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Effect of Grain Size on Orange Peel in Oxygen Free Copper Wire Produced by Upcast

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Abstract— An experimental study was carried out to investigate the solidification on a copper rods manufactured by continuous casting process into two types UPCAST and CAST & ROLL technologies. Continuous casting parameters, low yield stress, SEM inspections and grain size calculations has been experimentally studied to ensure the effect of orange peel defect which appear directly after applying the cold formation on the copper rod. There is no orange peel defect appears on the copper rod produced by sequential continuous casting-hot formation processes.

Index Terms —Continuous casting, CAST & ROLL, UPCAST, Cold formation, Hot formation, Orange peel, SEM inspection, Grain size.

1 INTRODUCTION

THIS study is about UPCAST (Fig. 1-a), a process which the molten metal is continuously casting into crystallizer around which a facility for quick cooling the molten metal to the point of solidification.

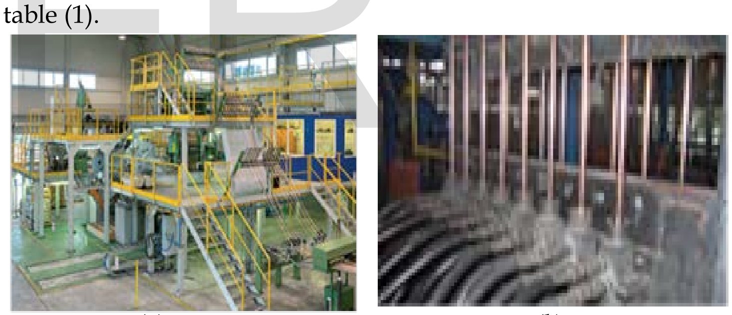
The solidified metal is then continuously extracted from the crystallizer (Fig. 1-b) at predetermined rate [1]. In general the casting process involves the solidification of liquid metal following different rates of heat extraction to obtain the desired shape and properties simultaneously. The mechanical properties of the cast product depend on the size and orientation of the grains. To obtain consistency of mechanical properties, phases should be distributed uniformly throughout the matrix [2]. Heavily drawing copper wire, particularly if it is coarse grained, often develops a rough surface texture commonly known as orange peel (Fig. 2-a). When metal with a coarse grain size is drawn or stretch formed, the surface roughens and develops an appearance resembling orange peel. Such a surface is more difficult and costly to polish and buff. Therefore, when a part requiring a buffed surface is to be produced, much effort is expended in designing the tools and process to use copper with a fine grain size [3].

Orange peel, is a surface roughening on the scale of the grain size. It occurs because of different orientations of neighboring grains on the surface. During elongation, some grains contract more in the direction normal to the surface and others contact more in a direction in the surface [4]. The subsequent casting-hot formation CAST & ROLL process used to release the effect of *Orange peel* (Fig. 2-b).

2 MATERIALS AND METHODS

Copper has excellent electrical and thermal conductivities, exhibit good strength and formability. It is used extensively for electrical wire and cable, and various other parts that are required to pass electrical current [5]. In Fact, there are two important types of high purity copper, deoxidized copper (electrolyte tough pitch ETP) and oxygen-free high conductivity copper. The first copper type is particularly suitable for applications requiring hot working, annealing, soldering, brazing or welding. While the second copper type is produced by melting and pouring copper in the presence of carbon or carbonaceous gases, so that no oxygen can be absorbed. No deoxidizing agent is required.

The casting processes technological specifications are the most important factor. The lowest possible pouring temperature needed to suit the size and form of the solid metal should be used to encourage as small a grain size as possible. Experience has shown that success in achieving good quality castings depends on avoiding slow cooling rates [5]. The chemical analysis of copper samples used in this search is shown in table (1).

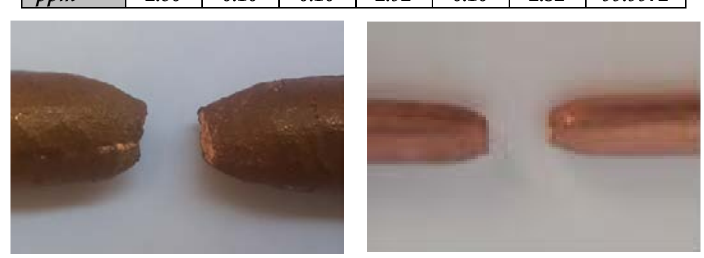


(a) *(b)*

Fig. (1) UPCAST machinery ***(a)*** and Crystallizers ***(b)***.

TABLE 1. Chemical Analysis of Copper Samples.

Element	*Ag*	*Al*	*As*	*Bi*	*Cd*	*Co*	*Cr*
ppm	***9.30***	***0.39***	***0.89***	***0.10***	***0.10***	***0.10***	***0.46***
Element	*Fe*	*Mg*	*Mn*	*Ni*	*P*	*Pb*	*S*
ppm	***0.56***	***0.10***	***0.66***	***1.11***	***1.14***	***0.10***	***0.10***
Element	*Sb*	*Se*	*Si*	*Sn*	*Te*	*Zn*	*Cu%*
ppm	***2.80***	***0.10***	***0.10***	***2.92***	***0.10***	***2.52***	***99.9972***



(a) *(b)*

Fig. (2) Surface of copper rods after tensile test for: ***(a)*** UPCAST and ***(b)*** Cast & Roll processes.

2.1 Continuous Casting

The variety of processes involved in casting and manufacturing in general, provide excellent opportunity to educate oneself about the phase change process and its importance. Continuous castings, all involve a phase change which plays an important part i.e. determining the properties of the castings. The rate of cooling is considered to be the most important parameter that influence the strength of the casting. The molten metal when cast into die has to solidify at a fixed rate to obtain the desired qualities. Grain and grain boundaries are terms involved with the study of microstructure of metals. Finer grains offer greater hardness but lesser strength, as the metal becomes brittle. On the other hand, slow rate of cooling ensures that any thermal consists of coarse grains which have greater strength.

It is obvious that crystallizer heat transfer consists of many complex mechanisms, including conduction, convection and phase change. In the liquid region of the strand, heat is transferred by conduction and convection. In the solid region heat transfer is due to both conduction and the solid body translation of the solidified wire. Heat flow to the crystallizer is controlled by the nature of the gap that forms between the wire and the crystallizer [6].

2.1.1. UPACAST Technology

Vertical upwards casting methods with graphite crucible (Fig. 3) with their negative metallostatic pressure strip action within the crystallizer [7], have been found therefore to be the only way to produce pure electrical grade oxygen free high conductivity copper (Cu-OF) rod products, using submerged die continuous casting processes.

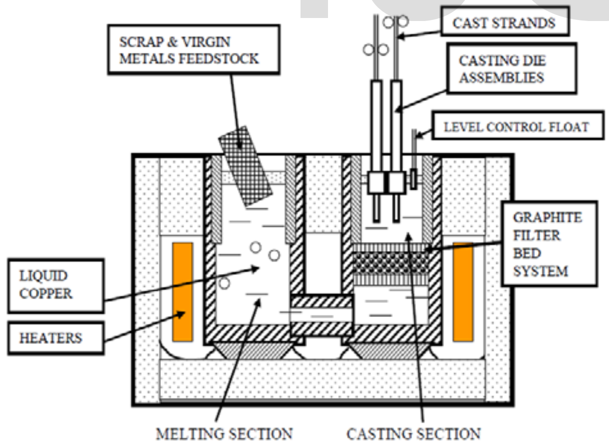


Fig. (3) Graphite crucible for UPCAST process (after Technology of Ratumead Co. [7]).

It is possible to increase the output of upwards casting machines by using separate melting furnaces and by producing larger size sections of strand (copper rod) product. From the standpoint of successful wire drawing, whilst a great deal depends on the internal and surface qualities of the continuously cast product (lack of inclusions and overall cleanliness, structural consistency etc.) much depends on the precision of the downstream processing, which is usually rolling, coating, coiling and packing [8].

2.1.2. Cast & Roll Technology

Molten copper is poured from a "pour pot" into the mold just as the steel band joins the wheel to form the fourth side of the mold. Tundish serves as an intermediate holder to ensure stable copper flow from the ladle to the caster wheel (Fig. 4), and in case of a trapezoidal caster, distribute copper to the strands.

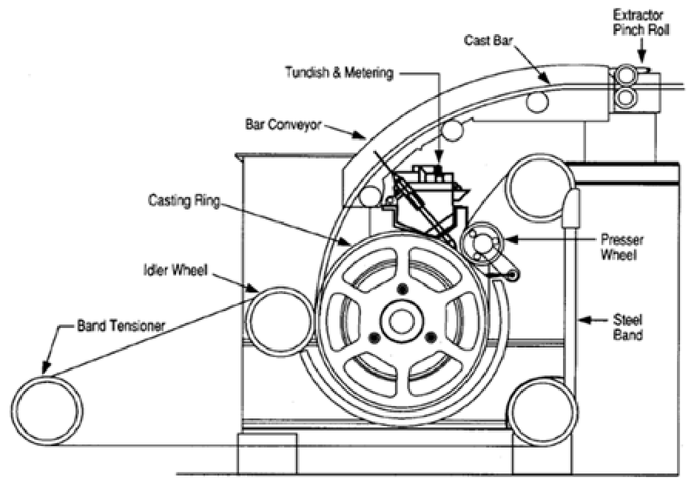


Fig. (4) Schematic diagram of casting wheel, SCR technology of Southwire Company for producing copper rod.

By increasing the tundish size, it is possible to let inclusions float up to the molten copper surface more easily and to suppress the suspension of molten in copper at the teeming position from the ladle. The wheel and band move together through water sprays as the copper solidifies. Molten copper from the above described melting furnaces flows into a holding furnace before being directed to continuous casting.

2.1.3. Cooling System

Theoretical basis of continuous casting resides in the research and knowledge related to the conditions of solidification, which determine the cooling conditions according to the cross section and the chemical structure of the material, as well as some of the technological and constructive parameters of the installations such as casting rate, number of strands, height and curve radius of the installation, etc. [9].

3 Experimental Work

3.1 Experiment with Standard Conditions

The first group of expermintal work was carried out in AL-SHAHEED General Company, located in Iraq. They used the Rautamead UPCAST machinery with graphite crucibles furnace to produce 8 mm diameter copper rod. Ten samples of pure copper were taken at five molten metal temperatures (i.e. 1170, 1171, 1172 to 1179 º C), for a casting speed of 0.6 m/min and 32 L/min cooling water flow with ΔT range of 6.6 to 7.4 º C for in-out cooling water.

3.2 Changing the Cooling Flow Rate in UPCAST

The second group of experimental work carried out in Egyptian Copper Workes Company located in Alexandria-Egypt. Five sample of pure copper were taken with a molten metal temperature range (1160, 1163, 1148, 1143 and 1146 ºC), five different cooling rates (20, 15, 12, 8, and 5 Lit. /min) respectively, constant casting speed (0.4 m/min) and the ΔT range (7.0 –20.8 º C) for in-out cooling water used.

3.3 Changing the Casting Speed in UPCAST

The third group of experimental work also carried out in Egyptian Copper Workes Company located in Alexandria-Egypt. Another five sample of pure copper where taken with a molten metal temperature range (1158, 1164, 1167, 1169 and 1171 ºC), five different casting speeds (0.25, 0.30, 0.35, 0.40, and 0.45 m/min) respectively, constant cooling rate (20 L/min) and the ΔT range (4.8 - 7.9 º C) for in-out cooling water used.

3.4 Standard Condition for Cast & Roll

The fourth group of experimental work was carried out in AL-SWIEDY Group/United Company for Metals, located in Cairo/Egypt. This company uses the SCR southwire technology for producing the copper rod with 8mm in diameter. Also, five samples of pure copper were taken with a molten metal temperature (1130±5 º C), (0.7 m/min) casting speed, (1831 L/min) cooling water flow and the ΔT range (5 - 6 º C) for (in-out) cooling water.

All of four groups of the samples are machined to the circular cross-sectional shape with 12.5 mm in diameter and 105 mm in length according to the ASTM E-8M (Standard Test Method for Tension Testing of Metallic Materials, 2010, PP. 6). These samples are subjected to tensile test, chemical analysis, grain size calculation and SEM inspection.

4 Results and Discussion

4.1 Types of Crystals

The size of the columnar dendrites is about ten times bigger than that of the equiaxed dendrites. Columnar dendrites have higher risk of internal cracks formation than equiaxed dendrites and a long columnar zone increases the severity of centreline because columnar grains are very long and thin, with long parallel grain boundaries. The cross-sectional image (Fig. 5-a) illustrates the columnar and thin particles, which they are perpendicular to the longitudinal axis of the sample (SHAHEED 10). The longitudinal image (Fig. 5-b) illustrates the equiaxed particles, which they are parallel to the longitudinal axis of the sample (SHAHEED 10). The longitudinal SEM image (Fig. 5-c) illustrates the Luder's bands which they appear after carrying out the tensile test.

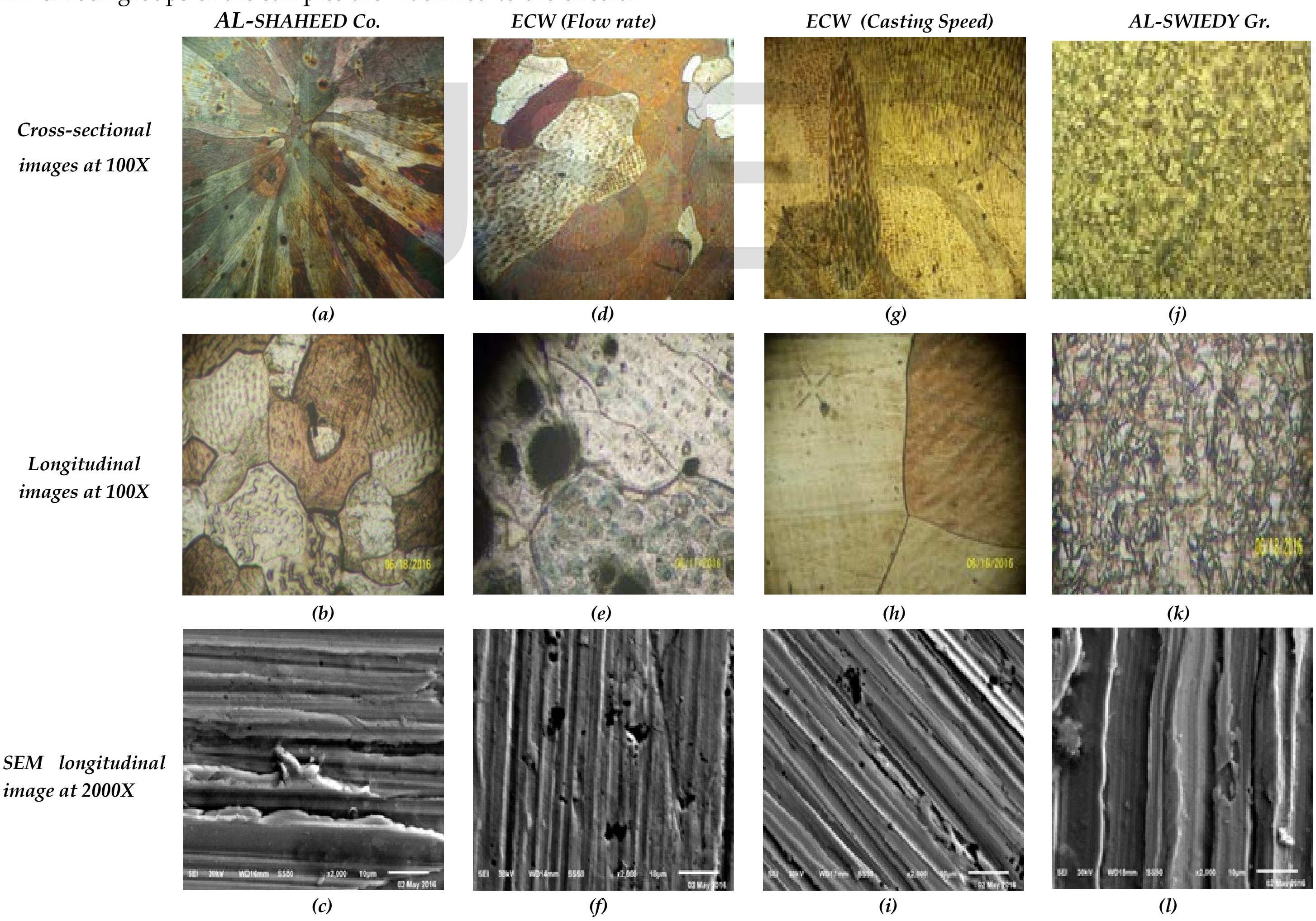


Fig. (5) Cross-sectional images (columnar crystals at 100X), longitudinal images (equiaxed crystals at 100X) and SEM longitudinal images at 2000X for AL-SHAHEED Co. (a, b, c for sample SHAHEED 10), Egyptian copper works (d, e, f for sample ECW 11 and g, h, i for sample ECW 16) and AL-SWIEDY Group (j, k, l for sample SWIEDY 21) respectively.

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The cross-sectional images (Fig. 5-d and g) respectively illustrate bigger and widely of the columnar particles, which they are perpendicular to the longitudinal axis of the samples (ECW 11 & ECW 16). The longitudinal images (Fig. 5-e and h) respectively illustrate the equiaxed particles, which they are biggest in size more than in (SHAHEED 10) and parallel to the longitudinal axis of the samples (ECW 11 & ECW16). The increasing in grain size of samples (ECW 11 & ECW 16) is a response to the increasing of cooling rate due to the decreasing in cooling water flow and casting speed. The longitudinal SEM images (Fig. 5-f and i) illustrate the Luder's bands which they appear after the tensile test carryingout.

The cross-sectional image (Fig. 5-j) illustrates smaller and moer equiaxed particles. There are no columnar particles. These particles are perpendicular to the longitudinal axis of the sample (SWIEDY 21). The longitudinal image (Fig. 5-k) illustrates the equiaxed particles, which they are smallest in size more than in (SHAHEED 10) and parallel to the longitudinal axis of the samples (SWIEDY 21).

The decreasing in grain size of sample (SWIEDY 21) is a response to the recrystallization of of paricles due to the hot formation obtained at recrystallization temperature in the range (800-850) ºC.

4.2 Quantity of crystals

The quantity of particles for each samples used in this search is calculated according to the ASTM gran size. Obiviously the quantity of particles in cross-sectional image is more than particles in longitudinal images for sample illustrated in table (2).

TABLE 2 ASTM GRAIN SIZE AT 100X ACCORDING TO TO THE DIRECTION OF IMAGES

Specimen No	*ASTM grain size at 100x according Direction of the image*	
	Cross-sectional image	*Longitudinal image*
SHAHEED 10	63 Gr./12 in^2=5.25 grain/in^2	20 Gr./12 in^2=1.7 grain/in^2
ECW 11	36Gr./12 in^2=3.00 grain/in^2	13 Gr./ 12 in^2=1.08 grain/in^2
ECW 12	28Gr./12 in^2=2.50 grain/in^2	8 Gr./ 12 in^2=0.67grain/in^2
ECW 13	27Gr./12 in^2=2.30 grain/in^2	7Gr./ 12 in^2=0.58 grain/in^2
ECW 14	27Gr./12 in^2=2.25 grain/in^2	6Gr./ 12 in^2=0.58 grain/in^2
ECW 15	24Gr./12 in^2=2.25 grain/in^2	5Gr./ 12 in^2=0.50 grain/in^2
ECW 16	18Gr./12 in^2=2.00 grain/in^2	5Gr./ 12 in^2=0.42 grain/in^2
ECW 17	15Gr./12 in^2=1.25 grain/in^2	3Gr./ 12 in^2=0.25 grain/in^2
ECW 18	14Gr./12 in^2=1.75 grain/in^2	3Gr./ 12 in^2=0.25grain/in^2
ECW 19	9Gr./12 in^2=1.15 grain/in^2	2Gr./ 12 in^2=0.17 grain/in^2
ECW 20	9Gr./12 in^2=0.75 grain/in^2	2Gr./ 12 in^2=0.17 grain/in^2
SWEIDY 21	1224Gr./12 in^2=102 grain/in^2	423Gr./ 12 in^2=36.1 grain/in^2

4.3 Mechanical properties

These changes in microstructure yield a completely different mechanical manner of the UPCAST (SHAHEED & ECW) samples. In contrast to the CAST & ROLL (SWIEDY) samples, both of (SHAHEED & ECW) samples show a stress–strain pursue by failure caused by necking. The considerable plastic deformations associate by work hardening cause microstructural changes. UPCAST specimens show intermediate elongation of the grains after tensile testing and a huge raise in surface roughness. Furthermore, a diameter reduction in loaded specimens can be observed in the analysis of the fracture surfaces. Obviously, these specimens have the ability to work harden substantially as the dislocation density is much lower than in the CAST & ROLL specimens. Moreover, as the grain size is extremely major, the fraction of grains at the surface is higher in the UPCAST specimens. These grains can deform more easily due to the reduced constraints at the surface [9]. Nevertheless, some differences in microstructure for specimen of 8 mm diameter has to be expected, especially for the configuration of dislocation barriers (e.g. grain boundaries and as a consequence grain size) and for the dislocation density [10]. A reduction of the grain size by 30% increases the yield stress by 20%, an increase of the dislocation density by 100% increases the yield stress by 40% [11]. Figure (6-a) presents the stress-strain curves for ECW samples using five different cooling rates (i.e. 20, 15, 12, 8, and 5 litre /min, samples ECW11-15) respectively. While, figure (6-b) shows the effect of casting speed on the tensile test results for ECW16-20 samples.

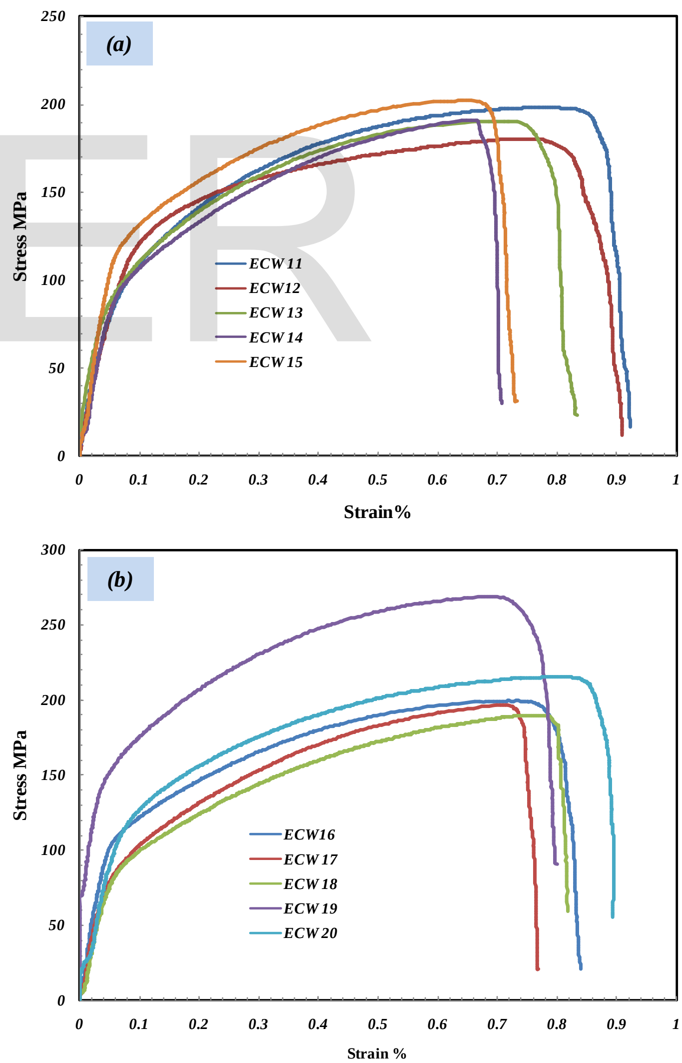

Fig. (6) Stress-strain graph for a. (ECW11-15) and b. (ECW16-20)

5 Conclusion

The secondary grain growth which leads of the surface roughness can only be mainely attributed to the sequential casting –cold working. So we need to apply the sequential casting – hot formation in producing the copper rod with UTS 233 MPa, small and equiaxed particles.

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