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EXPERIMENTAL ANALYSIS OF MICROSTRUCTURE AND MECHANICAL PROPERTIES OF COPPER AND BRASS BASED ALLOYS

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ABSTRACT

The significant demand for copper and brass in industrial applications, the automotive industry and building industry is increasing; this requires the improvement of their mechanical properties by the addition of suitable alloying elements. The objective of this research is to study the effect of adding various alloys to copper and brass and their effects on their tensile strength, hardness and microstructure. The mechanical properties of two copper alloys and two brass alloys have been characterized in terms of tensile strength, impact strength and Rockwell hardness. The mechanical properties and microstructure of annealed specimens of Cu and brass alloys were observed. The results showed that by increasing the addition of alloys, the tensile strength also increases for both cases. The microstructure of the fracture surface after tensile testing has been examined using an inverted microscope. The experimental result shows that after the annealing at two temperatures of specimens of two copper alloys and two brass alloys, E-Cu shows more ductility than pure copper and C38500 brass alloy shows more ductility, yield strength and tensile strength than brass type 1.

***Keywords*:** Copper alloy; brass alloy; mechanical properties; microstructure; fracture..

INTRODUCTION

The tensile strength of copper and brass alloys can be improved by cold working, whereas their ductility is quickly reduced, which can be improved by temper annealing [1]. The post-irradiation annealing of copper and its alloys has been investigated to find its effects on the tensile properties of Cu-Ni alloy. First the specimen was irradiated at room temperature by a 15 MeV electron beam, then it was annealed under vacuum at 450°C for 15–120 min and it was found that the yield strength and tensile strength decreased as the annealing time and temperature increased, whereas the percentage elongation increased [2]. An experimental analysis was done to test the fine-grained microstructure in copper and its stability during heat treatments, and also to compare test results of uniaxial compression and tension properties at room temperature, with the response based on the interaction of dislocation anticipated from calculations [3]. The mechanical properties and microstructure of the nanostructures and ultra-fine-grained copper alloys were observed by varying the annealing time and temperature, and it was found that the hardness and tensile strength of the copper depend on the grain size [4]. Copper and brass types are classified based on the percentage weights of metals in their compositions. Copper in its pure, unalloyed state is soft and has high electrical and thermal conductivity with high corrosion resistance. E-Cu is oxygen-free copper which has more applications where high magnetic fields are utilized and also in windings. E-Cu has high conductivity and relatively high corrosion resistance. Table 1 shows the chemical analysis of pure copper and E-Cu by % weight basis of each element.

Table 1. Chemical analysis of pure copper and E-Cu.

Alloy Name	Cu	Sn	Pb	Zn	Fe
Pure Copper	99.28	0.07	0.07	0.51	0.03
E-Cu	99.85	0.03	0.03	0.015	0.06

Brass is an alloy made from copper and zinc and also includes a small percentage of other metals like iron, nickel, lead, tin, aluminum and antimony. The composition of pure brass is 85% copper and 15% zinc, where the high percentage of copper imparts ductility and zinc imparts the strength of brass. The % of zinc added to brass varies from 30 to 42% and is easily hot worked for improved strength, but the higher content of zinc also increases brittleness. Generally, optimal mechanical properties can be achieved by 30% zinc addition and the degree of deformation during production of the alloys, while at the same time heat treatment also has considerable impacts on the mechanical properties of brass alloys [5, 6]. Quan Li et al. [7] concluded from an experimental analysis that HPb59-1 brass can be replaced by Sb-Mg brass due to its higher mechanical properties and good cutting performance, as well as to protect the environment. Compared to copper, brass has low electrical conductivity but greater strength. Due to the excellent forming and drawing properties of brass, as well as its ease of machining, it has more industrial applications like fire extinguishers, flexible hose, jewelry, radiators, etc. The strength of brass can be increased by the addition of a small amount of manganese, tin, aluminum, iron and nickel to make high-strength fasteners, springs, pump shafts, etc. The strength and corrosion resistance of brass can be improved by the addition of nickel, iron, chromium, niobium, and/or manganese for use as tubes for condensers in ships and also for various applications in marine products. CuZn39Pb3 or C38500 brass is a soft and easily machined material. Unlike many copper alloyed materials, brass does not produce long chips during machining and therefore the surface quality is much better. Table 2 shows the chemical analysis of C38500 brass and brass type 1 by % weight basis of each element.

Table 2. Chemical analysis of C38500 and brass type 1.

Alloy Name	Cu	Sn	Pb	Zn	Fe
C38500	57.80	0.12	2.71	39.02	0.15
Brass type 1	57.20	0.09	2.81	39.42	0.05

The main objective of this research is to investigate the influence of alloying elements on the tensile properties and hardness of copper and brass alloys and their significance for the microstructure of the alloys. This study also observes the mechanical properties of annealed specimens of copper and brass alloys with different dimensions, and their impacts on the tensile strength and ductility of the alloys. This article is organized as follows: Section 2 addresses the materials and experimental methods. The results and discussion are presented in detail in section 3, and section 4 makes some concluding remarks.

MATERIALS AND METHODS

This research considers two materials, copper alloys and brass alloys, to study the impact of the addition of the alloying elements on their mechanical properties. The chemical compositions of their alloys are shown in Tables 1 and 2. The cryorolling treatment was used to produce ultra-fine-grained pure copper, which was further heat treated to improve the mechanical properties like tensile strength and ductility [8]. The impacts of cold working operations on the microstructure of Cu-Ag alloys, and the mechanical and electrical properties of the alloys were investigated and it was found that the tensile strength was improved by the addition of a small % of chromium, but that at the same time the electrical conductivity was reduced [9]. Specimens of each material were tested at room temperature on the GUNT Universal Testing Machine [10] with constant crosshead movement of 2 mm/min for tensile strength of the material. An extensometer was used to calibrate and measure the sample strain upon loading. Tensile tests were performed at room temperature on 6 mm diameter cylindrical specimens with a gauge length of 30 mm for the E-Cu and C38500 brass alloy specimens, whereas for pure copper and brass type 1 alloy the gauge diameter and lengths were 5.8 mm and 33 mm respectively. The tests were run under constant and continuous application of load at an initial strain rate of 1×10^{-4} s^{-1} for copper alloys and 1.3×10^{-4} s^{-1} for brass alloys on the GUNT UTM. The specimens were loaded continuously until failure. The impact tests were carried out on a GUNT Pendulum Impact Tester of 300 Nm maximum capacity for a specimen dimension of 55×10×10 mm as length, width and height. The microstructure of the fracture surfaces of the specimens after tensile and impact tests was examined using an inverted microscope after polishing using etchant of 10 ml HNO_3 and 90 ml water for copper alloys for 15 seconds, and etchant of 25 ml NH_4OH, 25 ml H_2O and 50 ml H_2O_2 for brass alloys. A Rockwell hardness test was carried out on each specimen using a Universal Hardness Testing machine in F scale with a 1/16 in. steel ball indenter and 60 kg load.

The mechanical properties of AA 6060 and 6061 were tested on the same machine to determine the effects of the addition of Mg alloy to the aluminium alloy on the tensile strength presented in [11]. Nachimani [12] has found that by increasing welding current will increase the weld nugget diameter and finally increased the loading force while doing tensile test, but by increasing the electrode pressing force will reduce the nugget diameter of the weld and finally reduced the loading force. Saleh et al. [13] did tensile test, impact test and creep test on composite materials and found that CKCF cabon composites have better mechanical properties in comparison of CRCF and CYCF carbon composites. During the test, a single-axis stress state was generated by applying an external load to the specimen in a longitudinal direction. This results in a uniform normal distribution of stress across the test cross-section of the specimen. The load on the specimen is increased slowly and continuously by turning the hand wheel until it breaks. The resulting maximum test force is a measure of the material's strength, called ultimate tensile strength R_m in N/mm^2, and is calculated from the maximum test force F_B in N, determined from the force-elongation diagram and the initial cross-section A_0 of the specimen in mm^2. The elongation at fracture is the ratio of the change in length of the specimen to its original length L_o and is calculated by measuring the length L_u of the specimen after fracture. The result of the tensile tests has been represented in a stress-elongation diagram. From the graph, the ultimate tensile strength R_m, the proportionality limits R_p, the yielding point R_e and the fracture strength R_f were calculated and these are reported in Tables 3-6 for all four specimens.

Tensile Test

From a literature survey it was found that many varieties of tensile specimens with different dimensions have been used by different authors based on the availability of materials. In many cases, the specimen dimensions are other than dictated by ASTM. They investigated the impacts of specimen size and geometry on the tensile strength of pure ultra-fine-grained copper [14]. The tensile properties of two materials were investigated, observing the impacts of changing the gage length on the mechanical properties [15]. This research considered two test pieces for each material; for copper, one specimen was E-Cu material and the other was pure copper, and similarly for brass one specimen was CuZn39Pb3 or C38500 brass material and the other was brass type 1 and all were used for determining the tensile strength of the materials on a UTM. The annealing of one specimen of E-Cu and C38500 was done at a temperature of 150°C for 20 minutes and then cooled in air; similarly, annealing for pure copper and brass type 1 was done at 180°C for 30 minutes and cooled in air. The tensile test was carried out on a UTM of 20 kN capacity at a crosshead speed of 2 mm/min, and the load deflection curve was obtained for each specimen. Data generated during the test included the applied load, elongation, stress and % elongation in the table, and graphs and curves were plotted for each specimen by continuous application of load until fracture. After the test, the yield strength, tensile strength, fracture strength and ductility were measured and fracture surfaces were examined using the inverted microscope. Increase in yield strength and decrease in tensile elongation can be achieved by decreasing the thickness of the specimen, as has been investigated on Cu, Al, Au and Ni foils with thickness less than 250 µm [16, 17]. From the literature survey and experimental observation, it was found that the tensile properties of specimens depend on the annealing temperature as well as time, and by increasing any one of these, the tensile strength normally reduces and ductility increases. Figure 1 shows the experimental setup for tensile tests on the UTM of each specimen, and fractured specimens after the test.

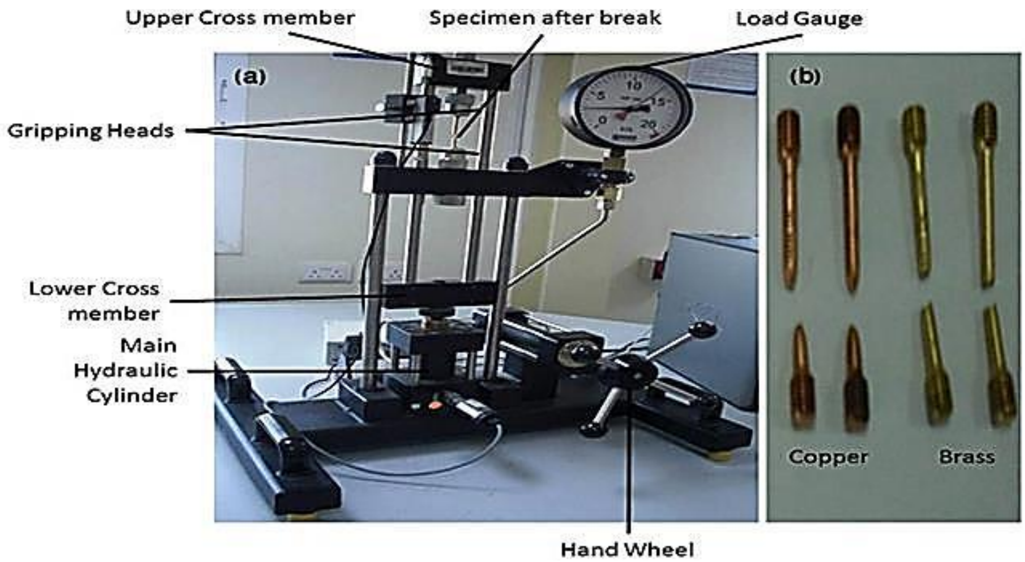

Figure 1. (a) Universal Testing Machine; (b) specimens after fracture.

Copper is a ductile metal with very high thermal and electrical conductivity. Pure copper is soft, malleable and has low hardness. The major applications of copper are in electrical wires, roofing and plumbing and industrial machinery. The hardness of copper can be improved by inclusions of alloying elements like Sn and Zn to produce brass and bronze.

2.1.1 Specimen details for E-Cu copper

Gage length (l_0) = 30 mm, gagediameter (d_0) = 6 mm and increased length (l_u) = 35 mm reduced diameter (d_f) = 5 mm. Figure 2 shows the increase in length after failure of the specimen in the tensile test.

Specimen details for pure copper

Gagelength (l_0) = 33 mm, gagediameter (d_0) = 5.8 mm and increased length (l_u) = 34.2 mm reduced diameter (d_f) = 2.4 mm.

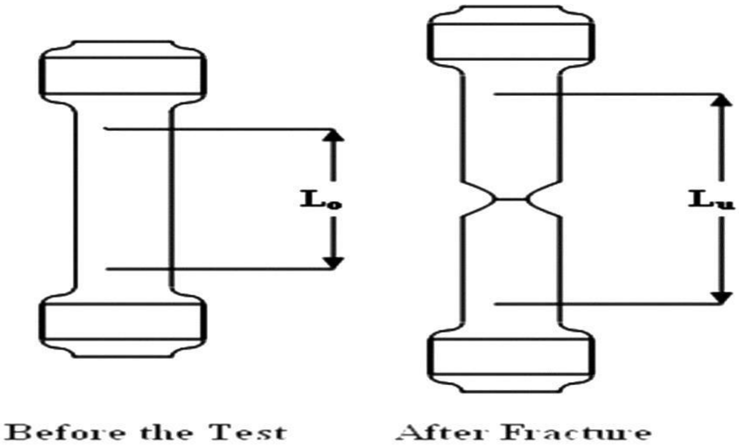

Figure 2. Change in length of a specimen after fracture.

The experimental results for each specimen are presented in Table 3, which shows the experimental results for E-Cu material, and Table 4, which shows the experimental results for pure copper. The machinability of brass can be improved by the addition of lead, whereas the addition of aluminum and tin improves its properties like strength, corrosion resistance, hardness and toughness, enabling the brass to be used for marine applications, gears, valves, and electrical applications, etc. The impacts of Ti and Sn in Cu40Zn brass alloy have been investigated on the microstructure, precipitation behavior, phase transformation and mechanical properties at different sintering temperatures and it was found that Ti and Sn in the form of $CuSn_3Ti_5$ particles significantly improve the yield strength and tensile strength of brass alloy [18]. Hariprasad et al. [19] have explained that tensile strength and impact strength of an alkali-treated banana-coir epoxy hybrid composite is more than untreated banana-coir epoxy hybrid composite, whereas flexural strength of untreated banana-coir epoxy hybrid composite is more. The tensile strength of brass alloy decreases from 400 to 260 N/mm^2 as the annealing temperature increases from 0 to 300°C and, similarly, for copper alloys the tensile strength decreases from 350 to 260 N/mm^2 by increasing the annealing temperature, as described in detail in [20].

Table 3. Tensile test results for E-Cu material.

S. No.	Load P (N)	Elongation e (mm)	Stress (MPa)	% Elongation	Imp. Stress (N/mm^2)
1	105	0.024	3.730	0.081	
2	288	0.098	10.173	0.326	
3	1208	0.146	42.725	0.488	
4	2033	0.195	71.886	0.651	
5	4036	0.293	142.755	0.977	
6	5158	0.342	182.428	1.139	
7	7114	0.366	251.601	1.221	R_p = 252
8	8073	0.464	285.510	1.546	
9	9089	0.488	321.453	1.628	
10	9923	0.586	350.953	1.953	
11	10115	0.781	357.735	2.604	R_m = 358
12	9875	1.953	349.258	6.510	
13	9175	3.223	324.504	10.742	
14	8140	4.102	287.883	13.672	
15	7104	4.663	251.262	15.544	
16	4995	5.103	176.667	17.008	R_f = 177

Table 4. Tensile test results for pure copper.

S. No.	Load P (N)	Elongation e (mm)	Stress (MPa)	% Elongation	Imp. Stress (N/mm^2)
1	38	0.000	1.451	0.000	
2	1699	0.064	60.110	0.213	
3	3572	0.163	126.385	0.544	
4	6462	0.437	228.657	1.458	
5	9511	0.732	304.814	2.219	R_p = 305
6	9444	0.806	359.970	2.441	R_m = 360
7	9290	0.806	357.430	2.441	
8	9033	0.806	340.738	2.441	
9	8322	0.830	314.974	2.515	
10	7354	0.830	278.324	2.515	
11	6011	0.830	227.522	2.515	R_f = 228

Specimen details for CuZn39Pb3 or C38500 brass

Gauge length (l_0) = 30 mm, gauge diameter (d_0) = 6 mm and increased length (l_u) = 38.4 mm reduced diameter (d_f) = 5 mm.

Specimen details for brass type 1

Gauge length (l_0) = 33 mm, gauge diameter (d_0) = 5.8 mm and increased length (l_u) = 38.3 mm reduced diameter (d_f) = 5.1 mm. The experimental results for each specimen are presented in Table 5, which shows the experimental results for C38500 brass material, and Table 6 which shows the experimental results for brass type 1.

Table 5. Tensile test results for C38500 brass alloy.

S. No.	Load (N)	Elongation (mm)	Stress (MPa)	% Elongation	Imp. Stress (N/mm^2)
1	10	0.024	0.339	0.081	
2	2272	0.293	80.363	0.977	
3	3413	0.342	120.363	1.139	
4	4746	0.439	167.847	1.465	
5	7095	0.513	250.923	1.709	
6	8571	0.635	303.142	2.116	
7	9818	0.708	347.223	2.360	
8	10795	0.757	381.810	2.523	R_p = 382
9	11112	0.879	393.000	2.930	
10	11419	1.099	403.850	3.662	R_e = 403
11	12166	2.100	430.299	6.999	
12	13001	4.004	459.799	13.346	
13	13231	4.980	467.937	16.602	
14	13432	6.860	475.058	22.868	R_m = 475
15	13087	7.764	462.851	25.879	
16	12531	8.252	443.184	27.505	R_f = 443

Table 6. Tensile test results for brass type 1 alloy.

S. No.	Load P (N)	Elongation e (mm)	Stress (MPa)	% Elongation	Imp. Stress (N/mm^2)
1	29	0.024	1.089	0.074	
2	1224	0.048	46.345	0.148	
3	3319	0.171	125.678	0.518	
4	6625	0.415	250.745	1.258	R_p = 251
5	8907	1.025	337.109	3.107	R_e = 337
6	9319	1.440	352.712	4.365	
7	9856	2.110	373.034	6.362	
8	10316	2.710	390.452	8.212	
9	11035	3.979	417.667	12.059	
10	11284	4.565	427.102	13.835	
11	11917	6.470	451.052	19.605	
12	12224	7.568	462.664	22.934	
13	12387	8.813	468.832	26.708	$R_f = R_m$ = 469

Impact Test

The impact strength of a material is the resistance to a suddenly applied load, which is equal to the work performed in breaking a specimen during the test and is also related to the toughness of the material. The toughness of the material, enabling it to absorb energy during the plastic deformation when subjected to suddenly applied loads, can be studied during impact testing. Due to the small plastic deformation before failure, a brittle material has low toughness, whereas a ductile material has greater resistance to a suddenly applied load, as it can absorb considerable energy before failure. The impact test is normally used to find the safe condition of structural members during industrial and building applications. A specimen with a notch is tested in the impact test, so that the specimen fails at the notch under a single hammer blow and at less energy compared to a specimen without a notch. The energy required to break the specimen is a measure of its impact strength. The impact strength of copper and brass alloys was tested on a Pendulum Impact Testing Machine with a capacity 150 J that can be increased to 300 J at room temperature. Each specimen is a square rod 10 mm × 10 mm × 55 mm length with a V-notch 27.5 mm from one end. The depth of notch is 2 mm and the internal angle of the V is 45° with a root radius of 0.25 mm and the specimen is kept on an anvil for support during the test. The energy absorbed by the specimen during fracturing has been computed by the initial energy of the hammer before striking minus the final energy remaining in the hammer after it breaks the specimen. The absorbed energy (E) = $m \times g \times (h - h_1)$ has been displayed in software installed for supporting the test on the pendulum impact testing machine to generate data associated with the test, where m is the mass of the pendulum, g is the gravitational acceleration, h is the height of the hammer before striking and h_1 is the maximum height after fracture of the specimen. The impact strength of the material depends on the lattice type of the material, the test temperature, chemical composition of the material, degree of strain hardening, etc. Figure 3 shows the experimental setup used during the experiment to find the impact strength, and the finally fractured surface of the specimen's microstructure was observed using the inverted microscope, as has been summarized in Table 7.

Figure 3. Equipment used for impact test.

Hardness

The hardness of a material imparts the most important properties for determining the strength and resistance to wear and scratching of the surface of the material. The hardness of a material can be defined as the ability of a material to resist indentation or deformation marked on the surface with an indenter under load. The Rockwell hardness of the materials has been determined using a steel ball of $\frac{1}{16''}$ diameter and 60 kgf force. The Rockwell hardness was measured on the surface at five different locations, then the values were averaged and noted for each specimen. The hardness of copper and brass alloys varies due to their Sn, Fe and Zn content.

RESULTS AND DISCUSSION

Microstructure

The microstructure of copper and brass alloys imparts the mechanical properties of copper and brass. After the tensile and impact tests, the fractured specimens were cleaned and polished for microscopic observation of the fracture surface. The impact of dynamic loading on the microstructure and mechanical properties of a Cu-Zn alloy at liquid nitrogen temperature (77 K) with different strains was studied and it was found after the tensile test that during dynamic loading brass showed a high strength and limited ductility [21, 22]. Figure 4 shows the microstructure of the fracture surface after the tensile testing of E-Cu and pure copper alloys. The microstructure of the specimen was observed by the inverted microscope after fracture and copper dendrites surrounded by zinc and lead alloys in grey phase were identified. Figure 5 shows the microstructure of the fracture surface after tensile testing of C38500 brass and brass type 1 alloys. In this case, in the microstructure observed by the inverted microscope after fracture copper dendrites surrounded by zinc, lead and iron alloys in grey phase were identified. Figure 6 shows the microstructure of the fracture surface after impact testing of E-Cu, pure copper, C38500 brass and brass type 1 alloys.

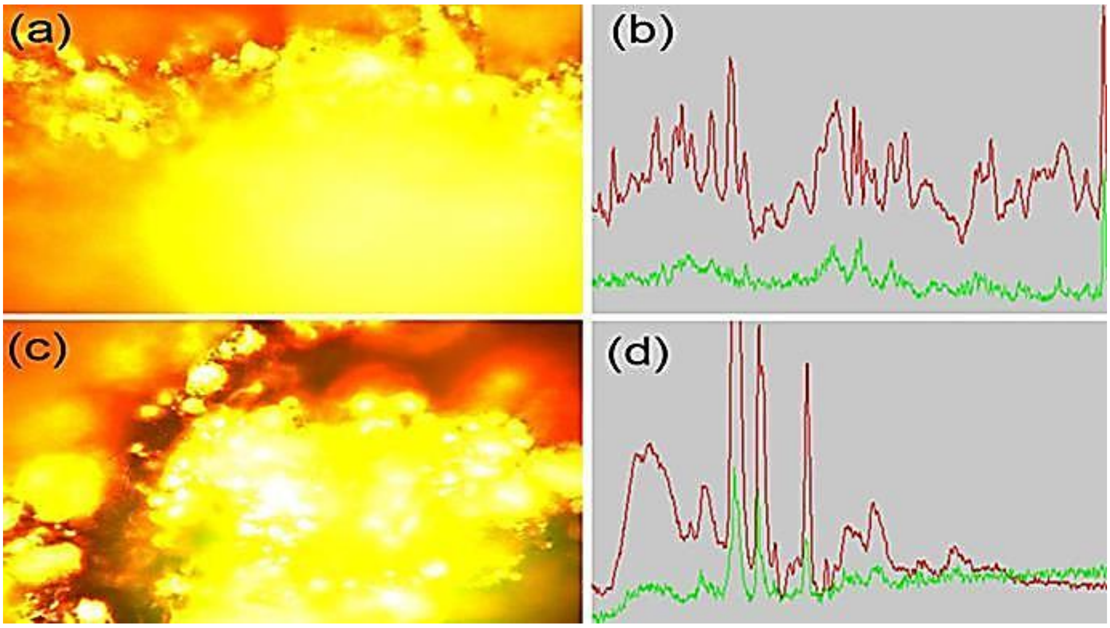

Figure 4. Typical microstructure of copper alloys with addition of various alloying elements after tensile test at Mag. 20X: (a) E-Cu alloys; (b) the bright primary phases containing alloys in E-Cu on line; (c) pure copper alloys; (d) the bright primary phases containing alloys in pure copper on line.

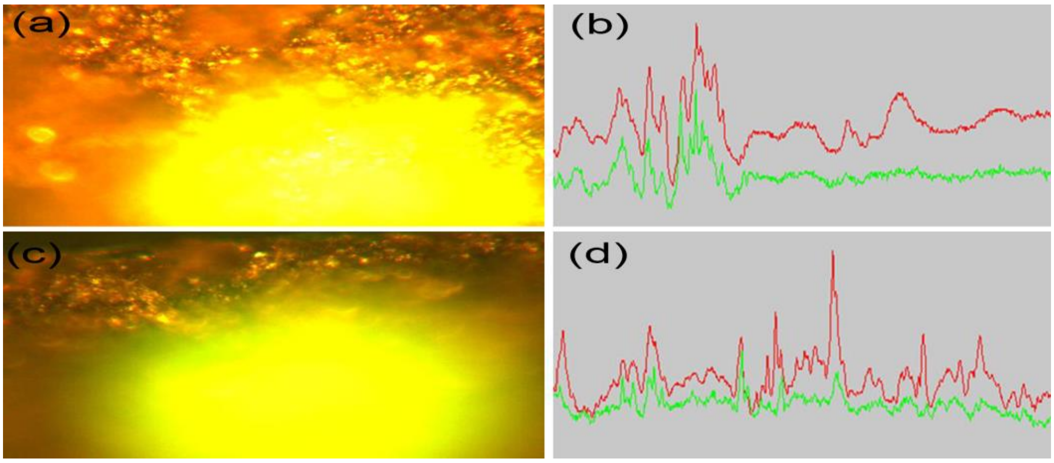

Figure 5. Typical microstructure of brass alloys with addition of various alloying elements after tensile test at Mag. 20X: (a) C38500 or CuZn39Pb3 brass alloys; (b) the bright primary phases containing alloys in C38500 on line; (c) brass type 1 alloy; (d) the bright primary phases containing alloys in brass type 1 on line.

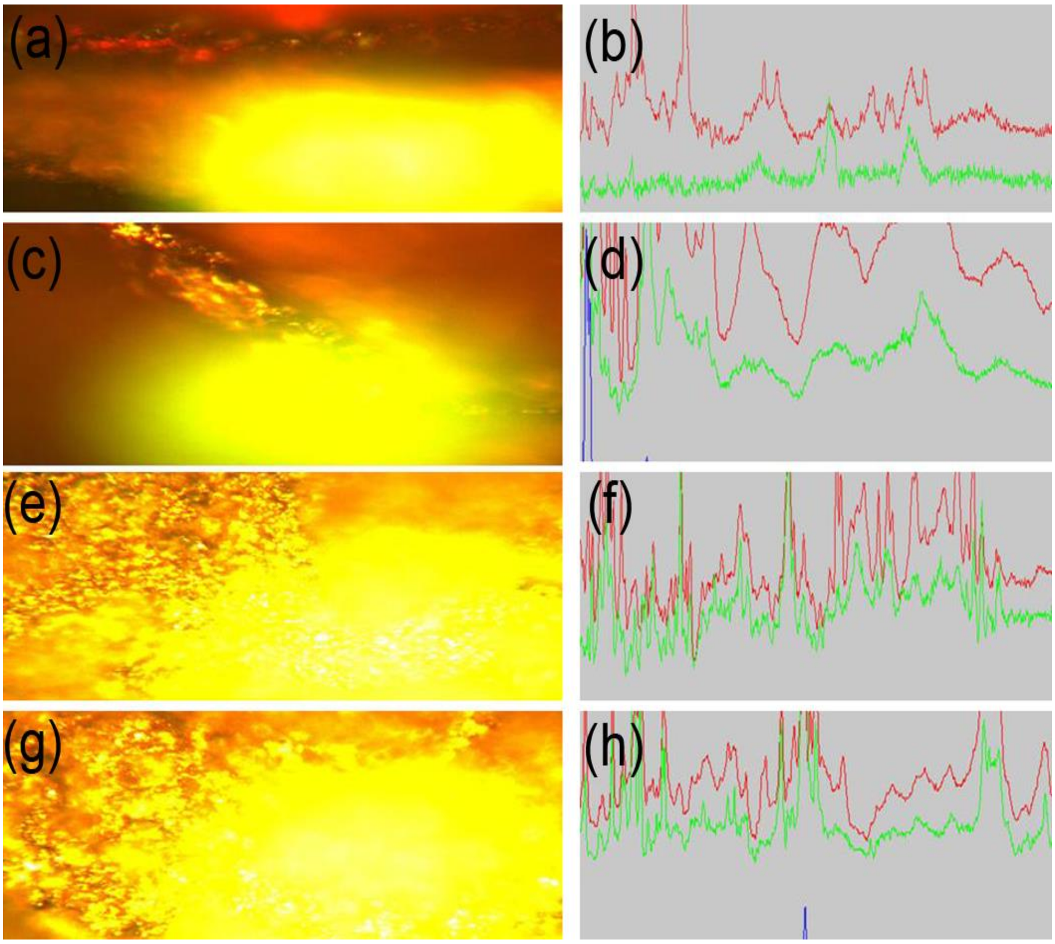

Figure 6. Typical microstructure of E-Cu and brass alloys with addition of various alloying elements after impact test at Mag. 20X: (a) E-Cu alloys; (b) the bright primary phases containing alloys in E-Cu on line; (c) pure copper alloys; (d) the bright primary phases containing alloys in pure copper on line; (e) CuZn39Pb3 brass alloys; (f) the bright primary phases containing alloys in CuZn39Pb3 on line; (g) brass type 1 alloys; (h) the bright primary phases containing alloys in brass type 1 on line.

Tensile Properties

The study of two commercial brass alloys, HPb 59-1 and H62, by subjecting them to superplastic treatments and observing the microstructural changes of brass alloys before and after the tensile test has been presented.

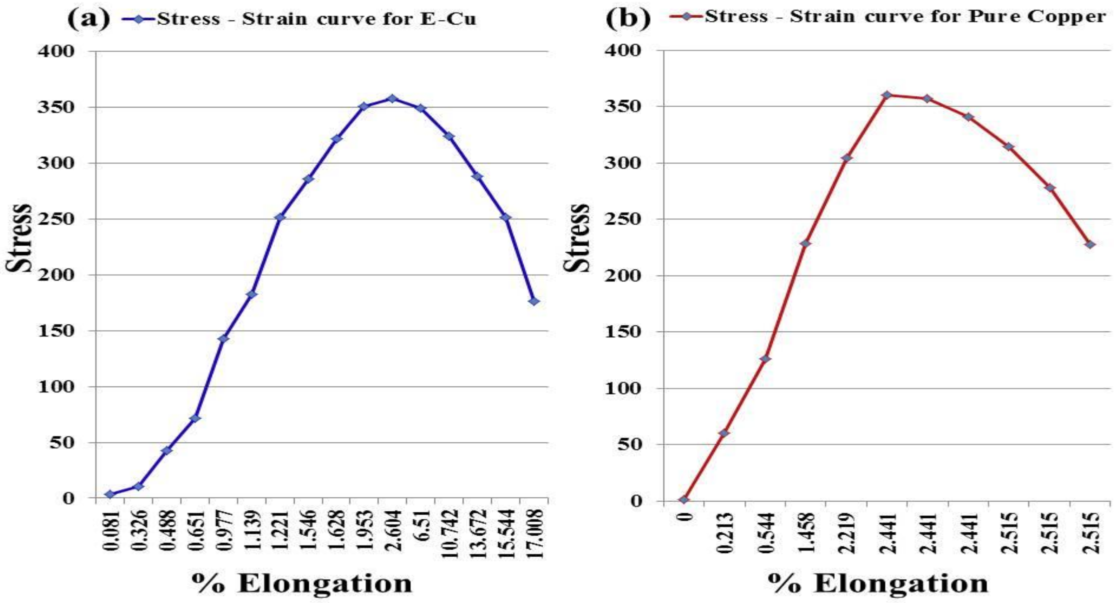

Figure 7. Typical stress–strain curves for (a) E-Cu alloy; (b) pure copper alloy at strain rate of 1×10^{-4} s^{-1}.

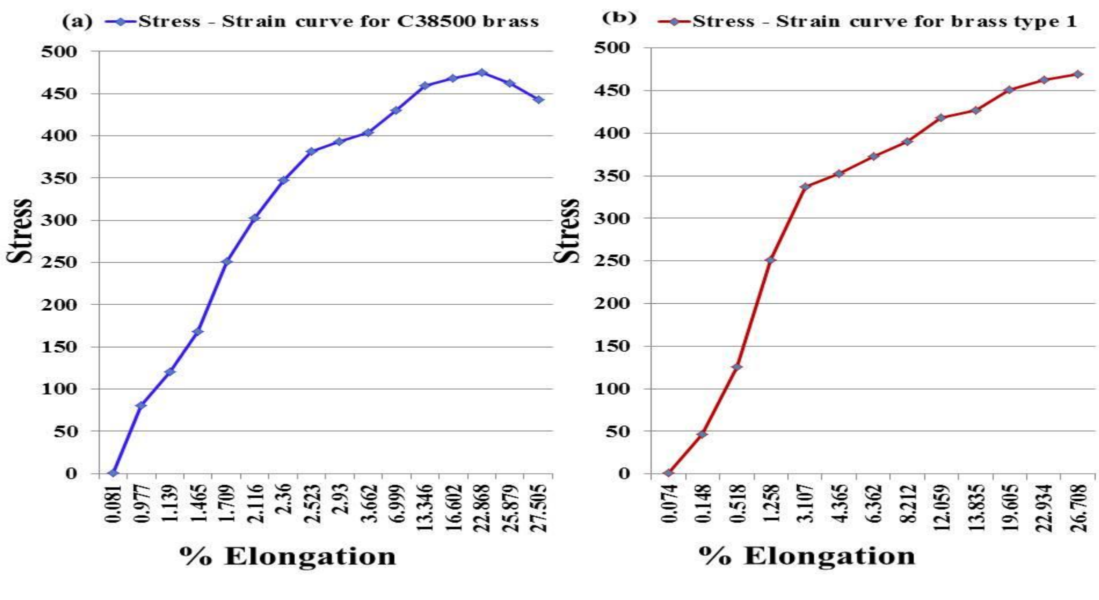

Figure 8. Typical stress–strain curves for (a) C38500 alloy; (b) brass type 1 alloy at strain rate of 1.3×10^{-4} s^{-1}.

It was also observed that after superplastic treatment, the tensile ductility of HPb 59-1 brass can be increased by up to 500% without fracture at 620°C, whereas H62 brass can be increased by up to 624% without fracture at 750°C [23]. Figure 7 shows the plotted stress–strain curves based on the data generated for E-Cu and pure copper material. From the graph, it is observed that E-Cu alloy has lower ductility and greater tensile strength and hardness compared to pure copper alloy. Figure 8 shows the comparative diagrams for C38500 and brass type 1 alloys. From the graphs, it is observed that C38500 brass alloy has more yield stress, tensile strength and ductility but low fracture strength compared to brass type 1 alloy. From the graphs plotted in Figures 7 and 8, it is found that for brass alloys small changes in the specimen dimensions are not a major cause of change in tensile strength and ductility, whereas for copper alloys they have a significant impact on ductility. Figure 9 shows the comparative stress–elongation graph for E-Cu alloy and pure copper alloy plotted in the software supporting the UTM test. Figure 10 shows the comparative stress–elongation graph for C38500 brass alloy and brass type 1 alloy plotted in the same software.

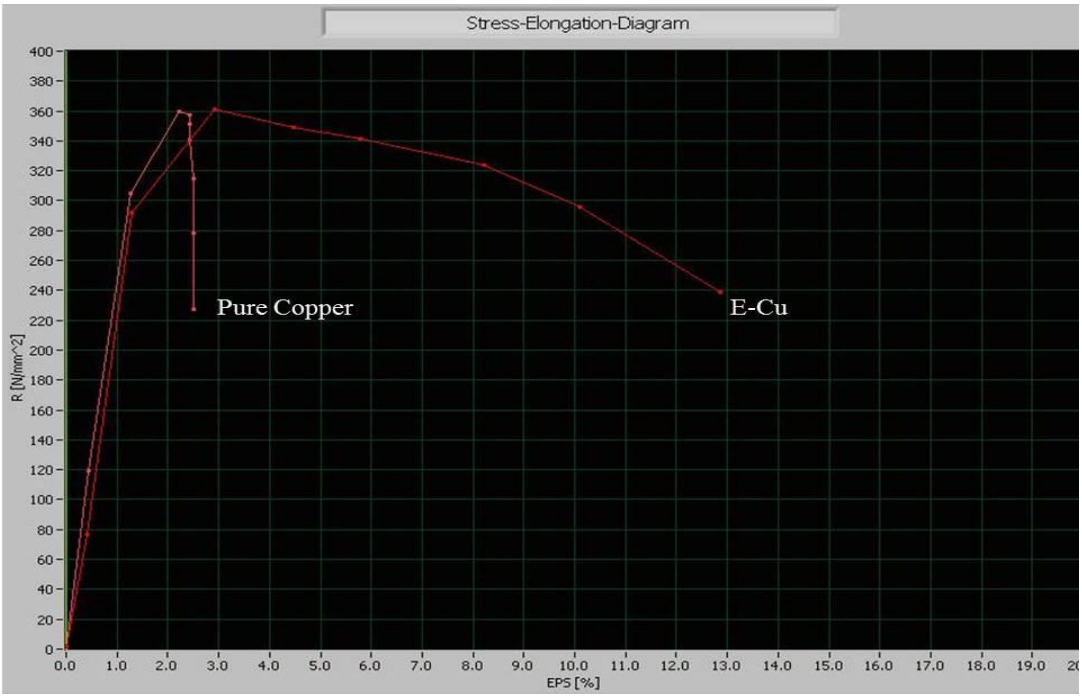

Figure 9. Comparative study of stress–elongation graph for E-Cu alloy and pure copper alloy.

The addition of Sn to Cu forms a solid solution which significantly increases the strength and corrosion resistance, whereas addition of Sn to brass enhances the solid solution strengthening effect of Zn and improves the mechanical properties of the brass. The increased content of Zn in brass reduces the ductility, whereas Fe content increases the strength. The specimen dimensions also influence the tensile strength and ductility of the material. As the gauge length increased, it reduced the effect of localized deformation at necking on total elongation, i.e., by increasing the gauge length the % elongation of the specimen will reduce. The strain-hardening capacity of the material also has an impact on the % elongation. While performing the test, increase in the strain rate significantly increased the flow stress. The results of the hardness tests are summarized in Table 7.

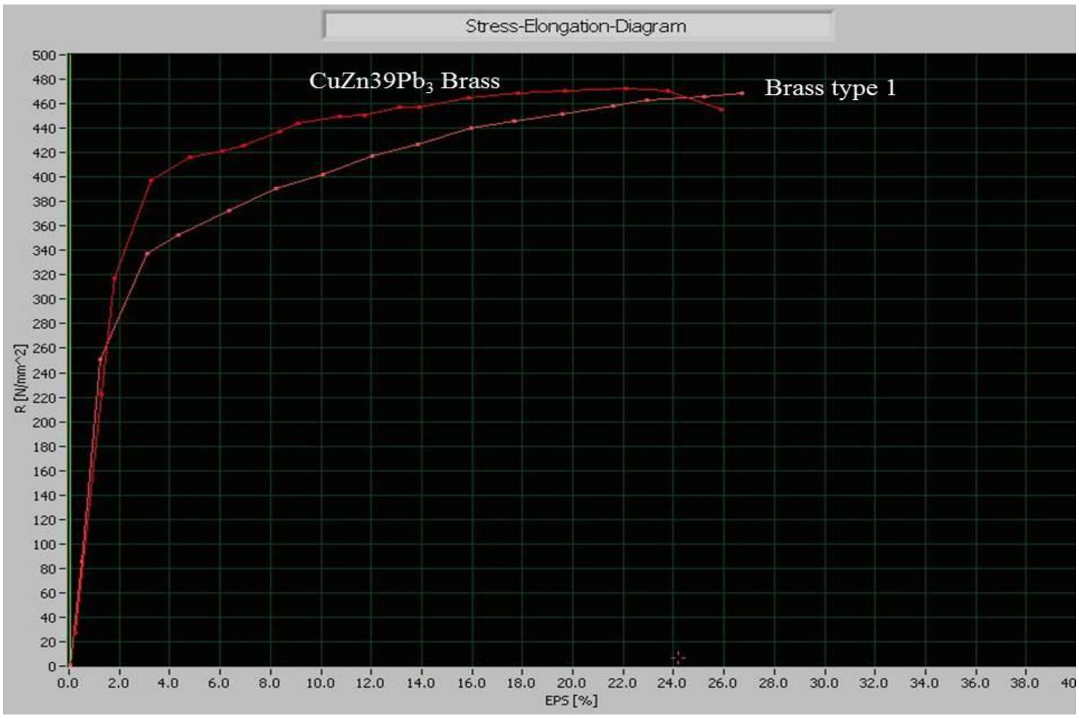

Figure 10. Comparative study of stress–elongation graph for C38500 brass alloy and brass type 1 alloy

Table 7. Mechanical properties of copper and brass alloys after tensile and impact tests at room temperature.

Material properties		C38500	Brass type 1	E-Cu	Pure copper
Young's modulus	N/mm^2	382	251	252	305
Yield stress	N/mm^2	403	337		
Ultimate tensile strength	N/mm^2	475	469	358	360
Tensile strength at fracture	N/mm^2	443	469	177	228
Total elongation	%	28	27	17	3
Rockwell hardness	HRF	96.8	94.9	74.4	79.6
Impact strength	J/cm^2	8.57	14.69	174.23	187.63

CONCLUSIONS

This study investigated the influence of the addition of alloy elements on the tensile properties and hardness of two specimens of different compositions, gauge diameter and gauge length. The mechanical properties of brass type 1 alloy have low values of elongation, tensile strength and hardness, but greater impact strength compared to C38500 brass alloy. Similarly, pure copper alloy has significantly higher fracture strength, tensile strength, impact strength and hardness, but very low ductility. The increased %wt content of Sn significantly improves the tensile strength and yield strength, and reduces the elongation of Cu and brass alloy. Two specimens were annealed at different temperatures, as the temperature increased beyond 180°C for the same composition has low tensile strength.

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