Changes in structure and properties of copper wire during the production and processing

Jandrlić, Ivan; Kozina, Franjo; Brlić, Tin; Mrkobrada, Lorena

I. JANDRLIĆ[1], F. KOZINA[1], T. BRLIĆ[1], L. MRKOBRADA[1]
[1]University of Zagreb Faculty of Metallurgy (CRO)

CHANGES IN STRUCTURE AND PROPERTIES OF COPPER WIRE DURING THE PRODUCTION AND PROCESSING

ABSTRACT

Irreplaceability of copper, as an electrical conductor, makes it the most important non-ferrous metal in application. The most frequently used methods of producing the copper conductors involves continuous casting of the copper wire, subsequent cold drawing deformation and heat treatment processes to improve copper mechanical and electrical properties. In this paper the research was performed on copper wire produced by continuous casting. During production various structural changes and changes in mechanical properties occur. To investigate those changes and to clarify their influence on final product, structure and hardness were recorded and measured in all stages of production. While macrostructure and microstructure were observed by light microscopy, the hardness was measured using Vickers hardness testing method. The results indicate that the initial coarse-grained structure in as-cast condition, brakes down into a fine-grained structure during reduction. Those fine grains are orientated in the direction of cold drawing during plastic deformation. There is an increase in the hardness. The purpose of heat treatment is to achieve better conductivity while maintaining good mechanical properties. The results of microstructure analysis indicate the presence of twin crystals in the structure of the final product

KEY WORDS: copper wire, cold drawing, twin crystals, structure, hardness

1. INTRODUCTION

In addition to steel and aluminum, the most frequently used technical metal is copper. As a metal, pure copper is very soft and as such is rarely used for machine parts. Due to its high thermal and electrical conductivity (right behind silver), moderate cost of materials and easy plastic processing as well as good corrosion resistance, today copper still remains irreplaceable in electrical engineering as a conductor of electricity and in heat exchangers of smaller refrigerators.

This work is focused on copper wire, its production and processing. The production of copper wire itself is a very complex process that includes various stages of production. The quality of the produced wire will ultimately depend on numerous parameters. The most used technology to produce copper wire is certainly the cold drawing of the wire to the desired dimension. Cast wire obtained by some of the direct casting processes is used as an insert for drawing wire.

During wire processing, significant changes occur in the mechanical properties and structure of the drawn wire. During the drawing process, it is very important to understand the behavior of the material, which depends on several factors such as: initial properties of the material, drawing speed, use of lubricants, etc., as well as the interactions of all the mentioned factors to achieve the highest product quality [1,2].

1.1. Production of copper wire

The production process itself, as well as the final properties of the copper wire, is primarily influenced by the choice of the raw material. The copper electrodes obtained by electrolytical refining of copper produced by the pyrometallurgical or hydrometallurgical processes are primarily used as raw material to produce copper wire. It is primarily important for further processing that copper electrodes have high purity, without the presence of impurity elements in the copper, as well as residual moisture or electrolytes from the refining process [3,4]. For production, it is necessary to obtain the initial wire through some of the procedures. Today, the most frequently used casting processes are Contirod, Dip Forming and UPCAST.

Over the past few decades, copper wire production processes have improved considerably, and the biggest advantage is that the development of continuous processes has reduced energy consumption. Some processes require heat treatment such as Contirod, Dip Forming and others, while in a process such as UPCAST, heat treatment is skipped, i.e. the wires are drawn in a cold state [5].

It is specific for all of them that they use cathode copper as an insert, which is then melted in some type of melting furnace, and subsequently continuously cast in Cu wire. The Contirod process for the production of wires from rods was developed at Metallurgie Hoboken Overplet SA [6]. With the help of automatic metal supply and control of the melt level, the copper rod is cast continuously, followed by rolling on rollers, and after cleaning the winding on reels [5,6].

The Dip Forming procedure implies melting of copper electrodes, then the smaller diameter copper wire (9 - 12 mm diameter) is passed through the melt, whereby the melt sticks to the rod and the output diameter of the wire is up to 20 mm. The obtained wire is hot-rolled in a controlled atmosphere and then wind on reels [5,6]. The Southwire procedure was developed in the USA, and there is the most widely used. In this process the cathode copper is melted in a shaft furnace and then brought to a holding furnace, from where continuously casted into the wire. The casting system consists of a vertically placed steel wheel that has a groove on the periphery. On the other side is a steel belt, which closes the slot and forms a cavity for forming the wire [7,8]. While the wheel is spinning, casting is done, and the copper wire is cooled with water, after which it is chemically cleaned and wax is applied before winding onto the reels. Such wire is subsequently processed by cold drawing or similar technology. In Finland, Europe, in the 60s, the so-called UPCAST procedure was invented, Fig. 1.

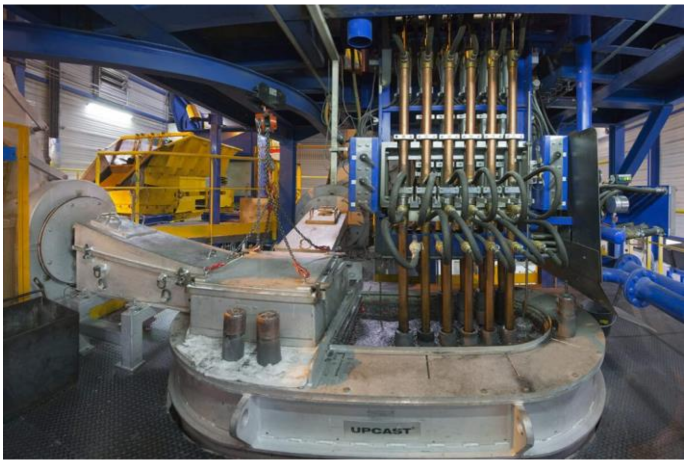


Figure 1. UPCAST process

The UPCAST process, like all the above, uses cathode copper that is melted in an induction furnace. At the same time, graphite powder is placed on the top of the melt in order to reduce the oxygen in the melt and prevent absorption of oxygen from atmosphere into the melt. Piece of copper mounted on rode is immersed in the melt through special dies. The crystallization of copper starts on the inserted piece, and it is withdrawn with the rode through the die cooled by water. In this case, pulling is carried out vertically upwards in relation to the melt. When the copper wire is formed, it is introduced into the system with electric motors, which automatically pulls the wire over the pulleys, and is brought to the winder, Fig. 2.

Figure 2. Pulling the wire towards the winder

In doing so, the wire is cooled in the air until it reaches the winder, where it is wound up onto a reel. Depending on the type of system, it is possible to simultaneously cast several wires at the same time. After cooling, the wire is processed by some of the subsequent plastic forming procedures to the desired dimensions. Cold drawing is the most commonly used [7,10].

1.2. Influence of plastic processing on the structure and properties of copper

G. E. Dieter established that the modifications that occur in metals during the cold deformation process during drawing affect the mechanical and electrical properties of the material. Changes in the metal structure, during cold drawing process, are caused by the material hardening [11]. Research on the deformation of Cu-wires showed that the deformed structure contains a higher density of dislocations as well as small clusters of vacancies that are created by deformation, while the results of tensile tests showed that after deformation there was an increase in the yield strength and tensile strength [12-14].

In the last few years, studies have shown that where grain boundaries are denser, grain smoothness on submicrometer and nanometer sizes leads to significant strengthening. Those grain boundaries create barriers to dislocation movement. However, the presence of denser grain boundaries in metals results in a decrease in conductivity [15]. Significantly reduced electrical conductivity of metals, although with improved mechanical strength, prevents their technological applications for conductors.

Research on copper with coherent grain boundaries shows that dislocation movements are also hindered in the presence of twinned grains. But on the other hand, such strengthening by twinning does not lead to a decrease in copper conductivity [15,16].

Investigations of different recovery procedures and recrystallization processes clarify their influence on microstructure and texture development. In the case of copper, it was shown that regardless of the amount of reduction, all grains of all orientations have the same ability for grain growth, and structure becomes isotropic because the mechanism of twinning occurs with the formation of new grain orientations [17,18].

In the aim of understanding the recrystallization behavior during heat treatment, studies were carried out to determine the texture and microstructure development in pure copper. It was concluded that the microstructural evolution during the recrystallization process is crucial for the final properties such as fatigue resistance, corrosion resistance and mechanical properties [19].

From all this, one can say that in order to achieve a conductor with satisfactory properties, it is necessary to take several factors into account. On one hand, Cu as a conductor is the most optimal, but during processing by cold drawing, certain structural changes occur that reduce its conductivity. It is to be expected that in the case of copper, there will be grain refinement and an increase in dislocations density, which leads to decrease in conductivity.

The aim of this research is to determine the structural changes that occur during the production of copper wire for conductors by the cold drawing process.

2. EXPERIMENTAL

Copper wire samples were taken at different stages of production. The wire is produced by continuous casting using the UPCAST process, Fig. 1. The melting process was previously described in the UPCAST production process. In the observed example of copper wire production, 12 wires with a diameter of 8 mm are cast simultaneously. After solidification in the crystallizer, each individual wire is transferred via a pulley system to a reel winder, where the wire is cooled in air, Fig. 3.

Figure 3. Copper wire in a coil

In order to determine the initial state, samples were taken several times from the as cast wire after cooling. After cooling, the wire is unwound and fed into a cold drawing machine. Depending on the target diameter of the final wire, the machine has multiple dies placed in line, Fig. 4.

Figure 4. Machines for continuous wire drawing

In the wire drawing process, a machine with preload is used to reduce the load on dies when pulling the wire. Before each drawing stage, the wire is specially lubricated before drawing. After the last pass, the wire is wound on the final reel. Samples for testing at all stages of reduction were taken, i.e. after reductions of 24%, 46% and 67.5%.

During drawing process, the wire hardens significantly, and is not applicable for the production of electrical conductors. Therefore, in the production process, it is subjected to annealing in order to soften it. Annealing of the wire is carried out in a continuous production process, in such a way that the wire is passed through a chamber in which there are wheels connected to a high voltage. By passing over them, the wire closes the circuit, whereby due to the current passing through it, the wire itself is heated to approx. 600 °C, after which it is suddenly cooled by water vapor, dried with compressed air and taken out of the chamber. In order to establish the structural changes that occur during this stage of production, wire sampling was carried out after 67.5% reduction and normalization. From all stages, wire samples were taken for structural tests and hardness measurement using the Vickers method, Fig. 5.

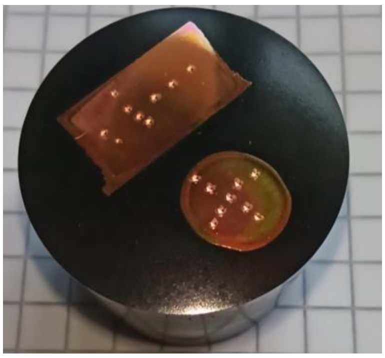
a) Wire sampling

b) Samples in conductive mass

Figure 5. Sampling for structural tests and hardness testing

Samples for structural tests were embedded in the conductive mass, Fig. 5b), by means of a hot-pressing process under high temperature and pressure using the Buehler Simplimet1000 embedding device. Grinding and polishing was carried out on the Buehler "Phoenix Beta" with different grits of sandpaper (120x, 400x, 800x, 1200x) with constant water cooling and 10 N load, for 2 minutes. After grinding, polishing was performed with the constant presence of an aqueous suspension of Al_2O_3 alumina. Etching of the samples was carried out by immersing the surface of the sample in the BERAHA solution. The structure was recorded with a metallographic microscope Olympus GX 51. After recording the structure, hardness values were measured on the same samples using the Vickers method on a Mitutoyo Hardness Testing Machine. Test conditions were indentation load 1 kg, indentation time 25 sec, Fig. 6.

Mitutoyo Hardness Testing Machine



Samples with hardness test impressions

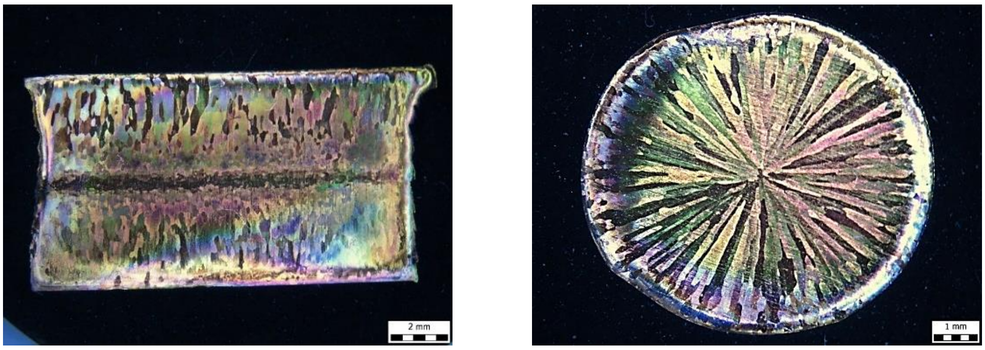
Figure 6. Measuring the hardness of copper wire

3. RESULTS AND DISCUSSION

In the production process, the quality of the wire is regularly controlled, and after the production process, by casting a wire with a diameter of 8 mm was obtained with the following characteristics, density 8.9 kg/dm^3, tensile strength (R_m): 170 N/mm^2 and elongation at break according to ASTM E 8M 45%.

3.1. The results of microstructure analysis

Initially, the microstructure was analyzed on the wire samples in the as-cast condition. The microstructure analysis was performed in the casting direction and perpendicular to the casting direction, Fig. 7.



a) b)

Figure 7. Cast wire macrostructure
a) in the casting direction
b) perpendicular to the casting direction

The macrostructure shows that in the as-cast state the wire has a coarse-grained structure typical for the permanent mold casting. In order to observe in more detail, the microstructure of the wires cross-section in the as cast state was recorded, Fig. 8.

a) b)

Figure 8. Wire microstructure in cross-section
a) Surface edge of cast wire
b) The middle of the cast wire

From recorded structures on wires, it can be seen that there is a thin zone of frozen crystals in the outer edge, Fig. 8 a). This is the result of rapid cooling in contact with the die during solidification. From that peripheral part towards the middle of the wire, large columnar crystals are clearly visible, which is typical for this type of solidification. Small equiaxed crystals can be observed in the center of wire, Fig. 8 b), which are found in very small numbers.

At individual reductions of 24%, 46% and 67.5%, macrostructures were recorded, shown respectively on Fig. 9.

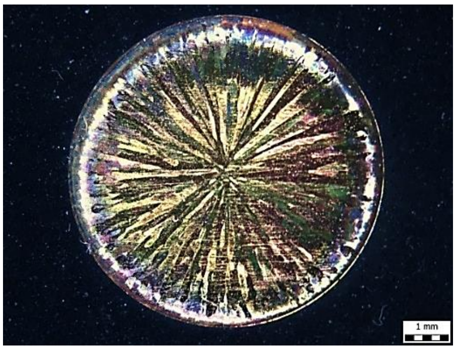
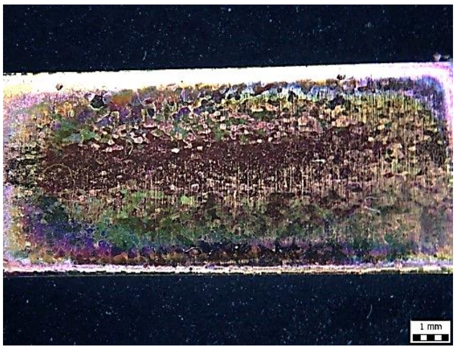
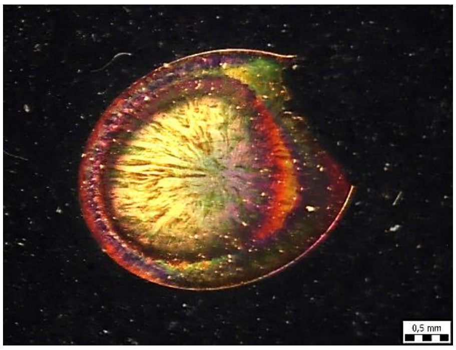
Reduction by cold drawing	Perpendicular to the drawing direction	In the drawing direction
24%		
46%		
67,5%		

Figure 9. Macrostructure of the cooper wire at the selected reductions

Recorded macrostructures show that by increasing the reduction degree of wires cross-section, coarse grains obtained by solidification during casting are gradually reduced. In order to more clearly determine what changes occurring in the structure, microstructure was recorded at the same degrees of reduction, Fig. 10. The microstructures were recorded on samples taken perpendicular to the drawing direction.

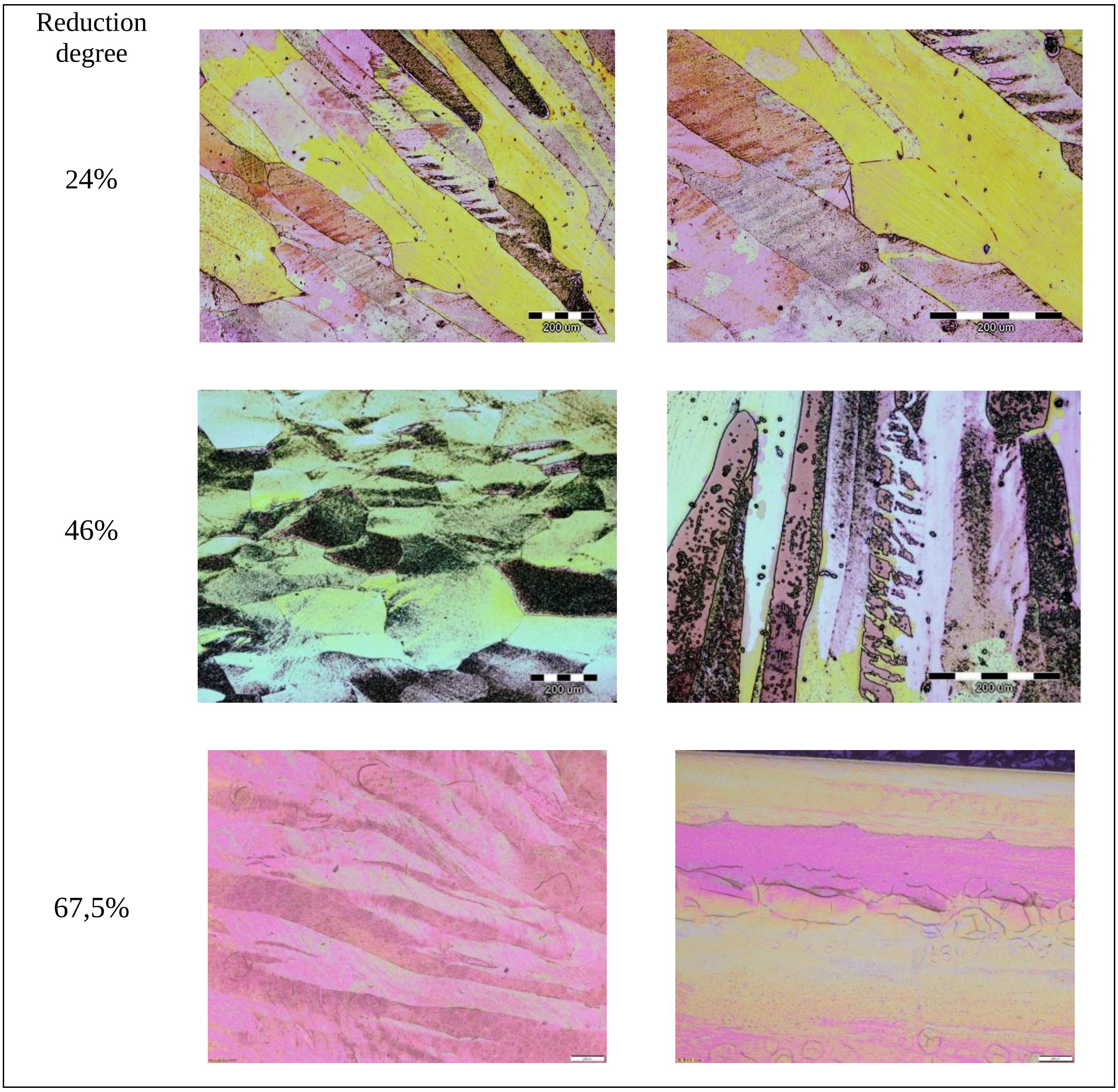
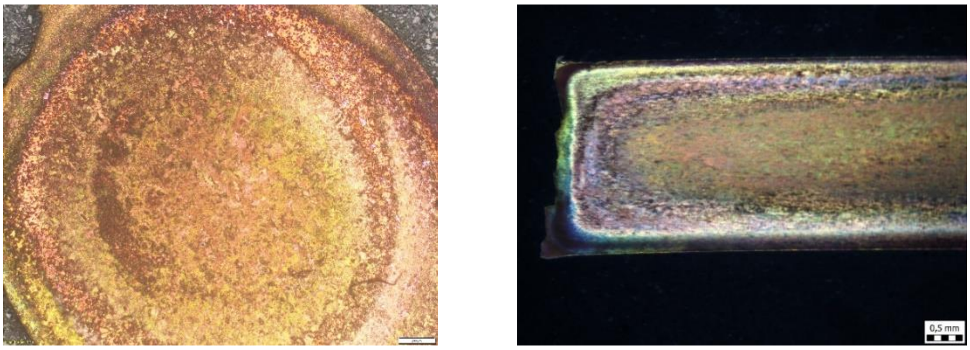


Figure 10. Microstructure of the cooper wire at the selected reductions

From the recorded microstructures it can be observed that the initial columnar crystals in the cast structure brake as the result of cross section reduction. It is observed that their breakage at low reductions occurs only in the marginal surface zones. This shows how in the initial passes the deformation takes place in the edge parts of the wire closer to the contact with the drawing die. As the degree of cross-section reduction increases, the wire is gradually deformed throughout the whole cross-section.

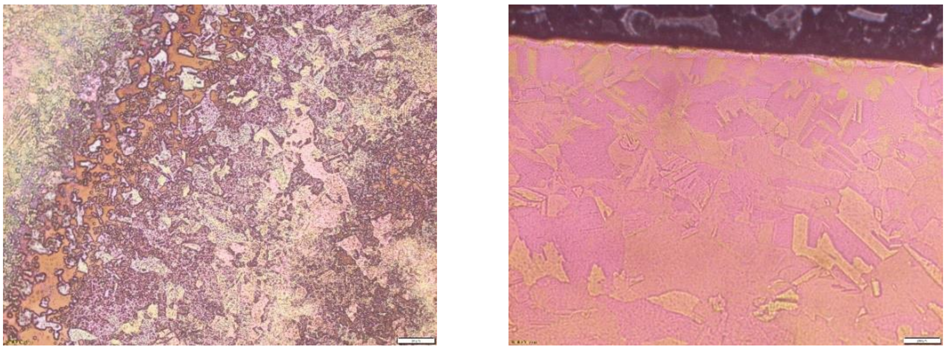
Recorded macro and micro structures indicate that during high reductions there is a strong orientation of grains in the drawing direction of wire. This is particularly visible in the images of the macrostructure, Fig. 9. Furthermore, it can be seen that there is a strong fragmentation of the grains with increasing reduction, and the accumulation of a large number of dislocations. As a result of the mentioned processes, the wire is strengthened, and it is not suitable for further processing. In wire production, after grate degree of deformation, the annealing is carried out in the manner described earlier. Fig. 11 and Fig.12, show the macro and micro structures after the annealing.



a) b)

Figure 11. Macrostructure of the wire after 67.5% of reduction and annealing

a) Perpendicular to the drawing direction
b) In drawing direction



a) b)

Figure 12. Microstructure of the annealed copper wire

a) Enlargement 200X
b) Enlargement 500X

From the recorded structures after annealing, it can be seen that the deformed grains recrystallized. In doing so, the grains are reorganized and there is an equalization of the structure over the entire cross section of the wire. The recrystallized grains are significantly smaller compared to the initial ones in the as-cast state, and the structure is more homogeneous throughout the cross-section. Also, as a result of recrystallization the dislocations were canceled, as theye are not observed in the annealed state in the cross-section. In the recrystallized microstructure twin crystals can be observed. So this is clear indication that the recrystallization in cooper takes place through the formation of twin crystals, Fig. 12 b).

3.2.The results of the hardness test

Hardness testing was performed on as cast wire, at each reduction (24%, 46%, 67.5%), and after subsequent annealing. Mean values were calculated from the measured values, which were used to construct the diagram, Fig. 13.

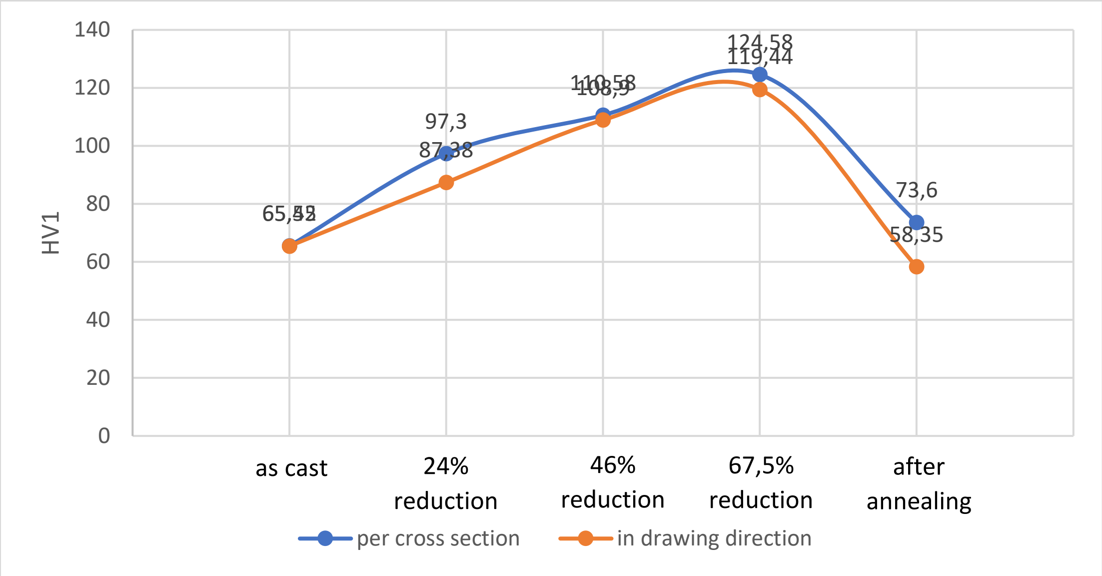


Figure 13. Measured changes in hardness during drawing and annealing

From obtained diagram it is clearly visible that by increasing the reduction degree leads to an increase in the measured hardness values. This is attributed to the cold strain hardening effected during wire drawing. The annealing drops the hardness values to the beginning values in as cast state. This is a clear indication that the process of recrystallization and recovery was carried out during annealing. Since in this state the wire has the same mechanical properties as in the as-cast state, in order to increase its strength and, according to some research conductivity, after annealing the wire is passed through another set of dies. The presented researches did not cover that part of production.

4. CONCLUSIONS

The following conclusions can be drawn:

- During the production of copper wire by the UPCAST process, as a result of rapid solidification in the die, a non-uniform structure is formed in cross-section of the copper wire, which was confirmed by structural analysis. In the outer peripheral parts of the wire, the frozen fine-grained crystals form. Further during solidification, the large columnar crystals are formed directed towards the center of the cast wire, and finally in the middle we have a small amount of equiaxed crystals.
- At low levels of reduction, large columnar crystals gradually break. This is more pronounced in the peripheral part of the wire immediately next to the surface that is in contact with the drawing die.
- In deformed state, from structure it can be seen that deformed crystals rearrange in direction of drawing wire.

- With an increase in the degree of deformation, the entire equiaxed grains gradually break across all cross-section of wire. With an increase in deformation degree, there is an increase in dislocations density in the structure.
- The measured hardness values show that the hardness of the wire increases significantly with the increase in reduction, and at 67.5% it is almost twice as high as in the initial cast state.
- After annealing observed structure indicate that the recrystallization was carried out completely, which is also confirmed by the measured hardness values.
- The recrystallized grains are significantly smaller compared to the cast structure, and it is observed that during recrystallization twin crystals are formed.

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