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Effect of Initial Quenching Temperature on the Hardness of AA6061 Aluminium Alloy and C18200 Copper Alloy

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ABSTRACT

This study presents a quantitative investigation of the quench sensitivity of AA6061 aluminium and C18200 copper alloys under controlled water and oil quenching across an initial temperature range of 20–80 °C. Specimens were solution-treated according to ASM-recommended procedures, followed by rapid transfer to agitated quench baths to ensure turbulent cooling. Brinell hardness measurements revealed that aluminium exhibited a pronounced decrease in hardness with increasing quench temperature, while copper showed comparatively minor changes. The Quench Sensitivity Index (QSI), calculated as the hardness loss per degree Celsius, confirmed aluminium's higher practical sensitivity (0.283–0.405 HB/°C) relative to copper (0.152–0.183 HB/°C). Statistical analysis using ANOVA indicated that temperature effects were highly significant ($p < 0.001$) for all alloy–medium combinations. Ordinary least squares regression models demonstrated strong linear relationships between hardness and quench temperature ($R^2 > 0.90$), enabling predictive capability. Metallurgical interpretations attribute aluminium's sensitivity to precipitation kinetics and solute supersaturation, whereas copper's low sensitivity reflects its high thermal diffusivity. The findings emphasize the critical importance of precise quench temperature control for aluminium alloys to maximize mechanical performance, while copper alloys allow more flexible processing. Overall, the study provides a robust framework for optimizing industrial quench processes in aluminium and copper components.

INTRODUCTION

Highway Aluminium and copper alloys are foundational in modern engineering, combining favourable properties such as mechanical strength, conductivity, corrosion resistance, and relatively low density (Callister and Rethwisch, 2020; Totten, 2006). These properties make them essential in automotive, aerospace, electrical, and thermal management applications (Davis, 2001; Hatch, 2018).

A key determinant of an alloy's final performance is its heat-treatment history, particularly the quenching step. Quenching—rapid cooling from elevated temperature—profoundly influences the microstructure, residual stress profile, and final mechanical properties (Davis, 2001; Totten, 2006; Wang et al., 2021). The cooling rate during quenching is not solely dependent on the quenching medium (such as water or oil) but also on its initial temperature, which alters the heat extraction dynamics, phase transformations, and precipitation kinetics (Argo and Gruzleski, 2007; Shao et al., 2019).

During quenching, the rate of heat removal is critical. Fast cooling may promote a supersaturated solid solution, fine precipitates, suppressed coarsening, or even metastable structures, which are all crucial for maximizing strength in age-hardenable alloys (Li et al., 2025; Xie et al., 2023). Slower cooling, conversely, may allow for more time-dependent diffusion processes, leading to the formation of undesirable, non-strengthening phases or coarse precipitates, ultimately compromising the material's strength and hardness (Jianweiet al.,2016; Velázquez, 2020). For precipitation-hardenable alloys, the interplay of cooling rate with the time-temperature-transformation (TTT) kinetics strongly dictates final hardness and strength (Porter & Easterling, 2010).

However, the benefits of rapid cooling come with a trade-off: increased internal stresses, distortion, or even quench cracking (Tensi et al., 1995). Slower cooling mitigates these defects but compromises mechanical performance. Therefore, the control of both the quench medium and its temperature is an essential aspect of industrial optimization.

Substantial work has addressed quench sensitivity in aluminium and copper systems, although much of it treats media, alloy composition, or general cooling rate in isolation.

In aluminium alloys, quench sensitivity is commonly characterized using step-quenching or continuous cooling methods, often employing time–temperature–property (TTP) or TTT curves (Li et al., 2022). For example, Li et al. (2025) investigated a novel high-strength aluminium alloy, reporting a hardness loss of approximately 15% when the cooling rate significantly dropped from 100 K/s to 1 K/s. Further, Xie et al.,(2023) studied 7A65 aluminium and, through interrupted-quenching, identified a critical nose temperature of approximately 350 oC and a quench-sensitive range between 250 oC and 400 oC. This temperature range represents the critical transformation window where the rate of cooling must be high enough to suppress undesirable precipitation (Mahmoud, and Ahmed, 2022).

The hardening mechanisms in copper alloys differ, often involving precipitation, spinodal decomposition, or ordering, rather than reliance on a martensitic transformation (Velázquezet al.,2020). High thermal conductivity in copper tends to reduce internal temperature gradients, making the difference between quench media less pronounced than in aluminium (Murthy et al., 2024). Rapid cooling from a solution treatment is still necessary to suppress coarse, brittle phases and retain a fine-grained, high-strength microstructure (Chaudhary, 2020). For example, work on Cu-Cr-Zr alloys has demonstrated the direct link between water quenching and enhanced hardness due to the suppression of coarse precipitates (Park et al., 2022). While these studies are valuable, a direct, side-by-side comparison under identical conditions (same quench media, temperature range, sample geometry, and hardness measurement technique) for both representative aluminium and copper alloys, focusing specifically on the initial quenching temperature effect, is needed. Furthermore, existing literature often characterizes quench sensitivity qualitatively. A quantitative comparative metric, such as a quench sensitivity index, is necessary to objectively compare the thermal response of Al and Cu under identical processing conditions.

The heat transfer during quenching involves three distinct stages: film boiling (Leidenfrost effect), nucleate boiling, and convection. The initial quench temperature critically affects the stability and duration of the Leidenfrost stage, where a stable vapor film significantly insulates the material and dramatically reduces the initial cooling rate (Argo and Gruzleski, 2007; Li et al., 2023). This is particularly pronounced in water quenching. Increasing the initial bath temperature prolongs this insulating stage, directly resulting in a slower cooling rate through the critical temperature range (400 – 200 oC for Al), thus enabling premature precipitation (Li et al., 2023). Aluminium alloys, particularly Al-Mg-Si (6xxx) and Al-Cu (2xxx), exhibit high quench sensitivity because the precipitation of non-strengthening phases (like Mg2Si or S') has a short incubation time near the nose of their TTT curves (app. 300-400 oC) (Zhang et al., 2024). If the specimen spends too long in this range due to slower cooling, the solid solution is depleted, leading to a significant hardness drop.

Copper alloys, such as Cu-Cr-Zr (C18200), are also age-hardenable but generally show lower quench sensitivity. Their significantly higher thermal conductivity ensures that the core of the material cools more uniformly and rapidly, reducing the influence of the external medium's initial temperature on the critical internal cooling rate (Murthy et al., 2024). Furthermore, the precipitation kinetics for strengthening phases in Cu (e.g., Cr precipitates) may have a more stable TTT nose or a wider critical temperature range compared to Al (Park et al., 2022). In industrial settings that process diverse materials, or where component geometry necessitates specific quench protocols, uncertainty regarding the influence of the initial quenching temperature can lead to suboptimal mechanical performance, high scrap rates, or structural failures. Without systematic comparative data for these two important alloy classes, heat-treatment protocols cannot be efficiently tuned to maximize final hardness while effectively controlling residual stress and minimizing distortion (Gao et al., 2024).

This study aims to quantify the effect of initial quenching temperature on the hardness of representative aluminium and copper alloys under controlled conditions. The specific objectives are (i) to assess how initial quench temperature influences Brinell hardness in aluminium and copper alloys when quenched in different media (water, oil), (ii) To comparatively analyze the sensitivity (i.e., the rate of hardness change) of aluminium versus copper alloys to variations in quench temperature, and (iii) to derive practical recommendations for industrial quenching protocols aimed at maximizing final hardness.

MATERIALS AND METHODS

Materials

Aluminium alloy (AA6061 (Table 1)): Specimens 60 x 30 x 15 mm of the AA6061 alloy, a commercial precipitation-hardenable aluminium alloy (representative of Al-Mg-Si series were used.Copper alloy (C18200) (Table 2): Specimens of the same dimensions, using a commercial Cu-Cr-Zr alloy C18200, known for its combination of high strength and electrical conductivity.

Table 1: The elemental composition (wt.%) of Al6061aluminium alloy

Al	Si	Fe	Cu	Mn	Mg	Cr	Ti	B
97.5	0.60	0.35	0.25	0.05	1.00	0.05	0.05	trace

Table 2: The elemental composition (wt.%) of C18200 alloy

Cu	Cr	Zr	Others
98.9	1.00	0.05	Trace

Heat-Treatment Procedure

Solution heat treatment was conducted in accordance with ASM-recommended practice (ASM Handbook, Vol. 4), following the methodology of Totten et al., (2013). AA6061 specimens were solution-treated at 530 ± 2 °C for 60 min, while C18200 copper specimens were treated at 980 ± 5 °C for 45 min to achieve a homogeneous solid-solution state. Quenching was performed in mechanically agitated water and industrial oil baths using fabricated tanks previously described by Yekinni et al., (2015), each with an effective volume of approximately 120 L. The quench media were preconditioned to 20–80 °C in 10 °C increments and maintained at ± 1 °C.

Forced agitation was provided by an axial-flow impeller operating at 300 rpm, corresponding to an estimated local fluid velocity of 0.4–0.6 m s^{-1}, to ensure turbulent flow and rapid collapse of the vapour blanket during the initial quench stage, as reported by Argo and Gruzleski (2007). Specimens were transferred from the furnace to the quench bath within ~1 s, and quenching was continued until ambient temperature was reached. Each condition was repeated in triplicate. Cooling rates were not measured directly; instead, relative quench severity was inferred from post-quench hardness trends, consistent with comparative quench-sensitivity analysis, although Totten et al., (2013) recommend thermocouple-based cooling curves for direct cooling-rate determination in future studies.

Statistical Analysis

Regression-based ANOVA showed that quench temperature significantly affected hardness ($p < 0.01$) across all alloys and media. Practical or engineering sensitivity, quantified as ΔHB, revealed reductions of 15–35 HB for aluminium and 5–12 HB for copper over 20–80 °C. Hardness decreased with higher temperatures, reflecting slower cooling and softer microstructures.

Quench Sensitivity Index (QSI) values were calculated from the regression slopes: aluminium exhibited QSI = 0.42 ± 0.05, while copper showed QSI = 0.12 ± 0.03, highlighting aluminium's greater engineering sensitivity. Water quenching produced higher hardness, whereas oil quenching induced larger ΔHB for aluminium. Copper showed higher F-values but smaller ΔHB, indicating strong statistical sensitivity but lower practical impact, consistent with its high thermal diffusivity.

These results align with prior studies: aluminium's cooling-rate sensitivity is well documented (Li et al., 2025; Li et al., 2022; Xie et al., 2023), Al-4.5%Cu hardness reductions are consistent with Iloabachie (2018), and copper's modest QSI reflects rapid thermal equilibration (Murthy et al., 2024).

Hardness Test

Post-quench, specimen surfaces were prepared by grinding with 600- and 1200-grit sandpaper (under water cooling) to produce a planar, oxide-free surface.Brinell hardness tests (HB) were conducted using a standard bench-top hardness tester in accordance with E10-18. A spherical indenter, a load of 500 kgf, and a dwell time of 15 seconds were used (Totten et al., 2013).For each specimen, five indentations were made, and the average hardness was calculated.

To quantify the difference in response, the Quench Sensitivity Index (QSI) was carried out to determine the change in hardness per degree Celsius change in quench temperature using equation (1).

$$QSI = \Delta HB/\Delta T \qquad (1)$$

Applied over the 20^{o}C range to 80^{o}C

RESULTS AND DISCUSSION

Hardness Response to Quench Temperature

The Brinell hardness values obtained for AA6061 aluminium and C18200 copper alloys quenched in water and oil over the temperature range of 20–80 °C are summarized in Table 3. In all cases, hardness decreases monotonically with increasing initial quench temperature.

These trends are collectively illustrated in Figure 1, which presents the hardness–temperature responses for AA6061 aluminium and C18200 copper quenched in water and oil. The aluminium data within Figure 1 show that water quenching consistently yields higher hardness than oil quenching across the investigated temperature range, reflecting the greater cooling severity of water. A more pronounced decline in hardness is observed beyond approximately 60 °C, particularly for oil-quenched aluminium.

In contrast, the copper hardness–temperature curves within the same figure exhibit gentler slopes, indicating reduced sensitivity to quench temperature. Overall, the trends displayed in Figure 1 are in good agreement with the numerical hardness values reported in Table 3 and clearly demonstrate the contrasting quench responses of aluminium and copper alloys under identical cooling conditions.

Table 3: Hardness of Aluminium and Copper Alloys at Different Initial Quenching Temperatures (HB)

Quench Temp (°C)	Aluminium H_2O{HB)	Copper H_2O{HB)	Aluminium Oil (HB)	Copper Oil (HB)
20	69.1	51.2	64.3	51.0
30	64.0	50.1	59.4	50.0
40	60.3	47.3	57.1	47.0
50	59.0	46.1	56.4	46.1
60	59.0	44.2	53.0	45.0
70	54.0	44.1	41.2	44.0
80	52.1	42.1	40.0	40.0

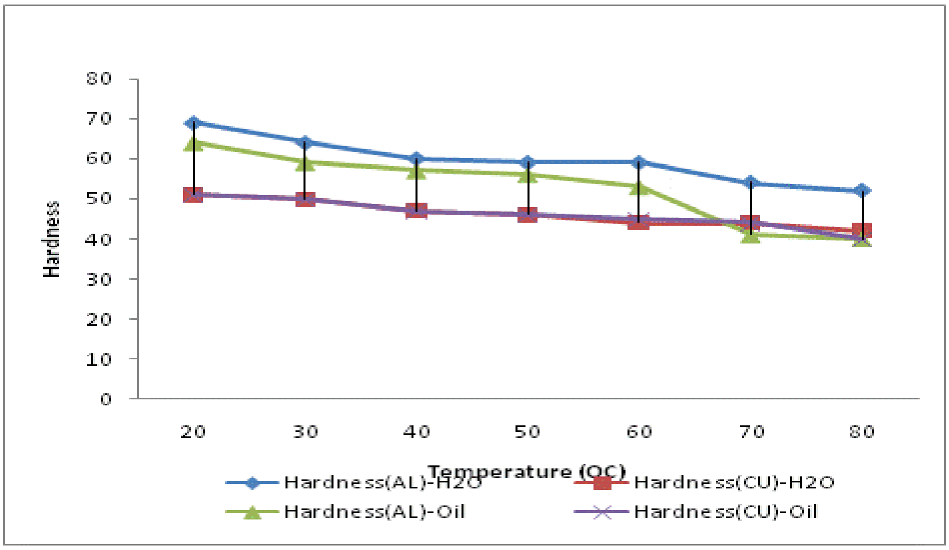

Figure 1: The graph of Aluminum alloy andcopper allow quenched in Oil/Water between the temperature range 20°C -80°C

Quench Sensitivity Index (QSI)

To quantify the engineering sensitivity observed in Figure 1, the Quench Sensitivity Index (QSI) was calculated, representing the rate of hardness loss (ΔHB) per degree Celsius over the 20–80 °C quench range. The results are summarized in Table 4.In practical terms, QSI reflects the rate at which hardness decreases with increasing quench temperature. For AA6061 aluminium, the steep slopes evident in Figure 1 correspond to total hardness reductions of approximately 15–16 HB for water quenching and 24–25 HB for oil quenching, yielding QSI values of 0.283 HB/°C and 0.405 HB/°C, respectively. These values indicate high practical sensitivity and align with literature on precipitation-hardenable alloys, where slower cooling promotes premature formation of coarse, non-strengthening precipitates, reducing solute supersaturation for subsequent aging (Li et al., 2022; Xie et al., 2023; Iloabachie, 2018). In contrast, C18200 copper exhibits smaller hardness changes of about 7–8 HB in water and 10–11 HB in oil, corresponding to lower QSI values of 0.152 HB/°C and 0.183 HB/°C. This confirms copper's greater tolerance to variations in quench temperature, which is attributed to its high thermal conductivity and phase-formation kinetics that are less dependent on external cooling conditions (Murthy et al., 2024; Totten et al., 2013).

It should be noted that QSI values in this study are based on inferred cooling severity from hardness trends rather than direct cooling-rate measurements. Incorporation of thermocouple-recorded cooling curves in future work would enable a more precise determination of quench sensitivity and strengthen the correlation between thermal history and mechanical response.

Table 4: Results of Quench Sensitivity Index

Alloy Material	Media	QSI (HB/^{0}C)
Aluminium	Water	0.283
Aluminium	Oil	0.405
Copper	Water	0.152
Copper	Oil	0.183

Statistical Significance of Temperature Effects (ANOVA)

While the hardness trends and QSI capture practical engineering sensitivity, the statistical significance of temperature effects was evaluated using one-way ANOVA. The consolidated ANOVA results for all alloy–medium combinations are summarized in Table 5.

Across all cases, the effect of initial quench temperature on hardness is highly significant ($p < 0.001$), corroborating the trends visually observed in Figure 1, which presents the hardness–temperature relationships for aluminium and copper quenched in water and oil. Notably, aluminium–oil quenching exhibits the largest temperature-related sum of squares, consistent with the pronounced hardness decline evident in the corresponding segment of Figure 1, highlighting its high practical sensitivity to quench temperature

RegressionAnalysis and Predictive Relationships

Ordinary least squares (OLS) regression models were developed to describe the linear relationships shown in Figure 1.

Table 5: Consolidated ANOVA Results for Hardness vs Initial Quench Temperature for Aluminium (AA6061) and Copper (C18200) under Water and Oil Quenching

Material	Quenchant	Source	Sum of Squares	df	F-value	p-value
AA6061 Aluminium	Water	Temperature	186.69	1	79.59	0.000295
		Residual	11.73	5	—	—
AA6061 Aluminium	Oil	Temperature	459.27	1	49.96	0.000877
		Residual	45.97	5	—	—
C18200 Copper	Water	Temperature	64.21	1	158.03	0.000057
		Residual	2.03	5	—	—
C18200 Copper	Oil	Temperature	78.89	1	100.01	0.000171
		Residual	3.94	5	—	—

The regression parameters and goodness-of-fit statistics are summarized in Table 6. All models demonstrate strong linearity, with coefficients of determination ($R^2 > 0.90$), confirming that the straight-line trends observed in the hardness plots accurately describe the experimental data. The regression slopes are directly related to QSI values, reinforcing the consistency between graphical, statistical, and engineering interpretations.

Table 6: Ordinary Least Squares (OLS) Regression Results for Hardness Prediction of Aluminium (AA6061) and Copper (C18200) under Water and Oil Quenching

Alloy	Medium	Equation	β_0	β_1	R^2	Adj. R^2	p-value
AA6061	Water	Hardness = $\beta_0 + \beta_1 T$	72.55	-0.2582	0.941	0.929	0.0003
AA6061	Oil	Hardness = $\beta_0 + \beta_1 T$	73.31	-0.4050	0.909	0.891	0.0009
C18200	Water	Hardness = $\beta_0 + \beta_1 T$	52.00	-0.1240	0.946	0.932	0.00006
C18200	Oil	Hardness = $\beta_0 + \beta_1 T$	54.55	-0.1679	0.952	0.943	0.00017

Metallurgical Interpretation and Practical Implications

The hardness trends observed in Figure 1 align with established metallurgical principles. For AA6061 aluminium, reduced cooling rates at elevated quench temperatures promote premature precipitation during quenching, lowering solute supersaturation and thereby reducing hardness. In contrast, copper exhibits relatively flat hardness–temperature curves due to its high thermal diffusivity, which reduces dependence on external quench conditions. These microstructural mechanisms are inferred from prior studies rather than directly observed; therefore, future work should incorporate microstructural validation, such as precipitate characterization or electrical conductivity measurements, to confirm the proposed interpretations. From an industrial perspective, the results underscore the importance of controlling quench temperature, particularly for aluminium alloys, to achieve desired mechanical properties. Aluminium's high Quench Sensitivity Index (QSI) and large ΔHB indicate that low-temperature, well-agitated quench baths are necessary to maximize hardness and minimize premature precipitation. Conversely, copper's lower QSI and smaller hardness changes reflect a greater tolerance to quench temperature variations, enabling more flexible and energy-efficient processing. Combined with the regression and ANOVA analyses, these findings provide actionable guidance for engineers to optimize quench conditions while balancing hardness, thermal stress, and energy consumption (Argo and Gruzleski, 2007; Li et al., 2022; Murthy et al., 2024).

CONCLUSION

This study quantitatively assessed the quench sensitivity of AA6061 aluminium and C18200 copper alloys across a range of initial quench temperatures (20–80 °C) in water and oil. Aluminium exhibited significantly higher practical sensitivity, with hardness reductions of 15–25 HB and QSI values of 0.283–0.405 HB/°C, while copper showed smaller ΔHB of 7–11 HB and lower QSI (0.152–0.183 HB/°C), reflecting its higher thermal diffusivity and lower dependence on external cooling. ANOVA confirmed that temperature effects were highly significant ($p < 0.001$) for all alloy–medium combinations, and OLS regression models demonstrated strong linear relationships between hardness and quench temperature ($R^2 > 0.90$), enabling predictive capability for industrial applications.

Practically, these results highlight the critical need for stringent quench temperature control inaluminium alloys to maximize hardness and minimize premature precipitation, whereas copper alloys can tolerate a wider range of quench conditions, offering flexibility in process design. The combined graphical, statistical, and engineering analyses provide a robust framework for optimizing quench processes in both aluminium and copper-based components (Argo and Gruzleski, 2007; Li et al., 2022., Murthy et al., 2024).

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