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INFLUENCE OF COLD REDUCTION ON THE STRUCTURE AND HARDNESS OF COLD DRAWN COPPER WIRE

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Abstract

The production of copper wires involves the application of various processing operations thatlead to the certain structural changes. The electrical properties of wire depend on certain structural changes. Research was carried out on copper wire produced by the UPCAST process. Copper wire was subsequently subjected to the cold drawing through the dies in multiple passes. The structural changes in the process of cold drawing of Cu-wire were observed. During the cold drawing of Cu-wire through dies, a significant change in deformed structure occurred in relation to the initial cast structure. The microstructure analysis and hardness values of the deformed sample indicated that during the initial reduction the majority of the deformation was performed at the surface area of the Cu-wire that was in contact with the die. The initial equiaxed grains at the surface of the Cu-wire elongated in the drawing direction as a consequence of the deformation degree increase.

Keywords: *cold drawing, copper wire, microstructure, hardness*

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INTRODUCTION

Today, copper is used as a technical metal in various technologies. In addition to silver and aluminium, copper is most frequently used as an electrical conductor and according to the electric conductivity it is right behind the silver. Copper wire manufacturing is a complex process that involves several parts of production. The quality of the produced copper wire depends on numerous production parameters, such as raw material purity, the technological process of production, thermomechanical processing, etc. [1,2].
Over the past few decades, copper wire production processes have significantly improved, while the energy consumption was reduced by the development of continuous processes. Some processes, such as Contirod, Dip forming, south wire procedure, etc., require heat treatment [3-5].

The UPCAST process is specific because it does not require heat treatment of cast wire [5,6]. Copper wire with a certain cross-section is obtained with the UPCAST process by continuous casting. After casting, Cu-wire is wound on coils and cooled on air. After cooling, the continuously cast wire is subjected to the cold drawing through the dies. Deformation and reduction of the wire's cross-section is achieved by the reduction in the cross-section of the die opening during cold drawing. The 99,90 % pure copper, i.e. Electrolytic-Tough Pitch (ETP) Cu is used for the production of copper wire. In more demanding cases, such as the modern electronic circuits, a 99,95 % pure copper, i.e. copper without oxygen content (Oxygen Free, OF-Cu), is used.

George Ellwood Dieter (1988) argues that the mechanical and electrical properties of materials are affected by modifications that occur in metals during the cold deformation drawing process. Microstructure changes of the metal, caused by the drawing process, occur due to the material hardening phenomenon. Therefore, it is necessary to carry out heat treatment to improve the electrical conductivity of Cu [2].

It is necessary to take care that the conductors have the lowest possible specific resistance in the production of electrical conductors. Higher specific resistance means higher electricity consumption, i.e. certain energy loss during transmission of electricity. Therefore, the numerous studies have been conducted on the influence of deformation and subsequent heat treatment on Cu specific resistance [7–10].

The hardening effect of Cu during cold deformation is a consequence of grain size reduction. The subsequent heat treatment leads to the processes of recovery and recrystallization improving the mechanical properties of the cold drawn Cu-wire.[9-10].The heat treatment of cold drawn Cu-wire will result in a hardness decrease, but the electrical conductivity will be increased, respectively [7, 9].

Research on cold-drawn wire shows inhomogeneous deformation through the cross section and more pronounced deformation in the edge parts of the wire [10]. They associate this with inhomogeneous recrystallization. In order to avoid inhomogeneity, it was concluded that higher reduction degrees have to be used for drawing [8, 10].

Other research [11] states that the conductivity of a copper alloy wire with 3 % of Zr increases with a certain reduction degree. This is associated with the formation of a fine not – like deformed microstructure. The microstructure orientation in drawing direction enables the acquirement of harder wire with good conductivity.

The aim of this paper is to explain the structural changes that occur in the cold drawing process of copper wire during plastic deformation. Special attention was placed to the influence of the reduction degree on copper wire microstructure changes. The tests were performed in perpendicular cross-section and longitudinal cross-section with respect to the direction of wire drawing. In order to show the effect of the reduction degree on the changes in Cu-wire hardness, the hardness measurements were preformed through the cross sections.

MATERIALS AND METHODS

In the experimental part, continuously cast Cu-wire (99 % Cu) with a diameter of 8,00 mm obtained by the UPCAST method was used. Drawing through the dies with two reduction degrees, 23 % and 46 % whit respect to the initial cross section, was carried out. During the second reduction, the deformation was stopped in order to take a sample from the deformation zone within the drawing die.

Sampling for structural tests and hardness measurements was performed in as cast state, after each reduction, and from deformation zone during second pass. Samples were prepared from perpendicular cross-section and longitudinal cross-section with respect to the direction of wire drawing. For the longitudinal cross-section, samples about 2 cm long were taken in all three states. They were then cut in half lengthwise and embedded in a conductive mass. After standard metallographic preparation of grinding and polishing, the samples were etched in a Behar's etching solution containing 200 g CrO_3, 20 g $NaSO_4$, 17 ml HCl and 1000 ml H_2O.

Microstructure analysis of the samples was performed using Olympus GX51 metallographic microscope with a DP 70 digital camera. After structural testing, on all sample's hardness measurement by the Vickers method was carried out on Mitutoyo hardness testing machine. The test conditions were: loading time of 15 s, load of 100 N and the tests were performed according to the given scheme, Figure 1.

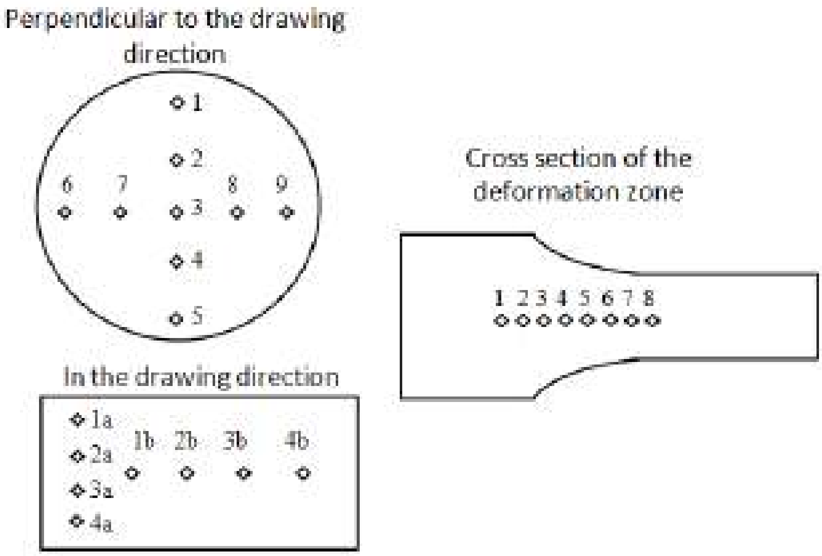
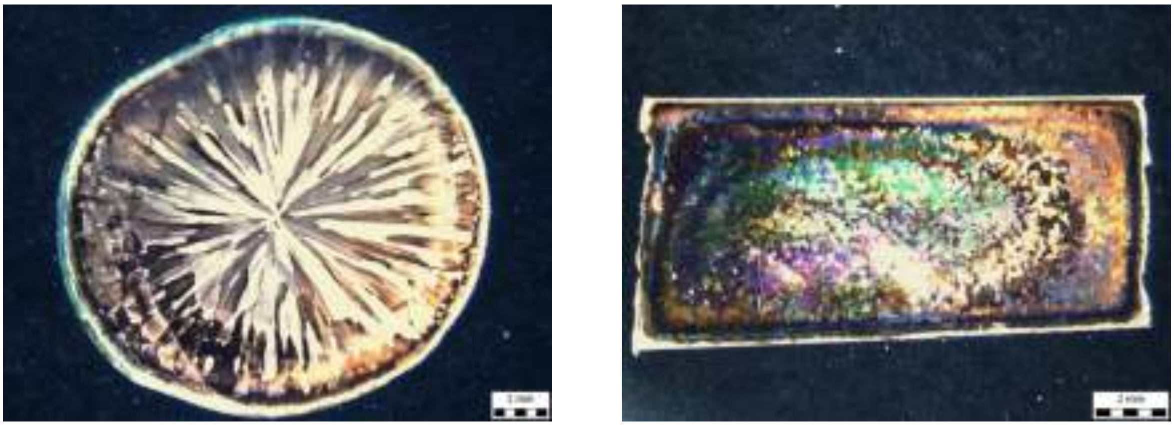


Figure 1. Scheme of hardness measurement on the samples

The results of the microstructure analysis and hardness measurements enabled the impact assessment of the structure changes on mechanical properties. The structure changes occurred during the manufacturing process by wire drawing through the dies.

RESULTS AND DISCUSSION

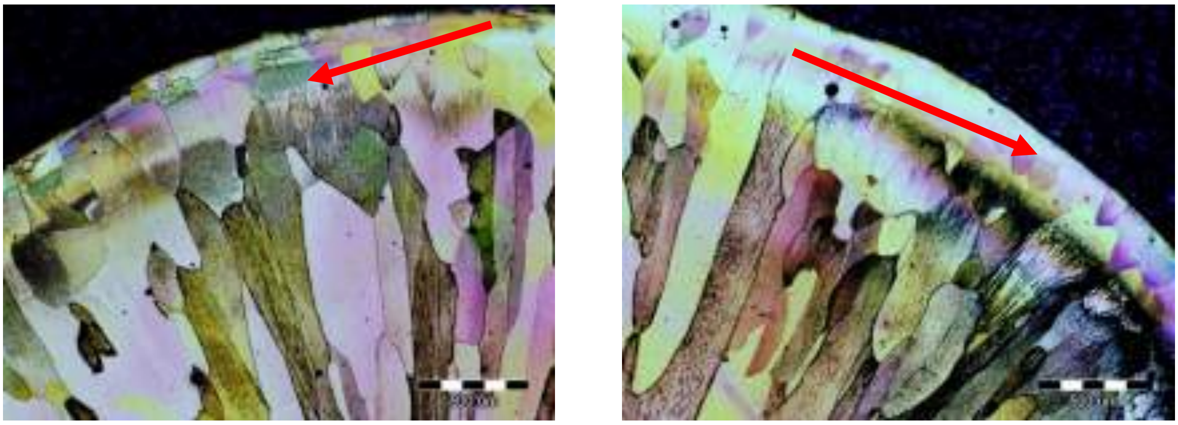
The macrostructure analysis of the sample in as cast condition indicates a typical macrostructure for the continuously cast copper wire, Figure 2.



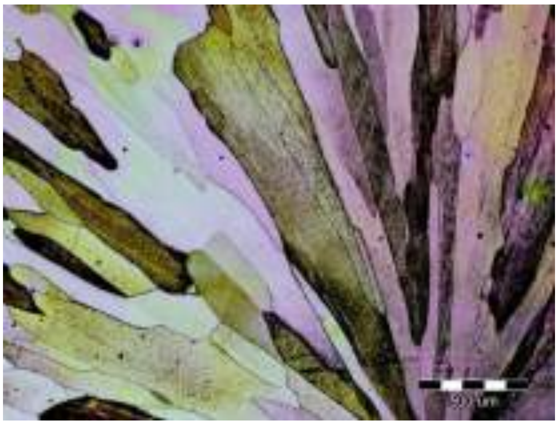
a) b)

Figure 2.The macrostructure of the sample in as cast condition:
a) perpendicular to the casting direction
b) longitudinal to the casting direction

In the macrostructure of the copper wire sample taken perpendicular to the casting direction, three zones are observed, Figure 2. The edge of the cross-section consists of the chill crystals zone, followed by the columnar crystals zone and the equiaxed grains in the central zone, Figure 2 a). The macrostructure of the wire, longitudinal to the casting direction consists of fine equiaxed grains, Figure 2 b).
The cross-sectional microstructure of the continuously cast wire is shown in Figure 3.



a) b)



c)

d)

e)

Figure 3. Microstructure of the as cast copper wire perpendicular to the casting direction:

a) left edge part of the wire

b) right edge part of the wire

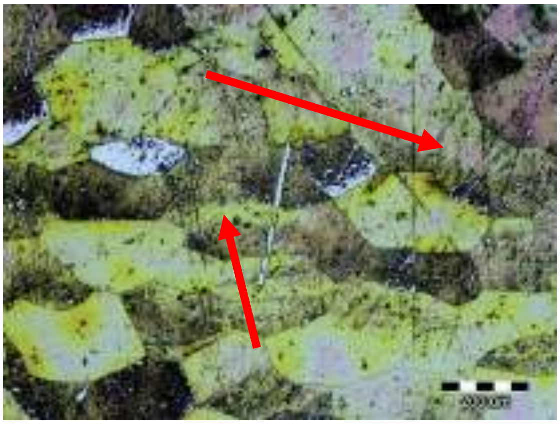
c) left middle part of the wire

d)right middle part of the wire

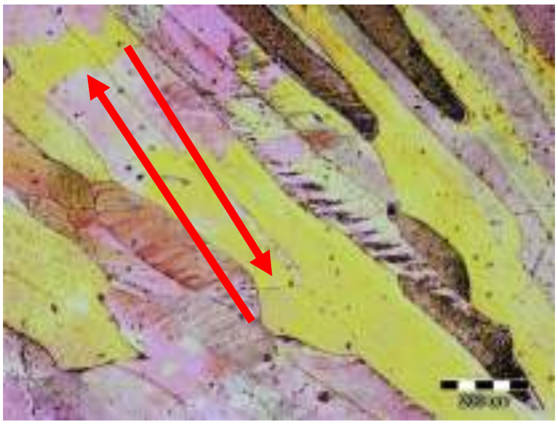
e) the central part of wire

The external edges of the as cast sample consist of the chill crystal zone (Figure 3 a and 3 b indicated by the arrow) that is formed due to the high cooling rate. The high cooling rate is ensured through the contact between the melt and graphite mould. The chill crystal zone is followed by the columnar crystal zone, Figure 3 c and d. The columnar crystals extend from the edge zone of the frozen crystals to the centre of the continuously cast wire. The equiaxial crystals (Figure 3 e - marked with a circle) are observed in the centre of the wire's cross section.

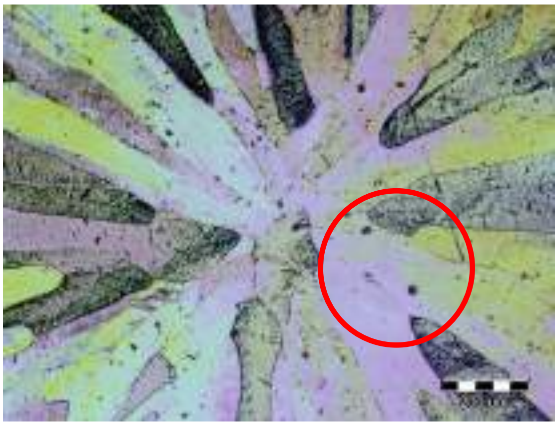
The microstructure of the deformed Cu-wire after first reduction of 23 %, is given in Figure 4.



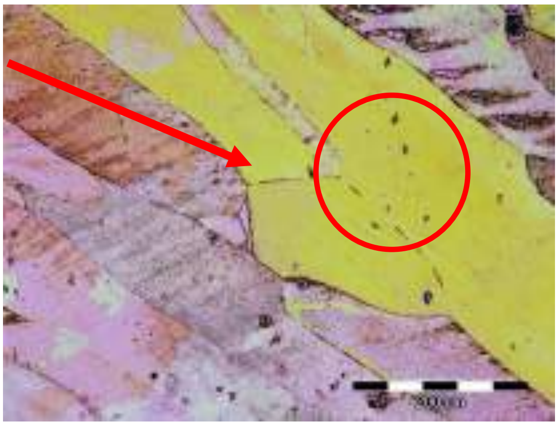
a)



b)



c)



d)

Figure 4. Microstructure of the copper wire sample after 23 % of reduction

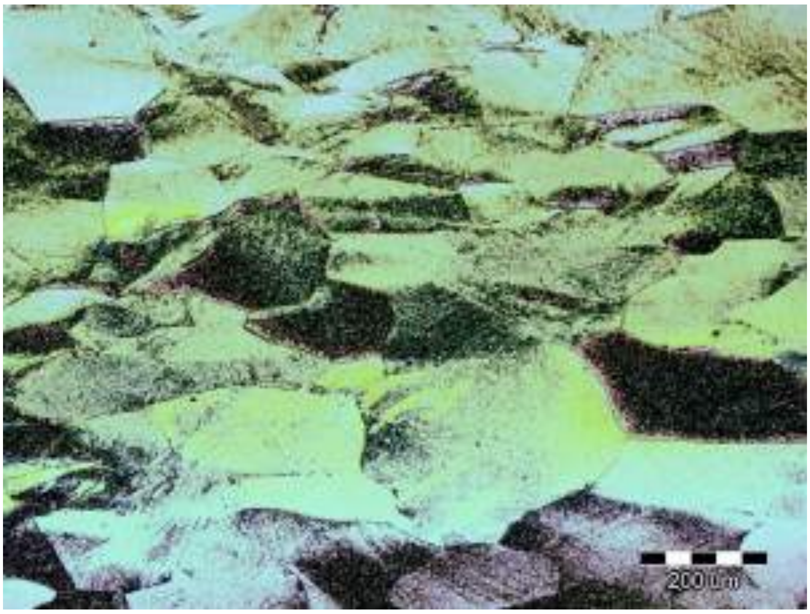
a) microstructure on cross section in the drawing direction

b) and c) microstructure in cross section perpendicular to the drawing direction

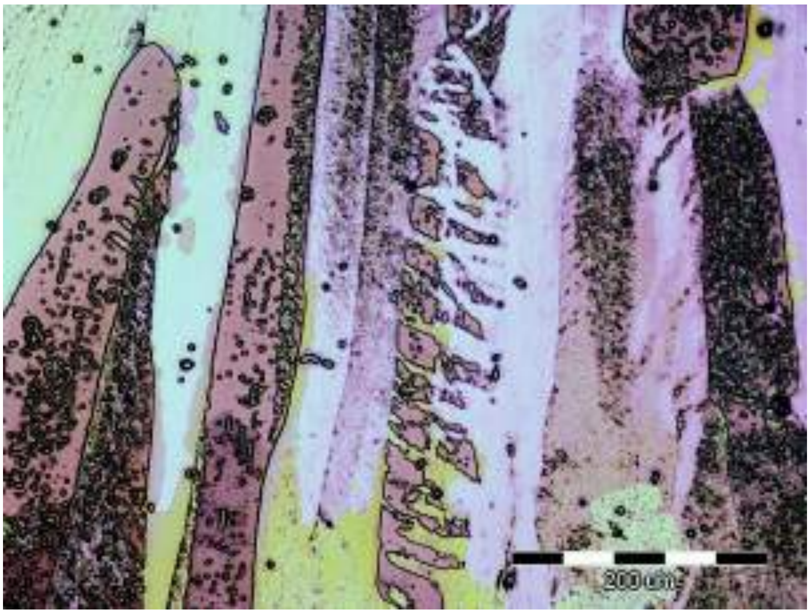
d) microstructure perpendicular to the drawing direction, grain fracture

After reduction, dislocations are visible in the microstructure, indicated by arrows in Figure 4. The appearance of dislocations is clearly visible in the edge region of the wire, i.e. in the chill crystals zone, Figure 4 a. It is visible that the one part of the elongated grains broke due to the deformation, Figures 4 b and 4 d.

The microstructure after second reduction (46 % of relative reduction) is shown in Figure 5. A significant grain orientation in the wire drawing direction is observed. This is especially visible at the edge of the wire in the area where the chill crystals were initially observed.



a)



b)

Figure 5. Microstructures after 46 % of reduction
a) the surface part
b) the central part of the sample

The microstructure shows the initial elongated columnar crystals fracture during plastic deformation due to stresses after second pass, Figure 5 b. There is a greater number of dislocations in the cross section of the Cu-wire (Figure 5 b) as the deformation degree increases. Given that, the increase in hardness values is expected. The orientation in the drawing direction is clearly visible from the macrostructure of the sample taken from part of the wire that was in the deformation zone during second pass, Figure 6.

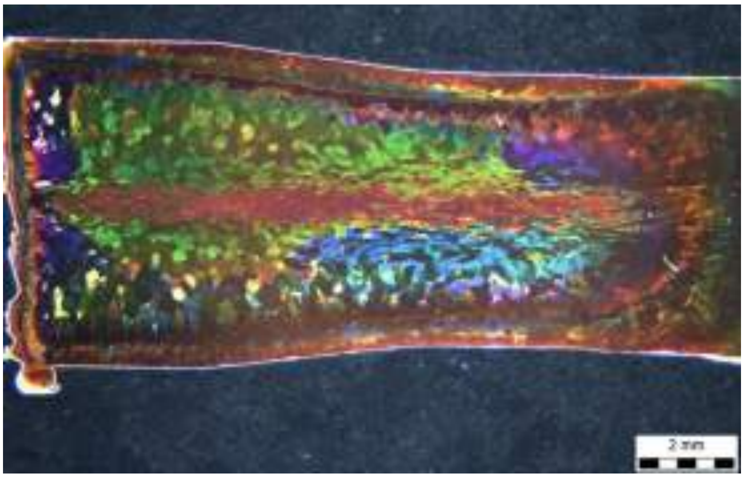


Figure 6. Macrostructure of the deformation zone during second pass

It can be seen that in the deformation zone during drawing, the structure is oriented in the drawing direction, and at the same time the equiaxial grains elongate in the direction of deformation and pass into the elongated grains.

Table 1 shows the measured hardness values along the cross section of the continuously cast Cu - wire, according to the given scheme, Figure 1.

Table 1.Measured hardness values in as cast state, HV10

	Perpendicular to the casting direction		Longitudinal to the casting direction
1.	66.0	1.a)	79.2
2.	69.4	2.a)	73.7
3.	64.9	3.a)	73.0
4.	69.3	4.a)	70.5
5.	71.8	1.b)	73.0
6.	79.5	2.b)	69.6
7.	69.3	3.b)	63.7
8.	65.2	4.b)	70.3
9.	78.0		

Table 2. Measured hardness values after 23 % and 46 % of reduction. HV10

23 % of reduction				46 % of reduction			
	Perpendicular to the drawing direction		Longitudinal to the drawing direction		Perpendicular to the drawing direction		Longitudinal to the drawing direction
1.	97.5	1.a)	83.6	1.	113.1	1.a)	112.6
2.	90.3	2.a)	87.2	2.	110.8	2.a)	107.4
3.	90.9	3.a)	90.3	3.	102.7	3.a)	110.1
4.	89.4	4.a)	94.7	4.	104.3	4.a)	109.5
5.	91.4	1.b)	89.5	5.	114.4	1.b)	108.7
6.	92.0	2.b)	91.3	6.	113.6	2.b)	104.2
7.	87.0	3.b)	91.8	7.	110.9	3.b)	108.7
8.	91.8	4.b)	92.8	8.	109.3	4.b)	104.1
9.	84.1			9.	109.2		

The measured hardness amounts show their uniform distribution across the wire cross section in the as cast state. Table 1. Slightly higher amounts were measured in the chill crystals area in the edge part of the wire (Figures 3a and 3b).The hardness measurements indicate an increase in the hardness of the Cu wire after each drawing. This is particularly evident from the measured hardness values through the deformation zone during second pass. Table 3.

Table 3. Measured hardness amounts through the deformation zone during second pass

Measurement position	1	2	3	4	5	6	7	8
Measured hardness. HV10	89.4	89.5	90.3	98.4	99.5	107.0	106.6	105.8

The measured hardness values after second pass indicate a more pronounced hardening in the edge of wire that is in contact with the die during drawing. It was noticed that in this part. There is a greater directed orientation in the wire microstructure. Figure 5 a.

It can be concluded. by comparing hardness and microstructure changes that during Cu-wire drawing hardening occurs due to grain refinement. increased dislocation density and directed orientation of microstructure. The hardness increase is more pronounced with an increase in the reduction degree. Directed microstructure with the finer grains formed by refinement of the initial elongated grains is observed. Figure 5.

CONCLUSIONS

The aim of the paper was to establish the impact of macrostructure and microstructure changes during cold drawing of continuously cast Cu-wire on the hardness. The conducted research shows the following:

- The macrostructure analysis of the sample in as cast condition indicates a typical macrostructure for the continuously cast copper wire consisting of chill crystal zone followed by columnar crystal zone and equiaxed zone.
- Significant changes in the microstructure in the form of grain refinement occur due to the Cu-wire deformation by drawing through the dies.
- The increase in the deformation degree caused columnar crystal fracture and microstructure orientation in drawing direction.
- The equiaxial grains elongate in the deformation direction and turn into elongated - grains as the deformation increases.
- The grain refinement caused by the cold deformation caused increase in hardness values.

Acknowledgements

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