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EFFECT OF HOT AND COLD ROLLING ON ELECTRO-MECHANICAL PROPERTIES OF A COMMERCIAL HIGH-CONDUCTIVE METALLIC MATERIAL

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ABSTRACT

High conductive materials may undergo hot and cold rolling in the process of manufacturing and utilization as machine parts. For such rolling, there are some changes in the electro-mechanical properties, which, in turn, affect the operational ability of these materials. In this paper the experimental investigations are carried out to observe the effect of hot and cold rolling on the electro-mechanical properties of copper and few of its alloy materials. To do so, samples are prepared as flat bars of different suitable sizes and dog-bone shapes. To prepare the samples for rolling, they are first homogenized for eight hours and then solution treated for two hours in resistance furnaces. Some of the samples are kept free from rolling and others are rolled from a low to higher temperatures. Then a series of experiments are carried out to determine the changes in a number of electro-mechanical properties. Most of the mechanical properties are found to be influenced quite significantly by the condition of rolling. On the other hand, the corresponding change in the electrical conductivity is not that significant as observed in case of mechanical properties. It is also observed that the microstructure has shown a significant geometrical effect on deformation without occurring any grain refinement after rolling.

Keywords: *Hot and Cold Rolling, Micro-Hardness, Conductivity, Micro-Structure*

1.0 INTRODUCTION

It is well-known that copper and its alloys are among the commercially available highly conductive metallic materials, which are used extensively for several industrial, domestic and marine applications in the form of wire, strip, disc, pipe or plate. Many a times, these materials undergo rolling in the process of manufacturing as well as utilization. This rolling may be deliberately done or occurred as either hot work or cold work, or a combination of both hot and cold work.

Cold work is the term normally used for processes that are performed at room temperature or if the grains are deformed to plastic level at temperatures much below the recrystallization temperature i.e. less than 40% of the metal's melting temperature [1-2]. Cold working leads to anisotropy with increased stiffness and strength in metals or alloys. There is a corresponding decrease in ductility and malleability as the metal strain hardens. Thus, cold rolling is often used in the final stages of production to ensure a good surface finish and optimize the mechanical properties for a given application [1-2].

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On the other hand, when the processing temperature of the mechanical deformation is above the recrystallization temperature, the process is termed as hot working [3]. Hot working achieves both the mechanical purpose of obtaining the desired shape and size, and also the purpose of improving the physical properties of the material by destroying its original cast structure. The porous cast structure, often with a low mechanical strength, is converted to a wrought structure with finer grains, enhanced ductility and reduced porosity. Large shape changes are also possible without ruptures through hot work. Impurities are broken up and distributed throughout material. However, metal loss occurs due to high temperature, which also weakens the surface [1-3].

Copper has a cubic crystal structure i.e., face centered cubic (FCC) that gives it high ductility and malleability [2-3]. It results copper atoms to have the ability to roll over each other into new positions without breaking the metallic bond. The rolling of copper material causes work hardening and introduces defects, known as dislocations, into the structure. These defects interfere with further deformation, making the copper harder and stronger. To make ease of the situation annealing of the copper is required at a high temperature. Copper melts at 1357^0 Kelvin and annealing generally occurs at greater than half the melting point in degrees Kelvin. As such, typical temperature to use for high temperature annealing is 400 ℃ [2-4]. Annealing causes the structure to create and grow new grains that are free of strain. The new grains remove all dislocations and other defects caused by the deformation, thus leaving the material in its original soft condition, although may not be in its original shape. However, properly annealed copper wire can become harder during storage due to precipitation hardening [4-6].

For both the cases of rolling, the thickness is reduced as a result of the compressive stresses exerted by the rolls and it can be treated as a two-dimensional deformation in the thickness and length directions neglecting the width direction. This is due to the fact that the length of contact between the rolls and work-piece is generally much smaller than the width and the undeformed material on both sides of the roll gap is restraining the lateral expansion along the width direction. During rolling, there are some changes in the electro-mechanical properties due to change in grain-size, recrystallization, solid-solution alloying and strain hardening.

As such, the present paper is an attempt to investigate the effect of hot and cold rolling, especially in the electro-mechanical properties, for instance, electrical conductivity, micro-hardness, strength, elongation, microstructure etc of copper and its alloys as a function of individual hot and cold rolling as well as in combination. To carry out the required experimental investigations, the samples are prepared from the high conductive bulk materials commercially available in Bangladesh market.

2.0 SAMPLE PREPARATION AND MEASUREMENTS

In an attempt to study the effect of hot and cold rolling on electro-mechanical properties of highly conductive materials, copper and one of its alloys have been chosen to be the most prosing candidate. The selected copper based materials are commercially available and collected from the open market of Bangladesh. The chemical compositions of these two materials have been checked using XRF machine and the results are shown in table 1. The material sample-I consists of mainly copper with small presence of other elements; so it may be termed as copper samples. The material sample-II has dominant level of copper, zinc and iron along with few other elements; so it may be termed as alloy samples for subsequent reference.

The collected bulk shape materials are cut into long bars and sized up of length 300 mm with a cross-section of 15 mm x 20 mm. In order to prepare the samples for rolling, they are first homogenized for eight hours and then solution treated for two hours in resistance furnaces. The corresponding homogenization and solution treatment temperatures are 500° and 700°C, respectively.

Table 1: Chemical composition of sample materials (mass fraction %)

Composition	Sample Material -I	Sample Material -II
Cu	97.4922	24.85
Zn	2.061	28.15
P	0.2297	8.93
Si	0.1824	2.25
S	-	1.71
Cr	-	1.15
Mn	-	3.26
Fe	0.0347	23.43
Ni	-	2.38
Zr	-	0.5
Pb	-	3.37

Four pieces of prepared bars (two from material sample-I and two from material sample-II) have been cold rolled at room temperature to reduce the thickness from 15 mm to 3 mm i.e. 80% reduction. There have been 12 passes of cold roll with one millimeter for each pass of rolling. Similar four other bars have been hot rolled at 400 ℃ to reduce thickness from 15 mm to 9 mm i.e. 40% reduction by 6 passes with one millimeter for each pass, and then they have been cold rolled at room temperature to reduce thickness from 9 mm to 3 mm i.e. further 40% with one millimeter for each rolling pass. Therefore, these four bars are also rolled for the reduction in total 80% of thickness by combination of hot roll and cold roll (hot-cold roll). By these way, we have found long thin bars of 3 mm thickness from both material sample-I (copper) and material sample-II (copper alloy). Thereafter, they have been cut into rectangular pieces of 20 mm by 20 mm sizes to carry out a series of experiments.

The prepared samples are then divided into different groups. Few group samples are heat treated isochronally at various temperatures such as 25 ℃ (room temperature), 100 ℃, 150 ℃, 200 ℃, 250 ℃, 300 ℃, 350 ℃, 400 ℃ and 450 ℃ for a period of one hour. The conductivity and micro-hardness of these heat treated samples are measured for each temperature using a Technofour Conductivity Meter (Type 979) and Micro Vickers Hardness Tester (HV-100) respectively. Based on maximum and minimum hardness values over isochronal aging, two temperatures have been selected for isothermal heat treatment, and then few group samples are given isothermal aging on that temperature with the variation of time i.e. 15 minutes, 30 minutes, 60 minutes, 120 minutes and 240 minutes. Thereafter, conductivity and micro-hardness are measured again for each defined time interval. The measurements are repeated four times for each condition of a sample so that validation of the reading can be developed. Two group samples are taken after isochronal heat treatment at 25 ℃ and 400 ℃, and micro-structure conditions are observed using electronic microscope. Moreover, sixteen samples have been prepared of overall size 100 mm x 10 mm having dog-bone shape of ASTM D638 Type IV and their tensile tests are carried out using a computer based universal testing machine (Model:1000 HDX-G-G7CB).

3.0 RESULTS AND DISCUSSIONS

3.1 Micro-Hardness

While isochronal thermal aging is done at lower temperature i.e., room temperature to 150 ℃, the micro-hardness of material sample-I i.e. copper samples are not portraying any significant changes with the average values of 160 -170 HV for both cold or hot-cold rolled conditions, which is remarkably higher than the hardness of nominal copper element (35-38 HV) [6-9]. While the aging temperature is increased to about 200℃, micro-hardness values are found little higher for both cold and hot-cold rolling conditions. At the aging temperature of 200°C, the micro-hardness of cold rolled copper samples is observed as 180 HV, and this is its maximum hardness value over the whole isochronal aging range. However, the hot-cold rolled copper based samples aged at 200°C indicate the micro-hardness of 172 HV and this hardness value is increased further while aging temperature is increased to 250°C. But the hardness of both group samples gets reduced with further rising of isochronal aging temperature to 300°C or higher. As a result we can see the downward converging trend of micro-hardness against isochronal thermal aging temperature for both cold rolled and hot-cold rolled copper as depicted by black and red lines respectively in figure 1.

On the other hand, the material sample-II i.e. copper alloy samples show micro-hardness values of 135 HV and 95 HV for cold rolled and hot-cold rolled conditions respectively, while isochronal aging is done at room temperature or 100°C. Here it is noticed that the rolling condition has significant influence on the micro-hardness of copper alloy than that of pure copper. The hardness due to cold roll is found quite more than that of hot-cold roll after thermal aging at 100°C or below. While isochronal thermal aging is done at 150 °C, the micro-hardness values of both cold and hot-cold rolled alloy samples are coming closer and while the aging temperature is increased further, micro-hardness curves of both group samples show similar pattern with intersections at number of points on green and blue lines in figure 1. The isochronal aging at 300 and 350°C are giving the same micro-hardness values for both condition of rolling. So, this aging temperature range can be considered as unaffected or less affected temperature region for copper alloy samples after both cold and hot-cold rolling.

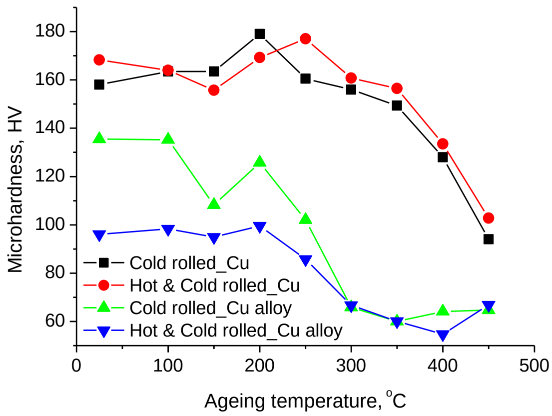
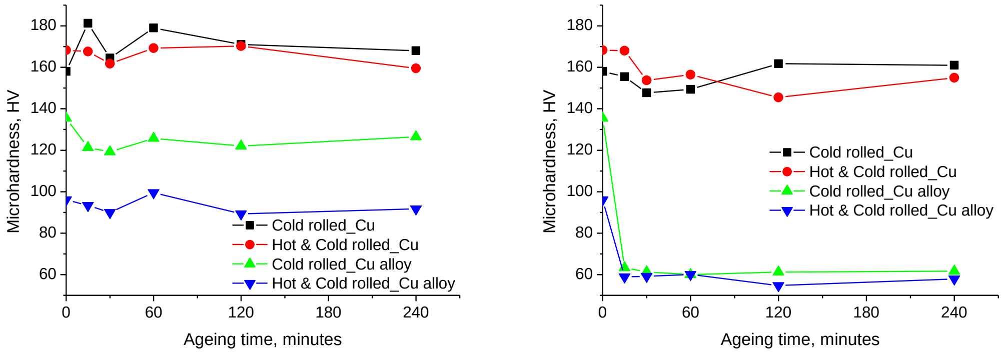


Figure 1: Isochronal ageing curve of micro-hardness of Cu and its alloy, aged for 1 hour

The isochronal aging curves of figure 1 depict the maximum hardness, in turn the strength, at the aging temperature of 200°C, and the down fall of isochronal curves become clear and stable at 350°C. As such, isothermal aging of two group samples are done at these two temperatures i.e., 200°C and 350°C, and the micro-hardness values of these samples are presented in figures 2(a) and 2(b), respectively. Both figures show that micro-hardness of copper fluctuates at isothermal aging for 15 minutes and 30 minutes like a transient variation. Thereafter, the results are like steady state condition of showing almost horizontal graphs for all samples for higher period aging. Another point to note, the hardness values are very closer for both cold rolled and hot-cold rolled copper. However, the alloy samples indicate significantly different hardness level while rolling condition is different, and the hot-cold rolled alloy sample seems to be very soft with the hardness value of 95 HV in comparison to cold rolled alloy with the hardness value of 125 HV after isothermal aging at 200°C. But the isothermal aging at 350°C does not indicate the same results as of 200°C for alloy samples. As a matter of fact, alloy samples have shown similar hardness values and patterns for both cold and hot-cold rolling conditions. Therefore, a deduction may be drawn that rolling condition has less effect on the copper alloy while thermal aging is done at elevated temperature.



(a) Micro-hardness while aged at 200ºC (b) Micro-hardness while aged at 350ºC

Figure 2: Isothermal ageing effect on hardness of Cu and its alloy, aged at 200ºC and 350ºC.

3.2 Conductivity

Due to change in rolling condition i.e. cold and hot-cold, the conductivity of copper samples is not showing any remarkable deviation (black and red lines in figure 3). Throughout the range of isochronal aging temperature of 25 to 350 ℃, both group samples show similar steady values of conductivity for copper samples. The minimum conductivity is observed as 38 meter/ohm.mm^2 for both cold rolled and hot-cold rolled copper samples. But the minimum values are obtained at different aging temperatures, i.e. for hot-cold rolled samples at room temperature and for cold rolled samples at 150 ℃. However, while the aging temperature is increased to 400℃ and higher, the conductivity of copper samples is found accelerated to the maximum value of 45 meter/ohm.mm^2 at 450℃ as shown in figure 3.

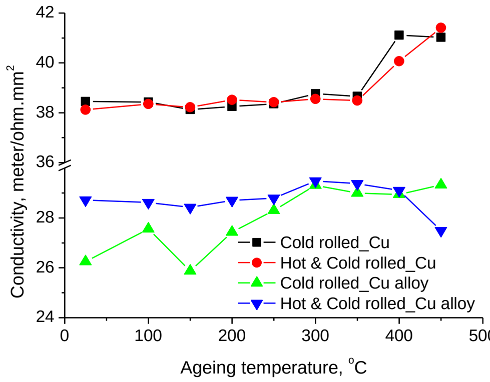
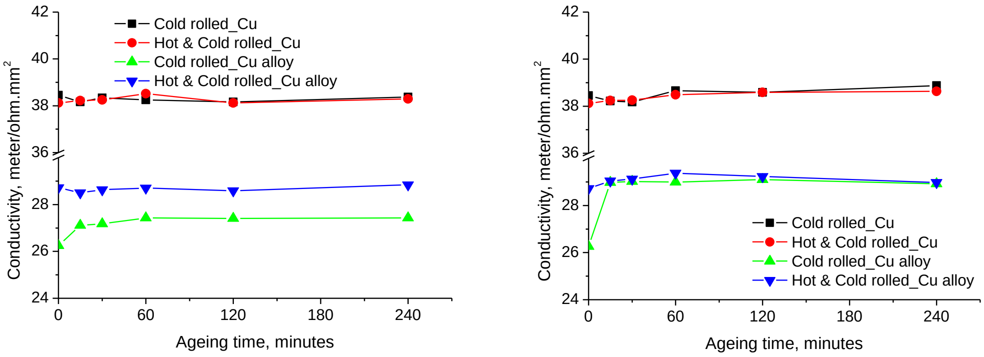


Figure 3. Conductivity variation of Cu and its alloy at isochronal ageing for 1 hour.

Figure 3 also indicates the conductivity of copper alloy samples as green and blue lines, where it is noticeable that the conductivity of copper alloy is very less compared to copper sample for every corresponding thermal aging temperature. It may be noted that the conductivity of cold rolled alloy seems to be varied widely ranging from 25 to 30 meter/ohm.mm^2, whereas the hot-cold rolled alloy shows small variation with a range from 28 to 29 meter/ohm.mm^2 over the whole thermal aging temperature range of 25 to 450 ℃. The results obtained here can provide some link to the findings of Kimura et al [10].

The effects on conductivity for isothermal aging at 200°C and 350°C over a period of 15 to 240 minutes are presented in figures 4(a) and 4(b). Both the figures indicate that copper is not affected by the rolling temperature, and the value is 38 meter/ohm.mm^2. But the alloy samples show that the conductivity is highly affected by the rolling condition while isothermal aging is done at 200°C temperature as shown in figure 4(a). The difference of conductivity in this case is quite high, which gets reduced and remains steady over the time period of 240 minutes with a value of 29 meter/ohm.mm^2 and 27 meter/ohm.mm^2 for hot-cold rolled and cold rolled alloy, respectively. The same alloy samples show different behavior, while isothermal aging is done at 350°C temperature as depicted in figure 4(b). Basically, the conductivity emanates to be the same level for both cold rolled and hot-cold rolled alloy after isothermal aging at 350°C for a period of 15 minutes or more. The reason behind this phenomenon is considered to be the recrystallization effect of the sample materials.



(a) Conductivity while aged at 200°C (b) Conductivity while aged at 350°C

Figure 4. Conductivity variation of cold and hot-cold rolled Cu and its alloy for isothermal aging, aged at 200°C and 350°C.

3.3 Tensile Properties

The collected copper sample has shown the ultimate tensile strength (UTS) of 220 MPa and ultimate elongation of 12.56%, which are very well within the range of the ultimate tensile strength and elongation of annealed copper i.e., within 200 to 250 MPa and 12 to 16% respectively. From 220 MPa UTS value has risen to 447.63 MPa after 80% cold roll and 358.51 MPa after 40% hot and 40% cold roll [Table 2]. Here it is clear that the tensile strength of copper sample has increased more for cold roll than that of combination i.e., hot-cold roll. With the rise of tensile strength the ultimate elongation limit has been reduced. It was anticipated that the ultimate elongation for cold roll would be less than that of hot-cold roll copper sample. But the tensile tests have disproved such anticipation and have shown higher ultimate elongation for cold roll (5.774%) than that of hot-cold roll (4.786%) copper sample.

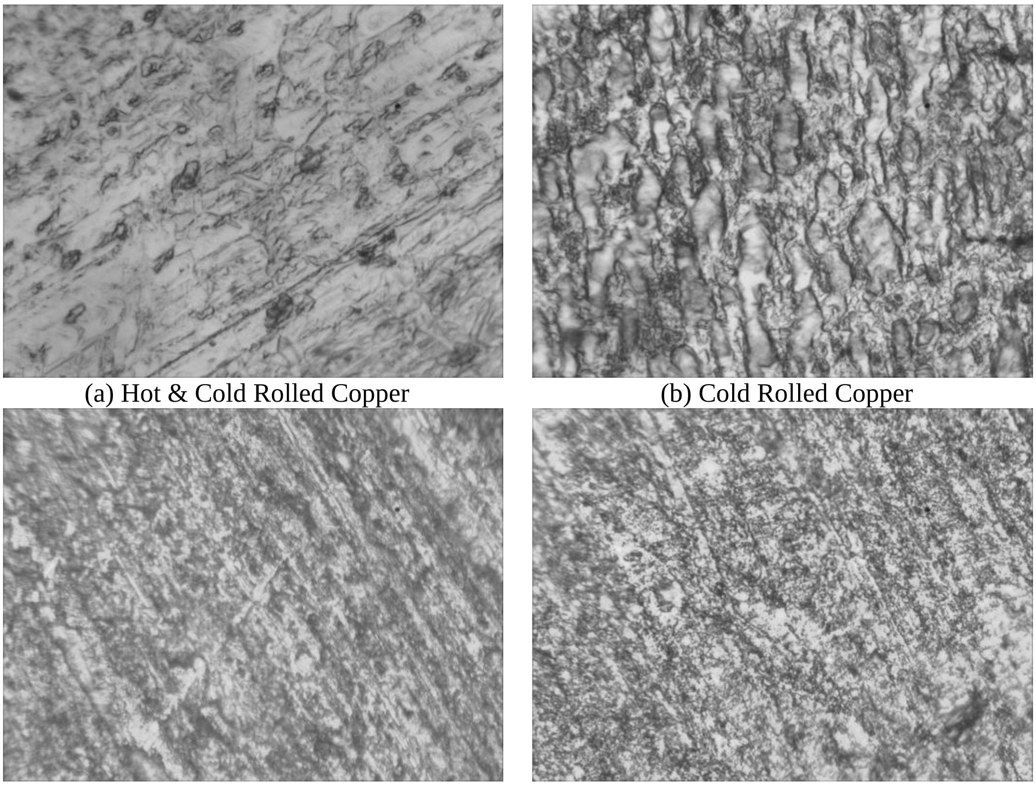
The UTS value for the alloy sample has not been increased as it happened for the copper sample while cold rolling was done. However, the combination of hot and cold roll has contributed better to increase UTS of alloy sample. Here also the ultimate elongation for cold roll is higher than hot-cold roll similar to copper sample.

Table 2: Tensile properties of copper and its alloy.

Sample	Ultimate tensile strength [MPa]	Elastic Modulus [MPa]	Ultimate elongation [%]
Cold rolled Copper	447.6320	12892.10	5.774
Hot & Cold rolled Cu	358.5102	13652.01	4.786
Cold rolled Alloy	300.8322	8757.50	9.295
Hot & Cold rolled Alloy	400.4883	9706.54	8.454

3.4 Microstructure

It has been found that microstructure of copper has a significant geometrical effect on deformation without occurring any grain refinement after both hot-cold and cold rolling. Out of four pictures (Figure 5), top two represent hot-cold and cold rolled copper samples and bottom two hot-cold and cold rolled alloy sample with thermal treatment at 400℃.



(a) Hot & Cold Rolled Copper (b) Cold Rolled Copper

(c) Hot & cold rolled alloy (d) Cold rolled alloy

Figure 5: Microstructure of rolled Cu and its alloy at thermal ageing temperature of 400℃ with a magnification factor of 1600

As per the conclusion of Malin and Hatherly [11], the microstructure of heavily rolled copper consists of long, thin, elongated cells with sharp boundaries. Basically the microstructure of heavily rolled copper has two remarkable components: (i) the diffusion in boundaries which causes micro-bands to sharpen the grains and become aligned parallel to the rolling plane, and (ii) the effect on shear bands. These both components are visible in the micro-structure of copper samples of the present research, which provides good agreement with the findings of Malin and Hatherly. The geometry of the shear bands indicates the predominant existence and influence over the macroscopic plasticity.

When the copper based materials are cold worked, permanent defects change their crystalline makeup. These defects reduce the ability of crystals to move within the metal structure and the metal becomes more resistant to further deformation. But when metallic materials are hot worked, microstructural deformations are not similar to permanent defects occurred by cold work. This reasons might results in different configurations for hot-cold and cold rolling as indicated in figure 5(a) vs 5(b) and 5(c) vs 5(d). Moreover, the crystalline deformation seems to be significantly longer for cold work than those of hot work [12-15].

4.0 CONCLUSIONS

The hardness of copper and its alloy under different rolling conditions exhibits gradual reduction with the rise of isochronal aging temperature, though the patterns are not same for copper with respect to its alloy sample. For isothermal aging the micro-hardness values are obtained to be at the respective steady level for both cold and combined hot and cold rolled copper. Similar pattern is observed for alloy sample also, with the exception to different level for isothermal aging at 200°C. Here, the hardness due to combined hot and cold roll results of copper sample is much higher value than that of hot and cold rolled alloy sample. The hardness values are found commensurate with the tensile test results. Therefore, it can be said that most of the mechanical properties are found to be influenced quite significantly by the condition of rolling.

The conductivity variation is not significant for different rolling conditions. So, copper wire production through drawing whether hot or cold may be considered safe for maintaining conductivity levels. The micro-structure of both copper and alloy samples indicate significant grain deformation along the rolling pass. But there is no indication to occur any grain refinement after rolling. As a result the increase of tensile strength after rolling can be considered as the outcome of geometrical effect on deformation in the direction of rolling.

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