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Presented and supported by:

**KHelfaOussama**

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# **Fabrication of thin metallic wire**

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**Jury :**

**Dr      Messaoudi Salim                      MCB      University of Biskra                      President**

**Pr      Boumerzoug Zakaria                      Pr      University of Biskra                      Supervisor**

**Dr      Ouannes Karima                              MCA      University of Biskra                      Examiner**

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# DEDICATION

*In the beginning, I want to thank Allah for giving me the strength and courage to lead this modest work.*

*To my parents*

*I dedicate this dissertation to my loved parents who have always teach me to trust in Allah, believe in hard work and teach me that so much could be done with little.*

*To my sister and brother*

*Thank you for your everlasting love and warm encouragement throughout my research.*

*I want to thank everyone who helped me out on my journey.*

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- I would especially want to thank Pr. Zakaria Boumerzoug, my supervisor, who suggested this research topic to me and who has inspired me with his support, counsel, and worldwide perspective in this field.
- I express my gratitude to the members of the jury, Dr Messaoudi Salim and Ouannes Karima who agreed to evaluate my research.
- Finally, I thank all those who have supported me in this work, and thank my friends for all the support they have given me.

*Thank  
you* so much

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# General Introduction

Thin metallic wires are widely used in industries such as electronics, automotive, construction, and medicine. Producing these wires requires high precision in both dimension and quality, especially as the diameter becomes smaller. The manufacturing process typically involves continuous casting, rolling, and wire drawing, each playing a crucial role in shaping the final product.

Traditional wire drawing uses rigid dies to reduce wire diameter, but this method can face limitations such as die wear and surface defects. To overcome these issues, dieless wire drawing has emerged as an alternative. This technique relies on controlled heating and tension, offering greater flexibility and smoother finishes, especially for ultra-fine wires.

The objective of this dissertation is to study the manufacturing of thin metallic wire through dieless drawing method. It also includes the design and testing of a custom dieless drawing machine using induction heating.

This work is divided into four chapters:

- Chapter I covers traditional manufacturing processes and applications of metallic wire.
- Chapter II focuses on dieless drawing techniques and key process parameters.
- Chapter III presents the design and operation of the developed drawing machine. The techniques of characterization have been presented.
- Chapter IV contains the characterization results of the samples of the wires reduced by this process

# **Chapter I:**

# **Manufacturing processes of metallic wire**

# **Chapter I: Manufacturing processes of metallic wire**

## **Introduction and Scope**

The manufacturing of metallic wires is essential for various industries, including automotive, electronics, and construction. This chapter examines three key processes involved in wire production: continuous casting, wire drawing, and rolling. Continuous casting produces the initial billets or ingots, while wire drawing reduces the wire's diameter to achieve desired properties. Rolling refines the wire's structure and ensures accuracy. The chapter will also explore the industrial applications of metallic wire, demonstrating how these processes contribute to producing high-quality wires for diverse sectors.

To better understand the complexity and importance of wire manufacturing, the following sections will delve into each of these processes in detail, beginning with the continuous casting process.

## **1. Continuous Casting Process**

### **Definition and purpose:**

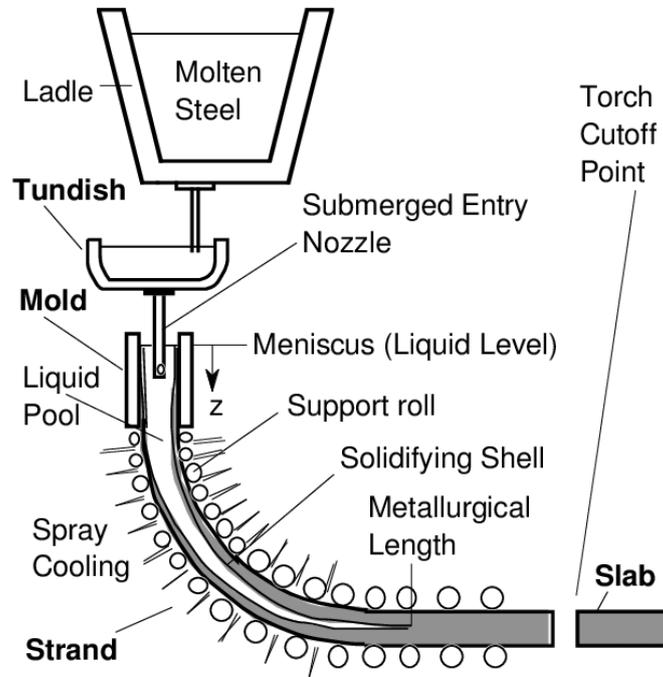
Continuous casting is a process used to solidify molten metal into semi-finished forms like billets or rods, which serve as raw materials for further manufacturing. The process is widely used for metals like steel, aluminum, and copper due to its efficiency and consistency

### **Principle of continuous casting process:**

The continuous casting process as shown in **Figure I.1.** involves transferring liquid steel from a ladle to the casting machine. When the process begins, the nozzle at the bottom of the ladle is opened, allowing the steel to flow at a controlled rate into a tundish. From the tundish, the steel flows through a submerged entry nozzle into one or more molds, typically made of water-cooled copper. Solidification starts at the metal/mold interface, and the solidified shell thickness gradually increases as

## Chapter I: Manufacturing processes of metallic wire

the steel moves through the machine. By the time the strand exits the mold, the shell must be sufficiently thick to support the liquid steel. Below the mold, the strand is further cooled with water spray, known as secondary cooling, while the mold itself is cooled with water, referred to as primary cooling. At the end of the process, the strand is cut and transferred to a rolling mill [1]



**Figure I.1:**Schematic of continuous casting process[2]

### **1.2. Types of Continuous Casting:**

The continuous casting process can be categorized into three types:

#### **1.2.1. Vertical Continuous Casting:**

Vertical casting produces billets with excellent structural uniformity and minimal defects. It is commonly used in large-scale operations requiring high-quality billets, such as for steel and aluminum wire production. However, it requires tall infrastructure and has higher setup costs, making it space-intensive.

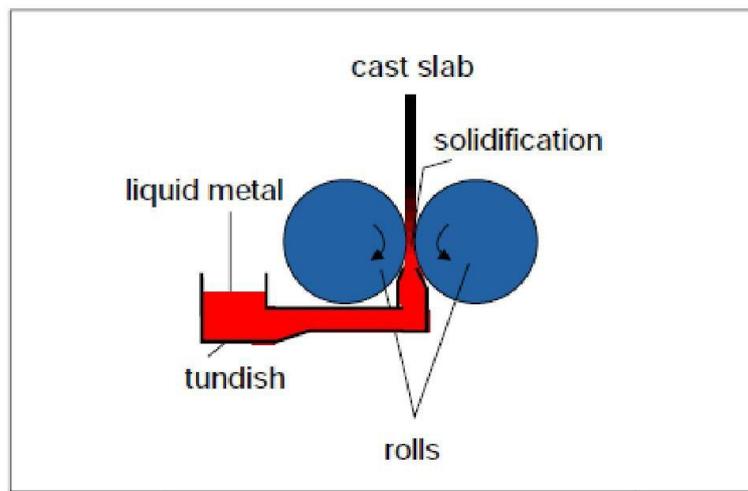
##### **1.2.1.1 Vertical Upward Continuous Casting (VUCC):**

A schematic of vertical upward continuous casting is presented in **Figure I.2**.

##### **Working Principle**

## Chapter I: Manufacturing processes of metallic wire

This process involves molten metal flowing from a furnace into a tundish and then into a vertically positioned, water-cooled mold. Solidification begins as heat is rapidly extracted at the mold walls. A pulling mechanism steadily draws the solidifying metal upward, maintaining a uniform solidification front and minimizing defects like porosity. Secondary cooling enhances the product's microstructure and mechanical integrity, while the upward motion reduces turbulence and prevents impurities from settling. This process is efficient for producing high-quality metals like copper and aluminum [3].



**Figure I.2:** Vertical upward continuous casting[4]

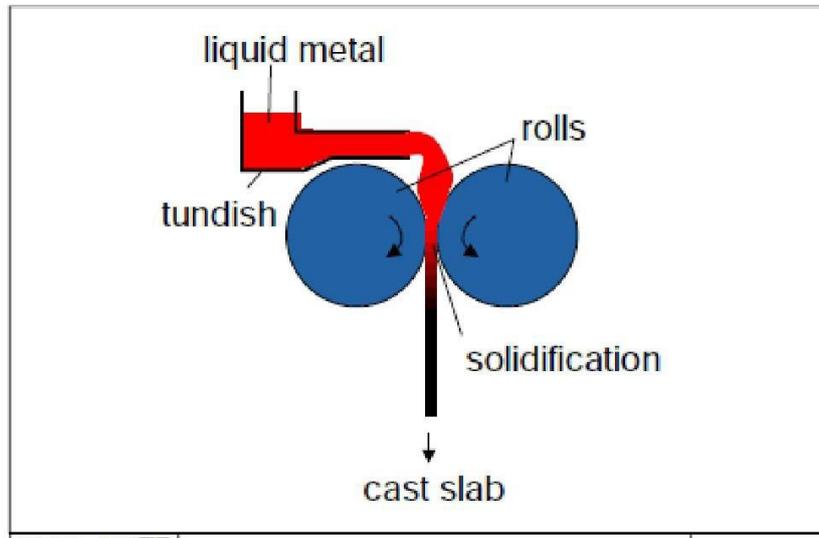
### **1.2.1.2. Vertical Downward Continuous Casting (VDCC):**

In VDCC (**Fig.I.3**), molten metal is first poured into a tundish, which serves as an intermediary vessel to regulate the flow into a vertically positioned water-cooled mold. As the molten metal enters the mold, heat is rapidly extracted through the mold walls, initiating solidification. The solidifying metal is continuously withdrawn downward by a precisely controlled pulling mechanism, ensuring uniform solidification and maintaining the integrity of the structure. Secondary cooling systems are applied as the partially solidified product exits the mold to complete the solidification process and enhance product quality.

The downward movement, aided by gravity, minimizes turbulence and eliminates issues such as porosity and segregation. This allows for the production of large, defect-free metal sections with uniform grain structure and high mechanical

## Chapter I: Manufacturing processes of metallic wire

properties, making VDCC particularly suited for manufacturing robust materials used in heavy industries[3].



**Figure I.3:** Verical downward continous casting [4]

### **1.2.2. Horizontal Continuous Casting(HCC):**

It is widely used for casting nonferrous metal wires such as aluminum, magnesium, zinc, copper, and their alloys. This process is favored for its low investment cost, reduced energy consumption, high efficiency, and superior surface quality. HCC is particularly effective in the continuous extrusion forming of aluminum alloys and other metals, offering advantages such as energy savings, high extrusion ratios, high production efficiency, consistent product length, and uniformity. It can produce various forms, including tubes, solid profiles, complex shapes, and coaxial products.

The HCC process begins with metal melting in a furnace, after which the molten metal is either transported in a ladle to the casting furnace or directly fed into the tundish. From the tundish, the hot metal flows under gravitational force through a graphite mold installed in a horizontal crystallizer. The metal is cooled and solidifies, forming a defined shape. Roll supports guide and adjust the casting speed, while a moving circular saw cuts the product into desired lengths as it exits the machine horizontally.

## **Chapter I: Manufacturing processes of metallic wire**

### **2. Wire Drawing Process**

Wire drawing is a cold working process in which a metal rod or wire is reduced in diameter and elongated by being pulled through a series of dies. It is a primary method for producing wires with precise dimensions and high-quality surface finishes [5]. A schematic sketch of the wire drawing process is shown below in **Figure I.4**.

#### **2.1 Working Principle:**

##### **2.1.1. Cleaning and Lubrication:**

The metal rod is cleaned to remove oxide layers and contaminants that might damage the dies. A lubricant, such as soap or oil, is applied to reduce friction during the process.

##### **2.1.2. Die Arrangement:**

The dies are arranged in a series with progressively smaller diameters. Dies are made of hard materials like tungsten carbide or diamond for durability and precision.

##### **2.1.3. Drawing Process:**

The metal rod is tapered at one end to pass through the first die. A drawing machine pulls the rod through the die, reducing its diameter while increasing its length. Successive passes through smaller dies achieve the desired final diameter.

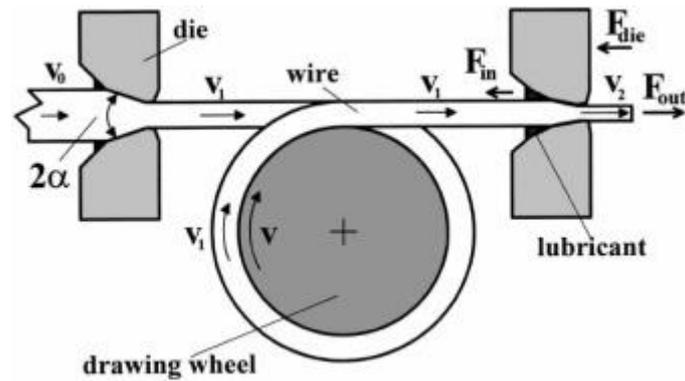
##### **2.1.4. Annealing:**

During the drawing process, the material undergoes work hardening. Annealing (heating and slow cooling) is performed to restore ductility before further drawing.

##### **2.1.5. Finishing and Coiling:**

The wire is polished to achieve the required surface finish. It is then coiled for storage and transportation.

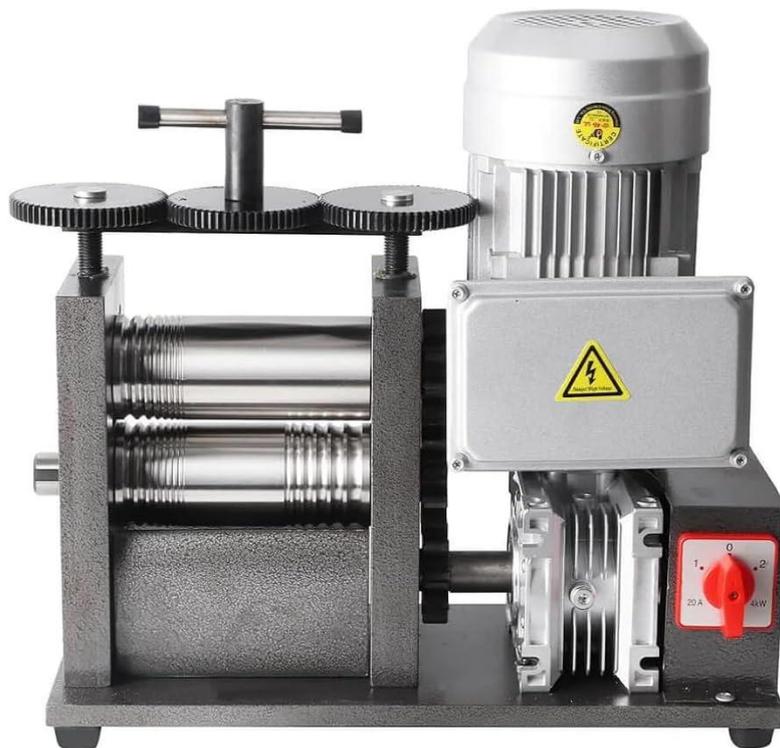
## Chapter I: Manufacturing processes of metallic wire



**Figure I.4:** Drawing in a multiple-die machine [6].

### 3. Rolling Process

Rolling is a metal forming process where metal rods or wires are passed through a pair of rotating rolls to reduce their diameter or alter their cross-sectional profile. Rolling can be performed either at high temperatures (hot rolling) or room temperatures (cold rolling) [7].



**Figure I.5:** Rolling mill machine [8].

#### 3.1. Working Principle:

##### 3.1.1. Hot Rolling:

The metal is heated above its recrystallization temperature to enhance ductility. Large reductions in size are achieved in a few passes.

## Chapter I: Manufacturing processes of metallic wire

### **3.1.2. Cold Rolling:**

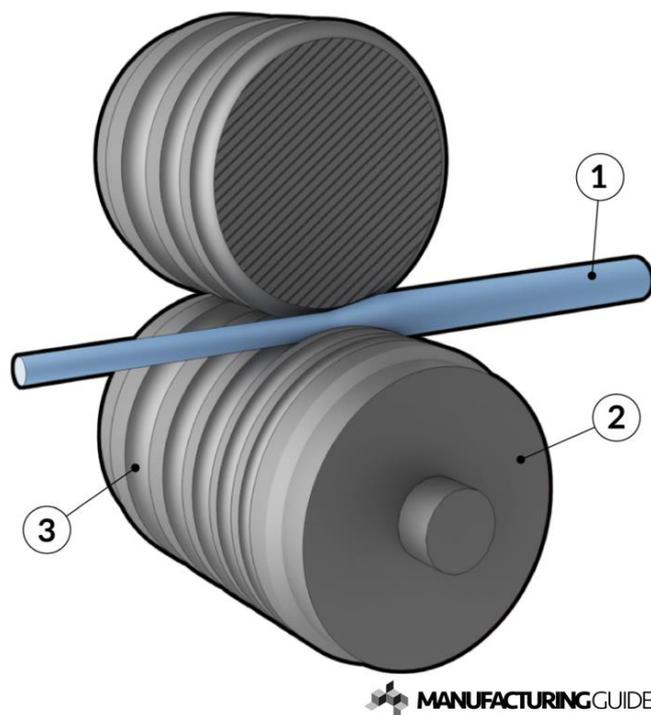
The wire or rod is processed at room temperature, leading to improved surface finish and mechanical properties[9]. Work hardening occurs during the process, increasing strength and hardness .

### **3.1.3. Passes Through Rolling Mills:**

The wire is fed through a series of rolls, each reducing the diameter or shaping the cross-section. Rolls may be flat for plain wire or grooved for specific profiles like hexagonal or square sections.

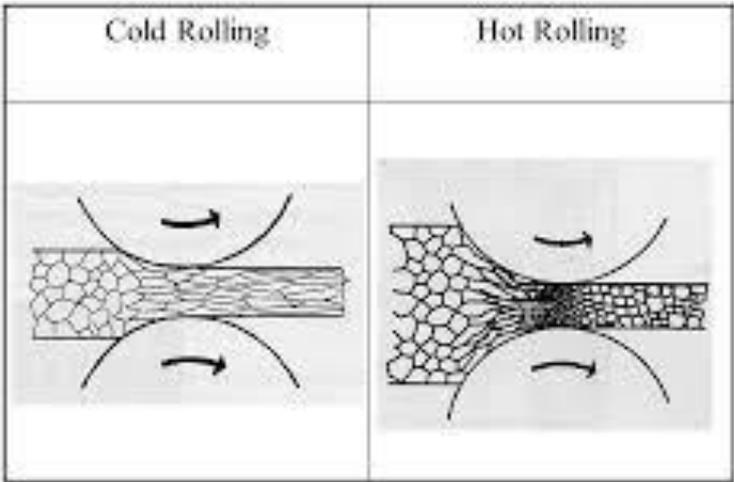
### **3.1.4. Coiling and Inspection:**

The rolled wire is coiled for handling and storage. It is inspected for dimensional accuracy, surface defects, and mechanical properties [7].



**Figure I.6:** Wire rolling illustration[10]

**Chapter I: Manufacturing processes of metallic wire**



**Figure I.7:** Hot rolling and cold rolling on structural perspective[11].

**4. Industrial applications of metallic wires**

Metallic wires are essential components in various industries, owing to their excellent mechanical properties, electrical conductivity, and versatility. These wires are tailored for specific applications through surface treatments and dimensional control .

**4.1. Electrical Industry:**

Metallic wires are used in power transmission lines, magnet wires, and cables. Fine wires are used for electronic circuits and telecommunications.

## Chapter I: Manufacturing processes of metallic wire



**Figure I.8:** Ethernet cables [12].

### **4.2. Construction:**

- The reinforcement wires used for prestressed concrete.
- Fencing, barbed wire, and welded meshes .

### **4.3. Automotive Industry:**

- Wire harnesses for electrical systems .
- Control cables, such as brake and throttle wires.

### **4.4. Medical Applications:**

- Stainless steel surgical wires and orthodontic wires .
- Biocompatible wires for implants.

## Chapter I: Manufacturing processes of metallic wire



**Figure I.9:** Orthodontic threads[15].

### **5. General Manufacturing:**

- Wire ropes for lifting and hoisting .
- Springs, fasteners, and components for industrial machinery .

### **Partial conclusion and outlook:**

This chapter has outlined the main processes involved in metallic wire production, including continuous casting, wire drawing, and rolling. Each method involves specific stages and equipment designed to shape and refine metal into wire form. These processes enable high-precision outputs for diverse industrial applications.

## **Chapter I: Manufacturing processes of metallic wire**

### **References**

- [1] S. Louhenkilpi, Continuous Casting of Steel, Department of Materials Science and Engineering, Aalto University School of Chemical Technology, Espoo, Finland, pp. 373–434, 2014.
- [2] ResearchGate, “Measurement of temperature, solidification, and microstructure in a continuous cast thin slab - Scientific Figure,” [Online]. Available: [https://www.researchgate.net/figure/Schematic-of-continuous-casting-process\\_fig3\\_242266407](https://www.researchgate.net/figure/Schematic-of-continuous-casting-process_fig3_242266407). [Accessed: Dec. 23, 2024].
- [3] T. Engh, Principles of Metal Casting, McGraw Hill, 2018.
- [4] Core Materials, “Vertical upward continuous casting,” [Online]. Available: <https://www.slideshare.net/corematerials/talat-lecture-3210-continuous-casting>. [Accessed: Dec. 24, 2024].
- [5] B. Avitzur, Metal Forming: Processes and Analysis, McGraw-Hill, 1968.
- [6] Elsevier, “Image of a schematic,” [Online]. Available: <https://ars.els-cdn.com/content/image/3-s2.0-B0080431526009669-gr1.jpg>. [Accessed: May 7, 2025].
- [7] W. L. Roberts, Hot Rolling of Steel, CRC Press, 1983.
- [8] Amazon, “Image of book cover,” [Online]. Available: [https://m.media-amazon.com/images/I/61IB5kUhMhL.AC\\_UF894,1000\\_QL80.jpg](https://m.media-amazon.com/images/I/61IB5kUhMhL.AC_UF894,1000_QL80.jpg). [Accessed: May 7, 2025].
- [9] Precision Kidd Steel Co., Inc., “Cold Drawn Steel Bar Process,” Precision Kidd Steel, [Online]. Available: <https://www.precisionkidd.com/technology.htm>
- [10] Manufacturing Guide, “Wire rolling illustration,” [Online]. Available: [https://www.manufacturingguide.com/sites/default/files/styles/illustration/public/illustrations/wire\\_rolling\\_1069.png?itok=-VYNVzzR](https://www.manufacturingguide.com/sites/default/files/styles/illustration/public/illustrations/wire_rolling_1069.png?itok=-VYNVzzR). [Accessed: May 7, 2025].
- [11] Azar Ghaltak, “Hot rolling vs cold rolling,” [Online]. Available: <https://www.google.com/url?sa=i&url=http%3A%2F%2Fazarghaltak.com%2Fen%2F2019%2F08%2F17%2Fhot-rolling-vs-cold-rolling%2F>. [Accessed: May 7, 2025].
- [12] University of Rochester, “Ethernet switch image,” [Online]. Available: [https://www.cs.rochester.edu/u/nelson/courses/csc\\_robcon/robot\\_manual/external\\_images/ethernet\\_switch.jpg](https://www.cs.rochester.edu/u/nelson/courses/csc_robcon/robot_manual/external_images/ethernet_switch.jpg). [Accessed: May 7, 2025].

**Chapter II:**  
**Manufacturing processes of**  
**thin metallic wires**

## **Chapter II: Manufacturing processes of thin metallic wires**

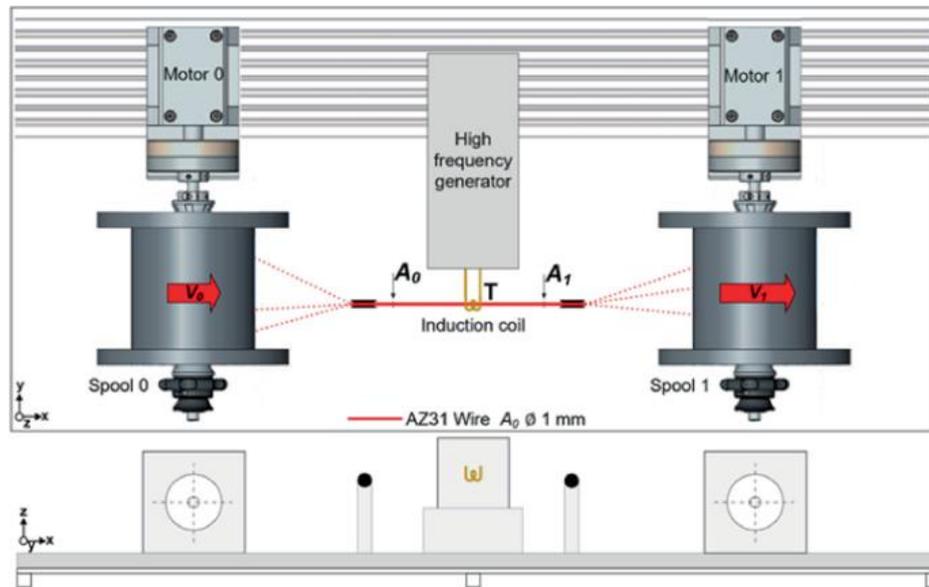
### **Introduction:**

This chapter explores the various manufacturing processes used to produce thin metallic wires, focusing on the key parameters that influence the quality and characteristics of the final product. These processes, such as traditional drawing, extrusion, and advanced methods like dieless drawing and micro-drawing, are essential for achieving wires with specific mechanical, electrical, and thermal characteristics. Parameters like tensile force, temperature, strain rate, and material properties play a crucial role in determining the final dimensions, strength, ductility, and conductivity of the wires. A thorough understanding of these processes and their parameters allows for the optimization of wire production to meet the requirements of diverse applications in industries such as electronics, telecommunications, and automotive.

### **1. Dieless drawing**

Dieless drawing (**Fig II.1**) is a new technique of metal forming which does not use dies. The drawing bar (solid or hollow) is fixed at one end, and is locally heated to a high temperature by an induction heating coil. It is then pulled at the other end with a constant axial velocity  $V_t$ , while the induction coil is moved in the opposite or same direction at a constant velocity  $V_2$ . Since the heated zone of the bar has a low flow stress, necking occurs only in this region. Necking, however, is diffused out by the continuous motion of the induction coil, yielding a straight uniform bar [1].

## Chapter II: Manufacturing processes of thin metallic wires



**Figure II.1:** Experimental setup for dieless drawing [2].

### 1.2. Types of dieless drawing :

Dieless drawing can be categorized into two types :

- Conventional one-pass DD
- Multi-pass dieless drawing MPDD

#### 1.2.1. Conventional one-pass (DD:)

In this process, the velocity  $V_1$  mono-tonically increased until the wire broke. In such a way, the maximum strain of the wire can be determined for given conditions. [3]

#### 1.2.2. Multipass Dieless Drawing (MPDD) :

Multipass dieless drawing involves repeating the dieless drawing process multiple times. At each pass, the wire undergoes a smaller amount of strain to maintain process stability. Between passes, the bobbins' rotation direction is reversed, and the process continues until the desired wire size or breaking point is reached [3].

### 1.3 Equipment and components:

1. Wire

## **Chapter II: Manufacturing processes of thin metallic wires**

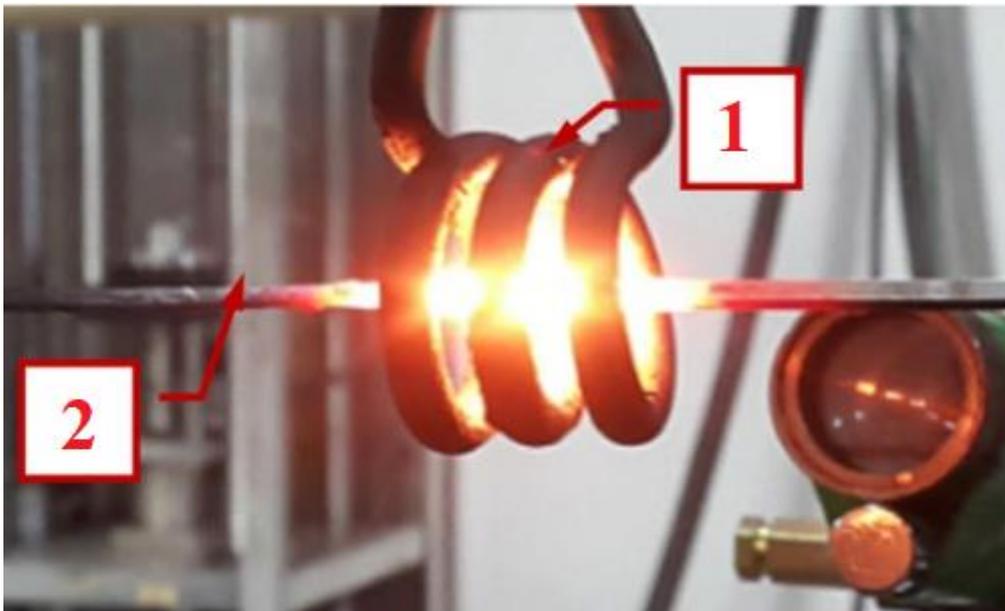
2. Electrical induction heating device
3. Support rollers
4. Bobbins
5. Engines
6. Power supply for electrical induction heating device
7. A computer with software for the process control

### **1.3.1 Wire :**

- The metal wire serves as the raw material for the dieless drawing process.

### **1.3.2 Electrical Induction Heating Device**

The induction heating device is presented in **Figure II.2**. Provides localized heating to the wire, reducing its flow stress for easier deformation.



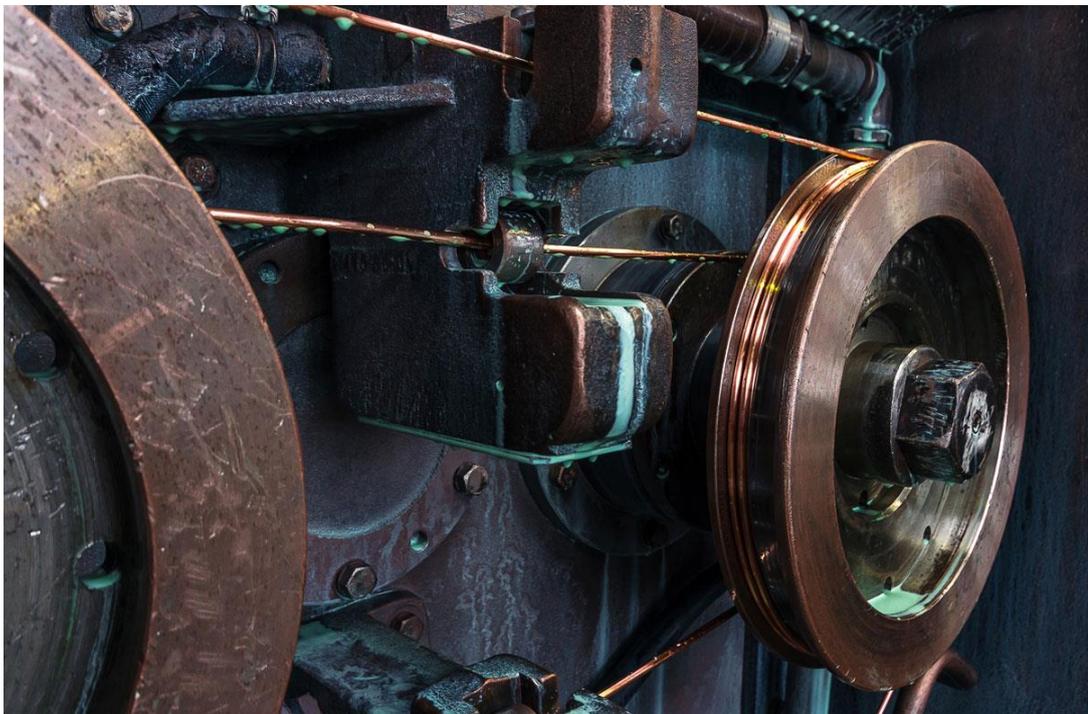
**Figure II.2:** Principle scheme of DD process 1—the heating device (inductor); 2—the sample [4].

### **1.3.3 Support Rollers**

Support rollers maintain the position of the wire and ensure smooth, continuous movement during the drawing process (**Fig II.3**) and (**Fig II.4**):



**Figure II.3:** drawing machine roller [5].



**Figure II.4:** Copper wire drawing application [6].

## Chapter II: Manufacturing processes of thin metallic wires

### 1.3.4. Bobbins

A commercial copper bobbins are presented in **Figure II.5**. These bobbins are used to feed and collect the wire before and after the dieless drawing process.



**Figure II.5:** bobbins for winding wire [7].

### 1.3.5. Engines (Motors)

An hd servo motor is presented in **Figure II.6**.drive the movement of the wire and the induction coil, ensuring precise and synchronized velocities.



**Figure II.6:** A motor with the ability to control its speed and direction of rotation by computer [8].

## **Chapter II: Manufacturing processes of thin metallic wires**

### **1.3.6. Power supply for both electrical induction heating device and servo motors :**

A power supply is presented in **Figure II.7.** delivers the required energy to the induction heating device for efficient heating also adjust voltage and current to control motor torque and speed.



**Figure II.7:** Power supply [9].

### **1.3.7. Computer with process control software**

Provides automated control of the process, including heating temperature, wire tension, and the speed of movement for optimal operation

## **1.4. Dieless drawing parameters :**

### **1.4.1 Wire velocities $V_0$ , $V_1$ :**

## **Chapter II: Manufacturing processes of thin metallic wires**

The condition is : (  $V_1 > V_0$  )

### **1.4.2 Longitudinal strain:**

The engineering formula assuming constant volume was used to describe the wire longitudinal strain in a single pass:

$$\varepsilon_{pass} = 1 - \frac{V_0}{V_1}$$

### **1.4.3. Number of MPDD passes**

### **1.4.4. Final diameter of wire before fracture ( $d_{final}$ )**

### **1.4.5. The temperature in the heating device**

### **1.4.6. Final longitudinal strain :**

Calculated using equation value  $d_{final}$  and Equation:

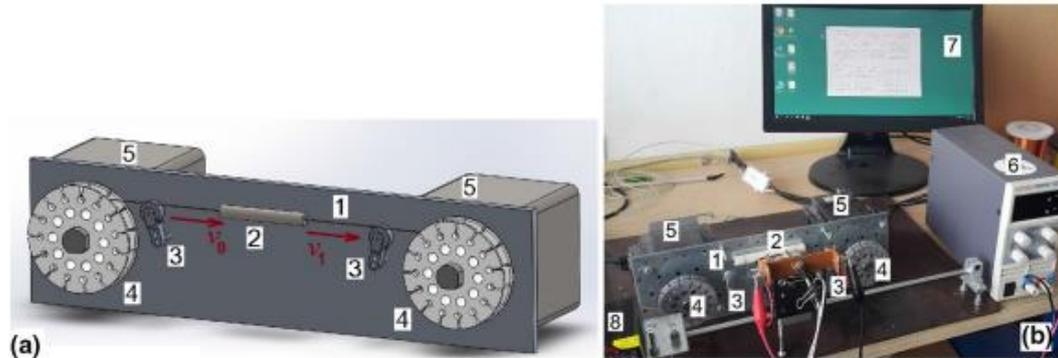
$$\varepsilon_{final} = -2 \ln\left(\frac{d_{final}}{d_0}\right)$$

## **1.5. Case study on dieless drawing and multi-pass dieless drawing of thin brass wires**

This case study is based on the research conducted by Milenin et al. [3]. The primary objective of their experiment was to investigate the workability and surface roughness of thin CuZn37 brass wires with diameters ranging from 0.14 to 0.18 mm produced through dieless drawing (DD) and multi-pass dieless drawing (MPDD) technologies. They aimed to determine how these processes could improve the workability and surface quality of the wires while identifying optimal operational parameters.

## Chapter II: Manufacturing processes of thin metallic wires

For their investigation, they used Commercial cold-drawn CuZn37 brass wire with an initial diameter of 0.2 mm. The experiment was conducted using a specialized dieless drawing setup (Fig.II.8).



**Figure II.8:** Scheme a and general view of the setup b: 1-wire 2 electrical heating device: 3 support rollers; 4 bobbines;5-engines ;6-power supply for engines; 7-electrical heating device, 8-a computer with software for the process control; 8-alternative laser heating device (in the waiting position) [3].

The operating mode of this machine and its main components are as follows:

**Wire Feed and Support:** The brass wire was fed into the system and guided by support rollers to maintain a straight path.

**Heating Device:** The wire passed through an electrical mini-furnace with a diameter of 0.5 mm and a length of 20 mm, where it was heated to high temperatures. The setup allowed for alternative heating methods, such as laser or induction heating.

**Bobbins and Motors:** Bobbins controlled by motors rotated at different speeds to stretch the wire. The initial velocity ( $V_0$ ) and the pulling velocity ( $V_1$ ) determined the amount of strain applied.

**Process Control:** A computer-controlled system monitored and adjusted the bobbin speeds to ensure stable drawing conditions.

### **Operating principle:**

**Initial Heating:** As the wire enters the heating zone, it is heated locally, reducing its flow stress and making it more malleable.

## **Chapter II: Manufacturing processes of thin metallic wires**

**Stretching:** One end of the wire is fixed to a rotating bobbin while the other end is pulled at a controlled velocity. This stretching action causes the wire to undergo deformation.

**Strain Application:** In the DD process, the velocity  $V_1$  is continuously increased until the wire fractures, allowing researchers to measure the maximum strain achievable.

**Multi-Pass Process:** For MPDD, the same setup is used, but the process is repeated multiple times. After each pass, the bobbin direction is reversed, and smaller strain increments are applied to stabilize the deformation and improve workability.

After the drawing process, the wire is collected on an output bobbin for analysis.

This setup ensured precise control over the heating, deformation, and collection stages, providing reliable data for the study.

To study the wires reduced using this technique, they characterized their samples using a metallographic microscope and a scanning electron microscope for microstructure analysis. An optical profiler for surface roughness measurements, and X ray diffractometer for crystallographic texture analysis have been used.[3].

The study provided detailed experimental and simulation data for both processes [3]:

Experi- ment no.	$V_0$ , mm/s	$V_1$ , mm/s	$\epsilon_{pass}$	$n$	$d_{final}$ , mm	$t_d$ , °C	$t_{FEM}$ , °C	$\epsilon_{final}$	$E$
1	12.16	14.7	0.173	1	0.184	300	262	0.167	–
2	12.16	18.1	0.328	1	0.170	400	347	0.325	–
3	12.16	16.7	0.272	1	0.175	500	437	0.267	–
4	12.16	18.2	0.332	1	0.170	600	531	0.325	–
5	12.16	13.38	0.091	8	0.137	400	351	0.757	2.33
6	12.16	12.77	0.048	16	0.136	400	353	0.771	2.37

In Table 1,  $V_0$ ,  $V_1$  wire velocities during DD and MPDD,  $\epsilon_{pass}$  longitudinal strain, calculated by Eq. (4),  $n$  number of MPDD passes,  $d_{final}$  final diameter of wire before fracture,  $t_d$  the temperature in the heating device, measured by thermocouple,  $t_{FEM}$  maximal temperature of wire in the deformation zone, calculated by FE model,  $\epsilon_{final}$  final longitudinal strain, calculated using value  $d_{final}$  and equation  $\epsilon_{final} = -2\ln(d_{final}/d_0)$ ;  $E$ —process efficiency calculated using equation  $E = \epsilon_{final\_MPDD} / \epsilon_{final\_DD}$

The man key findings were :

**Workability:** MPDD achieved over twice the workability of the conventional DD process. For example, the longitudinal strain increased from 0.325 in DD to 0.757 and 0.771 in MPDD for eight and sixteen passes, respectively.

## **Chapter II: Manufacturing processes of thin metallic wires**

**Surface Roughness:** The roughness of the wires processed through MPDD was significantly lower than that of DD wires despite similar elongation levels.

**Temperature Influence:** The study found no clear relationship between temperature and workability within the technological temperature window (300°C to 600°C). However, higher temperatures increased surface roughness.

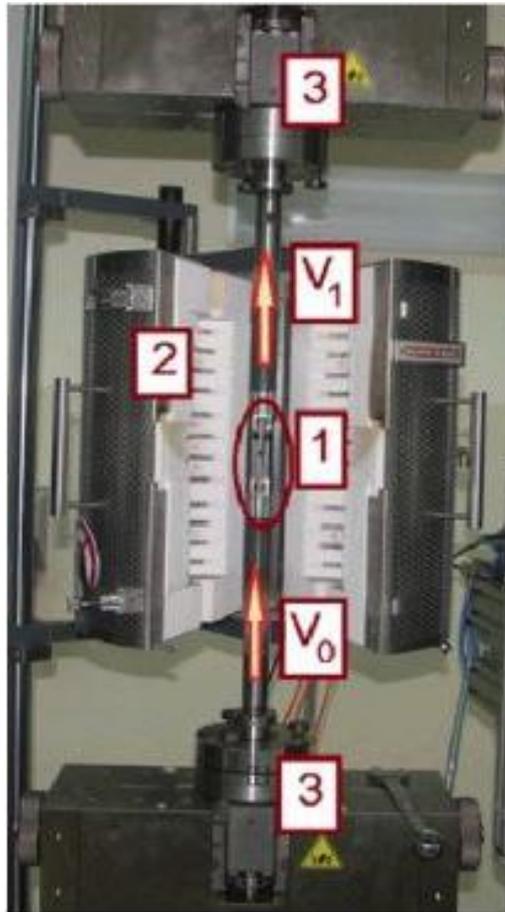
**Optimal Parameters:** The best results for MPDD were achieved at a heating temperature of 400°C, with deformation increments per pass ranging from 0.048 to 0.09.

### **Conclusion**

They concluded that this study demonstrated that multi-pass dieless drawing (MPDD) significantly improves the workability and surface quality of thin CuZn37 brass wires compared to conventional dieless drawing (DD). By applying smaller, controlled strain increments in multiple passes, MPDD not only enhanced the maximum longitudinal strain but also reduced surface roughness, making it a more efficient and reliable process for thin wire manufacturing [3].

## **2. Dieless drawing by tensile machine :**

This second type of fabrication of thin wires is based on tensile machine. Dieless drawing by a tensile machine (**Fig II.9**) is the same concept as the process previously examined, but it differs in that the material deformation is driven purely by axial tension, allowing for continuous and localized cross-sectional reduction without the need for external constraints like dies or rollers. This process leverages plastic instability to achieve controlled elongation, with the final wire dimensions governed by strain rate sensitivity, material ductility, and process parameters such as applied force and temperature[4].



**Figure II.9:** Scheme of the experiment of stretching of sample by tensile machine 1- sample; 2- furnace in the opening state; 3- deformation device Zwick 250 [4].

## **2.1. Process Overview:**

**Wire Clamping:** A thin metallic wire is clamped at both ends using the grips of a tensile testing machine.

**Axial Tension Application:** The machine gradually applies a tensile load, elongating the wire while reducing its cross-section.

**Controlled Deformation:** The process parameters, such as strain rate, initial wire diameter, and applied force, are controlled to ensure uniform deformation.

**Temperature Influence :** applying heating to facilitate deformation and reduce flow stress, allowing for higher reductions in cross-section.

## **Chapter II: Manufacturing processes of thin metallic wires**

**Final Wire Formation:** After reaching the desired reduction, the wire is released and analyzed for mechanical properties and dimensional accuracy.

### **2.2 Key Parameters Affecting the Process:**

**Strain Rate:** The speed at which the tensile force is applied affects the deformation behavior.

**Material Properties:** The wire's initial strength, ductility, and work-hardening characteristics determine how much reduction can be achieved before failure.

**Temperature:** Increasing temperature can improve ductility and reduce the required force for deformation.

**Surface Condition:** Friction between the grips and the wire must be minimized to avoid premature failure.

### **2.3 Advantages of dieless drawing by tensile machine :**

The main advantages are :

- Eliminates the need for expensive dies, reducing tooling costs.
- Can be used for materials with high strain hardening, where traditional drawing is difficult.
- Allows for continuous monitoring and control of the deformation process.
- Potential for customized wire shapes without specific dies.

### **2.4 Challenges and Limitations :**

- Limited to specific strain ranges before necking and fracture occur.
- Requires precise control of force and strain rate to prevent wire breakage. Not as efficient as conventional drawing for large-scale production.

Table II.1. summarize some previous research works devoted to the study of section reduction of some metals by the dieless drawing process. Owever Table 2 is related to copper and copper alloy.

## **Chapter II: Manufacturing processes of thin metallic wires**

Table II.1 . DLD process applied for some metallic materials.

Researchers	DLD Type	Used Material	Original Diameter (mm)	Maximum Reduction Ratio (%)	Maximum Feeding Velocity (mm/s)	Maximum Drawing Velocity (mm/s)
Present Work	Continuous	Stainless Steel SUS304 Wire	1.6	38	2.9	5.0
Present Work	Continuous	Stainless Steel SUS304 Wire	2.0	41	3.2	5.0
Carolan and Tiernan (2009)	Non-Continuous	AISI-O1 Steel Rod	5.0	35.5	0.233	0.083
Tiernan et al (2011)	Non-Continuous	AISI-O1 Steel Rod	5.0	36	1.2	0.417
Hwang and Kuo (2013)	Non-Continuous	SUS304 Tube	6.35x1	40	1.2	0.8
Furushima et al (2014)	Continuous	SUS304 Tube	0.5x0.13	40	1.0	1.67
Hwang et al (2015)	Non-Continuous	SUS304 Tube	6.35x1	50	0.4	0.4
Milenin et al (2016)	Continuous	MgCa0.8 Tube	5x1	60	0.1	0.25
Furushima and Manabe (2016)	Continuous	AZ31-Magnesium Tube	5x1.5	60	0.5	1.25
Milenin et al (2017)	Continuous	AZ31 Tube	5x1	37.5	0.5	0.8
Furushima and Manabe (2017)	Continuous	3Y-TZP Ceramic Tube	6x1	84	0.01	0.0625
Furushima and Manabe (2018)	Continuous	AZ31-Mg Tube	5x1.5	58.1	0.5	1.2
Li et al (2018)	Continuous-Semi-DLD	Pure Titanium Wire	3	34	0.25	0.38
Hwang et al (2018)	Non-Continuous	Titanium Wire	1	30	0.7	0.3
Li et al (2019)	Continuous-Semi-DLD	Ti-6Al-4V Wire	3	34	0.25	0.38

## **Chapter II: Manufacturing processes of thin metallic wires**

Table II.2 . DLD process applied for copper and copper alloy

<b>Material</b>	<b>Initial Ø (mm)</b>	<b>Final Ø (mm)</b>	<b>Temperature (°C)</b>	<b>Strain (s<sup>-1</sup>)</b>	<b>Tensile Force (N)</b>	<b>Key Findings</b>	<b>Source</b>
Copper	0.1	0.09	150- 300	0.05-0.2	1.27	-Surface roughness occurs above 300°C	[2]
Brass (CuZn37 Alloy)	0.5	0.38	400-750	0.55		- Lower forces reduce surface defects	

### **3. Partial conclusion and outlook :**

This chapter presented advanced manufacturing methods specific to thin metallic wires, with a focus on dieless drawing. Through a detailed case study, the practical implementation and material response were highlighted. The use of tensile machines for dieless drawing was also discussed, demonstrating its potential for precise, controlled deformation in fine wire applications.

### **References**

- [1] H. Sekiguchi, K. Kobatake, and K. Osakada, "A Fundamental Study on Dieless Drawing," in Proceedings of the Fifteenth International Machine Tool Design and Research Conference, S. A. Tobias and F. Koenigsberger, Eds. London: Palgrave, 1975. [Online]. Available: [https://doi.org/10.1007/978-1-349-01986-1\\_63](https://doi.org/10.1007/978-1-349-01986-1_63)
- [2] Springer Nature, "Illustration from continuous casting study," [Online]. Available: [https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-78424-9\\_5/MediaObjects/511818\\_1\\_En\\_5\\_Fig2\\_HTML.png](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-78424-9_5/MediaObjects/511818_1_En_5_Fig2_HTML.png). [Accessed: May 7, 2025].
- [3] A. Milenin, M. Wróbel, and P. Kustra, "Investigation of the workability and surface roughness of thin brass wires in various dieless drawing technologies," Archives of Civil and Mechanical Engineering, vol. 22, no. 10, 2022. [Online]. Available: <https://doi.org/10.1007/s43452-021-00331-2>
- [4] A. Milenin, T. Furushima, P. Du et al., "Improving the workability of materials during the dieless drawing processes by multi-pass incremental deformation," Archives of Civil and Mechanical Engineering, vol. 20, no. 86, 2020. [Online]. Available: <https://doi.org/10.1007/s43452-020-00092-4>
- [5] CN Suntech, "Block capstan wire drawing machine roller tower wheel aluminum pulley copper," [Online]. Available: [https://www.cnsuntech.com/photo/pc144779321-block\\_capstan\\_wire\\_drawing\\_machine\\_roller\\_tower\\_wheel\\_aluminium\\_pulley\\_copper.jpg](https://www.cnsuntech.com/photo/pc144779321-block_capstan_wire_drawing_machine_roller_tower_wheel_aluminium_pulley_copper.jpg). [Accessed: May 7, 2025].
- [6] Copper Wire Drawing, "Copper wire drawing application," [Online]. Available: <https://149376038.v2.pressablecdn.com/wp-content/uploads/copper-wire-drawing-application.jpg>. [Accessed: May 7, 2025].
- [7] TradeIndia, "Enameled aluminum winding wire," [Online]. Available: <https://tiimg.tistatic.com/fp/1/007/520/enameled-aluminum-winding-wire-for-electrical-with-0-4ms-cm-bobbins-conductivity-166.jpg>. [Accessed: May 7, 2025].
- [8] Moog Inc., "HD servo motor family," [Online]. Available: [https://www.moog.com/content/dam/sites/moog/images/Products/motors-servomotors/101-55-2\\_HD-servo-motor-family-white-bkgrd.jpg](https://www.moog.com/content/dam/sites/moog/images/Products/motors-servomotors/101-55-2_HD-servo-motor-family-white-bkgrd.jpg). [Accessed: May 7, 2025].
- [9] Amazon, "Product image," [Online]. Available: <https://m.media-amazon.com/images/I/71DeY-4msYL.SS700.jpg>. [Accessed: May 7, 2025].

**Chapter III:  
Fabrication of metallic thin  
wire machine and  
experimental procedure**

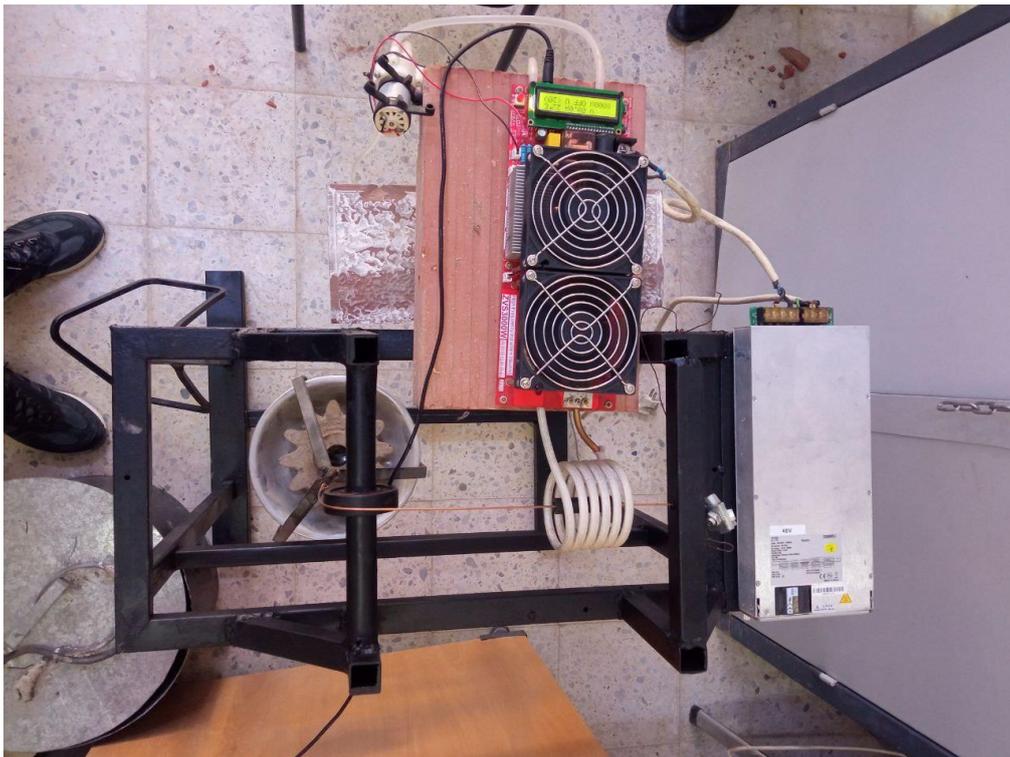
## **Chapter III: Fabrication of metallic thin wire machine and experimental procedure**

### **Introduction:**

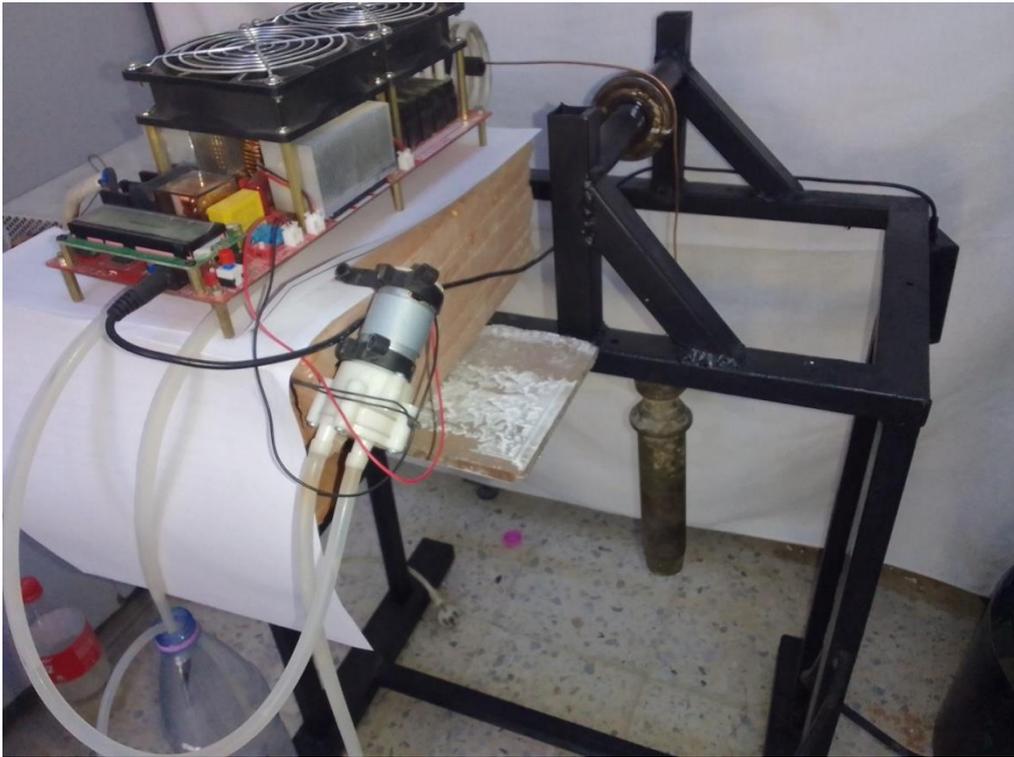
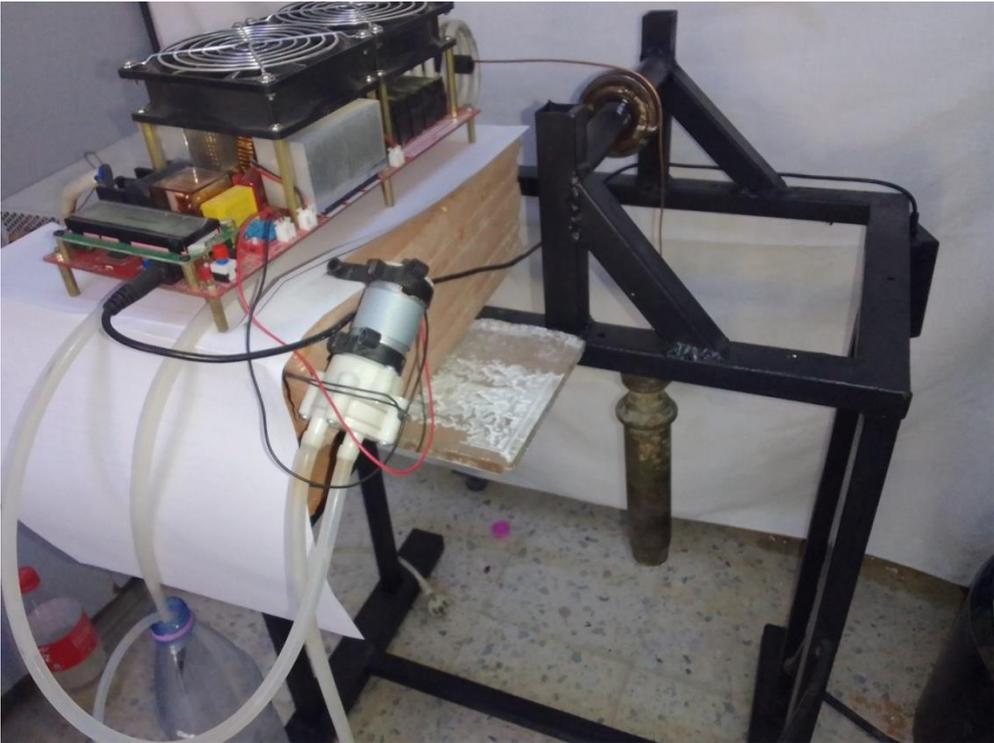
This chapter is devoted to the fabrication of metallic thin wire machine and its main functions. The conditions for reducing copper wires have been presented. The characterization methods of reduced wires by dieless process are also presented.

### **1. Fabrication of metallic thin wire equipment setup :**

A general overview of the metallic thin wire machine following the final assembly of all of its components is presented in figure III.1.



**Chapter III: Fabrication of metallic thin wire machine and experimental procedure**

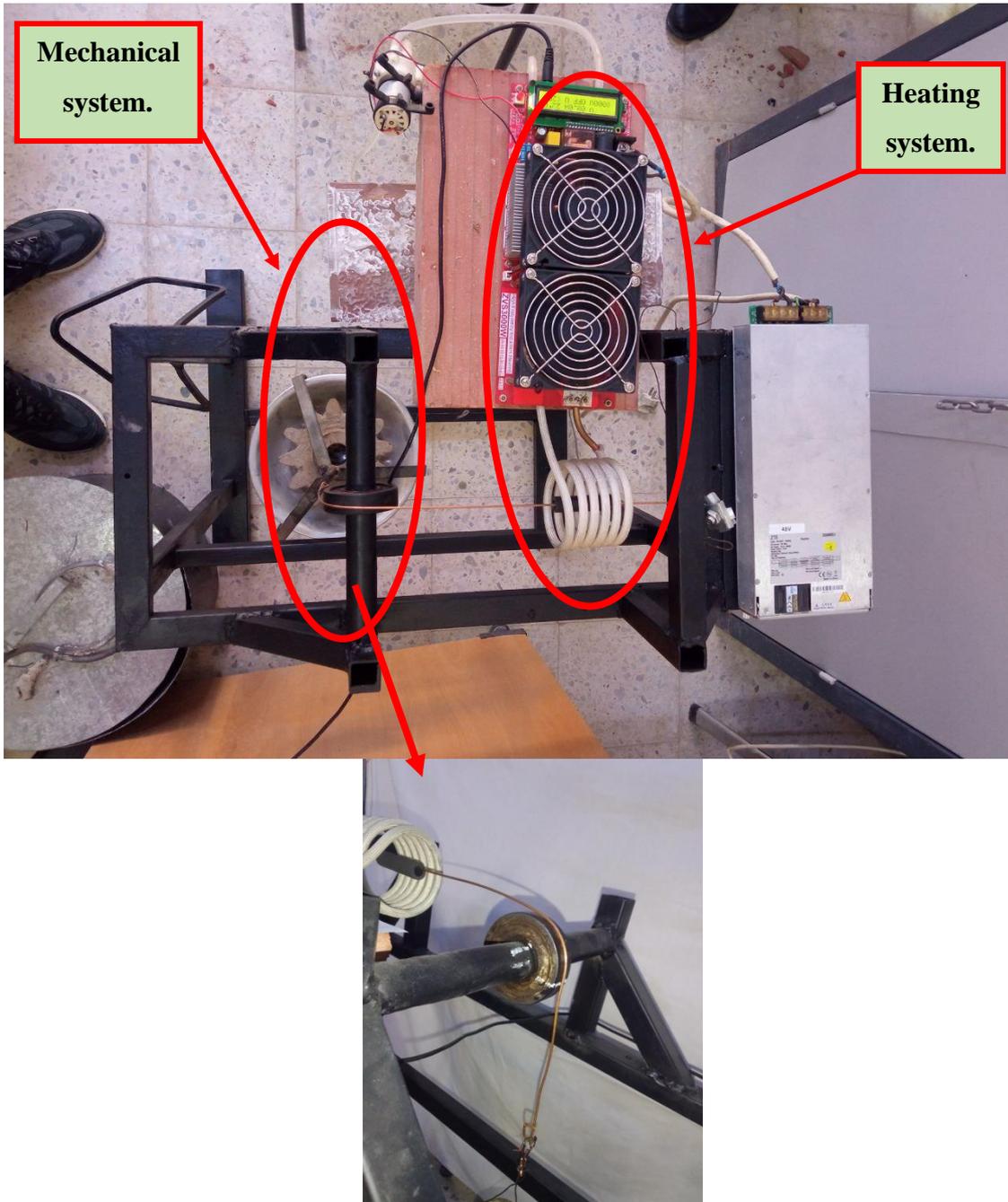


**Figure III.1.**Machine of fabrication of metallic thin wires

**2. The parts of dieless drawing process:**

This machine is made up of two parts, as shown in figure III.2:

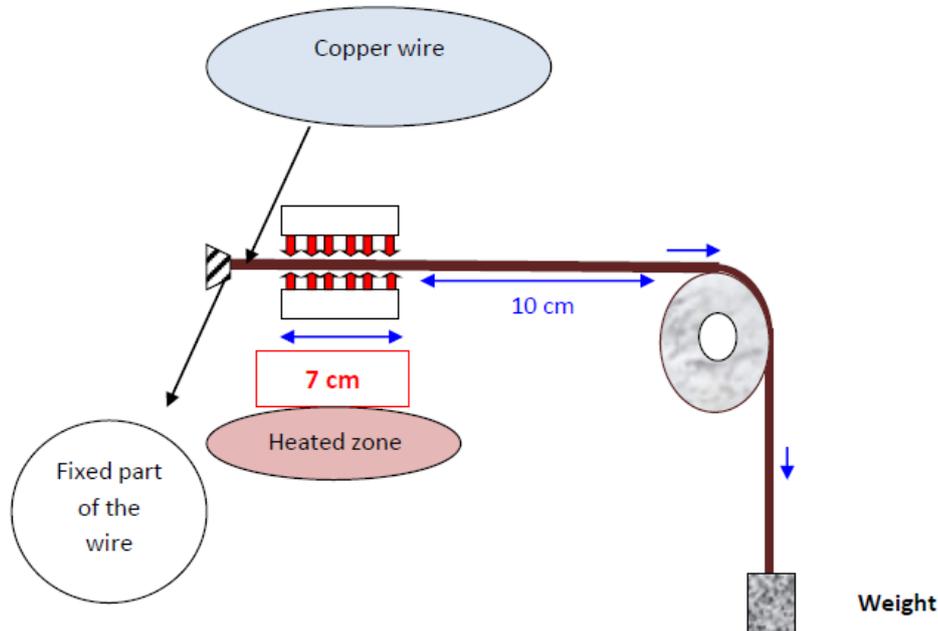
- ✓ Heating system.
- ✓ Mechanical system (pulling).



**Figure III.2.**Machine of fabrication of metallic thin wires showing the the two main parts.

## Chapter III: Fabrication of metallic thin wire machine and experimental procedure

Figure III.3 shows the simplified diagram of this machine.



**Figure III.3.**Schematic representation of fine metal wire making machine

### **2.1. Heating system:**

This system contains an induction furnace, which is divided into two parts, the induction heating device and the graphite crucible.

#### **2.1.1. The induction heating device:**

Induction heating is the process of heating electrically conductive materials, namely metals or semi-conductors, by electromagnetic induction, through heat transfer passing through an inductor that creates an electromagnetic field within the coil to heat up and possibly melt steel, copper, brass, graphite, gold, silver, aluminum, or carbide.

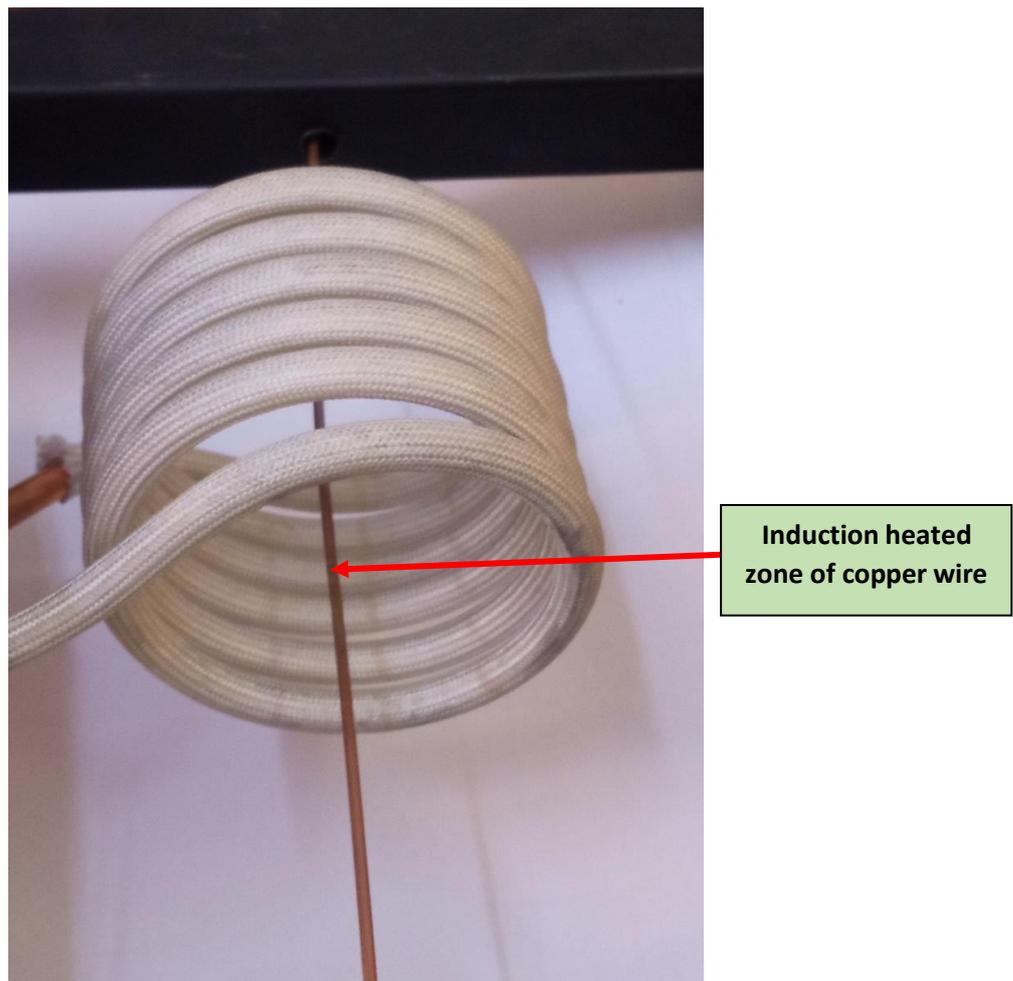
An induction heater consists of an electromagnet and an electronic oscillator that passes a high-frequency alternating current (AC) through the electromagnet. The rapidly alternating magnetic field penetrates the object, generating electric currents inside the conductor called eddy currents. The figure III.4 shows the induction heating device used in heating system.

### Chapter III: Fabrication of metallic thin wire machine and experimental procedure



**Figure III.4:** The induction heating device with its power supply.

The figure III.5 shows the induction heated zone of copper wire.



**Figure III.5:** Copper under induction heating

### **2.3. Mechanical System (Tensioning):**

The tensioning system in this setup uses weights instead of motors to apply a pulling force on the copper wire. After passing over a guide roller, the wire is attached to a container filled with metal weights. These weights pull the wire downward, creating constant tension.

To keep the movement straight and stable.

### **3. Dieless drawing's manner of operation:**

The dieless drawing machine operates in the following manner:

**1<sup>st</sup> step:** we fix the metal wire from the input then we pass it through the induction heater and passing it over the guide roller and in the output we attached it with the container filled with weights

**2<sup>nd</sup> step:** we turn on the induction heating device on. A cycle is defined as the wire passing through heating and cooling.

In this study, several copper wires of different diameters were subjected to diameter reduction by the machine developed in the laboratory. Table III.1 summarizes the conditions used for reducing the diameter of the copper wire.

**Table III.1** Conditions used and the results obtained after diameter reduction.

<b>Number of sample</b>	<b>Initial diameter (mm)</b>	<b>Loadused (kg)</b>	<b>Flow stress (MPa)</b>	<b>HeatingTime ( min )</b>
1	1.80	24	112.78	7
2	1.80	24	112.78	7
3	1.80	16	76.16	7
4	1.80	16	78.1	15
5	0.85	8	177.6	3
6	0.85	4	101.9	15
7	0.57	4	199.9	3
8	0.57	1.05	59.3	15
9	0.47	0.850	63.1	5

## **4. Techniques of characterization**

### **4.1. Metallographic preparation**

The material used in the present study was commercially pure copper with an initial diameter of 1.80 mm (FigIII.5). Samples were cut from wires that underwent diameter reduction as shown in Figure III.6. Then, they were coated to facilitate their polishing as shown in Figure III.7.



**Figure III.6.** Sample for metallographic preparation

Figure III.5. Samples of copper wire that underwent diameter reduction.



**Figure III.7.** Coated sample of copper wires.

### **Chapter III: Fabrication of metallic thin wire machine and experimental procedure**

An abrasive paper (120 / 180 / 240 / 600 / 800 / 1200 / 2500) was used to polish the samples of copper and finished by the polishing cloth with diamond past (Fig.III.8). Polishing machine is used to prepare the surface of the samples ( Fig.9).



**Figure III.8.** Abrasive paper and polishing cloth.

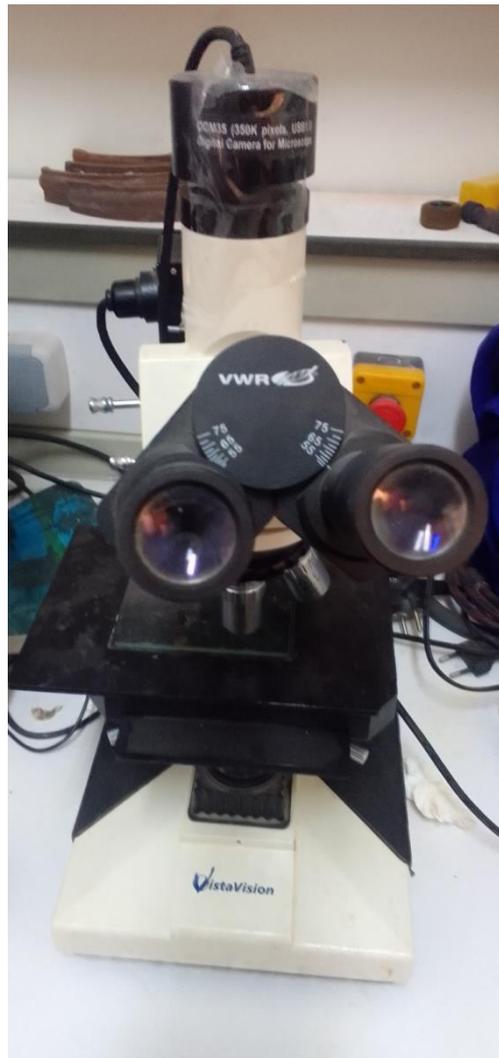


**Figure III.9.** Polishing machine

The polished samples were etched with nitric acid  $\text{HNO}_3$  solution for 1 second then rinsed with water and finally dried.

#### **4.2. Optical microscope :**

An optical microscope (Vistavision) was used to examine the microstructure of the wire samples after polishing and etching (Fig.III.10).



**Figure III.10.** Optical microscope.

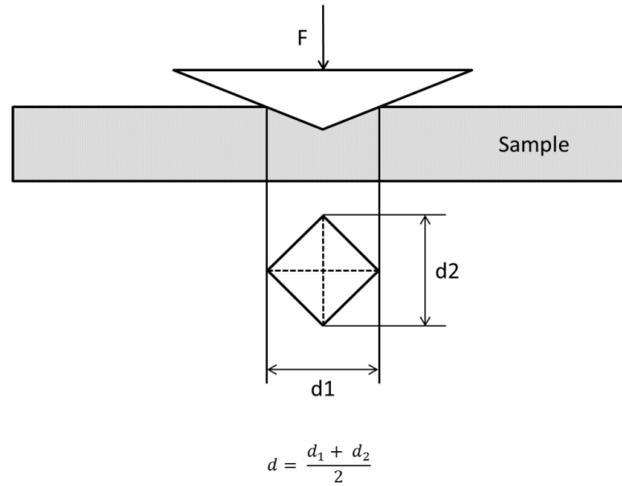
### **4.3. Hardness measurements**

The equation for determining the Vickers hardness value is given by:

$$\mathbf{HV=0.1891[F(N)/d^2(mm^2)]}$$

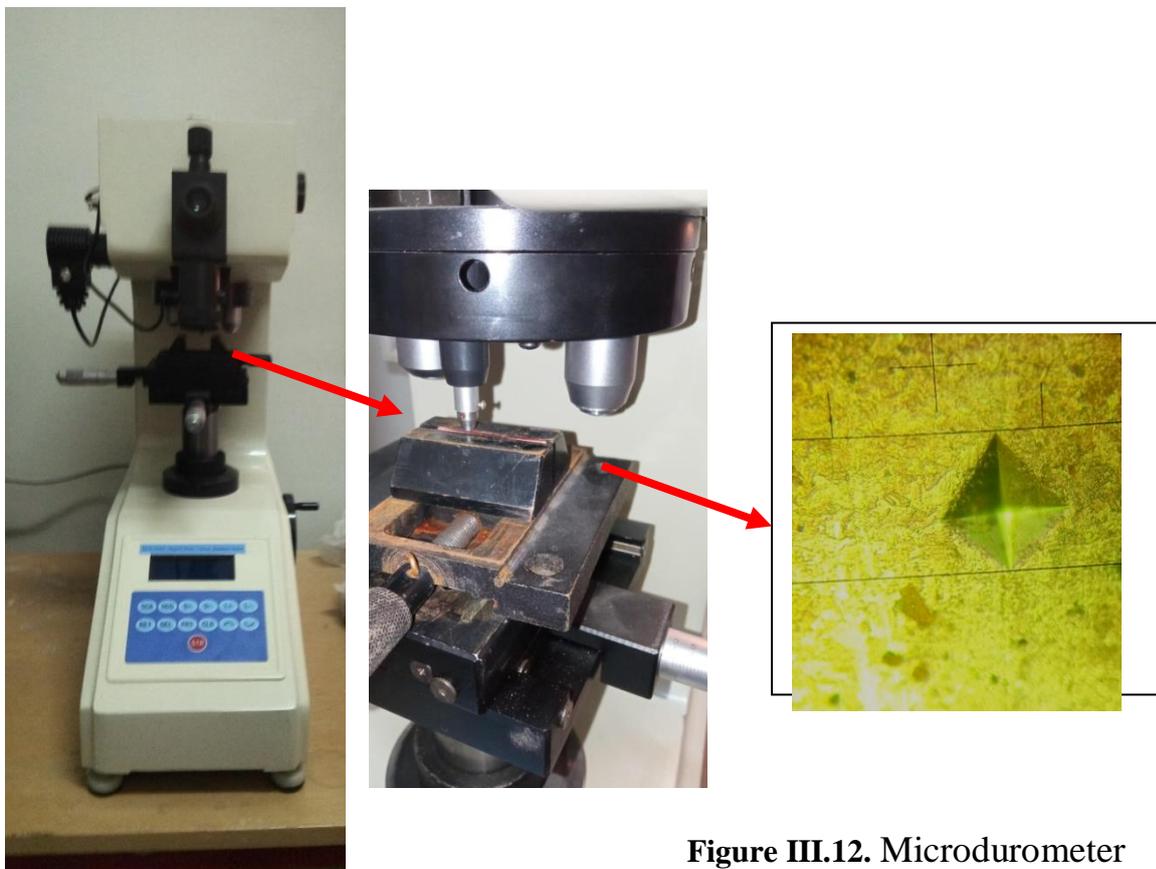
Where  $d$  represents the average diagonal distance ( $d_1$  and  $d_2$ ) of the indentation mark and  $F$  the force applied to the indenter (Fig.III.11).

**Chapter III: Fabrication of metallic thin wire machine and experimental procedure**



**Figure III.11.** Hardest Vickers test

Vickers microhardness measurements were carried out along the longitudinal section of the copper wire using a type microdurometer and under a load of 200 g (Fig.III.12).



**Figure III.12.** Microdurometer

Vickers.

# **Chapter IV:**

# **Results and Discussion**

## **Chapter IV. Results and Discussion**

### **Introduction**

This chapter is dedicated to the obtained results and their discussions. The macrographic results of the wires that have undergone the reduction of their sections have been presented and explained. Then, the longitudinal microstructures of the wires reduced by dieless process will be presented and discussed in depth to highlight the microstructural evolution. Finally, the Vickers microhardness measurements along the longitudinal section of the reduced wires will also be shown and discussed to evaluate the mechanical properties of the reduced wires compared to the unreduced wires.

### **IV.1. Effect of dieless process parameters on copper wire reduction**

In this part of the manuscript, the effect of the dieless process parameters on the reduction of copper wires is presented. Table IV.1 gathers all the data after the different operations of reduction of copper wires by dieless process. It can be seen that the section reduction ratio is high when the applied load is low and also the annealing time is long.

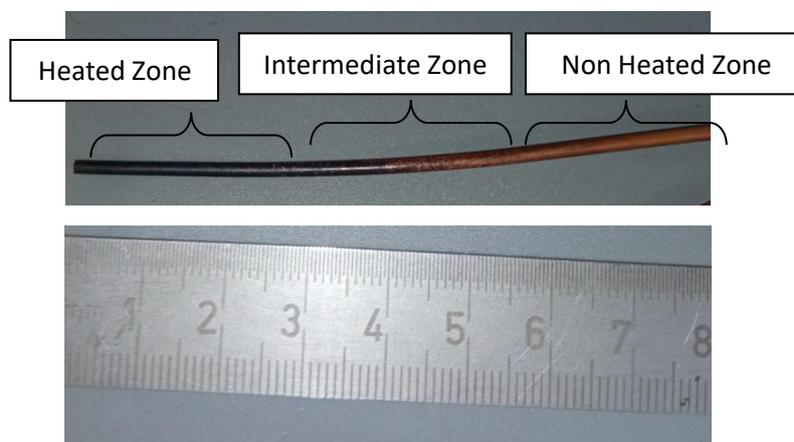
## Chapter IV Results and Discussion

**Tableau IV.1.** Effect of dieless process parameters on copper wire reduction

Number of sample	Initial diameter (mm)	Load used (kg)	Flow stress (MPa)	Heating time ( min )	Number of cycles	Final diameter (mm)	section reduction ratio (%)
1	1.80	24	112.78	7	5	1.63	9.44
2	1.80	24	112.78	7	11	1.63	9.44
3	1.80	16	76.16	7	48	1.62	10.00
4	1.80	16	78.1	15	34	1.60	11.11
5	0.85	8	177.6	3	1	0.75	11.76
6	0.85	4	101.9	15	1	0.70	17.64
7	0.57	4	199.9	3	1	0.50	7.01
8	0.57	1.05	59.3	15	2	0.47	17.54
9	0.47	0.850	63.1	5	8	0.41	12.76

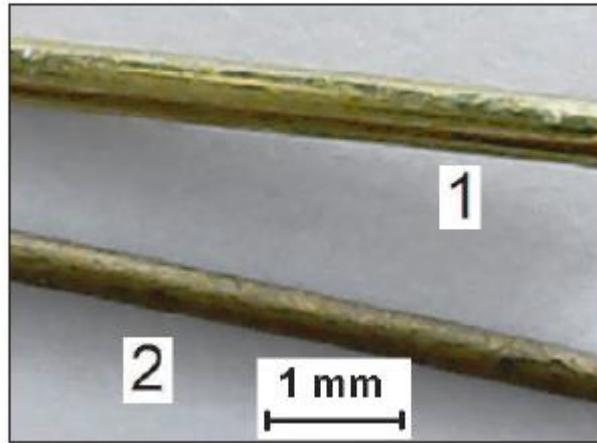
### **IV.2. macrographic view of a copper wire after reduction of its cross-section by a dieless process**

Figure VI.1 shows the macrographic view of a copper wire after reduction of its cross-section by a dieless process. It can be seen that the cross-section of the wire is further reduced in the induction heating zone. Figure VI.1 shows an example of results obtained by Milenin et al.[1].



**Figure VI.1.** Macrographic view of a copper wire after reduction of its cross-section by a dieless process.

## Chapter IV Results and Discussion



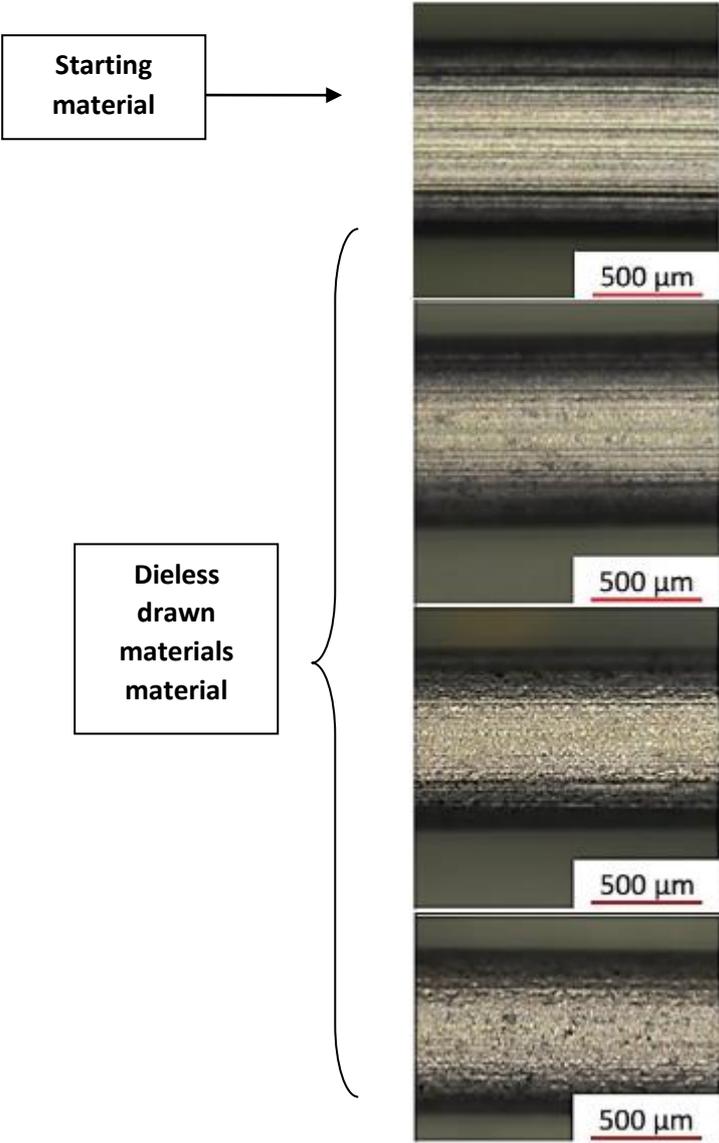
**Figure VI.2.** Wires made of the CuZn37 alloy before (1) and after (2) dieless drawing [1].

In addition, according to previous work, the roughness of wires that have undergone a dieless drawing process is generally affected. In our case, this phenomenon was not observed, as shown in Figure IV.3. Some authors have reported this phenomenon, such as the work of Braatz et al.[2], who found that the surfaces of magnesium (Mg)-based drawn wires are slightly rougher than the starting material as it shown in Figure IV.4. Another phenomenon observed in wire that has undergone reduction by dieless drawing process is the oxidation of its surface, which appears black. This same phenomenon was observed by et Hwang al. [3] when studying steel wires that were drawn by dieless drawing process. They found that the wire surface becomes darker and the oxidation layer becomes thicker. The results indicate that even though the wire was drawn in argon gas, slight oxidation still occurred. Concerning these two phenomena, the roughness and the oxidation of the surface of copper, it has been found that the surface roughness of the copper wire after dieless drawing increases significantly at a deformation temperature above 300°C. The total roughness is associated both with the formation of oxides and the strain induced roughness [4].





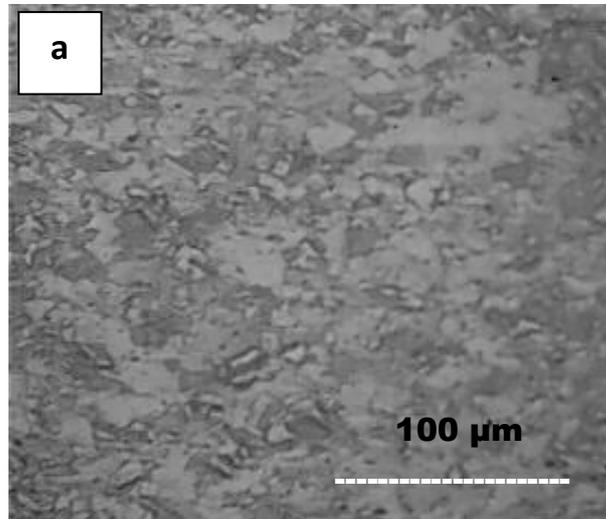
**Figure IV.3.** Surface of the copper wire (a) before and (b) after reduction of its section by dieless drawing process.

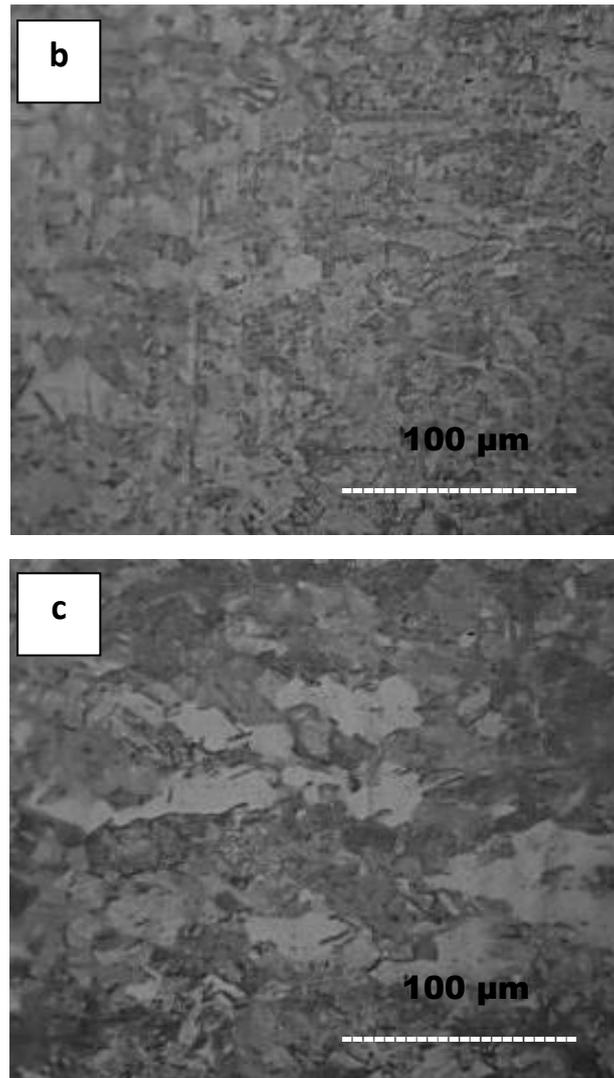


**Figure IV.4.** Laser scanning microscope analysis of starting material and dieless drawn Mg-alloy [2].

### **IV. Microstructure observation of reduced copper wire.**

Micrographic observation along the copper wire was necessary to understand the metallurgical phenomena that developed within the wire during the dieless process. Micrographic observation along the copper wire was necessary to understand the metallurgical phenomena that developed within the wire during the process. Microstructures of the copper wire were performed on the unaffected zone, the intermediate zone and the heat-affected zone. The microstructure in the unaffected zone is characterized by fine grains formed by several twins (Fig.IV.5a). The grain size is about 10  $\mu\text{m}$ . For the intermediate zone, there is a slight change in the microstructure, as there is the beginning of formation of slightly larger grains as shown by an arrow in Figure IV.5b. Therefore, this is an initiation of the growth reaction. For the heat-affected zone during the process (Fig.IV.5c), it is observed that the grains undergo more growth but are oriented in the direction of the copper wire drawing. It can be considered as exaggerated growth or a secondary recrystallization. A recrystallization phenomenon was observed by Braatz et al.[2] during the reduction of the section of magnesium alloy wires but for a critical reduction by dieless process.

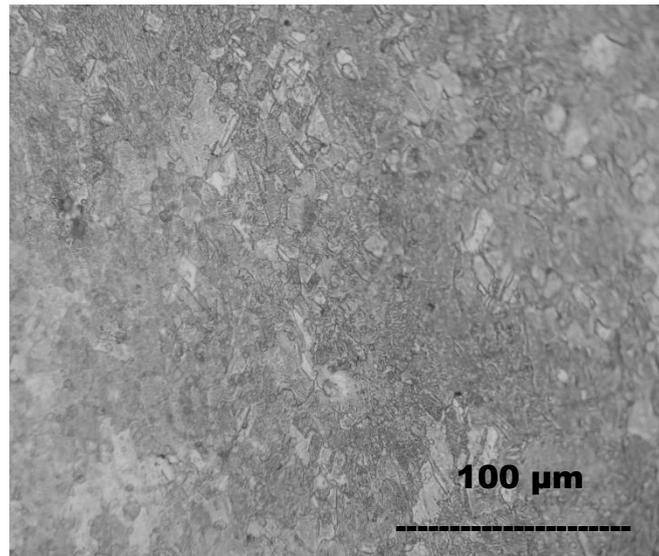




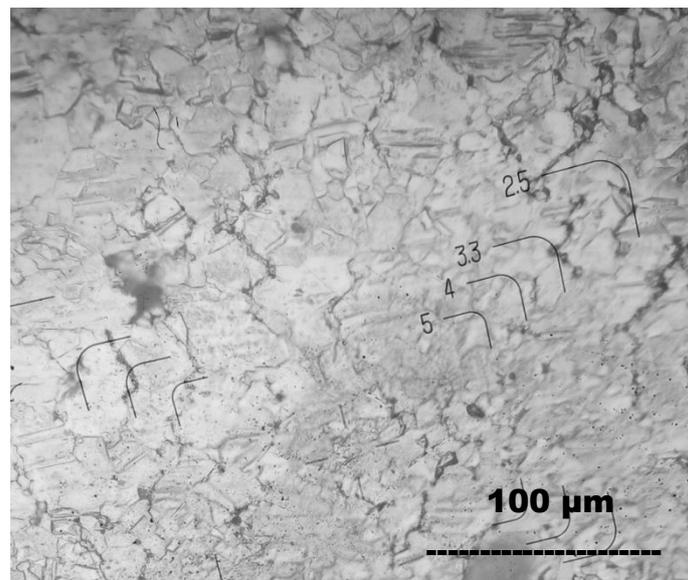
**Figure IV.5.** Microstructures of copper wire at ( a ) : non affected zone, ( b ) : the intermediate zone and ( c ) : heat affected zone.

### **IV.3. Effect of dieless process parameters on the microstructural evolution of copper wire**

Figure VI.6 and 7 show the effect of dieless process parameters on the microstructural evolution of copper wire. It is clear that changing the reduction parameter by dieless process affects the final microstructure of the reduced wire as shown in Figure IV.3.



**Figure VI.6.**Macrographic view of a copper wire after reduction of its cross-section by a dieless process (  $d_0 = 1.80$  mm,  $d_f = 1.60$ ; load used= 16kg ,Number of cycles = 34,,Heating time = 15min)



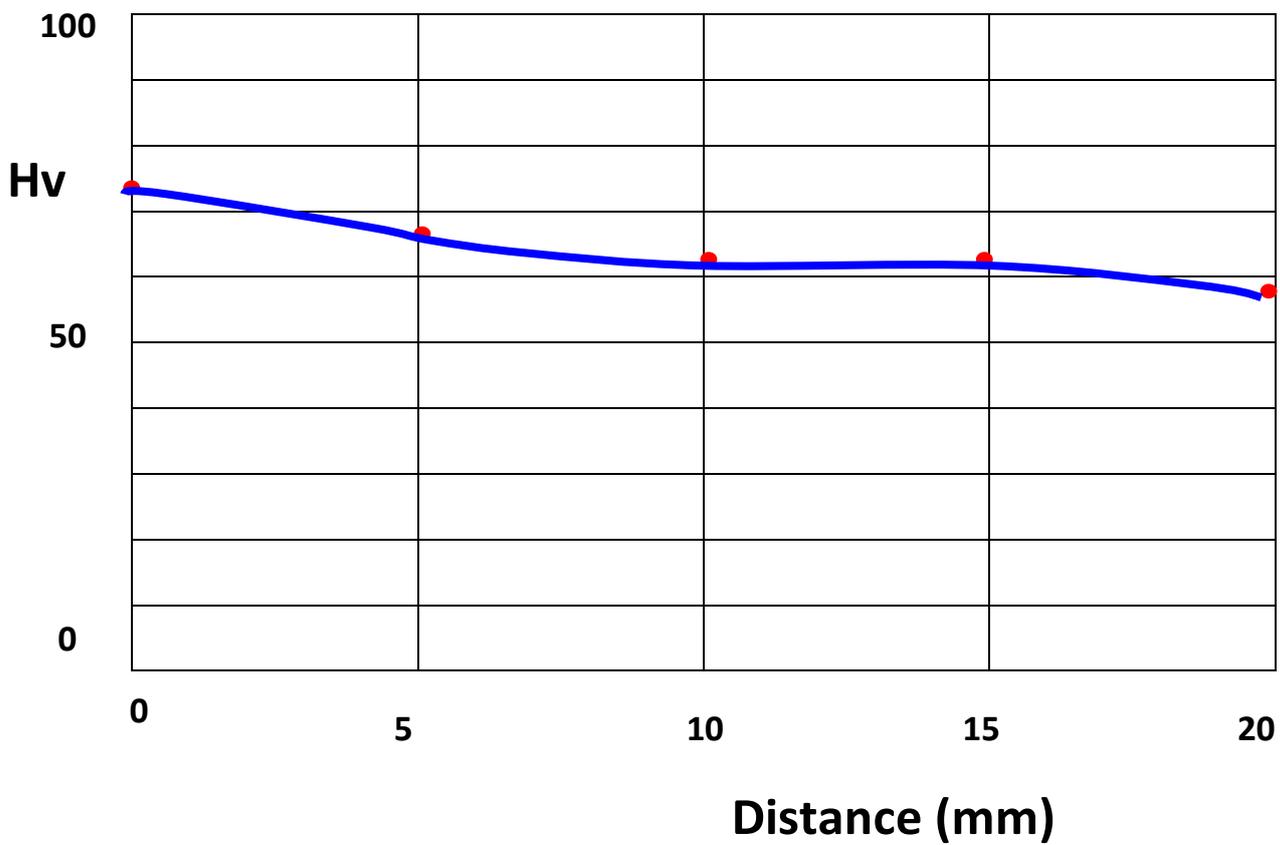
**Figure VI.7.**Macrographic view of a copper wire after reduction of its cross-section by a dieless process (  $d_0 = 1.80$  mm,  $d_f = 1.63$ ; load used = 24kg, Number of cycles = 11, Heating time = 7 min).

#### **IV.4. Effect of dieless process parameters on the hardness of copper wire**

Figure VI.8 shows the variation of Vickers hardness along the copper wire which has undergone a reduction of its section by dieless process. It can be seen that the hardness is high in the heat-affected zone and is equal to 73.01 Hv then, it gradually decreases towards the thermally affected zone to reach the value of 57.80 Hv. That is to say there was a softening phenomenon in the thermally affected zone. This result is consistent with the microstructural

## Chapter IV Results and Discussion

observations because the thermally affected zone underwent a grain growth reaction which decreased the hardness of the wire.



**Figure VI.8.** shows the variation of Vickers hardness along the copper wire which has undergone a reduction of its section by dieless process.

## **Chapter IV Results and Discussion**

### **References :**

- [1] A. Milenin, P. Kustra, M. Wróbel, V. Pidvystskyy and M. Packo, Dieless drawing process for elongation of thin copper and copper alloy wire, *Journal of Metallic Materials*, 2019, 71(3), p.12-13.
- [2] M. Braatz, J. Bohlen and N. Ben Khalifa, Process Stability and Reproducibility of the Dieless Drawing Process for AZ31 Magnesium Wires, *Key Engineering Materials*, 2022, Vol. 926, pp 389-400.
- [3] Hwang, Y.-M.; Liu, H.-H. Formability Analysis and Oxidation Layer Effects in Dieless Drawing of Stainless Steel Wires. *Metals* **2019**, *9*, 828.
- [4]. Milenin, A., Byrska-Wójcik, D., & Wróbel, M. (2021, February). Physical modelling of strain induced roughness of copper wire during dieless drawing process. In *Materials Science Forum*(Vol. 1016, pp. 900-905). Trans Tech Publications Ltd.

## **General Conclusion**

The research carried out within the framework of this master's thesis is a contribution to the work related to wire cross-section reduction processes using the method called the Dieless Process. To achieve our objectives, a dieless process cross-section reduction machine was developed.

This machine consists of a thermal part for heating the wire and a mechanical part for drawing the wire under a well-defined load. Note that the heating is performed using induction heating.

The metal wire studied is a copper wire manufactured by wire drawing. We studied copper wires of different diameters. These wires underwent cross-section reduction using this machine under different loads and heating times. The heating temperature was kept constant (360°C) for all cross-section reduction operations.

The most important results obtained are as follows:

- The lower the applied load and the longer the heating time, the smaller the wire cross-section.
- The microstructure of the heat-affected zone of the wire during the dieless process is characterized by a grain growth reaction. This heat-affected zone has a lower hardness than the non-heat-affected zone of the wire.

### **Prospects:**

It would be preferable to continue research to further reduce the wire cross-section and obtain a thinner wire.

## Abstract

This dissertation presents a simple setup for dieless drawing of thin copper wires using localized heating and weights. The results showed it is possible to reduce wire diameter smoothly without breakage, proving the method's efficiency and potential. The metal wire studied is a copper wire manufactured by wire drawing. It was found that the lower the applied load and the longer the heating time, the smaller the wire cross-section. The microstructure of the heat-affected zone of the wire during the dieless process is characterized by a grain growth reaction. This heat-affected zone has a lower hardness than the non-heat-affected zone of the wire.

## Résumé

Ce mémoire présente un dispositif simple pour le tréfilage sans filière de fils de cuivre fins, en utilisant un chauffage localisé et des poids. Les essais ont montré qu'il est possible de réduire le diamètre sans rupture, confirmant l'efficacité de la méthode. Le fil métallique étudié est un fil de cuivre tréfilé. Il a été constaté que plus la charge appliquée est faible et plus le temps de chauffage est long, plus la section du fil est petite. La microstructure de la zone affectée thermiquement du fil pendant le procédé sans matrice est caractérisée par une réaction de croissance des grains. Cette zone affectée thermiquement présente une dureté inférieure à celle de la zone non affectée thermiquement du fil.

## ملخص

تعرض هذه المذكرة نظامًا بسيطًا لسحب الأسلاك النحاسية الرفيعة بدون قالب باستخدام تسخين موضعي وأوزان. أظهرت النتائج إمكانية تقليل القطر بسلاسة دون انقطاع، مما يؤكد فعالية الطريقة. السلك المعدني المدروس هو سلك نحاسي مُصنَّع بتقنية السحب. وقد وُجد أنه كلما انخفض الحمل المُطبَّق وطول زمن التسخين، قلَّ المقطع العرضي للسلك. تتميز البنية الدقيقة للمنطقة المتأثرة بالحرارة من السلك أثناء العملية الخالية من القوالب بتفاعل نمو الحبيبات. وتتميز هذه المنطقة المتأثرة بالحرارة بصلابة أقل من المنطقة غير المتأثرة بالحرارة من السلك.