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Effect of Temperature on Mechanical Properties of Pure Copper

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Abstract

Copper is an essential element for major industrial metals because of its high ductility, malleability, thermal and electrical conductivity, and resistance to corrosion. Copper and its alloys are mainly used in wire production, piping, automotive, and architecture. Unfortunately, some copper and copper alloys require heat treatment to attain the desired properties for each application. Based on the material's characteristics, changes in mechanical and physical properties occur at different critical temperatures. As a result, the exposure of copper to different temperatures in this research (100°C, 200°C, and 300°C) with times of 1 hour, 2 hours, and 3 hours is to study the change in tensile properties, referring to tensile strength, elongation, and its hardness. This study explores the basic connection between changes in temperature and the mechanical properties of pure copper. The mechanical characteristics—such as hardness, ductility, and tensile strength—were methodically investigated at various temperatures. Using cutting-edge technology, pure copper specimens were tested under controlled conditions at different temperatures to simulate real-world conditions.

1. Introduction

Temperature plays an important role in determining the state of substances and undergoes annealing as it's heat treatment process. An increase in the temperature of a solid might cause its length to increase. For liquids and gases, temperature affects their volume. The temperature of a material plays a significant role in its mechanical properties and affects its elasticity (Abbas et al., 2020). The goal of heat treating is to analyze a material's mechanical properties—typically its ductility, hardness, yield strength, tensile strength, and impact resistance. In addition to improving mechanical properties such as tensile strength, yield strength, ductility, corrosion resistance, and creep rupture, heat treatment also affects softness and hardness. These procedures also increase their versatility and machining effect.

1.1 Effect of Temperature on Tensile Strength of Pure Copper

The temperature affects copper's tensile strength. It is evident that the tensile and bending strengths decrease as the temperature rises (Andrzej Posmyk et al., 2018). Fig 1 shows the stress-strain diagram of the relationship between low temperature and high temperature.

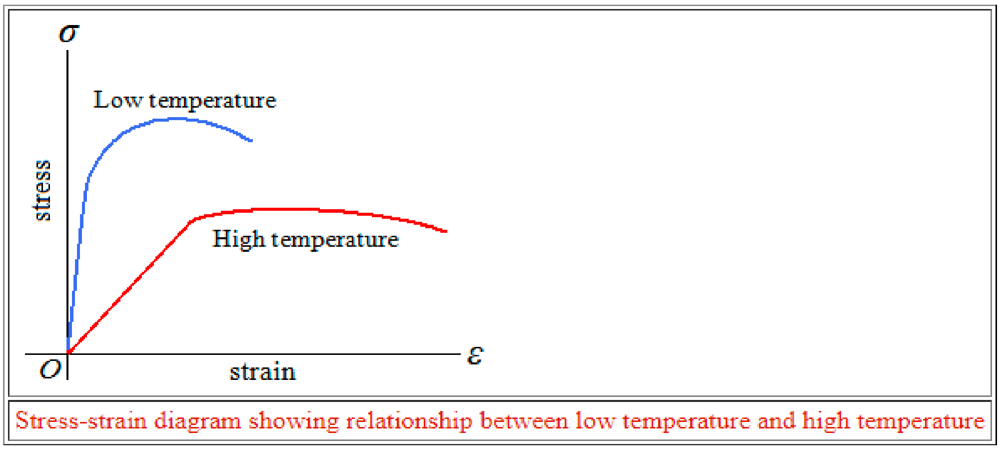

Fig 1 *Stress-strain diagram of the relationship between low temperature and high temperature*

Sun Fei & Xhu Cheng (2019) agree, based on their test results, that empirical models of copper's yield strength, tensile strength, and elastic modulus at high temperatures were developed; the test revealed that copper's yield strength, tensile strength, and elastic modulus all significantly decreased as temperature increased. A study by Kesharwani & Ramkumar, (2018) is been carried out where the high temperature characteristics of both pure and alloy copper have been studied between room temperature and 500 degrees Celsius. As temperature increased, a significant drop in yield strength and ultimate strength was noted for both pure and alloy copper.

1.2 Effect of Temperature on Hardness of Pure Copper

A previous study by Alsaleh Naser (2016 said that further expansions in the grain dimensions along the bending layers were brought on by the rising temperature. It also lessened the bend zone's hardness. On the other hand, the hardness effect was less affected by temperature between 125°C and 200°C, and the opposite was true for grain lengths along the tension layer. In another study in 2020 was conducted by Sengupta, S., Kumar, P., Makhatha, M.E. et al., stated that at lower temperatures, substructures were visible; at higher temperatures, substructures were largely absent from the sample. As a result, it is suggested that the restoration mechanism at lower temperatures involves copper recovery, whereas at higher temperatures, partial recrystallization occurs. Because more substructures were present at lower temperatures, hardness increased; however, partial recrystallization increased conductivity at higher temperatures.

2. Methodology

2.1 Materials

In this study, T2 pure solid copper with 99.99% purity will be used as a suitable sample. The dimensions of this plate are 100mm x 100mm x 1.5mm. At first, ensuring the sample is free from any surface defects or impurities is an important part, and use the fine-grit sandpaper to clean the surface. Figure 2 shows the copper plate and the sandpaper.

(a) **(b)**

Fig. 2 *Material use (a) Copper plate; (b) Fine-grit sandpaper*

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2.2 Tensile Test Specimen

In this study, one temperature consists of three (3) measurements. There are three (3) times taken, with four (4) temperatures desired. Each sample then needs to have three (3) samples. It is then later that the average data is calculated and taken as the results. Fine sandpaper was rubbed on the outer surface of every specimen to achieve a good surface finish and to reduce surface cracks. A flat plate is cut with dimensions of 20mm x 100mm x 1.5mm (Figure 3).

Fig. 3 *Tensile test specimen*

2.3 Hardness Test Specimen

For the microhardness test, one temperature consists of one specimen, as shown in Figure 4. The data collected with 5 times indentation at each specimen and later than the average will be taken. The specimen is ground from 200 to 1200 grit sandpaper using a grinding machine, then polished to obtain a smooth surface.

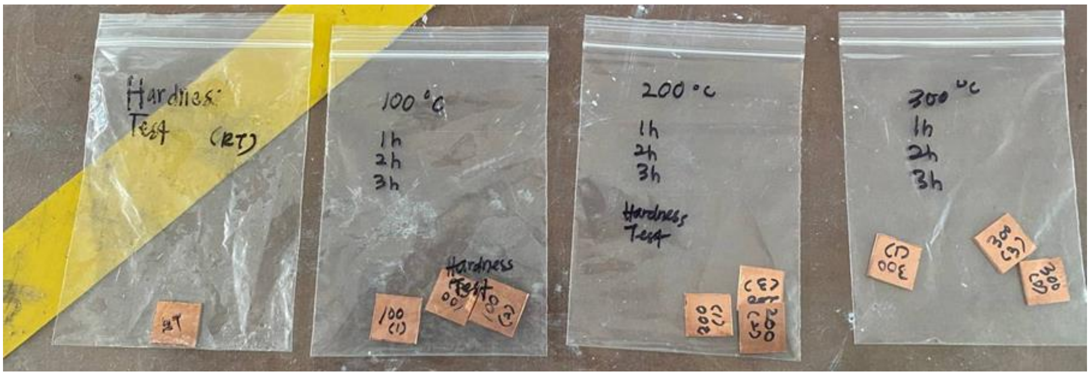

Fig. 4 *Microhardness test specimen*

2.4 Exposure of Specimen to Temperature

Tests were conducted at different temperatures of 100ºC, 200ºC, and 300. For 100, a drying oven is used; for 200, a high-capacity oven; and for 300, a furnace is used to carry out the experiment (Figure 5). After exposing the plate to the temperature, the specimen is cooled down at room temperature for 15 minutes.

(a) **(b)** **(c)**

Fig. 5 *Equipment used to expose specimens to temperature (a) Drying oven; (b) High capacity oven; (c) Furnace*

2.5 Tensile Test

The most common materials test is the tension test, in which tensile loads are applied (M. Singh, 2022). The original cross-sectional area of the specimen and the maximum force required to cause rupture during a tension test are used to compute the tensile strength. The American Society for Testing and Materials (ASTM), a national technical society that publishes specifications and standards for materials and testing, is one of the main standards organizations. The National Bureau of Standards (NBS) and the American Standards Association (ASA) are two more standardizing bodies. The machine used is ASTM E8. This is so that characteristic values like offset yield, yield strength, yield point elongation, tensile strength, strain at break, and area reduction can be determined. It also describes the uniaxial tensile test on metals at room temperature.

The purpose of tensile testing, also called tension testing, is to ascertain a material's maximum strength. Based on ASTM E8, the specimen geometry complies with the ASTM standard. In compliance with earlier research, specimens are subjected to tensile tests at a standard test speed of 5 mm/min and a gauge length of 40 mm. Every test follows the previously mentioned experimental design. This test can yield tensile characteristics such as elongation, tensile strength, and tensile modulus, also known as Young's modulus. By dividing the load at the break by the initial cross section area, one can calculate the tensile strength. Megapascals (MPa) are the unit of measurement, and they have important numbers. Tensile strength is also known as tensile stress. The following is the theoretical tensile strength equation:

$$\text{Tensile strength (MPa)} = \frac{\text{(Load at the break, N)}}{\text{(Original width × Original thickness, mm)}} \tag{1}$$

By dividing the moment of elongation at rupture by the initial gauge length and multiplying the result by 100, one can determine the percent elongation. The distance between grips can be used in place of the gauge marks or extensometers, which are used to determine the test section. Results are given as a percentage (%) with significant figures. The following is the theoretical equation for the percent elongation:

$$\text{Elongation (\%)} = \frac{\text{(Elongation at rupture, mm)}}{\text{(Initial gauge length, mm)}} \times 100 \tag{2}$$

2.6 Microhardness Test

In this study, the experiment carried out for the hardness test of pure copper is a microhardness test as the load used is below 1kg. A Vickers diamond pyramid is chosen. In situations where test samples are unsuitable for macro-hardness testing, microhardness testing serves as a means of assessing a material's hardness or resistance to deformation. Microhardness testing is the best method for determining the hardness of intricate shapes, surface coatings and plating, very small/thin samples, and individual phases of a material. The micro hardness test works well for determining surface contamination, grind burns, carburization or decarburization depths, and case-hardened layer depths. In this experiment, a test load of 980.7 mN (HV0.1) is used for 10 seconds. The following is the theoretical Vickers hardness equation:

$$HV = \frac{2P \sin \frac{136°}{2}}{d^2} \tag{3}$$

P = Load (N)
d = Mean of indention of diamond length (mm)
HV = Hardness Vickers (unit)

3. Result and Discussion

This section presents the observed data obtained throughout the study. The physical and mechanical properties were determined using the methods described in the previous section. The results and corresponding analyses of all tests conducted on the peat samples are discussed here. Based on the objectives outlined earlier, the collected data are used to support the study's conclusions.

3.1 Variation of UTS (MPa) vs time

The summary of values on stress and strain trends in pure copper plate with different temperatures (°C) and time exposure (hrs) is measured as shown in Table 1.

Table 1 *Values on stress and strain in pure copper plate with different temperatures (°C) and time exposure (hrs)*

Temperature (°C)	Time exposure (hrs)	Stress (N/mm²)	Strain (%)
RT		246.802	27.089
	1	249.205	33.918
100	2	248.729	30.786
	3	237.316	24.913
	1	232.396	25.633
200	2	238.917	25.499
	3	243.271	26.025
	1	232.396	36.56
300	2	189.26	65.09
	3	195.997	67.1

a) UTS in 100°C °

It is observed that at 100ºC, the stress over 3 hours of exposure decreases (Figure 6), indicating involvement in the reduction of internal stresses within the metal, leading to a more stable structure. It decreases consistently over time due to stress-relief annealing, allowing copper atoms to rearrange.

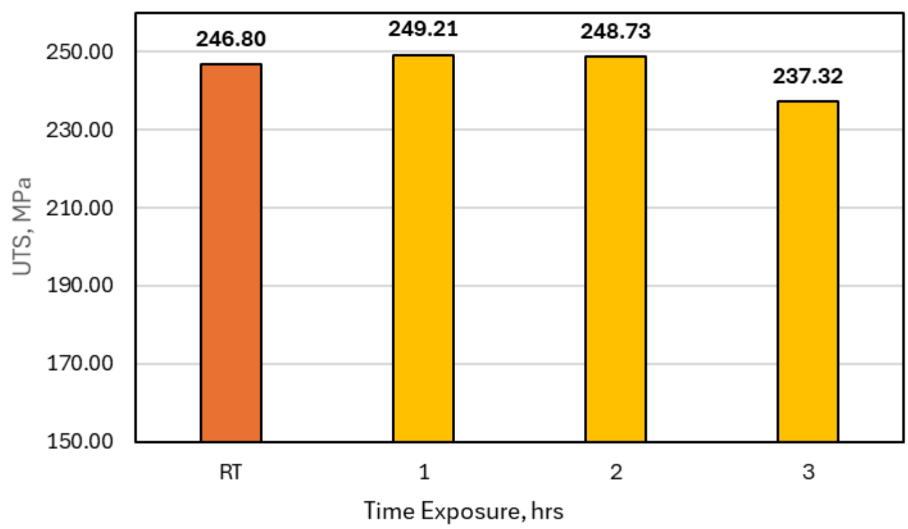

Fig. 6 *UTS in 100°C in across 3 hours of exposure*

b) UTS in 200°C

At 200°C (Figure 7), the stress increases over time because the elevated temperature induces hardening, causing the copper's microstructure to become harder and potentially introducing new stresses.

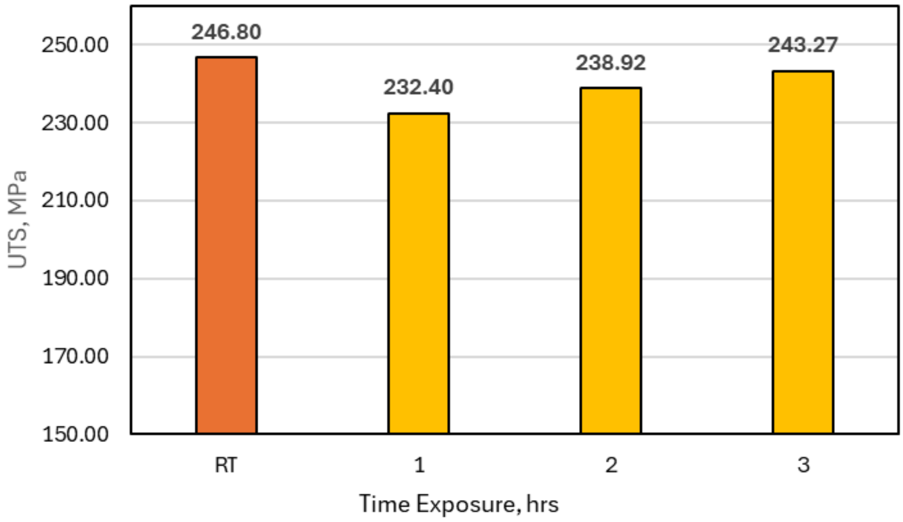

Fig. 7 *UTS in 200°C across 3 hours exposure*

c) UTS in 300°C

For 300°C shown in Figure 6, the initial decreases in stress over 2 hours could be due to an extensive stress relief annealing process, allowing the copper to relax and rearrange its structure. However, at 3 hours, despite the initial relief, other factors might come into play such as, grain growth or phase transformations that reintroduce stress into the material, leading to an increase in stress despite the earlier relaxation. The interplay of these factors can cause fluctuation in stress levels across different temperatures and exposure times.

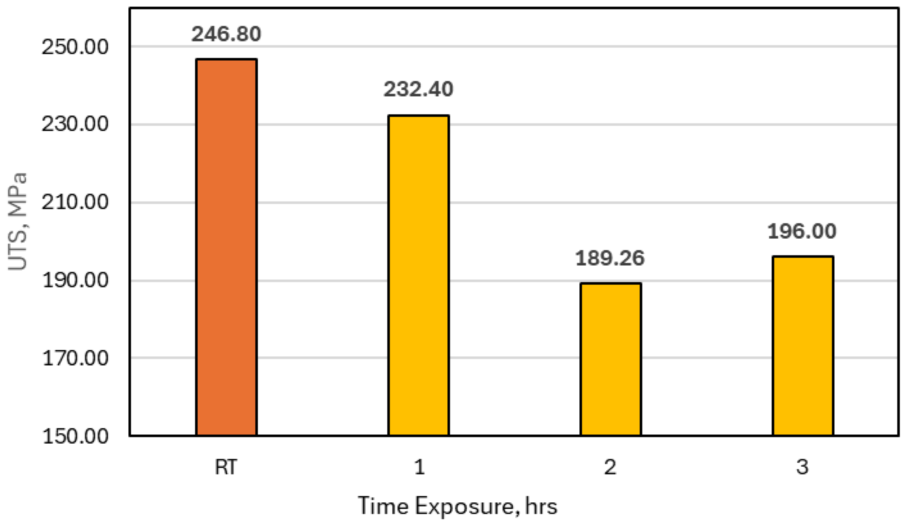

Fig. 8 *UTS in 300°C in 3 hours exposure*

3.2 Variation of UTS (MPa) vs temperature (°C)

Table 2 shows the summary of UTS (MPa) with temperature (°C) while the graph below shows the data obtained for the UTS(MPa) vs temperature (°C). In Fig. 9 UTS (MPa) in 1 hour 2 hours and 3 hours.

Table 2 *Summary of UTS (MPa) with temperature (°C)*

Time exposure (hrs)	Temperature (°C)	Stress (N/mm²)	Strain (%)
RT		246.802	27.089
1	100	249.205	33.918
	200	238.917	25.633
	300	232.396	36.56
2	100	248.729	30.786
	200	238.917	25.499
	300	189.26	65.09
3	100	237.316	24.913
	200	243.271	26.025
	300	195.997	67.1

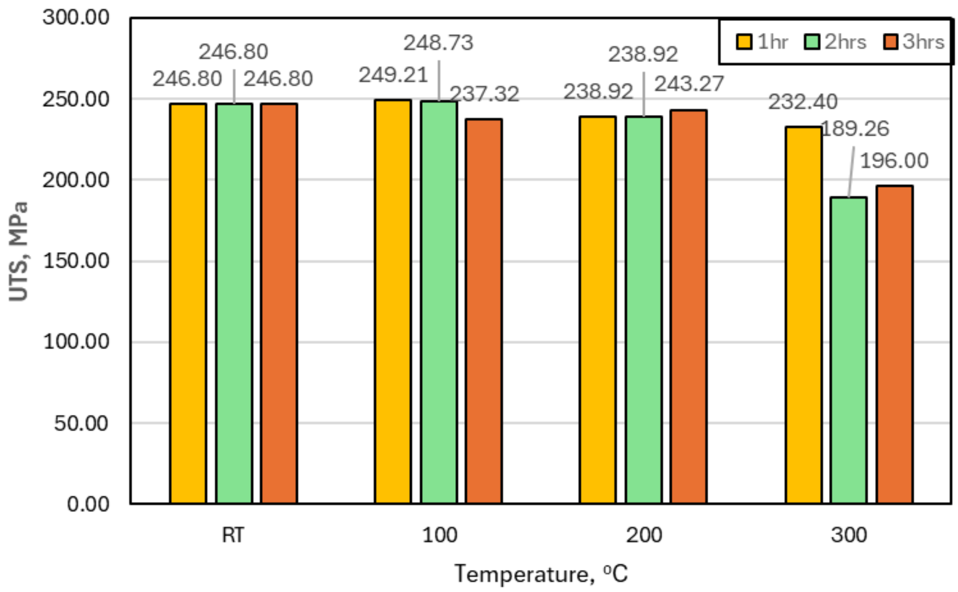

Fig 9 *UTS (MPa) in 1 hour, 2 hours and 3 hours at different temperatures*

From the graphs, it can be seen that the tensile strength of pure copper decreases linearly with temperature. The process of recrystallization could be the cause of the consistent decrease in tensile strength observed in the first one and two-hour exposures at 100°C, 200°C, and 300°C. As previously mentioned, copper tends to recrystallize at high temperatures. This results in the formation of new, strain-free grains that usually improve ductility while decreasing tensile strength.

However, the observation of a shift after three hours of exposure shows an intriguing change as in Fig 6. The first increase in tensile strength from 100°C to 200°C, followed by a decrease from 200°C to 300°C, may indicate a more complex process that affects the material in both positive and negative ways. One possible explanation for the first three-hour increase in tensile strength from 100°C to 200°C could be a complete and noticeable recrystallization at the lower temperature. This temperature range may make it easier to reduce defects and dislocations, leading to a brief increase in strength.

The beginning of grain growth may be connected to the subsequent drop in tensile strength from 200°C to 300°C during the same exposure period. The microstructure may become coarser as a result of the copper grains beginning to grow significantly at higher temperatures and longer exposure times. Because the boundaries between grains become weaker and more prone to deformation, larger grains usually result in decreased strength.

Consequently, the combined effects of recrystallization and grain growth could account for the observed pattern, which shows an initial increase in tensile strength followed by a decrease over a three-hour period at temperatures of 100°C, 200°C, and 300°C. The first phase encourages recrystallization, which momentarily increases strength; the second stage, which occurs after extended exposure to higher temperatures, encourages grain growth, which results in smaller grains and decreased strength.

3.3 Variation of elongation (%) in 3 hours exposure

Table 3 below shows the values of elongation (%) of pure copper with temperature in 3 hours exposure and graph showing the comparison between temperature and its elongation (%) within time can be seen in Fig 10.

Table 3 *Values of elongation (%) of pure copper with temperature (°C)*

Temperature (°C)	Time exposure (hrs)	Elongation (%)
RT		10.836
100	1	13.567
	2	12.905
	3	9.965
200	1	10.253
	2	10.200
	3	10.410
300	1	14.624
	2	26.036
	3	26.840

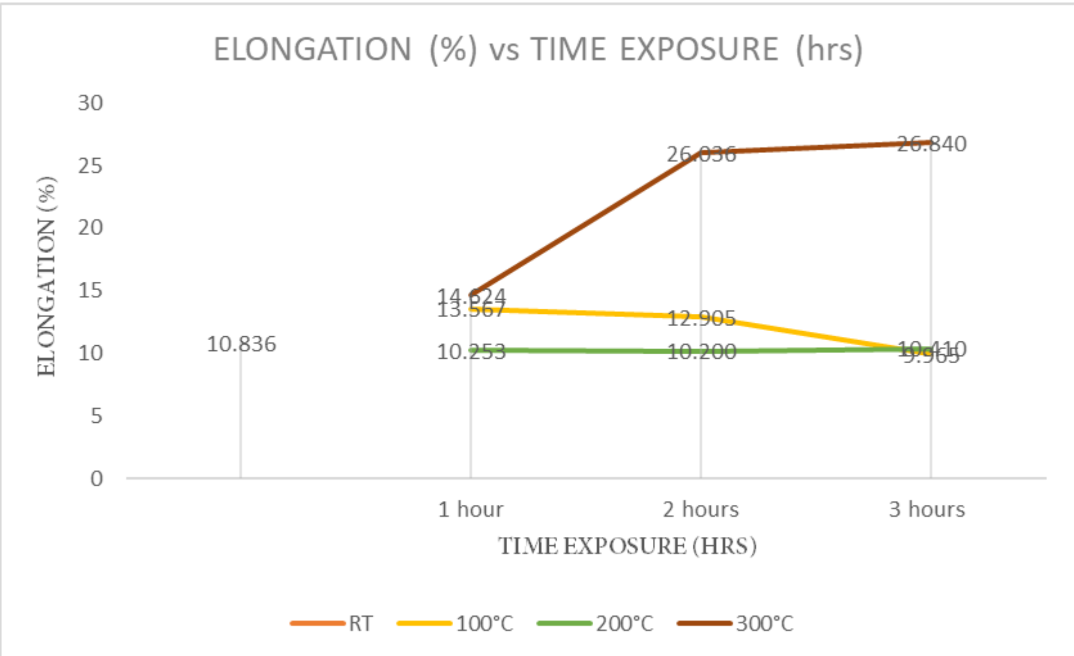

Fig. 10 *Elongation (%) vs time exposure (hrs)*

At 100°C and 200°C, it can be seen that the elongation decreasing along with time. This is related to the thermal expansion due to the prolonged exposure to the temperature, and it does involve the atoms repositioning themselves to relieve stress and reduce defects. This leads to a reduction in the copper's ability to elongate as it has become more structurally stable. Besides that, higher temperatures promote grain growth in the copper plate and reduce its ductility.

As for the elongation at 300°C, there is rapid changes in 2 hours of exposure. This is because recrystallization occurs. The process involved the formation of new, smaller grains within the copper plate.

3.4 Microhardness Analysis

The summary of microhardness analysis for pure copper with time exposure (hrs) is shown in Table 4 and Fig 11. hardness value at 100°C, 200°C, and 300°C with different durations.

Table 4 *Summary of microhardness analysis for pure copper with time exposure (hrs)*

Temperature (°C)	Time exposure	Hardness (HV)
RT		62.253
	1	46.074
100	2	50.879
	3	62.017
	1	68.646
200	2	68.817
	3	72.098
	1	75.049
300	2	75.070
	3	89.397

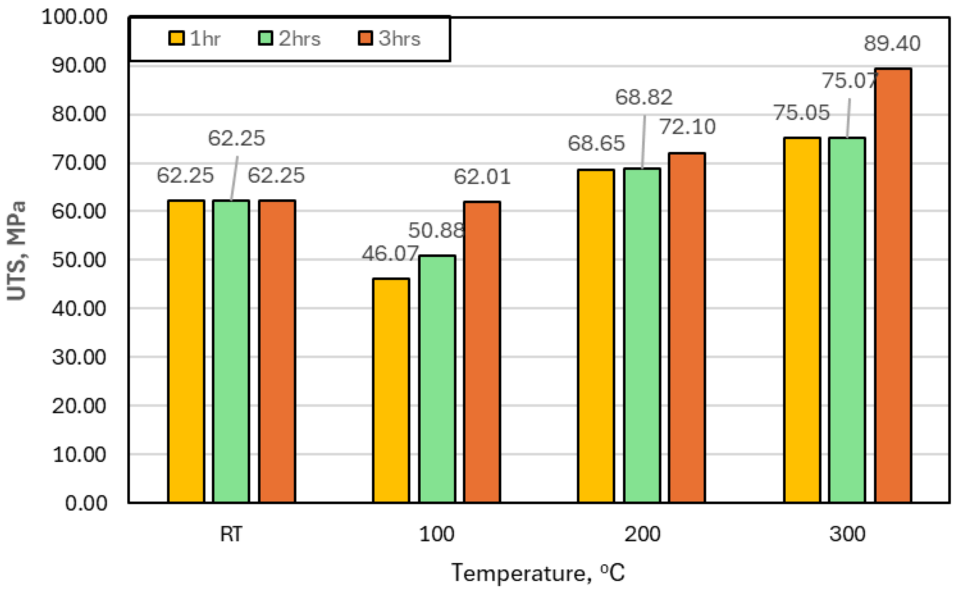

Fig. 11 *Hardness at 100°C, 200°C and 300°C with different durations*

From Figure 11, it is observed that the hardness increases at all temperatures over 3 hours of exposure. Increases in temperature and exposure duration often cause materials to soften through annealing or a decrease in dislocation density. But pure copper shows a consistent increase in hardness across all exposure times and temperatures, suggesting that another mechanism may be at work. Age hardening or precipitation hardening may be one explanation. Fine precipitates form within the material's structure as a result of this process, increasing hardness by preventing dislocation movement.

The variation in pure copper's hardness values across different temperatures and exposure times suggests intricate interactions among concurrent metallurgical processes. The predicted increase in hardness at 100°C and 200°C for one and two hours is consistent with mechanisms such as work hardening, precipitation hardening, or other processes that typically improve a material's resistance to deformation over time. Increasing the temperature and duration increases the hardness values. The observed variations in hardness values at each temperature over the course of 1, 2 and 3 hours indicate the presence of multiple competing metallurgical processes. These variations in the material's hardness could be influenced by a shift, over longer exposure times, from hardening to possible softening mechanisms.

3.5 Summary of Data Analysis

Table 6 *Summary of data analysis*

Temp (°C)	Time exposure (hrs)	UTS (MPa)	Elongation (%)	Hardness (HV)
RT		246.802	10.836	62.253
100	1	249.205	13.567	46.074
	2	248.729	12.905	50.879
	3	237.316	9.965	62.017
200	1	232.396	10.253	68.646
	2	238.917	10.200	68.817
	3	243.271	10.410	72.098
300	1	232.396	14.624	75.049
	2	189.26	26.036	75.070
	3	195.997	26.840	89.397

4.0 Conclusion

This research investigated the effects of temperature (100°C, 200°C, and 300°C) and exposure time (1, 2, and 3 hours) on the mechanical properties of T2 pure copper. The experimental results demonstrated that:

- **Tensile Strength:** The Ultimate Tensile Strength (UTS) generally decreases as temperature increases. The lowest UTS value of 189.26 MPa was recorded at 300°C after 2 hours of exposure. This reduction is primarily attributed to the recrystallization process, which forms new, strain-free grains.
- **Ductility:** Elongation showed a significant increase at 300°C, reaching a maximum of 26.84% after 3 hours. This indicates that higher temperatures promote the formation of smaller grains and recrystallization, which enhances the material's ability to deform.
- **Hardness:** Interestingly, the microhardness of pure copper increased consistently with both temperature and duration, reaching a peak of 89.40 HV at 300°C after 3 hours. This suggests a mechanism such as age hardening or precipitation hardening, where fine precipitates within the copper structure impede dislocation movement.

In summary, while elevated temperatures reduce the tensile strength of pure copper, they simultaneously enhance its ductility and hardness due to complex metallurgical interactions between recrystallization and hardening mechanisms.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm their contributions to the research as follows: Nur Aida Muzirah Mohd Murad and Mohd Yussni Hashim were responsible for the study conception and design. Data collection was carried out by Nur Aida Muzirah Mohd Murad. The analysis and interpretation of results, as well as the preparation of the draft manuscript, were performed collaboratively by Nur Aida Muzirah Mohd Murad and Mohd Yussni Hashim. All authors have reviewed the experimental data and approved the final version of the manuscript for publication.

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