the β -phase under these conditions. In contrast, the sample heat-treated at 300°C exhibits an interconnected network of the β -phase morphology, which facilitates more severe and continuous dezincification (Figure 4b).

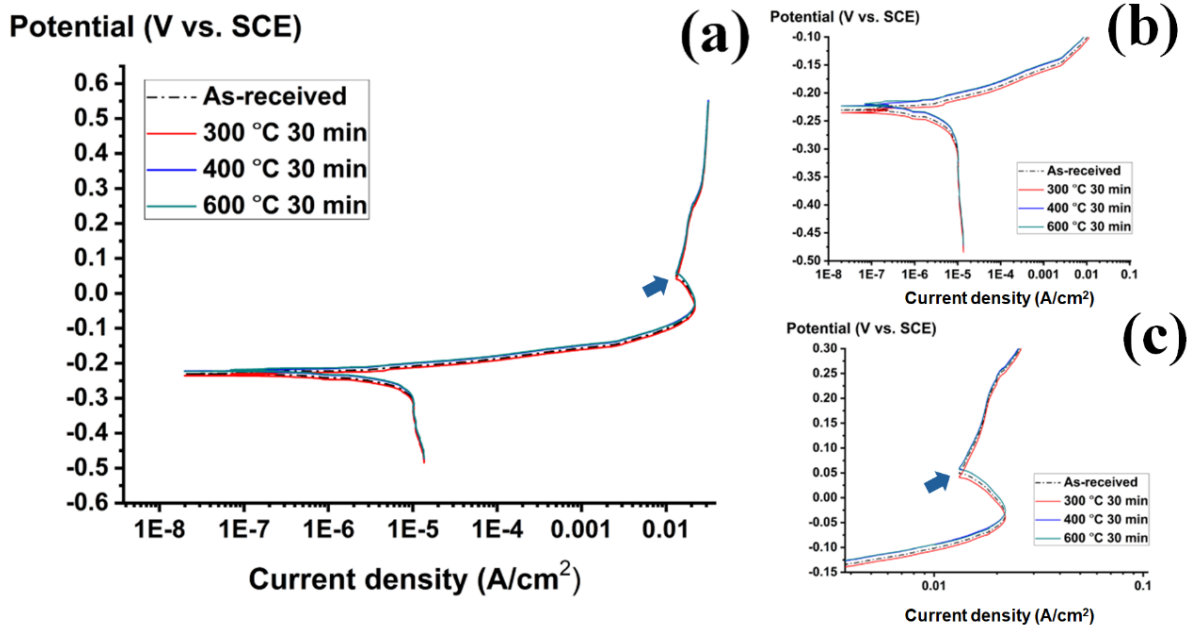
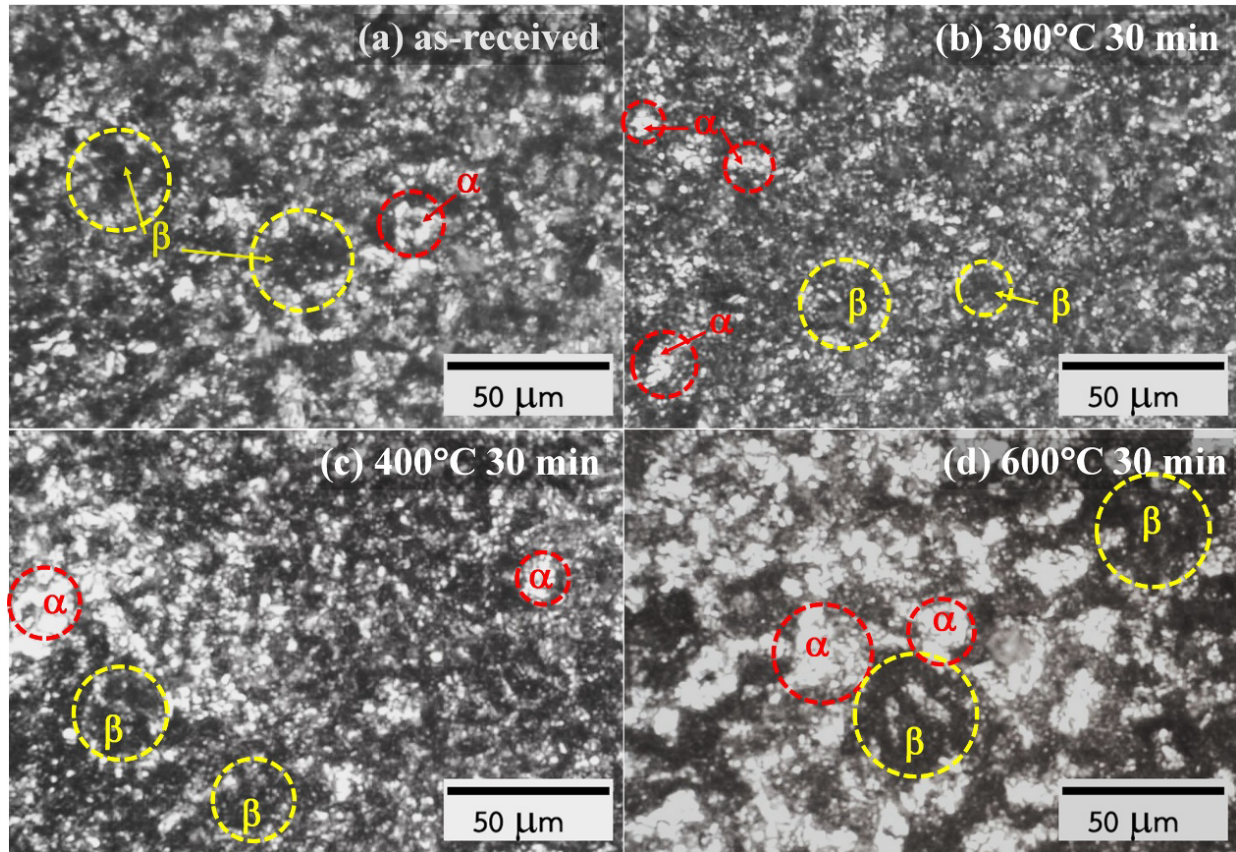


Figure 3. Potentiodynamic polarization of duplex brass in a 3.5% NaCl solution (a) full curves, (b) cathodic and anodic branches before the current density decrease, (c) detail of the current density drop region

Table 2. Open circuit potential (E_{ocp}), corrosion potential (E_{corr}) and corrosion current (i_{corr}) of as-received and heat-treated duplex brass

Sample	E_{ocp} (mV)	E_{corr} (mV)	i_{corr} ($\mu\text{A}/\text{cm}^2$)
AR	-499 ± 3.00	-230 ± 2.00	8.50 ± 0.35
300°C	-504 ± 4.00	-234 ± 5.00	9.68 ± 0.41
400°C	-492 ± 2.00	-222 ± 3.00	8.08 ± 0.27
600°C	-491 ± 3.00	-223 ± 4.00	8.21 ± 0.38


Figure 4. Optical micrographs of surface morphology showing dezincification for: (a) as-received, and heat-treated at (b) 300°C, (c) 400°C, (d) 600°C

At 600°C, phase coalescence produces a coarser, more heterogeneous corrosion profile. As shown in Figure 4d, the surface features large, bright α -phase that resists attack, contrasted with dark, porous regions where the coarsened β -phase undergoes severe dezincification. Cross-sectional analysis (Figure 5d) confirms the β -phase forms discrete islands rather than the interconnected networks observed at lower temperatures.

Corrosion depth evaluations (Table 4) reveal significant variations in dezincification resistance

among the specimens. The sample heat-treated at 300°C exhibited the highest susceptibility, with a maximum depth of $25.9 \pm 0.6 \mu\text{m}$, reflecting severe zinc loss compared to the as-received sample ($20.5 \pm 0.7 \mu\text{m}$). Conversely, thermal processing at 600°C and 400°C significantly enhanced corrosion resistance, minimizing corrosion depths to $16.8 \pm 0.9 \mu\text{m}$ and $17.7 \pm 1.5 \mu\text{m}$, respectively. Overall, these cross-sectional findings demonstrate a strong correlation with the surface and cross-sectional dezincification area results.

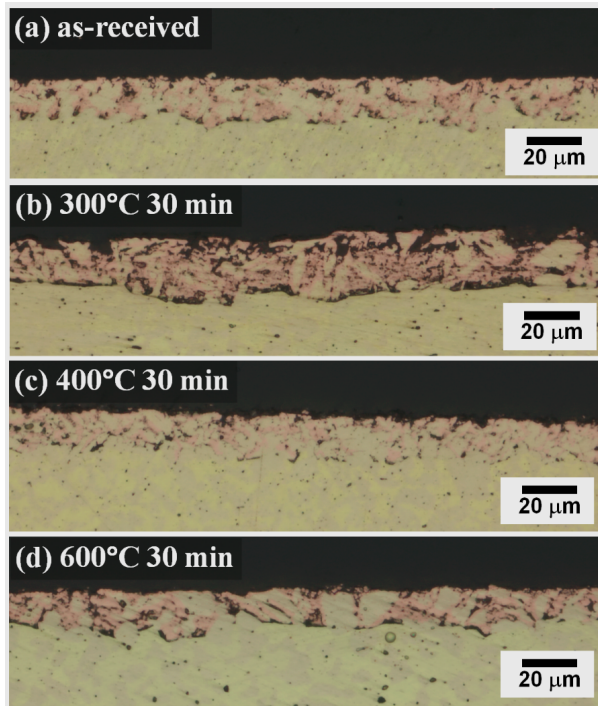


Figure 5. Optical micrographs of the cross-sectional dezincification layer (reddish: dezincification area, yellowish: non-dezincification area). (a) as-received, and specimens heat-treated at (b) 300°C, (c) 400°C, (d) 600°C

Pre-test backscattered electron (BSE) micrographs (Figure 6a–d) display a distinctly brighter β -phase (point 2) compared to the α -phase (point 1) due to its higher initial zinc concentration (Table 3). However, post-corrosion SEM micrographs and elemental composition data (Figure 7, Table 3) reveal a significant overall reduction in zinc concentration. This dezincification predominantly targets the former β -phase (point 2), which undergoes severe dissolution, while the former α -phase (point 1) exhibits better resistance. Consequently, the corroded as-received specimen (Figure 7a) displays localized regions of initial degradation. In contrast, heat treating the specimens at 300°C (Figure 7b) leads to significant morphological alterations, characterized by visible surface porosity following dezincification. This high degree of porosity points to an accelerated dezincification rate, which leaves behind a porous, copper-rich residual structure (Moriarty et al., 2021). Furthermore, the 300°C treated samples showed notably elevated zinc levels inside these pores (point 1) when compared to the surrounding β -phase. Together, these findings

strongly suggest that the dezincification process occurs through a dissolution-redeposition mechanism. Initially, both copper and zinc dissolve from the brass matrix. This is followed by the preferential redeposition of copper onto the surface, generating a porous structure that physically entraps adjacent zinc species within the dezincification layer (Zhou, 2017). As temperatures increase, morphology continues to evolve. Notably, the sample heated to 400°C (Figure 7c) exhibits isolated regions of beta-phase dezincification, aligning with the results shown in Figure 4c. By 600°C (Figure 7d), these features expand into larger, discrete areas of dezincification (comparable to Figure 4d and 5d). Additionally, copper content in the dezincified zones rose significantly, ranging from 88.04 wt% to 96.29 wt%, whereas zinc dropped to as low as 1.78–3.75 wt%. The presence of oxygen (1.94–8.20 wt%) further confirms the formation of a porous, copper-rich oxide structure (Karpagavalli & Balasubramaniam, 2007). Ultimately, while localized composition affects electrochemical potential, the overall extent of dezincification is governed primarily by the α -phase area fraction and the physical interconnectivity of the zinc-rich β -phase.

Table 4 correlates initial α/β phase area fractions with dezincification areas. The 300°C sample (α/β ratio 45/55) exhibited the most severe dezincification, showing 77% surface and 45% cross-sectional dezincification. As shown in Figures 4b and 5b, its fine, interconnected β -phase—which is highly electronegative and zinc-rich—acts as the primary anodic site, providing a continuous pathway for corrosive percolation (Pelto-Huikko et al., 2025). Once the attack initiates, it propagates rapidly through the continuous β network (Moriarty et al., 2021), leading to the maximum observed damage. At 400°C, corrosion resistance improves due to a peak α -phase fraction (~54%). This lower-zinc α -phase is electrochemically nobler than the β -phase, effectively resisting dezincification (Berne et al., 2015; Morales et al., 1995). Increasing the α -grain fraction improves

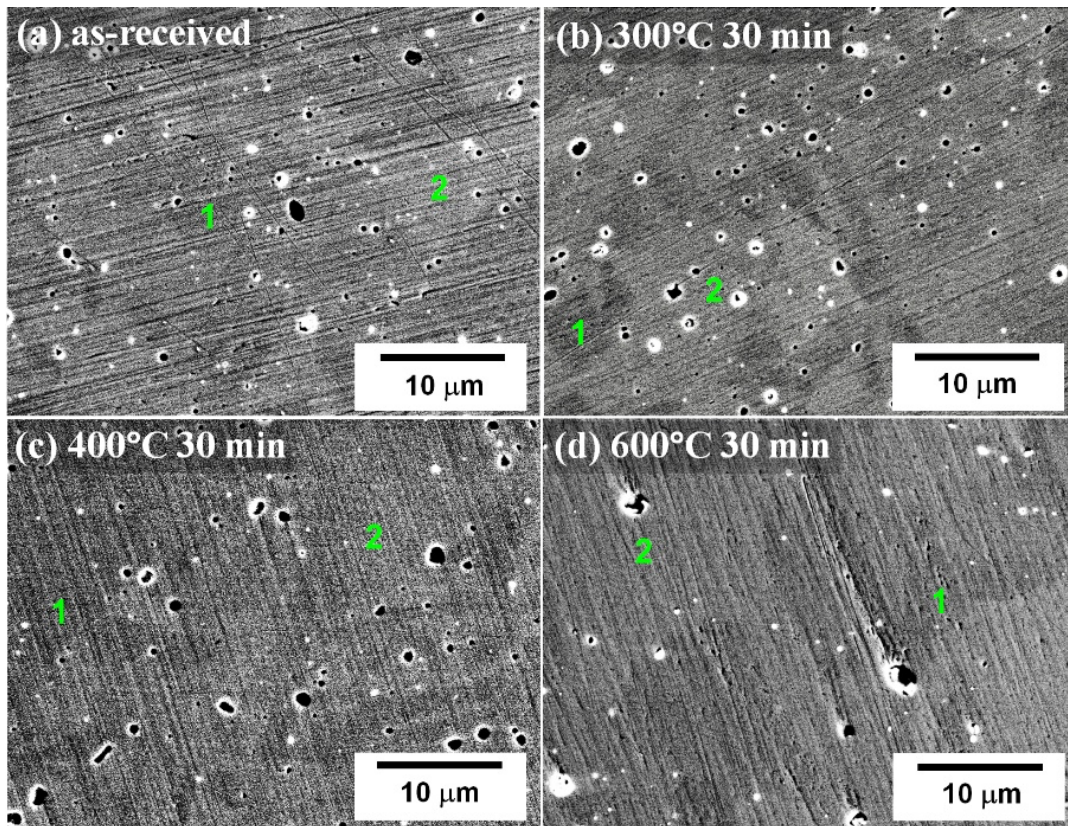


Figure 6. BSE images illustrating duplex brass morphology for (a) as-received brass and specimens heat-treated at (b) 300 °C, (c) 400 °C, (d) 600 °C

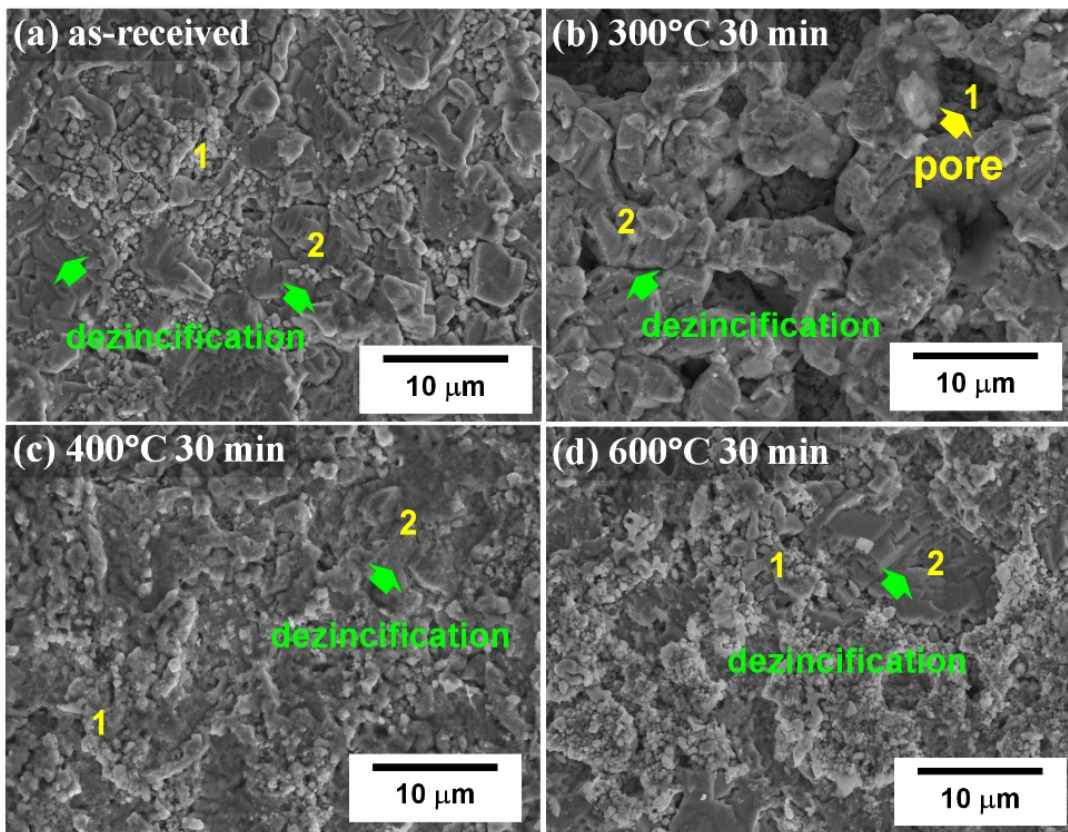


Figure 7. SEM images illustrating dezincification morphology for (a) as-received brass and specimens heat-treated at (b) 300 °C, (c) 400 °C, (d) 600 °C

corrosion resistance by disrupting continuous propagation pathways within the susceptible β -matrix (Pelto-Huikko et al., 2025). Despite a high fraction of the detrimental zinc-rich β phase, the 600°C specimen (65%) exhibits better corrosion resistance. Extensive coarsening forms isolated β islands rather than a continuous network. While these individual islands corrode rapidly, the surrounding coarse α matrix prevents attack propagation, significantly reducing overall dezincification compared to the interconnected 300°C sample.

Post-test Vickers hardness decreased across all specimens due to the selective dissolution of zinc, which leaves a porous, mechanically weakened copper network (Table 4). The 300°C sample exhibited the maximum hardness loss, corresponding to its extensive dezincification and pronounced porosity (Figure 7b). Across all samples, hardness reduction correlated proportionally with the dezincification area

Table 3. EDS Analysis of duplex brass before and after dezincification

Sample	Point	Phase	Chemical composition (wt%)					
			Original			After dezincification		
			Cu	Zn	O	Cu	Zn	O
AR	1	α	61.61	36.03	1.35	96.08	3.03	0.89
	2	β	56.35	42.12	1.53	94.81	2.91	2.27
300°C	1	α	62.09	36.52	1.40	93.25	6.40	0.35
	2	β	55.66	42.88	1.46	96.29	1.78	1.94
400°C	1	α	59.32	39.28	1.40	87.44	12.11	0.45
	2	β	54.81	43.61	1.59	88.04	3.75	8.20
600°C	1	α	60.76	37.71	1.53	89.94	7.60	2.47
	2	β	57.19	41.45	1.36	93.68	2.44	3.88

Table 4. Phase area fraction, Dezincification area, Vickers hardness, and Dezincification appearance of duplex brass

Sample	Phase fraction	Dezincification area (%)		Corrosion Depth (μm)	Vickers Hardness (HV)		Dezincification Appearance
	α/β	Surface	Cross section		Original area	Dezincification area	
AR	42/58	~66	~22	20.5±0.7	132.6±2.8	78.8±5.9	isolated occurrences of dezincification were identified within the interconnected structure

Table 4. Phase area fraction, Dezincification area, Vickers hardness, and Dezincification appearance of duplex brass (continuous)

Sample	Phase fraction α/β	Dezincification area (%)		Corrosion Depth (μm)	Vickers Hardness (HV)		Dezincification Appearance
		Surface	Cross section		Original area	Dezincification area	
300°C	45/55	~77	~45	25.9±0.6	124.6±5.5	50.2±3.4	formation of pores due to dezincification in the interconnected β
400°C	54/46	~54	~19	17.7±1.5	126.7±8.7	103.3±12.2	isolated beta-phase dezincification
600°C	35/65	~55	~13	16.8±0.9	130.3±6.4	91.2±3.4	localized dezincification occurred along isolated β islands

4. Conclusion

This investigation establishes that thermal processing of duplex brass alters not only the phase area fraction but also the overall microstructure. Notably, phase area fraction alone does not govern the dezincification behavior of the heat-treated samples. Instead, the microstructural transition from an interconnected β -phase to isolated β islands disrupts phase connectivity, severing the corrosion pathways necessary for dezincification to propagate. This structural transition significantly enhances dezincification resistance.

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